Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2021.27506

231 (2021) 1–15
August

Desalination in Morocco: status and prospects

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Received 12 January 2021; Accepted 4 June 2021

ABSTRACT

Morocco, like other the Middle East and North Africa countries, is a water-scarce country confronted with dwindling groundwater reserves, due to climate change impact, and a strong dependence on rain-fed agriculture. Thus, sustainable water resources management is a top priority in the national strategy. Seawater desalination was considered as one of the possible responses to satisfy the water demand of overcrowded coastal towns. The greatest constraints of seawater desalination remain its energy consumption per cubic meter of produced water and the environmental impacts due to the discharge of brines into the natural environment. Despite the many advantages of desalination, its environmental impact, therefore, remains a major concern. Its advantages and drawbacks must be assessed in terms of costs and benefits, societal and environmental aspects, and compared to other freshwater production processes. The objective of this work is twofold. Firstly, the objective is to present thoroughly a bibliographic study on water desalination by highlighting the problems related to energy consumption, fouling and brine management. With an aim to provide an insight on the cost of desalination, this review collates different research studies which evaluate and compare the economic cost of the produced water by three based-membranes processes, nanofiltration, reverse osmosis and electrodialysis, for seawater and brackish water desalination. The second objective meant to review the Moroccan experiences on seawater and brackish water desalination with the technologies used and their operating status. This part of the study is done through synthesis and analysis of expert reports established in the desalination field, which are consulted in the context of the bibliographic research. Finally, this review also focuses on the Moroccan experience in the use of unconventional water for irrigation, with a particular emphasis on the Agadir desalination plant.

Keywords: Morocco desalination plants; Economic cost desalination; Reverse osmosis; Membrane; Renewable energy; Brine management; Seawater; Brackish water; Unconventional water

1. Introduction

Water is one of the most abundant substances on earth. Every day, humans accomplish a remarkable variety of industrial, agricultural and domestic activities, which directly or indirectly affect the use of water in very large quantities. The geographical position is one of the factors, which have a considerable influence on human water consumption, for example, the Saharan Region of Africa and the Great Lakes region of North America. In the United States, the average water consumption reaches 400 L per person per

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day [1], while it can decrease in other Western countries to 150 L, where actions have been implemented with success in reducing demand for freshwater [1]. On the other hand, in different African countries which suffer from severe water shortages, the consumption of freshwater is of the order of 20 L per day per capita [2]. In addition, the World Health Organization (WHO) recommends a freshwater survival limit of 15 to 20 L which can only guarantee basic needs such as drinking, food preparation, personal hygiene and laundry [3]. This minimum amount must be increased significantly, up to 50 L per person per day, to guarantee needs beyond individual needs, such as those related to hospitals, schools, basic infrastructure, etc.

Based on the above, not all water resources available on the earth are readily usable. Freshwater resources that are ready to use due to low salinity represent only 2.5% of the total water present on the earth. Only 30% of total freshwater is potable, that is, 0.75% of the total water on earth, with 70% as inaccessible resources in the form of glaciers and snowcaps, 30% as groundwater, and 0.27% as surface water [4]. Saline water represents almost 97.5% of total water present on earth and accessible to nearly all countries, making desalination the only option choice to secure water supply in many water-stressed countries [5]. The current global desalination capacity is almost 100 million cubic meters per day (MCM/d) from about 16 thousand plants in 175 countries around the globe, with the Middle East and North Africa (MENA) countries holding about 50% of the desalination capacity [6].

In 2016, the total production capacity of desalinated water by all operating desalination plants around the world was 95.6 million m^3/d supplied by, approximately, 18,983 projects [6]. At the end of 2017, the declared production capacity was 99.8 million m^3/d [7]. Thus, in 2020, the number of desalination plants amounted to 20,971 projects which is translated into a significant increase in desalinated water production into 114.9 million m^3/d [8,9]. The most desalination technologies used in these projects are reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MED), electrodialysis (ED), and hybrid technologies with a share of 63%, 23%, 8%, 3%, and 3%, respectively [10,11]. This trend confirms continued growth in the desalination market.

In this context, current water desalination technologies are available and classified into two categories, thermal-based processes involving a change of phases; freezing and distillation (MED and MSF [12,13]) and membrane-based processes; RO and ED. Among the aforementioned processes, distillation and RO are technologies whose performance has been proven for seawater (SW) and brackish water (BW) desalination. These two processes are the most marketed in the world desalination market. The other techniques such as membrane distillation [14], forward osmosis [15], capacitive deionization (CDI) [16], freezing [17], humidification–dehumidification [18] and gas hydrate-based desalination [19] have not experienced significant development because of problems generally associated with energy consumption and/or the size of the required investments. A lot of expectations and results are being put into these new technologies, which are still either, at the laboratory scale or pilot scale. In addition, there are a number of technologies, which have other supporting and pretreatment applications to increase the performance and efficiency of desalination plants. These include ultrafiltration (UF) [20], nanofiltration (NF) [21] and ion filtration [22]. Besides, the hybrid desalination technologies such as MSF-MED [23], MED adsorption (MED-AD) [24] and RO-MSF [25] are a judicious way to increase the efficiency of desalination plants and overcome the shortcomings of each technology.

Morocco, by its geographical position, climate, its coastline, is strongly impacted by climate change. Global average warming over the entire territory estimated at around 1°C, temporal and spatial variability of precipitation with a significant decrease ranging between 3% and 30% depending on the region, acceleration of extreme phenomena (especially droughts and floods) constitute the main phenomena identified in Morocco during the last decades. This climatic situation has a negative impact on several sectors, in particular the production of water intended for drinking water and agriculture. In the latest decades, surface water runoffs are low and irregular. They originate from a few floods, often brief and intense. Rainfall presents significant regional disparities (Fig. 1).

In this context, the major part of the water demand of the country, which suffers from a significant water deficit is found mainly in the basins of Bou Regreg, Oum Errabiâ, Tensift and Souss-Massa, and Moulouya. Of the total available water resources, generated by efficient rains, only 16 billion m^3 can be mobilized under acceptable technical and economic conditions. In fact, the average annual rainfall is greater than 800 mm in the wettest region in the north and less than 50 mm in the basins of Sakia El Hamra and Oued Eddahab in the south.

Overall, Morocco has natural water resources potential estimated, an average year, as about 20.7 billion m^3, which is an average per capita allocation of about 691 m^3/y. Besides these inherent characteristics, the water potential is highly prompted, with overexploitation of the near-total of the country's aquifers. This leads to a significant drop in piezometric levels, a reduction inflow, if not the drying up of springs, a disruption and decline of traditional irrigation and oases.

The increase in this potential is being mobilized for the large-scale development of irrigated agriculture on around 1.6 million ha, which, although consuming considerably is still far from producing any impressive results. Water losses (unaccounted for water) in irrigation and drinking water distribution are estimated to 4,790 million m^3/y, of which 2,300 million m^3 are considered as recoverable under acceptable technical and economic conditions.

To alleviate the problems of water scarcity, the mobilization of unconventional water resources in Morocco, in particular the desalination of SW and BW or the reuse of treated wastewater, is an option to be considered in parallel with the actions demand management, especially since Morocco has 3,500 km of coastal potential and BW of the order of 500 million m^3 [27]. The map in Fig. 2 shows all the country's water tables and their salinity levels. Salinization and degradation of groundwater quality are due to high evaporation, low recharge, seawater intrusion, intensive agriculture (nitrate, fertilizers, and pesticides) and also the lack of wastewater treatment [27].

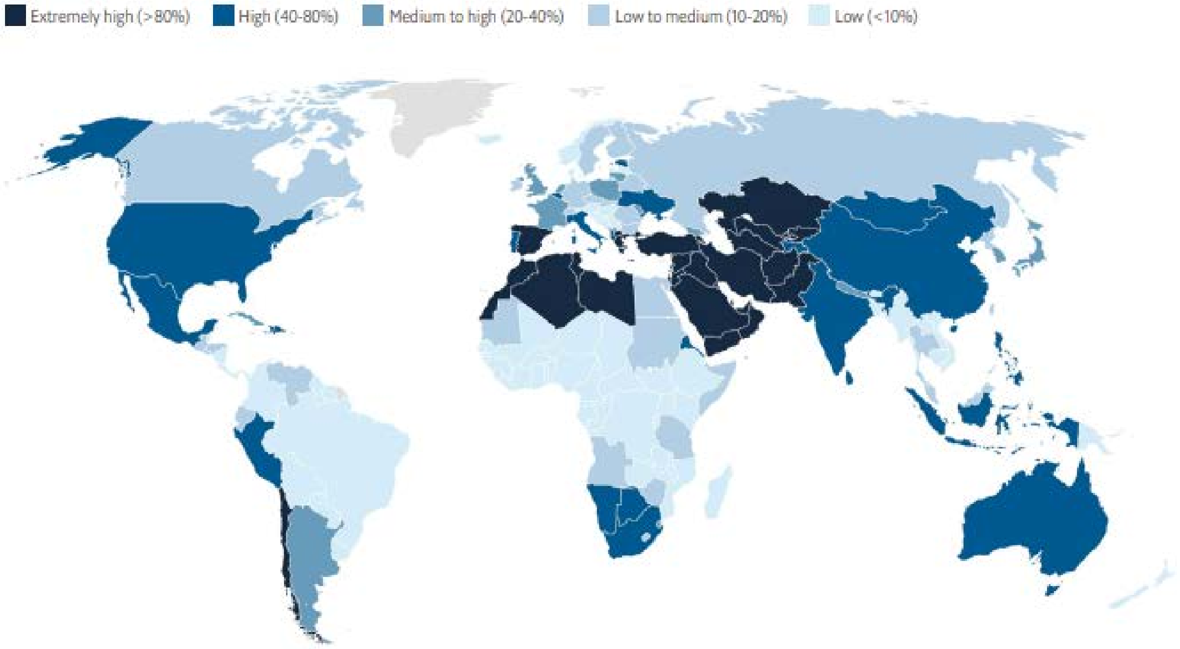

Fig. 1. Water stress by country (Ratio of water withdrawals to water supply, 2040 forecast) [26].

Morocco has garnered 30 y experience in the field of SW desalination and brackish demineralization, which has provided it with a capacity installed of 20,000 m^3/d, which represents 1.5% of the national drinking water production capacity [28–30]. The rest of the drinking water sources are shared between groundwater and surface water with a percentage of 33.5% and 65%, respectively. In fact, the main plants are located in the Southern provinces (Laâyoune, Boujdour, Tarfaya and Tan Tan), owing to almost nonexistent conventional water resources in these zones.

As over a half of the urban population lives on the coast or near the sea, the desalination of SW or BW can, indeed, represents a suitable solution not only for the cities of South but also for large cities of center and north. In fact, projects have already been incepted in Agadir, El Jadida, Laâyoune and Tan Tan.

On other hand, Moroccan research works have been carried out recently on desalination by freezing. These studies aimed to develop a process for desalination of SW by freezing on cold. These tests were performed at the laboratory scale with synthetic solutions of NaCl of different concentrations, as well as with SW from Rabat, Nice and Marseille. The results obtained show the feasibility of the technique and give a good idea of the operating conditions that can be employed to produce drinking water [31].

The aim of this work is twofold, the first objective is to present thoroughly a bibliographic study on water desalination by highlighting the problems related to energy consumption, fouling and brine management. With an aim to provide an insight on the cost of desalination, this review collates different research studies which evaluate and compare the economic cost of the produced water by three based-membranes processes, NF, RO and ED, for SW and BW desalination. The second objective meant to review the Moroccan experiences on SW and BW desalination with the technologies used and their operating status. This part of the study is done through synthesis and analysis of expert reports established in the desalination field, which are consulted in the context of the bibliographic research. Finally, this review also focuses on the Moroccan experience in the use of unconventional water for irrigation, with a particular emphasis on the Agadir desalination plant.

2. Components of BW and seawater reverse osmosis desalination plants

Desalination processes make freshwater from the separation of salt from SW or BW. SW, in abundance, constitutes a reliable sustainable source of freshwater, with high potential to fulfill the continuously increasing freshwater demand of the future.

Freshwaters may have total dissolved solids (TDS) up to 1,500 ppm, brackish waters exhibit TDS in the range of 3,000–10,000 ppm, it is sometimes surface water but most often groundwater, and its TDS is higher than freshwater (TDS < 1 g/L) and lower than SW. While TDS of SW typically ranges from 10,000 ppm (as in the case of the Baltic Sea) up to 45,000 ppm (as in the Arabian Gulf). Low TDS may be a result of the presence of inflow from rivers and melting icecaps, as well as due to the abundance of precipitation. High TDS may be a result of the remoteness from land and of high temperatures promoting evaporation [32–34].

Moreover, a Long-term consumption of water with high TDS can cause digestive diseases, skin infections, hypertension, kidney stones and even various types of cancers [32]. On other hand, prolonged use of BW for agricultural irrigation will deteriorate the structure of the soil, which can affect the permeability and water retention performance of the soil abnormally crops to grow. In addition, industrial use of BW is also problematic to the equipment due to the high TDS contained in water.

Based on the above, desalination of BW and SW by thermal processes (e.g., multi-stage flash, multi-effect distillation) [35] are rarely used compared to membrane processes (e.g., RO, ED, NF) due to their flexibility in water supply and processing capacity, adaptability of source water quality, small equipment footprint, simple operation and low capital and operating costs [35–39].

Generally, a desalination plant consists of three stages: pretreatment, the desalination process itself (thermal or membrane processes) and post-treatment (f. 3).

2.1. Pretreatment

The choice of pretreatment is fundamental in a membrane desalination process because it makes it possible to protect the membrane against mineral, organic or bacterial fouling which would quickly cause a dysfunction of the membrane stage, if it proved insufficient.

Pretreatment is intended to:

- Reduce strongly the turbidity of raw water as well as the suspended matter associated with it.
- Eliminate all forms of hydrocarbons present in raw water.
- Eliminate algae during their seasonal development.
- Reduce strongly the clogging power of water by treating by adsorption, absorption or precipitation all the mineral or organic substances that take part in it.

Pretreatment processes can be divided into two categories: physical pretreatments and chemical pretreatments. Physical pretreatments include mechanical pre-filters, cartridge filters, sand filtration, dissolved air flotation and membrane filtration. Chemical pretreatment involves the addition of scale inhibitors, coagulants, disinfectants and polyelectrolytes.

Today, most RO plants use a conventional pretreatment process, which generally consists of physical and chemical pretreatment without a membrane process.

With the constant fall in the price of membrane elements and the deterioration in the quality of water resources, pretreatment by membrane processes such as microfiltration, UF and NF is increasingly finding its place in the pretreatment stages before RO [40,41].

Usually, the BW from underground is good in terms of quality and it does not require membrane pretreatment or sand filters, cartridge filters are enough to separate the colloidal particles. In seawater reverse osmosis (SWRO) desalination plants, for example, it is more frequent to install sand filters behind the cartridge filters. Surface water almost always requires additional pretreatment. There are many colloidal fouling indices in the field of membrane water treatment, which help to assess the effectiveness of the pretreatment. The most commonly used by membrane manufacturers is the Silt Density Index, introduced by the company DuPont (France) 40 y ago, developed by the ASTM (American Society for Testing and Materials) under the reference ASTM D4189-07. This test corresponds to the evaluation of the phenomena that occurs during the first phase of fouling by accumulation in the pores of the membrane. Modified Fouling Index is the second most used method [42], which was recently approved by the ASTM (ASTM D8002-15) [43].

The desalination process receives pretreated water to separate the solvent (water) from salts and to produce water ready for post-treatment. This operation leads to two output streams, the permeate or product water, and the concentrate or brine.

2.2. Desalination process

There are several available technologies for water desalination. Among them, RO, which is now very widely used. This technology operates at room temperature and does not involve phase change as in thermal methods. For desalination of SW, this technology requires a very high pressure in order to separate salt from water, and the water recovery rates are low, slightly above 50%, which means that half of the volume of treated SW is recovered in brine. This operation is done by the high-pressure pump that pumps raw water with enough pressure to overcome the osmotic pressure. Two types of pumps are used in RO desalination plants: centrifugal and positive displacement pumps. Centrifugal pumps are used in medium to large-scale RO systems since they are easier to install and operate than positive displacement pumps, which are more frequent in smaller plants. Usually, the operating pressure needed for BW desalination ranges from 5 to 25 bar (and the water recovery rate is high), and between 55 and 70 bar for SW [13,44–46]. This pressure depends on the characteristics of the feed water, the water recovery rate, the required quality of permeate water, and the configuration of the RO system.

2.3. Post-treatment

During post-treatment, water is conditioned differently depending on its purpose: human consumption, agricultural irrigation, industrial use, boilers, or any other. This step generally includes mineralization with reducing its corrosive properties, and then disinfection. The techniques used for remineralization aim to increase the calcium hardness and alkalinity of the desalinated water to make the remineralized water-stable when it is released into nature or water distribution networks. There are various ways to remineralize desalinated water. However, those used most often in practice are remineralisation with calcium carbonate and carbon dioxide, and with calcium hydroxide and carbon dioxide. Next, disinfection consists of adding chlorine or other chemical agents (sodium chloride or chlorine dioxide) that can help to eliminate micro-biological material that managed to pass through the membranes or could have found their way into the stored desalinated water, ensuring that it meets with drinking water standards required for public distribution. In addition, in the last few decades, alternative systems to conventional disinfection methods were developed. The most promising ones are based on the in-situ electrogeneration of disinfection agents (electrochemical water disinfection). These technologies are environmentally friendly, economically and operationally competitive; they are also applicable to a wide range of microbiological contaminations in water [47]. Finally,

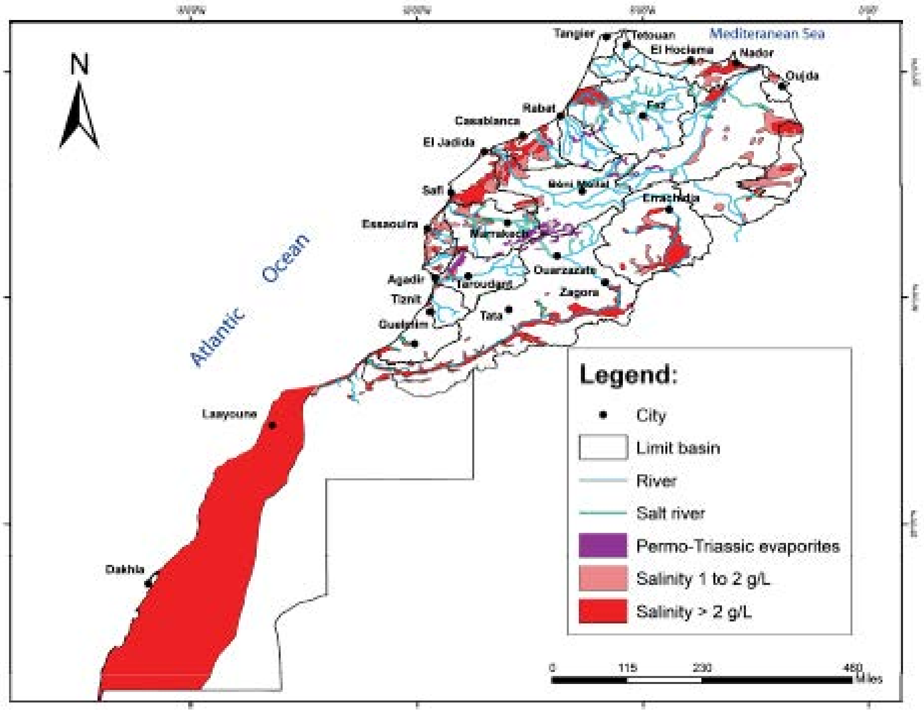

Fig. 2. Spatial distribution of saline groundwater in Morocco [27].

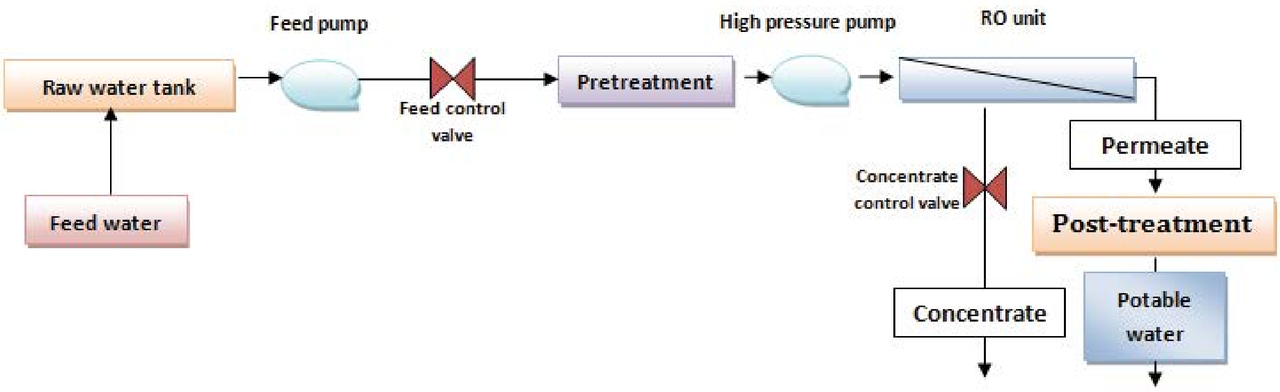

Fig. 3. Basic design model of a RO water desalination system.

the adjustment of pH or the addition of other chemicals is needed in the post-treatment, this operation depends on the quality of the produced water [48].

3. Desalination experiences in Morocco

Morocco is committed to mobilizing unconventional water to alleviate the water deficit. These are the reuse of treated wastewater, the artificial recharge of groundwater and the production of freshwater by desalination of SW or demineralization of BW for supplying drinking water to the provinces, which are poorly endowed with conventional water. The seven-year plan 2020–2027, which defines the national program for drinking water supply and irrigation, covering all aspects related to water, in particular improving and securing the available supply water capacity, has a budget of $12 million.

Currently, the use of SW desalination and the demineralization of brackish groundwater for the supply of drinking water to cities and centers in deficit is limited to the Saharan areas of southern Morocco. The capacity was around 13.11 million m^3 in 2011 (35,910 m^3/d including 5,030 m^3/d of BW demineralization; [49], but it is expected to increase to over 100 million m^3 in 2020, with in particular the installation of a desalination plant in Agadir [28], Sidi Ifni and Tan Tan (10,000 m^3/d) [50] and 400 million m^3 in 2030 according to the national water strategy [51].

In addition to the mobilization of unconventional water and the desalination of SW, Morocco is orienting its water management policy towards the rationalization of demand. The low efficiency of water use manifests itself in poorly performing irrigation systems and drinking water distribution networks causing significant losses in water volumes. Efforts are being made to save water in irrigation by promoting the adoption of localized irrigation systems as well as in drinking water consumption by improving distribution networks and billing.

3.1. National Office for Electricity and Drinking Water case

Historically, in 1973 the National Drinking Water Supply Master Plan highlighted the need to use desalination of BW and SW as a drinking water supply solution. Since then, the National Office for Electricity and Drinking Water (ONEE) has carried out several projects relating to the construction, operation and maintenance of desalination plants, mainly in the southern provinces, for reasons of aridity of the climate, scarcity of conventional water resources, but also due to the availability of SW resources and the competitiveness, in terms of desalination cost compared to other methods of supplying drinking water. In fact, it was in 1975 that the first installation for demineralization by ED of BW was installed in the center of the town of Tarfaya, with a production capacity of 75 m^3/d. Two years later, the city of Boujdour was equipped with a mechanical vapor compression distillation unit, producing 250 m^3/d of freshwater from SW [29,52].

The scarcity of water resources in the southern provinces and the socio-economic development of the region led ONEE to further accentuate its efforts in the use of SW desalination techniques to meet the growing needs of the population and by the end of the 1990s, the choice of ONEE will focus on RO instead of other processes.

Thus, to supply the city of Laâyoune, ONEE built one of the biggest SWRO plant in 1995 with a capacity of nearly 7,000 m^3/d expandable to 26,000 m^3/d after the completion of two phases in 2005 and 2010 [53].

The town of El Marsa, the Center of Foum El Oued and the fishing village of Tarouma in the province of Laâyoune are also supplied using this desalination technique. In the city of Boujdour, a new desalination plant has just been commissioned as part of the new development model for the southern provinces with a production capacity of up to 7,000 m^3/d, thus allowing to meet the city's needs at middle term.

Today, ONEE supplies around ten localities with drinking water from SW desalination or BW demineralization, with a total service capacity of around 100,000 m^3/d. These localities are mainly Lâayoune, Boujdour, Dakhla, a fishing village in Sidi El Ghazi, Daoura, Tan Tan, Akhfennir, Tarfaya, Tagounite and Khénifra [53,54].

Other desalination projects, but also demineralization, are being developed by the Office by 2020, totaling a capacity of around 300,000 m^3/d, in particular at Lâayoune with a capacity of 26,000 m^3/d, Sidi Ifni (8,600 m^3/d), Zagora (demineralization: 5,200 m^3/d), Tarfaya (1,296 m^3/d), Al Hoceima with a capacity of 17,300 m^3/d [53]. Table 1 and Fig. 4 summarize some of ONEE's achievements in SW desalination and BW demineralization [29,52–54].

3.2. ONEE and Department of Agriculture

One of the biggest desalination projects is currently being installed in Morocco's southern coastal city of Agadir, it called Douir SWRO plant. It is the first shared project (Public private partnership) under construction, the desalinated water produced would be dedicated jointly to the supply of drinking water and irrigation. This project has a budget of 3 billion Moroccan dirhams, and a treatment capacity of around 75 million cubic meters of desalinated water per year. In addition, the plant is expected to produce nearly 275000 m^3 of desalinated water daily before reaching its maximum capacity of 450,000 m^3/d. It will be accompanied by reservoirs for storing drinking water, at least five pumping stations, 22 km of pipelines and about 490 km of distribution network. At least 150,000 m^3/d of water is dedicated to fresh water needs and will be transported daily to greater Agadir, including the city and the territory. 125,000 m^3/d (part of the water treated by RO will be used to supply an irrigation system in the Chtouka plain (area of 13,000 ha) [55]. It is an unprecedented realization in SW desalination that is under construction. The process of desalinating water by RO is quite energy-intensive. In order to reduce the plant's electricity consumption, it is

Table 1
Achievements of ONEE in SW desalination and BW demineralization

City	Technology	Water nature	Production capacity (m^3/d)	Year of commissioning
Tarfaya	ED	BW	75	1976 (replaced by the unit realized in 2001)
	RO	BW	800	2001
Boujdour	MED – VCD: Vapor Compression Distillation	SW	250	1977 (replaced by units realized in 1995 and 2005)
	RO	SW	3,700	1995–2005–2011
Laâyoune	RO	SW	26,000	1995–2005–2010
Tan Tan	RO	BW	12,000	2003–2014
Akhfenir	RO	SW	860	2011
Tagounite	RO	BW	400	2008
Khenifra	RO	BW	30,000	2012
Dakhla	RO	BW	17,280	2015
Khouribga	RO	BW	30,000	2019

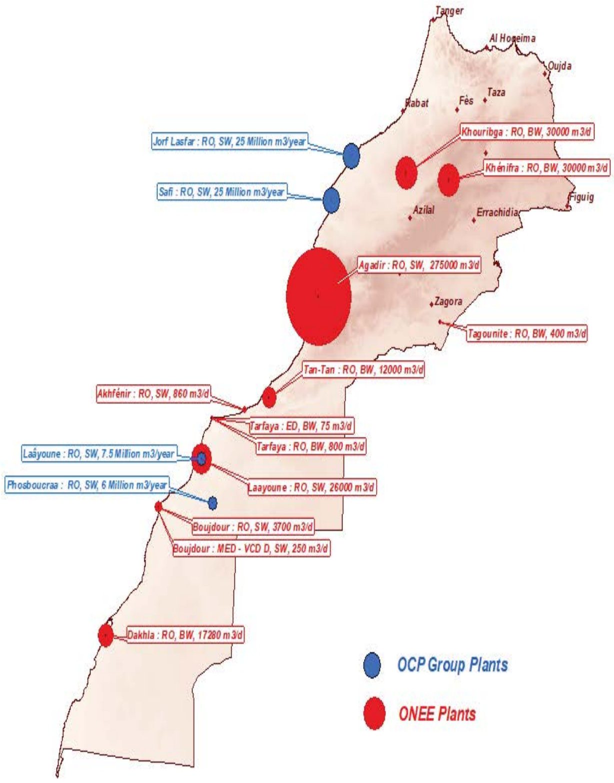

Fig. 4. Desalination projects developed and under development by ONEE and OCP Group in Morocco. Disk sizes are based on plant capacities.

chosen to install a pressure exchanger system, which is derived from high-pressure filtration, which allows energy to be recovered. The system has a very positive impact on the cost of energy, which is estimated to reduce by about 43% per m^3 produced [56]. ONEE expected to devote additional investments of 66 Million Dollars for the construction of 44 km of pipelines, 35,000 m^3 drinking water tank, the installation of 3 high voltage power lines over 55 km from the Tiznit source plant which is already connected to the Noor Ouarzazate solar complex and the construction of two pumping stations and two loading tanks [55]. The specifications of the Chtouka Ait Baha project are the following (Table 2).

3.3. *Office Cherifien des Phosphates group case*

Before 2005, the Office Cherifien des Phosphates (OCP) Group used thermal processes (MSF, TC) to meet its water needs in the industrial process. While from 2005, the group abandoned thermal processes in favor of RO (the first realization is the plant of Laayoune station, 4000 m^3/d).

Table 2
Specifications taken from the Chtouka Ait Baha project [56]

Desalination technology	RO
Daily water production (m^3/d)	275,000
Annual availability rate (%)	95
Amortization (y)	20

Moreover, the OCP Group has undertaken a vast program to develop its mining and industrial capacities which will ultimately bring this capacity from 23 to 50 million tons of phosphate per year. The effort to increase production capacity is naturally accompanied by an increase in water needs, which will go from 66 million m^3/y currently to more than 158 million/y. Water is a key resource at the heart of the phosphate industry.

In a citizen-based and voluntary approach, the OCP Group launched in 2008 his first "Water Program" with the aim of abandoning conventional water resources for its needs by 2020. This program was followed by another one "Sustainability Circular Economy" in 2018, in which the OCP Group targets to cover 100% of its water needs exclusively from unconventional water resources including the reuse of treated wastewater and desalination of SW. The "Water Program" is fully in line with the achievement of the United Nations Sustainable Development Goals. It addresses international challenges in clean water and sanitation, responsible consumption and production, action on climate change and the challenge of building strong and inclusive partnerships to achieve the United Nations Sustainable Development Goals.

The "Sustainability Circular Economy" initiative is jointly aimed at the preservation of phosphate resources and strategic conventional water resources for Morocco. Many R&D and innovation projects were launched by OCP Group in partnership with various partners to implement innovative solutions based on advanced technologies for the use of water in the industrial process.

OCP Group is using more desalinated SW in its manufacturing operations. The Jorf Lasfar complex is supplied by the largest SWRO desalination plant in Morocco, with an annual capacity of 25 million m^3. An extension to the station, planned for 2021, will increase capacity to 40 million m^3/y. At Laâyoune, a station with a capacity of 7.5 million m^3 is planned to meet the water needs of Phosboucraa by 2022, adding to a current station of 1.2 million m^3.

All the desalination programs are summarized in Table 3 and Fig. 4.

4. Membrane processes economics

4.1. Economic cost of the produced water by RO and electrodialysis reverse

Improvements in membrane technology and the development of energy recovery systems are important factors in reducing significantly RO water production costs. Different studies have dealt with this role according to the capacity plant. With desalination plants ranging from 100,000 to 320,000 m^3/d, the cost of water production varies between 0.45 and 0.66 US$/$m^3$. Whereas, plants with a medium capacity of between 15,000 and 60,000 m^3/d reported a water production cost ranging from 0.48 to 1.62 US$/$m^3$. Thus, the cost varies between 0.7 and 1.72 US$/$m^3$ for small-scale plants ranging from 1,000 to 48,000 m^3/d.

In this context, RO and ED are two technologies that suit for BW treatment (TDS < 10,000 ppm). Different researches have compared economically the two technologies, RO and ED, for BW treatment depending on the quality of the water to be treated. In the case of salinity higher than 5,000 ppm, RO is the most economical technology; whereas, ED is more economically profitable only in the case of water salinity lower than 5,000 ppm and a high recovery rate. In addition, the water production cost of large capacity BWRO treatment plants (40,000–46,000 m^3/d) range from 0.26 to 0.54 US$/$m^3$, whereas the water production cost of electrodialysis reverse plants range from 0.6 to 1.05 US$/$m^3$, with cost depending greatly on the salinity of the feed water [59–65].

4.2. Economic cost of the produced water by NF

The assessment of the economic cost of NF itself depends on several factors: flow rate, plant capacity, feed water characteristics and the quality required for the produced water [44,47,48,66–70].

Different studies have established models to estimate the investment and operating cost of NF. Table 4 gives the cost per cubic meter of some NF plants.

5. Renewable energy sources for desalination

5.1. Renewable energy: Moroccan strategy

Morocco has adopted since 2009, under the High Royal Guidelines, an energy strategy, which has set for objective the rise of renewable energies, the strengthening of energy efficiency and regional integration. This strategy has been broken down into road maps with short, medium and long-term objectives, accompanied by a clear vision of legislative, regulatory and institutional reforms. The period 2009–2013 saw the launch of the National Priority Action Plan (NPAP), with a view to restoring the balance between electricity supply and demand by acting, on the one hand, on the strengthening of production capacities by the realization of an additional capacity of 1,400 MW and, on the other hand, on the rationalization of the use of energy [74]. For the medium term, the objective set for 2020 is to increase the share of renewable energies to 42% through the development of an additional clean electricity production capacity of 3,000 and 6,000 MW by 2030 [74,75].

The evaluation of the implementation of the first phase of the strategy yielded very encouraging results. Thus, in December 2015, Morocco set a new objective to accelerate its energy transition by increasing the share of renewable energies from 42% of installed capacity planned for 2020, to 52% by 2030 [74,75].

Legislatively, renewable energy projects (Fig. 5) are made possible thanks to the implementation of many regulatory and institutional provisions [76].

5.2. Renewable energy-driven desalination systems

Desalination technologies have become necessary and unconventional waters are required for hydrological planning as is the case for conventional water resources. One of the main obstacles to the implementation and extension of a desalination plant is the high cost of the produced water, which is strongly impacted on the one hand by energy consumption (accounts for 50%–60% of the total cost) and on other hand, by the operation cost, maintenance and investment [7].

Renewable energy systems such as solar thermal, solar photovoltaic, wind, and geothermal technologies are currently used as energy suppliers for desalination systems. This coupling is a reliable and particularly promising process

Table 3
OCP Group SW desalination program [57,58]

Plant	Capacity (million m^3/y)	Objective	Year of commissioning
Jorf Lasfar	25 to 40	Manufacturing operations	2021
Safi	25	OCP Group needs	Under project
Phosboucraa	6	OCP Group needs	Under project
Laâyoune	7.5	OCP Group needs	2022

Fig. 5. Renewable energy projects (developed and under development) in Morocco [75].

Table 4
Cost per cubic meter of some NF plants

Type of water	Capacity (m^3/d)	Cost of product water (US$/$m^3$)	Information source
Surface water	100,000	0.214	[71]
	53,000	0.23	[72]
Underground water	20,000	0.23	[73]

for remote areas where there is no access to the electricity grid and where water is extremely scarce. As the technologies continue to improve, and as freshwater becomes scarce and fossil fuel energy prices rise, renewable energy desalination becomes more viable economically. In addition, many studies repeatedly addressed one of the major environmental impacts of the desalination process, which is the high carbon footprint due to energy consumption (indirect impacts). Powering desalination processes with renewable energy resources is considered the main solution to address this problem with interesting rates [10].

Until today, the most important SW desalination plant using PV energy was built in Al Khafji, Saudi Arabia with a production capacity of 65,000 m^3/d. At Kwinana close to Perth (Australia), the important SW desalination plant (2007) with a production capacity of 144,000 m^3/d works exclusively with energy from the wind farm located 200 km north of Perth. The cost of the produced water in the Perth plant is estimated at AUS$1.17/$m^3$ (0.852 US$/$m^3$) [77–79].

A review of published studies proves that the cost of drinking water produced by a desalination plant coupled with renewable energy varies significantly depending on various factors such as solar or wind profile of the plant location, feed water quality, plant capacity, a renewable resource used for power generation and off-grid or grid-connected operation. Below is a summary of some of the available technologies, water production capacity and costs:

- The size of the PV-based desalination system varies from 0.8 to 60,000 m^3/d, and the declared cost of the produced water, in this case, is approximately US$34.21 to 0.825/$m^3$ [80].
- The size of desalination plants based on wind energy varies from 1 to 250,000 m^3/d, and the cost is approximately $15.75 to 0.66/$m^3$ [80].
- In many countries and regions, desalination systems based on hybrid wind-photovoltaic energy have been implemented, ranging from 3 to 83,000 m^3/d, and the cost of the water from this combination ranges from US$6.12 to US$1.4/m^3 [80].

In this context, Morocco has proceeded, a long time ago to the use of other non-conventional water resources such as desalinated water. At the same time, Morocco has been exploiting two locally important and natural resources of renewable energies available in the country, especially solar and wind energies. In March 2014, the first decentralized desalination plant, using NF coupled with renewable energies (photovoltaic and wind), was launched at Al Annouar high school of Sidi Taibi, Kenitra. This project was designed to supply the 1,200 students of the school with potable water, with a production capacity of 500 L/h (3L/d/student). The local underground water, which is slightly brackish and nitrated, has been treated by NF, using both renewable energy processes [47,70,81]. Today, it is the only demineralization plant in operation using a based-membrane process coupled with a renewable energy production and storage system in the country. After six years of operation, the plant shows the stability of hydraulic performance, electricity production, retention performance and lower energy consumption. This kind of decentralized desalination plant using the NF membrane process is a promising way to provide water especially in rural areas and remote zones that are suffering from water scarcity and who do not have access to the electric grid and where solar radiation and wind speed are abundantly available.

6. Limitations and challenges of desalination

6.1. Energy consumption

The desalination of SW and BW for drinking purposes is limited by the high specific energy consumption (SEC) (kWh/m^3). This is in turn dependent on plant capacity, unit design, materials used and the SW feed stream quality [22,82]. It should be noted that the energy consumption in distillation processes (MSF, MED and VC) is not influenced by the salt concentration in the feed water, while it is highly influenced by the salt concentration in the membrane processes. This is due to the high osmotic pressure, which is related to the TDS of the feed water. Therefore, water with high TDS requires a higher amount of energy. In addition, thermal desalination technologies have been replaced with membrane processes due to their lower energy consumption, especially RO membrane [83]. Many studies confirm that RO unit sizes vary from a very small unit with a plant capacity of 0.1 to a 395,000 m^3/d. The average reported energy consumption ranges from 3.7 to 8 kWh/m^3 [84,85]. The consumption may exceed 15 kWh/m^3 for small sizes units. For a typical size SWRO unit of 24,000 m^3/d, the electricity consumption ranges from 4 to 6 kWh/m^3 with an energy recovery (ER) system for SW. On other hand, BW desalination needs a low pressure compared to SW desalination. Therefore, different membranes are used and much higher recovery rate is possible, which makes energy consumption low. For a BWRO unit, the electrical energy consumption ranges from 1.5 to 2.5 kWh/m^3 [84,85].

However, some devices reduce the energy consumption of the high-pressure pumps and hence the SEC of the plant. The first energy recovery device (ERD) used in SWRO desalination plants were the Francis turbines at the beginning of the 90s with a yield of around 77% achieving an SEC of 4–5 kWh/m^3. Subsequently, another device, the Turbocharger, was incorporated with a yield of 80%, which could achieve a reduction in energy consumption of 30%. Later, in the late 90s, the most frequently used energy recovery was the Pelton turbines. This device consists of a drum with buckets, mounted on a common shaft, with an electric motor and a high-pressure centrifugal pump (Fig. 6). The concentrate stream, which leaves the RO unit under pressure, impinges on the bucket, turns the drum and provides additional torque to the pumping device. The efficiency of current Pelton Wheel energy recovery devices are in the range of 84%–88% [1].

Recently even more efficient energy recovery devices have been introduced commercially. They are called isobaric chambers or pressure exchangers. They arose to avoid efficiency losses associated with the energy conversion produced in centrifugal devices, where hydraulic energy is converted into mechanical energy. The energy savings achieved through these systems can reach 40%, working with high efficiency (up to 97%). It represents an SEC close to 2.5 kWh/m^3 [86]. Representative examples of energy requirements of pumping systems, in an SWRO plant, are given in Table 5.

For BW treatment by NF or RO the energy consumed is about 0.5 kWh/m^3. Therefore, the application of concentrate energy recovery devices would not be cost-effective because

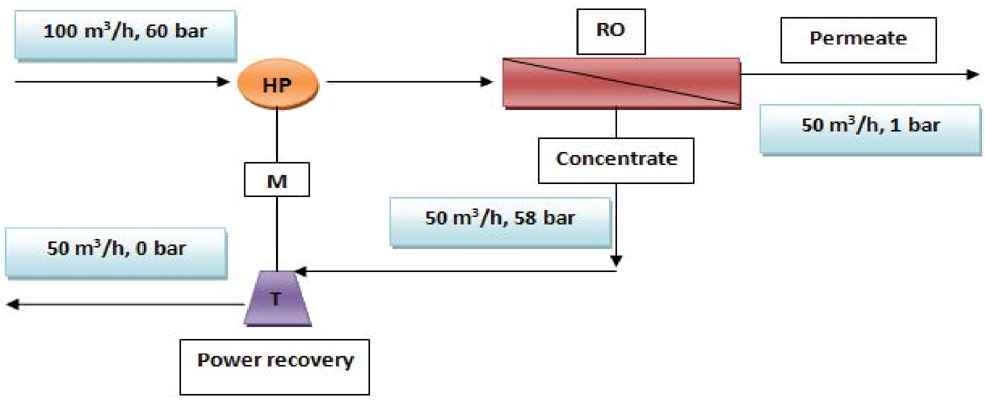

Fig. 6. Configuration of a SWRO unit with a Pelton Wheel energy recovery device. Energy consumption of RO process: 2.60 kWh/m^3 (9.84 kWh/kgallon) [87].

Table 5
Typical values of energy requirements for high pressure pumping equipment in SWRO desalination plants. Feed pressure 6.0 MPa, recovery rate 50% [1]

Configuration	High pressure pump only	High pressure pump with Pelton Wheel	High pressure pump only with isobaric device
Energy use, kWh/m^3	3.9	2.6	2.1
Energy usage reduction, %	–	33	46

the concentrated pressure is low and the flow rate is small (due to a high recovery rate) [1].

6.2. Fouling

Despite the progress made in membrane-based desalination processes, membrane fouling is still considered to be one of the main drawbacks of desalination, considerably affecting operating and maintenance costs [88]. Although several approaches and methods have been proposed in recent years to mitigate fouling, this continues to be a major challenge in desalination operations [89]. Fouling is caused by the unwanted deposition of materials on the surface or inside the pores of the membranes. Depending on its nature, fouling can be classified into four types: organic fouling, inorganic scaling, colloidal fouling and bio-fouling [90]. Organic fouling is caused by natural organic matter present in surface water and SW, such as humic substances, polysaccharides, proteins, lipids, nucleic acids, amino acids, organic acids and cellular components [91]. Inorganic scaling is due to scale formation in the membrane module. Indeed, it is strongly linked to the solubility and the precipitation of certain minerals. Colloidal fouling is influenced by particle size in the colloidal range, shape, charge and ion interaction of colloids [92]. Bio-fouling is due to the formation of a biofilm on the surface of the membrane. Biofilm formation is due to the presence of microorganisms whose growth is affected by temperature, tides, currents, turbidity, nutrients and organic precursors [93].

Fouling affects the overall performance of the process, reducing permeation flow and increasing operating pressure. In addition, the formation of fouling results in an increase in the frequency of chemical cleaning, which can damage and decrease the life of the membranes. In the literature, several fouling monitoring techniques have been proposed to obtain real-time information [94].

Currently, the most reliable approach to obtain more detailed information on the fouling type is to perform a membrane autopsy. An autopsy of a fouled membrane provides detailed information including whether pretreatment is appropriate or whether operating conditions are well managed. The procedure can help find problematic materials (or dominant soils) on the membrane. The most common inorganic colloids found in fouled membranes consist mainly of colloids of iron, aluminum silicate clays, aluminum and silica. According to a previous study, 70% of deposits found in membrane autopsies are associated to organic deposits [95]. Silica plugging has been considered to be one of the most problematic types of plugging, while the catalytic effect of iron and aluminum ions leads to the formation of silica scale below the saturation point [96].

Tran et al. [97] performed a full-scale autopsy of the BWRO membrane (BW30LE-440DRY Filmtec™) after one year of operation with a recovery rate of 75%. As a pretreatment, it had coagulation, flocculation, flotation, dissolved air filtration, pH correction and cartridge filters (5 and 1 μm). The quality of the treated water is characterized by a TDS of 900 mg/L and a pH of 9.1. The main contaminants found were organic-Al-P complexes, aluminum silicates and polysaccharides. In addition, El-Ghzizel et al. [81] performed an autopsy of a NF membrane (NF90 40*40) after 10 months of operation with a recovery rate of 75% and a pressure of 5 bar. The pretreatment used in this plant is composed of two cartridges (25 and 5 μm) connected in series, the first one allows the removal of sludge which may be present in the wellbore, it identifies the size of particles less than 25 μm and the second one allows the removal of fine particles greater than 5 μm. The feed water is pumped from groundwater well which is characterized with a salinity of 796 mg/L. The fouled material found on the autopsied membrane is inorganic consisting mainly of calcium carbonate ($CaCO_3$). Another study was performed on a large-scale BWRO membrane after 6 y of operation. This desalination plant took the raw water from groundwater well which is characterized with a salinity of 6,000 mg/L. The desalination plant had two stages working with a recovery rate of 75%. The plant uses a sand and cartridge filters, acid and antiscalant dosing as pretreatment. Materials deposited on the autopsied membrane surface are inorganic (SiO_2, clay, $CaSiO_3$, Fe_3O_4, $AlPO_4$ and $CaSO_4$) and organic matters (polysaccharide) [98]. On other membrane autopsy study, performed on a full-scale SWRO desalination plant located on the Red Sea, 100 km north of Jeddah in Saudi Arabia, the pretreatment includes a high rate multimedia filtration system spruce media filter, and cartridge filter (CF) micro-filtration units containing wound polypropylene cartridges with a 5 μm nominal pore size. The autopsy of the membrane used in this plant revealed the presence of a heterogeneous fouling layer. The fouled material found is mainly organic and inorganic deposits composed of aluminum, iron, and magnesium silicate [99].

The propensity of membrane fouling is strictly associated with the quality of the feed water. Although many approaches to mitigate fouling can be found in the literature, the most effective fouling control is to improve feed water quality [90,100]. Therefore, a well-designed pretreatment is crucial to improve the performance of the desalination process [101]. Pretreatment processes and design should be selected based on feed water quality and type of intake [102,103]. Several efforts have been made to control and study membrane fouling using different pretreatment technologies [104].

6.3. Brine management

In desalination, the feed water is divided into two streams, the product stream (freshwater) and the by-product stream (brine). Despite the fact that desalination produces freshwater, a crucial environmental issue is the brine coproduced from desalination processes [105,106]. Brine, also known as concentrate or reject, is the highly concentrated saline water produced in desalination processes. This liquid stream contains most of the TDS of feed water in concentrated form, as well as some pretreatment chemicals (e.g., residual amounts of antiscalants, coagulants and flocculants) and microbial contaminant [107]. Brine can be harmful to the environment due to its salinity, temperature and chemical substances. Both brine salinity and temperature depend on the production process. The brine salinity is 1.6–2 times higher than the SW salinity (35 g/L). Regarding the temperature, the brine produced by membrane-based technologies is at ambient SW temperature (22°C), whereas the brine produced by thermal-based technologies is 1.37–1.82 times higher than 22°C [108]. Considering that desalination processes produce significant amounts of brine, different methods of brine disposal have been developed by the desalination industry around the world. These methods include surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application. However, none of the previously listed disposal methods can be widely applied to any type and size of the desalination project [107]. The choice of the most appropriate brine disposal method depends on several factors, mainly quantity, quality and composition of the brine; geographical location of the disposal site; availability of receiving site; the permissibility of the option; public acceptance; capital and operating costs and the capacity of the facility for future expansion [108,109]. The brine disposal cost varies from 5% to 33% of the total cost of the desalination processes and depends on the characteristics and volume of the brine, the level of pretreatment, means of disposal and the nature of the disposal environment [110].

In Morocco the most desalination plants are installed on the Atlantic coast. Until today, the produced quantities of brine are low. So, they are diluted and discharged into the Atlantic Ocean without induce risk to the marine environment. Indeed, unlike Mediterranean Sea which is a closed sea, the Atlantic Ocean is open and the sea currents are strong.

With the development of desalination and the construction of several plants in the future, this brine disposal method appears to be environmentally unsustainable and a new approach should be considered for the brine disposal in Morocco. Recent studies [107] highlight the approach of Zero Liquid Discharge (ZLD) which is a sustainable alternative for brine disposal. In addition to the additional water recovered from the brine, the recovery and valorization of other resources is a significant economic incentive to aim to reduce the overall cost of desalination. The ZLD can be achieved by membrane-based and thermal-based technologies. Hybrid technology offers interesting opportunities and is required because no single technology is capable to achieve ZLD of the brine. The technologies involved are not yet mature, Feasibility, sustainability and technical and economic studies should be carried out on a large scale before industrial application. All these aspects constitute a real research challenge for universities and research development in the near future.

7. Conclusion

Desalination of SW is perceived as one of the most viable solution to the problems of scarcity of drinking water. Besides fouling problem, these technologies remain large consumers of energy and the question of their environmental impact in terms of brine is a major problem to be taken into consideration and studied when setting up a desalination unit. Different methods of brine disposal have been developed by the desalination around the world. These methods include surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application. The technical application of these methods requires a deep study of different factors such as quantity, quality and composition of the brine; geographical location of the disposal site; availability of receiving site; the permissibility of the option; public acceptance; capital and operating costs and the capacity of the facility for future expansion.

On other hand, the problem of energy consumption can be solved by the use of energy recovery devices called isobaric chambers or pressure exchangers in conjunction with control and reduction of fouling. Membrane fouling affects negatively the performance of the desalination plant by the increasing the energy consumed.

To reduce the effect of fouling and biofouling, the best way is to improve feed water quality type of intake. In addition, innovative pretreatments should be put in place to stop species which playing a crucial role in the development of fouling. Online dosing systems for these species can help operators act promptly and do what is necessary as soon as the tolerance thresholds are exceeded. The pretreatment remains the key to optimal operation of a membrane-based desalination plant.

In Morocco desalination can play an important role in facilitating adaptation to climate change, mainly because it allows the diversification of the water supply and increases the capacity to resist to degradation of water quality by producing very pure water, even from heavily contaminated source water. Diversification of water supply can provide alternative or complementary unconventional water resources when conventional water resources are insufficient in quantity or quality.

In addition, improving the resilience of the already depleted per capita water source supply is one of the most important challenges in adapting to climate change. If classical desalination plants are taxed to promote greenhouse gas emissions, desalination process driven by renewable energy sources appears to be promising for reduction of CO_2 footprint and mitigation of the effects of climate change.

The most widely used technology for Moroccan desalination experience is RO. However, RO technology has a negative impact on the environment due to its high energy consumption, carbon footprint and brine disposal. Therefore, using renewable energy to power desalination processes will minimize this impact, although the cost of the produced from renewable-energy-coupled desalination systems is much higher than the water cost of conventional desalination systems. However, this high cost is compensated by the environmental advantage. Due to this high cost, desalination systems powered by renewable energy resources are currently only economic in rural areas without access to the electric grid, where water scarcity is a major problem, and where solar radiation or wind speed is abundant. With further technological advances, and incentives that aim to encourage the use of solar panels, such as reduction of interest on investment expenses, tax exemption and reduction of the land cost, capital costs will be reduced and reliable, compact renewable energy systems will be available in the market at a reasonable cost, which will lead to a remarkable decrease of the cost of water produced.

NF will see a flourishing future in the field of desalination of certain type of BW. However, it does not make sense to view RO and NF technologies as competitive but rather complementary. While in the field of SW, RO remains the most profitable technology, NF can replace it in some BW desalination cases.

Finally, SW and BW desalination are considered as an alternative to which Morocco can turn to resolve water shortage problems. Moreover, as we have mentioned before, this country has acquired expertise and undeniable experience in water desalination that is useful for the development of its future desalination program (ONEE, OCP Group) and has shown its agreement with the concept given the various investments in plant installations in the South. In addition to impact of the climatic change and the variety of hydric resources in Morocco, the country has recourse to a coupling between renewable energies such as solar mainly in the South, wind turbines in Atlas or even hydraulics with the many dams built like desalination.

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