Desalination in Mexico

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Since the sixteenth century, water desalination systems have been developed. Mexico is a country that faces a severe water shortage, mainly due to its territorial extension, because the concentration of water resources is located in the southern zone of the country, while the main industrial activity is carried out in the north (which presents scarcity conditions). The distance and the technical limitations of transporting water between the northern and southern zones make water desalination the main tool to combat water stress in Mexico.

Keywords: desalination ; developing countries ; environmental impact

1. Introduction

Water is a crucial element for the development and survival of living beings; its availability declines as the population increases and as a consequence of climate change [1]. In the last decades, the percentage increase in water use worldwide has doubled the percentage increase in population [2]. It is estimated that if the current rate of exploitation continues, in the year 2030, there will be a 40% water deficit worldwide, a deficit predicted to be greater in arid regions [3]. It is worth noting that, according to regional forecasts, the regions with greater solar radiation—*Mexico, for instance*—are the ones that will face severe droughts [4].

Since the sixteenth century, water desalination systems have been developed; nevertheless, those early systems were unable to produce water that could be used for human consumption [5]. Desalination technologies are classified into two categories: thermal (phase change) and membrane desalination [6]. Currently, membrane desalination technologies are the most widely used due to the expansion of Reverse Osmosis (RO) technology. However, thermal technologies are attractive because of their potential for integration with thermal energy sources such as waste heat and/or renewable energy sources, and they also perform better for the desalination of high-salinity water [7].

For the year 2022, the worldwide installed capacity percentages for membrane technologies are the following: Reverse Osmosis (RO), 70%; Nanofiltration (NF), 4%; and Electrodialysis (ED), 2%. It is worth noting that the high percentage of membrane desalination systems' installed capacity is closely related to the rise of RO technology since its installed capacity has significantly increased in comparison to the rest of the membrane technologies. The worldwide installed capacity percentages for thermal desalination systems are the following: Multi-Stage Flash (MSF) at 17%; and Multiple-Effect Distillation (MED) at 6%. The remaining 1% is distributed among the rest of the technologies; Membrane Distillation (MD), Vapor Compression (VC), Freezing (FR), Humidification-Dehumidification (H-DH), and Solar Still (SS) [8]. Thermal technologies, also known as *phase-change technologies*, were the pioneers in the desalination area, and they dominated the world's installed capacity until the year 2000 when Reverse Osmosis technologies reached the same installed capacity [9].

Since 2010, the percentage increase in capacity and installation of new desalination plants worldwide has been 6.8% per year (4.6 million m^3/d per year). According to Zotalis et al. [10], in 2012, the worldwide desalination capacity was 79 million m^3/d. Four years later, Catrini et al. [11] reported that the worldwide installed desalination capacity in the year 2016 was 88.6 million m^3/d, resulting in a 12.15% increase. In 2018, the total capacity reported was 92.5 million m^3/d, representing a 4.4% increase. In 2019, Jones et al. [9] reported an installed capacity of 95.37 million m^3/d, a 3.1% increase. In the year 2020, Eke et al. [12] reported an installed capacity of 97.5 million m^3/d, representing a 1.9% increase.

The worldwide desalination installed capacity for the year 2022 is 115.62 million m^3/d, distributed in 20,956 desalination plants, presenting an increase of 18.9% with respect to the year 2020 [8]. This is a considerable increase with respect to those obtained in previous years; even though the increase spans over two years, the yearly percentage increase is approximately 9%.

An analysis of the worldwide installed capacity indicates that the country with the largest installed capacity is Saudi Arabia, with 14.58 million m^3/d, followed by the United States of America, with 11.90 million m^3/d, and by the United Arab Emirates, with 9.47 million m^3/d. Membrane desalination technologies amount to 88.96% of the worldwide desalination capacity, while thermal (phase change) technologies amount to 10.56%. The remaining percentage (≈0.5%) corresponds to hybrid and/or unknown technology plants [8].

The installed capacity percentages of membrane and thermal technologies worldwide are mostly similar at a country level. Nevertheless, in the Persian Gulf region, the percentages are inverted; thermal technologies amount to 85% of the total installed capacity. This is due mainly to the availability of fossil fuels in oil-producing countries, where the residual heat of electrical energy generation processes is used to activate desalination systems, mainly through MED or MSF technologies. It is also worth noting that these two technologies easily adapt to the high salinity and high-temperature conditions of the Persian Gulf's water. Furthermore, MED and MSF systems are more robust for the desalination of water with a proliferation of marine biology, which is highly detrimental to RO technology [13].

Dévora-Isiordia et al. [14] conducted a comparative evaluation of the desalination processes used in Mexico in terms of production costs (USD/m^3) and energy consumption (kWh/m^3). The authors report that the most widely used desalination technology in Mexico in 2013 is reverse osmosis, and the results of their evaluation support this fact because this technology consumes 2 to 2.8 kWh/m^3 at the cost of 0.6 USD/m^3, while its direct competition (MED and MSF) consume between 3.4 to 4 and 5 to 8 kWh/m^3 at the cost of 1.5 and 1.1 USD/m^3, respectively.

In summary, reverse osmosis technology is the current leader in the desalination area. However, there are factors that potentialize the implementation of thermal technologies, such as thermo-physical conditions of the water to be desalinated or the availability of energetic resources (waste heat, electrical energy, renewable sources) for the activation of desalination systems. Another potential area of improvement that can accelerate the growth of thermal desalination technologies is their hybridization with cooling [15][16][17][18] and/or electrical energy generation systems [19][20][21].

Despite having a water availability of 3620 m^3 per capita per year, Mexico is a country that faces a severe water shortage, mainly due to its territorial extension, because the concentration of water resources is located in the southern zone of the country, while the main industrial activity is carried out in the north (which presents scarcity conditions). The distance and the technical limitations of transporting water between the northern and southern zones make water desalination the main tool to combat water stress in Mexico.

RO technology is currently the most widely used; however, Mexico has some bodies of water with high salinity and a high potential for biofouling, factors that limit the proper performance of RO technology. In addition, there is a great diversity of renewable energy sources, such as solar, geothermal, and biomass, that can directly activate thermal desalination systems. For this reason, it is of interest to know the state of the art of the different desalination technologies used in Mexico and their respective advances in technological development to increase their viability. Additionally, modifications or hybridizations with other systems allow the cogeneration of electrical energy and/or cooling.

2. Current State of Desalination in Mexico

2.1. Water Availability in Mexico

The population growth rate in Mexico has caused its population to quintuplicate in the time lapse between 1950 and 2020 [22]. In the same period, its per capita (pc) amount of available water has decreased by almost 80% [23], mainly due to the decrease in annual precipitation in some regions of the country and to its extraction rate. The average annual precipitation in Mexico is 718.3 mm, which presents a decrease of ≈7% from the year 2000 to date. However, in regions such as the Baja California peninsula, the average annual precipitation is ≈168 mm, which presents a decrease of 10% with respect to the year 2000 and is 77% lower than the national average. It is worth noting that Mexico rates as the fourth country with the largest water extraction (88.84×10^9 m^3/year), only below China, the United States of America, and Indonesia [24].

The Water Stress Indicator (WSI) was proposed by Falkenmark and Lindh in 1974 [25] and is currently the most utilized indicator to measure water scarcity [26]. This method defines water scarcity in terms of the total amount of water available for the population of a delimited region. Therefore, it is expressed as the amount of renewable drinking water available for each person every year [27]. **Table 1** shows the limits established for the classification of the level of water scarcity.

Table 1. Water scarcity-level classification in accordance with the Water Stress Indicator.

WSI (m^3/pc/Year)	Category
WSI < 500	Absolute scarcity
500 < WSI < 1000	Chronic scarcity
1000 < WSI < 1700	Regular scarcity

The national average per capita (pc) water availability in Mexico reported for the year 2019 is 3620 m^3/pc/year. However, there is a marked disparity in the per capita water availability among the administrative hydrological regions (AHR) in Mexico. In the Northern, Central, and Northeastern zones, the water availability is 1558 m^3/pc/year, while in the Southern zone of the country, it is 10,508 m^3/pc/year [28]. Therefore, currently, the largest part of the country is under regular scarcity conditions, although there are regions that present chronic and absolute scarcity conditions. **Figure 1** shows that AHRs 1 (Baja California and Baja California Sur) and 6 (Chihuahua, Coahuila, Nuevo León, and Tamaulipas) are facing regular scarcity, and the forecast is that, in the year 2030, they will be under chronic scarcity conditions. AHR 13, located in the central zone of Mexico, presents conditions of absolute scarcity and is forecast to remain in this status until 2030, this is due to the fact that AHR 13 has the second largest population (23,721,664 inhabitants) only behind AHR 8 (24,981,524 inhabitants), but its territorial extension is 957.23% smaller.

Figure 1. Water availability per AHR in Mexico [28].

It is worth emphasizing that the Northern, Central, and Northeastern zones of Mexico cover 78% of the national territory, host 77% of the Mexican population, and contribute 83% of the Gross Domestic Product (GDP). In these zones, there is a larger population concentration and, therefore, greater activity in the agricultural, industrial, and services sectors, which results in a greater water requirement in the zones with less availability [29]. The economic sectors with the largest water consumption are the following: agricultural (75.7%), public supply (14.7%), industrial (4.9%), and electrical energy generation (4.7%). It should be noted that human consumption through public supply should be the main usage of water and that in some AHRs that have water scarcity, there have been shortages reflected in supply cuts for the housing sector [30]. There have also been socio-hydric problems derived from the population's disapproval of the construction of new industrial plants with high water-consumption processes.

Throughout the different AHRs, 1186 monitoring points have been installed. Their purpose is to assess the quality of underground water in terms of their total dissolved solids (TDS). Their results for the year 2018 show that in the Northern, Central, and Northeastern zones of Mexico, 78.53% of the underground water is sweet water, 13.42 is slightly brackish, 7.92% is brackish water, and 0.11% is saline water. In the Southern zone of the country, 81.58% of the underground water is sweet water, 13.92% is slightly brackish, 4.48% is brackish water, and there is no presence of saline water (or saltwater intrusion).

It is projected that the population of Mexico will increase by 10% in the year 2030, 141.8 million inhabitants, even though the growth rate tends to reduce. It is estimated that 56% of the population growth will occur in the Central and Northern regions of the country, which currently have low water availability. This will worsen their status, moving from regular scarcity (WSI ≈ 1000) to chronic or absolute scarcity (WSI ≈ 500), as shown in **Table 1**.

2.2. Desalination Plants in Mexico

Mexico's installed desalination capacity in the year 2022 is 749,751 m^3/d, distributed throughout 351 desalination plants located in 28 of its 32 federative entities—*also called states*. The federative entity with the largest installed capacity is Mexico City, located in AHR 13, with 276,453 m^3/d, followed by Baja California, located in AHR 1, with 97,382 m^3/d, and Quintana Roo, located in AHR 12, with con 63,523 m^3/d. Mexico City's desalination capacity is 183.89% higher than Baja California's, but its WSI is 91.28% lower. Therefore, this can be interpreted as a response to the absolute scarcity faced by AHR 13. Another factor to take into account is that Mexico City (and all of AHR 13) is located far from the coastline; therefore, its main feed waters are brackish, river, and wastewater. **Figure 2** shows the installed desalination capacity in Mexico compared to the five countries with the largest installed capacity in the world.

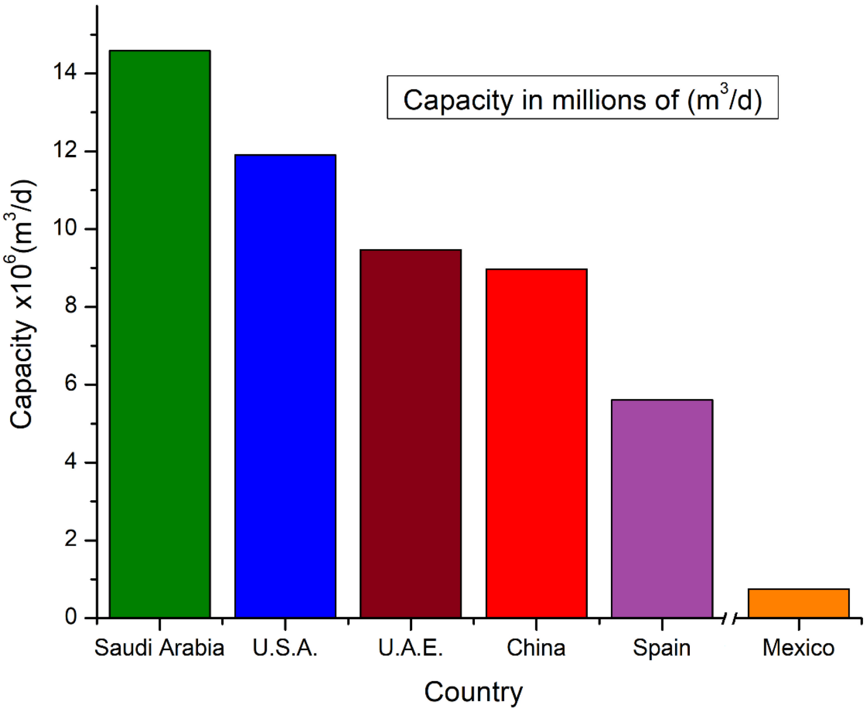

Figure 2. Comparison between the countries with the largest desalination capacity and Mexico [8].

The increase in desalination capacity in Mexico from 2013 to 2022 is 240% (2.4 times) [14]. Until 2013, only 19 of the 32 federative entities in Mexico had desalination plants (59% of the federal entities); in 2020, 28 federative entities had desalination plants (87.5%). **Figure 3** shows the number of desalination plants per federative entity. Considering the federative entities that already had desalination plants, those with the largest increase in capacity during the last 10 years are Nuevo Leon, with 1734%, Tamaulipas, 666%, and Jalisco, 595%. It is worth mentioning that Nuevo Leon is one of the entities with the lowest WSI (839 m^3/hab/year), the highest industrial activity, and, therefore, the highest contribution to GDP. Currently, its government continues to seek to increase its desalination capacity despite its distance from the coast.

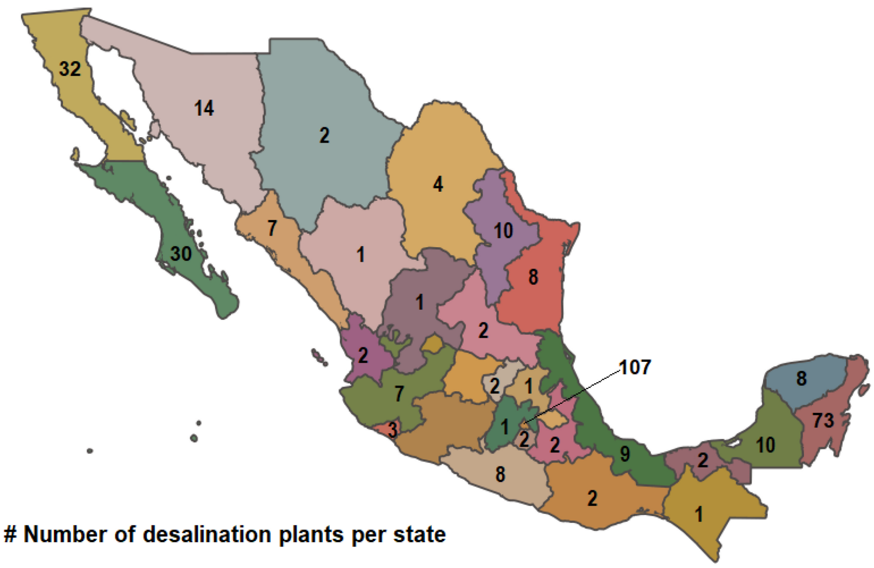

Figure 3. Number of desalination plants per state in Mexico, 2022.

The number of installed desalination plants that use membrane technology in Mexico amount to 85.7% of the total plants; the plants based on thermal (phase change) technology amount to 14.3% [8]. However, in terms of installed capacity, membrane technology plants amount to 88.85%, while thermal technology plants amount to the remaining 11.15%. These percentages are similar to those of worldwide installed capacity, where membrane technology amounts to 90%, while thermal technology amounts to 10%. **Figure 4** shows the percentages of installed capacity in Mexico and in the rest of the world. In **Figure 4**a), the category -*Other*- groups; forward osmosis (FO), freezing (FR), humidification–dehumidification (HDH), membrane distillation (MD), solar still (SS), and vapor compression (VC), due to their low percentages of installed capacity worldwide. In **Figure 4**b), the category -*Other*- groups; humidification–dehumidification (HDH) and solar still (SS) due to their low percentages of installed capacity in Mexico.

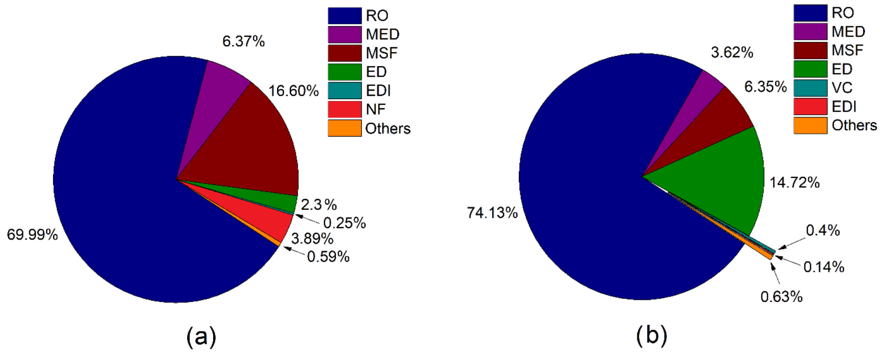

Figure 4. Percentages of installed capacity by technology: (**a**) worldwide; (**b**) México [8].

The technologies used in the desalination plants in Mexico are the following: electrodialysis (ED), electrodeionization (EDI), reverse osmosis (RO), multiple-effect distillation (MED), multiple-stage flash (MSF), and vapor compression (VC). Within the category -*others*- we can find humidification-dehumidification (HDH) and solar distillation (SS) technologies, which present a lower capacity and efficiency compared to the rest of the desalination technologies. However, they are appropriate for the satisfaction of low water demand (1–100 m^3/d) [31] and highlight their low and null electrical energy consumption required for their activation, respectively [32]. **Figure 5** shows the installed capacity (m^3/d) per type of technology in Mexico.

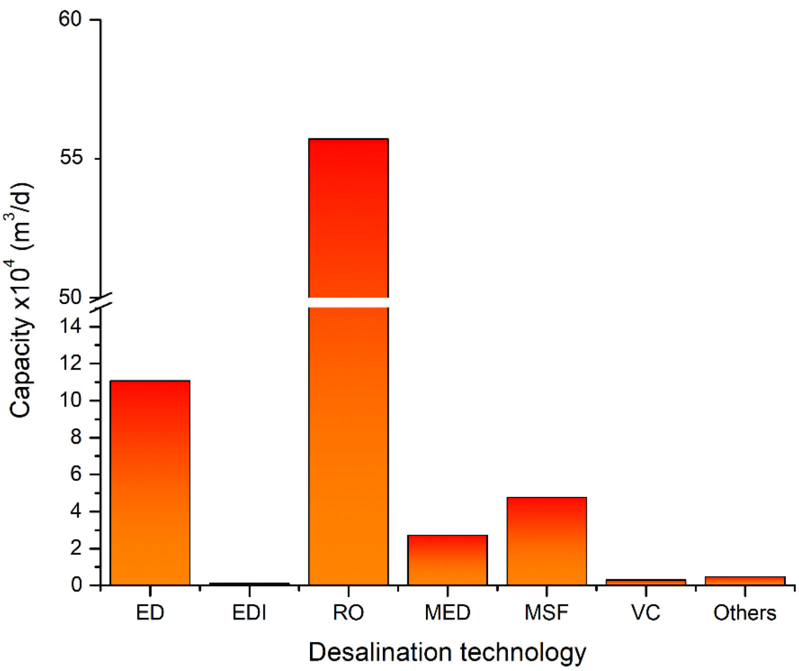

Figure 5. Installed capacity per type of desalination technology in Mexico in 2022 [8].

The number of desalination plants installed in the Northern and Southern zones of the country is similar; however, in terms of installed capacity, the Northern zone has a larger capacity. For instance, AHR 1, which corresponds to the Baja California Peninsula, whose population is 4,672,579 inhabitants, has 91 desalination plants and an installed capacity of 161,470 m^3/d. On the other hand, AHR 12, which corresponds to the Yucatan Peninsula, whose population is 4,857,556 inhabitants, has 91 desalination plants and a capacity of 81,480 m^3/d. This shows that in the Southern zone of the country, there are more low-capacity installed plants, a situation that could be related to the installation of autonomous desalination systems by the private, touristic activities-related sector in the Yucatan Peninsula.

AHR 4, which covers the northern states of the country, has regular scarcity conditions, and it is expected that in 2030 it will be in chronic scarcity conditions, with WSI levels similar to those in AHR 1. However, Nuevo León, the most affected federative entity belonging to AHR 4 is approximately 300 km away from the coast of Tamaulipas, where seawater desalination plants could be installed. Regardless of having the second largest number of aquifers (102), only below RHA 6, AHR 4 has the second lowest per capita water availability in Mexico (**Figure 1**). To solve this problem, aqueducts are needed for either the transportation of water from zones with availability or for the transportation of desalinated water from the coasts near the urban zones, as proposed by Roggenburg et al. [33].

The difference in per capita water availability between the AHRs in Mexico is an indicator of the need to increase per capita water availability in the Northern, Central, and Northeastern zones of the country. This has induced federative entities governments, as well as members of the private industry, to continue pursuing the construction of desalination plants under the BOT scheme in order to guarantee a continuous supply, especially in the federative entities of Nuevo Leon, Baja California, Baja California Sur, and Mexico City.

2.2.1. Reverse Osmosis

In the 1980s, derived from the Sonntlan project, a reverse osmosis desalination plant was constructed in the fishing community of Barrancas, which belongs to the municipality of Comondú, Baja California Sur. It had a capacity of 20 m^3/d and was activated using solar PV energy, as well as a backup diesel generator. The project worked for some time, but nowadays, it is abandoned.

Currently, the largest reverse osmosis desalination plant has a capacity of 94,500 m^3/d, 12.6% of the total desalination capacity in Mexico, and is located in Mexico City, where it desalinates brackish water. It started operations in 2011 and is still in operation. The second largest reverse osmosis desalination plant, with a capacity of 29,184 m^3/d, is located in the municipality of Cadereyta, in the federative entity of Nuevo León, where it desalinates wastewater to be used in industrial processes. It started operations in 2015 and is still in operation. The third place in installed capacity (21,600 m^3/d) belongs to the Ensenada desalination plant located in the federative entity of Baja California, which started operations in 2011 and still operating to desalinate seawater to be used for human consumption.

2.2.2. Electrodialysis

The electrodialysis desalination plant with the largest capacity is located in Mexico City. It has a capacity of 29,331 m^3/d, started operation in 2001, and desalinates brackish water for human consumption. The second largest plant is located in Zacatecas, has a capacity of 6480 m^3/d, started operations in 1995, and is still in operation. The third largest plant is located in Veracruz, has a capacity of 6240 m^3/d, started operation in 1996, and is still operational.

It is worth noting that Mexico has a high percentage of electrodialysis technology installed capacity (14.72%) compared to world averages (2%). This is due to the fact that Mexico is a country with a high level of beer production, and this industry usually uses electrodialysis to desalinate water for its processes [34].

2.2.3. Electrodeionization (EDI)

The only electrodeionization technology plant is located in Mexico City; it has operated since 1999 with a capacity of 1091 m^3/d, desalinating drinking water to be used as distilled water for industrial processes.

2.2.4. Multi-Stage Flash

In the 1970s, a collaborative project between the governments of Mexico and Germany resulted in the construction of a 10 m^3/d MSF desalination plant in the municipality of La Paz, Baja California Sur. This MSF plant started operations in 1980, and it used a 194 m^2 field of flat plate solar collectors and a 160 m^2 field of 2-axis parabolic trough channel concentrators for activation. In addition, it had 324 m^2 of flat-plate solar collectors to heat a working fluid and store thermal energy to ensure continuous operation of the plant for 28 h.

The Federal Electricity Commission (CFE) operates the MSF desalination plants with the largest capacity. The largest plant has a capacity of 28,388 m^3/d, is located in the municipality of Rosarito, Baja California, started operations in 1966, desalinates seawater, produces distilled water for electrical energy generation processes, and is still in operation. The plant with the second largest capacity (4800 m^3/d) is also located in Rosarito, started operations in 1987, and is still in operation. In the third place of MSF desalination capacity, there are two 2400 m^3/d plants; one is located in the municipality of Tuxpan, Veracruz, and the other in the municipality of Manzanillo, Colima. Both plants started operations in 1985, are still in operation, and desalinate seawater, generating distilled water for electrical energy generation processes.

2.2.5. Multiple-Effect Distillation (MED)

The MED desalination plant with the largest capacity (10,900 m^3/d) is located in Mexico City, started operation in 1998 (is still in operation), and desalinates wastewater, producing distilled water for industrial use. The plant with the second largest capacity (2424 m^3/d) is located in Topolobampo, Sinaloa, started operations in 1991, is still in operation, administered by the CFE, and desalinates seawater for electrical energy generation processes. The third place in capacity (2400 m^3/d) is shared by two plants, both located in the municipality of Tuxpan, Veracruz. One of them started operations in 1991, is still in operation, and desalinates seawater for human consumption. The other plant started operations in 1993, is still in operation, and desalinates seawater for industrial processes.

2.2.6. Vapor Compression (VC)

There are six vapor compression desalination plants in Mexico. The one with the largest capacity (772 m^3/d) is located in the municipality of Rosarito, Baja California, has been in operation since 1999, is managed by the CFE, and desalinates seawater in order to produce distilled water for electrical energy generation processes. The second place of installed capacity (768 m^3/d) is shared by two plants, both controlled by the CFE. These plants desalinate seawater in order to produce distilled water for electrical energy generation processes. One is located in the municipality of Ciudad Victoria, Tamaulipas, and has been in operation since 2003. The other plant is located in Mazatlán, Sinaloa, and has been in operation since 2005. The plant with the third largest capacity (360 m^3/d) is located in Rosarito, Baja California, and has been operated by a private company since 2007. It desalinates seawater for electrical energy generation processes.

2.3. Social, Economic, and Legislative Scenario for Desalination in Mexico

2.3.1. Social

Due to its large extension (1,964,375 km^2) [35], Mexico has a large number of remote rural communities without access to the water distribution network. Even though the national percentage of access to water is 97.4% in urban areas, only 88% of the population in rural areas have access to drinking water [28]. Some of these remote communities are located near 11,122 km of the Mexican coastline; therefore, water desalination is an attractive solution to this problem. However, it is necessary to conduct the corresponding environmental, economic, and technical feasibility studies in order to compare the cost of the process to that of extending the water distribution network from the closest interconnection point.

Overall, rural communities have a low number of inhabitants, which results in a low water demand—*or decentralized demand* (<100 m^3/d). The market-leading desalination technologies (RO, MED, MSF) have more feasibility when used on a large scale [36]. It is common for rural populations to be in conditions of social marginalization and without access to the electrical energy transmission grid. Such is the case of Puertecitos, Baja California, and Punta Chueca, in the Seri indigenous community of Sonora, just to list a few examples. For these reasons, it is complicated to make the initial investment required to install a new desalination plant without external investment (government or private). Moreover, the activation and continuous operation of the plant could be affected by the lack of a continuous and reliable supply of electrical energy, as well as qualified personnel for preventive and/or corrective maintenance and for in site decision making regarding the plant's operation.

The National Hydric Policy (2019–2024) [37] sets as its priorities to progressively guarantee the human right to water access, to make more efficient use of water in order to contribute to sustainable development, and to reduce vulnerability during droughts, especially for indigenous populations. In remote coastal communities with decentralized demands, it may be more feasible to implement thermal desalination systems such as humidification-dehumidification or distillation, to mention a few examples. For this reason, it is of national interest to advance in the technological development of emerging or not commercially mature technologies and their implementation in demonstration projects or pilot plants. In addition, the availability of renewable energy sources in almost all territorial extensions can increase the feasibility of implementing decentralized desalination systems activated with renewable energy in remote or indigenous communities. Rural, indigenous, or remote communities usually access drinking water by exploiting underground aquifers. These, when exploited at a rate greater than their natural renewal rate, start to present a decrease in their availability, an increase in the depth in which the phreatic water is found (static level), or changes in the physical-chemical composition of the water. For instance, aquifers close to the sea may present marine intrusion, which increases the salinity of the aquifer to levels inappropriate for direct consumption. The number of aquifers with marine intrusion in Mexico has increased, mainly in the Baja California Peninsula, where there is a convergence of low rainfall rate, high levels of solar radiation, and the presence of high-salinity congenital water and easily soluble evaporitic minerals [28]. In these cases, the implementation of reverse osmosis desalination systems could represent an attractive solution because the energy consumption of this technology is proportional to the salinity of the water, which is generally found in brackish water conditions. In addition, the membrane lifetime, which is usually a limiting factor for the viability of this technology, is longer compared to its lifetime when desalinating seawater directly.

2.3.2. Economic

When there is no nearby aquifer, the population carries water in containers in order to have access to it. Worldwide, millions of women and children travel approximately 6 km in order to have access to water, and Mexico is not an exception [38]. Furthermore, there are people that commercialize water carriage in containers from a site with availability to remote communities in which it is scarce. Some documented cases reach costs of 40 USD/m^3, a price above that reported by IDA (2017) of 15 USD/m^3 of desalinated water. Moreover, this carriage is conducted using trucks with metallic containers in which iron sediments that damage the quality of the water and, consequently, human health have been found [14]. Furthermore, water carriage in vehicles that use internal combustion engines causes a greater environmental impact due to the emissions caused by the consumption of the fuel required to carry large amounts of water, which also increases the economic cost of water with the aim of seeking business profitability.

Being a medium-low-income country, most of the desalination plants installed in Mexico have been built and operated by private sector companies in alliance with state and/or municipal governments in the BOT (building, operating, and transfer) modality. The private company is in charge of the plant's building and operation, obtaining an economic remuneration for the water produced for an agreed-upon number of years (≈20 years); after this period, the plant is transferred to the government to be managed through its Public Services State Commissions. This is the case of the first desalination plant installed in the state of Sonora, which has a capacity of 200 L/s.

Another factor to take into account in the economic aspect is the operating cost of the desalination plants; although the reverse osmosis technology leads the market, it shares with the rest of the technologies the limiting factor of the specific energy consumption, to reduce it, it has been proposed; The integration of energy recovery devices, the activation with energy coming from renewable energy sources, the hybridization with systems for cooling and/or electric energy generation and the high-pressure pump with solar thermal energy, etc. In some regions of Mexico, as in AHR 1, the availability of electricity is a problem for the industrial, commercial, and residential sectors. For this reason, the construction of desalination plants must have correct energy planning that does not compromise the availability of electricity for other sectors. Some of the measures to reduce the energy consumption of desalination plants may mean a higher initial investment, but if they significantly reduce the cost of operation, they may be more economically viable.

Desalination continues to be a technologically viable solution, but its economic viability is still a limiting factor; for this reason, it is most widely used in developed countries. On the global scale, the cost of producing desalinated water dropped by 50% from 1985 [39]; nonetheless, studies in California and Mexico identify desalination as having the highest marginal costs among all realistic water-supply alternatives [40]. The final USTDA (2009) report estimates that Puerto Peñasco, Mexico, could build a plant with the capacity to produce 0.5 m^3/s in the first phase, with the expected expansion of up to 2 m^3/s by 2020 at the cost of 2.29 USD/m^3 (not including conveyance and storage). This is approximately seven times more expensive than the current cost of water production and delivery (0.339 USD/m^3) (USTDA, 2009) [41]. For this reason, in countries such as Mexico, the economic impact derived from the investment required to build high-capacity plants is minimized because the design, construction, and operation are carried out jointly with private industry under the BOT modality.

With respect to environmental impact, the greatest challenge of desalination at present is the disposal of brine since it is usually discharged directly into seas and oceans near the coast; in Mexico, there are draft standards that establish guidelines for desalination plant discharge works, but they are in the process of being approved (PROY-NOM-013-CONAGUA-2015) [42]. However, Mexico has water bodies with different hydrodynamic characteristics; information reported in the literature indicates that the environmental impact caused by brine discharge is lower in water bodies with turbulence (waves and currents), such as the Pacific Ocean, but discharging brine in calm seas such as the Sea of Cortez has a greater environmental impact [43]. Therefore, the discharge work must be carried out in accordance with the regulations (when approved) and considering the characteristics of the water body in question. In second place are the emissions of gases into the atmosphere derived from energy consumption.

To cite a recent example reported by Wilder et al. [44] on the Puerto Peñasco desalination plant project, which could produce 0.5 m^3/s of freshwater (in its first stage), an estimated 0.73 m^3/s of brine concentrate will be produced. Project engineers recommend discharging near the surface to take advantage of prevailing winds and stronger currents to help disperse the brine concentrate [42]. An environmental impact assessment was initiated but not completed [45]. In addition, energy use at the desalination plant would likely come from fossil fuel sources that produce GHG emissions.

2.3.3. Legislative

Regarding legislation, the 1992 National Water Law established that the exploitation of national water will be conducted through concession titles emitted by the National Water Commission (CONAGUA, by its Spanish acronym). Therefore, in order to install a desalination plant, a concession for the water extraction is required, whether from the sea –*direct intake*– or from underground aquifers –*wells*–. For the rejected water discharge, as is the case of brine, discharge permission emitted by the same institution is also required.

Other Official Mexican Norms (NOM, by its Spanish acronym) applicable for desalination are the following. NOM-001-SEMARNAT-2021 [46] established the maximum level of pollutants allowed for wastewater discharge into national waters, which applies to the discharge of brine from desalination plants. NOM-003-CONAGUA-1996 [47] established the requirements for the construction of water extraction wells looking for the prevention of aquifer pollutants, which applies in the case of the construction of an extracting well for a desalination plant. NOM-006-ENER-2015 [48] established the energetic efficiency required for pumping systems for water extraction wells in operation, limits, and testing method, which applies to the selection of the pumping equipment used in desalination plants that extract water from underground wells.

In 2015, the Mexican Official Norm project PROY-NOM-013-CONAGUA-2015 [42] was proposed. This project seeks to establish specifications and requirements for the extraction and discharge works that must be met in desalination plants or processes (public or private) that generate brackish or saline rejection waters and discharge them to the coastal, marine, and/or continental environment, in order to protect the environment. The Norm project was presented by the National Consultative Committee for Standardization of the Water Sector, with the collaboration of private sector organizations, institutions, and companies.

Regarding the quality of the product water obtained from desalination plants, NOM-0127-SSA1-2004 [49], originally published in 1994, establishes the maximum permissible levels that produce water should meet for human consumption. This norm determines that water for human consumption should have a maximum of 1000 ppm of TDS.

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