2020, Instituto Mexicano de Tecnología del Agua

DOI: 10.24850/j-tyca-2020-04-09

Notes

Review of water desalination techniques towards an energy saving approach

Revisión de las técnicas de desalinización de agua con perspectiva de optimizar requerimiento de energía

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Abstract

As a contribution to the care of "our common home", in line with the sustainable development objectives related to water and energy, which seek to reduce the emission of greenhouse gases and the excessive requirement of energy, including both the conventional and green or alternative energy, we revised technological improvements occurring in water desalination process at international levels. Starting from the reverse osmosis technique, some aspects of future scenarios are presented regarding to the development of membranes and new technologies to obtain and use sustainable energy. We present the efficiency of photovoltaic solar panels and their relationship with temperature. We also revised the progress of some devices and materials for capture, concentration and transformation of solar radiation. Based on the information gathered regarding the capacity of fresh water production and the energy required in the whole process of some of the largest plants in the world we present the evolution as well as the short, medium and long term goals, expressed in terms of energy requirements by unit of desalinated water volume, which is related to an ongoing project in the Northwest of Mexico. This review aims to promote the development of these technologies and their application in the water desalination process in Mexico.

Keywords: Desalination plants, reverse osmosis, technological improvements, energy requirements.

Resumen

Como una contribución al cuidado de “nuestra casa común”, en consonancia con los objetivos de desarrollo sostenible relativos al agua y la energía, que buscan reducir la emisión de gases de efecto invernadero y el requerimiento excesivo de energía, incluyendo la energía convencional y la derivada de energías verdes o alternativas, a continuación se revisarán los avances tecnológicos que están ocurriendo en el proceso de desalinización de agua en el ámbito internacional. Partiendo de la técnica de ósmosis inversa, se presentan algunos aspectos del panorama futuro en cuanto al desarrollo de las membranas y las nuevas tecnologías hacia el uso sostenible y obtención de la energía. Se plantea la eficiencia de los paneles solares fotovoltaicos en su relación con la temperatura. Se revisaron los avances de algunos dispositivos y materiales para captación, concentración y transformación de la radiación solar. Con información sobre la capacidad de obtención de agua desalinizada de algunas de las plantas más grandes en el mundo y la energía que se requiere en todo el proceso, se presenta la evolución y metas en el corto, mediano y largo plazo, expresadas en unidades de energía necesaria por unidad de volumen desalinizado, lo que se relaciona con un proyecto en proceso en el noroeste de México. Esta revisión pretende promover el desarrollo de estas tecnologías y su aplicación en el proceso de desalinización de agua en México.

Palabras clave: plantas desalinizadoras, ósmosis inversa, mejoras tecnológicas, requerimientos de energía convencional y/o limpia.

Received: 09/07/2018

Accepted: 12/10/2019

Introduction and objective

As a contribution to the care of "our common home", in line with the sustainable development objectives related to water and energy, which seek to reduce the emission of greenhouse gases and the excessive requirement of energy, including both the conventional and green or alternative energy and those that contribute to reducing social problems around water and poverty (Figure 1), we reviewed technological improvements occurring in water desalination process at international levels.

Figure 1. March 22, 2012: A girl captures murky water from an excavation near a well that has dried up in Jamam, South Sudan Hannah McNeish/AFP. Sim (2015).

Also, in order to encourage the application of technological advances that result in a lower energy requirement for the process of desalination plants that are designed, manufactured and operated in Mexico, here we present a review of the experiences that are taking place in different parts of the World.

Literature review

Sustainable development objectives SDGs (English acronym) that were presented at the Assembly of the United Nations Organization (ONU, 2015), with emphasis on the objectives directly related to water (6. Clean water and sanitation) and energy (7. Afordable and clean energy) and the urgency of attending the poorest sectors, constitute the framework in which this work was elaborated.

A proposal was raised to feed a desalination plant with a double barrier of pumping wells that, located through the Seawat model applied by Canales, Islas and Velázquez (2016), and based on other research, had the dual purpose of supplying drinking water to Guaymas, Empalme and Sonora populations, and to protect the aquifer of Boca Abierta Valley, Sonora, against the saline intrusion advance. This also proposes energy savings by using brackish water from wells with lower saline concentration instead of sea salt water. This description has not yet taken into account the use of solar energy that the hybrid system of high efficiency and high thermal photovoltaic concentration already offers at laboratory scale.

Regarding the application of solar energy, through photovoltaic cells for the desalination process (Figure 2) there are several international references that demonstrate the feasibility of its use. On the one hand, Fthenakis, Atia, Morin, Bkayrat and Sinha (2015), present experiences in Saudi Arabia and on the other, Zimmermann *et al*. (2015) describe a hybrid system of high efficiency and thermal photovoltaic concentration (HCPVT).

Figure 2. Solar powered desalination plant in Kenya provides fresh water for 25,000 people daily. PSC Solar UK (2019).

At present, IBM with the high thermal photovoltaic concentration (HCPVT) system (Figure 3), can achieve 90°C to operate the membrane distillation process with which it has the capacity to obtain 30-40 liters per day per m^2 of reception area.

Figure 3. IBM research. High thermal photovoltaic concentration system (HCPVT). Williams (2013).

For Sommariva (2017), the main problem encountered in the application of the progress in this process, presented by Williams (2013), is related to closing the gap between research and development, as well as the commercialization of these concepts. Sommariva (2017), synthesizes and projects desalination volumes from 2000 to present and makes a prediction until 2020, where it also mentions some costs. Water scarcity is not just a phenomenon limited to the Middle East; there are several large-scale desalination projects in other parts of the world, such as in North Africa, South Asia, as is the case of Saudi-Arabia, the Middle East, Israel and Southern California, North America.

As shown in Table 1, desalination volumes have doubled from 2000 to 2008 and are expected to triple by 2020, reflecting a compound annual growth rate of 8%. As water stress increases and the use of desalination expands outside of the areas that have recently adopted it, as the Middle East, it is predicted that volumes of desalinated water will reach 54 $x10^9$ m^3/ year in 2020.

Table 1. Desalination volumes in the world. Sommariva (2017).

Year	**2000**	**2008**	**2020**
Desalinated annual volumes in billions (m^3)	9.8	18.1	54

Desalination is now used in more than 120 countries around the world. Over the past 30 years, several large-scale projects have demonstrated that it is technically feasible to generate large volumes of water of acceptable purity through desalination of seawater, brackish water and water reuse Sommariva (2017).

The same author mentions that in the past the cost of seawater desalination was below USD 0.50 / m^3 in many projects; however due to the increase in material costs, the total cost of desalination has subsequently increased to 1 -1.5 USD / m^3.

Shahzad, Burhan, Ang and Ng (2017) present advances and the state of the art in water-energy-environment links, which represents the sustainability of future desalination foundation. The desalination treatment process is the largest energy consumer, about 0.4% of total electricity (75.2 x 10^9 kWh / year in 2016) and is the largest source of fossil fuels CO_2 emissions. Improving the efficiency of the two major sources, water and energy is important to control such emission and protect the environment.

Solar concentration power plants (CSP, English acronym) represent a promising solution for many countries in the Middle East and North Africa region (MENA) (Atanosovska 2016). In 2014, there were around 2,800 desalination plants in MENA that supplied 27 x 10^6 m^3/ day, this represents an average of 10,000 m^3 / day in each plant. In that year, Algeria had one of the largest plants in the region supplying 500,000 m^3/ day.

According to the same author and the Association of the Solar Industry for the Middle East, the CSP projects that were in progress in 2014, reached a record of 294 MW capacity. Morocco had a massive solar power plant in Ouarzazate. In Tunisia for 2012, a solar plant was built in TuNur; while in Qatar the project of a low energy consumption desalination plant was launched.

At present, worldwide, in terms of the use of energy and environmental impact related to desalination, reverse osmosis (RO) processes are dominating the market for brackish water and, in the period 2005 to 2008, they showed a growth trend in supply going from 2.0 to 3.5 million m^3 / day.

Processes to desalinate water contributed in 2016, 76 x 10^6 tons of CO_2 (0.2% of the total emission of 36 100 x 10^6 tons / year) globally, estimating by 2040, emissions of 218 x 10^6 tons of CO_2. To have an idea of what this means, the author mentions that 2/3 of the required reduction has been used to keep the global temperature increase below 2 °C, the COP 21 objective, and the remaining third would be exhausted by 2050. **Sachs (2014)**comments that, the above-mentioned CO_2 emissions will lead to an annual increase of 2 ppm in the atmospheric concentration of this gas. In the last 150 years there was an increase of 280 to 400 ppm, so if in 25 years it rises to 450 ppm, there will be a planet with 2 °C more than before the Industrial Revolution, with the consequences of extreme weather events and the deterioration of terrestrial and marine ecosystems, already evident.

Energy requirements and technological innovations in the desalination process

For future water supplies in arid and semi-arid areas of the planet, the best choice will be the one that involves high efficiency desalination processes integrated with renewable energy sources. This is equivalent to coupling desalination technologies with renewable energy sources, with three major future benefits for the world: environmental sustainability and supply of fresh water and energy.

To achieve the goal of future sustainable water supply, high flow membranes, selective, resistant to clogging, stable and with minimal cost and manufacturing defects are required. Among the variety of efficient materials that have been proposed to improve the operation of membranes based on ceramics and polymers, of which Shahzad *et al*. (2017) cite several examples, the best functioning ones, the bio-inspired membranes, are detailed below.

Ceramic-based membranes and conventional polymers that are used in the RO process currently consume 3 to 5 kWh / m^3. Driven by sustainable water supply objectives, it is necessary to improve the functioning of these membranes with more efficient materials such as, coated ceramics with nano-particle (nano = 10^{-9}) catalytic, zeolitic, organic-inorganic nano-compounded, or bio-inspired ones that include biomimetic polymer-protein, block isoporous copolymer and aligned nanotubes. The bioinspired are the best functioning but still about 5 to 10 years away, research for commercial availability. However, nanocomposite membranes with significant improvements are already commercially available.

As for the desalination process, reverse osmosis (RO) processes are promising as they are expected to be reinforced in the future by the high efficiency development of aquaporin and graphene in membranes. Aquaporin proposed by Agre, Sasaki and Chrispeels (cited in Shahzad *et al*., 2017), is an element that controls the flow through biological membranes with protein channels. Reverse osmosis membrane covered with 75% aquaporin increases the permeability of commercially available membranes by one order of magnitude; however, they have not been massively applied due to the difficulty in producing large areas of protein. However, there is a potential to incorporate biological aquaporin into RO membranes in the future, so more research is required to optimize the formation of biological structures in terms of selection, robustness, material cost, scalability, and in the process of RO, specific energy consumption less than 2 kWh / m^2. The author also concludes that thermal hybrid desalination processes can reach between 20 and 25% efficiency, with 1 or 2 years of experience, which would be sustainable and save energy, protect the environment and be consistent to COP21 objectives.

Amya *et al*. (2017) explore the state of the art in seawater desalination practices, with an emphasis on membrane-based technologies, while identifying future opportunities in improvements by conventional technology stages and the development of out of trends emerging and potential technologies, through advances in materials sciences, engineering processes and integration of systems. In this article, seawater RO is considered as the starting technology. The discussion goes beyond desalination processes in membranes that are based on energy production processes with salinity gradients. The future scenario of desalination and energy membranes with saline gradients is projected to include hyper-high permeability RO membranes, renewable energy for desalination and emerging processes, including closed RO circuits, distillation membranes, future osmosis, delayed osmosis pressure and reverse electrodialysis, according to several application and / or combined niches (hybrids), operating separately or in conjunction with RO.

Given the problem of variable salinity due to the collection of brackish water in pumping barriers with beach wells for protection against saline intrusion, it´s necessary to consider that changes in pressure and number of membranes in RO, as well as reducing the efficiency of feed pumps to absorb changes in salinity, are issues that are related with the cost that will ultimately affects the user.

On the other hand, Raval and Maiti (2016) emphasize that the electrical efficiency of the photovoltaic (PV) solar panel decreases with the increase in its temperature and therefore, the heat transfer from the panel is a very important point to be considered. Capitalizing the heat transferred for some useful purpose is of first importance since the solar panel (PV) has a conversion efficiency of only 5-17% and consequently, much of the solar radiation remains unused. This article pointed out the control of the temperature of the PV solar panel, mentioning the possibility of establishing a direct contact of the heat exchanger with the feed water flowing to the RO system from the upper end of the panel, thus recovering the energy together with a better operation of the PV panel. Also, the RO system at high temperature results in a better membrane flow. In addition, the modification of the membrane morphology by controlling the treatment with sodium hypochlorite increases the efficiency of the flow by increasing the ability to mix, dissolve or moisten the membrane; and as an evidence we get the declination of the contact angle that goes from 48.05 ° to 26.22 °. Thus, two techniques, the temperature control of the PV panel and the heat transfer and the adjustment of the membrane morphology towards the increase in capacity, helped to significantly improve the flow permeability in the RO system and in the electrical operation of the PV panel. As a result, the total energy consumed by RO has been reduced by 40%. This novel approach opens the channels to significantly reduce energy consumption of RO systems for brackish water.

Research on "hybrid" technologies spectral beam splitting concentrated photovoltaic/thermal (SBS CPVT), having started in the ‘80s, have been improving until the full use of solar irradiation of its entire spectrum using photovoltaic cells (PV) and thermal absorbers. Different SBS attempts were used to achieve better conversion efficiencies, including several types of filters (Xing *et al*., 2017) and Fenga, Zhengb, Wangc and Mab (2016), based on the optical refraction principle, calculated the dimensions of each Fresnel lens element. An optical simulation was performed to obtain the optimum efficiency of the concentrator, at the same time as Widyolara *et al*. (2017) designed, simulated and tested an innovative photovoltaic-thermal hybrid solar collector (PV/T). The PV/T system uses a non-reflective composite parabolic concentrator (CPC) to focus sunlight towards a receiver with a high concentration battery of the simple arsenic-gallium junction, solar cells that simultaneously generate electricity and high temperature thermal power. Finally, Srivastava (2017), in his article presents the linear and parabolic thermal and electrical analyzes through a photovoltaic concentrator collection system (CPV) under different design and operation conditions. A composite parabolic collector (CPC) was incorporated as a secondary reflector to homogenize the flow. Below we present a global example of water supply and required power, as well as a comparative series of the energy required per unit of water obtained by desalination systems.

Results

The use of energy for selected cases is presented, referring to the unit of volume of desalinated water obtained: Ras Al Khair Desalination Plant,(2014), has the capacity to contribute 728 x 10^3 m^3 per day (8.5 m^3/s) of desalinated water for the population. The project has the infrastructure for 2 650 MW for a plant with combined cycle power in the second phase that will comprise blocks of five combined cycle gas turbines (CCGT) and two simple gas turbine units (SCGT).

Poseidon (2010), capable of desalinating seawater in the world, expresses that at the end of the last century, in 20 years, the use of energy went from 30.16 to 3.7 kWh / m^3 due to improvements in membrane materials of RO and energy recovery equipment coupled with increasing efficiency of feed pumps and reducing pressure losses in membrane elements. Taking into account that the cost of energy typically represents between 20 and 30% of the total seawater desalination cost, these technological innovations contribute significantly to reducing it; and with the new energy recovery systems a reduction of 10 to 15% can be expected.

Talbot (2015) mentions that water supplies and energy use in kilowatts-hour / m^3 (0.1-4.0) are the lower and upper limits of the ranges for each operation in the supply. Pressure at the high-pressure seawater changers directly concentrated in the feed water of RO has an efficiency of 95% or greater. Future elements of low energy RO would still operate with low pressures to continue improving the cost effectiveness of RO technology. The constitution of membranes tends to deteriorate naturally over time due to a combination of the use and tearing of the material and the inevitable clogging of membrane elements. Improvements in membrane polymer chemistry and production processes have made membranes more durable and have extended their useful life to more than five years. Pretreatment of seawater, using ultra-membrane and microfiltration membrane systems prior to desalination by RO, is expected to extend the life of the membrane to more than seven years, thereby reducing replacement and joint costs, of the entire water supply process. Shahzad *et al*. (2017), show in their studies the amount of energy needed to obtain a m^3 of drinking water from different sources. So for groundwater it is 0.48 kWh/m^3 and for seawater 2.6 to 8.5 kWh/m^3. At present, as shown in Table 2, RO processes for seawater require 3 to 8 kWh/m^3 and for brackish water 1.5 to 2.5 kWh/m^3 for large to medium-sized plants (pumping pressure 55 to 82 bars); for small plants the necessary energy is up to 15 kWh/m^3.

Table 2. Energy requirements in RO processes.

Number of years	**Number of years**	**Target below requirement (kWh/m^3)**
Present	Present	3* a 8 (4**)

Less than three	Less than three	3
Less than five	Less than five	2
More than five	More than five	1.5

*Shahzad *et al*. (2017) mention 1.5 a 2.5 to brakish water, for large to medium plants.

** Personal communication to El Cochorit Plant, Sonora, Mexico.

Noriega (2014) provides data for the Rosarito desalination plant project, in Baja California, Mexico, and calculates the energy requirement at 3.07 kWh/m^3 for a drinking water collection of 4.4 m^3/s, with recovery of 50.4 percent of the hydraulic energy available in the brine return to the sea. The required net power is 48,660 kW. Among desalination plants in Mexico that are in their initial phase of development, El Cochorit in the State of Sonora and Rosarito in the State of Baja California, already have information on the energy requirement. Figure 4 shows the location of these plants.

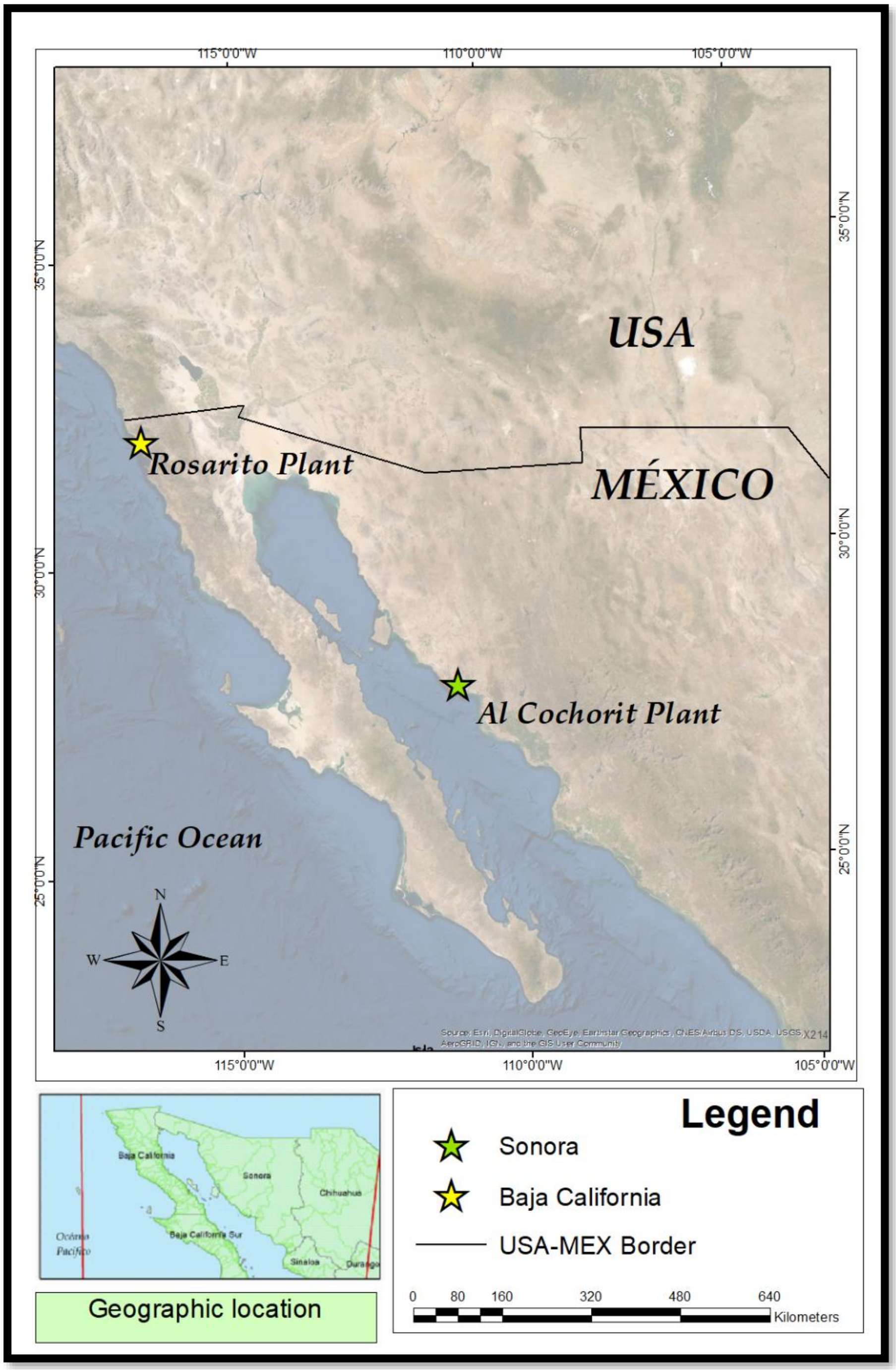

Figure 4. Location of desalination plants. The Cochorit, Sonora, and Rosarito, Baja California, México.

Discussion

All desalination methods available at present operate quite far (10 to 15%) from the ideal or thermodynamic limit of 0.78 kWh/m^3, which means that for future sustainable desalination, conventional techniques need to increase their efficiency to a range of 25 to 30% of thermodynamic limit or investigate alternative sources of sustainable energy.

Regarding energy objectives, the International Desalination Association set the short-term goal of reducing energy requirements by 20% for seawater RO (SWRO), which is equivalent to a requirement of less than 3 kWh/m^3 with a minimum of 1.2 kWh/m^3 for 50% recovery. The practical thermodynamic limit is 1 kWh/m^3. Table 2 shows the short, medium and long term goals in relation to the current requirement.

Difficulties already existing in many countries due to the shortage of fresh water, have forced to take into consideration the possibilities of using the enormous reserves of sea water and brackish water from different sources for their treatment and, currently, there is an increasing interest in studies and projects related to the use of different desalination technologies. However, the system did not show sustainable routes in terms of the amount of energy needed to obtain water of sufficient quality for human use.

The United Nations climate change convention argues that "the removal of coal as a source of energy is a priority." At the last Climate Summit (COP23) meeting in Bonn, where representatives from almost 200 countries discussed the application rules of the "Paris Agreement against climate change", they concluded that news are not good, because CO_2 global emissions grew again in 2017 to reach 41,500 x 10^6 tons, the same figure as in 2015, when the maximum historical peak was reached.

Among environmental impacts of desalination processes are those related to rejection water (brine) on the coastal and marine ecosystem, as described by Liu, Weng and Sheu (2018). Petersen, Paytan and Bar-Zeev (2018), also point out the potential negative impact of some chemical agents used in desalination processes, which cause the mortality of key species related to ecosystem services of coastal and marine environments. Authors highlight the appropriate selection of discharge sites as a good management practice, consistent with what is recommended by Palao-Puche (2018), who suggests the proper installation of submarine emitters, encouraging that natural conditions of currents and tides allow the maximum dispersion of these pollutants thus reducing the environmental impact. However, the lack of studies on this issue is still a worrying factor and where future research should be coupled, with its well-designed and ongoing monitoring programs, to really meet the millennium goals; in particular, those that evaluate the economic factor in order to really assess the overall impact of desalination operations and to regulate and/or minimize potential damage to the seabed .

Conclusion

As described in this review, there are several technological advances at global level that lead to a sustainable management of the desalination process from a perspective of optimization of energy requirements.

The future scenario of desalination and energy membranes with saline gradients is projected to include RO membranes of hyper-high permeability, renewable energy for desalination and emerging processes.

According to this review, research in Mexico should focus on improvements in conventional and emerging technologies, engineering processes, use of integrated systems with advances in materials sciences such as, formation of biological structures. in terms of selection, robustness, cost, scalability such as, the production of large areas of protein for "Aquaporin", and with all this, achieve the reduction of energy requirements in the desalination process.

Acknowledgments

To Peter Carlwright, Hildebrando Ramos Luna, and Cecilia Canales Noriega; to the Asociación Geohidrológica Mexicana.

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