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Environmental Impact Cost Analysis of Multi-Stage Flash, Multi-Effect Distillation, Mechanical Vapor Compression, and Reverse Osmosis Medium-Size Desalination Facilities

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Analysis of various medium Size Desalination Facilities

Abstract

In response to increasing global water demand, desalination has become an important source of water in many regions of the world. The objective of this research is to compare four different desalination methods operating at a production capacity between 100 and 200 m^3/d: 1) multi-stage flash (MSF), 2) multi-effect distillation (MED), 3) mechanical vapor compression (MVC), and 4) reverse osmosis (RO). Brine disposal and energy consumption for treatment are also discussed in the paper. The source water and brine disposal requirements for each method vary based on system efficiency. As a system's treatment efficiency increased, the source water requirement decreased and the salinity of the brine solution increased. RO was the least energy intensive treatment method, requiring 3-5.5 kWh/m^3. MED and MVC had similar energy requirements at 6.5-12 kWh/m^3. The least efficient treatment method was MSF, requiring 13.5-25.5 kWh/m^3. High salinity and large energy requirements can be mitigated by pairing the desalination facility with a waste water treatment plant. Effluent can be mixed with the brine to reduce salinity and thermal energy can be supplied to reduce energy demand.

Introduction

The population growth create high demand for fresh water. In Florida, desalination plants will meet the state's future water needs (1)

The existing desalination technologies are: 1) membrane reverse osmosis (RO), b) multiple effect distillation (MED), c) multistage flash (MSF), and mechanical vapor compression (MVC). The energy needs various for each each desalination type. RO uses 3-5.5 kWh/m^3; MSF uses 13.5-25.5 kWh/m^3; MED and MVC use 6.5-12 kWh/m^3. The system reliability of RO is moderate, MVC is high and both MSF and MED are very high. The selection of each technology depends on the industry's needs and capabilities (1).

The cost of desalination plants has decreased significantly over time due to the price reduction of membranes. Even more so, the desalination process has been improved and became more efficient. Yet, the water sources are becoming increasingly diverse. Therefore, source water type has major effect on the cost of desalination. Seawater RO uses more energy than brackish RO, due to increases in treatment costs. In addition, site-specific factors can also change the system decision. The various impacts and costs of using these technology can be reduced by using alternative energy sources such as renewable energy. And placing these facilities in a co-location with a renewable power plant, and a water treatment facility that can reduce capital, and operational costs (1).

Desalination Methods

There are two competing processes to desalinate raw water: vacuum distillation and the use of a system of semipermeable membranes. Vacuum distillation is the process by which water is boiled at less than atmospheric pressure so that a lower than normal boiling temperature can be achieved. There are a variety of desalination methods based on vacuum distillation. The primary membrane treatment method is RO. Reverse osmosis treatment involves forcing a water with a high solute concentration such as salts and other impurities through a semipermeable membrane to a locale of low solute concentration by increasing pressure to a point above osmotic pressure, effectively reversing the natural process of osmosis (2, 3).

Multi-stage flash

Multi-stage flash by which water is desalinated by flashing portions of the water in multiple stages. There is a cold end and a hot end for the stages with intermediate temperature stages in between. Each stage has a different pressure that correlates to the water temperature, allowing the system to utilize the optimal boiling point for a given water temperature. Each stage contains a heat exchanger and condensate collector. The heat exchanger condense the steam produced and collected in the condensate collector. The condensate water is distilled and is ready to be used for consumption. Figure 1 presents a schematic of the MSF process. Multi-stage flash produce about 60% of the world's desalinated water (4, 5).

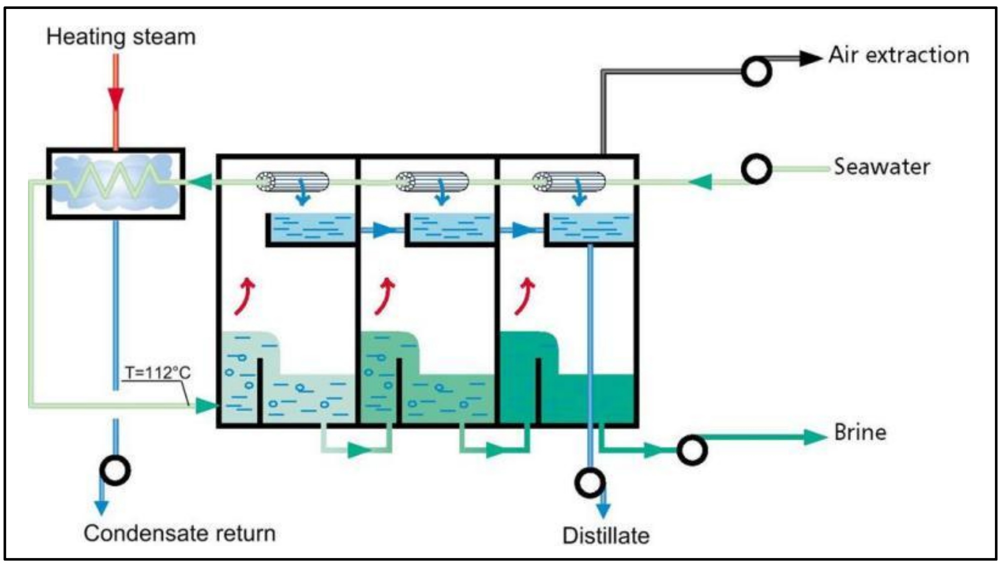

Figure 1 Schematic of MSF process

Multi-effect distillation

Multi-effect distillation also known as effects. Like MSF, the number of effects varies based on the engineering of the system. In MED, each effect is maintained at a decreasing level of pressure and temperature. Each effect has a horizontal tube bundle. The top of the bundle is sprayed with the seawater and utilizes gravity to flow downward. Steam for heating is pushed through the tube bundle and cooled by the seawater introduced, causing it to condense. This warms the seawater and partially evaporates it, creating a higher saline solution at the bottom of the effect, or brine. The seawater vapor has a lower temperature than the heating steam, but due to pressure changes between effects, the vapor can still be used as a heating medium. In the final effect, the steam condenses via heat exchanger as the distillate is collected. Figure 2 presents a schematic of the MED process (6). Like MSF, MED has also proven itself in large scale drinking water production (4).

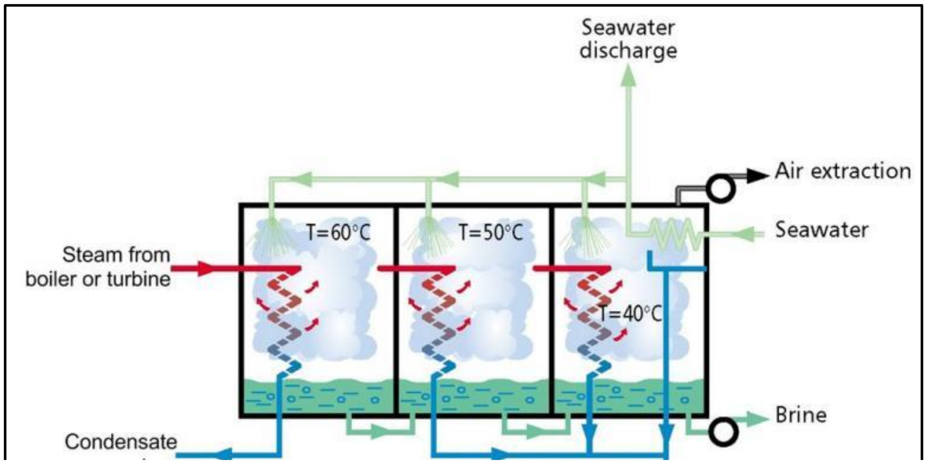

Figure 2 Multi-effect distillation process

Mechanical vapor compression

Mechanical vapor compression is the process by which heat is transferred by mechanically compressed vapor to evaporate seawater. The water vapor can be compressed in one of two ways: vapor or vacuum vapor compression, the former taking place at monomeric pressure and the latter at a vacuum pressure. Regardless of vapor creation method, once vapor is generated, it is passed over a heat exchanger to condense the vapor into distillate. MVC is often applied to other treatment methods as a way to increase energy efficiency (7). Figure 3 presents a schematic of MVC being applied to MED. Mechanical vapor compression has been proven to be effective in the small to medium plant capacity ranges and is extremely popular in hybrid desalination plants. The capacity of MVC plants is limited by the lack of availability of large vapor compressors (4).

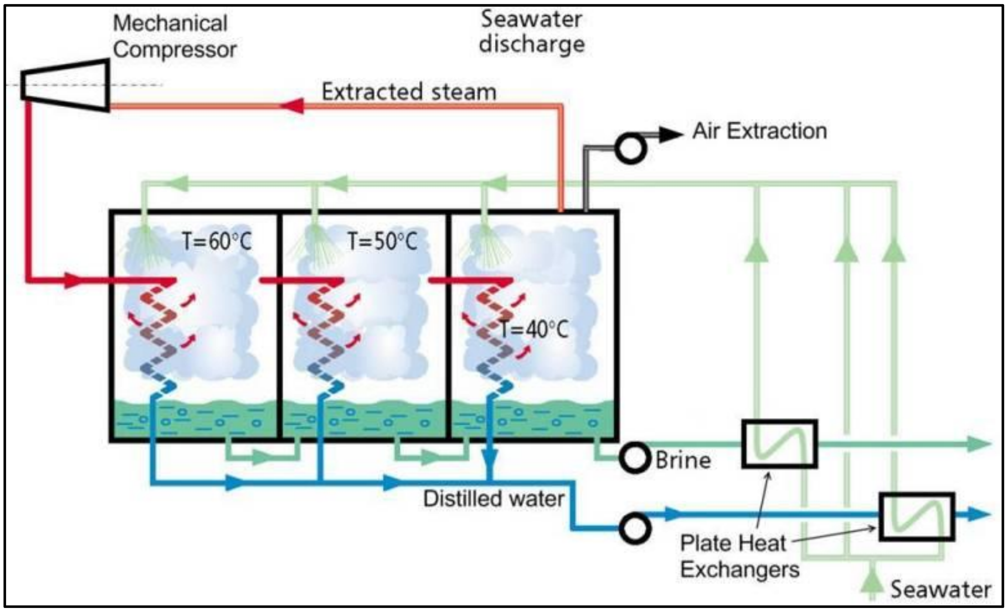

Figure 3 Schematic of MCV process

Reverse osmosis

Reverse osmosis is the process by which water is forced through a semipermeable membrane via the application of pressure in excess of osmotic pressure. Under these pressure conditions, the pure water is pushed through the membrane and collected while the dissolved salts are repelled and collected as brine. Figure 4 presents a generic membrane element design schematic. There are a variety of membrane materials used in RO systems and RO is rapidly growing in popularity. (2) Reverse osmosis is effective for high capacity treatment plants. And is even heavily relied on by the United States Military for supplying drinking water (4, 8).

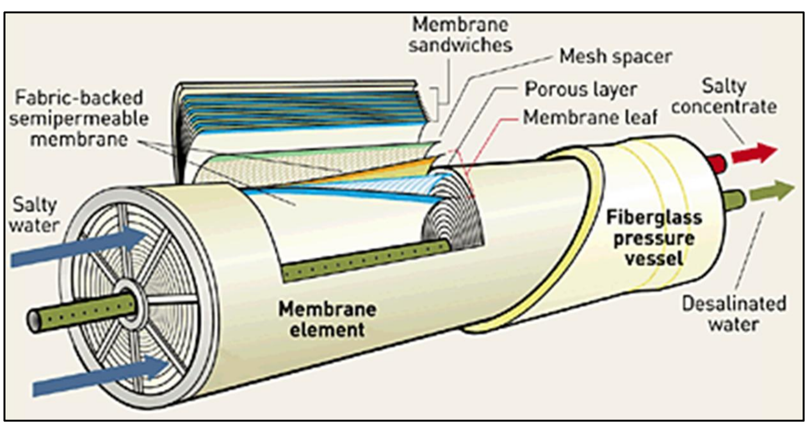

Figure 4 Schematic of generic membrane element

Marine Water Salinity

All desalination processes produce large quantities of brine water contain residues of pretreatment and cleaning chemicals, their reaction by-products, and heavy metals due to corrosion. High concentrations of salt are discharged to the sea through the outfall of desalination plants, which leads to the increased level of salinity of the ambient seawater. Also, chemical pretreatment and cleaning is a necessity in most desalination plants, which typically includes the treatment against biofouling, scaling, foaming and corrosion in thermal plants, and against biofouling, suspended solids and scale deposits in membrane plants. The chemical residues and by-products are typically washed into the sea (10).

Negative effects on the marine environment can occur especially when high waste water discharges coincide with sensitive ecosystems. The impacts of a desalination plant on the marine environment depend on both, the physical-chemical properties of the reject streams and the hydrographical and biological features of the receiving environment (10).

Marine Water Temperature

Desalination processes that require thermal energy input release brine effluent of a temperature higher than the ambient seawater temperature, leading to an increase of seawater temperature in the near vicinity of the treatment plant. Most organisms can adapt to minor deviations from optimal salinity and temperature conditions, and might even tolerate extreme situations temporarily, but not a continuous exposure to unfavorable conditions. The constant discharge of reject streams with high salinity and temperature levels can thus be fatal for marine life, and can cause a lasting change in species composition and abundance in the discharge site (10).

Energy Consumption

Desalination of water by any process involves energy consumption. The exact energy amount depends on the temperature and concentration of salts in the water. Higher salt concentrations require more energy for treatment to levels acceptable for drinking (11). In treatment methods like MSF and MED that involved treatment of water in stages or effects, as a portion of the water is purified, the remainder of the water has a higher salt concentration and thus, more energy is needed to separate the next unit of water in subsequent stages. Table 1 shows the energy needed based on the method used for the desalinization process (12).

Table 1 Typical unit size and electrical energy consumption

Component	MSF	MED	MVC	RO
Typical unit size (m^3/d)	50,000 -70,000	5,000 - 15,000	100 - 2500	24,000
Electrical Energy Consumption (kWh/m^3)	4 – 6	1.5 – 2.5	7-12	3 – 5.5

There are no major technical obstacles to desalination as a means of providing an unlimited supply of fresh water, but the high-energy requirements of this process pose a major challenge. Theoretically, about 0.86 kWh of energy is needed to desalinate 1 m^3 of salt water (12). Clearly, it is necessary to make desalination processes as energy-efficient as possible through improvements in technology and economies of scale.

Global Distribution of Disalination Methods

The cost of desalinated water taken at the outlet of a plant may vary widely from one site to the other. It depends on several factors which are: energy requirements, source, water characteristics, geographical and location constraints, product water requirements, waste disposal options, operational and maintenance issues and utilization rates (14).

High capital, operational and maintenance costs, high energy cost, and environmental impact costs are the main challenges facing desalination plants. The RO desalination method has grown in popularity during the last decade because it has experienced noticeable developments while other desalination methods have reached a stagnation point in advancements. In addition, costs of desalinating with RO have steadily decreased with time (15). Table 2 presents Performance comparison between MSF method and RO method (16).

Figure 5 presents that MSF accounts for 36.5% of the world's desalination plants, second only to RO at 47.2% (16). The MSF process utilizes a process with simple mechanics making it extremely popular despite its high cost. Environmental impacts among all methods are approximately similar while energy costs of all methods are dramatically different. Furthermore, RO can be considered as the most cost-effective method compared to the other methods, therefore, RO is the most widely used method in the world.

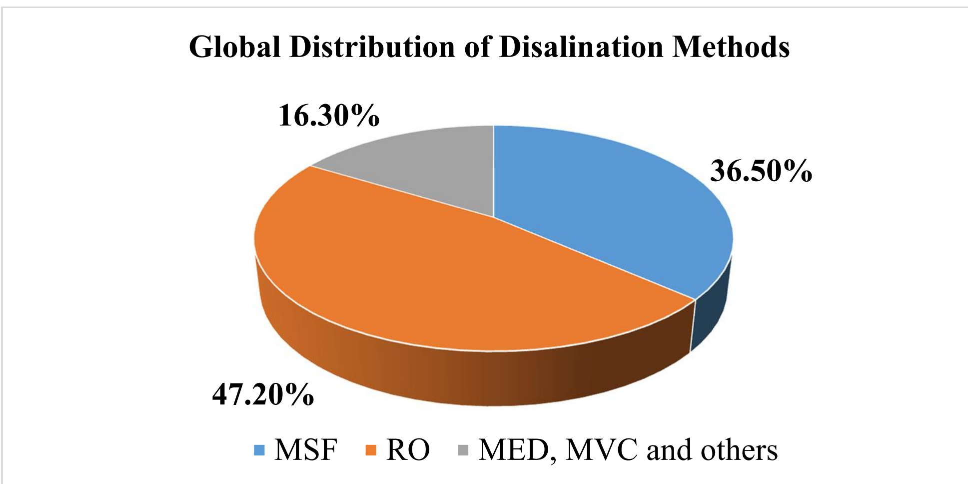

Figure 5 Global distribution of desalination methods

As shown in Figure 5, RO and MSF methods have the highest shares globally. Therefore, these two methods are normally associated with rejection of high saline concentration waste in addition to the thermal pollution in case of thermal processes like MSF.

Table 2 Performance comparison between MSF method and RO method

Component	**MSF**	**RO**
Recovery Percentage	10%-20%	30%-50%
Investment ($/(m^3/day))	1,000-1,500	7,00-1,500 (Including 10% for membranes)
Chemicals ($/m^3)	0.03 to 0.05	0.06 to 0.1
Brine Quality	Chemicals and Heat	Chemicals
Robustness	High	Medium (Problems: Fouling sensitivity and feed water monitoring)
Improvement Potential	Low	High

Building a desalination plant in line with a power plant can allow for the desalination plant to utilize excess power plant heat to account for thermal energy requirements in thermal treatment processes, reducing energy demand. Some researchers are even exploring coupling a power plant that utilizes cold air rather than water for cooling and using waste heat to power a low-temperature desalination plant to drastically improve energy efficiency in both systems and reduce water temperature in discharged brine. Theoretical estimates predict that this power and desalination method could be as much as 50% more efficient than current processes (17).

Case Study

A study of the biological impact of a large-scale desalination plant was conducted in Key West, Florida over the course of 18 months. The study showed an overall reduction in biotic diversity as a result of the operation of the plant (13).

Organisms from the study that were more prevalent than others in the control areas were able to isolate themselves from the plant's brine effluent. The temperature and salinity of the brine caused the effluent to stratify at the bottom of the receiving body, reducing water circulation. It was noted that the harbor acted as a settling basin for the effluent, lessening the impact of the brine discharge on the natural environment (13).

During the course of the study, the plant was shut down for periodic maintenance and cleaning. As it resumed operations, the brine effluent was of lower temperature and the same salinity as the ambient seawater, but contained high concentrations of ionic copper. It was determined that these sudden, high discharges of ionic copper were more detrimental to local flora and fauna than were discharges of increased temperature and salinity over an extended period of time (13).

The study resulted in the plant's staff making dramatic changes to correct corrosion issues to lower ionic copper discharges after shutdowns, but it's important to note that the discharge of brine of higher temperature and salinity than ambient seawater also resulted in negative biological impacts (13).

Findings

Desalinization of seawater is one of solutions to the growing problem of global water demand. However, desalinization concerns are with total source water requirement, brine disposal and energy consumption for treatment.

The desalinization process involves a large intake of salt water that will be converted into drinkable water. The water is received from different sources, but open seawater intakes are the most common option. The use of open intakes may result in losses of aquatic life when they collide with intake screens or are drawn into the plant with the source water. The construction of the intake structure and piping causes an initial disturbance of the seabed, which results in the re-suspension of sediments, nutrients or pollutants into the water column (18).

A desalinization plant using the MSF method and producing 100 m^3/day of potable water requires 3900 kWh/day of energy to operate. For the same amount of water produced, the required amount of energy would be 1750 kWh/day for MED, 1900 kWh/day for MVC, and 850 kWh/day for RO (12). The adverse effects of using large amounts of energy for desalinization is seen in the level of greenhouse gas (GHG) produced due to the burning of fossil fuels.

Regardless of which method is applied for the desalinization of seawater, a highly concentrated salt solution called brine is left behind as a by-product. The constant discharge of huge quantity of brine and high temperature levels back in the sea is fatal for marine life (18).

Conclusion and Recommendations

Reverse osmosis can be considered as the most cost-effective most widely used method in the world. However, desalinization concerns are with total source water requirement, brine disposal and energy consumption for treatment.

Further research and development will help reduce energy demand and cost of desalination, making it more environmentally friendly and boosting treatment efficiency to reduce various negative impacts. New technological advances can vastly improve treatment methods and improve energy efficiency.
Committing to hybrid desalination plants is likely the way of the future. Powering a desalination plant with solar energy could lead to a net zero release of GHGs. Coupling the brine discharge from a desalination plant with the discharge from a wastewater treatment plant can both reduce the salinity and the temperature of the brine to levels closer to that of the ambient seawater, lessening the negative environmental impacts of brine disposal.

High salinity and large energy requirements can also be mitigated by pairing the desalination facility with a waste water treatment plant in a co-location with a renewable energy plant such as solar. Effluent can be mixed with the brine to reduce salinity and thermal energy can be supplied to reduce energy demand.

References

1 Desalination in Florida: Technology, Implementation, and Environmental Issues, Division of Water Resource Management, Florida Department of Environmental Protection, April 2010. www.dep.state.fl.us/water/docs/desalination-in-florida-report.pdf. Accessed Nov. 3, 2015.

2 Vacuum distillation specifications, University of California, Department of Chemistry and Biochemistry.www.chem.ucla.edu/~bacher/Specialtopics/vacuum%20distillation.html. Accessed Nov. 10, 2015.

3 Kneen, B., Lemley, A., and Wagenet, L. Reverse Osmosis Treatment of Drinking Water. Cornell Cooperation Extention, College of Human Ecology. Fact Sheet 4, November 2005.

4 Introduction of Nuclear Desalination, A Guide Book. www.pub.iaea.org /MTCD/publications /PDF/TRS400_scr.pdf Accessed Nov. 1, 2015.

5 Multiple Stage Flash Processes.www.sidem-desalination.com/en/Process/MSF/. Accessed Nov. 10, 2015.

6 Multiple Effect Distillation Process.www.sidem-desalination.com/en/Process/MED/Process/. Accessed Nov. 1, 2015.

7 Enhanced Process using Vapor Compression. www.sidem-desalination.com/en /Process / MED/MED-TVC/. Accessed Nov. 9, 2015.

8 Contingency Water System Installation and Operation. www.wbdg.org/ccb/AF/AFH/ afh10_ 222_v11.pdf. Accessed Nov. 6, 2015.

9 Membrane. membrane.ces.utexas.edu/files/2012/08/membraneelement.gif. Accessed Nov. 15, 2015.

10 Dawoudl, M., and Al Mulla M. "Environmental Impacts of Seawater Desalination: Arabian Gulf Case Study", Water Resources Department, Environment Agency, Abu Dhabi, United Arab Emirates. International Journal of Environment and Sustainability, Vol. 1 No. 3, pp. 22-37.

11 Energy Use. www.usbr.gov/research/AWT/energy_use.html. Accessed Nov. 12, 2015.

12 Energy Requirements of Desalination Process. www.desware.net/desa4.aspx. Accessed Nov.9, 2015.

13 Chesher, R., "Biological Impact of a Large-Scale Desalination Plant at Key West," 1971. Westinghouse Ocean Research Laboratory, Office of Research and Monitoring, Environmental Protection Agency.

14 Seawater Desalination Success Story. www.linkedin.com/pulse/20140711034652-105135096-seawater-desalination-success-story?trkSplashRedir=true&forceNoSplash=true. Accessed Nov. 11, 2015.

15 Zhou, Y., and Tol, R.S.J., "Evaluating the Costs of Desalination and Water Transport," 2004. Research Unit Sustainability and Global Change and Center for Marine and Atmospheric Science, Hamburg University, Hamburg, Germany.

16 Banat, F., and Jwaied, N. "Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units". Chemical Engineering Department, Jordan

University of Science and Technology, Received 13 December 2006; accepted 3 January 2007.

17 Desalination and Power Plants-An Ideal Partnership? www.wateronline.com/doc/desalination-and-power-plants-an-ideal-partnership-0001. Accessed Nov. 30, 2015.

18 International Journal of Environment and Sustainability, Vol. 1 No. 3, 2012. pp. 22-37.

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