The Effect of Salt Amount on Desalination Process

Study Project

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December 2012
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Abstract

As an approach to water scarcity in the world, desalination is seen to be a sustainable technology. Desalination is a process to take the salt amount from a water matrix to provide fresh water. Reverse osmosis technology is currently the most used and seem to be the cheapest one. Black Sea and Mediterranean Sea are two regions in the paper to examine and the facility in Jeddah, Saudi Arabia is selected to be a reference point to support the information and application on selected seas for examination. Economical values are realized to be stable for each region and the most important factor is naturally the salt amount in the water matrix. It affects the cost according to the salinity and Black Sea is seen to be a better region to invest, even though there is no such facility there.

1. Introduction

Water scarcity is becoming a more serious problem each day. Available drinking water amount is one of the most important facts of this problem. Fresh water amount of the world is only 3% of the whole water amount in the planet and 2% percent is the glaciers and that remaining 1% is the fresh water we use. This problem should be taken too much care and it leads people to find new approaches and methods for drinking water sources.

Desalination is a worldwide popular method which has been applied by many countries in many regions to produce drinking water from sea water. The aim is simple in this process. It is producing drinkable water from sea water by taking the salt content out. The most known and used methods are reverse osmosis, thermal distillation desalination and electrodialysis desalination and there are some other methods which are still under development and not so often used. They are freezing desalination, solar humidification-dehumidification, geothermal desalination and methane hydrate crystallization.

There are many advantages of this application. Mainly the production of drinkable water is really important. For this process, there is almost an unlimited source which is the oceans in the world. Heat is an important effect for this process. It is used to keep system work (more information will be discussed further). Therefore, heat can be used instead of giving it to atmosphere and this way, no contribution to global warming would be done. On the other hand, the process is costly and requires a lot of energy and maintenance of the facilities are an important task.

Within the current water situation of the world and having such technology to provide a solution for the problem, this paper is being written by the aim of understanding the process, learning how the system works and examining the effect of salt amount on the process and cost by using the information learned about the process. Examining the variation of costs and process details according to salt content is quite important. Two different seas will be selected and one currently used facility will be studied in order to support the examination of selected seas. This support is needed because in these selected seas, possible desalination will be discussed and the differences between the processes and the costs will be revealed.

2. Desalination

Desalination process is applied to provide suitable fresh water for human consumption or irrigation. Although salt is an important byproduct, obtaining fresh water is the main target.

The process of conversion of seawater to drinking water (desalination) can also be used in order to increase the quality of the water from brackish or marginal sources. “Membrane desalting technologies are also used in home or tap water treatment systems, in industrial wastelining treatment to reclaim and recycle, to produce high-quality water for the semi-conductor and

2.1. Desalination Methods and Processes

There are three main methods of desalination. Throughout the paper, these three main processes will be evaluated in details. They are thermal (distillation) process, membrane process and electrodialysis. The reason of these methods being considered in the main category is that they have been used frequently and they have been currently the best technology with highest efficiency in treatment and economical basis.

However, there are some other processes, that are freezing desalination, solar dehumidification, geothermal desalination and methane hydrate crystallization. These methods are either newly discovered or not in application yet. Therefore they cannot be considered to be in the main category of methods.

2.1.1. Reverse Osmosis Desalination

2.1.1.1. Reverse Osmosis [App 1]

“When two solutions with different concentrations of a solute are mixed, the total amount of solutes (i.e. salts) in the two solutions will be equally distributed in the total amount of solvent (i.e. water) from the two solutions. In the natural occurring phenomenon of osmosis this is achieved by diffusion, in which solutes will move from areas of higher concentration to areas of lower concentrations until the concentration on both sides of a membrane and the resulting mixture are the same, a state called equilibrium. Equilibrium occurs when the hydrostatic pressure differential resulting from the concentration changes on both sides of the semi-permeable membrane is equal to the osmotic pressure of the solute. In reverse osmosis, salt water on one side of a semi-permeable plastic membrane is subjected to pressure, causing fresh water to diffuse through the membrane and leaving behind a more concentrated solution than the source supply containing the majority of the dissolved minerals and other contaminants. The major energy requirement for reverse osmosis is for pressurizing the source, or “feed” water. Depending on the characteristics of the feed water, different types of membranes may be used. Because the feed water must pass through very narrow passages as a result of the way the membrane packaged, fine particulates or suspended solids must be removed during an initial treatment phase (pretreatment).” [1] (http://www.amtaorg.com/wp-content/uploads/8_WaterDesalinationProcesses.pdf)

2.1.1.2. Process

There have been some different type of membranes in different processes but the main application for membrane process for desalination is reverse osmosis (RO). Some researchers were investigating a non-permeable membrane technology known as electrodialysis (ED). Both ED and RO processes use membranes to separate dissolved salts from water. [1] (http://www.amtaorg.com/wp-content/uploads/8_WaterDesalinationProcesses.pdf) This method is more preferred when the membrane desalination is mentioned. It is a very common method to use. The process is generally about taking the water from its source, applying a pre-treatment, then applying reverse osmosis method and then one final post-treatment phase before the delivery.

In order to select this process over the other methods, these key factors should be taken under consideration:

- Quality and salinity of the water intake
- Temperature of water intake
- Efficiency of membranes has improved significantly
- Energy consumption has reduced and is less than other processing methods
- Lower capital and operating costs

A very important and typical problem about membrane treatments is membrane fouling. \(^[^2]\) To avoid such problem and keep the membrane life as long as possible, sea water is pre-treated. The pre-treatment step is to get rid of any material and particle which will be too big for reverse osmosis membrane pores and also trying to prevent any clogging. \(^[^2]\) ([http://www.goldcoast.qld.gov.au/attachment/goldcoastwater/EBWS_FS4.pdf](http://www.goldcoast.qld.gov.au/attachment/goldcoastwater/EBWS_FS4.pdf)) Other applications during the pre-treatment phase are pH adjustment and adding threshold inhibitors to control scaling caused by constituents.

After pre-treatment, separation of water from salt takes part. First of all, there must be enough pressure on the water in order to make the process work. The pre-treated water is pressurized to an appropriate level for the membrane. “The permeable membranes inhibit the passage of dissolved salts while permitting the desalinated product water to pass through. Applying feed water to the membrane assembly results in a freshwater product stream and a concentrated brine reject stream. Because no membrane is perfect in its rejection of dissolved salts, a small percentage of salt passes through the membrane and remains in the product water.” \(^[^3]\) ([http://www.oas.org/DSD/publications/Unit/oea59e/ch20.htm](http://www.oas.org/DSD/publications/Unit/oea59e/ch20.htm)) Product water is the term for the water which was treated and desalinated.

After the salt content is desalinated, a post-treatment is needed to be done. This part includes the applications on water to make it appropriate for human use. This is mainly the pH adjustment, typically increased to 7 from 5. This is essential for the water to be used as a drinking water.
2.1.1.3. Operation and Maintenance

The main aspects for the operation and maintenance for a reverse osmosis desalination plant is to monitor the system day by day with a systematic program. This includes calibration, pump adjustment, chemical feed inspection and adjustment, leak detection and repair and structural repair of the system on a planned schedule. The most important maintenance point should be on membrane fouling. Operation, maintenance and monitoring of reverse osmosis plants require trained engineering staff.

2.1.1.4. Effectiveness of the Technology

After many years of research and work for making the process more efficient and better, today, the separation success of the process is 98% at TDS (Total Dissolved Solids) levels of 2500 to 3000 mg/L, using pressures of 13.6 to 17 atm and a flux of 24 L/m²/day. Twenty five years ago, the situation was 90% separation rate of the salt in feed water at TDS levels of 1500 mg/L, using pressures of 600 psi and a flux through the membrane of 18 L/m²/day. Also now, current effectiveness provides the facility to use the membranes for five years without any replacement. Today's state-of-the-art technology uses thin film composite membranes. This membrane replaced older cellulose acetate and polyamide membranes. Composite membranes can work over a wider range of pH, higher temperatures and higher chemical limits. Composite membranes are generally used in industrial applications because this membrane has a higher resistance to operational abuse.

2.1.1.5. Advantages

- It is a simple process.
- Systems may be assembled from prepackaged modules to produce a supply of product water ranging from a few liters per day to 750 m³/day for brackish water, and to 400 m³/day for seawater; the modular system allows for high mobility, making RO plants ideal for emergency water supply use.
- Installation costs are low.
- RO plants have a very high space/production capacity ratio, ranging from 25 to 60 m³/day/m².
- Low maintenance costs due nonmetallic materials are used in construction.
- Energy use to process brackish water ranges from 1 to 3 kWh per 1 m³ of product water.
- RO technologies can make use of use an almost unlimited and reliable water source, the sea.
- RO technologies can be used to remove organic and inorganic contaminants.
- Aside from the need to dispose of the brine, RO has a negligible environmental impact.
- The technology makes minimal use of chemicals. \(^3\) [App 3]

2.1.1.6. Disadvantages

- The membranes are sensitive to abuse.
- One complicated factor is to find or to produce a clean feed water to minimize the necessity of cleaning of the membrane.
- The feed water usually needs to be pretreated to remove particulates (in order to prolong membrane life).
- There may be interruptions of service during stormy weather (which may increase particulate re-suspension and the amount of suspended solids in the feed water) for plants that use seawater.
- Operation of a RO plant requires a high quality standard for materials and equipment.
- There is often a need for foreign assistance to design, construct, and operate plants.
- An extensive spare parts inventory must be maintained, especially if the plants are of foreign manufacture.
- Brine must be carefully disposed of to avoid deleterious environmental impacts.
- There is a risk of bacterial contamination of the membranes; while bacteria are retained in the brine stream, bacterial growth on the membrane itself can introduce tastes and odors into the product water.
- RO technologies require a reliable energy source.
- Desalination technologies have a high cost when compared to other methods, such as groundwater extraction or rainwater harvesting. [3]

2.1.1.7. Costs

Aside from the capital cost, electricity costs, membrane replacement and labor are the other main costs for this process. Labor is quite important as the facility needs trained engineers. The costs of the application changes from region to region or from country to country. But the main effects on cost are the plant capacity and the salt content.

![Desalination plant costs breakdown](http://www.lenntech.com/processes/desalination/energy/general/desalination-costs.htm)

Figure 2 – Cost Distribution of Reverse Osmosis Process

However, there is an inverse proportion between the plant capacity and the unit cost of the plant. As the plant capacity increases, the capital cost per unit of capacity decreases.
The main expenditure for a reverse osmosis plant for desalination is the electricity consumption. The main reason of this is the principle of reverse osmosis. In order to provide such effect, high amount of pressure is required. Therefore, electricity is the main expenditure.

Membranes are thought to be the most complicated issue of reverse osmosis, as they need to be repaired or renewed quite often and the money spent of maintenance would increase the costs. However, membranes alone don’t hold a very big part when the whole costs for the facility is considered. The second highest expenditure is on consumables. Consumables mean goods that are intended to be used and then replaced. These goods can be the pumps, engines, chemical and some other stuff. Material circulation in reverse osmosis is quite much and therefore this term consumables hold the second biggest cost amount.

2.1.2. Thermal Distillation Desalination

2.1.2.1. Process

This process works by the principle of hydrologic cycle\[^{App~4}\]. In hydrologic cycle, water evaporates from the planet surface and then condenses which comes back to earth surface by precipitation. (Detailed information can be found in appendix section) Distillation is a phase separation method whereby saline water is heated to produce water vapor, which is then condensed to produce freshwater. During this cycle, it gets rid of its salt content. Thermal distillation desalination method is the oldest and the most commonly used desalination method. There are numerous methods of this desalination process. These are;

- Multi stage flash evaporation (MSF)
- Multi effect distillation (MED)
- Vapor compression (VC)

The various distillation processes used to produce potable water, including MSF, MED, VC, and waste-heat evaporators. All of these methods generally operate on the principle of reducing the
vapor pressure of water within the unit to permit boiling to occur at lower temperatures, without the use of additional heat. Distillation units routinely use designs that conserve as much thermal energy as possible by interchanging the heat of condensation and heat of vaporization within the units. Therefore, the major energy requirement in the distillation process becomes providing the heat for vaporization to the feed water.

There are two other methods which are not used or developed enough like these basic methods written above. They are membrane distillation and dual purpose. Thermal energy holds a very big amount of overall desalting cost. Therefore, distillation processes recovers and reuse waste heat from electrical power plant in order to decrease the total energy requirements. The needed energy amount can also decrease in significant amounts when boiling in successive stages when operated at a lower temperature and pressure. These evaporation methods are mainly used for seawater conversion.

MSF and MED require thermal input, additional to electric power. Material selection is important for these methods because they handle hot sea water. On the other hand, VC uses only electrical power with the thermal input which comes from the heat of compression. VC is generally the most economical process but the fan compressors limit the output capacity. [1] (http://www.amta.org/wp-content/uploads/8_WaterDesalinationProcesses.pdf)

### 2.1.2.1.1. Multistage Flash (MSF)

The first step of this method is the heating stage(s). The seawater passes through a heating stage and it is heated further in the heat recovery sections of each stage. This is a multiple stage with the same application and after the last part, flashing occurs. By using an externally supplied system, the feed water is further heated. This application makes the water to reach its highest temperature and then, flashing takes place at some various stages. The vapor pressure is controlled at each state because the vapor should enter each chamber at appropriate temperature and pressure. This is applied to cause instantaneous and violent boiling and evaporation.

After this step, fresh water is started to be collected by condensation. The water is collected at each stage and they pass with brine parallel. At each stage, the product water is also flash-boiled so that it can be cooled and the surplus heat recovered for preheating the feed water.

Because of the large amount of flashing brine required in an MSF plant, a portion (50% to 75%) of the brine from the last stage is often mixed with the incoming feed water, re-circulated through the heat recovery sections of the brine heater, and flashed again through all of the subsequent stages. This makes the plant to be named “brine cycle” plant. This is important to reduce the need of the amount of water-conditioning chemicals and it significantly affects the operation costs. However, this increases the salinity of the brine and this increases the boiling point of the water and also causes corrosion and scaling in the plant. In order to build a convenient brine density system, a portion of the concentrated brine from the last stage is discharged to the ocean.
2.1.2.1.2. **Multiple Effect Distillation (MED)**

This method can be simply explained that there are two sides where some action takes place. In one side, steam is condensed on one side of a tube wall and on the other side, the water is evaporated. The energy source of this method is the heat of the condensation of the steam. Condensation-evaporation is a series in this method. The saline water is usually applied to this tubes which are in a thin film form in order to make it evaporate easily. MED is accepted to be the most important large-scale evaporative process. There is also a significant potential water cost reduction compared to other large-scale desalination processes. The working principle of MED units is reducing the ambient pressure at each successive stage. It allows the feed water to go under a multiple boiling sessions without being in necessity to supply additional heat.

In MED units, steam and/or vapor from a boiler or some other available heat source is fed in to a series of tubes. It condenses here and it heats the surface of the tube. This process acts as a heat transfer to surface and it evaporates saline water on the other side. The energy source of this process is the heat of condensation of the steam in the tube. The evaporated saline water is sent to the next lower-pressure stage where it condenses to fresh water product. During this process, it gives up its heat to evaporate a portion of the remaining seawater feed.

“A well-designed multi-effect-distillation plant will cover approximately 40 - 65% of the feed as product water. Product water quality is highly pure with TDS values typically less than 10 mg/L TDS.

MED plans typically drive their energy from low pressure steam generators or industrial process steam. MED units are also unique in that ability to recycle waste heat from thermal power plants,
diesel generators, incinerators or industrial processes and as a consequence, are often sited adjacent to such plans or incorporated with them at the design stage.” [5]


Figure 5 - Multiple Effect (MED)
(http://www.sidem-desalination.com/en/Process/MED/MED-MVC/)

2.1.2.1.3. Vapor Compression (VC)

Instead of creating a direct source of heat energy, this method applies a mechanical energy. The water vapor is taken from the evaporation chamber and condensed on the outside of the tubes except the first stage. This method is short and easy to describe. It is also simple, reliable and highly efficient because of its low energy requirements.

This process is similar to MED but the main difference is that the vapor produced by evaporation is not collected in a separate condenser. With a help of a compressor, it is sent back to the steam side of the same evaporator.

The energy needed for evaporation is not obtained from a main steam source. It is obtained from a vapor compressor. “Typically these units are no smaller than 300 to 400 m$^3$/day and the most economic with feed water of high TDS levels, typically greater than 50,000 mg/L TDS (higher than seawater). High-quality product water can also be achieved with VC units generally less than 10 mg/L TDS, and in some cases even as slow as 2 mg/L TDS. Recoveries of approximately 50% can be achieved with these units.” [5]

Figure 6 – Vapor Compression (VC)
(http://prodimages.vertmarkets.com/image/49e06816/49e06816-cb2c-11d4-8c85-009027de0829/original/image1.jpg)

2.1.2.1.4. Membrane Distillation

This process is a new method. The process works by using a specialized membrane which will pass water vapor but not liquid water. This membrane is placed over a moving stream of warm water, and as the water vapor passes through the membrane it is condensed on a second surface which is at a lower temperature than that of the feed water.

2.1.2.1.5. Dual Purpose

Most of the large distillation units in the world are dual-purpose facilities. Specifically, they derive their source of thermal energy from steam that has been used for other purposes, usually for power generation. Thus, the feed water is heated in a boiler to a high energy level and passed through a steam turbine before the steam is extracted for use at a lower temperature to provide the heat required in the distillation plants.

2.1.2.2. Operation and Maintenance

In these (generally named thermal distillation) facilities, they are mostly built on some locations where the construction is difficult and fuels, chemicals or technical parts are difficult to find. The operation of distillation facilities require careful planning, well trained operators and a strong budget to provide a good supply of quality water. The common operation and maintenance aspects of the facilities for all three methods include:

- Repairing damage (cracks) to the stainless steel liners in the stages.
- Removing scale and marine growths in the tubes in all stages using high pressure "hydrolaser" sprayers.
- Removing the vacuum system ejectors for cleaning, inspection, and replacement as necessary; most parts have a lifetime of 3 to 4 years.
- Inspecting all pumps and motors, replacing bearings and bushings, and renewing protective coatings on exposed parts.

2.1.2.3. Effectiveness of the Technology

2.1.2.3.1. MSF

MSF (multistage flash) system is proven to be a very efficient system, even though the desalination of sea water is a relatively expensive application. Still, it produces high quality product water. One benefit of the system is that because of the water is boiled; there is a minimal risk of any bacterial or pathogenic virus contamination. However, MSF is thermodynamically inefficient.

2.1.2.3.2. MED

Compared to MSF, MED is thermodynamically efficient. A MED unit is an evaporator. It evaporates the sea water one or more times (up to 14 times). The temperature is low during these evaporation stages. It is smaller than 70°C, in order to produce clean distillate water. MED process is designed to produce distilled water with steam or waste heat from power production or chemical processes, and/or to produce potable water.

2.1.2.3.3. VC

VC is known to be a very efficient system because the system is electrically driven, clean and highly reliable in terms of operation and maintenance. This reliability increases its effect especially in the market.

2.1.2.4. Advantages

The advantages written below are the common points for thermal distillation system. As this system will be compared to the other two desalination systems (reverse osmosis and electrodialysis), pointing out the common advantages will bring better results for the paper.

- Distillation offers significant savings in operational and maintenance costs compared with other desalination technologies.
- In most cases, distillation does not require the addition of chemicals or water softening agents to pre-treat feed water.
- Low temperature distillation plants are energy-efficient and cost-effective to operate.
- Many plants are fully automated and require a limited number of personnel to operate.
- Distillation has minimal environmental impacts, although brine disposal must be considered in the plant design.
- The technology produces high-quality water, in some cases having less than 10 mg/L of total dissolved solids (TDS).
- Distillation can be combined with other processes, such as using heat energy from an electric-power generation plant. [4]
  (http://www.oas.org/DSD/publications/Unit/oea59e/ch21.htm)

2.1.2.5. Disadvantages
The disadvantages written below are the common points for thermal distillation system. As this system will be compared to the other two desalination systems (reverse osmosis and electrodialysis), pointing out the common disadvantages will bring better results for the paper.

- Some distillation processes are energy-intensive, particularly the large-capacity plants. (Disposal of the brine is a problem in many regions)
- The distillation process, particularly MSF distillation, is very costly.
- Distillation requires a high level of technical knowledge to design and operate.
- The technology requires the use of chemical products, such as acids, that need special handling. [4](http://www.oas.org/DSD/publications/Unit/oea59e/ch21.htm)

However, there are different advantages and disadvantages of each method. This little section will reveal those differences but for the comparison in bigger frames, the points above will be used.

### 2.1.2.5.1. Advantages and Disadvantages of MSF

#### 2.1.2.5.1.1. Advantages

- MSF plants can be constructed to handle larger capacities.
- The salinity of the feed water doesn’t have much impact on the process or costs.
- It produces very high quality product water (less than 10 mg/L TDS).
- There is only a minimal requirement for pre-treatment of the feed water.
- The strict operational and maintenance procedures for other processes are not as rigorous for MSF.
- There is a long history of commercial use and reliability.
- It can be combined with other processes (for example, using the heat energy from an electricity generation plant). [5](http://www.environment.gov.au/water/publications/urban/pubs/desalination-full-report.pdf)

#### 2.1.2.5.1.2. Disadvantages

- They are expensive to build and operate and require a high level of technical knowledge.
- Highly energy intensive due to the requirement to boil the feed water, although energy efficiency is substantially enhanced via the heat recovery process.
- The recovery ratio is low; therefore more feed water is required to produce the same amount of product water.
- The plant cannot be operated below 70-80% of the design capacity.
- Blending is often required when there is less than 50 mg/L TDS in the product water. [5](http://www.environment.gov.au/water/publications/urban/pubs/desalination-full-report.pdf)

### 2.1.2.5.2. Advantages and Disadvantages of MED

#### 2.1.2.5.2.1. Advantages

- The pre-treatment requirements of the feed water are minimal.
- Product water is of a high quality.
- MED plants are very reliable even without a strict adherence to maintenance.
- The plant can be combined with other processes such as using the heat energy from a power plant.
- The plant can handle normal levels of biological or suspended matter.

2.1.2.5.2.2. Disadvantages

• They are expensive to build and operate – energy consumption is particularly high.
• The plant can be susceptible to corrosion. This can usually be controlled by the choice of material.
• The product water is at an elevated temperature and can require cooling before it can be used as potable water.

2.1.2.5.3. Advantages and Disadvantages of VC
2.1.2.5.3.1. Advantages

• The plants are very compact and can be designed to be portable.
• Minimal pre-treatment is required.
• The capital cost of the plant is reasonable and operation is simple and reliable.
• The recovery ratio is good.
• The product water is of a high quality.

2.1.2.5.3.2. Disadvantages

• Starting up the plant is difficult. An auxiliary heater is normally required to get the temperature of the feed water up to a point where some vapor is formed. After this the compressor can take over.

2.1.2.6. Costs

The main factors affecting the cost are the type of process used, plant capacity, salinity of the water and level of familiarity of the region to the process. Naturally, cost increases as the capacity of the facility increases. In many applications, distillation provides the best means of achieving waters of high purity for industrial use: for volumes of less than 4000 m³/day, the VC process is likely to be most effective; above that range, the MSF process will probably be preferable.
Table 1 – Costs of Processes in Three Different Thermal Distillation Methods

![Table Image]

This table shows the capital and operating costs for the main technologies used in seawater Desalination and these technologies are: Multi-Stage Flash Distillation (MSF), Multi-Effect Distillation with Thermal Vapor Compression (MED-TVC) (can be referred to MED) and Mechanical Vapor Compression (MVC) (can be referred to VC).

According to this table, the most two important expenditures – installation cost and operation and maintenance cost – are highest at MSF and lowest at MED. Each technology has its cheaper or more expensive ways, which leaves the investor to decide which one to choose. Operation and maintenance, spare part and chemicals costs are not too much and they are proportional to the area of the facility and the treated water amount.

As seen in the table, installation cost is the highest in MSF (average value is 1385 €/m$^3$/day) and lowest in MED (average value is 930 €/m$^3$/day). The average value of VC is 1260 €/m$^3$/day.

2.1.3. Electrodialysis Desalination

2.1.3.1. Process

Electrodialysis (ED) is an electrochemical used to separate the salt from the water in desalination process. The separation takes place with opposite charged membranes from one solution to another by using the electrical potential difference as a driving force. This process has been widely used for production of drinking water and process water from brackish water and seawater, treatment of industrial effluents, recovery of useful materials from effluents and salt production. [6]

In a typical process, a series of membranes with anion and cation ends are arranged. This is the typical process and as naturally expected, positively charged ions (cation) move towards cathode and the other ions (anion) move towards anode. [7]
2.1.3.2. Operation and Maintenance

Necessarily, product water monitoring is essential and required. Estimation of chemical usage and power consumption costs are also important parts of operational monitoring. Additional to these, controlling of the membranes are the other typical necessity. Anion and cation membrane life is estimated at 4 and 7 years respectively. One important problem of the process is the fouling and scaling of membranes. This problem may cause the ions to trap in membranes’ network. This problem’s solution is called flushing which is reversing the polarity of the direct current source. Frequent reversals of the current (3 to 4 times per hour) are essential for effective operation. However, the product water quality deteriorates as a result of contamination when the brine and product compartments are switched after such polarity reversals. In order to avoid loss of partially desalinated water during this 30 to 60 second period, the product water is recycled back to the feed tank.

To control the flow rate of the water and stack pressure, valves are used. Monitoring of the pressure stages is very important. Cross leakage can pollute the product stream. This is avoided by maintaining the brine loop pressure slightly below that of the dilute stream (about 450 and 480 kPa, respectively). Operation of the system also requires the continuous removal of brine and gases formed as by-products of the electro dialysis process, including hydrogen, chlorine and oxygen. [7] (http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/electro.asp)

2.1.3.3. Effectiveness of the Technology

There are three main subjects that can be listed to reveal the aspects of effectiveness. These three subjects are:

- Concentration polarization and limiting current density
- The limiting current density, causes and consequences
- The current utilization

2.1.3.3.1. Concentration Polarization and Limiting Current Density
“An electric current passing through an electrodialysis cell pair is carried in the solution by both cat- and anions according to their transport numbers which are in aqueous solutions not very different for cat- and anions. In the ion-exchange membranes, however, the current is carried mainly by the counter ions. The differences in the transport numbers of ions in the solution and in the ion-exchange membranes results in a depletion of counter-ions at the surface of the ion exchange membranes facing the dilute solution, and a concentration gradient is established in the solution between the membrane surface and the well mixed bulk. This concentration gradient results in a diffusive electrolyte transport. A steady state situation is obtained when the additional ions that are needed to balance those removed from the interface due to the faster transport rate in the membrane are supplied by the diffusive transport. The other side of the ion-exchange membrane is facing the concentrate solution. Here, an accumulation of ions occurs, because more ions are transferred through the membrane that can be carried away by the electric current due to the lower transport numbers in the solution than in the membrane. Thus, a concentration gradient of the salt is established in the solution which results in an additional diffusive salt flux from the membrane into the solution.” [8] (http://gwri.ic.technion.ac.il/pdf/IDS/82.pdf)

2.1.3.3.2. The Limiting Current Density, Causes and Consequences

“The consequences of concentration polarization in electrodialysis are twofold. In the dilute containing cell the salt concentration at the membrane surface is decreased and in the concentrate containing cell increased. Both effects impair the technical feasibility and the economics of the process. When, due to concentration polarization, the salt concentration in the concentrate cell exceeds the solubility limits of the solution constituents, precipitation of salts occurs. When, due to concentration polarization, in the dilute containing cell the salt concentration at the membrane surface is reduced to zero there are no more salt ions available to carry the electric current. Thus, the voltage drop across the boundary layer increases drastically resulting in higher energy consumption and in an electric field enhanced water dissociation. The consequence of the water dissociation is a loss of current utilization and drastic pH-value shifts, with an increase of the pH value at the surface of the anion-exchange membrane in the concentrate containing cell and a decrease of the pH-value at the surface of the cation-exchange membrane. The increase in the pH-value can lead to a precipitation of multivalent ions on the membrane surface. Thus, in a practical application of electrodialysis the concentration polarization effects should be minimized and especially water dissociation should be avoided.” [8] (http://gwri.ic.technion.ac.il/pdf/IDS/82.pdf)

2.1.3.3.3. The Current Utilization

“In any practical electrodialysis process not all of the current flowing through the stack can be utilized for desalting the feed solution. Several factors may contribute to incomplete current utilization in an electrodialysis stack: the membranes are not perfectly selective, there may be parallel current paths through the stack manifold, and there is water transfer across the membranes due to osmosis and electro osmosis.” [8] (http://gwri.ic.technion.ac.il/pdf/IDS/82.pdf)

2.1.3.4. Advantages

The advantages are mainly compared to reverse osmosis and nanofiltration.

- High water recovery rates even for raw water with high sulfate content.
- Long useful life of membranes due to higher chemical and mechanical stability.
- Operation at elevated temperatures up to 50 °C possible.
- Less membrane fouling or scaling due to process reversal.
- Less raw water pretreatment.
- Ion-exchange membranes tolerate higher level of chlorine and extreme pH-values.
• The process can easily be adjusted to varying feed water quality.
• Easy start-up and shut-down of the process for intermittent operation. [8] (http://gwri-ic.technion.ac.il/pdf/IDS/82.pdf)

2.1.3.5. Disadvantages

• Neutral toxic components such as viruses or bacteria are not removed by electrodialysis. Therefore, a post-treatment may be required prior to the use as potable water.
• Generation of chlorine gas at the anode can lead to corrosion problems in the surrounding of the plant if the venting is insufficient.
• In spite of the fact that electrodialysis reversal is significantly less sensitive to membrane fouling than reverse osmosis some pretreatment of the feed water is required to achieve trouble free operation. [8](http://gwri-ic.technion.ac.il/pdf/IDS/82.pdf)

2.1.3.6. Costs

The cost of the process contains the costs of investment and operation mainly. The technical costs hold an important role, including electrodialysis stacks, pumps, electrical equipment, monitoring and control devices, and membranes.

The total operating costs of the electrodialysis plant include energy and maintenance costs and all pre- and post-treatment procedures. They are also a function of the membrane properties, feed and product composition, and several process and equipment design parameters such as stack construction.

Applied current density is a very influential effect on costs in electrodialysis process. It directly affects the investment costs and energy costs. Thus, the total product costs which are the sum of energy costs, amortization and maintenance costs are a function of the current density and will reach a minimum at a certain current density. The optimum operating current density in electrodialysis depends to a large extent on the equipment, and especially on the membrane costs and life, and on the cost of energy. The current density to be applied in electrodialysis is determined by the limiting current density.

Figure 8 – Cost Diagram of Electrodialysis as a Function of the Applied Current Density (http://gwri-ic.technion.ac.il/pdf/IDS/82.pdf)

2.1.4. Freezing Desalination
Short frost periods were used to free salt water from ditches where it was then allowed to melt in the sunlight. Some of the salty water start freezing initially in open waters. However, as solidification continues to take place, mass transport also takes place throughout the semisolid layer. The salinity decreases by time as this process occurs. This results glacial and sea ice to be relatively salt free. [9](http://www.rpi.edu/dept/chem-eng/Biotech-Environ/Environmental/desal/freeze.html)

As should have been noticed so far, desalinization happens in two ways. One is removing the water and leaving the concentrated salt and the other, opposite, removing the salt and leaving the fresh water. Removing the water principle cannot be applied for freezing desalination. Because, as a function of salinity, salty waters have a critical temperature and when the temperature is reduced to this amount, ice crystals are formed which are composed of salt free fresh water. It is only then possible to separate these crystals mechanically.

Freezing desalination is not a very practical method. Especially when applied to large scale process, problems will occur. The main problem is the economical aspects of initial capital costs and the maintenance costs. The other problem is the thermodynamic efficiency. On the other hand, there are some advantages of this process also. Because of the operating temperature is at or below zero degrees, scaling and corrosion are greatly reduced. This is a very important problem for other methods.

There are different methods to separate the ice crystals from the liquid. Choosing the right method is depending on the characteristic of the ice crystals. Two things that should be considered are crystal size and specific gravity. Even though filtration seems to be the best approach, it is actually impractical because it requires a slow and complicated system. A better approach would be separation as it can consider the specific gravity. [9](http://www.rpi.edu/dept/chem-eng/Biotech-Environ/Environmental/desal/freeze.html)

### 2.1.5. Solar Humidification-Dehumidification

“The solar humidification-dehumidification method (HDH) is a thermal water desalination method. It is based on evaporation of sea water or brackish water and consecutive condensation of the generated humid air, mostly at ambient pressure. This process mimics the natural water cycle, but over a much shorter time frame.”

It is simply implemented in a solar still, making the sea water evaporate inside a glass covered box and then condensing the water on the lower side of this cover. In some more developed systems, evaporation and condensation sections are different which causes a solar heat gain. This desalination cycle is called multiple-effect humidification (MEH) method of transportation. [10](http://en.wikipedia.org/wiki/Solar_humidification)

### 2.1.6. Geothermal Desalination

This is an under development process for obtaining fresh water by using the heat energy. The main benefit of the method is that it will be using geothermal energy which is a green energy. This way, less maintenance will be required compared to reverse osmosis membranes. [11](http://www.energia.gr/geofar/articlefiles/geothermalinnovative-desalination.pdf)

This method is considered to be having a lot of advantages and a method which is quite invested on. The main benefits are like below:

- Yielding fresh water of high quality.
• Cost effective.
• Low energy requirements.
• Friendly to the environment, as only renewable energy is used with no emissions of air pollutants and greenhouse gasses.
• Aiding local development and improves employment perspectives.
• Saving foreign currency as no imported fossil fuels are used. [12](http://egec.info/wp-content/uploads/2011/03/Brochure-DESALINATION1.pdf)

2.1.7. Methane Hydrate Crystallization

Methane hydrate is a solid clathrate compound in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice. This originally can be founded in cold places, which are outer regions of Solar system and deep points in oceans. [13](http://en.wikipedia.org/wiki/Methane_hydrate)

Clathrate hydrate desalination is not on the horizon as it stands now, as there are no operational facilities running on a continuous basis, even at the pilot plant scale. Before hydrate desalination is realized as a viable commercial technology, the fundamental issues of controlled hydrate nucleation, hydrate size and morphology, agglomeration, amount of entrapped salt, and the efficient recovery of hydrates must be thoroughly and effectively solved and optimizations implemented. [14](http://prod.sandia.gov/techlib/access-control.cgi/2007/076565.pdf)

2.2. Comparison of Methods

As the main methods of desalination are well known by now, a good comparison can be made between each other, revealing the best and worst processes for the terms discussed. The discussed terms are mainly the effectiveness, operation and the costs of the processes. However, it should not be ignored that there is no such thing as “the best method” because each method are different and when choosing such method, the quality of the water, the demand from the process, environmental and geographical circumstances and the budget should be considered.

Understandably, monitoring is essential for all processes. And these processes are different than each other. Therefore, each process has specific parts and materials to maintain. The common things for all processes are that they require well trained engineer stuff to run the operation and maintenance. Also, the technical devices, such as pumps are the other common things. Reverse osmosis and electrodialysis process have a common things to maintain, which is the chemicals amount. In thermal distillation, it is not an issue. Also, membrane fouling is the common problem for reverse osmosis and electrodialysis. Thermal distillation has no such problem.

The effectiveness of the processes is high, especially when reverse osmosis and thermal distillation desalinations are considered. One advantage of thermal distillation is that it kills the bacteria due to high temperature treatment. As electrodialysis has three important factors affecting its effectiveness (mentioned above in the section), it can be accepted to have a limited effectiveness compared to other processes. The reason of this difference is the cause of those three factors.

A cost comparison is difficult to do because the variation of costs from country to country is huge. Because of this reason, even for the same process, it is not so instructive to do a comparison. But a cost comparison for these processes about their costs distribution is possible. Even though such estimation is difficult, it will be instructive to give any source regarding such cost comparisons with strict numbers whenever possible. Figure 9 is a good example of such data.
This figure shows the unit production costs in $/m$^3$ and electrical energy in kWh/m$^3$. The comparison is between reverse osmosis, thermal distillation (all three methods), solar desalination, adsorption (AD) and adsorption with multi-effect distillation. The numbers show the value how much of what is consumed. For example, in solar dam, there is a unit production cost of 0,05 $ for one cubic meter.

The highest unit production cost is MSF (multistage flash) process with a value of 1,1 $/m^3$ and the lowest value is for solar/dam process with a value of 0,05 $/m^3$. The highest electrical energy is VC (vapor compression) with a value of 11,1 kWh/m$^3$ and the lowest value is again for solar/dam process with a value of 0,63 kWh/m$^3$.

However, these are the only two aspects of the whole energy consumption. Solar/dam process is a good example for this. It has the lowest two values for the things examined here but it has the highest energy consumption with a value of 475,01 kWh/m$^3$. Reverse osmosis has the lowest value for this manner, with a value of 14,29 kWh/m$^3$. Unit production cost and electrical energy consumption holds great importance for reverse osmosis because when compared with others, these two things have the greatest affect on whole energy consumption because they have the highest percentage in consumption.

The advantages and the disadvantages of the desalination methods have been widely examined. The main idea that can remain is that reverse osmosis technique is a low cost and a low energy consumption technology but also being eligible to have systems that can break down easily and needing too much material to operate. Thermal distillation process has main advantages of producing high quality water and having many options (different methods) to apply but also being more difficult and expensive. Electro dialysis is easy to use and having a long life of operation but also possible to have contamination and corrosion in the system. These advantages and disadvantages are revealing according to the processes and comparison to each other. But to be specific, there can be three things mentioned for these processes, which one of them has an advantage in it while the other has a shortcoming about it. For example, bacteria: in thermal distillation process, bacteria are killed due high temperature while in electrodialysis cannot remove these bacteria. Another example
is membrane fouling; in electrodialysis, membrane fouling is less due to the process reversal but in reverse osmosis, it is a very common problem. One another example can be given on extra material use. Reverse osmosis requires a lot of extra materials such as chemicals and technical devices but in the other two processes, thermal distillation and electrodialysis, the necessity of such material amount is lower. The other points mentioned in the advantages and disadvantages section for each process should be studied and the investor should choose the best method according to the circumstances.

3. Selection of Seas
   3.1. Black Sea

Black Sea has coasts to countries Turkey, Bulgaria, Romania, Ukraine, Russia and Georgia and holds an area of 461000 km². The deepest point of the sea is 2210 meters. It has been an important sea throughout the history for many countries in economical and geological ways.

Under the deepness level after 200 m, there is no oxygen found in the sea. Therefore the variety of living population in the sea is limited. Studies have shown that Black Sea used to be a lake, till the end of ice age [App 5], 10000 years ago. This means that the content of the sea was not that much salty, making it right to consider the water as fresh water. [15] (http://www.karalahana.com/makaleler/karadeniz/Karadeniz.htm)

![Figure 10 – Black Sea (Google Earth)](Google Earth)

The salinity of the Black Sea is 17.5 – 18 g/L. In the depth points, this rises to 20-22 g/L. Below the depths 150 m, temperature is stable and around 8.5 – 9 °C. The reason of the sea having no oxygen in deep points is that the water is saturated with hydrogen sulphide. Because of its location, the water transport in Black Sea is very low. As it used to be a lake, it is quite normal and now, by Istanbul Bosphrous, the sea connects to Marmara Sea and by Çanakkale Bosphorus, the sea connects to Aegan Sea, which is an extension of Mediterranean Sea. [16] (http://www.europe.culturebase.net/contribution.php?media=307)
As also can be seen in this figure, the salt content of the water is less in coastal regions and gets more when reached to middle parts of the sea. This makes the surface water having less salt amount also.

3.2. Mediterranean Sea

Mediterranean Sea has coasts to countries Turkey, Syria, Cyprus, Lebanon, Jordan, Israel, Egypt, Libya, Tunisia, Algeria, Morocco, Spain, France, Monaco, Italy, Malta, Slovenia, Croatia, Bosnia Herzegovina, Montenegro, Albania and Greece and holds an area of 2500000 km². The average depth of the sea is 1500 m and the deepest point is 5267 m in the Calypso Sea. Mediterranean Sea used to be most important sea throughout the history because of its location, especially before the discovery of New World [App 6].
The salinity of the Mediterranean Sea is 38 g/L. Because of this amount, the sea is considered to be salty sea, which means that sea content is high. The reason of this is that there is not enough river flow, discharging to the sea. The other reason is the evaporation of the water which is quite much due to high evaporation rates.\(^{17}\) (http://www.enbasit.com/akdeniz-suyu-neden-daha-tuzludur-kisaca-ozet.html)

As seen in the figure, the salt content of the Mediterranean Sea is getting higher as it gets to East. This may have some reasons, such as Red Sea having more salt content (41 g/L) than Mediterranean Sea may affect the closer regions and the Atlantic Ocean having a salt amount of 37 g/L. It was also mentioned that one of the reasons of this sea to have higher salt amount was the evaporation. Considered the regions, Middle East has higher temperatures compared to Western European regions. This can also be a leading effect.
When compared, it is seen that the salinity of Mediterranean Sea is almost two times more than Black Sea. The water flow in Black Sea is less than Mediterranean Sea but the river connections of Black Sea are a lot more than Mediterranean Sea.

The other reason for this fact is the temperature and the evaporation process happening accordingly. Evaporation is an important factor for salinity, as it directly affects the water amount and affects salt amount percentage in the water.

   4.1. Desalination in Saudi Arabia

Saudi Arabia is a country which did a lot of investments on desalination process in the past years in many other regions of the country. Desalination is an important process for obtaining fresh water. To support the current process in the country, a desalination plant in Jeddah, which operates on Red Sea, has been chosen. The process is applied by SAWACO Company. (www.sawaco.com) The name of the facility is SOJECO. As proceeded in the paper, some information will be revealed about the facility, process, operation and costs. All these information are shared by the company only for the aim of contributing to this project and none of the information below about the facility can be shared in any platform or with third parties.

   4.1.1. Red Sea

The information about Red Sea is like below;

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Seawater</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>Conductivity</td>
<td>micS/cm</td>
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</tr>
<tr>
<td>pH</td>
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<td>7.71</td>
</tr>
<tr>
<td>Chlorine</td>
<td></td>
<td>Nil</td>
</tr>
<tr>
<td>Alkalinity</td>
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</tr>
<tr>
<td>Hardness</td>
<td>mg/L as CaCO3</td>
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</tr>
<tr>
<td>Calcium</td>
<td>mg/L as Ca+</td>
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</tr>
<tr>
<td>Magnesium</td>
<td>mg/L as Mg+</td>
<td>1686,42</td>
</tr>
<tr>
<td>Iron</td>
<td>mg/L</td>
<td>0.09</td>
</tr>
<tr>
<td>Sodium</td>
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</tr>
<tr>
<td>Chloride</td>
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<td>25092,22</td>
</tr>
<tr>
<td>Sulfate</td>
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</tr>
<tr>
<td>Nitrate</td>
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</tr>
<tr>
<td>Odor</td>
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<tr>
<td>Salinity</td>
<td>g/L</td>
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</tr>
<tr>
<td>Taste</td>
<td></td>
<td>Salty.</td>
</tr>
</tbody>
</table>

Table 2 – Characteristics of Red Sea
   (SAWACO Company)
4.1.2. Facility

The size of the facility is 22000 m$^2$. The daily capacity of the facility is like below. The terms SWRO and BWRO refer to Sea Water Reverse Osmosis and Brackish Water Reverse Osmosis respectively.

- Intake water capacity 31,500 m$^3$/day
- Raw water total feed flow 29,856 m$^3$/day
- SWRO water capacity 10,000 m$^3$/day
- BWRO water capacity 3,800 m$^3$/day

The devices are also listed below by their names, description, amounts and specifications. These are the devices that are used in the facility, during the process.
<table>
<thead>
<tr>
<th>Tag Number</th>
<th>Description</th>
<th>Duty</th>
<th>Standby</th>
<th>Total</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>P101</td>
<td>SEAWATER SHALLOW WELL PUMP</td>
<td>8</td>
<td>2</td>
<td>10</td>
<td>CENTRIFUGAL, 154M3/HR, 45KW</td>
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<tr>
<td>P108</td>
<td>MF BACKWASH PUMP</td>
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<td>1</td>
<td>2</td>
<td>CENTRIFUGAL, 304M3/HR, 37KW</td>
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<td>CF104</td>
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<td>FRP, 363.4M3/HR</td>
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<td>320</td>
<td>200 MIC, 40&quot;</td>
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<td>SK105</td>
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<td>2129M3/H MAX, 164M3/H MIN</td>
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<td>272</td>
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<td>1</td>
<td>2</td>
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<td>0</td>
<td>1</td>
<td>CS</td>
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<tr>
<td>AR111</td>
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<td>P201</td>
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<td>5</td>
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<tr>
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<td>1,200PSI</td>
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<td>T301</td>
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<td>FRP, 20,000L</td>
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<td>0</td>
<td>1</td>
<td>304SS</td>
</tr>
<tr>
<td>MK406</td>
<td>MAIN CHLORINE MIXER</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>CS+POLYETHYLENE LINING</td>
</tr>
<tr>
<td>MK410</td>
<td>SUB CHLORINE MIXER</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>CS+POLYETHYLENE LINING</td>
</tr>
<tr>
<td>MK411</td>
<td>LIME MIXER</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>304SS</td>
</tr>
<tr>
<td>MK412</td>
<td>FeCl3 MIXER</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>CS+POLYETHYLENE LINING</td>
</tr>
<tr>
<td>P401</td>
<td>SBS DOSING PUMP (REDUCTION)</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>DIAPHRAGM, 7.02/H, SOLENOID</td>
</tr>
<tr>
<td>P402</td>
<td>SBS DOSING PUMP (SHOCK REDUCTION)</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>DIAPHRAGM, 28.2L/H, SOLENOID</td>
</tr>
<tr>
<td>P403</td>
<td>SBS DOSING PUMP (SHOCK)</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>DIAPHRAGM, 49.2L/H, MOTOR</td>
</tr>
<tr>
<td>P404</td>
<td>A/S DOSING PUMP (SWRO)</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>DIAPHRAGM, 0.68/H, SOLENOID</td>
</tr>
<tr>
<td>P405</td>
<td>A/S DOSING PUMP (BWRO)</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>DIAPHRAGM, 0.71/H, SOLENOID</td>
</tr>
<tr>
<td>P410</td>
<td>NaOH DOSING PUMP (BWRO FEED)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>DIAPHRAGM, 1.36/H, SOLENOID</td>
</tr>
<tr>
<td>P411</td>
<td>NaOH DOSING PUMP (BWRO PERM.)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>DIAPHRAGM, 0.27/H, SOLENOID</td>
</tr>
<tr>
<td>P406</td>
<td>CHLORINE TRANSFER PUMP</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>MAGNET PUMP</td>
</tr>
<tr>
<td>P414</td>
<td>CHLORINE DOSING PUMP (INTAKE SHOCK)</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>DIAPHRAGM, 224.3L/H, MOTOR</td>
</tr>
<tr>
<td>P427</td>
<td>CHLORINE DOSING PUMP (INTAKE)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>DIAPHRAGM, 56.1L/H, MOTOR</td>
</tr>
<tr>
<td>P408</td>
<td>CHLORINE DOSING PUMP (SWRO PERM.)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>DIAPHRAGM, 3.72/H, SOLENOID</td>
</tr>
<tr>
<td>P409</td>
<td>CHLORINE DOSING PUMP (BWRO PERM.)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>DIAPHRAGM, 0.77/H, SOLENOID</td>
</tr>
<tr>
<td>P410</td>
<td>CHLORINE DOSING PUMP (MF WASH)</td>
<td>8</td>
<td>0</td>
<td>8</td>
<td>DIAPHRAGM, 52.3L/H, SOLENOID</td>
</tr>
<tr>
<td>P411</td>
<td>LIME DOSING PUMP</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>SCREW TYPE, 30.1L/H</td>
</tr>
<tr>
<td>P412</td>
<td>FeCl3 DOSING PUMP</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>DIAPHRAGM, 9.36/H, SOLENOID</td>
</tr>
<tr>
<td>T501</td>
<td>CIP TANK</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>FRP, 12,000L</td>
</tr>
<tr>
<td>P501</td>
<td>CLEANING PUMP (CIP)</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>FRP, 120M3/H</td>
</tr>
<tr>
<td>CF502</td>
<td>CIP CARTRIDGE FILTER (HOUSING)</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>FRP, 1200M3/H</td>
</tr>
<tr>
<td>CF502 ELMNT</td>
<td>CIP CARTRIDGE FILTER ELEMENT</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5 MIC, 40”</td>
</tr>
<tr>
<td>XV</td>
<td>PNEUMATIC VALVE AND MOTORIZED VALVE</td>
<td></td>
<td></td>
<td></td>
<td>LOT</td>
</tr>
<tr>
<td>INSTRUMENTS</td>
<td>INSTRUMENTS,</td>
<td></td>
<td></td>
<td></td>
<td>LOT</td>
</tr>
</tbody>
</table>
Table 3 – List and Amount of Devices
(SAWACO Company)

This table shows in detail what kinds of devices are used in order to provide the desalination purpose. It is also possible to find their tag numbers which makes it easier to code and recognize in the facility and in the market and also their specifications. It is very important because it gives a huge clue to understand the process and the devices. For example, a P101 device, which is a seawater shallow well pump, is chosen with the specification “centrifugal, 164 m$^3$/h, 45 kW”. The same device with different specifications could be used for some other water sources or for some other processes.

4.1.3. Process

As mentioning the capacity of the facility, it should have been understood that the facility is using the reverse osmosis method for desalination. It will be now examined how the facility applies the desalination step by step.

1. Seawater Intake

Raw sea water is taken from 10 shallow wells. Normally 8 shallow well pumps are on duty and 2 are on standby. The intake flow volume of 1 shallow pump is approximately 164 m$^3$/h (3,936 m$^3$/day) for each shallow well.

2. Micro Filter Pretreatment System (MF)

A micro filtration (MF) system is adopted for RO pretreatment. The main function of MF is removal of suspended substances to improve the SDI value. The MF module cannot remove dissolve matter such as iron, manganese, natural organic matter etc. The total MF feed rate is 1,312.5 m$^3$/h (31,500 m$^3$/day). The MF unit is composed of 8 units (6 operations and 1 backwash, 1 standby) The MF unit has mainly 3 operation process; filtration, backwash and chemical cleaning. The filtration and backwash process are performed in automatic mode. The chemical cleaning process is performed manually.

3. Seawater Desalination System (SWRO)

The SWRO remove salt and the other dissolved matter. The SWRO is composed of 4 operation units with no standby unit. 1 unit includes 30 pressure vessels which contain 6 elements. The SWRO unit is designed to maintain the overall permeate recovery rate of minimum 35%. The SWRO system consists of the SWRO unit, instrumentation, a high pressure pump and an energy recovery turbine and it designed for continuous automatic operation. The chemical cleaning system is designed to remove foul ants from membrane surfaces by dissolving the fouling substances with chemical cleaning reagents.

4. Boron Removal System (BWRO)

The BWRO system consists of the BWRO unit, instrumentation and a feed pump, and is designed for continuous automatic operation. The chemical cleaning system is designed to remove foul ants from membrane surfaces by dissolving the fouling substances with chemical cleaning reagents.

5. Chemical Dosing
BWRO is designed to remove boron and improve TDS of SWRO permeate. The BWRO system is composed of 4 operating units with no standby unit. Each unit includes 6 pressure vessels which contain 6 elements of each vessel. BWRO unit is designed to maintain the overall BWRO permeate recovery flow rate of approximately 85%.

5.1. Sodium Hypochlorite

The chlorine disinfectant is applied to raw water and MF backwash water. Each dosing system has 1 stand by pump.

5.2. SBS

SBS dosing system is provided to remove residual chlorine for avoiding membrane oxidization. It is applied of the upstream side of the high pressure pump.

5.3. Anti Scalant

The Anti Scalant is applied to SWRO and BWRO feed water.

5.4. NaOH

NaOH is applied to the BWRO water to raise the pH level. Rising the pH level of BWRO feed water marvelously improves the boron removal rate. It is applied the upstream side of the BWRO system.

5.5. e) Ca(OH)₂

Ca(OH)₂ is applied to adjust the pH level and to add minerals into the treated water. It is applied to the upstream side of the storage tank.

5.6. Ca(ClO)₂

The chlorine disinfectant is applied to permeate water. The disinfectant chemical is Ca(ClO)₂. Each dosing system has 1 stand by pump.

4.1.4. Operation

This section is to clarify the salt amount treated by the facility and the efficiency of the process. Also, possible renovation which is done or planned to be done to improve the facility and the use of product water could be found below.

Base on design feed flow of each unit is $= 311 \text{ m}^3/\text{h} \times 24\text{h/day}$.

Computation:

Total Feed Flow

= $7464 \text{ m}^3/\text{day} \times 4 \text{ Units (SWRO skids)}$

= $29,856 \text{ m}^3/\text{day}$

Sea water (Feed Water) TDS. = 46,830 mg/L

= 46.83 grams/m³ $\times 29,856 \text{ m}^3/\text{day}$

Total Salt

= $1,398,156 \text{ grams/day}$ (app $1,400 \text{ kg/day}$)

1,398,156 grams/day salt treating from the 29,856 m³/day of water.
Water technology is constantly being advanced and SOJECO project is newly constructed by SKME (Japanese technology) based on advanced technology. The energy recovery device which we are using is the key factor that determined the plant electrical cost. And very soon, the facility is going for expansion of the plant due to more demand of water in the industrial field and domestic use.

Use of product water is mostly for industrial field (like food industries, steel industries, pharmaceuticals and petro chemical) and also domestic purposes.

The values for examining the efficiency are listed in four documents which can be found in Appendix A-B-C-D (App 7).

4.1.5. Costs

The costs of the facility are disclosed due to terms of confidentiality. Therefore, in this section, there will be average values for costs. This means that the data and the approximate costs for each matter of facility will be taken from self research, not from the facility. The cost amounts here have no relation with the SOJECO facility in Jeddah, Saudi Arabia. The costs will be calculated in United States Dollar ($) and will be converted to European Euro (€). (1 Euro is accepted to be as 1.2732 $ according to http://themoneyconverter.com/USD/EUR.aspx)

Five economical factors will be examined according to some average cost data [18] (http://www.water-wastewater.com/pages/ro_desc.html):

Capital cost of the facility is calculated according to the graph in Reverse Osmosis section (see figure 3). According to this information, the capacity is calculated to be;

\[
31,500 \text{ m}^3/\text{day} + 29,856 \text{ m}^3/\text{day} + 10,000 \text{ m}^3/\text{day} + 3,800 \text{ m}^3/\text{day} = 75156 \text{ m}^3/\text{day} = 75000 \text{ m}^3/\text{day}.
\]

75000 m³/day makes a capital cost per unit of capacity of 1300 $/m³/day which makes an amount of 75000 m³/day x 1300 $/m³/day = 9,750,000 $ = 7,657,870 €

According to the source that is used, a typical reverse osmosis plant consumes 11 kW for m³. As in 4.1.4 Operations section, it was said that 29,856 m³ of water is treated per day. This number is rounded to 30,000 m³/day. So, the energy consumed is 11 kW x 30000 m³/day = 330000 kW x m³/day and the cost for unit kW is 0.15 $/kW x m³. So the cost for energy consumption is 3300 (kW x m³) x 0.15 $/kW x m³/day = 49,500 $/day = 38,878 €/day

As looked at figure 2, it can be seen a distribution of costs for a reverse osmosis plant. Chemicals are called consumables in this graph which hold a 26% of total cost. In this graph, electricity consumption is shown as 41%. Chemical costs will be calculated with this phenomenon. Per 1 m³ water, the electricity cost was 1.65 $. If this holds 41% percent of a total cost, 26% cost would be 1.05 $. For the facility, the chemicals cost will be 1.05 $/m³ x 30000 m³/day = 31,500 $/day = 24,731 €/day. The cost for chemicals are 0.10 $/m³. This makes a total chemical amount of 31,500 $/day / 0.10 $/m³ = 315,000 m³/day.

Labor costs for the facility is estimated to be 0.007 $/m³. As the capacity increases, labor costs decrease. Therefore, an average value is taken to have a general look. This makes labor cost for an employee with a value of 0.007 $/m³ x 30000 m³/day = 210 $/day = 165 €/day.

Pumps are different than each other so they should be handled as different and general parts because they hold great importance for the facility. They also vary but an average value of 0.7 $/m³ is accepted to be the value. This makes a value of 0.7 $/m³ x 30000 m³/day = 21,000 $/day = 16,494 €/day.
The total cost should include the last four matters. Capital cost is something to be paid only once, which is at the beginning. Therefore it should not be counted in the sum. According to these information and these calculations, the cost of a reverse osmosis facility with a daily 30000 m\(^3\) water treated is **102,210 $/day or 80,278 €/day**.

5. Application of Desalination on Selected Seas

This section will reveal the desalination application on selected seas which are Black Sea and Mediterranean Sea. Some information has already been mentioned regarding their characteristics. The process will be focused for both seas. Differences of processes and their costs relating their salt amount will be examined. There will be a reference facility to rely on and support the possible facilities in both seas and that facility will be there desalination plant in Jeddah, Saudi Arabia. As mentioned before, the salinity amounts of Red Sea, Mediterranean Sea and Black Sea are 40 mg/L, 38 mg/L and 18 mg/L respectively. This gives an idea that a facility in Mediterranean Sea will be a little relevant to the one in Red Sea so the important point here is to reveal the differences for Black Sea.

As it to be the reference point, it is helpful to remind the daily desalination cost of the SAWACO facility, which was 102,210 $/day or 80,278 €/day (estimated by assumptions) and the capacity of the facility was 75000 m\(^3\)/day.

To support the financial aspects of SAWACO facility and the possible facilities in Mediterranean Sea and Black Sea, Victorian Desalination Project’s (Wonthaggi on the Bass Coast, Australia) economical verifications will be used. ([http://www.aquasure.com.au/cms_files/100824_Victorian%20Desalination%20Project_FAQs.pdf](http://www.aquasure.com.au/cms_files/100824_Victorian%20Desalination%20Project_FAQs.pdf)) This project is extremely bigger than the facility in Jeddah and the potential facilities in Black Sea and Mediterranean Sea. Therefore, some conversions will be made and all the data will be revealed as this facility in Australia has the same capacity like SOJECO in Saudi Arabia.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capacity (m(^3)/day)</th>
<th>Salinity (g/L)</th>
<th>Daily Cost (1000$)/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Victorian Wonthaggi</td>
<td>75000</td>
<td>38</td>
<td>520,548</td>
</tr>
<tr>
<td>SOJECO (Jeddah, Saudi Arabia)</td>
<td>75000</td>
<td>18</td>
<td>102,210</td>
</tr>
</tbody>
</table>

Table 3 – Numerical Data of Current Facilities

When the capacities are matched together, it is seen that Victorian facility with a 75000 m\(^3\)/day capacity would have a daily cost of 95000 $ or SOJECO facility with a 410959 m\(^3\)/day capacity would have a daily cost of 560055 $ and all calculations have been made according to the capacity of 75000 m\(^3\)/day. Victorian facility is 5,48 times bigger than SOJECO and it is the same ratio with the cost. The difference between the facility when the same capacity considered is 32,297 $. But more importantly, for one g/L value makes a cost difference of 1315,7 $. This makes the possible facilities to be something like:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capacity (m(^3)/day)</th>
<th>Salinity (g/L)</th>
<th>Daily Cost (1000$)/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Sea</td>
<td>75000</td>
<td>18</td>
<td>46,748</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>75000</td>
<td>38</td>
<td>98,689</td>
</tr>
</tbody>
</table>

Table 4 – Numerical Data for Possible Facilities on Selected Seas
The values can be different from each other when they are calculated from different reference points. For example, 98,689 $ for Mediterranean Sea is an average value because the values were different when it is calculated with a 40 g/L salinity value has been taken as a reference than 36 g/L salinity value. It also happens with an average change number (1315.7 $), the number are also different from each other. The best approach here is to calculate everything and taking the average value which will be very close to each other and not make any difference.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capacity (m³/day)</th>
<th>Daily Cost (1000$/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Sea</td>
<td>100000</td>
<td>62,331</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>100000</td>
<td>93,496</td>
</tr>
<tr>
<td>Black Sea</td>
<td>150000</td>
<td>131,585</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>150000</td>
<td>197,378</td>
</tr>
</tbody>
</table>

Table 5 – Cost Difference for Different Capacities

The financial difference is difference for each facility but they change with a ratio. For Black Sea, when the capacity is increased by 25000 m³/day, the daily cost increases 15,583 $ and it can be accepted for the capacity of 100000 m³/day. The increase is 31,165 $ when the capacity becomes 150000 m³/day.

For Mediterranean Sea, the difference for 25000 m³/day capacity day, it costs 32896 $ more. And the increase is also doubled when the capacity gets 150000 m³/day and the increase is 65,793 $.

6. Conclusion

This information explains that the salt amount in the water affects the cost of desalination directly. For certain water source, the treatment cost is fixed and no matter what happens to the capacity, it doesn’t change. But this comparison tells that every water source with different salt content has a different cost to treat. This is directly related to the salinity. As to support, here is the value for SAWACO:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capacity (m³/day)</th>
<th>Daily Cost (1000$/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAWACO</td>
<td>100000</td>
<td>136280</td>
</tr>
<tr>
<td>SAWACO</td>
<td>150000</td>
<td>204420</td>
</tr>
</tbody>
</table>

Table 6 – Daily Cost for SAWACO Facility in Different Capacities

The cost change for SAWACO facility, which works on Red Sea with a salinity of 42 g/L, is 34,070 $. As seen, Black Sea has the lowest cost difference and Red Sea has the highest cost difference. This chart below shows the difference:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Daily Cost Change (1000$/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Sea</td>
<td>15,583</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>32,896</td>
</tr>
<tr>
<td>SAWACO</td>
<td>34,070</td>
</tr>
</tbody>
</table>

Table 7 – Daily Cost Change for Facilities

This table is to show the changes in cost when the capacity changes by 25000 m³/day. It is possible and easy to build a relation to them according to the salinity values. Black Sea having such less
salinity compared to the other has almost half of the cost for Mediterranean Sea. The other two, Mediterranean Sea and SAWACO being similar is because that the salinity difference is only 2 g/L.

Capacity increase means also increase in devices, labor, chemicals used but they are all fixed costs. This fixed cost increase makes the increase of treatment also fixed. By this, it is tried to emphasize, that in desalination facilities, costs are fixes and always depending each other but the main dependence is the salt amount of the water.

For such facility construction, Black Sea should be kept as the first option to build such facility because of the lower salt content. It is an important question to ask, why there is no such facility in the region has been built yet? There might be two answers for that;

- After the process, as the by product, salt obtained is low, therefore it brings no income.
- The area of the Black Sea is not big and the only opening of the sea to the ocean is through Bosporus.

Still, further investigation should be made, as the capacity could be kept at some level to prevent potential damages to the environment.

7. Appendix

7.1. Reverse Osmosis: Diffusion is the movement of molecules from a region of higher concentration to a region of lower concentration. Osmosis is a special case of diffusion in which the molecules are water and the concentration gradient occurs across a semi permeable membrane. The semi permeable membrane allows the passage of water, but not ions (e.g., Na+, Ca2+, Cl-) or larger molecules (e.g., glucose, urea, bacteria). Diffusion and osmosis are thermodynamically favorable and will continue until equilibrium is reached. Osmosis can be slowed, stopped, or even reversed if sufficient pressure is applied to the membrane from the 'concentrated' side of the membrane. Reverse osmosis occurs when the water is moved across the membrane against the concentration gradient, from lower concentration to higher concentration. To illustrate, imagine a semi permeable membrane with fresh water on one side and a concentrated aqueous solution on the other side. If normal osmosis takes place, the fresh water will cross the membrane to dilute the concentrated solution. In reverse osmosis, pressure is exerted on the side with the concentrated solution to force the water molecules across the membrane to the fresh water side.

7.2. Membrane Fouling: Accumulation of substances on the membrane surface and/or within the membrane pores which results in deterioration of membrane performance is called membrane fouling.

7.3. Total Dissolved Solids: Total Dissolved Solids (TDS) are the total amount of mobile charged ions, including minerals, salts or metals dissolved in a given volume of water, expressed in units of mg per unit volume of water (mg/L), also referred to as parts per million (ppm). TDS is directly related to the purity of water and the quality of water purification systems and affects everything that consumes, lives in, or uses water, whether organic or inorganic, whether for better or for worse.

7.4. Hydrologic Cycle: The hydrologic cycle is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere, and the hydrosphere. Water on our planet can be stored in any one of the following major reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields, and groundwater. Water moves from one reservoir to another by way of processes like evaporation, condensation,
precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting, and groundwater flow. The oceans supply most of the evaporated water found in the atmosphere. Of this evaporated water, only 91% of it is returned to the ocean basins by way of precipitation. The remaining 9% is transported to areas over landmasses where climatological factors induce the formation of precipitation. The resulting imbalance between rates of evaporation and precipitation over land and ocean is corrected by runoff and groundwater flow to the oceans.

7.5. **Ice Age**: An ice age, or more precisely, a glacial age, is a period of long-term reduction in the temperature of the Earth's surface and atmosphere, resulting in the presence or expansion of continental ice sheets, polar ice sheets and alpine glaciers.

7.6. **New World**: The New World is one of the names used for the Western Hemisphere, specifically the Americas, certain Atlantic and Pacific oceanic islands to which the closest continental shelf is that of the Americas (such as Bermuda), and sometimes Oceania (Australasia).

7.7. **A-B-C-D**: These information are added to the paper

8. **References**

8.1. **Texts**


8.2. **Tables**

8.2.2. SAWACO Company

8.3. **Figures**

8.3.6. http://prodimages.vertmarkets.com/image/49e06816/49e06816-cb2c-11d4-8c85-009027de0829/original/image1.jpg
8.3.9. http://ars.els-cdn.com/content/image/1-s2.0-S0011916412004018-gr4.jpg
8.3.10. Google Earth
8.3.11. http://www.grida.no/graphicslib/detail/salinity-of-the-black-sea_8ed0#
8.3.12. Google Earth
8.3.13. http://odv.awi.de/fileadmin/user_upload/odv/data/MeditasII/MeditasII_allTS_Salinity_5m.gif

9. Appendix References
9.7. SAWACO – SOJECO Facility