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ENERGETICKÝ ÚSTAV

SEAWATER DESALINATION
ODSOLOVÁNÍ MOŘSKÉ VODY

BACHELOR´S THESIS
BAKALÁŘSKÁ PRÁCE

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Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma bakalářské práce:

Odsolování mořské vody

v anglickém jazyce:

Seawater desalination

Stručná charakteristika problematiky úkolu:

Podle Evropské agentury pro životní prostředí i v mnoha evropských regionech roste význam odsolování mořské vody, které má z hlediska životní prostředí značné negativní dopady, neboť je vysoce energeticky náročné.Podle Světového fondu na ochranu přírody odsolování mořské vody může závažně přispívat ke změnám klimatu. Světový fond na ochranu přírody hodnotí odsolování jako velmi drahý a energeticky náročný způsob získávání pitné vody, který produkuje velké množství skleníkových plynů.

Cíle bakalářské práce:

1.Rešerše možných fyzikálních principů odsolování
2.Podrobnější popis zařízení s využitím jaderné energie.
3.Srovnání zátěže na životní prostředí vybraných typů odsolovacích zařízení.

Seznam odborné literatury:

www.IAEA.org
www.world-nuclear.org

Vedoucí bakalářské práce: Ing. Tomáš Maar

Termín odevzdání bakalářské práce je stanoven časovým plánem akademického roku 2012/2013.

V Brně, dne 21.11.2012

L.S.

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Ředitel ústavu	Děkan fakulty

ABSTRACT

Everyday shortage of potable water leads to effort to address the problem. One of the options is desalination, which can utilize distillation process, reverse osmosis or unconventional ways as water freezing.

The purpose of this work is to introduce possibilities of desalination. It describes methods of distillation, reverse osmosis, solar desalination and does not forget the separation of potable water by freezing. Together with the process of obtaining fresh water from seawater appears energetic requirement. Hence, the paper also deals with question of energetic resources. The work includes exploiting of fossil fuels, renewable energy and nuclear energy.

The last chapter is dedicated to economic software analysis of the desalination plant, which works as multi-effect distillation and reverse osmosis powered by nuclear power plant. The used software is called DEEP.

Last but not least, you can read also about desalination impact on both local and global environment.

KEYWORDS

Seawater, desalination, distillation, reverse osmosis, multi-effect distillation, multi-stage flash distillation, unconventional desalination, nuclear energy, fossil fuel, renewable energy, brackish water.

ABSTRAKT

Každodenní nedostatek pitné vody vede ke snahám tento problém řešit. Jedna z možnosti je odsolování ať už destilační, za pomoci membrán a osmózy, či dalších nekonvenčních způsobů jako je zmražení vody.

Tato práce se zabývá možnostmi odsolování. Popisuje způsoby destilační, reverzní osmózu, solární odsolování a nezapomíná ani na separaci pitné vody pomoci zmražení. Spolu se získáváním pitné vody ze slané nastává také otázka energetických zdrojů. Využití fosilních paliv, obnovitelných zdrojů energie a jaderné energie, je tedy další nepostradatelné téma popisované v této práci.

V neposlední řadě se zde také můžete dočíst o možném dopadu odsolování na životní prostředí, ať už z hlediska globálního v podobě možné produkce skleníkových plynů nebo dopadů lokálních.

V závěrečné kapitole je podrobná ekonomická analýza odsolovacího zařízení pomoci počítačového programu DEEP. Popisované zařízení je na bázi multi-effect distillation a reverzní osmózy, pro které se získává energie z jaderné elektrárny.

KLÍČOVÁ SLOVA

Mořská voda, odsolování, destilace, reverzní osmóza, multi-effect distillation, multi-stage flash distillation, nekonvenční odsolování, jaderná energie, fosilní paliva, obnovitelné zdroje, solanka, brakická voda.

BIBLIOGRAPHIC CITATION

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AFFIDAVIT

I declare that I wrote this thesis on my own without using any other sources and aids as I state in the list. I had worked independently under the direction of Ing. Tomáš Maar.

Brno, date 22nd May 2013 ……………………...…..………..

Robin Kamenický

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CONTENTS

INTRODUCTION

Water is basic material essential for living. Mankind uses it every day in industry, agriculture or just at home for private use. Required amounts of water go hand-in-hand with increases in world population. According to the United Nations, in the year 2050 the world population will approach to 9 billion. It will cause significant changes, which we will have to adapt to. [31]

Many people feel that they are entitled to limitless amounts of drinkable water. Unfortunately there are a distinct number of water stress areas on Earth. More than 1.1 billion people do not have potable water and about 4 000 children, under the age of five, die daily because of diseases coming from undrinkable water. Lack of fresh water can even causes war conflicts, especially in water stressed areas. [32][33]

Time for solving the problem has come. There are two known ways of how to deal with it and both of them are necessary to implement. The first is improving water treatment; plenty of water is wasted every day. The second is finding new sources of water. Looking at the proportion of salt to fresh water, it seems obvious that desalination is our next step. Seawater desalination is the clue.

Seawater desalination does not have to influence only availability of potable water and subsequently population health but also can influence water price. A nuclear desalination can even reduce the price as it has happened with energy cost in some regions. [1]

Important factors influencing constructing and operating of desalination facility coupled with energy resource are cost, environmental impact, and safety. Various software, which are capable to evaluate and provide key information to considering, are mostly used to assess these factors.

1 DESALINATION TECHNOLOGIES

Desalination is a technological process whose outcomes are fresh water and highly concentrated brine. The beginning of industrial use was first recorded in the middle of the 20th century. Since that time, much has changed. Nowadays there are more than 15 000 desalination plants around the world, mostly seaside and in areas with water scarcity. Despite the great number, potable water reached by technology is only about two percent of world consumption. The main problem is energy requirement. [1][4][5]

Up to present time, many desalination principles have been tested and are still constantly developing. Major technologies are divided in two groups, distillation processes, membrane processes. Certainly there are utilized its combination and some next unconventional methods. [1][4][5]

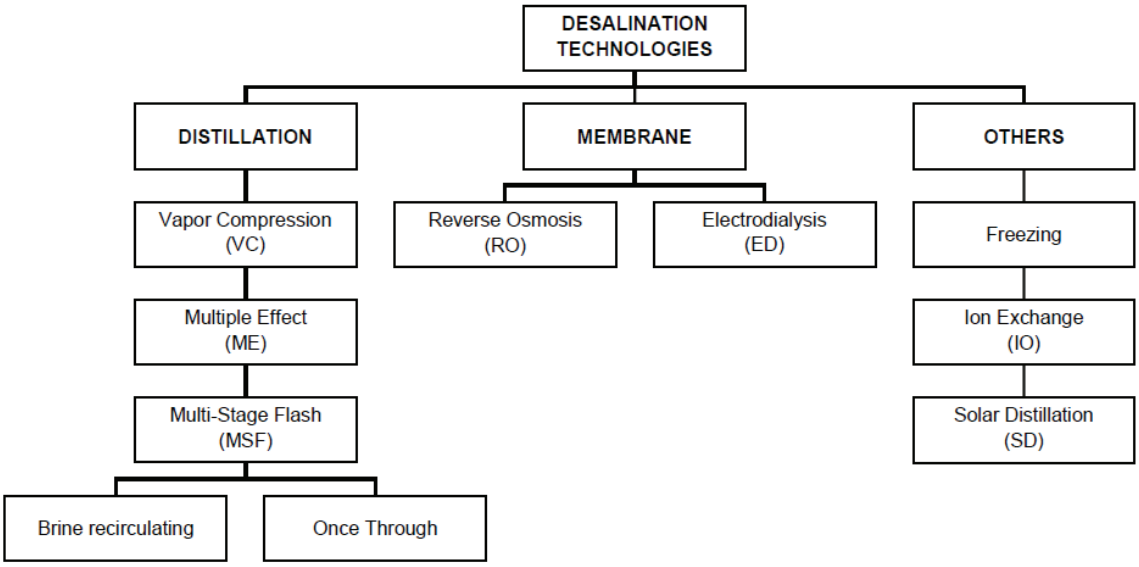


Figure 1 Classification of desalinating processes [3]

WATER POST-TREATMENT

According to purpose of use there are water requirements which are set by organisations such as World Health Organization (WHO). The distillation product has 2 to 5 ppm total dissolved solids (TDS). With RO, there usually has to be 2 stages to reach the value. The next benefit of utilizing thermal distillation, in comparison with RO, is that the product water is already de-aerated, thus helps to corrosion prevention [1]

Common adjustments for desalination methods are water hardening and the adding of burnt lime stone with CO_2. Other additives may include minerals. For disinfection during distribution, a small amount of chlorine is used. [1]

WATER PRE-TREATMENT

Thermal desalination meets with the problem of scaling. Calcium carbonate begins to precipitate at 56 °C in the case of normal concentration. Due to concentration and pH value, magnesium hydroxide and calcium sulphate start to precipitate at 120 °C to 135°C. To avoid that, the feed water can be adjusted by adding acids (H_2SO_4, HCl), which eliminate carbonates. The next possibility is to remove Ca by ion-exchange. The most common practice is to add “advance” additives, which depend on construction materials. [1]

Water pre-treatment for membrane desalination is considerably dissimilar. Scaling difficulty is replaced by suspended solids which are necessary to remove. This is done mainly by flocculation and filtration. In the case of using conventional filters, chlorine is added to avoid pathogens. [1][4][5]

1.1 DISTILLATION

We can define them as thermal processes. The most common are multi-stage flash (MSF) and multi-effect (ME) distillation, which are mainly used in areas with low fuel cost or residual heat from plants. Technologies are based on heating seawater to evaporating point, subsequently removing salt by passage through a system of chambers or effectors where the vapour condenses on a cool surface. Here the water drains with a low level of salinity. The feed water temperature can be up to 130°C because of rising scaling and corrosion. [3]

1.1.1 MULTI-STAGE FLASH DISTILLATION (MSF)

A desalination plant is paired with a power station in a cogeneration system. The rest of the heated medium from the station is used for warming-up salt water in a plant’s heat exchanger, thus achieving a higher efficiency of the whole system. [1][6]

Nowadays MSF are used in two configurations called once-through and brine recirculation. The brine recirculation system was invented at the beginning of seawater desalination. The reason was corrosion of material – only a minor part of the feed water is used as make-up water (water used for distillation). This small amount of water is de-aerated in a low-temperature vacuum chamber. The carbonates are removed by adding acids, thus steel can be used without corrosion problems. In the case of using low corrosion allowance materials and advance additives, this treatment is not necessary, so we can employ a once-through system with advantages. All feed water is de-aerated in the first stage and additives are added before entering the desalting system. Once-through desalination does not demand a recirculation pump, which is the most sensitive part. It also provides a bigger scale of the working temperature (because of lower salinity) and is easier to maintain and operate. [1][6]

PRINCIPLE

Seawater is pumped to a series of chambers, each containing a heat exchanger and condensate collector. Salt water, flowing in the collectors, absorbs heat which increases its temperature. After leaving the chambers, it enters in a brine heater in which flows water steam coming from a power station. The seawater achieves maximum temperature, and is subsequently derived back to the chambers. Every chamber operates on different pressure and temperature so that ensures rapid boiling process called as flashing of brine. The resulting steam is condensed into potable water at tubes with feed water. The equilibrium is kept stable. Latent heat is occluded by feed water and carried away. On one side, if more vapour forms in the chamber, the pressure increases and evaporation decreases. On the other side, condensation becomes higher. From the last chamber, the remaining brine is carried back to sea. [1][2]

Energy loss is mainly caused because of condensed fresh water and the waste, concentrated brine, which still hold small amounts of excess heat. It is equivalent to the heat given in the brine heater. [1][2]

The reason for not using just one chamber is that it would not utilize the whole thermodynamic potential. The single stage would operate only at a middle temperature, between brine temperature and cold feed seawater. The amount of condensate water would be smaller. [2]

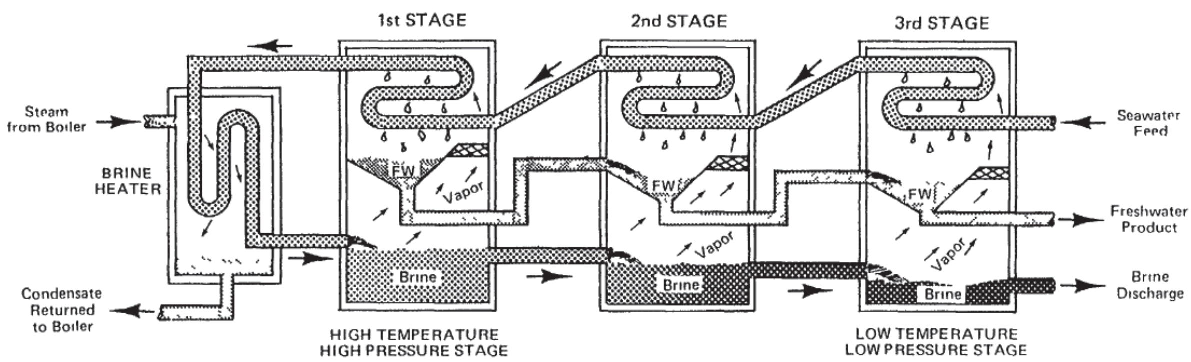
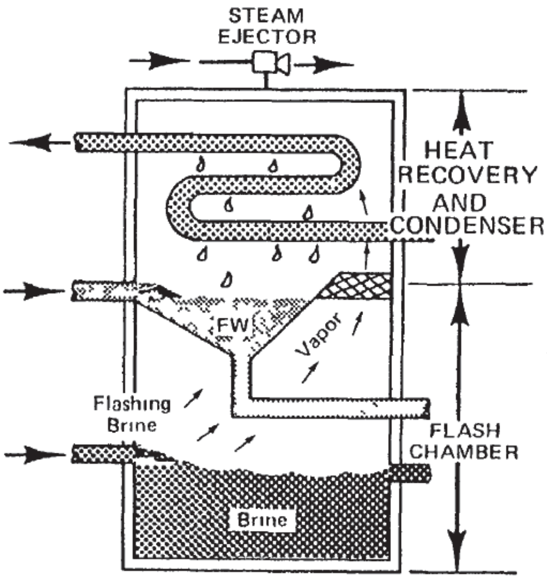


Figure 2 Schematic of multi-stage flash desalination [1][2]



[1]Steam ejector – to remove non condensate gases.

Demister – usually mesh which removes saltwater droplets from the vapour.

Figure 3 Diagram of multistage flash [1]

1.1.2 MULTI-EFFECT DISTILLATION (ME)

The process is replacing MSF in cases of thermal desalting. It results from lower power needs and high thermal efficiency caused by use of advanced technologies, including a horizontal tube design with a high heat transfer coefficient. Utilized materials are titanium or aluminium alloy and low heat loss. All of these factors provide a big advantage in comparison with MSF, and its temperature drop per effect is 1.5°C - 2.5°C. It allows arrangement of more effectors in raw. Maximum brine temperature is 70°C, thus temperature of residual heat from power station. The number of effectors is limited only by the difference between temperatures of seawater and incoming steam. Hand-in-hand with low temperature operation is the on-going reduction of scaling and corrosion. It means smaller expanse for water pre-treatment. The disadvantage is the capacity of MED plants, which is mostly used for medium power. Two main designs are Horizontal Tube Multiple Effect (HTME) and Vertical Tube Evaporation (VTE). [7][8]

HORIZONTAL TUBE MULTIPLE EFFECT (HTME)

The system consists of a number of effectors containing horizontal tubes. Evaporating and condensing is again based on pressure and temperature differences. First, hot steam from the heat source is blown into the tubes of the first effector, while seawater is sprayed onto the tube surface. The steam transmits the heat to feed and liquefy water, than is returned back to the heat source cycle. The evaporated water flows through the demister to the next effector where the process is repeated. ME can combine with thermal vapour compressor (TVC) which takes advantage of latent heat. The steam is divided into two parts. Minor part is drawn to condenser, where it passes heat on to feed seawater. The major part is heading to the steam jet ejector as motive steam. Due to the liquefying in the ejector, the outgoing steam has a higher temperature than the ingoing. By utilizing this component we can significantly raise thermal efficiency. [1]

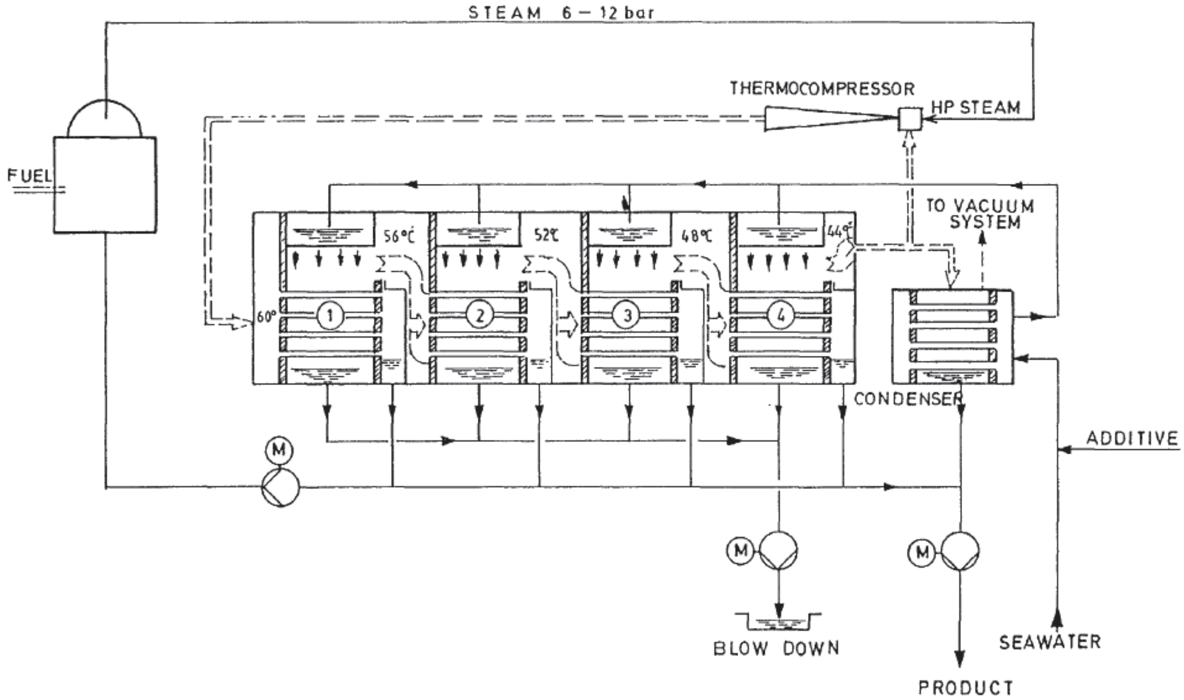


Figure 4 Basic principle of LT-HTME-desalination plant combined with thermal vapour compression[1]

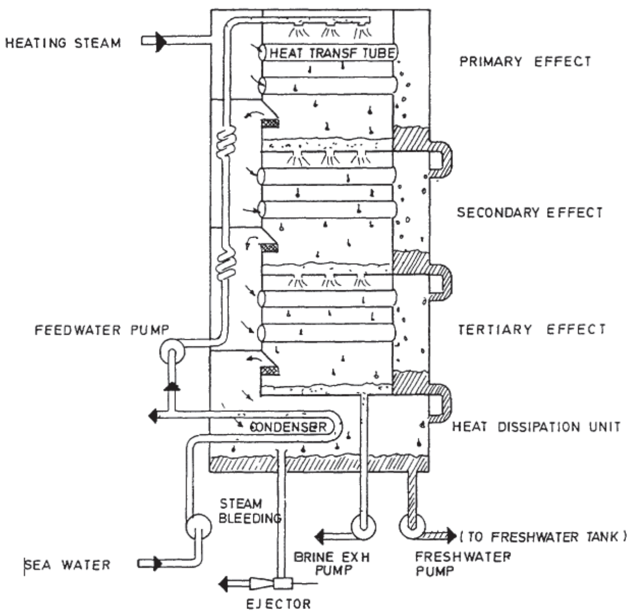


Figure 5 Horizontal tube multi-effect desalination evaporation.[1]

VERTICAL TUBE EVAPORATION (VTE)

The VTE process has a few types of constructions as evaporators with natural and forced circulation, falling film, and rising film evaporators.

Another division depends on direction of steam and feed water flow. Cocurrent, (forward feed) seawater and steam flows parallel from low pressure to a high pressure evaporator. In the countercurrent (backward feed) option, seawater and steam flows in from the opposite side. In concurrent installation, steam flows from a high temperature evaporator to a low temperature one, and feed water flows at a right angle to the steam.[1]

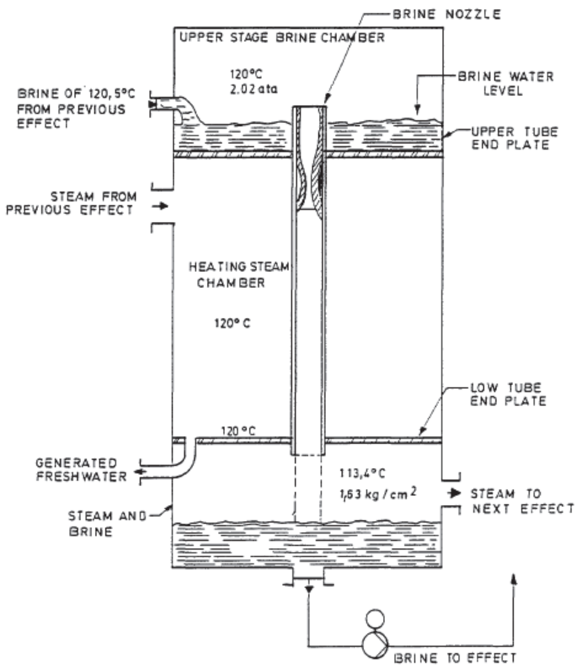


Figure 6 Falling film evaporator[1]

The steam enters a chamber and transmits the heat to seawater which flows as film on inter side of tube. Steam is condensate as fresh water. Seawater is fed into the tube by a device which is set on the top of the tube. After evaporating, it flows through a demister to the next chamber where it is used as a heating medium. [1]

1.2 MEMBRANE DESALINATION

Two main technologies are Reverse Osmosis (RO) and Electrodialysis (ED). Both of them are based on a process where saline water passes through a membrane. During the passage, salts are caught and the product is fresh water. These processes are possible not only for desalting sea or brackish water, but also for waste water treatment because of the membrane's ability to remove other contaminants. [3]

1.2.1 REVERSE OSMOSIS (RO)

Seawater reverse osmosis, at the end of 1970s, consumed about 20kWh/m^3. Thanks to developments, today consumption is about 2kWh/m^3. Gathered with the fact that it does not need a heat resource and high production capacity, it is currently the most used desalination process, accounting for 61.1% worldwide installed desalination capacity. [10]

RO desalination plants are built in many coastal areas with water scarcity. Nowadays we can observe many different types which are focused mainly on the improvement of lowering energy consumption, minimizing the effect of scaling the membrane, and acquiring a higher water flux membrane (purified water flow per unit area).

PRINCIPLE

Osmosis is physical phenomenon when solvent particles (molecules, ions) pass through a semipermeable membrane in the direction of a higher solute concentration to equalize concentration differences on the both sides. Despite molecules receiving kinetic energy, there is no necessary to deliver any. The passage is direct from a less concentrated (hypotonic) to a more concentrated (hypertonic) region, the driving force is osmotic pressure which is defined as pressure requisite to make and maintain an equilibrium. It depends on the chemical composition of the membrane, its thickness, pH, temperature and concentration. [9]

We can stop or even change the direction of particle movements by increasing pressure on the hypertonic region. This possibility exploits reverse osmosis when solute is forced into the concentration gradient. By utilizing this phenomenon in desalination, we attain purification of salt water, and salts cannot pass through the membrane. They are left in the hypertonic region. [3][9]

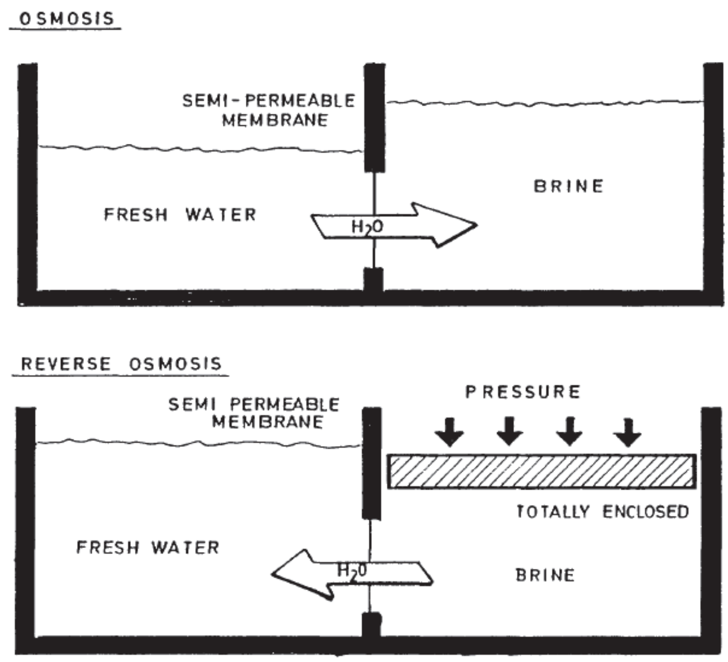


Figure 7 Principle of reverse osmosis[1]

The rejection behaviour of RO membranes depends on its chemistry and the structure of the polymeric layer.

PROCEDURE

The first is water pre-treatment. The objective is to avoid reduction of membrane fouling and scaling. Influencing factors are water salinity, temperature, depth, ocean currents and seaweed growth, as well as heavy metals, chemicals dissolved from agriculture and industry, organic residue, and the content of variant gases in the atmosphere. Thus, it is necessary to analyze feed water to make it the right option for pre-treatment. [12]

In the next step, a seawater pump is pressurised from 55 up to 85 bars and is derived to a cylindrical vessel where the scrolled membrane is inserted. Salt water is pushed in a radial direction from outside to inside of the membrane. After passing through, the RO unit remains in permeate (purified water) at about 0.5 or 1.5% salinity. In some cases the seawater has to undergo the process two times. [12]

According to a quite high quantity of salts in permeate, the subsequent step is post-treatment. Permeate is blended with a stream of fresh water for the purpose of decreased salinity. Lime ($Ca(OH)_2$), limestone bed ($CaCo_3$), or caustic soda (NaOH), is added to increase hardness and to avoid water distribution system corrosion. A decarbonator frequently used for removing carbon dioxide which could cause formation of carbon acid and corrosion. Oxygen for better taste, and calcium and magnesium salts are also added. [12]

Despite the fact that membranes are capable of blocking viruses and bacteria, RO is considered vulnerable to contamination by organic pathogens, which can be found in connections and joins. Thus, chemicals such as chlorine gas are used. [12]

The important part of the desalting system is the energy recovery turbine (i.e. Pelton turbine) or pressure exchanger, which exploits retentate (brine) pressure. Acquired recovered energy is used for partially powering pumps, and thus helps with energy efficiency. [12]

The final step is to deal with brine. There are a few options, but the most often used is sea discharge. Retentate is delivered by pipes to a far-out location as to avoid mixing with feed water. However, this solution does not have to meet toxicity standards and can be followed by environmental pollution and financial penalties. [12]

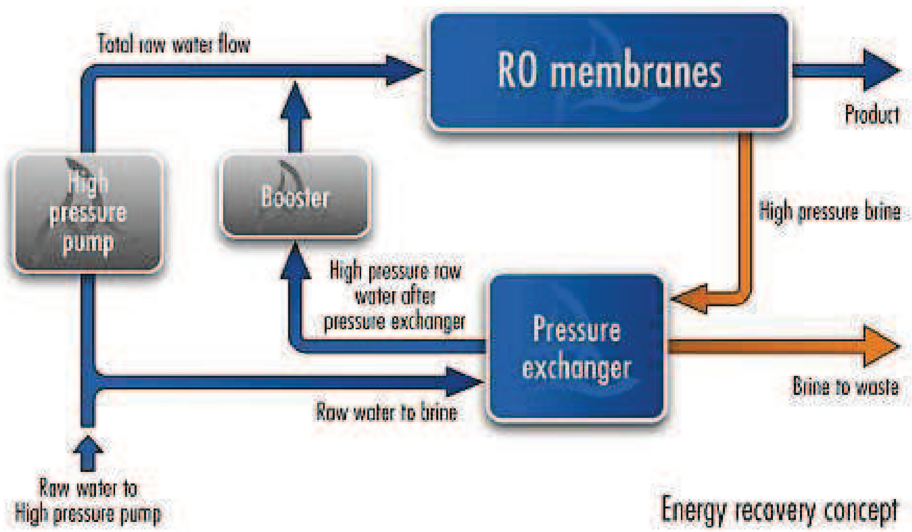


Figure 8 RO desalination with pressure exchanger[11]

1.2.2 Electrodialysis (ED)

In comparison with RO, electrodialysis is more economical, but only in the case of a salt concentration less than 5g/l. Hence, the procedure is used mainly for brackish water. [14]

ED is a process utilizing electrical potential difference. The processing area, mostly consisting of multi-cells, is bordered by electrodes. In each cell, flow feed water (diluate) and concentrate (brine) is channelled by ion exchange membranes. This whole arrangement is called an electrodialysis stack. The method is influenced by such factors as solution salinity, voltage, temperature, and stream velocity. [13]

Principle

Negatively charged ions (e.g. chloride), in stream D, are attracted by an anode. These ions get through a positively charged exchange membrane, but their further migration to the anode is stopped by a cation exchange membrane, thus it is separated in stream C. Positively charged ions (e.g. sodium), in the diluate, are attracted by a cathode and are passing through the cation exchange membrane. These ions are prevented from the next approach to the cathode by the anode exchange membrane. The overall result of the process is two streams: fresh desalinate water and concentrate. [13]

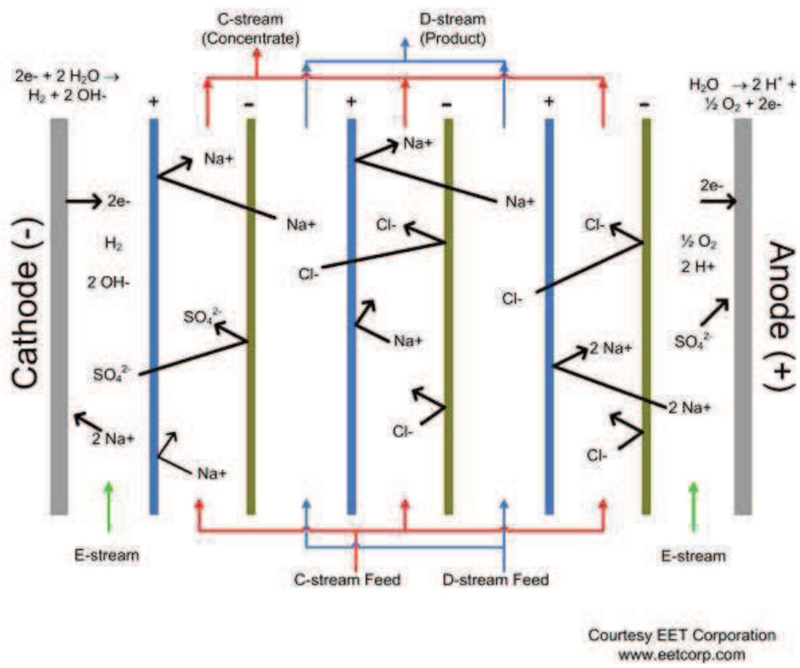


Figure 9 Electrodialysis [13]

1.3 Hybrid Technologies

Hybrid desalination technologies combine thermal, membrane processes and possibility of power generation. This effort represents needs to reduce energy consumption and improve efficiency. Major benefits can be operation flexibility and lower construction costs. Current commercial application are MSF/RO, ME/RO. Combination with other technologies as utilizing of renewable energy or nanofiltarion membrane (NF) can be taken in consideration. [3][34]

1.3.1 MSF/RO

The combination exploits advantages of both methods. The high TDS water of RO can be blended with high-purity MSF water, thus eliminating the requirement of some additives, which are necessary to add after the RO process. RO water productivity increases. The amount of permeation water through the membrane rises hand-in-hand with higher temperatures, and thus, lower viscosity of solution. Total costs for the facility can be reduced and expenditures for seawater pre-treatment decrease. The process can utilize single-stage RO and the life of the membrane increases by about 40%. The pressure from RO can be recovered and used for RO powering. [15]

PROCESS

The feed water is pumped to the last MSF stage where it is divided into two streams; the first is driven by tube through MSF and then to an intermediate heat exchanger where obtain heat energy from power plant. In the next step, the warm feed water is continuing back to MSF to be desalted. The second stream leads preheated seawater to the pre-treatment facility and booster, followed by a high pressure pump, which is powered by recovered energy. The formed brine, which remains after the RO process, leads to energy recovery. Finally the water product from MSF and RO is blended. [15]

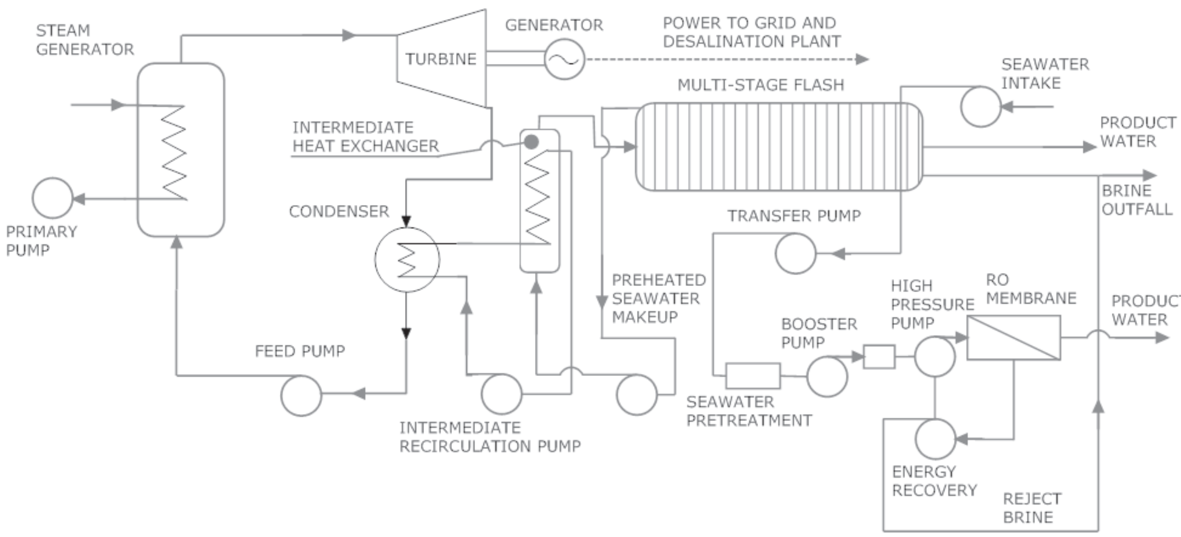


Figure 10 MSF/RO coupeling scheme [15]

The process ME/RO utilizes basically the same advantages as MSF/RO desalination. The difference is in the exchange processes of MSF for ME, and it results in smaller heat consumption as well as smaller productivity.

1.3.2 NF/RO/MSF

The advantage of using NF is lowering scaling process by removing scaling forming ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^-), and subsequently allowance to exploit higher temperature during thermal desalination. Thus, it leads to increase of fresh water productivity and performance ration. [34]

R&D Center (RDC) has built and operated the hybrid plant NF/RO in AL-Jubail. The highest used temperature has been 130°C without using of any additives. During 1200h product recovery reached 70%, conventional MSF product recovery is 35%. Finally was tested NF/RO/MSF which gives already mentioned benefits, as exploiting of preheated water from first stage of MSF for RO desalination. It results in higher productivity of desalted water in RO and allowance of using less expansive membranes. Finally the fresh water from MSF and RO is blended to get required level of TDS. [34]

It is running research focused on coupling ME and NF. The top temperature currently used in ME is up to 65°C. There is expected the top temperature up to 125°C with using of NF, thus significantly increase of efficiency should follow. [34]

1.4 Other desalination technologies

1.4.1 Freezing

This method is based on the freezing of feed water. While liquid seawater is becoming solid ice, crystals of pure water are making pockets of liquid brine. The reason for the effort of developing this process is that the required enthalpy of phase change for the freezing of water is rather low at 334KJ/Kg at normal atmospheric conditions, in comparison with water evaporation at 2 326 KJ/Kg. The next advantage can be low scaling, corrosion danger and almost no pre-treatment requirements. Unfortunately, the process is influenced by different factors such as salt concentration, flow-rate and operation components. The technology has been tested for seawater, brackish water and even RO brine. Nowadays special attention is given to refrigerant compressors, which seem to be the greatest obstacle for commercial use. [1][3][16][17]

After the detachment of phases by freezing, solid ice has to be cleaned by centrifugation, cross or counter washing. The next usual step is Vacuum Freezing Compression (VFVC). [1]

Vacuum Freezing Vapour Compression (VFVC)

Feed seawater is de-aerated and led to a heat exchanger where it meets with cooled product and brine, and its temperature is cooled down. The freezer is a low-pressurized chamber and it causes that pre-cooled water to simultaneously boil and freeze. The evaporation takes on excess heat. Subsequently, the vapour is compressed, thus rising the temperature about 0.5 °C, and then is driven into the melter. This vaporizes condensate and wash ice. [1]

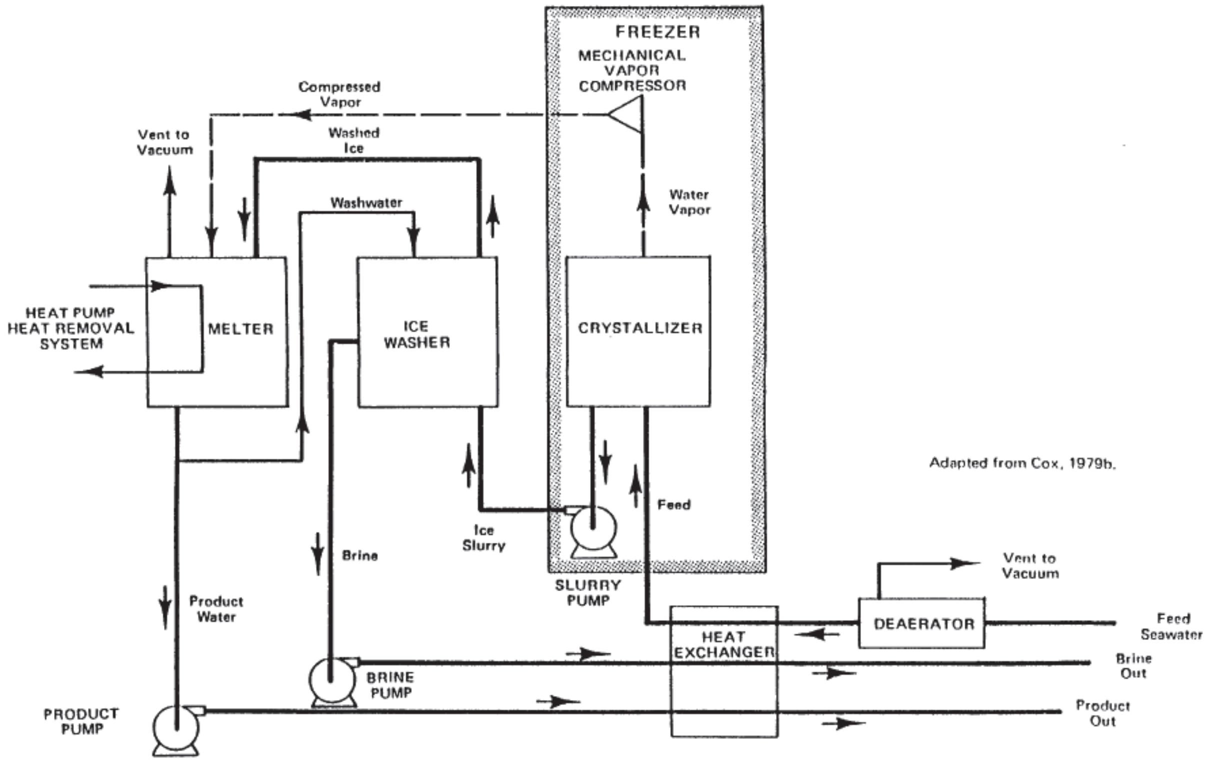


Figure 11 Diagram of a vacuum-freezing vapour-compression (VFVC) freezing process[1]

1.4.2 SOLAR DISTILLATION

It is the oldest desalination method which can be divided in two different options. The first one is direct use of solar energy for evaporating in solar collectors. The second is indirect heat recourse combined with the conventional desalination processes (MSF, ME, RO, VC) – chapter 2.2. [18]

DIRECT USE

The direct use method can convert saline and brackish water to potable water. However, it has a few disadvantages as only a small amount of useful product yielded, would have to be built in too large an area. The current direct solar desalting system outcome is counting up to 200m^3/day. The freshwater quantity is explained by the low pressure and temperature of the steam. [18]

The device (solar still) is simple: The base is a bowl (bath) filled with brine and roofed by a glass or plastic cover. Sun heats the brine; it evaporates and re-condenses on the cover, which is cooled by ambient air. Freshwater flows down from the roof to a reservoir. [18]
The product is potable. Undesired components are left behind in the bath, where the temperature of the water kills all pathogens. Regardless, it is necessary to flush out the developed sludge. The productivity of this system is 4-5l/m^2/day. Next, to increase the efficiency, auxiliary methods are used. These methods can be passive or active. [18]

Basin still can be improved by application of several techniques. Firstly, to use of single or double slope basin still. The better productivity depends on climate. Hence, single slope is better to use under cold climate condition and double slope for warmer climate. Secondly, the distillate yielded can increase by creating bigger temperature differences between basin and cover. There is also possibility to use passive condenser or inject black dye in the feed water. [18]

Wick still employs the wick (evaporation paper), radiation-absorb pan, through which feed water flows. The evaporation paper lowers feed water velocity and creates bigger evaporation area. The wick can be also titled to ensure better angle to sunlight. Pan also contain less seawater, thus water is heated up faster than in basin still. [18]

Diffusion still consists of three parts: heating and cooling cycles connected to a solar collector and a distillation effect. The optimal tested option contains four distillation effects which are defined by its temperature differences. Distillate yield can reached 8.7 kg $m^{-2}h^{-1}$ with 2 kW energy input, cross-section of 1 m^2, 4 m^2 evaporator and 4 m^2 surface for condensing. [18][35]

1.4.3 Ion exchange

Ion exchange utilizes resin, which helps to remove undesirable components from feed water. The resin used for microbial desalination cells (MDC). [3][19]

An anode chamber accepts bio-convertible substrates with simultaneous electron generation, which mediates electrical current flow and they are subsequently consumed by a cathode. The structure with a cation exchange membrane, nearer to cathode, and an anion exchange membrane, closer to anode, was suggested in 2009. However, approaching the end of the MDC procedure, salinity is decreasing. It means that resistance of the solution is rising. Hence, it has been proposed to use it as a pre-desalination process for RO. Another problem could be volume of Cl^- in the feed water. It causes passivity of microbials in the anode chamber. Therefore, lots of anode solution has to be exchanged to keep working efficiency. That could be a reason for utilizing MCD for a low salinity solution. If anion and cation are wrapped by ion exchange resin (IER), a higher efficiency is attained with better desalination results. The role of IER is to increase conductivity in the desalination chamber and to raise transmission between solution and exchange membrane. [19]

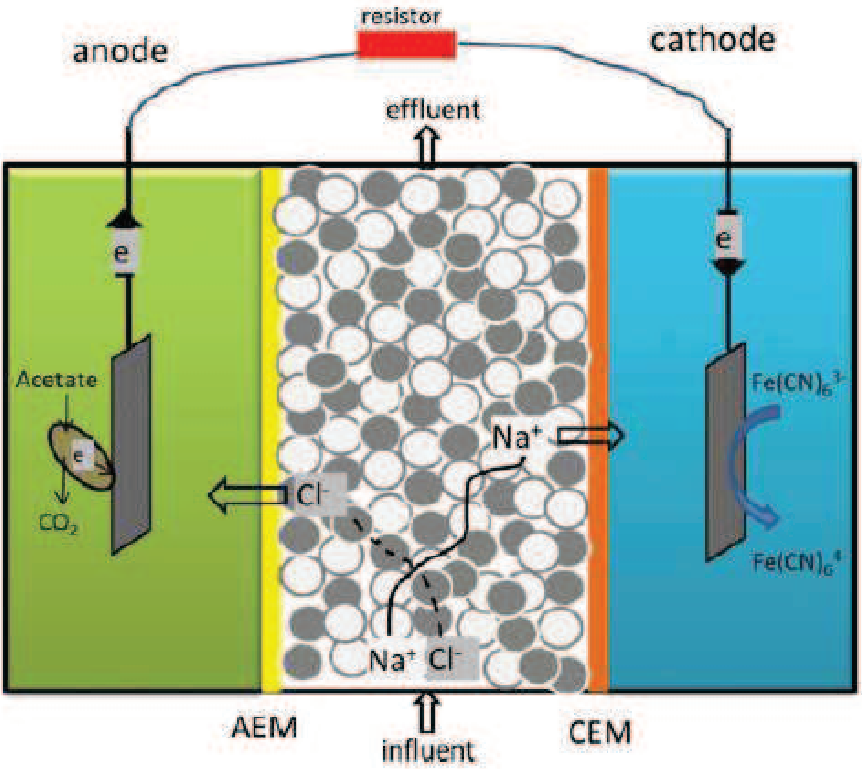


Figure 12 Configuration of microbial desalination cell with packed IER [19]

1.4.4 VAPOUR COMPRESSION

This is a thermal process which utilizes delivered heat from part of the produced vapour. The formed steam is compressed, thus a latent heat is exploited. As just an example, it will be described in conjunction use terms of mechanical vapour compression desalination structure (MVC) with two vertical evaporator condensers, but for the increasing of performance ratio (PR – heat input for kilogram of distillate) multi-stages are used in practice. [3][20]

Feed water is pumped from a preheated reservoir to effector1 where it is evaporated and led to a compressor. Vapour is compressed and flown with a higher temperature back to effector1 where it transmits latent heat to pre-heated brine. The formed water, which condensate on the tube surface, is a required product. Inside of the tubes, vapour forms. This is driven to the compressor and second effector for a second round. The pre-heated brine is pumped to the top of the effector where it is equally dosed in thin film inside the tubes. The process in effector2 is similar. Delivered vapour from the first effector surrounds the tubes and passes latent heat to the brine which flows inside the tubes. Formed steam is led to a demister and subsequently to the compressor. The second effector works with a lower temperature. [20]

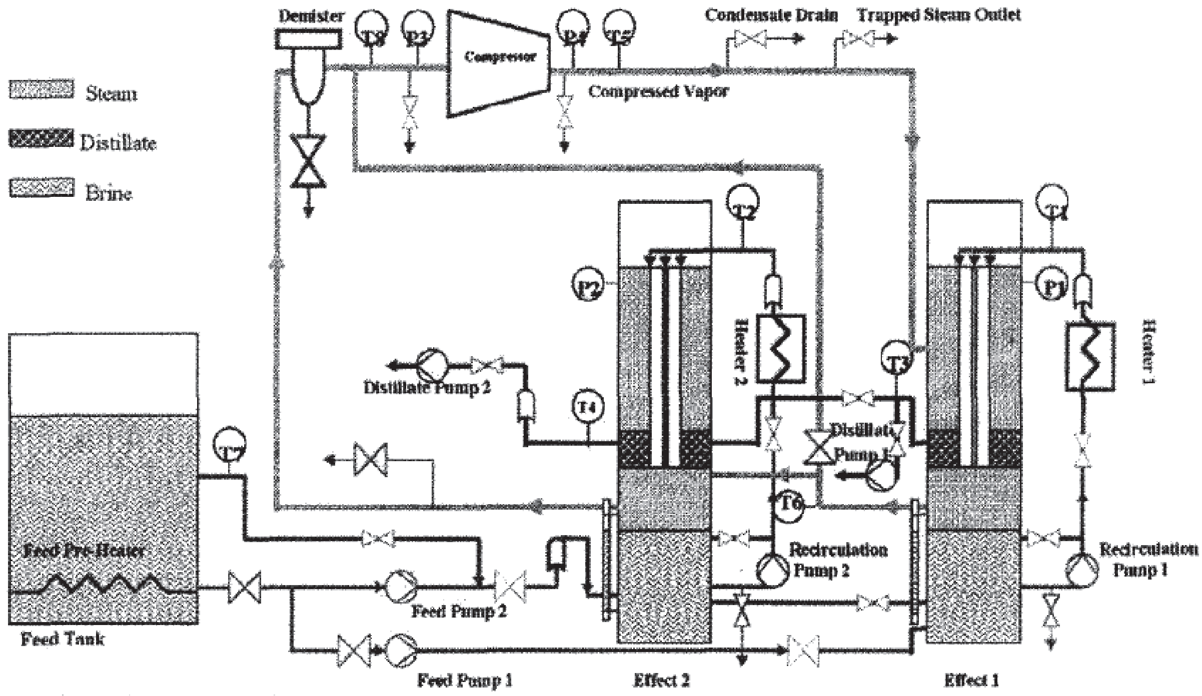


Figure 13 Diagram of MVC option [20]

2 ENERGY SOURCES

Desalination processes are energy-intensive, thus it is necessary to ensure a sufficient amount of energy intake. Desalination technology implores the use of energy in the form of heat or electricity. There are three basic options: fossil fuel plants, renewable energy, or nuclear energy; any of these can be used in combination too. The choice of energy solutions depends on many conditions such as climate, fuel availability, technological advancement, and the type and power of desalination facility.

2.1 FOSSIL FUEL

Fossil fuels are among the most frequently used sources. However, they bring along problems such as price inflation of desalinated water and pollution [1]

If we look at fossil fuels from the global view point, we have to imagine prices escalating. The prognosis is a rising trend in price. Global consumption is also increasing hand-in-hand with population and industry growth. A further negative impact is the speculation of fuel price on the commodities market, which can cause an unstable price of desalinated water. Furthermore, costs are linked with pollution and the fight against greenhouse gases. There is pressure to lower CO_2 fumes represented by a carbon tax. [1][21]

In the states of Middle East and North Africa (MENA) petroleum and natural gas are the most frequently used fuels. The price of the fuel is lower and more abundant in comparison with European and other states.

2.2 RENEWABLE ENERGY

In the case of considering a solution for water scarcity while remaining environmentally friendly, renewable energy seems to be an ideal way to meet mankind's needs. The advantages are no CO_2 emissions, and it avoids depleting fossil fuel supplies. Thus, the question of developing the desalination process, powered by renewable energy, seems crucial. [22]

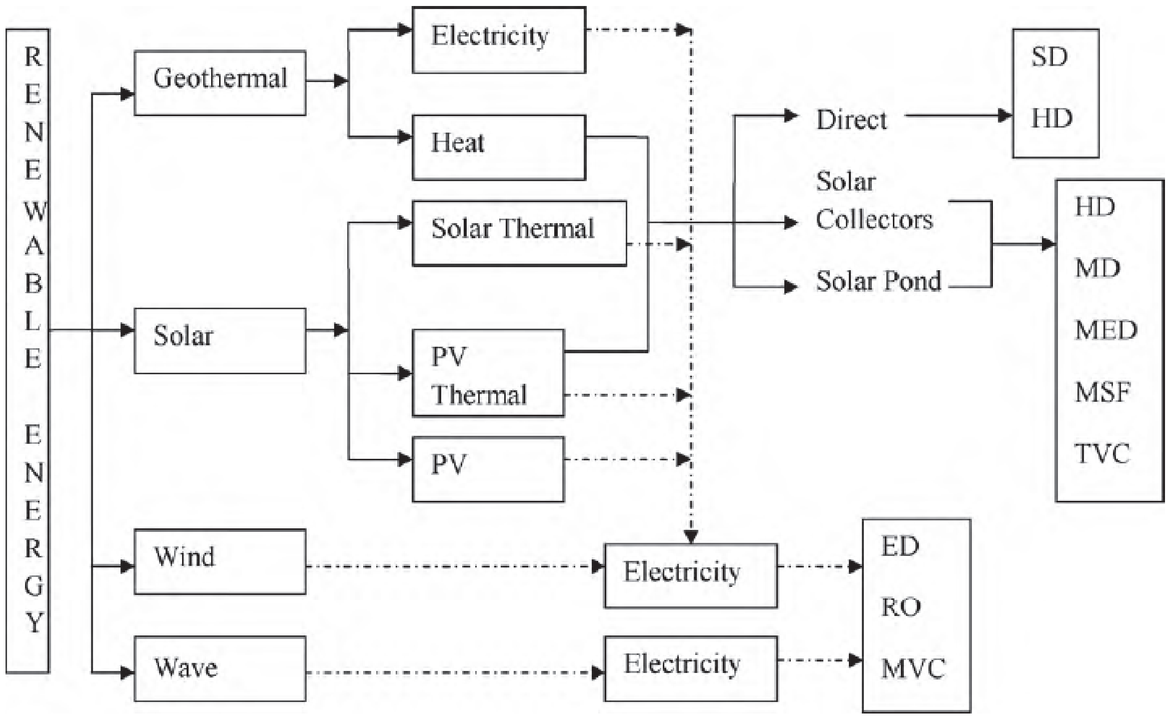


Figure 14 Possible coupling renewable energy sources with desalination process[22]

2.2.1 SOLAR ENERGY

A solar still, whose distillation method was described in chapter 1.4.2, is a direct possibility to reach fresh water for a small community. The utilization is economical. It demands very low operation and maintenance costs because there are no moving parts. The only necessity is sufficient solar radiation. [22]

Solar ponds transmit the energy to thermal form which can be used for MSF, ME and other thermal processes. Solar pond also can produce electricity or direct desalt seawater.
Salinity-gradient solar pond is consists of three layers, which are distinguished according to salinity rising with depth. Sun is heated the pond surface and transmit it to the highest salinity concentration water on the bottom. It stays on the bottom, because of the highest density, until its temperature approach to 100°C. Subsequently, this hot brine is used for generating energy. The surface layer is heated up to 85°C and can be used for next electricity generation or heating buildings. The middle layer performances the function of insulator between the bottom and the surface. [18][21]

Flat-plate collector (FCP) is a device consists of pattern of metal or plastic pipes on the flat dark plate in which flows a fluid. The fluid absorbs solar radiation and is heated up. Protection against thermal loos is cared by glass or plastic cover. This technology is not found as suitable for desalting according its low productivity. [18]

Evacuated tube collector (ETC) is different from FCP mainly because of isolation. The collector consists of a glass tubular tube with a fluid isolated by a vacuum cover. There are two options of the cover tubes. The first is two coaxial glass tubes which are sealed on both ends. The second technology is a receiver made of metallic sealed by glass. ETCs tubes gathered with reflective surface create the collector. These ECTs reach temperature around

200°C, thus higher efficiency. However, collector cost is also higher. The technology can be used as energy resource of desalination processes. [18]

Parabolic through collector (PTC) is a linearly shaped collector with a parabolic cross-section. Receiver tubes are heated with advantage of reflective surface which is directing the solar radiation. Reached temperature can fluctuate between 100 and 400°C. The device needs one axis for sun tracking. The technology is utilized for thermal as well as to membrane desalination. In compare with FCP and ETC PTC has higher price, but it is compensated by higher efficiency. [18]

Photovoltaic modules (PV) defined to make electricity, coupled with a battery, can provide constant input of electricity even for a limited time during nights and cloudy days. The utilization in combination with RO or ED is expanding. The problem is the battery shelf life, which is varies due to climate, lasting from 2 to 8 years. The cost of the battery and its efficiency are negligible. On the other hand, the installation capacity of modules has been constantly increasing and its price decreasing in the last few years. [22]

Coupling concentrated solar power (CSP) and desalination lead to a few complications: Firstly, the fluctuation of reached energy is reduced by weather changeability or even as a result of the stoppage of supplying steam during night. Secondly, there is the impossibility of gaining the same steam temperature as with fossil fuels or nuclear sources (480 – 560°C); the maximum temperature is 370°C. Thirdly, CSP demands a large size of usable area. Despite that, the MENA region is running a project focused on the combination. [23]

2.2.2 GEOTHERMAL ENERGY

Geothermal energy is not widespread desalination energy. It provides a stable input of energy in the form of electricity for RO or heat for thermal desalination. The heat temperature range is from 70 to 90°C which is ideal for a low-temperature ME. A good economic solution is using it as a pre-heater for future thermal technologies such as MSF. One notable disadvantage could be the high amount of minerals and salt in brine, which can cause scaling and concentrated brine disposal. [22]

2.2.3 WIND ENERGY

Wind may be found almost anywhere, and most countries in the world can exploit it. Seacoasts, mountains and islands are typically windy areas. However, it is necessary to utilize a desalination process that is not sensitive to intermittent turning on-and-off because of wind changeability. Variants which can be employed are RO or MVC. [22]

Because of the instability of wind conditions, it is suitable to combine the process with other renewable sources to provide a smooth supply of energy. There are projects focused on research in a field of combining with the geothermal and PV energy. Storage of fresh water is problem-free and we can produce it in a period of good weather conditions. [22]

2.2.4 WAVE ENERGY

Wave energy stands out of mentioned renewable sources especially because of its high conversion efficiency, which can rise over 80%. It is known that 2 m high water waves can provide sufficient irrigation in the stripe area of 5 km wide. Unfortunately harnessing of wave energy is not so widespread because of quite high capital costs and necessity for next development. The most important parameter is the high of waves. This information can be investigated by different methods. The first is radar which measures roughness of the ocean surface. The second way of researching waves is exploiting of buoys, which is limited methods because of small placement along coastlines. It is possible also to use methods as hindcasts and visual observing. [22][36]

The main effort inclines to electricity production and following coupling with electricity-driven desalination facility without need for next energy resource. [36]

The DELBUOY uses oscillating buoys to power pumps of submerged RO modules. Unfortunately, the technology is quite inefficient because of the absence of an energy recovery system and low recovery ration. However, the method is already practical employed. [22][36]

Salter duck is the second technology. The base function is pressurizing. The wave motion causes changeability of seawater level in a hull of the duck and vapor compression device contained in the duck generate pressures. The duck's dimension is 6 and 12 m in diameters, it ensures sufficient temperature of energized falling-film heat exchanger, which is used for the desalination. The process reaches 80% conversion efficiency.

The McCabe Wave Pump is the third technology. The device is creating by three-section hinged barge. Two floating arms are mounted to central part, which is prevented from pitching. Developed forces between arms and the center section are harness by pistons and feed RO or generate the electricity. It is expected that the full size device, 40 m long and 4 m wide, could pump 275 000 m^3/y at pressure of 70 bar. [36]

The Oscillating Water Column (OWC) is another option of harness wave energy. The principle is based on air column compression with rocking motion. The energy is generated by turbine from the air column. This device is employed in Vizhinjam, Kerala since 1990. The turbine used is an impulse turbine driving an alternator. The constant output is 130 V. It is used for battery charging. The energy is than inverted to 230 V, 50 Hz for deriving RO. In case of calm sea, diesel generator is employed. Performance of the desalination facility is 10 m^3 per day. [22][36]

Concept number five describes using of **trapped channel**. The proposal exploits water hammer effect to generate required pressure. Influencing factors are elasticity of pipe walls and compressibility of the water. The technology resembles to hydro-ram utilize for an irrigation. Sawyer and Maratos, authors of the idea, recommend using of several hydro-rams to purpose of increasing the pressure, so that the water could be derived directly to RO. [36]

The last technology is the **Wave jet.** The process is based on water collecting, which is in form of waves, in high level reservoir. Pressure intensifier device is need to use for propose of desalination. The collected water can be also used for generating electricity by turbine. [36]

The issue about employing the use of wave energy is the same as other renewable energy sources: the cost of the plant and the effort to continually develop the technology is daunting. Furthermore, well-situated states with the potential for wave energy, such as Norway, have been gifted with a natural wealth of petroleum. It means they don't need to develop such technology. For using renewable energy, we have to put forth a bigger effort into research. [22]

2.3 NUCLEAR ENERGY

The main interest about nuclear desalination for the last few decades is driven by the International Atomic Energy Agency (IAEA), which conducted many studies on the topic. According to their results, we can present advantages of nuclear desalination.

The energy price is lower in comparison to other options. It fulfils environmental requirements about green house gas emissions, toxic gases, and acid rain, which are connected with fossil fuel plants. The plus against renewable energy is also productivity. Security of the nuclear process is constantly improving along with the development of the fourth generation reactor. The new generation reactor also emits a lower amount of nuclear waste. [24]

The design has two options. All generated power can be used for desalting, or more often, for cogeneration. Cogeneration plant produces both electricity and potable water. Suitable nuclear reactors are high-temperature gas reactors (HTGRs) and liquid metal cooled reactors (LMRs). [25]

Nearly 200 applicants of nuclear desalination plants have had success, namely in Japan, Kazakhstan, Pakistan, and the Republic of Korea. All of them have been functioning without any operating or security problems. [25][26]

BASIC REQUIREMENTS

The often used term is safety. Nuclear desalination plants are as safe as nuclear power plants. It must be guaranteed that any changes of steam consumption in the desalination facility do not negatively influence proper operation and safety of the nuclear reactor. An isolation loop is the next tool which prevents the risk of passing radioactive radiation into the final water product. Two mechanical barriers and pressure reversal must be implemented between the brine and reactor prime cooling circuit. In the case of the most frequently and suitable pressurized water reactor (PWR), heat is transmitted through the interface of the steam generator. The necessary requirement is also to monitor the radioactivity level, and if needed, other measurements, such as the tritium level in the heating steam. It must abide by all standards relative to the issue. [25]

The next question is about facility lifespan and maintenance. The possibility to maintain or exchange desalination construction components has to be ensured without disruption of operation. Main segments of the nuclear power plant have more than a 40-year lifespan, and the desalination system can last up to 30 years due to improved technology. The lifespan of RO membranes is much shorter. [25]

It is also important to look at operational flexibility, which depends on the rationing of generated electricity and produced water to public demand. This is further influenced by local conditions as well as seasonal and daily changes. Concerning of desalination technology, RO is a more flexible than the thermal ones of MSF or ME. RO is mainly a power coupling in contrary to MSF and ME, which require close cooperation with a power plant because of necessity of heat delivering. [25]

There is also a coupling limitation according to the effect on the environment and the impact on ambient nature. The potential temperature and pressure of generated steam also has an influence on the choice of desalination technology. [25]

The economic side is also important, and different tools have been set up. IAEA developed one of them called Desalination Economic Evaluation Program (DEEP), which is mentioned in chapter 4. Basically we can say that nuclear desalination is cheaper than using fossil fuels, but costs can fluctuate by geographic position and energy costs. [25]

3 ENVIRONMENTAL IMPACT

Since the development of modern desalination technologies around the 1950s, many countries have had an interest in exploring the environmental impact; the effects on groundwater, the marine environment, land, and noise pollution all have to be considered. These impacts can be divided in two groups: indirect and direct. [27]

INDIRECT IMPACTS

Greater consumption of electricity, in the case of RO and thermal energy for distillation, has required an increasing need for power plant productivity, subsequently resulting in increased pollution, according to power station type. This can further contribute to the greenhouse effect and global warming.[27]

DIRECT IMPACTS

Discharged water has increased salinity. In the case of RO, the salt concentration is 1.3 or 1.7 times higher than the concentration of seawater. However, the impact also depends on several factors such as seafloor relief, sea currents, waves and depth. Furthermore, the marine habitat and presence of certain organisms, jaggedness of the coastline, and even variations between a sandy and rock beach all have an impact on the ambient environment. Hence, it is necessity to determine a suitable geographical region for construct desalination facility. Mathematical models are usually used for evaluating this. [27]

Brine contains chemical additives which are used for water pre-treatment. Chlorine serves as disinfection. Ferric chloride helps flocculation and the disposal of suspended particles, including the additives for managing pH and preventing scale formation. These chemicals can slightly differ due to needs and type of desalination technology being used. The discharge is generally neutralized. [27]

Noise pollution can reach 90dB. It is the result of turbines, and in the case of RO, by high pressure pumps. Desalination plants should be located further from populated areas and be properly silenced. [27]

The appearance of the facility and infrastructure should fit into the surrounding environment. One problem is leaking pipes or structural defects that can cause contamination to aquifers from brine. [27]

4 ANALYSIS OF ME/RO

IAEA developed a tool called DEEP. The program is used worldwide for economical evaluation of coupling energy sources and desalination plants. One disadvantage is that the tool does not include cogeneration with renewable energy. [29][37]

I would like to make a brief economical analysis of cogeneration systems, specifically a nuclear power plant with ME/RO. For this, it is necessary to explain a few terms. The first is Gain Output Ration (GOR), which is defined as a kilogram of water produced per kilogram of steam used. The second is Total Dissolved Solids (TDS) which is the total amount of dissolved ions and molecules, or suspended microgranules, contained in a liquid medium. Recovery ration is the proportion between permeate and feed water, indicated by a percentage. [1][28][29]

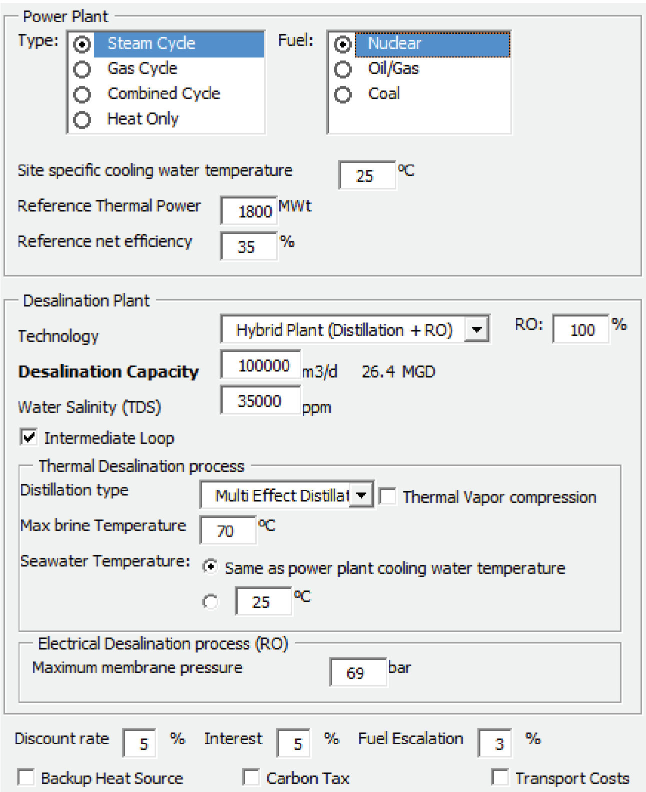


Figure 15 Basic nuclear desalination prarameters

Shown in the table is a nuclear power plant with a steam cycle and thermal power of 1800 MW. The desalination facility is ME/RO without a thermal vapour compression. The maximum brine temperature is 70°C. The maximum used pressure in RO is 69 bar.

Water temperature is 25°C with salinity at 35 000 ppm. Required amount of potable water is 100 000 m^3 a day.

The intermediate loop is necessary for prevention of nuclear radiation.

The facility is in the neighbourhood of the sea, thus it is cost-free transport, as well as carbon-tax free because it does not produce any.

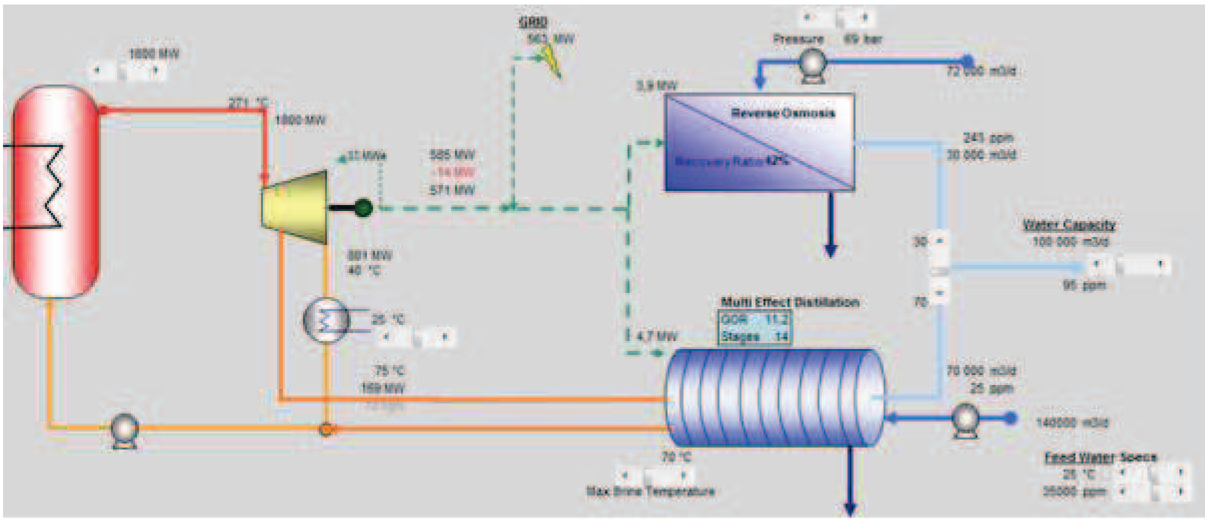


Figure 16 Nuclear desalination diagram

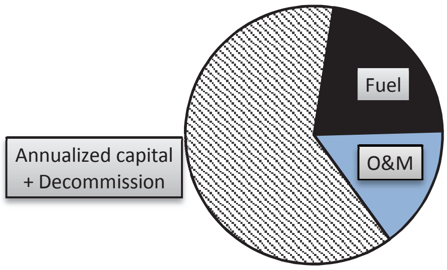
In the interactive diagram we can set up some parameters showing the proportion of produced water between RO (30%) and ME (70%). The recovery ration is 42%. GOR is 11.2 for 14 stages. The total amount of feed water per day is 212 000 m^3. It is possible to make changes as well for plant power, brine temperature, and pressure in RO. We can see that the heat required for desalination in ME is 169 MW. Electricity consumption is 4.7 MW in ME and 3.9 MW in RO. The 3.9 MW energy consumption of RO is a total power use; it means that it is already subtracted energy recovery.

SUMMARY OF COST RESULTS

Discount rate	5%
Interest	5%
Fuel Escalation	3%

Power plant

Type	Steam Cycle – Nuclear	
Reference thermal output	1800	MW(th)
Reference electricity output	558	MW(e)
Site Specific Electricity Production	4614	GWh/yr
Availability	90%	



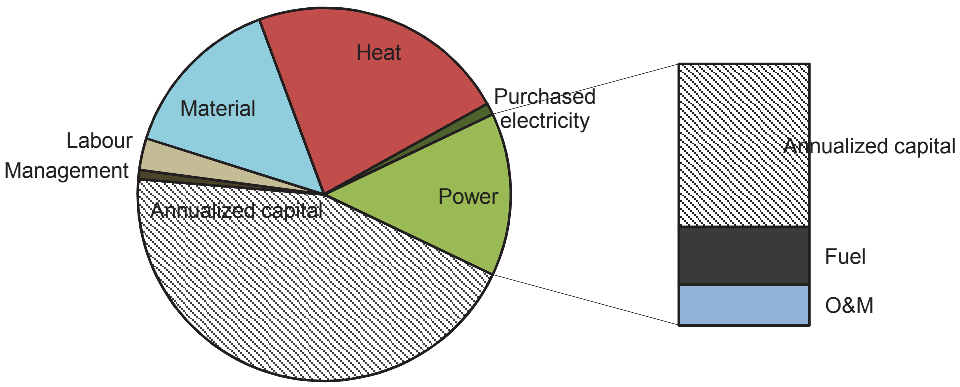
Capital Costs of Power Plant			
	Total (M$)	*Specific($/kW)*	*Share*
Overnight EPC costs	2232	4 000	72%
Owners cost	223	400	7%
Contingency cost	-	-	0%
Interest during construction	319	571	10%
Decommissioning costs	335	600	11%
Total Capital Costs	3109	5 571	
Annualized Capital Costs	164	294	
Sp. Annualized Capital Costs		0,036	

Operating Costs of Power Plant			
	Total (M$)	*Specific ($/kWh)*	*Share*
Fuel Costs	58	0,013	59%
Operation & Maintenance costs	41	0,009	41%
Carbon tax	-	-	0%
Annual Operating costs	99	0,021	

TOTAL ANNUAL COST	263	M$
Power Cost	0,057	$/kWh

Desalination plant

Type	MED RO		
Total Capacity	100000	m^3/d	MED:70000 m^3/d, RO: 30000
Feed Salinity	35000	ppm	
Combined Availability	81%		
Water Production	30,55	Mm^3/yr	
Power Lost	13,8	MW(e)	
Power Used for desalination	567	MW(e)	



Capital Costs of Desalination Plant

	MED	*RO*	*Total (M$)*	*Specific ($/m3 d)*	*Share*
Construction Cost	82	33	115	1 154	80%
Intermediate loop cost	-	-	-	-	0%
Backup Heat Source	-	-	-	-	0%
Infall/Outfall costs	-	-	8	77	5%
Water plant owners cost	4	2	6	58	4%
Water plant contingency cost	9	3	12	121	8%
Interest during Construction	2	1	3	33	2%
Total Capital Costs	98	39	144	1443	
Annualized Capital Costs			11		

Sp. Annualized Cap Costs				**0,36**	$/m3
Operating Costs of Desalination Plant					
	MED	RO	Total (M$)	*Specific ($/m3)*	Share
Energy Costs					
Heat cost	6		6	0,18	39%
Backup heat cost	-		-	-	0%
Electricity cost	1,9	1,6	3,5	0,11	24%
Purchased electricity cost	-	0,2	0,2	0,01	2%
Total Energy Costs	8	2	9	0,31	65%
Operation and Maintenance Costs				-	0%
Management cost	-	-	0,20	0,01	1%
Labour cost	-	-	0,68	0,02	5%
Material cost	1,9	1,73	3,6	0,12	25%
Insurance cost	0,5	0,19	0,7	0,02	5%
Total O&M cost	2	2	5	0,17	35%
Total Operating Costs	10	4	14	**0,47**	
Total annual cost				**25,44**	**M$**
Water production cost				0,833	$/m^3
Water Transport costs				-	$/m^3
Total water cost				0,833	$/m^3

Figure 17 Summery of cost results

In the table, important evaluations of the desalination facility and nuclear plant are shown. I would like to highlight just a few of them, such as reference to the electricity output of 558 MW and reference to the thermal output of 1800 MW. Capital cost of desalination facility is 144 M$, and 3 109 M$ of power plant. The total water cost is 0.833 $/m^3 in comparison with pipe water whose cost can be range from 0.01 to almost 8 $/m^3. This I would try to change by changing the proportion produced in RO or by reducing the amount of required fresh water, but it does not have to lead to reducing the price of produced water. [30]

CONCLUSION

In this project, I have focused on the introduction of commonly used desalination processes, as well as those which are not yet commercially utilized. Most of them still require further development. In the future, we can expect the spreading of RO, which is economically better than at the expense of MSF – a process in recess.

The issue of environmental harmony is divided into two aspects: The first is the influence of waste desalted water, which does not have to have devastating impact; much depends on the place where the facility is built. The second, and more pressing concern, comes from the point that desalination is an energy-intensive process. If the desalination plant is coupled with a fossil fuel plant, a lot of CO_2 is produced. It results in greenhouse gas emissions. On the other side, coupling with a nuclear power plant or renewable energy source is carbon free. However, the disadvantage of using renewable energy is the smaller amount of generated power.

Renewable energy is still in their infancy, so further development is needed to understand how they can efficiently power desalination plants. In conjunction with environmental concerns, nuclear power plants require big capital and specialized knowledge of the technology.

I cannot say which coupling is better. It depends on a variety of characteristics and circumstances ranging from geographical features to resource wealth. The technology is commonly used in the member states of MENA, powered by fossil fuels. Many RO users are operated around the Mediterranean Sea and in the Gulf of Mexico. In Japan, they are mainly in cogeneration with nuclear power plants.

The cost of produced water depends on a combination of factors. As a baseline, I can say that nuclear energy has a lower cost – up to 30% less than fossil fuels. And membrane processes are cheaper than thermal ones.

Desalination is a critical process that has become quite popular. However, improving the process and solving inefficiencies with the technology will require creative and wide-ranging research and development.

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LIST OF ABBREVIATIONS

AEM	Anion exchange membrane
CEM	Cation Eexchange membrane
CSP	Coupling concentrated solar power
DEEP	Desalination Economic Evaluation Program
ED	Electrodialysis
EPC	Engineering-procurement-construction
ETC	Evacuated tube collector
FPC	Flat-plate collector
HD	Hybrid desalination
HTGR	High-temperature gas reactor
HTME	Horizontal tube multiple effect
IAEA	International Atomic Energy Agency
IE	Ion exchange
IER	Ion exchange resin
LMR	Liquid metal cooled reactors
MD	Membrane desalination
MDC	Microbial desalination cells
ME	Multi effect distillation
MENA	Middle East and North Africa
MSF	Multi-stage flash distillation
MVC	Mechanical vapour compression
NF	Nanofiltration membrane
O&M	Operation & maintenance
OWC	Oscillating water column
PTC	Parabolic through collector
PV	Photovoltaic modules
PWR	Pressurized water reactor
RDC	R&D Center
RO	Reverse osmosis
SD	Solar distillation
TVC	Thermal vapour compressor
VC	Vapour compression

VFVC	Vacuum freezing compression
VTE	Vertical tube evaporation
WHO	World Health Organization

LIST OF SYMBOLS

Ca		Calcium
HCO_3^-		Hydrogen carbonate ion
SO_4^{2-}		Sulfate ion
$Ca(OH)_2$		Calcium hydroxide (Slaked lime)
Ca^{2+}		Calcium ion
$CaCO_3$		Calcium carbonate (Lime stone)
Cl^-		Chloride ion
Cl^-		Chloride ion
CO_2		Carbon dioxide
e^-		Electron
f	Hz	Frequency
$Fe(CN)_6^{-3}$		Ferrycianide
$Fe(CN)_6^{-4}$		Ferrocianide
GOR		Gain output ration
H	J	Enthalpy
H_2		Hydrogen
H_2O		Water
H_2SO_4		Sulfuric acid
HCl		Hydrochloric acid
L_p	dB	Power quantities
Mg^{2+}		Magnesium ion
Na^+		Sodium ion
Na^+		Sodium ion
NaOH		Sodium hydroxide (Caustic soda)
O_2		Oxygen
OH^-		Hydroxide ion
P	Pa;bar	Pressure

P	W	Power
pH		Power of hydrogeon
PR	J/kg	Performance ratio
Q	J	Heat
S	m^2	Area
t	°C	Temperature
t	s	Time
U	V	Voltage
V	m^3	Volume
ρ	g/l	Mass concentration

List of figures