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Πανεπιστήμιον Αθηνών

Technologies of seawater desalination

Marine resources

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1. Definition and Brief History

Water is a vital resource for the existence of living being on the earth surface and is necessary for economic and social development (Semiat, 2000). Only about 0.5% of the overall global water is available as fresh water while seawater accounts for about 97% of them. Because of the high salinity of the ocean water and the significant costs associated with seawater desalination, most of the world population's water supply has traditionally come from freshwater sources – groundwater aquifers, rivers and lakes (Voutchkov, et al., 2016). Ever since desalination was originally invented in antiquity, different technologies have been developed. Back in the 4th century BC, Aristotle, the Hellenic philosopher, described a desalination technique by which non-potable water evaporated and finally condensed into potable liquid. Likewise, Alexander of Aphrodisias in the 200 AD described a technique used by sailors, as follows: seawater was boiled to produce steam, and that steam was then absorbed by sponges, thereby resulting in potable water (Zotalis, et al., 2014). Since then, the technology for the production of potable water developed rapidly and has become quite popular.

Fig. 1. Sailors producing fresh water with seawater distillation (Kalogirou, 2005).

In many parts of the world, huge amount of fresh water is required for agricultural, industrial and domestic uses. However, changing climate patterns combined with the growing of world population, the need for fresh water is increasing. Some 700 million people don't have access to enough clean water. In 10 years the number is expected to explode to 1.8 billion.

World water resources are mainly salty (97.5%) and fresh water (2.5%). Salty water is found in oceans, seas and some lakes while fresh water is either stored underground (30%) or in the form of ice / snow covering mountainous regions, Antarctic and Arctic (70%) but only 0.3% is accessible by humans (Bigas, 2013). Available fresh-water resources from rivers and groundwater are presently limited and are being increasingly depleted at an alarming rate in many places. Furthermore, vast reserves of fresh water underlie the earth's surface, but much of it is too deep to access in an economically efficient manner (Khawaji et al., 2008). With this hardly accessible and limited amount of usable fresh water, desalination offers the means to meet the increasing demand for fresh water. Most countries in the Near East and North Africa suffer from acute water scarcity, as do countries such as Mexico, Pakistan, South Africa, and large parts of China and India (Islam et al., 2018). As a result, a solution such as salt-water desalination has emerged as the keys to sustaining future generations across the globe.

As a definition, desalination is a general term for the process that removes dissolved salts from water. However, freshwater is defined as containing less than 1000 mg/L of salts or total dissolved solids (TDS) (Radmor, et al., 2003). During World War II, it was felt that desalination technology - 'desalting' as it was called then - should be developed to convert saline water into usable water, where fresh water supplies were limited. Subsequently, "The Saline Water Act" was passed by Congress in 1952 to provide federal support for desalination. The U.S. Department of the Interior, through the Office of Saline Water (OSW) provided funding during the 1950s and 60s for initial development of desalination technology, and for construction of demonstration plants (Krishna, 2014). In recent years, with improvements in technology, desalination processes have developed to a large extent during the latter half of the 20th century and continue to undergo technological improvements even at the present time.

The notable increase in the use of desalination over the past 50 years is to a great extent the result of a long history of research and development efforts. Desalination became a totally commercial enterprise and developments in technology by the 1980s which led to an exponential growth in world desalination capacity. The worldwide distribution of desalination capacities is given in Table 1 (Nair and Kumar, 2013). For the drinking water purposes, many other countries of the world have begun to utilize desalination as a suitable technology but no other region of the world has implemented desalination on as large a scale as the Middle East (Islam et al., 2018).

Rank	Country total	Capacity (million m^3/d)	Market share (%)
1	Saudi Arabia	7.4	20.6
2	UAE	7.3	20.3
3	Spain	3.4	9.4
4	Kuwait	2.1	5.8
5	Qatar	1.4	3.9
6	Algeria	1.1	3.1
7	China	1.1	2.9
8	Libya	0.8	2.3
9	USA	0.8	2.2
10	Oman	0.8	2.2

Table 1: Top 10 countries employing seawater desalination technologies

2. Overview of Desalination Technologies

On a global basis, desalination capacity increased at almost 12 percent per year, from 1972 through 1999. Comparing with the capacity of 8.09 million m^3/day in 1980, the global contracted desalination capacity by 2014 has increased more than 10 fold in 34 years to 90.07 million m^3/day. About 53% of the total capacity was installed in the past 10 years since 2005 (Li et al., 2018). However, seawater desalination is being applied at 67% of installed capacity worldwide. Table 2 outlines the global desalting capacity by feed water sources (ESCWA, 2015).

Feed water sources	Desalination capacity (%)
Wastewater	6
River water	8
Brackish water	19
Sea water	67

Table 2: Global installed desalination capacity by feed water sources

A variety of desalination technologies has been developed over the years on the basis of three major types of technologies that are, namely: (i) thermally-activated systems in which evaporation and condensation are the main processes used to separate salts from water, (ii) membrane-based systems where either pressure or electric field is applied on the salty water to force it through a membrane, leaving salts behind and (iii) chemically-activated desalination methods (Glueckauf, 1966; Frederick, 2010; Thu et al., 2013). Within those three broad types, there are sub-categories (processes) using different techniques.

2.1. Thermal technologies

In the phase-change or thermal processes, the distillation of seawater is achieved by utilizing a thermal energy source. Water is heated and producing water vapor that in turn condenses to form distilled water. The thermal energy may be obtained from a conventional fossil-fuel source, or from a renewable energy sources such as nuclear energy, geothermal energy, and solar pond. For thermal desalination, the most commonly adopted technologies are multi-stage flash evaporation ("MSF") and multi-effect distillation ("MED"), but also Vapor compression distillation (VCD) is used.

2.1.1. Multi stage flash (MSF)

The multi-stage flash (MSF) is a type of thermal desalination which has already been in use since around 1960s. MSF facilities consist of a number of chambers connected to one another, with each successive chamber operating at a progressively lower pressure. Source water/pre-treated water (i.e. feed water) first passes from back to front through a tubing system to the brine heater, where water is heated under a high pressure. The heated water then enters the first chamber at reduced pressure, causing it to boil rapidly with a portion evaporating into vapor (**Figure 2**). In each successive chamber which operates at a reducing pressure, the same process repeats. The vapor generated by evaporation is converted into fresh water by condensation. The MSF plants usually operate at top brine temperatures of 90-120°C, depending on the scale control method selected. Operating the plant at higher temperature limits of 120°C tends to increase the efficiency, but it also increases the potential for scale formation and accelerated corrosion of metal surfaces in contact with seawater. Typically, an MSF plant can contain from 4 to about 40 stages. Multi-stage flash evaporation is considered to be the most reliable, and is probably the most widely used of the three principal distillation processes.

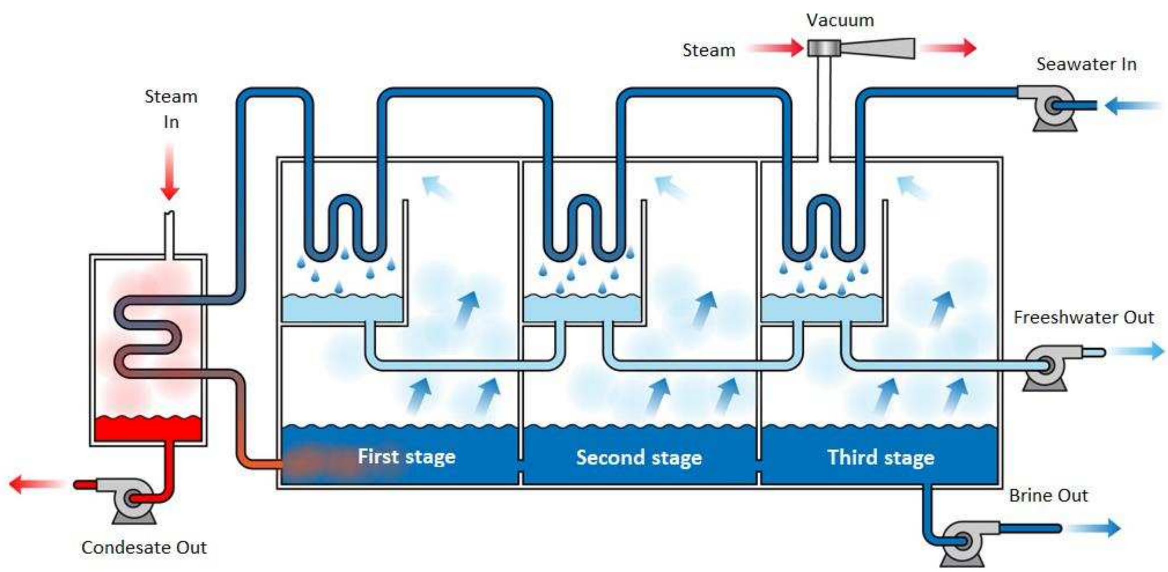


Figure 2: Basic process of multi-stage flash evaporation
Note: (1) Brine is the high salty solution after partial evaporation.
Source: Renewable and Sustainable Energy Reviews 24(2013)343–356

2.1.2. Multi-effect distillation (MED)

The multiple-effect distillation (MED) process is the oldest desalination method and is very efficient thermodynamically. Similar to MSF, MED is an evaporation process going through a series of chambers (also known as "effects"), with each successive chamber operating at a progressively lower pressure. In this process the vapour formed in one chamber condenses in the next chamber with the heat released acting as a heating source. In addition, feed water is sprayed over the tube bundle on top of each chamber in a typical MED process. As shown in Figure 3, external steam is introduced in the first chamber and feed water evaporates as it absorbs heat from the steam. The resulting vapour enters through the tube to the second chamber at a reduced pressure. The heat released by condensation causes the feed water in the second chamber to evaporate partly. The process repeats for several effects, with 4 to 21 effects and performance ratio from 10 to 18 being found in a typical large plant. In each chamber, the vapour condensing into fresh water inside the tube is then pumped out.

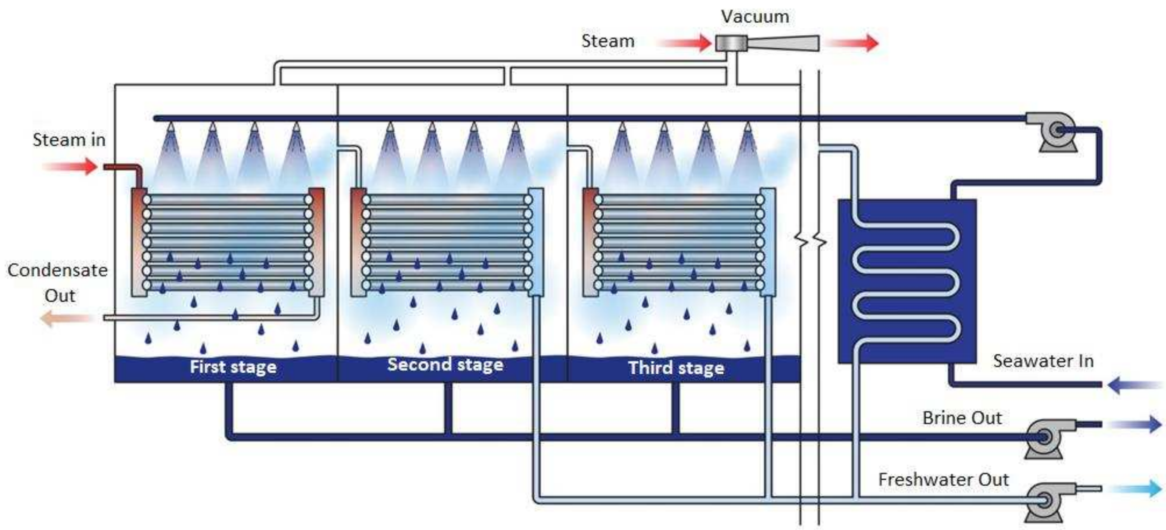


Figure 3: Basic process of multi-effect distillation
Sources: Renewable and Sustainable Energy Reviews 24(2013)343–356

The MED process is used for what, at the time it began operating, was the largest desalination plant in the world in Jubail, Saudi Arabia, producing over 800,000 m3/day. The plant began operating in April 2009.

2.1.3. Vapor compression distillation (VCD)

In a vapor compression (VC) system, the distillation process begins in the boiling chamber, just as it does in virtually any other distiller. What separates this method from other distillation methods is what comes after the boiling chamber. The steam from the boiling water flows through a baffling system and then into the compressor. In the compressor, the steam is pressurized, which raises the steam's temperature before it is routed through a special heat exchanger located inside the boiling chamber. The steam (under pressure) is at a higher temperature than the feed water inside the boiling chamber. The pressurized steam gives off its heat to the tap water inside the boiling chamber, causing this water to boil, which creates more steam. While the pressurized steam is giving up its latent heat, the steam will condense. At this stage, the condensed steam is considered distilled water but is still very hot--only slightly cooler than boiling temperature. To get maximum efficiency from the VC systems, the hot distilled water preheats the incoming feed water that will be distilled. As the incoming water is preheated, the outgoing distilled water is cooled.

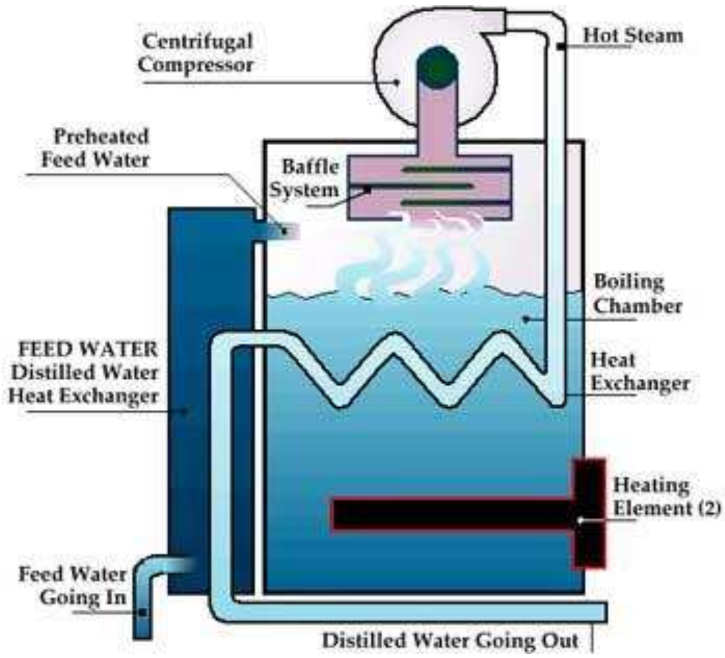


Figure 4: Basic process of vapour compression distillation. Source: https://www.aquatechnology.net/vaporcompressiondistillers.html

Vapour compression distillation is usually used where the requirement for desalinated fresh water is relatively small such as in small communities, ships or in holiday resorts.

2.2. Membrane Technologies

2.2.1.1. Reverse osmosis

The first viable reverse osmosis membrane was made from cellulose acetate as an integrally skinned asymmetric semi-permeable membrane. This membrane was made by Loeb and Sourirajan at UCLA in 1959. The current generation of reverse osmosis (RO) membrane materials are based on a composite material patented by FilmTec Corporation in 1970 (now part of Dow Chemical Company) (Sagle and Freeman 2004).

The basic principle for RO desalination is reversing the natural phenomenon of osmosis. When two liquids of different density (salinity) come in touch through a semipermeable membrane, solvent molecules move through into a region of higher solute concentration, in the direction that tends to equalize the solute concentrations.

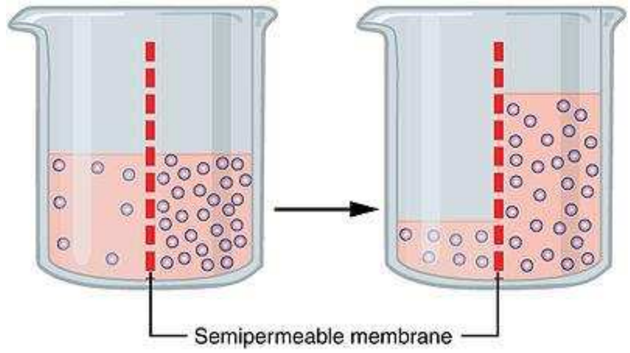


Figure 5 Osmosis, source: https://cnx.org/contents/FPtK1zmh@8.108:q2X995E3@12/The-Cell-Membrane

However if we exert pressure on the dense solution (salty water), greater than the osmotic pressure, then there is movement of the solvent molecules (fresh water) through membrane to the less dense solution (not salty water).

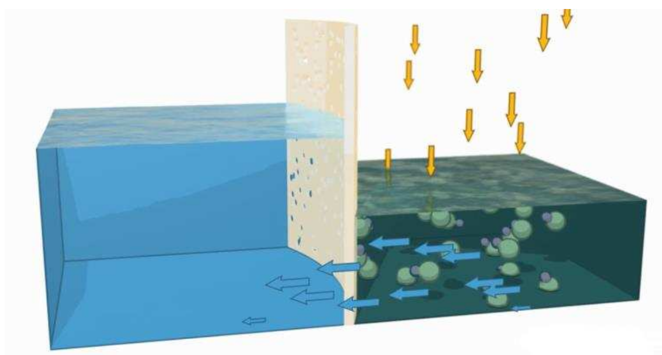


Figure 6 Osmosis,source:#ADP, #Adelaide Desalination Plant, #Adelaide desalination, #Desalination, #Reverse osmosis, #Water security

In case of desalination technologies, sufficient pressure is applied by high pressure pumps to force water passing through the semipermeable membranes, leaving behind the dissolved salts. Disinfection and pH adjustment makes desalinated water potable (Wabag; Sagle and Freeman 2004, Ράπτης 2012; Evoqua; Gude et al., 2018).

The typical single-pass sea water reverse osmosis system consists of: Intake, Pretreatment, High pressure pump (if not combined with energy recovery), Membrane assembly, Energy recovery (if used), Remineralisation and pH adjustment, Disinfection, Alarm/control panel

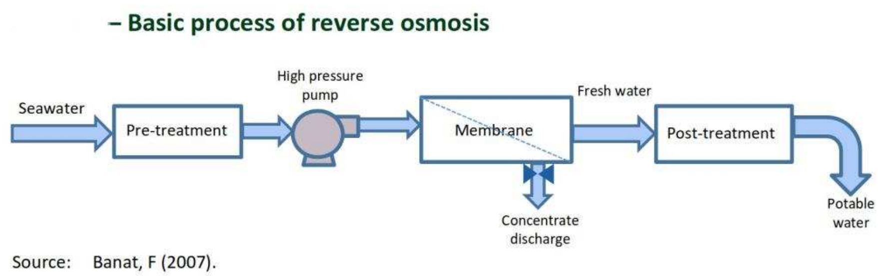


Figure 7 Osmosis

Pretreatment is important for RO as the design does not allow for backpulsing with water or air agitation to remove solids. Since accumulated material cannot be removed the membranes are highly susceptible to fouling (loss of production capacity). Pretreatment in sea water RO systems has four major components:

1) Screening of solids: prevent fouling by fine particle or biological growth, reduce the risk of damage to high-pressure pump.

2) Cartridge filtration: string-wound polypropylene filters are used to remove particles of 1–5 µm diameter.

3) Dosing: Oxidizing biocides, such as chlorine, followed by bisulfite dosing to deactivate the chlorine, which can destroy a thin-film composite membrane. Biofouling inhibitors prevent the growth of slime on the membrane surface and plant walls.

4) Prefiltration pH adjustment: If the pH, hardness and the alkalinity in the feedwater result in a scaling tendency in the reject stream, acid is dosed to maintain carbonates in their soluble carbonic acid form.

$CO_3^{2-} + H_3O^+ = HCO_3^- + H_2O$

$HCO_3^- + H_3O^+ = H_2CO_3 + H_2O$

Carbonic acid cannot combine with calcium to form calcium carbonate scale. Calcium carbonate scaling tendency is estimated using the Langelier saturation index. Adding too much sulfuric acid to control carbonate scales may result in calcium sulfate, barium sulfate, or strontium sulfate scale on RO membrane.

Prefiltration antiscalants: prevent formation of all scale; carbonate and phosphate, sulfate and fluoride scales. Antiscalants disperse also colloids and metal oxides. Antiscalants can control acid-soluble scales at a fraction of the dosage required to control the same scale using sulfuric acid (Malki, 2008).

Small scale desalination units may use 'beach wells' drilled on the seashore. These intake facilities are easily built and the seawater is slowly filtered through the subsurface sand/seabed formations. Raw seawater collected using beach wells is often of better quality regarding solids, silt, oil and grease, natural organic contamination and aquatic microorganisms, compared to open seawater intakes. They may also yield water of lower salinity.

Apart from conventional filtration technologies, highly effective micro- and ultrafiltration systems are employed. For example, WABAG has built the first plant in Duqm, Al Wusta Oman, using microfiltration units for pre-treatment as well as at new Sohar International Port (2013), where an in-line RO system was successfully executed. The Nemmeli RO-drinking water plant in Chennai, one of the largest plants in India, employs ultrafiltration membranes for highly effective pre-treatment upstream of the RO system.

The high pressure pump pushes water through the membrane, which rejects the passage of salt. Typical pressures for brackish water range from 225 to 376 psi (15.5 to 26 bar, or 1.6 to 2.6 MPa). For seawater, the range is from 800 to 1,180 psi (55 to 81.5 bar or 6 to 8 Mpa), requiring a large amount of energy.

The membrane assembly consists of a pressure vessel with a membrane that allows feedwater to be pressed against it. R/O systems employ thin film composite spiral wound membrane elements for superior performance. These special membranes allow only high quality water, the "permeate water" to permeate them, rejecting metals, salts, ionic and organic impurities. Suspended solids are removed by pre-filters.

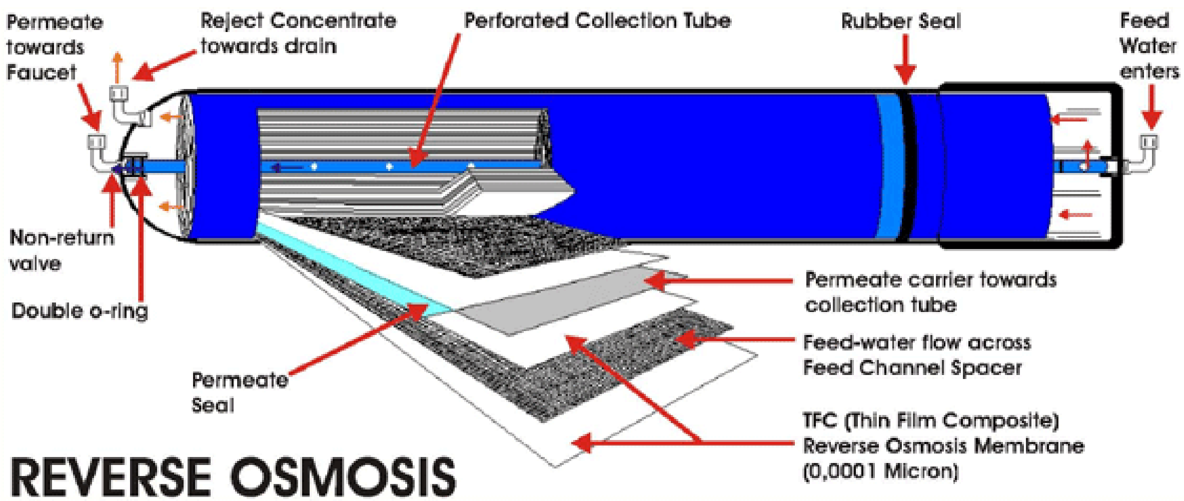


Figure8. Osmosis

RO membranes are made in a variety of configurations. The most common are spiral-wound and hollow-fiber. Thin film composite spiral wound membrane elements are employed for superior performance (Ράπτης 2012; Sagle and Freeman 2004; Lanxess).

The membranes consist of two separate layers. The “skin” is the drastic part of the membrane for separating water from dissolved or suspended particles. Membranes are made of polymer compounds and are thin and fragile. Between membranes there is a separator from porous material – usually a net of pet – Dacron impregnated with resins, which prevents membranes from attaching to each other due to high pressure, and facilitates the uniform flow of clean water between membranes. The two ends of membranes are attached to a central perforated pipe, through which the permeated water is collected (Ράπτης 2012, Sagle and Freeman 2004).

Part of the saline feed water pumped into the membrane assembly passes through the membrane with the salt removed. The remaining "concentrate" flow passes along the saline side of the membrane. As "recovery ratio" is called the percentage of desalinated water produced versus the saline water feed flow. Typically varies between 20% for small seawater systems, 40% – 50% for larger seawater systems, and 80% – 85% for brackish water (Cape Coral Annual Report 2012).

Initially cellulose based membranes have been used. RO membranes made their commercial debut when Gulf General Atomics and Aerojet General employed the Loeb-Sourirajan cellulose acetate (CA) membranes made by a cellulose repeat unit, found in plants, particularly from acetylated cellulose (Sagle and Freeman 2004).

Thin Film Composite Membranes (TFC or TFM) are manufactured for water desalination or purification systems. They resemble a molecular sieve in the form of a film from two or more layered materials and are classified as nanofiltration (NF) or Reverse Osmosis (RO) membranes. They are made of a cross – linked polyamide layer (<200 nm) deposited on a poly ethersulfonate or polyposulfone porous layer (50 microns) above a non – woven support polyester sheet. The three layer configuration gives the desired properties of high rejection of undesired materials (like salts), high filtration rate, and good mechanical strength. The polyamide top layer is responsible for the high salt rejection and is chosen primarily for its permeability to water and impermeability to various dissolved impurities (lanxess, Sagle and Freeman 2004).

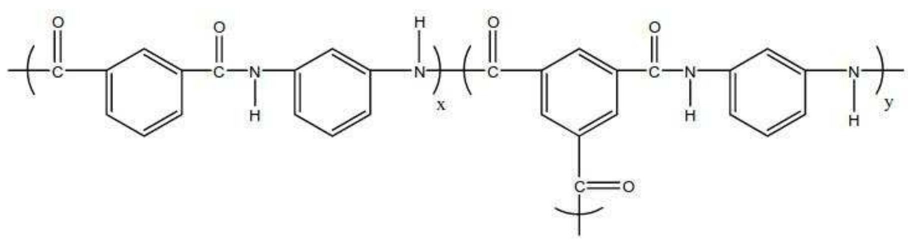


Figure 9; chemical structure of polyamide membranes used in TFC, source: Sagle et Freeman 2004

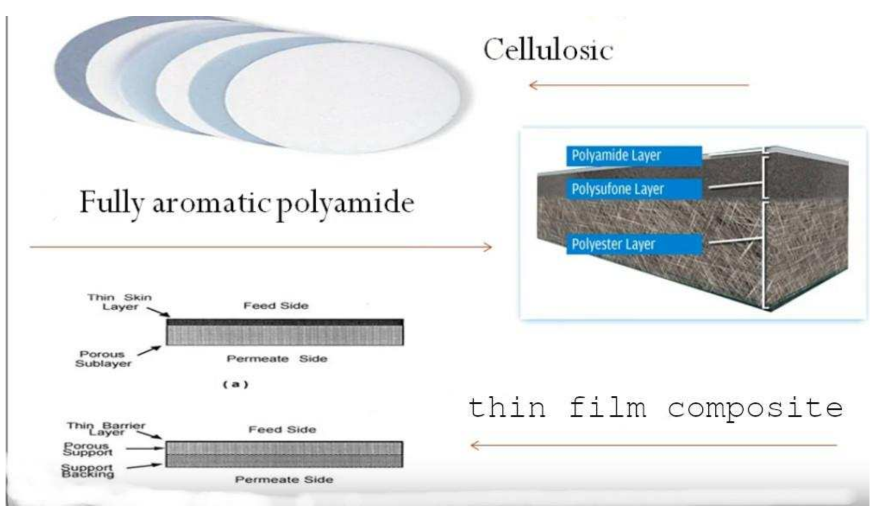


Figure 10: Ro membranes

RO membranes are rated by the amount of dissolved solids they reject from water. For example if feed water contains 100 ppm of dissolved solids and the product water after the membrane has 10 ppm, the rejection rate IS 90%.
Water quality from an RO system is determined with a conductivity meter which measures total dissolved solids in the water. For higher purity a second pass can be added which requires re-pumping. Purity can vary from 100 to 400 ppm or milligram/litre on a seawater feed. A level of 500 ppm is generally accepted as the upper limit for drinking water, while the US Food and Drug Administration classifies mineral water as water containing at least 250 ppm.

Silt density index (SDI) is an indicator that describes the amount of colloidal material in water and approximates the fouling potential of feed water (Lanxess, 2013).

Post – treatment

Produced water from RO plants has low hardness and low pH and has to be adjusted with addition of sodium hydrogen carbonate. Dose is adjusted according to the pH of produced water and desired value. Hardness can be adjusted either by adding $CaCl_2$ and $MgCl_2$ or specific columns that contain magnesium and calcium salts. The second way is preferable because this way is not increased the concentration of chlorine ions.

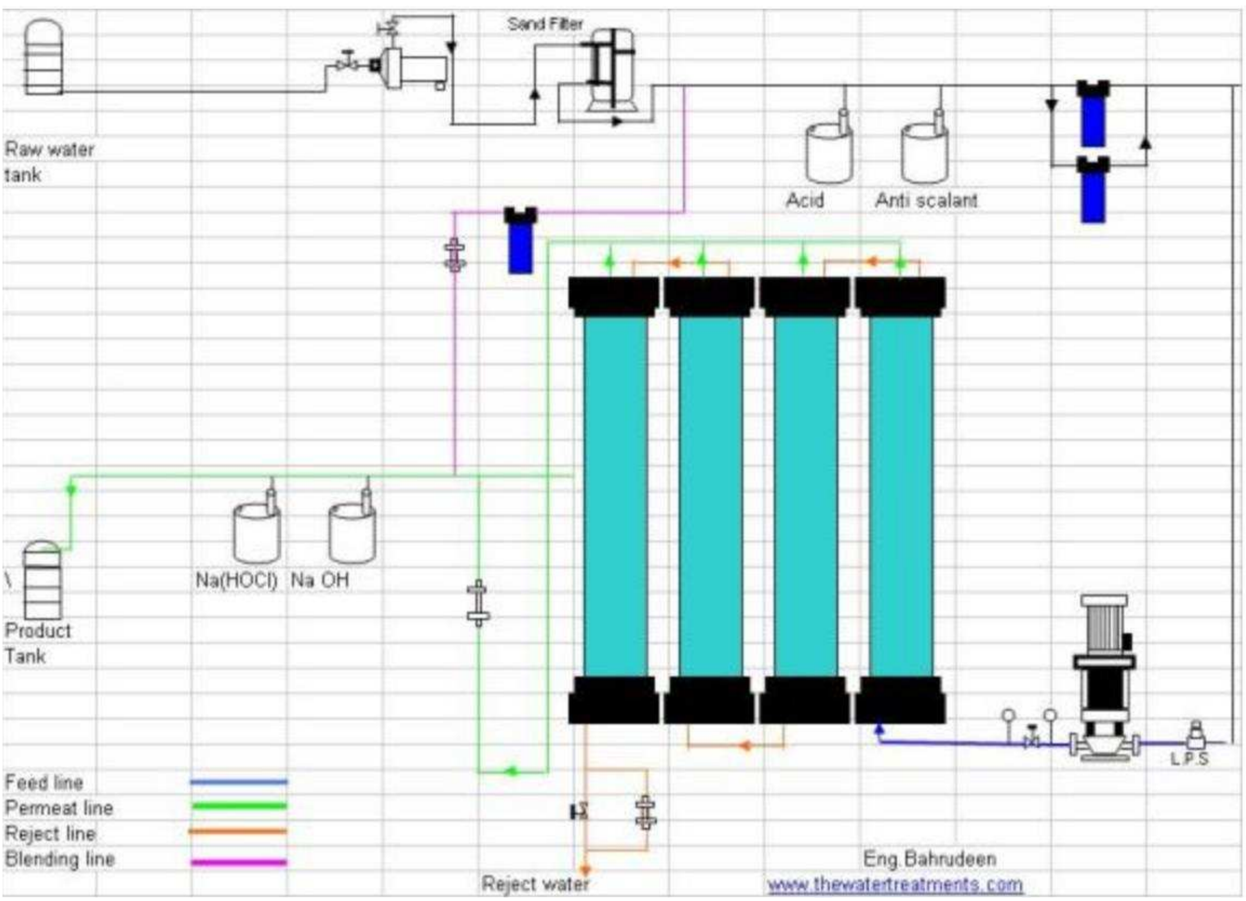


Figure 11. RO PLant in Vertical type,
source: http://chemicalengineeringdata.blogspot.com/2011/06/flow-diagram-of-reverse-osmosis-plant.html

The world's largest and cheapest reverse-osmosis desalination plant is running in Israel and is called Sorek. Built by Desalination Enterprises, or IDE Technologies, at a cost of around $500 million it produces 627,000 cubic meters of water daily and provides 20 percent of the water consumed by the households in Israel . It is built by Desalination Enterprises, or IDE Technologies, at a cost of around $500 million and produces 627,000 cubic meters of water daily. Desalination plants in Israel cover 40% of country's water supply (Talbot 2015). Sorek plant incorporates a number of engineering improvements that make it more efficient than previous RO facilities. It is the first large desalination plant to use pressure tubes that are 16 inches in diameter rather than eight inches.

RO System parameters and quantitative characteristics of an RO system:

Osmotic pressure is defined by van't Hoff law:

$\Pi = RT\Sigma\chi i$

where Π is osmotic pressure (kPa), T temperature (K), R is the Universal Gas Constant equal to 8.314 kPa * m3 / kgmol*K, Σχi is the total concentration of all compounds in the solution (Kgmol/m3).

The operation pressure for the unit has to be larger than the osmotic pressure of the solution, plus the friction losses Salt rejection is defined as(Ράπτης 2012, Sagle et Freeman 2004);

SR=(1-Xp/Xf)*100 where Xf is the concentration of the feed water , Xp concentration of the permeate, If the feed water is sea water of 42000 ppm and permeate has 150 ppm concentration, then the salt rejection will be:

SR = 100% (1-150/5000) = 97%

Nowadays membrane technologies can yield an SR> 99%

Recovery is defined as Y = (Mp/Mf)*100%

where Y is the percentage of recovery (%), Mf is the water feed flow, Mf the permeate flow.

The water transport through the semipermeable membrane is described by the equation

Mp = (ΔP-ΔΠ) **Kw** *A , Mp , water flow rate m3/sec, ΔΠ ; difference of osmotic pressure between the two sides of membrane, Kw; coefficient of permeability of water m3/m2*s*kPa, A is the surfaceof membrane (m2) , ΔP ; difference of hydraulic pressure between two sides of membrane's salt transport

Ms = (C-Cp)*K*A , Ms ; salt flow through membrane (Kg/s), Ks;coefficient of membrane permeability , Cp; total concentration of dissolved solids in product (Kg/m3), A; surface (m^2), Cf concentration of water feed , Cb brine, concentration , C=(CfMf+CbMb)/(Mf+Mb)

RO desalination has low energy demands that can be covered by wind turbines or photo-voltaic systems having therefore low environmental impact. RO (SWRO) is widely realized as more economical way than mature thermal desalination technologies (Caldera et al., 2016; Amy et al., 2017)

RO water recovery rate is higher, as a tonne of desalinated water can be produced with an input of 2.5 – 3.2 tones of seawater. It has low demands for space and is one of the most successful desalination technologies that has been used around the world (Research Office Legislative Council Secretariat, 2015). Regarding seawater desalination, RO places with a marketshare of 65% in total global market of the 2015 installed capacity of 86.5 Mm 3 /day (Burn et al., 2015; Voutchkov, 2016).

Energy consumption is still a matter for RO desalination plants, as well as emissions of GHG (Greenhouse Gases) (G. Amy et al 2016). Optimization of energy consumption in SWRO plants depends on factors such as increases in capital costs for equipment or costs related to chemical consumption. (G. Amy et al 2016). Future of membranes in desalination and salinity gradient energy includes ultrahigh permeability RO membranes, renewable-energy driven desalination, and emerging processes discussed below, such as membrane distillation (MD) AND FO,. It is an extensive demanding engineering task (H. Ludwig, 2010). RO process does not require thermal energy, but needs electrical power due to the high pressure pumping. Brine energy recovery systems have also been optimised (Wabag).

RO membranes are made of cellulose acetate or composite polymers, susceptible to fouling. Pre – treatment for removing particles and organic matter is an extra cost (Penate et Rodriguez 2011, Topaloglou et al 2018). High level of skills is required for operating an RO facility. Technological advances pursue to reduce the energy consumption and to minimize the harmful effects of scaling and fouling and to obtain higher water flux membranes (Penate ET L Garcia – Rodriguez, 2011). RO practices have negative impacts of brine on sea life, air pollution from greenhouse gases, low boron removal, land use restrictions, noise pollution and aquifer salination (Topaloglou et al., 2018).

Ultrafiltration (UF) provides optimum pre-treatment for SWRO, removing all suspended solids which in turn reduces significantly microbiological activity (F knops et al, 2012). As it has happened on SWRO desalination unit in Chile, cleaning frequency can be substantially reduced. The South-Pacific seawater is one of the most difficult to pre-treat for reverse osmosis desalination. Dissolved Air Flotation followed by single stage sand filtration has been implemented, but has its limits on high peaks of SDI, especially during red tide events. High rate air flotation, and two stages of pressurized dual-media filtration have been applied giving good results. Water intake location is critical and preference is given to a deep intake. Drawing water from 20 meters below the surface provides stable feed water quality. Low water temperature and increased viscosity results in higher energy consumption for achieving the demanded pressure.

Regarding Greece and especially the anhydrous Greek islands, desalination technologies can give the best environmental, economic, and social outcomes leading to a sustainable solution for providing fresh water.

2.2.1.2. Forward Osmosis

In FO, impaired water is in contact with the dense side of a semi-permeable membrane and a highly concentrated draw solution is in contact with the support side of the membrane. The draw solution is typically an aqueous solution of a low molecular weight salt (T.Y. Cath et l, 2006). Water diffusion occurs from the low concentration side to the high concentration side. This is the process of forward osmosis (FO) and the semi-permeable membrane is classified as a forward osmosis membrane (FO membrane). More specifically pure water is transported from the impaired water into the draw solution. A desalination process (e.g.,reverse osmosis (RO) or distillation) is required for reconcentrating the draw solution and simultaneously producing high-quality product water.

The driving force for water diffusion in **forward osmosis processes** is quantified by the **osmotic pressure** $\prod$. In ideal solutions with low solute concentration the osmotic pressure can be approximated by the Morse equation:

$\prod = iRTM$

> I; is The Van't Hoff factor, which reflects the dissociation multiple of the solute species. For a dilute acquous solution of sodium chloride, the Van't Hoff factor is equal to 2 because 1 mole of NaCl dissociates into 2 moles of solutes, R ; gas constant in $L*atm*K^{-1}*M^{-1}$, T; solution temperature [K] , M; molarity [M]

A key component for FO technologies is the selection of an optimal draw solution which must have a higher osmotic pressure than the feed solution to produce high water flux. Water flux (Jw) in FO can be expressed by:

$Jw = A (\pi_{d,b} - \pi_{F,B})$

Where;

A; mebrane water permeability coefficient, $\pi_{d,b}$; bulk osmotic pressure of the draw solution and $\Pi_{f,b;}$ bulk osmotic pressure of the feed solution, assuming that the FO membrane is ideally impermeable to the draw solution and that there is absence of concentration polarization. Concentration polarization is the accumulation or depletion of solutes near the membrane surface. FO membranes are comprised of a dense layer on top of a porous support layer. Concentration polarization occurs externally at the feed–membrane and draw solution membrane interfaces, and internally in the porous membrane. It results in the solute being concentrated on the feed side of the membrane and diluted inside the support layer, reducing the effective osmotic pressure difference across the membrane and hence, water flux. It may occur even with ultrapure water used as the feed solution ($\pi_{,Fb}$=0). A modified expression of the equation taking into account ICP in FO applications (McCutcheon et M. Elimelech) is:

$Jw= A(\pi D,b \exp(-jwK))$

$\exp(-JwK)=\pi D,i / \pi D,b$ where $\pi D,i$ osmotic pressure of the draw solution at the interface between the dense and support layers of the membrane and is referred to as the effective draw solution osmotic pressure.

Where $\pi D,b$ is draw solution osmotic pressure.

At the table below are presented osmotic pressures (in bar) of common solutions encountered in FO processes;

Solute	Concentration in aqueous solution	Osmotic pressure
Mixture of ions in average seawater	N.A.	≈28 bar
NaCl	35,2 g/l	28 bar
CaCl2	43,8 g/l	28 bar
MgSO4	141,3 g/l	28 bar
MgCl2	34,2 g/l	28 bar

Table 3 : Achilli et. al. 2010: Selection of inorganic-based draw solutions for FO

In most water treatment applications, FO is not the ultimate process but a high-level pretreatment process before an ulti-mate reconcentration/desalination process. The main advantage of FO is that it operates at very low hydraulic pressure, has high rejection of a broad range of contaminants, and may have lower fouling propensity and fouling that is more reversible than in RO processes (Mi, B. and Elimelech, M. 2010, A. Achilli et al 2009).

Modern Water has developed a FO desalination process on a commercial scale. The hybrid FO/RO desalination provides many advantages such as reducing RO fouling and scaling, recovery of osmotic energy of RO brine and minimizing the use of chemicals required for conventional pretreatment steps. Future success of FO desalination depends on designing new membranes in terms of structure and configuration specifically tailored for FO. New configurations were intended to improve performance of the modules in terms of water flux and effectiveness of backwashing as well as to lower pressure drop in the membrane envelope (Bamaga et al 2010).

FO combines seawater desalination and water reuse. In a FO-reverse osmosis (RO) hybrid process, high quality water recovered from the wastewater stream is used to dilute seawater before RO treatment. Lower desalination energy needs can be obtained while delivering safe water for direct potable reuse thanks to the double dense membrane barrier protection. Typically, FO-RO hybrid can be a credible alternative to new desalination facilities (Blandin et al 2016).

A successful desalination example has been launced in by Modern Water at a site is located 450 km south of Muscat near the fishing village of Al Khaluf in Wilayat Mahoot, in the Al Wusta region of Oman. The containerised water plant was designed to tie in with the existing pre- and post- treatment equipment. (Thompson Neil A, Nicoll Peter G). Despite the challenging conditions, the FO system has been operating successfully with a seawater recovery of 35%. With post-treatment, the product water fully meets the requirements of the Omani Standard. The untreated product typically has a TDS content of less than 200 mg/l and a boron content of between 0.6 and 0.8 mg/l.

2.2.2. Membrane distillation (MD)

Membrane distillation (MD) is a thermally driven method in which separation is enabled due to phase change. A hydrophobic membrane displays a barrier for the liquid phase, allowing the vapor phase (e.g. water vapor) to pass through the membrane's pores (Warsinger,2017).The driving force of the process is given by a partial vapor pressure difference commonly triggered by a temperature difference. Membranes used for membrane distillation (MD) inhibit passage of liquid water while allowing permeability for free water molecules and thus, for water vapor (Warsinger,2017). These membranes are made of hydrophobic synthetic material (e.g. PTFE, PVDF or PP) and offer pores with a standard diameter between 0.1 and 0.5 µm. As water has strong dipole characteristics, whilst the membrane fabric is non-polar, the membrane material is not wet by the liquid (Rezaei et al 2018).

2.2.3. ED desalination technologies

There are a few other desalination techniques that are not as widely used. One of these and the most promising is electrodialysis (ED), where separation is achieved under the influence of an electric potential gradient and passing saltwater through a series of stacked anionic and cationic membranes. Ions are transported through selective ion permeable membranes from one solution to another.

Brackish water salinity is lower than that of seawater, but high for human consumption. Often groundwater is too salty and treatment is required to reduce salinity. Conventional desalination, ED has been used for brackish water feed (Van der Bruggen and Vandecasteele 2002), as is not very efficient for highly concentrated salt solutions (Alyson and Freeman 2004).

According to Pat Buzzell from Evoqua Water Technologies, which has been performing extensive R&D on ED technology since 2008, with Evoqua's Nexed module providing a low – energy membrane, intelligent flow distribution, tunable dissolved solids removal capability has been a cost-effective treatment option for consistent water quality with variable feed water parameters or partial removal of contaminants without the need for blending. The ED features are: low pressure, quiet operation, and tunable performance.

Pilot plants have been launched on some sites that are ocean-driven, brackish water areas, with 2,000 ppm during outgoing tide and perhaps 35,000 ppm during incoming tide, which is a big swing regarding TDS (Total Dissolved Solids). From an ED standpoint Evoqua increases the amount of power demanded for removing salts from sea water, according to Buzzell. The amount of power needed is based entirely on how much salt is needed to drive out, so it's a function completely of flow rate and salt concentration in the water flowing through the module. Whatever energy that isn't needed is saved, but output is consistent. With RO, consistent water quality is dependent on a certain (high) pressure to pump and filter feed water through tiny membrane pores, regardless of how much salt is being removed.

Hazardous chemicals have been used for removing the dissolved solids (TDS) from brackish water. Evoqua Water Technologies' launched on 2016 a NEXED module for ED desalination, which reduces salinity without use of chemicals and it operates at up to 30% less energy. Alternating ion selective membranes (anionic and cationic) create separated streams of concentrated and diluted feed water that can be influenced by the electrical potential gradient and resulting current by the use of an innovative crossflow membrane. NEXED modules were designed as desalting engines and have many potential applications including: (1) Brackish Water TDS Reduction, (2) Reverse Osmosis (RO) Reject Recovery.

Whereas RO is dependent on high pressure for its membrane treatment, ED works by cross-flow separation using ion exchange (IX) membranes, which is a low-pressure flow process. ED operates quietly and doesn't require specialized piping, valves, and pumps to accommodate RO's intense pressure. Operation is possible at under 7 bar over 70 bar for RO, according to Buzzel. "For a 1000-psi pump to be operating during RO desalination there must be taken into account during designing the noise, vibration, and pressure (Westerling, 2015).

2.3. Chemical Technologies

Chemical desalination systems depend on chemical differences rather than pressure differences or phase change (Gibbs).

2.3.1. Ion Exchange

The ion exchange technologies consists of the interchange of ions between two phases (solid and liquid) and it is an analytical chemical separation technique where different ionic materials are allowed to be selectively retained on an ion exchange resin. These resins have a large number of firmly attached bonds on their surfaces, which can reversibly absorb one type of ions. Resins are like small spheres with diameters in the range of 0.4 to 0.8 micro meters. Positive charged ions are captured by cation exchange resin, while anion exchange resin capture negatively charged ions (Greiter et al., 2002). The seawater enters a tank containing high capacity exchange beads (cation exchange resin). These beads are saturated with either sodium or potassium which is known as replacement ions. While water passes through this tank, an exchange occurs between contaminant ions and replacement ions which are released to the water. The sodium or potassium from the brine permeates the resin pores and displaces the previously removed contaminants.

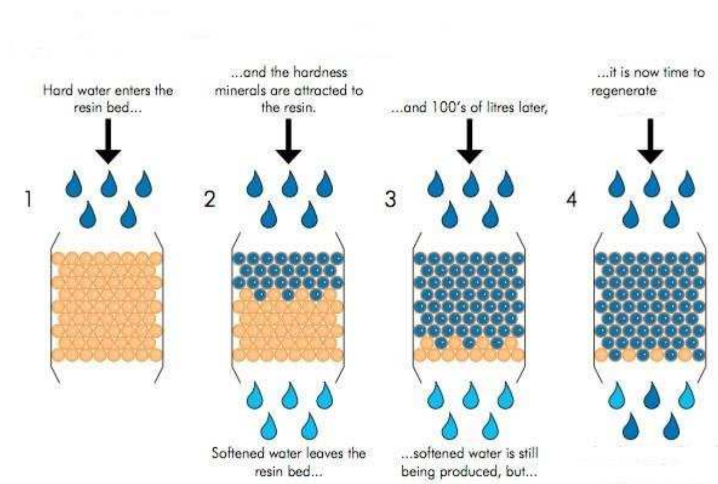


Figure 12. Ion exchange process

Ion exchange is a reversible process and the resin can be regenerated for re-use. Regeneration process is needed to recover replacement ions which were released into the water (Youssef et al., 2015). A salt brine solution is used to flush the ion exchange resin for the regeneration process. For removal of negative ions such as nitrate, arsenic and bicarbonate, anion exchange resin is used. In this resin, breads are saturated with negatively charged ions such as chloride and hydroxide. This type of desalination was found to be suitable for water treatment and for brackish water desalination (Amirault et al., 2003; Weiss, 1966; Egozy et al., 1980; Harland, 1994; DeSilva, 1999).

2.3.2. Hydrates formation

Gas hydrates are nonstoichiometric crystalline inclusion compounds formed by water and a number of small molecules such as CO_2, N_2, CH_4, H_2 and others are formed under low temperature and high pressures conditions (Park et al., 2011). In other words, if small hydrocarbon molecules or nonhydrocarbon compounds are in gas or liquid phase and at high pressure was cooled to temperature near 0^{o}C, then solid crystals like snow may form. These solid water crystals act as host water molecules can form cage structures which contains guest compounds are entrapped in (Youssef et al., 2015). This is called ‘‘gas hydrates’’ and belongs to the category known as clathrates which is thermodynamically solid solutions. Although gas hydrate could be formed by a pure gas or mixture of gases, some compounds such as acetone and 1, 4-dioxine are also entrapped in hydrate lattice (Javanmardi and Moshfeghian, 2003).

In the desalination process with hydrates formation, seawater is pumped into the reactor then it is cooled in heat exchanger. Ambient reactor pressure and temperature and the type of hydrocarbon (refrigerator) are important for the formation of hydrate crystals (Javanmardi and Moshfeghian, 2003). Then, the produced slurry of the reactor which contains the hydrate crystals is filtered and washed in the separator and is then divided into two streams; brine and washed hydrate crystals. This brine exchanges heat with seawater and the refrigerant (i.e. excess of hydrate former) of the refrigeration cycle is discharged from the process. The washed hydrate crystals are transported to the decomposer, where potable water and gaseous hydrate former are produced. Decomposing is done by pressurizing the hydrates which leads to formation of hydrocarbon gas and fresh product water. Heat energy released during crystal formation can be used in the decomposition step to increase the process efficiency (Ghalavand et al., 2014). Finally, potable water exchanges heat in the heat exchangers then is collected out of the system.

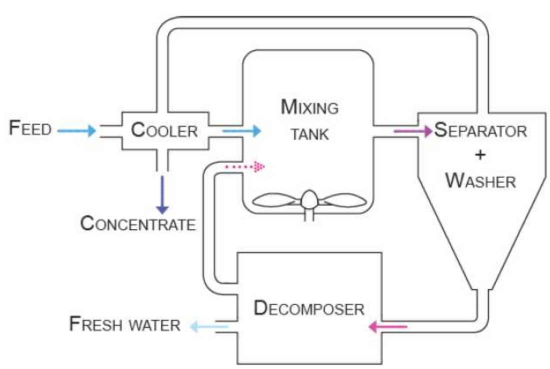


Figure 13. Schematic representation of the hydrates formation process (Galama, 2015)

The desalination process by gas hydrate is based on phase change from liquid to solid with a physical process to separate the solids from the remaining liquid phase (Park et al., 2011). Additionally, the gaseous hydrate former has two roles in the process: it takes part in the hydrate structure; and it acts as direct heat exchange agent.

2.3.3. Desalination by extraction

Desalination by extraction is a process in which a solvent is added to the water phase. There are two ways in which desalination can take place, either the water phase is extracted from the saline water mixture or the ions are extracted from the saline water. Both processes include an extraction step and a separation step where water or ions are separated from the solvent. Extraction of water can be done with certain oils and medium chain fatty acids, which have the ability to dissolve water while rejecting the solutes (like ions) in water. When seawater is contacted with these solvents, two phases are produced; a polymer phase containing dissolved water and an aqueous phase in which the polymer is insoluble. It is important that the solvent does not dissolve in water but only water in the solvent; this is what happens with a so called directional solvent. The directional technology uses directional solvents going through a cyclic process that consists of first forming a saline water-in-solvent emulsion, heating the emulsion so that pure water is dissolved into the solvent, removing the brine-phase, and cooling the solvent to precipitate out pure water (Luo et al., 2011).The water solubility can be increased at higher temperature. Recent research shows that the process works at water temperature not more than 60°C, but the efficiency is increased at higher water temperature (Mauro, 1957; Ray, 1960).

For the process of salt or metal ion extraction so called ionic liquids can be used. Ionic liquids are salts that are in pure form liquid at room temperature. Ionic liquids are composed of large ions, which are held together by their electrostatic interactions (Schlögl, 1955; Anderson and Malone, 1974; Medved and Černý, 2013). By changing the structure of the ionic liquid, it can be made task specific.

3. Combination of Desalination Technologies and Renewable Energy

It is important to know the amount of the conventional energy required by the desalination processes to understand why we need to move toward the renewable and sustainable energy resources. Typically, desalination processes are powered by energy derived from combustion of fossil fuels which contribute to acid rain and climate change by releasing greenhouse gases as well as several other harmful emissions such as carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO2), and sulfur dioxide (SO2). Moreover, high salinity brine containing a considerable amount of chemicals disposal can have serious impacts on marine ecosystem in near-shore environments (Al-mutaz, 1991). In addition, as the limited fossil fuel reserves are being depleted, the need to develop new and alternate energy sources is becoming crucial for energy security and future sustainable development. Desalination processes require large quantities of energy as shown in Table4. Therefore, it is necessary to develop alternatives to replace conventional energy sources used in the desalination process with renewable ones and reduce the energy requirements for desalination by developing innovative low-cost, low-energy technologies (Gude et al., 2010).

Desalination Technologies	Energy Consumption	References
MSF	299	Wagner L. (2007)
	230	Darwish and Al (2000)
MED	152	Dvornikov (2000)
VC	25-43	G. W. (2013)
	14-29	Mandani (2000)
RO	61	Wahlgren (2001).
	27	Darwish and Al (2000)
	14-20	Wilf and Klinko (2001)
	14	Glueckstern (2001)
	18-24	Rautenbach (2001)
ED	0.4-1.8	Demircioğlu (2001)

Table 4. The Energy consumption by different Desalination technologies
(kJ/kg fresh water – divide by 3.6 for kWh/m3) (Miller, 2003)

Renewable energies for use in desalination processes include solar, wind, geothermal, wave and tidal. The renewable energy desalination (RED) systems are witnessing an increasing interest worldwide; more than 130 RED plants have opened within the last few years (Hasan, 2015). Table 3 shows selected RED plants in different countries (Xevgenos et al., 2016).

Desalination plant name	Location	Desalination technology	Capacity (m3/d)	Renewable energy source
Kimolos	Greece	MED	200	Geothermal
Keio University	Japan	MED	100	Solar collectors
PSA	Spain	MED	72	Solar power
Ydriada	Greece	RO	80	Wind turbine
Morocco	Morocco	RO	12-24	Photovoltaics
Oyster	Scotland	RO	n.a	Wave energy

Table 5. Selected RED plants (Xevgenos et al., 2016)

Renewable energies and desalination plants are two different technologies, which can be combined in various ways. In the following diagram different combinations of RE (renewable energy) and desalination technologies are depicted. Not all the combinations of RES-driven desalination systems are considered to be suitable for practical applications. The optimum or just simple specific technology combination must be studied in connection to various local parameters as geographical conditions, the topography of the site, capacity, and type of energy available in low cost, availability of local infrastructures (including electricity grid), plant size and feed water salinity (Mathioulakis et al., 2007).

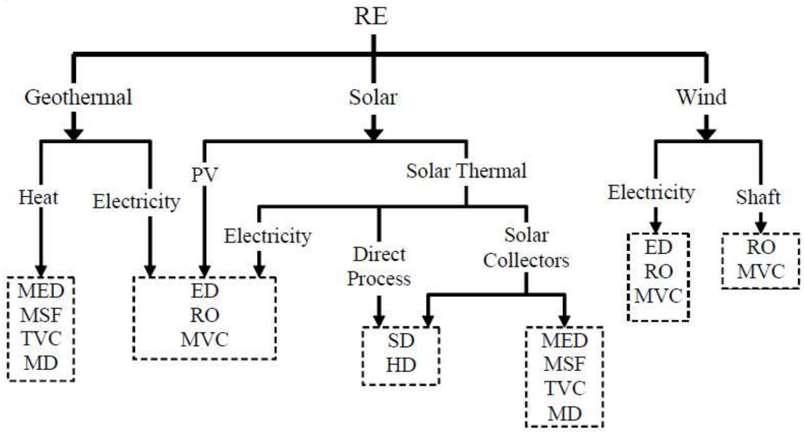


Figure 14. *combination of RE with desalination technologies,* (Eltawil et al., 2009)

3.1. Solar Energy Systems

Solar energy is the oldest energy source ever used and it has the lowest pollution and it is virtually a non-limited supply of all known energy sources. It is one the most resourceful sources of energy for the future. One of the reasons for this is that the total energy we receive each year from the sun is around 35,000 times the total energy used by humankind. However, about 1/3 of this energy is either absorbed by the outer atmosphere or reflected back into space. Several kinds' very practical solar energy systems are in use today (Raluy et al., 2005).

Desalination by way of solar energy is a suitable alternative to small-scale conventional methods to providing freshwater, especially for remote and rural areas where there is no electric grid connection.

Seawater desalination processes are driven by solar energy generally fall into two categories; thermal and electrical (Goosen et al., 2013).

3.1.1. Solar Thermal Energy

Solar thermal energy is one of the most promising applications of renewable energy to seawater desalination. A thermal solar distillation system consists of two main parts the solar collector and the conventional distiller. Solar energy for desalination processes can be used directly when all parts are integrated into one system like solar stills, while the case of indirect processes refers to the heat coming from a separate solar collecting device, usually solar collectors or solar ponds (Kalogirou, 2005; Mathioulakis et al., 2007). Within the category of indirect processes installations based on conventional thermal desalination technology, as MED and MSF, are also included.

Solar still

This technology has been in use for many decades and it is based on the principles of the greenhouse effect. The incident solar radiation is transmitted through the transparent cover and is absorbed as heat by a black surface in contact with the salty water to be distilled. Thus, the water is heated and evaporates partially. Then the water condenses on the cooler glass panels and the condensed droplets run down the

panels in order to collect for use. The average production of the solar still ranges from 4 to 6 l/day (Al-Karaghouli and Kazmerski 2013; Papapetrou et al., 2010).
One of the biggest solar still plants was installed in 1967 on the island of Patmos in Greece. The solar still had an area of 8,640 m² and was desalinating seawater with a production capacity of 26 m³/day. Long lasting solar stills have been built, at current prices, for a unit cost of US $ 50–150 /m².10 The main potential for technical improvements is to be found in reducing the cost of materials. Increased reliability and better performing absorber surfaces would slightly increase production per m² (Papapetrou et al., 2010).
Using solar still systems to provide fresh water becomes a suitable and competitive solution for many remote and rural regions, especially when small quantities of water for human consumption are needed (Al-Karaghouli et al., 2009; Qiblawey and Banat, 2008; El-Sebaii et al., 2012).

Solar collectors

Solar energy collectors are a special kind of heat exchanger that absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the medium. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use at night and/or cloudy days. Then it can be utilized to drive MSF, MED and MD processes (Kalogirou, 2005; Szacsvay et al., 1999).

Solar ponds

Solar ponds combine solar energy collection and the large capacity of long-term (seasonal) thermal storage. Solar ponds are able to store heat due to their unique chemically stratified nature. There are three layers in a solar pond: (1) the upper or surface layer, called the upper convection zone, (2) the middle layer, which is the non-convection zone or salinity gradient zone, and (3) the lower layer, called the storage zone or lower convection zone. Salinity is relatively constant in the upper and lower convection zones, and it increases with depth in the non- convection zone (Al-Karaghouli et al., 2013). In this system, hot brine was pumped from the bottom of the solar pond where salt concentration is highest and passed through a heat exchanger to supply heat. Cold water from the surface of the solar pond was passed through a heat exchanger to provide cooling. High and low temperatures for system operation were obtained by changing the flow rates for solar pond hot and cold water. The large storage capacity of solar ponds can be useful for continuous operation of MED, MSF (Gude et al., 2010).

Solar ponds provide many advantages to power desalination plants, including: the large capacity of heat storage allows solar ponds to power desalination units during cloudy days and nighttime; the waste reject brine from desalination units could be used to build the solar pond; and when the solar pond is used for electricity generation, the rejected heat from the power plant could be used in a thermal desalination plant (Al-Karaghouli et al., 2009).

Photovoltaic

The photovoltaic (PV) process converts sunlight directly into current (DC) electricity by solar cells. A PV cell consists of various thin layers semiconductors. The materials of semiconductors most commonly used are silicon (Si) and compounds of cadmium sulphide (CdS), cuprous sulphide (Cu2S), and gallium arsenide

(GaAs) (Kalogirou, 2005). When the semiconductor such as silicon is exposed to light, electrical charges are generated and this can be conducted away by metal contacts as direct current (DC). The electrical output from a single cell is small, so multiple cells are connected together and encapsulated (usually glass covered) to form a module (also called a 'panel') (Trivedi et al., 2005). PV equipment has no moving parts and as a result, requires minimal maintenance and has a long life (20 to 30 years. It generates electricity without producing emissions of greenhouse or any other gases, and its operation is virtually silent (Goosen et al., 2013; Kalogirou, 2005).

The photovoltaic technology can be connected directly to a RO system, the main problem, however, is the current high cost of PV cells (Kalogirou, 2005). Besides that, the maximum efficiency of the PV modules is reported as 14.5%. A PV-electricity system includes PV arrays, DC inverter, and battery bank. The advantage of employing a battery bank which is an equipment of PV system in the PV–RO system is to provide constant energy flow during night time and to buffer the variations in the electricity production due to passing clouds and rainy days (Keefer et al., 1985).

The other potential combination is between solar photovoltaic (PV) power and reverse-osmosis. This combination has generated growing interest because of the compatibility of reverse osmosis with solar photovoltaic power (Gude et al., 2010).

3.2. Geothermal

Geothermal energy is the thermal energy that is generated and stored comes in the interior of the earth and is related to the geothermal gradient of temperature. The geothermal gradient is the difference in temperature between the core of the planet and its surface and drives a continuous conduction of thermal energy in the form of heat from the core to the surface of the earth, and is contained in natural steam, surface water and groundwater and dry rocks (Dye S.T., 2012).

Geothermal power is cost-effective, reliable, sustainable, and environmentally friendly (*Glassley, William E. 2010)* but has historically been limited to areas near tectonic plate boundaries. Geothermal wells release greenhouse gases trapped deep within the earth, but these emissions are much lower per energy unit than those of fossil fuels.

The use of geothermal energy for thermal desalination can be justified only in the presence of cheap geothermal reservoirs or in decentralized applications focusing on small-scale water supplies in coastal regions (Goosen M. et al , 2010).

Desalination plants may be run with geothermal energy used directly to heat the saline or brackish water in multiple effect distillation units and/or it could be used indirectly to generate electricity for operating reverse osmosis units (Kalogirou S. , 2005). Ophir A. (1982) presented an economic study of desalination powered by a geothermal resource of 110–130 °C. Another technical and economic study was conducted by Karytsas C. (1996) to analyze the feasibility of using geothermal resources between 75 and 90 °C to power a multiple effect boiling system (MEB). Furthermore, with membrane distillation technology, the utilization of direct geothermal brine with temperature up to 60 °C has shown a promising option (Goosen M. et al 2010).

At the following diagram a Process schematic for an example of Brackish Water Greenhouse coupled to geothermal system is presented by Mahmoudi H. et al (2010) as referred in the work of Goosen M. et al (2010). Greenhouse cover is plastic sheeting and the feed water to the pump is either brackish groundwater or sea water from a beach well:

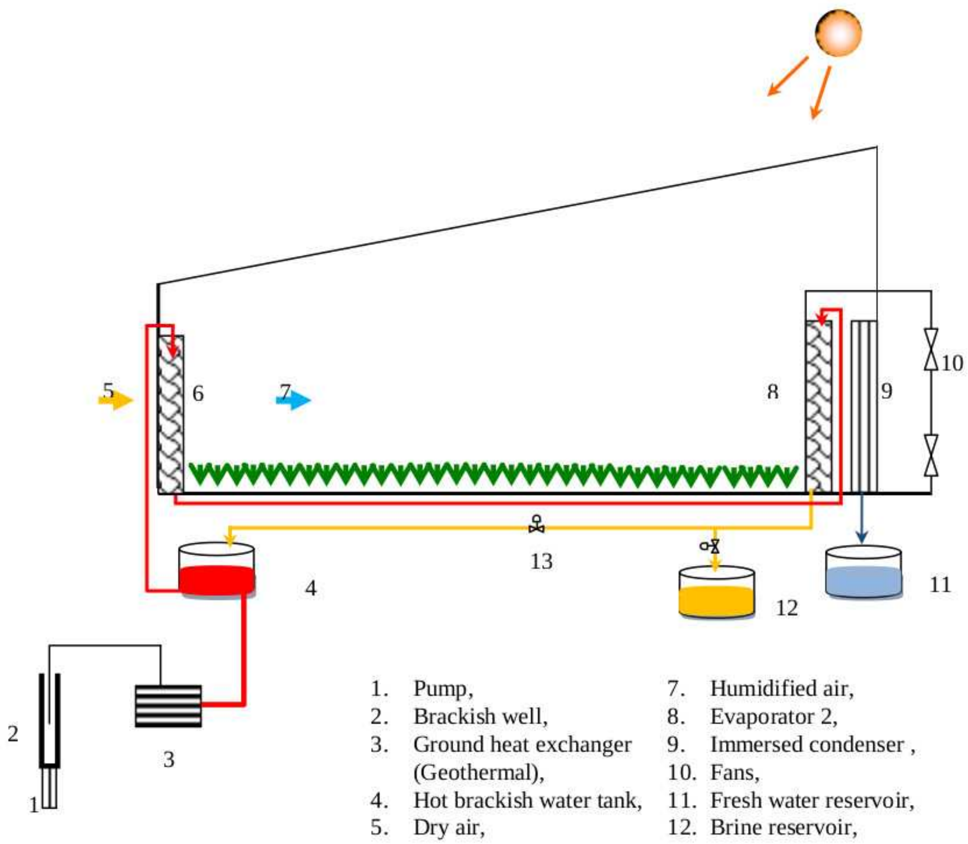


Figure 15. Brackish Water Greenhouse coupled to geothermal system Source: Goosen M. et al (2010)

In the work of Mahmoudi H. et al (2008) as referred on the review of Goosen M. et al (2010) is mentionned that 2004 Seawater Greenhouse Ltd in collaboration with Sultan Qaboos University built a new pilot Seawater Greenhouse near Muscat, Oman presented in the following picture:

Figure 16, Source: Goosen M. et al (2010)

According to Karytsas et al (2004) referred by Goosen M. (2010), Milos Island is located in the Aegean Volcanic Arc and is characterized by abundant geothermal resources (Goosen M. 2010 , Karytsas et al 2004, Νάνου Μάρθα 2010). the Institute of Geological and Mining Research of Greece indicated that the plain of Zefyria at the eastern part of the island was the region with the highest temperature gradients, suitable for high enthalpy geothermal potential. Later drilling identified geothermal fluids of temperature 300–323 °C at depths 800–1,400 m below sea level. Karytsas et al (2010) found that the eastern half of the island was suitable for exploitation of shallow, low enthalpy (<100 °C) geothermal resources. The deep geothermal fluids corresponded to boiled seawater of 80,000 ppm salinity.The upper 2 km of the hot rocks below Zefyria could support a 260 Mwe geothermal power plant.

Milos Island dual system desalination unit produces 80 m^3/h of drinking water and comprises a 470 kWe power generator unit. Hot water from the deep geothermal wells is employed to run organic Rankine cycle (ORC) turbines for electricity generation and is also used directly in a multiple effect distillation unit (MED). In organic Rankine cycle (ORC) the working fluid pumped to a boiler to evaporate, passes through a turbine electricity generation and is finally re-condensed. MED is a boiling process that consists of multiple stages. In each stage the feed water is heated by steam in tubes. Some of the water evaporates (pure water), and this steam flows into the tubes of the next stage, heating and evaporating more water. Each stage uses the previous stage' s energy. The tubes can be submerged in the feed water, but more typically the colder salty feed water is sprayed on the top of a bank of horizontal hot tubes (containing the pure water vapor). The vapor inside the tubes then condenses and drips from tube to tube until it is collected at the bottom of the stage (Goosen M. et al, 2010).

The geothermal power and desalination plant of Milos consisted of the following components:

- Geothermal submersible pumps and inverters installed at the production wells.
- Piping network conveying the geothermal water to the main Plant.
- Organic Rankine Cycle (ORC) unit, transforming approximately 7% of geothermal energy to electricity designed to generate approximately 470 kWe.
- Multi Effect Distillation-Thermal Vapor Compression (MED-TVC) seawater desalination unit providing 75–80 m3/h desalinated water.
- Main heat exchanger, transferring the energy from the hot geothermal water exiting the ORC unit to the MED-TVC desalination unit.

- Reinjection wells (RE I and II) located at the margin of the geothermal field, close to the coast, downstream and at lower elevation of the main Plant.
- Geothermal water transmission lines from main heat exchanger to reinjection wells.
- Seawater transmission lines conveying 1,000 m3/h cooling seawater to the MED-TVC unit plus 200–575 m3/h cooling water for the ORC unit.
- Desalinated water transmission line from plant to water tanks near adjacent town.
- Power substation for power provision or delivery to the local power net: 500 kWe.
- Main computer monitoring and control system for real time data logging and automation control.

Comparison of CO_2, SO_2, H_2S emissions and fresh water usage from electricity generation (MWh) from different energy sources adapted in part from Fridleifsson, et al:

Energy Source	Coal	Oil (& Gas)	Geothermal
CO_2 (Kg/MWh)	994	893 (599)	40–120
SO_2 (Kg/MWh)	4.71		0.16
H_2S (Kg/MWh)		814 (550)	0.08
Amount fresh water used (L/MWh)	1,370	1,170	20

Table 6. Comparison of CO_2, SO_2, H_2S emissions

3.3. Wind

Wind energy, a kinematic form of renewable energy, is one of the most frequent renewable energies combined with desalination systems, and has the least impact on the environment among the various renewable energy resources. Thus, in high wind-potential areas where desalination is also required, wind energy is preferred.

The wind energy can be transformed to electricity, thermal energy, and gravitational potential energy, etc. first and then these medium energy forms are used to power. However, the extra energy conversion would lead to more energy loss, and decrease the usage ratio of wind energy. Thus several efforts have been made to directly couple the kinematical power from wind turbines with desalination units such as Projects AERODESA I and AERODESA II of Canary Islands Technological Institute, the brackish water desalination wind-powered RO plant built in Coconut Island, and the Wind DeSalter Technology proposed by Witte et al., and the direct use of wind energy have been proved with higher efficiency.

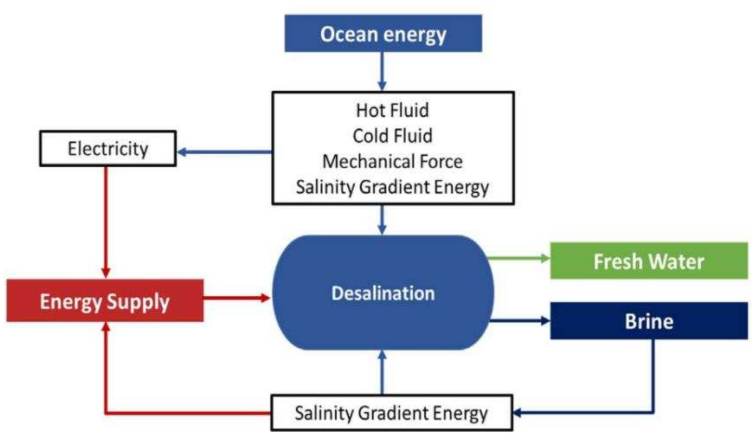
As to the desalination technologies combined with wind energy, RO is the most popular one. Wind-powered RO systems make up approximately 19% of total renewable energy source desalination facilities, and several feasible and economic analyses, prototypes and experiments were reported worldwide. However, RO is not always the appropriate one. For the remote areas which are short of fresh water but abundant of wind energy and seawater, more robust, easily operated wind powered desalination system should be explored. Considering environment protection, the system needs to discharge fewer chemicals and offer high quality fresh water but not the proper water from RO unit. Thus, in the long term, thermal desalination units directly powered by wind power are more attractive due to their little impact on environment, high quality of treated water and energy saving feature.

Mechanical vapor compression (MVC) is the major thermal desalination process integrated with wind. Due to the higher operation temperature (compared to the seawater temperature), additional heat source is always necessary. In the single wind powered desalination systems, the transformation of wind energy to heat must reduce the energy utilizing efficiency. Therefore, if the wind powered desalination unit can operate at lower temperature, eliminating the transformation from wind energy to heat, the desalination cost and energy utilizing efficiency might be improved.

Various small wind-based desalination plants have been installed around the world. As with solar energy, a drawback of wind desalination is the intermittence of the energy source. Possible combinations with other renewable energy sources, batteries or other energy storage systems can provide smoother operating conditions.

3.4. Ocean Power

The co-location benefit of ocean-based power generation for desalination systems is being investigated by scientist from around the world. As is known in the literature, oceans have several types of energy: tides, and waves, thermal gradient, saline gradient, (Z. Li et al, 2018). There is great potential of ocean energy for seawater (SW) desalination in terms of diverse energy forms, flexible integration methods and various deployment strategies.



Integration of ocean energy in seawater desalination.

Figure 17: OWC system for seawater desalination at Vizhinjam in India. Sharmila N, Jalihal P, Swamy AK, Ravindran M. Wave powered desalination system. Energy 2004;29:1659–72.

3.4.1. Tides and Wave

One of the most obvious combinations for RE –desalination is wave power coupled with desalination because, in most cases, the two main components of (wave) energy and (sea) water are available in abundance and at the same location (Papapetrou et al., 2010). Most of the work on wave energy conversion has focused on electricity production (Davies, 2005); any such converter could, in principle, be coupled to an electrically-driven desalination plant, either with or without connection to the local electricity grid.

Wave-powered technology to produce electricity has an experimental history of at least 30 years. The first reported wave powered technology was the DELBUOY, which used oscillating buoys to drive piston pumps anchored to the seabed and the unit produced an average of 2 m3/day (Gude et al., 2010). All of the wave-powered desalination plants built as prototypes up to now use reverse osmosis for the desalination process (Folley et al., 2008). The reverse osmosis plants are powered either by electricity generated by a wave energy plant or directly by using sea-water pressurized by the action of the waves. The current wave-powered desalination technologies are based on modifications of wave energy technologies designed for electricity production. Therefore, they are typically relatively large with unit capacities in the range of 500–5,000 m^3/day. Developers of wave-powered desalination technology currently include:

• A quamarine Power Ltd - Oyster® desalinator technology

• C arnegie Corporation Ltd – CETO desalinator technology

• O ceanlinx Ltd – OWC desalinator technology

All three of these technologies are based on the direct pressurization of sea water (avoiding the generation of electricity) that is then fed into a reverse osmosis desalination plant to produce fresh water (Papapetrou et al., 2010).

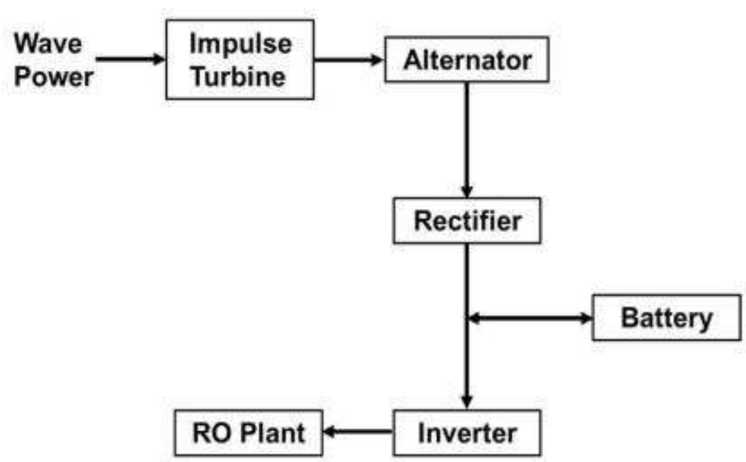


Figure 18: OWC system for seawater desalination at Vizhinjam in India. Sharmila N, Jalihal P, Swamy AK, Ravindran M. Wave powered desalination system. Energy 2004;29:1659–72.

Countries with large populations and long ocean shorelines have great potential in generating energy which can be used for desalination (Goosen et al., 2013). For this reason, the research about wave energy systems started in countries surrounded by oceans, due to their higher energy potential. An example of a desalination pilot plant (DPP) based on wave source is currently installed on Garden Island, in the Western part of Australia. This system uses several buoys in order to exploit the sea wave energy to pump the seawater into a RO desalination plant producing fresh water, with a production capacity of about 150 m3/day (Franzitta et al., 2016; Viola et al., 2016).

3.4.2. Thermal Gradient

Ocean thermal energy can be harvested by ocean thermal energy conversion (OTEC) cycle where warm seawater (30–32 °C) on the top is utilized as the heating source and cold seawater (4–6 °C) at a depth of 1000 m is the cooling source to drive a heat engine cycle and generate power (Finney KA 2008, Kim NJ 2009).

The plant could be land-based or located in floating platforms and operated by close-cycle using a working fluid (usually Ammonia) with warm and cold seawater, open-cycle using warm and cold seawater only, or hybrid cycles. The hybrid cycle OTEC combines a close-cycle (first stage) for power generation and an open-cycle (second stage) for desalination. For every megawatt of power generated by a hybrid OTEC plant, nearly 2.28 million litres of desalinated water can be produced per day.

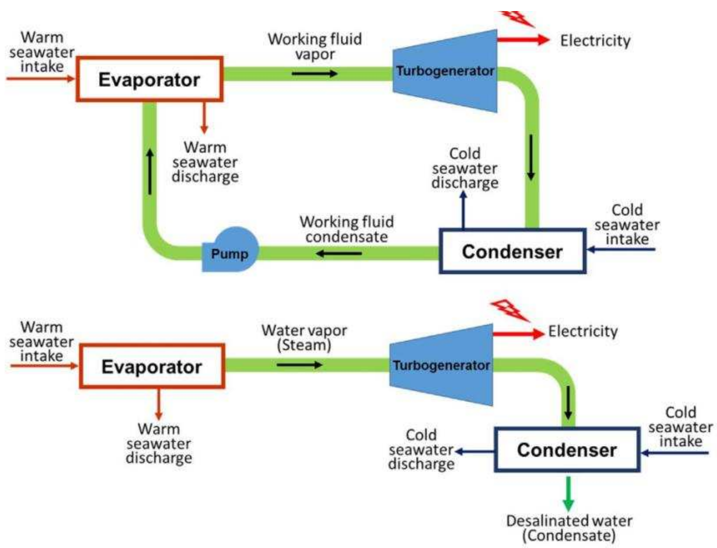


Figure 19: Schematic diagram of OTEC and integrated seawater de-salination processes (upper, close-cycle; lower, open-cycle usingseawater), Z.Li et al (2018)

3.4.3. Saline Gradient

Ocean chemical energy derives from the salinity gradient between saline water (e.g., seawater, con centrated brine) and fresh water (e.g., river water, municipal waste- water). Forward Osmosis (FO), pressure retarded osmosis (PRO) and reverse electrodialysis (RED) using ocean salinity gradient energy have been demonstrated at pilot scale (Z.Li et al).

Ocean salinity gradient energy is the most promising ocean energy in the near term for large-scale desalination because the relevant devices (e.g. PRO, FO and RED) can be fully integrated into the current desalination technologies, with no additional environmental and social risks. The modular design of ocean salinity gradient energy device, based on membrane technology, can allow for easy scale up. The utilization of other ocean energy systems for desalination is being developed, and progress is being made by large original equipment manufacturers (OEMs) around the world including Alstom, Andritz Hydro, DCNS, Hyundai Heavy Industries, Kawasaki Heavy Industries, Lockheed Martin, Siemens, and Voith Hydro (Li 2018).

As a conclusion, ocean-based power technologies present several advantages, including the availability of a more regular production compared to wind, the absence of soil consumption for energy converter installation, and the great energy potential, especially on small islands (Franzitta et al., 2016). But the harnessing of ocean energy is, as with other forms of renewable energy, expensive in terms of capital plant and the effort needed to develop the technology. It may well require the intervention of governments or international bodies. The failure to exploit the wave resource probably stems from the fact that the nations having the most abundant wave resources, such as the UK and Norway, have also been endowed with their own indigenous resources of oil and hydroelectricity. This has given them limited incentive to develop and exploit novel renewable technologies (Gude et al., 2010).

4. Comparison of the most common processes

Process	Pros	Cons
RO	• Lower energy consumption • Relatively lower investment cost • No cooling water flow • Simple operation and fast start-up • High space/production capacity • Removal of contaminants other than salts achieved • Modular design Maintenance does not require entire plant to shutdown	• Higher costs for chemical and membrane replacement • Vulnerable to feed water quality changes • Adequate pre-treatment a necessity • Membranes susceptible to biofouling • Mechanical failures due to high pressure operation possible • Appropriately trained and qualified personnel recommended • Minimum membrane life expectancy around 5–7 years
ED/EDR	• Energy usage proportional to salts removed not volume treated • Higher membrane life of 7–10 years • Operational at low to moderate pressures	• Only suitable for feed water up to 12,000 mg/L TDS • Periodic cleaning of membranes required • Leaks may occur in membrane stacks • Bacterial contaminants not removed by system and post-treatment required for potable water use
MSF	• Lends itself to large capacity designs	• Large capital investment required

	Advantages	Disadvantages
	• Proven, reliable technology with long operating life • Flashing rather than boiling reduces incidence of scaling • Minimal pre-treatment of feed water required • High quality product water • Plant process and cost independent of salinity level • Heat energy can be sourced by combining with power generation	• Energy intensive process • Larger footprint required (land and material) • Corrosion problems if materials of lesser quality used • Slow start-up rates • Maintenance requires entire plant to shut-down • High level of technical knowledge required • Recovery ratio low
MED	• Large economies of scale • Minimal pre-treatment of feed water required • Very reliable process with minimal requirements for operational staff • Tolerates normal levels of suspended and biological matter • Heat energy can be sourced by combining with power generation • Very high quality product water	• High energy consumption • High capital and operational cost • High quality materials required as process is susceptible • to corrosion • Product water requires cooling and blending prior • to being used for potable water needs
VCD	• Developed process with low consumption of chemicals • economic with high salinity (>50,000 mg/L) • Smaller economies of scale (up to 10,000 m3/d) • Relatively low energy demand • Lower temperature requirements reduce potential of scale and corrosion • Lower capital and operating costs • Portable designs allow flexibility	• Start-up require auxiliary heating source to generate vapour • Limited to smaller sized plants • Compressor needs higher levels of maintenance

Table 7 : Technologies' comparison

5. The situation in Greece

In Greece, and particularly in several south-eastern regions, there is a very low water availability, which is exacerbated by the high water demand of water for tourism and irrigation in summertime. Therefore, the integration of desalinated water, treated wastewater and other marginal waters into water resources management master plants is of paramount importance to meet future water demands. The problem seems to be more evident in the Aegean islands (particularly the Dodecanese and Cyclades), Thessaly in Central Hellas, the eastern Continental Hellas (Sterea Hellas), the eastern Crete and the southeastern Peloponnese.

In Hellas there are many desalination plants, especially in southeaster Water Supply and Sewerage Municipalities and big Hotels. Many desalination plants have been installed on islands, using the RO technology. Apart from the desalination plants which are owned by public enterprises, there is in operation a number of private plants, most of which are owned by hotels. A significant number of desalination plants are currently under construction or under planning.

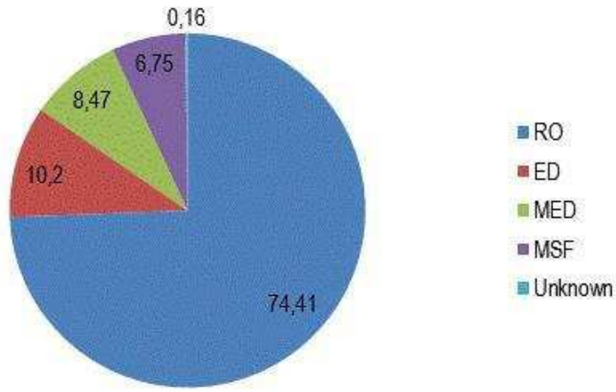


Fig 20. Desalinated water production according to the used technology, in Greece
Source: Zotalis K. et al Water 6(5):1134-1150 · May 2014

As, it is evident from the figure above, RO is the most popular desalinating technology in Hellas, since it produces the 74.41% of the desalinated water. ED is used for the desalination of the 10.20% of the total desalinated water produced, MED is used for the 8.47% of the produced water and MSF is used for the 6.75%.

6. Discussion

A number of seawater desalination technologies have been introduced successfully during the last several decades to augment the water supplies in arid regions of the world. Due to the constraint of high desalination costs, many countries are unable to afford these technologies as a fresh water resource. Nevertheless, the adoption of seawater desalination technologies by some countries has demonstrated that seawater desalination certainly offers a new water resource free from variations in rainfall. Although the desalination technologies are mature enough to be a reliable source of fresh water from the sea, presently active research and development work is being performed by several institutions in order to constantly improve the technologies and reduce the cost of desalination. Taking into consideration the importance of and promising potentials for desalination in the future in many countries, long term multidisciplinary and integrated research and development programs are needed for the purpose of making the seawater desalination techniques affordable worldwide. Such comprehensive and collective research and development programs would be required to develop in collaboration with the governments, industries, universities, and research institutions.

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