Open University of Cyprus

Faculty of Pure and Applied Sciences

Master Program *Sustainable Energy Systems*

SES 701B

Seawater Desalination with Renewable Energy Sources

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Summary

The aim of this Capstone project is to study desalination technologies and the possibility to combine them with Renewable Energy Sources. The first part of the project is a literature review of the most advanced desalination technologies, the need for desalination and their combination with RES. The second part is an analysis of Reverse Osmosis systems. The third part is a case study of a small Reverse Osmosis plant powered by photovoltaics in the island of Iraklia, Greece. The last part includes the conclusions and a discussion about further research on the subject.

Thank you notes

As this journey reach to its end, in my third and final Capstone project, I would like to thank all the professors of this Master Project that have passed on me some of their knowledge and introduced me the world of Sustainable Energy.

A special thank you note to my supervisor and Academic Coordinator, Paris Fokaides, who was always available for me and my colleagues for every problem we would face during our studies.

Finally, a last thank you, to my colleagues and family, that have stood by me during this effort.

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Introduction

Water plays an important role to everyday life and its consumption is constantly increasing due to increased living standards of mankind. A lot of regions worldwide suffer from water scarcity and many more of water pollution.

The increasing demand of water can be satisfied by using desalination technologies to produce fresh water. Desalination has a long history, and following the technological developments, a lot of desalination methods have been developed.

Unfortunately, the desalination industry has shown increased greenhouse gas emissions and environmental impacts, mostly due to the high energy needs and the use of conventional energy sources.

Desalination industry can be made sustainable if they are integrated with renewable energy sources. Different desalination units, regarding the technology they use, can be efficiently combined with different renewable energy sources, with the best combination depending on the specific installation.

Chapter 1
Literature review

1.1 Water scarcity

Without water there would be no life and humans have, since the start of times, organized their lives around sources of fresh water. Throughout history, water has been the essential element for economic and social developments and for the stability of cultures and civilization. Rivers, lakes, underground reservoirs and wells have provided man water for domestic use, agriculture and industry.

Unfortunately, overpopulation, technology growth and different life standards have resulted in a large escalation of demand for fresh water in parallel with the pollution of rivers and lakes by large amounts of waste.

Water covers the 70% of our planet but only 3% is fresh water, and two-thirds of that is hard to access.

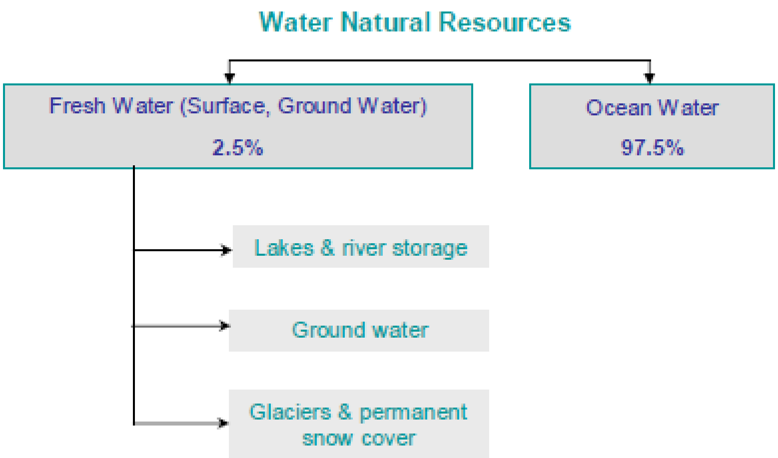

Figure 1: Water natural resources distribution [1]

Water scarcity is the lack of fresh water resources to meet water demand. Water scarcity can mean scarcity in availability, due to physical shortage, or scarcity in access, due to the failure of institutions to ensure a regular supply or due to a lack of infrastructure. It is expressed by partial or no satisfaction of water demand, economic competition for water, depletion of groundwater and environmental impacts.

Almost one-fifth of the world's population, live in areas of scarcity and another one quarter of the world's population face economic shortage. Nearly half the global population live in potential water scarce areas, at least one month per year, and this could increase to 5.7 billion by 2050. About 73% of them live in Asia [2].

The first step to deal with water stress and scarcity is for the governments to apply water conservation measures and understand that decoupling water use from economic growth is possible. Most governments tend into investing in inefficient solution, like dams, canals, aqueducts, pipelines and water reservoirs, which are generally neither environmentally sustainable nor economically viable [3].

1.1.1 Water scarcity in Greece

In some southeastern regions of Greece there is a very low water availability, which is worse in summertime due to the high water demand for tourism and irrigation. In central Greece there is a high water demand for agricultural irrigation, while on the islands there is a high water demand for potable water, especially in summer.

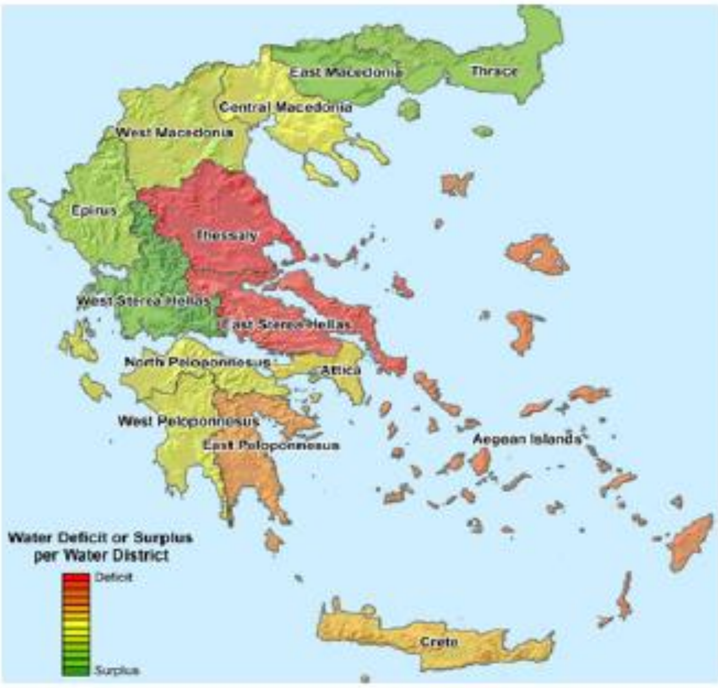

Figure 2: Water availability per district in Greece [4]

Water scarcity is a permanent problem in Greek islands, especially in Kyklades and Dodekannisa. Greek islands are dry rocky formations with limited precipitation during the year and a lot of them are tourist attractions, fact that makes the problem worse in the summer. Although some islands can satisfy the water demand during winter, the water quality is not as good as that of the mainland.

The Greek government deals with the problem mostly with water transportation from the mainland by tanker ships, with the cost of water reaching 10€/m^3 and a great environmental burden due to ship emissions. Table 1 shows the quantity and cost of the water transferred to Greek islands for a period of ten years. A part of the water demand in Greek islands is covered by public or private drillings, seawater desalination or even the collection of precipitation water.

	Cyclades islands			Dodecanese islands			Total	
YEAR	**Quantity m3/year**	**Cost €/year**	**Specific Cost €/year**	**Quantity m3/year**	**Cost €/year**	**Specific Cost €/year**	**Quantity m3/year**	**Cost €/year**
2000	145.000	1158000	7.99	555000	2.004.000	3.61	700000	3162000
2001	202.000	1625000	8.04	621000	2.722.000	4.38	823000	4347000
2002	329.343	2561178	7.78	617745	3.109.358,65	5.03	947088	5670637
2003	336.777	2772718	8.23	605019	3.214.680,89	5.31	941796	5987398
2004	338.812	2787235	8.23	759737	4.034.203,29	5.31	1098549	6821438
2005	464.562	4006916	8.63	969676	5.082.935,63	5.24	1434238	9089852
2006	567.719	4677686	8.24	1005338	4.905.044,06	4.88	1573057	9582730
2007	697.117	5802509	8.32	1101628	5.403.900,34	4.91	1798745	11206409
2008	687.731	5721921	8.32	1141724	5.765.706,20	5.05	1829455	11487628
2009	429.075	3569904	8.32	826910	4.175.895,50	5.05	1255985	7745799
2010*	429.075	2590291	9.84	340426	3.349.791,84	9.84	603667	5940083
TOTAL	**4.627.211**	**37.273.358**		**8.544.203**	**39.041.516**		**13.005.580**	**81.040.974**

Table 1: Water transfer to Greek Islands [1].

1.2 Desalination

Desalination is the process of removing dissolved salts from water, thus producing fresh water from seawater or brackish water. The most common use of desalination technology is the production of potable water from saline water for domestic or municipal purposes.

Water Source	**Approximate Salt Concentration (mg/lt)**
Brackish water	>1000, high brackish up to 11.000
Seawater	~35.000
Atlantic Ocean	35.000
Pacific Ocean	38.000
Persian Golf	45.000
Dead sea	~300.000

Table 2: Water classification [1]

The only inexhaustible sources of water are the oceans, with main drawback their high salinity. According to World Health Organization (WHO), the permissible limit of salinity for potable water is 500ppm, while seawater has salinity in the range of 35000-45000ppm in the form of dissolved salts, as shown in Table 3.

WHO Standards for drinking Water	**Contents in mg/l**	
	min acceptable	**max permissible**
Total dissolved solids, TDS	500	1500
Cl	200	600
SO_4^{2+}	200	400
Ca^{2+}	75	100
Mg^{2+}	30	150
F^-	0.7	1.7
NO_3^-	<50	100
Cu^{2+}	0.05	1.5
Fe^{3+}	0.10	1.0
NaCl	250	-
pH	7.0-8.5	6.5-9.2

Table 3: Fresh water composition [3]

Salinity of seawater depends on the specific region of the word, but the percentage composition of seawater is constant, as shown in Table 4 [3].

Chemical Ion	Concentration ppm, mg/kg	Part of salinity %	mmol/kg
Chloride Cl^{-}	19345	55.03	546
Sodium Na^{+}	10752	30.59	468
Sulfate SO_4^{2-}	2701	7.68	28.1
Magnesium Mg^{2+}	1295	3.68	53.3
Calcium Ca^{2+}	416	1.18	10.4
Potassium K^{+}	390	1.11	9.97
Bicarbonate HCO_3^{-}	145	0.41	2.34
Bromide Br^{-}	66	0.19	0.83
Borate BO_3^{3-}	27	0.08	0.46
Strontium Sr^{2+}	13	0.04	0.091
Fluoride F^{-}	1	0.003	0.068

Table 4: Seawater composition [3]

The purpose of a desalination system is to purify brackish water or seawater and give product water with Total Dissolved Solids (TDS) within the permissible limits. This is accomplished by several desalination methods, regarding a lot of factors, as the feedwater quality, the product water quantity, the specific site, etc.

1.2.1 Desalination history

As early as in the fourth century BC, Aristotle described a method to evaporate non-potable water and condense it into potable liquid.

Historically, probably the first application of seawater desalination was by sailors, as the need to develop fresh water onboard emerged by the long trips. Alexander of Aphrodisias in 200AD described a technique where seawater was boiled to produce steam and the steam was absorbed by sponges, producing potable water [5].

Since then, the technology of seawater desalination evolved rapidly and has become quite popular. The first big industrial desalination plants were built in the beginning of the 20th Century, the first probably in Egypt with 6 stages Multiple Effects Evaporator and capacity 75m^3/day (Tzen, E., CRES) [1].

The renewal of interest on solar distillation occurred after the first World War, when new devices have been developed. Interest grew stronger during the second World War, when allied troops suffered from lack of drinking water.

An increase in desalination industry followed the petroleum industry growth, as many thermal plants were built to satisfy the growing water demand, giving a large amount of thermal energy in low cost.

In the same period, membrane processes, such as Reverse Osmosis and Electrodialysis became more common. By the ‘80s, desalination technologies became commercial.

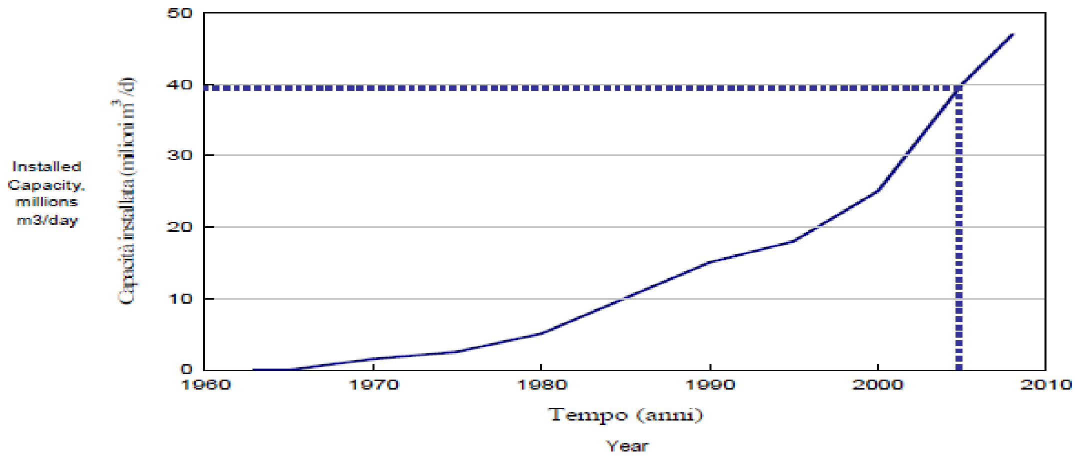

Figure 3: The development of desalination (Tzen,E., CRES) [3]

1.2.2 Desalination methods

There are three broad categories of desalination technologies: thermal processes or phase-changing, membrane processes and chemical processes. Recently, also adsorption technology has been investigated for desalination application.

Thermal processes use heat to evaporate and condensate the feedwater, to separate the salts. In these systems the heat transfer is used to boil or freeze the seawater to convert it to vapor or ice, so the salts are separated from the water. These processes include Multi-stage flash (MSF), Multiple effect boiling (MEB) or Multi Effect Distillation (MED), Vapor compression (VC), Solar Distillation (SD), Humidification-Dehumidification (HDH) and Freezing (Fr).

Membrane processes are systems that use permeable membranes to create two zones where water can pass through, leaving salt behind. These processes include Reverse osmosis (RO), Electrodialysis (ED), Nanofiltration (NF) and Forward Osmosis (FO).

Chemical processes include Ion-Exchange (I.Ex), Liquid-liquid extraction (LLE) and Gas Hydrate (G. Hyd). Generally, it is found that chemical approaches are too expensive to apply to the production of fresh water [6].

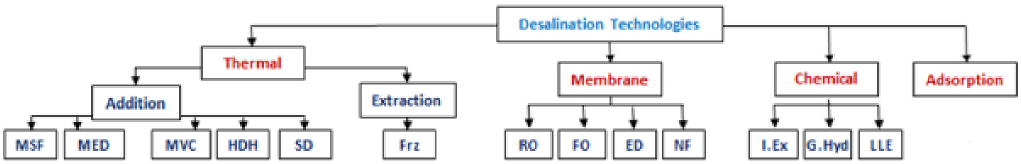

Figure 4: Classification of desalination technologies [6]

The most technologically advanced and commercial desalination technologies include thermal and membrane processes and are discussed further. The processes require a chemical pre-treatment of seawater to avoid scaling, foaming, corrosion, biological growth and fouling, and they require a chemical post-treatment to make the water usable.

Thermal processes

Thermal desalination involves distillation processes where saline feedwater is heated to vaporize, causing fresh water to evaporate and leave behind a highly saline solution, the brine.

Distillation processes were the first desalination processes to be conducted on a large commercial scale and account for a large portion of the world's desalination capacity.

The operating principle of these processes entails reusing the latent heat of evaporation to preheat the feed while, at the same time, condensing steam to produce fresh water.

In addition to the thermal component, phase-changing processes often include vacuum components to increase evaporation at lower temperatures.

The energy requirements of phase-changing systems are defined in units of distillate produced per unit mass of steam or per 2326kJ, which corresponds to the latent heat of vaporization at 73^{o}C (Performance Ratio, kg/2326kJ).

A performance ratio often applied to thermal desalination processes is the Gained Output Ratio (G.O.R.), defined as the mass of water product per mass of heating steam.

The thermal energy required to heat the water may be obtained from a conventional fossil-fuel source, nuclear energy or from a non-conventional solar energy source or geothermal energy.

1. Multi Stage Flash distillation (MSF)

MSF distillation is based on the generation of vapor from seawater or brine due to a sudden pressure reduction when seawater enters an evacuated chamber.

It involves evaporation and condensation steps that are coupled so that the latent heat of evaporation is recovered by preheating the feedwater. By fractioning the temperature differential between the heat source and feedwater to a number of stages, the system approaches ideal total latent heat recovery. To maximize water recovery, the process is repeated in multiple stages where the pressure is always decreasing.

MSF requires an external steam supply at temperature around 100°C and the maximum temperature is limited by the salt concentration to avoid scaling. The current commercial applications are designed with 10-30 stages with a 2°C temperature drop per stage.

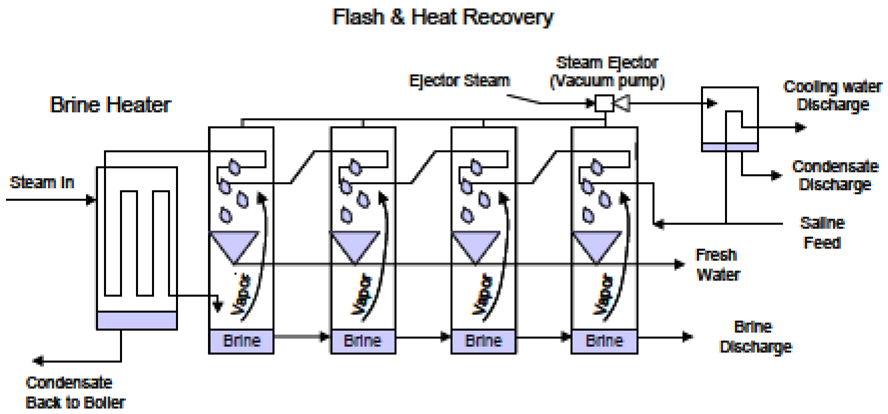

Figure 5: Schematic of Multi Stage Flash desalination process [7]

As seen in Figure 5, when the seawater is heated and discharged into a chamber maintained at slightly below the saturation vapor pressure of the water, a fraction of the water flashes into steam. The steam condenses on the exterior surface of the heat-exchanger tube. The condensed liquid drips into trays and the rest feedwater repeats the procedure in the next stage.

In MSF, bulk liquid boiling alleviates problems with scale formation on heat transfer tubes. A disadvantage of the process is the precise pressure levels required at each stage, which requires time to establish the normal operation of the plant. This makes the process not so suitable for solar applications, unless a storage tank is used for thermal buffering. Large MSF plants are often coupled with steam or gas turbine power plants for better utilization of the fuel energy.

MSF is the most widely used desalination process in terms of capacity, due to the simplicity of the process, performance characteristics and scale control. MSF units are widely used in the Middle east and they account for over 40% of the world's desalination capacity [7].

Typical characteristics of an MSF unit are shown in Table 5.

Multi Stage Flash desalination unit	
Typical unit size	50000 to 70000m^3/day
Top brine temperature	90°C to 110°C
Typical G.O.R.	6 to 8
Electrical energy consumption	4 to 6 kWh/m^3
Thermal energy	190kJ/kg to 390kJ/kg
Electrical eq. for thermal energy	13.5 to 25.5kWh/m^3
Total eq. energy consumption	13.5 to 25.5kWh/m^3

Table 5: Typical characteristics of an MSF unit [8]

2. Multiple Effect Distillation

MED unit consists of vessels, called effects, maintained at successively lower pressure, where the saline feed is sprayed.

On MED units the vapors are generated due to the absorption of thermal energy by seawater. As shown in Figure 6, the steam generated in one effect heats the salt solution in the next effect due to the pressure and temperature drop. The solutions condensed by all effects are used to preheat the feed.

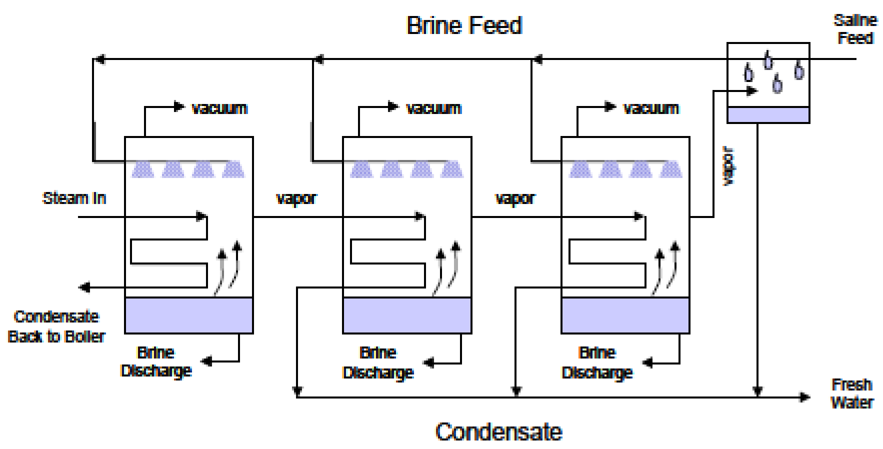

Figure 6: Schematic of a Multi Effect Distillation plant [7]

The process operates as a once through system without a large mass of brine recirculating around the plant. This reduces pumping requirements and scaling probability.

The MED plant can be configured for a high temperature (>90°C) and a low temperature (<90°C) operation. The top boiling temperature of the plant can be even 55°C, which helps reduce the possibility of corrosion and scaling.

There are many possible variations of MEB plants, depending on heat transfer configurations (vertical climbing film tube, rising film vertical tube or horizontal tube falling film) and flowsheets arrangements used (brine flow relative to the vapor flow) and they hey can be combined with heat input between the stages from a variety of sources, like Vapor Compression units [5].

Compared with MSF, MED depends on smooth evaporation of the water, rather than flash boiling. MED is not widely used, but it is gaining attention due to the better thermal performance compared to MSF and its better cooperation with solar thermal desalination. Typical characteristics of an MED unit are shown in Table 6.

Multi Effect Distillation desalination unit	
Typical unit size	5000 to 15000m^3/day
Top brine temperature	66°C to 72°C
Typical G.O.R.	8 to 12
Electrical energy consumption	1.5 to 2.5 kWh/m^3
Thermal energy	230kJ/kg to 390kJ/kg
Electrical eq. for thermal energy	5 to 8.5 kWh/m^3
Total eq. energy consumption	6.5 to 11 kWh/m^3

Table 6: Characteristics of MED unit [8]

3. Vapor Compression Distillation

In a VC plant, heat recovery is based on raising the pressure of the steam from a stage, by means of a compressor.

The feed saline water, heated by an external source, flashes, producing vapors that are compressed using Mechanical Vapor Compressor (MVC) or Thermo Vapor Compressor (TVC) to raise the condensation pressure and temperature of the vapor. The compressed vapor is then used to heat the same stage or feedwater of other stages, as shown in Figure 7.

MVC systems generally have only a single stage, as the specific power consumption is the same regardless the number of stages, while TVC systems have several stages, as the thermal efficiency of TVC systems is increased by adding stages.

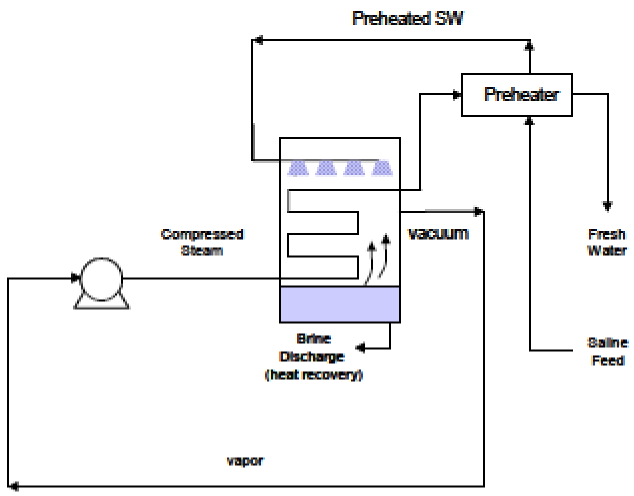

Figure 7: Schematic of Vapor Compression desalination [7]

Process designs show that this type of plant is not particularly convenient, unless it is combined with an MED plant [5].

Typical characteristics of a VC plant are shown in Table 7.

Vapor Compression Distillation desalination unit	
MVC Typical unit size	100 to 3000m^3/day
MVC Top brine temperature	74^{o}C
MVC Total eq. energy consumption	11 kWh/m^3
TVC Typical unit size	10000 to 35000m^3/day
TVC Top brine temperature	70^{o}C
TVC Typical G.O.R.	12
TVC Electrical energy consumption	1.8 kWh/m^3
TVC Thermal energy	187kJ/kg
TVC Electrical eq. for thermal energy	9.4 kWh/m^3
TVC Total eq. energy consumption	11.2 kWh/m^3

Table 7: Characteristics of a Vapor Compression desalination unit [8]

Membrane processes

Membrane processes use membranes to separate fresh water from salts in saline feedwater. Feedwater is brought to the surface of a membrane, and using pressure, the water passes, and the salts are withheld.

In membrane processes, a pretreatment of the feedwater is essential to protect the membranes. Membrane processes are used mostly for brackish water desalination, but Reverse Osmosis competes with distillation processes in seawater desalination.

The operating principle of these processes includes the direct production of electricity which is used to drive the plant. Energy consumption is expressed in kWh/m^3.

a. Reverse Osmosis

In Reverse Osmosis, water passes through a membrane that is impermeable to the solute, in response to a chemical potential gradient achieved through pressurization.

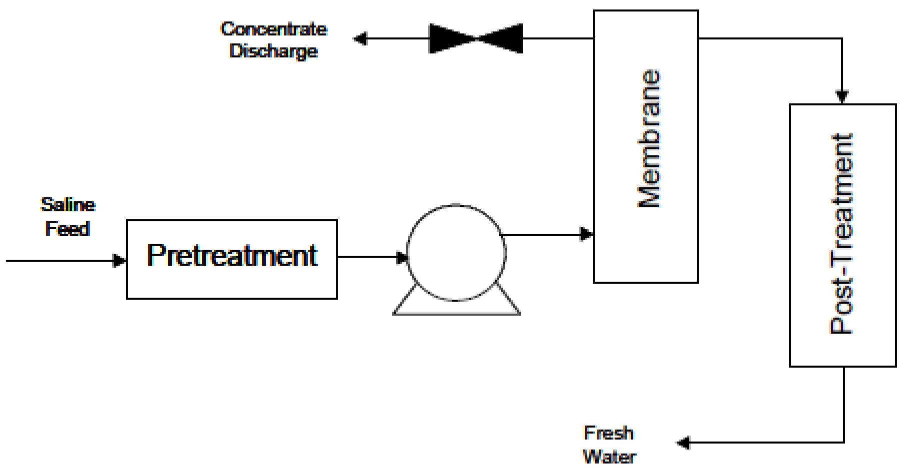

Figure 8: Schematic of Reverse Osmosis desalination plant [7]

RO utilizes electricity or shaft power to drive the pump that increases the pressure of the saline water to that required, to overcome the osmotic pressure and start the flow through the membrane.

As shown in Figure 8, saline feed inserts the membrane through a pump, that creates the pressure needed to pass the membrane. The permeate goes through a post treatment procedure to give fresh water and the remainder, together with the remaining salts, is rejected at high pressure.

In larger plants, it is economically viable to recover the rejected brine energy with a suitable turbine or pressure exchanger. Such systems are called energy recovery reverse osmosis systems (ER-RO).

Typical characteristics of an RO unit are shown in Table 8.

Reverse Osmosis desalination unit	
Typical unit size	24000m^3/day
Electrical energy consumption for seawater RO (41500ppm)	5 kWh/m^3
Electrical energy consumption for brackish water RO (5000ppm)	2.1 kWh/m^3

Table 8: Typical characteristics of a Reverse Osmosis desalination unit [18]

b. Electrodialysis

In Electrodialysis, ions in solution migrate through anion and cation selective membranes in response to an electric field. ED unit consists of compartments filled with saline water and separated by anion and cation exchange membranes. The unit utilizes a direct current source.

As shown in Figure 9, when DC polarity is applied across the cathode and anode, the negative ions pass through the anion exchange membrane, while the positive pass through the cation exchange.

In Electrodialysis the feedwater is fed in parallel to the channels. Cations and anions, due to the voltage, then migrate in opposite directions. Due to the charge selectivity of the membranes, the ion concentration increases and decreases in alternating channels. A single membrane stack may consist of hundreds of these alternating channels. This makes the process more economical and easier to control.

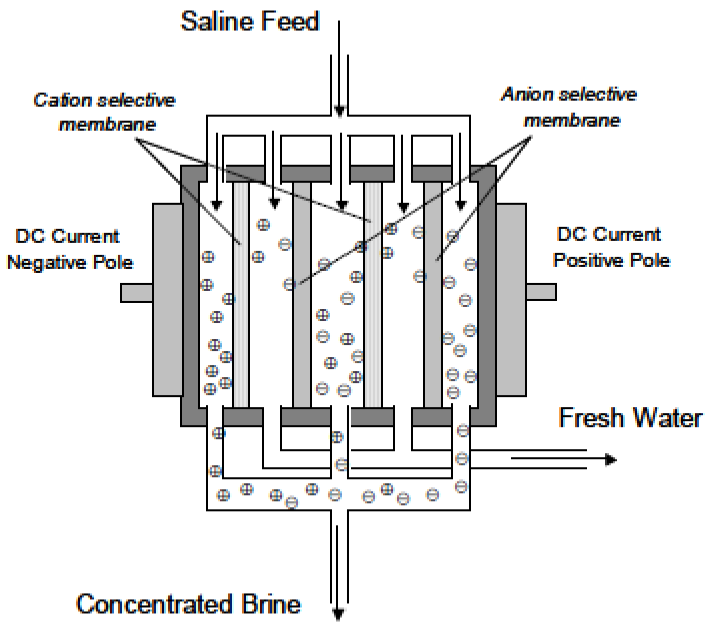

Figure 9: Schematic of Electrodialysis desalination plant [7]

Since the driving force for the separation is an electric field, Electrodialysis is the only process capable of removing ionic components from solution.

Typical characteristics of an RO unit are shown in Table 9.

Electrodialysis desalination unit	
Electrical energy consumption for brackish water ED (2500ppm)	2.64 kWh/m^3
Electrical energy consumption for brackish water ED (5000ppm)	5.5 kWh/m^3

Table 9: Typical characteristics of Electrodialysis desalination unit [8]

1.2.3 Environmental impacts of desalination

The main environmental impact concerns of desalination are intake of large quantities of seawater, brine disposal, land use and energy consumption [10].

a. Water intake

Seawater desalination plants can receive feedwater from different sources, but open seawater intakes are the most common option. The use of open intakes may result in losses of aquatic organisms when these collide with intake screens or are drawn into the plant with the water source.

Some steps to reduce the impacts to due water intake is to use low velocity water intake to prevent entrainment of living organisms, and take water from offshore and not near shore, as offshore water has better quality.

b. Brine discharge

It is reported that the discharge of brine into the sea may erode the seashore or harm the aquatic life.

Potential environmental impacts should be minimized by not disposing the brine directly to the sea, by treating the brine to remove chemicals before the discharge and by identifying the proper site to discharge the brine.

c. Land use

Land use issues emerge from the fact that seawater desalination plants are situated close to sites with sensitive environmental habitats and socioeconomic value.

Sites should be close to consumers, but sites with endangered species or with high importance in agriculture should be avoided.

d. Energy use

As far as energy consumption is concerned, desalination methods are energy intensive, and in most cases the power source is by fossil fuels, resulting to resource depletion and pollution.

The use of modern processes, energy recovery and Renewable Energy Sources can reduce the emissions of CO_2 and other pollutants.

1.2.4 Design of a desalination plant

The theoretical minimum energy for seawater desalination, with freshwater recovery, is about 3kJ/kg water [7]. This energy is linked to physical phenomena as boiling point elevation and osmotic pressure and as the freshwater recovery increases, the energy required to perform the operation must also increase, as shown in Figure 10.

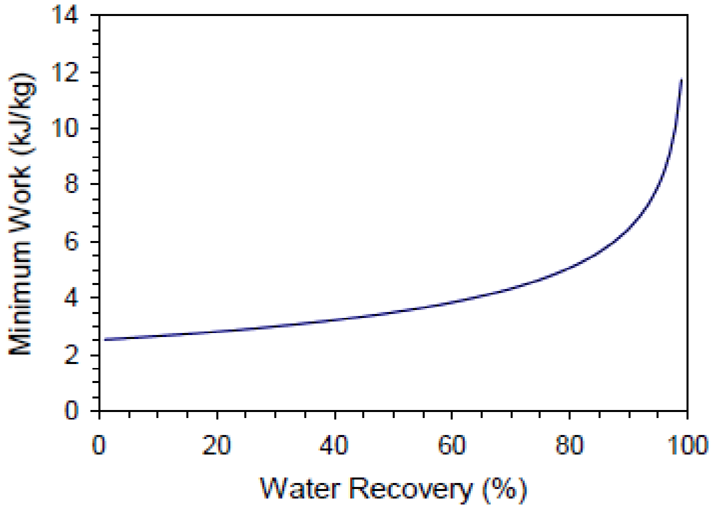

Figure 10: The theoretical minimum energy for desalination of seawater as function of freshwater recovery [7]

<u>Efficiency of the plant</u>

Design considerations show that the bigger the efficiency of the plant, the bigger the size of it and the bigger the capital costs. Thus, there is a tradeoff between capital costs and energy costs that leads to an optimum plant design and a minimum water cost, as shown in Figure 6.

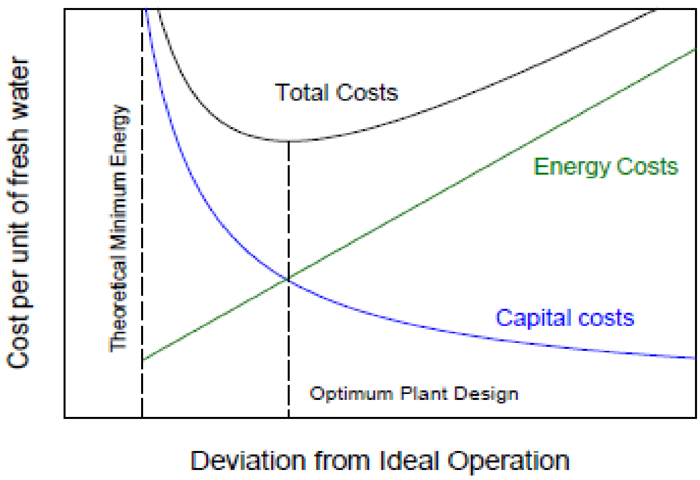

Figure 11: Optimum plant design regarding capital costs and energy consumption [7]

Recovery rates

As the recovery increases, the energy required increases and the scale potential also increases. This is the reason why for many applications low recoveries are chosen.

On the other hand, low recovery means more feedwater, thus more transport and pretreatment costs. In addition to that, the disposal of the concentrated brine creates and extra cost.

The optimum design of the plant considers all these factors.

Scaling

In order to avoid scaling, that can reduce the efficiency of the plant, the nature of the feedwater in each application must be considered. There are a number of measures to prevent scale formation, including limiting the operating temperature, limiting the water recovery, chemical pretreatment, etc.

Quality of product water

Regarding the final use of the product water, there are different qualifications for the water's composition. Generally, distillation processes produce water of a higher quality than membrane processes. Depending on the specific application, suitable desalination methods must be considered.

1.2.5 Desalination worldwide

According to International Desalination Association it is estimated that globally, about 90million m^3 of water is desalinated a day, by around 18500 desalination plants in 150 countries [11].

The Gulf Region has the biggest number of desalination plants in the world, followed by USA, Europe and Asia, as shown in Figure 12.

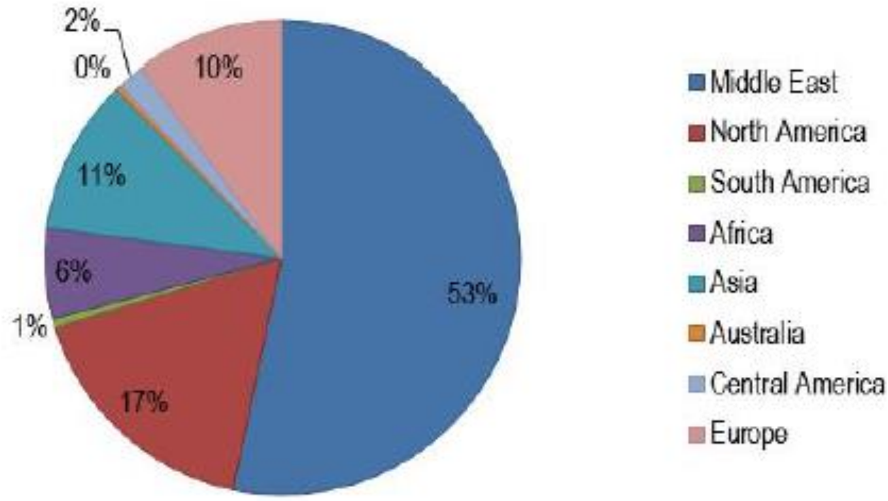

Figure 12: World desalination plants by geographical area (%) [9]

About 59% of the installed capacity is in the Middle East and North Africa. According to the International Energy Agency, half of the global energy consumption for desalination in 2016 was in the United Arab Emirates, at more than 13 million tons of oil equivalent [12].

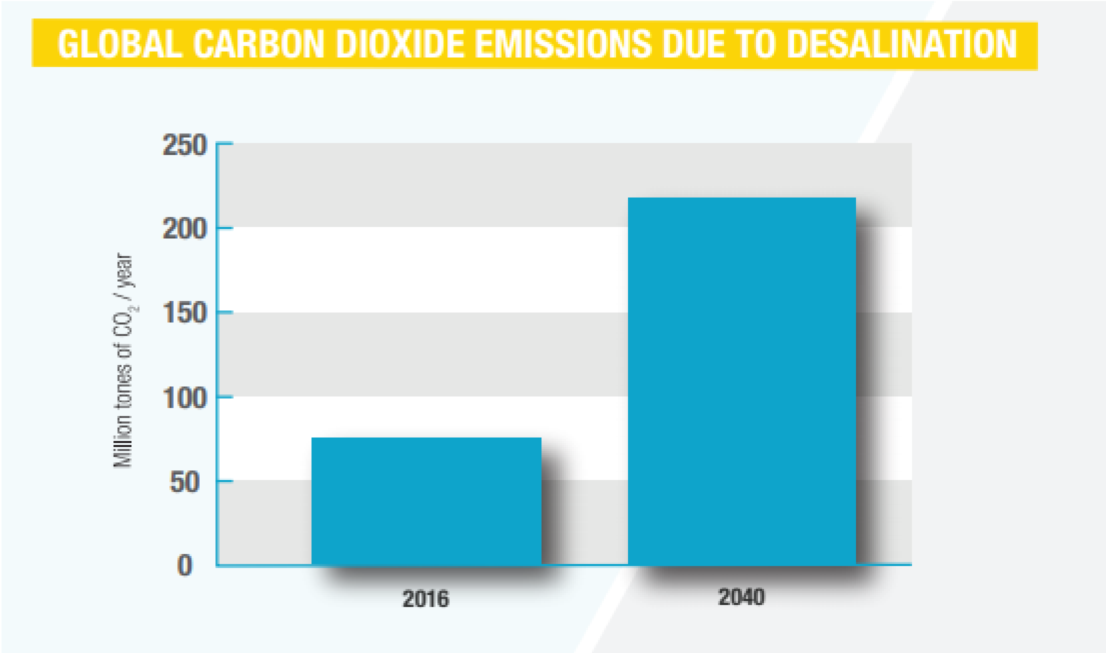

Figure 13: Global CO_2 due to desalination [12]

The world's installed capacity consists mainly of the Multiple-Stage Flash distillation and Reverse Osmosis processes, which make up about 87% of the total capacity as shown in Figure 7.

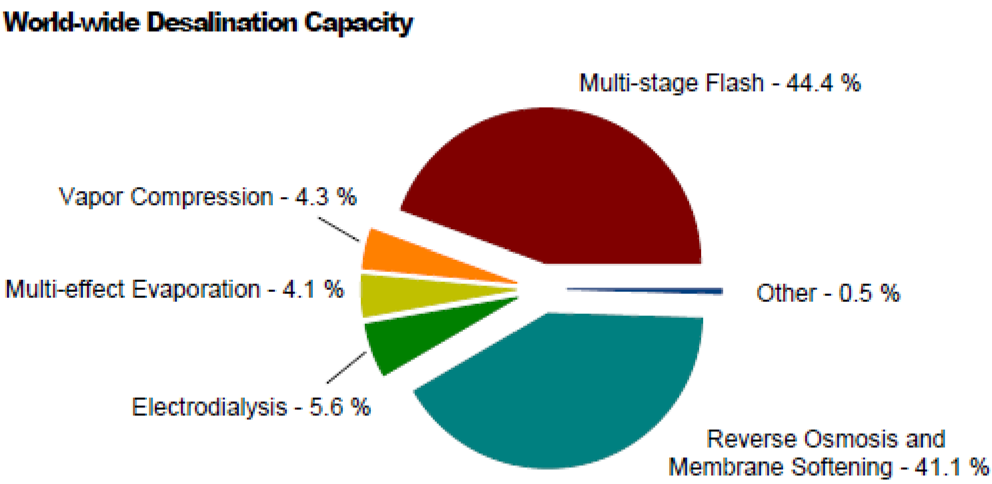

Figure 14: Global distribution of installed desalination capacity by technology [7]

1.2.6 Desalination in Greece

Water desalination is a practice that can solve the problem of water scarcity in Greek islands.

By 2011 there were 157 operating desalination plants in Greece, with a total capacity of 109115m^3/day, while another 35 were expected to be fully operational and five more were under construction [4].

The feedwater is mainly seawater, the desalinated water mostly supplies municipalities and the most popular desalination technology is Reverse Osmosis, as shown in Figure 15.

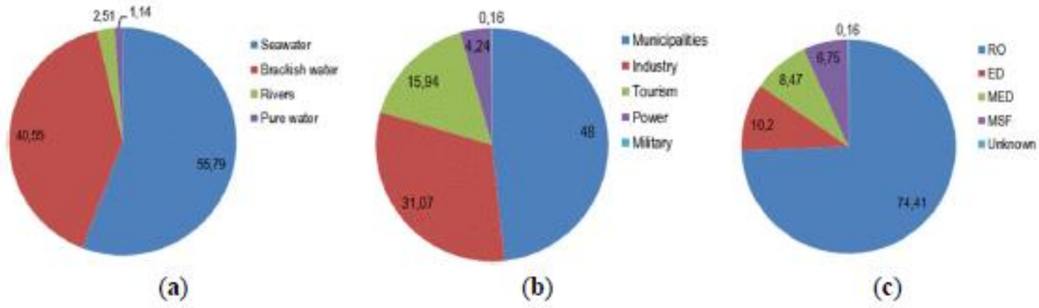

Figure 15: Desalinated water production in Greece according to: a) Feedwater, b) the use of fresh water, c) the used technology [9]

Reverse Osmosis desalination technologies have turned out to be the most appropriate in Greece, due to the relatively low energy requirements, which can be covered by Renewable Energy Sources, as the renewable potential in Greece and especially in Greek islands is very high.

There are about 70 Reverse Osmosis units in Ionian and Aegean islands, with a total capacity of over 52000m^3/day. About 80% of the installed units use seawater for the production of potable water. Some of the plants based in Greek islands are shown in Table 10.

Most of the installed RO units have an energy recovery system to reduce their energy needs.

The capacity of the installed RO plants is between 100-4500 m^3/day. The average operating costs of 30 Reverse Osmosis plants of seawater desalination is estimated at 0.85€/m^3. The cost of desalinated water in Greece is between 0.2 and 2.5€/m^3, with the exception of only a few cases (Tzen, E., CRES) [1].

Project	Year	Type	Capacity (m^3/d)	Initial cost (M €)	Operation cost (€)	Contractor	Acceptance
Almyros Iraklion	2014	RO & UF	2,400	0.850	0.25	Sychem S.A., GR	Good
Syros 1st Ermoupoli	1992	RO	800	0.589	2.70	Christ, CH	Good
Syros 2nd Ermoupoli	1997	RO	800	1.482	2.70	Christ, CH	Good
Syros 3rd Ermoupoli	2001	RO (SW)	40	0.346	2.00	Culligan Greece	Good
Syros 4th (Ano Syros)	2000	RO	250	0.215	0.50	Temak, GR	Good
Syros 5th (Ano Syros)	2002	RO	500	0.400	0.50	Temak, GR	Good
Syros 6th (Ermoupolis)	2002	RO (SW)	2,000	0.313	0.40	Temak, GR	Good
Syros 7th (Ano Syros)	2005	RO	1,000	1.000	0.40	Temak, GR	Under construction
Shinousa	2004	RO	100	0.120	0.70	Temak, GR	Under construction
Mykonos (Korfou) old	1981	RO	500	N/A	2.00	Metek, IT	Good
Mykonos (Korfou) new	2001	RO	2,000	1.276	0.50	Culligan Greece	Good
Paros (Naousa)	2001	RO	1,200	0.415	0.50	Ionics Italia	Good
Tinos (old)	2001	RO	500	0.434	0.62	Culligan Greece	Good
Tinos (new)	2005	RO	500	0.376	0.62	Culligan Greece	Good
Ia, Santorini 1st	1994	RO	220	N/A	2.00	Matrix, USA	Good
Ia, Santorini 2nd	2000	RO	320	0.210	2.00	Culligan Greece	Good
Ia, Santorini 3rd	2002	RO	160	N/A	2.00	Matrix, USA	Good
Sifnos	2002	RO (BW)	500	0.224	3.50	Hoh, DM	Good
Omiroupolis, Chios, Municipality, 1st	2000	RO (BW)	600	0.205	0.30	Culligan Greece	Good
Omiroupolis, Chios, Municipality, 2nd	2005	RO	3,000	0.710	0.26	Culligan Greece	Under construction
Omiroupolis, Chios, Municipality, 3rd	2005	RO	500	0.200	0.26	Culligan Greece	Under construction
Nisiros (old)	1991	RO	300	0.572	N/A	Metek, IT	Out of operation
Nisiros (new)	2002	RO	350	0.295	0.66	Temak, GR	Good
Ithaki, Kefalonia 1st	1981	RO	620	0.264	2.88	Christ, CH	Good
Ithaki, Kefalonia 2nd	2003	RO	520	0.587	0.58	Judo, DE	Good
Lerou (Municipal Enterpr.)	2001	RO	200	0.074	0.13	Culligan Greece	Good
Kassopeon (Municipality)	2001	RO	500	0.170	0.13	Culligan Greece	Good
Posseidonia (Municipality), 1st	2002	RO	500	0.464	0.56	Culligan Greece	Good
Posseidonia (Municipality), 2nd	2005	RO	1,000	0.574	0.45	Culligan Greece	Under construction
Agios Georgios (Municipality)	2002	RO	500	0.102	0.30	Culligan Greece	Good
Paksoi (Municipality) 1st	2005	RO	330	0.260	0.51	Culligan Greece	Good
Paksoi (Municipality) 2nd	2005	RO	150	0.162	0.59	Culligan Greece	Good
Total: 32	-	-	22,860	-	-	-	-

Table 10: Reverse Osmosis desalination plants in Greek islands by 2014 [4]

1.3 Renewable Energy Sources in desalination

Desalination is a very energy intensive process, which often uses energy from fossil fuels, resulting in resource depletion and environmental pollution. Furthermore, fossil fuels are vulnerable to volatile global market prices and they are not abundant in remote areas like islands, therefore they are not sustainable.

Renewable energy systems offer alternative solutions to decrease the dependence on fossil fuels. By 2013 only 1% of total desalinated water was based on energy from renewable sources [13]. As the technology in RES advances and the prices drop, renewable energy becomes a viable option, especially in energy-importing countries.

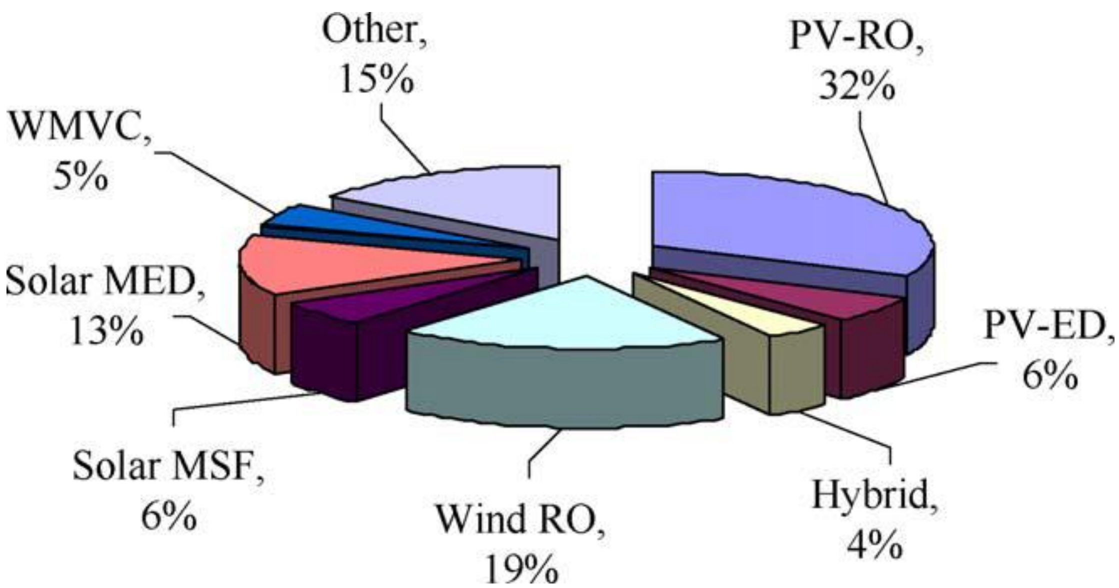

Figure 16: Distribution of renewable energy powered desalination technologies [14]

The most important factor that affects the desalination cost is low utilization of the plant as it is designed to satisfy peak water demand. The high installation cost with small water production during most of the year, can result in high cost of the water. The use of RES can reduce operational costs and even provide a supplementary income through the sale of electricity surplus to the grid.

The installation cost of a desalination unit can be also affected by the number of desalination units and their capacity, the period and length of the operation and the renewable energy system configuration.

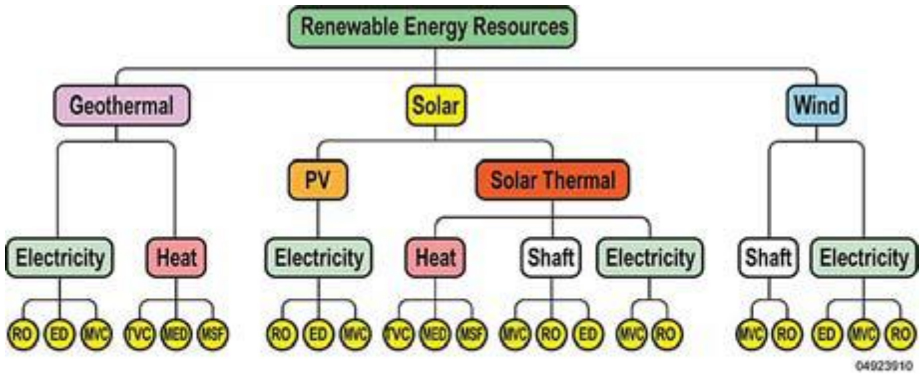

Figure 17: Combinations of Renewable Energy Sources with desalination technologies [8]

Over the last two decades, numerous desalination systems utilizing RES have been constructed. The most promising and applicable RES desalination combinations are shown in Table 11.

RES technology	Feed water salinity	Desalination technology
Solar thermal	Seawater	Multiple effect boiling (MEB)
	Seawater	Multi-stage flash (MSF)
Photovoltaics	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Brackish water	Electrodialysis (ED)
Wind energy	Seawater	Reverse osmosis (RO)
	Brackish water	Reverse osmosis (RO)
	Seawater	Mechanical vapor compression (MVC)
Geothermal	Seawater	Multiple effect boiling (MEB)

Table 11: RES desalination combinations regarding the feedwater [5]

The most commercial renewable desalination is based on the Reverse Osmosis process, followed by thermal processes. The most common energy source is Photovoltaics, followed by solar thermal energy, wind energy and geothermal energy.
Solar energy can be used for seawater desalination either by producing the thermal energy required to drive the phase-change processes or by producing electricity required to drive the membrane processes.

1.3.1 Solar thermal desalination

Seawater desalination via MSF and MED using solar heat as the energy input are promising desalination methods based on RES. Solar energy can be combined with desalination units in direct processes and indirect processes.

Direct processes are the processes where all the components are integrated into the desalination plant. This requires a simple technology which can be operated by non-skilled workers, it has low maintenance requirements and can be used anywhere. The most investigated mode of coupling between RES and desalination processes is the solar still.

Solar still desalination is mainly suited for small production, where the freshwater demand is low.

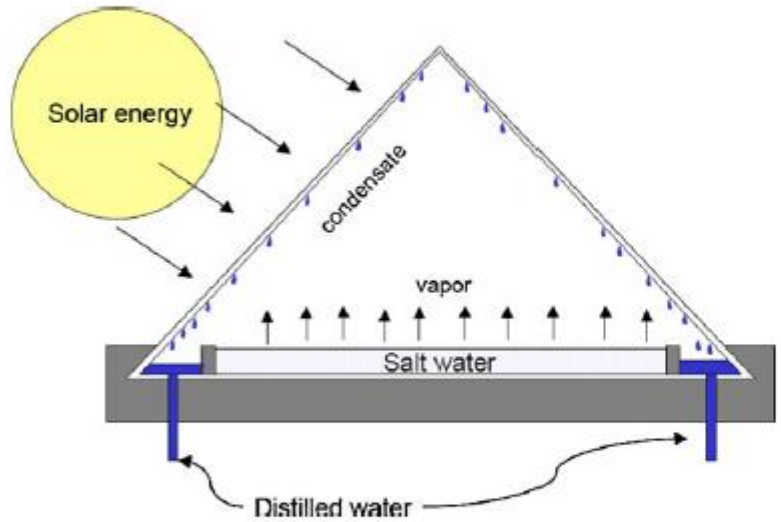

Figure 18: The basic design of a solar distillation unit [14]

Indirect processes include two separate systems: the collection of solar energy, by a conventional solar converting system, coupled to a conventional desalination method. These are the processes where the heat comes from a separate solar collector (Concentrated Solar Power, CSP) or solar ponds.

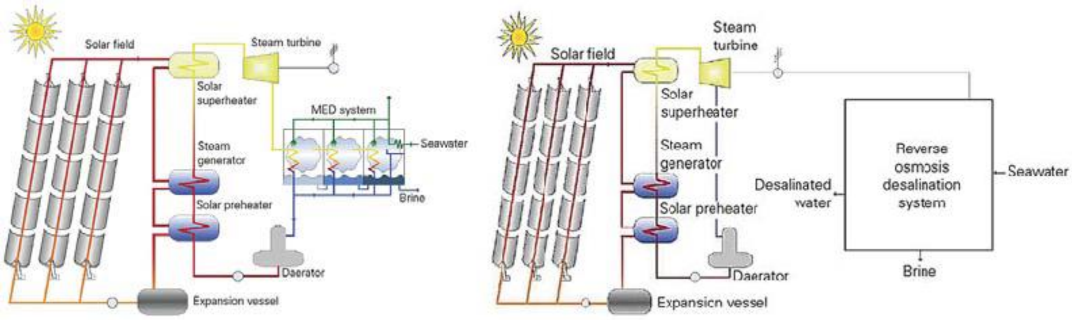

Figure 19: CSP power plant couple with MEB and RO desalination unit [8]

Concentrated Solar Power plants collect solar radiation and provide high-temperature heat for electricity generation, thus they can be combined with both thermal and membrane desalination processes. CSP plants are often equipped with thermal storage systems or are combined with conventional power plants for hybrid operation.

Salinity gradient solar ponds are a type of heat collector as well as a mean of heat storage.

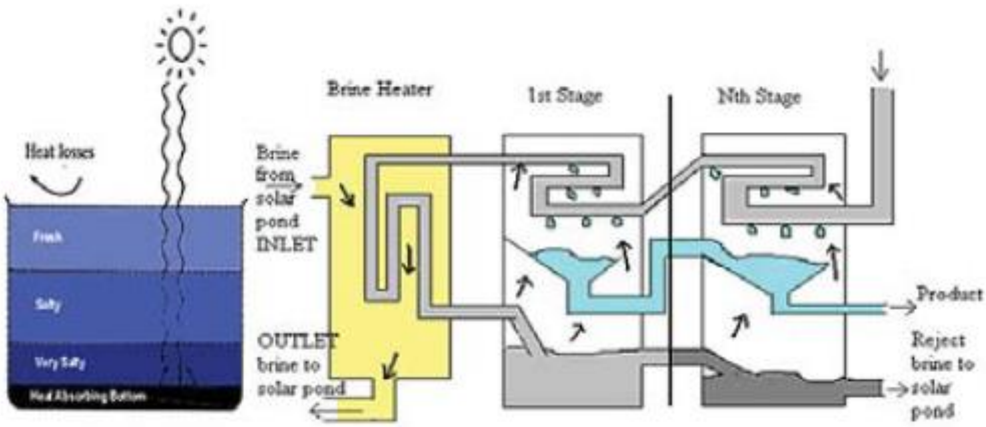

Figure 20: Solar pond assisted desalination [8]

1.3.2 Photovoltaic desalination

Photovoltaic technology can be connected directly to Reverse Osmosis or Electrodialysis desalination processes, which are based on electricity as the input energy.

PV systems consist of PV modules, or arrays, batteries, charge controller, inverter and control systems. Electrodialysis uses DC current for the electrodes, therefore the system does not include an inverter, which simplifies the system.

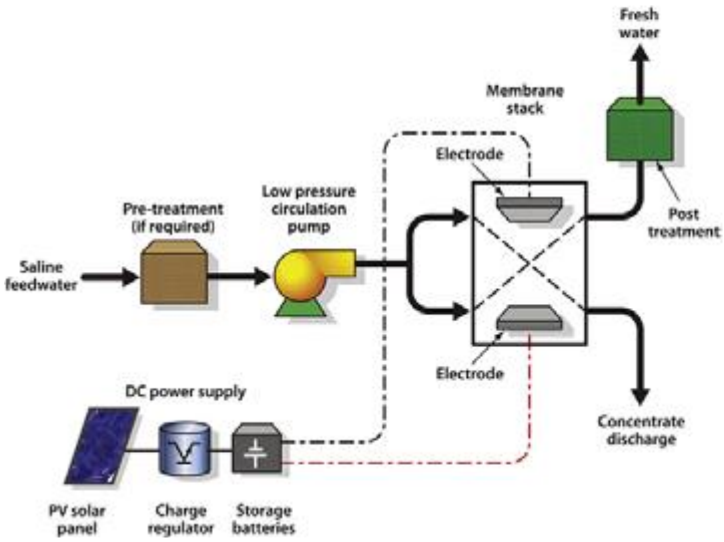

Figure 21: PV powered Electrodialysis desalination system [8]

The main issue of PV desalination is the high cost of PV cells and batteries for electricity storage. Careful maintenance and operation of battery systems are also necessary.

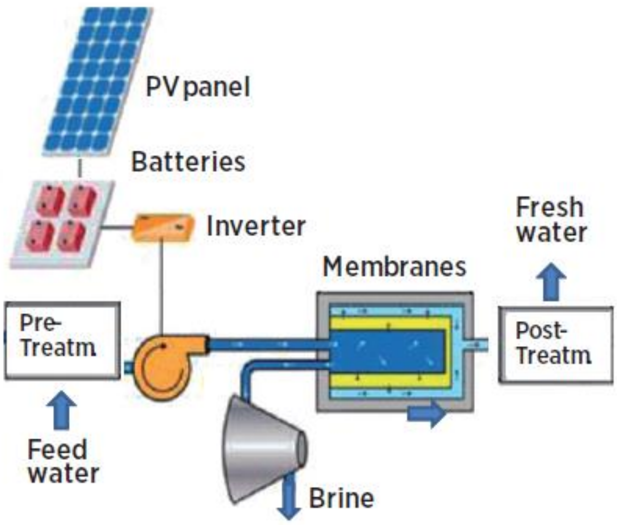

Figure 22: Coupled PV and RO desalination plants [13]

1.3.3 Wind powered desalination

The electrical and mechanical power generated by a wind turbine can be also used to power desalination plants, RO and ED units with the use of the electricity produced, and VC units, where the mechanical energy of the wind turbine is used directly for VC without further conversion into electricity.

Wind powered based desalination can be one of the most promising options for seawater desalination, especially in coastal areas. The main drawback of wind desalination is the intermittence of the energy source, which requires the use of batteries or possible combinations with another RES.

1.3.4 Geothermal desalination

As geothermal energy can produce electricity and heat, it can be combined with both thermal and membrane desalination technologies.

Geothermal reservoirs are classified as being low temperature ($<150^oC$) or high temperature ($>150^oC$).

Low-temperature geothermal energy is ideal for MED desalination units, however the exploitation of geothermal energy depends on the specific local conditions, with upfront investment costs that are usually very high.

High temperature geothermal fluids can be used to generate electricity to drive RO or ED plants.

1.3.5 Biomass desalination and wave energy desalination

The use of biomass in desalination is not a very promising alternative since organic residues in arid regions and the growing of biomass itself requires more fresh water than it could generate in a desalination plant.

On the other hand, in a rural area, the incineration of municipal waste could provide high temperature energy in the form of exhaust gases, which can be used to produce steam. Ocean Thermal Energy Conversion (OTEC) is a relatively new technology, that started to get attention around 1980 about the production of electricity and desalinated water [15]. Another form of energy regarding the oceans is the use of the kinetic energy of the waves, which is not a mature technology.

Renewable energy powered desalination systems can operate autonomously or be connected to the electrical grid. There is also the possibility to combine Renewable Energy Sources to cover the energy needs.

In autonomous systems all the energy needed for the desalination process comes from the renewable energy source. In that case, an energy storage should be incorporated in the system to overcome the problem of the intermittent power supply. Another option is the combination of various Renewable sources in one system, to improve its credibility.

Autonomous systems are suitable for remote areas, that are not connected to the grid and where there is a lot of renewable potential, e.g. in Greek islands.

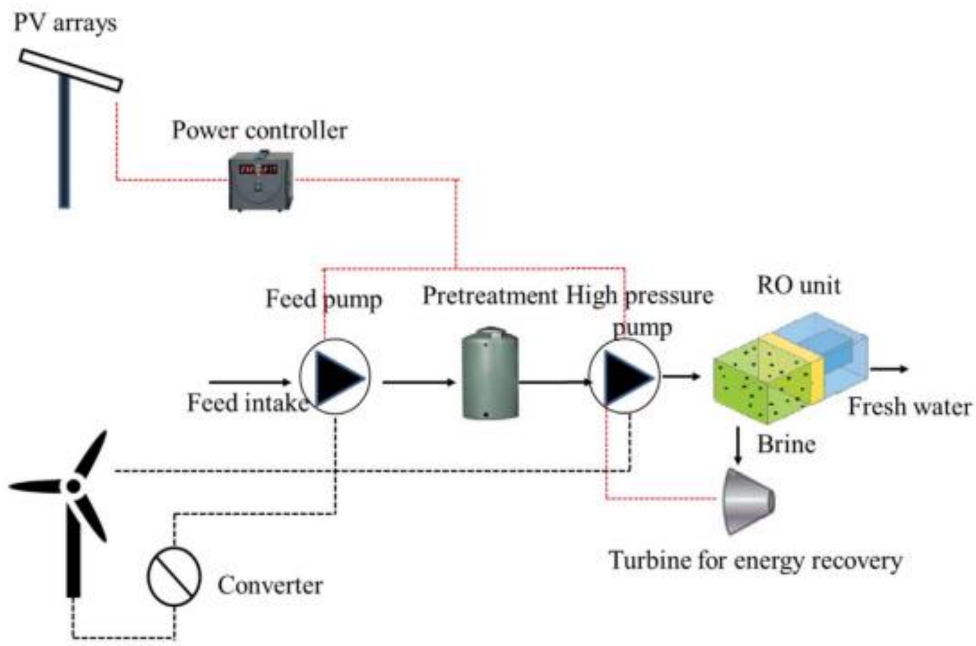

Figure 23: Schematic diagram of a solar and wind driven Reverse Osmosis system [20]

In systems that are connected to the grid the power supply of the desalination unit is not intermittent and the unit runs smoothly. There are two possibilities.

The first is that the power need of the desalination unit is covered by the renewable source. When the power of the RES is not enough, then it gets power from the grid. When the production of the RES is more than the desalination unit needs, then electricity is sold to the grid.

The second is that the desalination plant is always powered from the grid, and the installed RES always gives electricity to the grid.

1.3.6 Choice of desalination method

There are several parameters that affect the selection of desalination systems, including:

a) Quality and quantity of product water

The use of the product water must be defined and its chemical characteristics before selecting a desalination technology. Potable water has different specifications than water than will be used for agriculture purposes, thus the desalination technology that is more cost-effective for each case is different.

Desalination plants have different capacity capabilities, depending on their technology, thus the product flow required is another important factor. Figure 24 shows the possible capacity of each desalination technology.

b) Quality and quantity of feedwater

According to salinity of water, it could be categorized into brackish or seawater. Brackish water may be more attractive as the salinity is typically much lower. On a coastal site seawater is usually more available.

The capacity of the desalination technologies in feedwater is show in Figure 24.

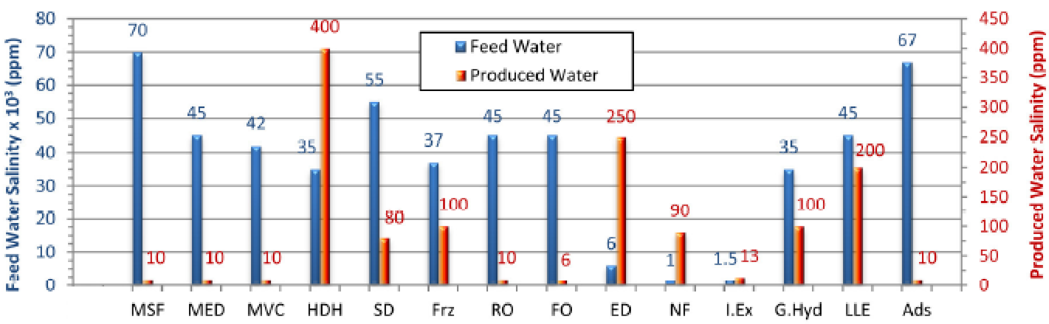

Figure 24: Capability of different desalination systems regarding salinity of feed and produced water, ppm [6]

c) Cost of installation and product water

The cost of desalination is largely dominated by the energy cost. Site specific aspects that have a significant impact on final cost include feedwater transportation, product water delivery to end users, brine disposal and the size of the plant [4].

The water production cost of desalination units depends on capital cost and operating cost. Capital cost includes the cost of land, installation, equipment and research. Operating cost includes the cost of energy, maintenance and replacement of equipment.

Desalination based on RES is still expensive, as the investment and generation costs are higher than of conventional energy sources. However, under certain conditions, e.g. in remote areas, it can be more convenient.

Costs of desalinated water from different desalination technologies is shown at the Figure below.

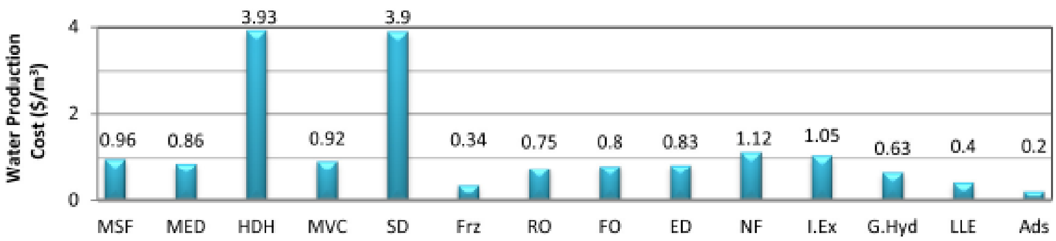

Figure 25 : Water production costs of different desalination technologies [6]

d) Input energy required

Desalination requires a considerable amount of energy. Membrane desalination processes require only electricity, while thermal desalination processes require both electricity and thermal energy.

The amount of energy required for different desalination technologies is shown in the Figure below.

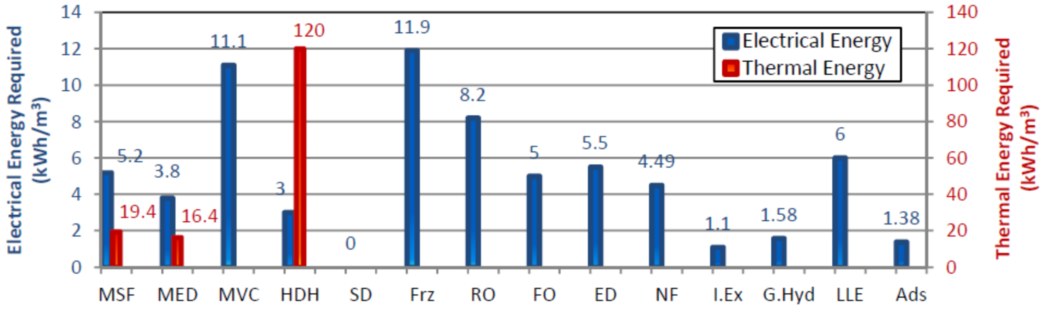

Figure 26: Amount of energy required for different desalination technologies [6]

e) Land area required

The land available for the installation of a desalination unit is very important when choosing the desalination technology to be used, as well as the renewable energy it can be combined with. Generally, thermal processes require more land area than membrane processes.

f) Environmental impact

The environmental impact of the desalination technology depends basically on the brine rejected and the CO_2 emissions of the plant. The brine rejected depends on the efficiency and recovery of each plant, while the CO_2 emissions depend on the technology.

The CO_2 emissions for different desalination technologies is shown in the figure below.

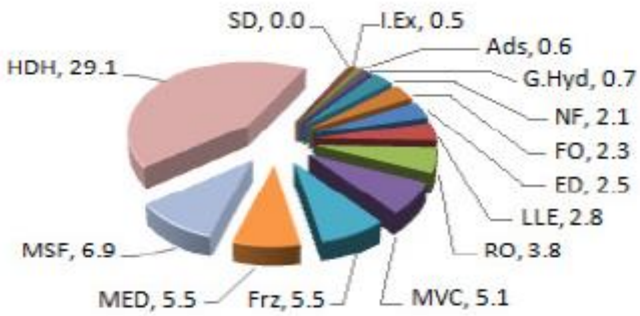

Figure 27: Amount of released CO2 for different desalination technologies, kg/m³ [6]

g) Available RES

The available Renewable sources in the site of the desalination unit must be considered and after the most effective RES is selected, then the matching desalination technologies must be considered. Not all combinations of RES-driven desalination systems are practicable or viable.

The optimum or just simple specific technology combination must be studied in connection to local parameters as geographical conditions, capacity and type of energy available in low cost, availability of local infrastructure, etc.

Chapter 2
Reverse Osmosis Desalination

Reverse Osmosis is the most widely used process for seawater desalination. Firstly, it was used for the production of potable water by brackish water, and after the improvement of semipermeable membrane technology, it was also used in seawater desalination.

As far as the combination of desalination technologies with Renewable Energy Sources, the combination of RO with Photovoltaic panels is the most common system in use, as shown in Figure 28.

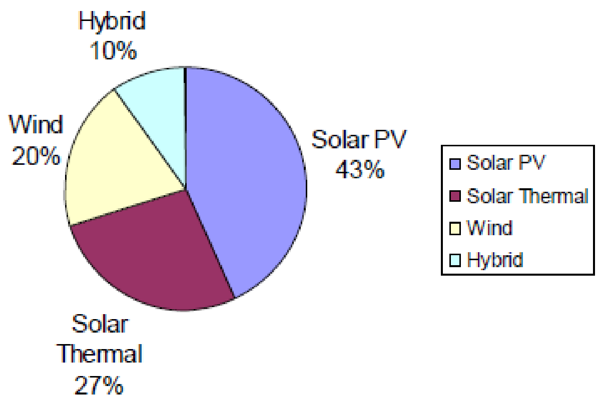

Figure 28: Combination of RES with desalination technologies [9]

2.1 Principle of operation

The principle of operation is based on the reverse of the natural phenomenon of osmosis.

When two liquids with different salt concentration are separated by a semipermeable membrane, water will flow from the volume of low-concentration liquid, to the volume of high-concentration liquid, until the system reaches an equilibrium. This phenomenon is called osmosis.

The phenomenon can be reversed by applying external pressure on the volume of high-concentration liquid, until the flow is reversed from the high concentration volume to the low-concentration. This phenomenon is called reverse osmosis.
The reverse osmosis process results in a stream of fresh water that is called permeate and a stream of the feedwater, which has elevated salinity, and which is called concentrate.

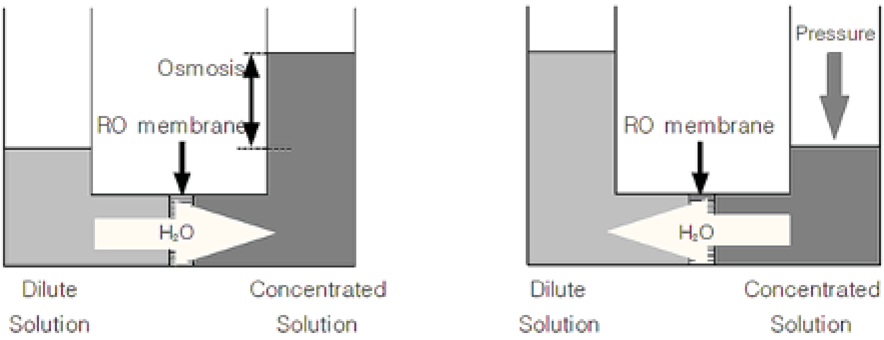

Figure 29: Osmosis and reverse osmosis phenomena [8]

Semipermeable membranes reject all suspended solids but there will be some passage of dissolved solids with the water. The key feature of these membranes is that the pass the water in a much higher rate than the dissolved solids.

2.2 Reverse Osmosis Unit

Reverse osmosis process includes the passage of a saline feedwater through a membrane, and its separation into fresh water and salts.

A high-pressure pump pressurizes the feedwater on the membranes. Feedwater is then divided into the permeate water (30-40% of the feedwater) and the discharge product, the brine (60-70% of the feedwater), in which remain over 99% of the salts.

The product water is transported to the end user and the remaining water is discharged, or reused, depending on the application.

RO operating pressure varies from 14-25 bar for brackish water and from 55-80 bar for seawater.

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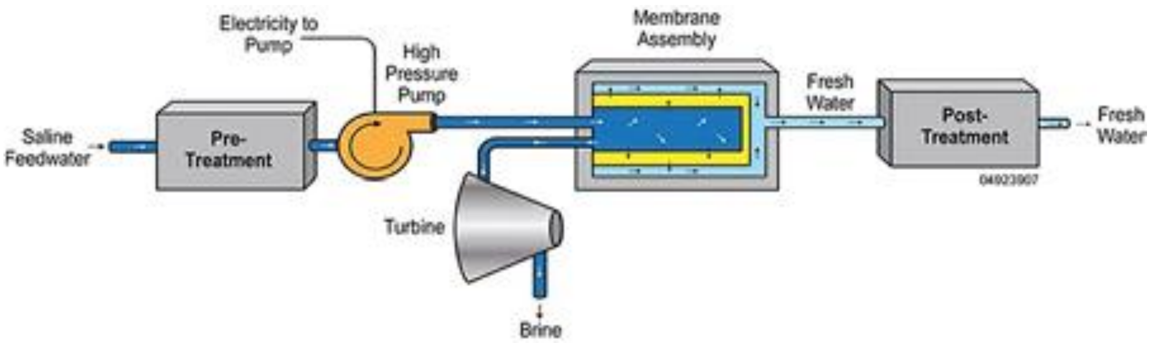


Figure 30: Reverse Osmosis Desalination system [8]

A RO unit consists of five subsystems, which include the intake system, the pretreatment system, the high-pressure pump, the membrane assembly, the post-treatment system and the brine disposal system.

The water intake system can consist from a feedwater tank or, for the case of seawater desalination it can be an open intake from offshore or near the shore.

The pre-treatment system consists of chemical dosing and filtration, that cleans the feedwater from precipitation and microorganisms, to reduce the contamination of the membrane surfaces.

The high-pressure pump pressures the feedwater to the membrane at a pressure adequate to overcome the osmotic pressure of the water and the energy losses associated with the separation process, to the point where the flow of the water through the membrane is achieved. The pump discharge pressure has to be controlled to maintain the designed product output and not exceed the maximum feed pressure of the membrane.

The membrane assembly is the main part of the RO unit, and is where the feedwater is divided to the permeate and brine.

A lot of large systems include Energy Recovery systems, in order to utilize the high pressure of the brine, since the pressure of the brine is high and about 2-5 bar less than the feed water.

The post-treatment system depends on the specifications for the product water of each application. It consists of sterilization, stabilization and mineral enrichment of the product water. PH adjustment and disinfection is used to kill any micro-organisms. Disinfection may be done by Ultraviolet radiation or by chlorination.

2.3 Membrane assembly

In reverse osmosis plants membranes are configured in membrane elements and assembled in membrane modules.

The membranes used are made of a semi-permeable thin film of aromatic polyamide (PA) or cellulose acetate (CA). The film is supported by a micro-porous polymeric layer, which is on a layer of reinforcing fabric, as shown in Figure 31.

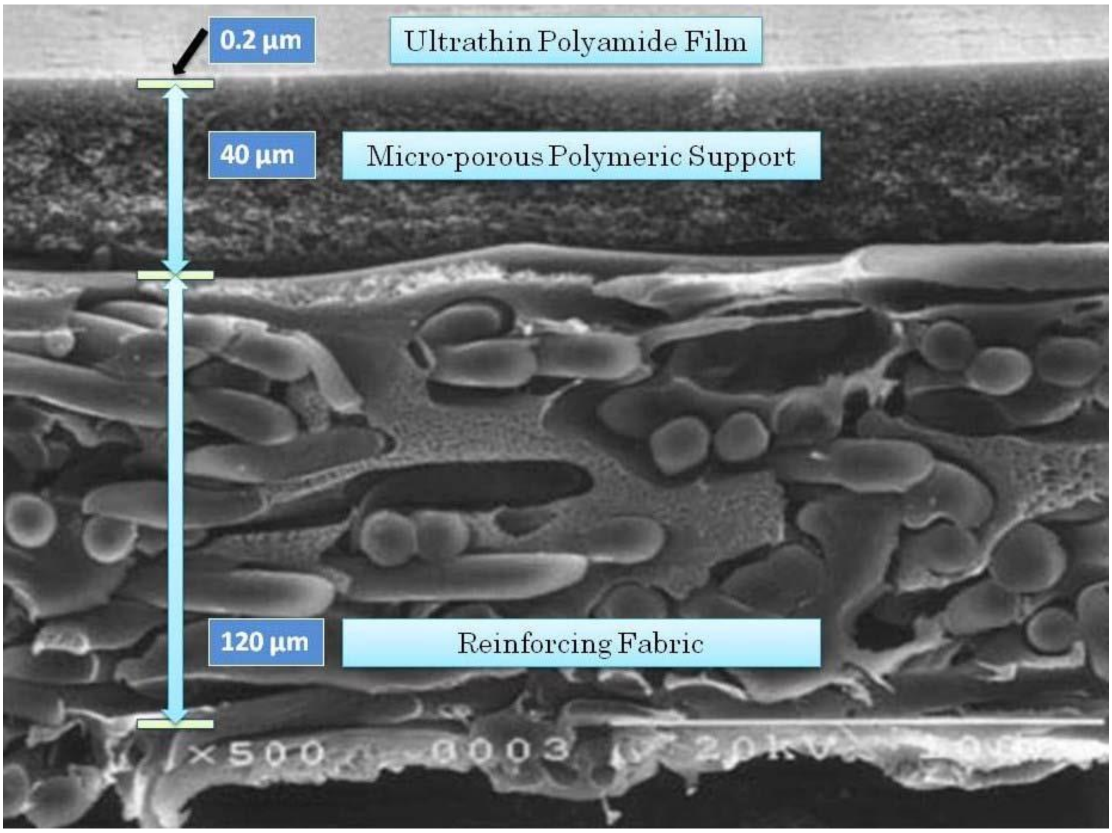


Figure 31: Structure of a RO membrane [15]

The main disadvantage of CA membranes is that they perform in a small pH range, from 4 to 8. They have high tolerance to oxidants, thus they are used mainly in municipal applications and for extra pure water production.

PA membranes are mostly used in commercial applications. Their main advantages are that they have higher specific flux, higher salt rejection, they work in a wider pH range (2-12) and they have longer useful life. Their disadvantage is that they are susceptible to degradation by oxidation.

The membranes are configured in commercially available membrane elements, of standard size and performance. The most widely used membrane elements are hollow-fiber and spiral wound types.

Hollow-fiber membranes are more suitable for high-salinity waters that have elevated scaling potential, as they have bigger surface area which means lower permeate flux for the same amount of water, thus lower concentration polarization and scaling potential. Their main disadvantage is that they are more susceptible to particulate- and bio- fouling.

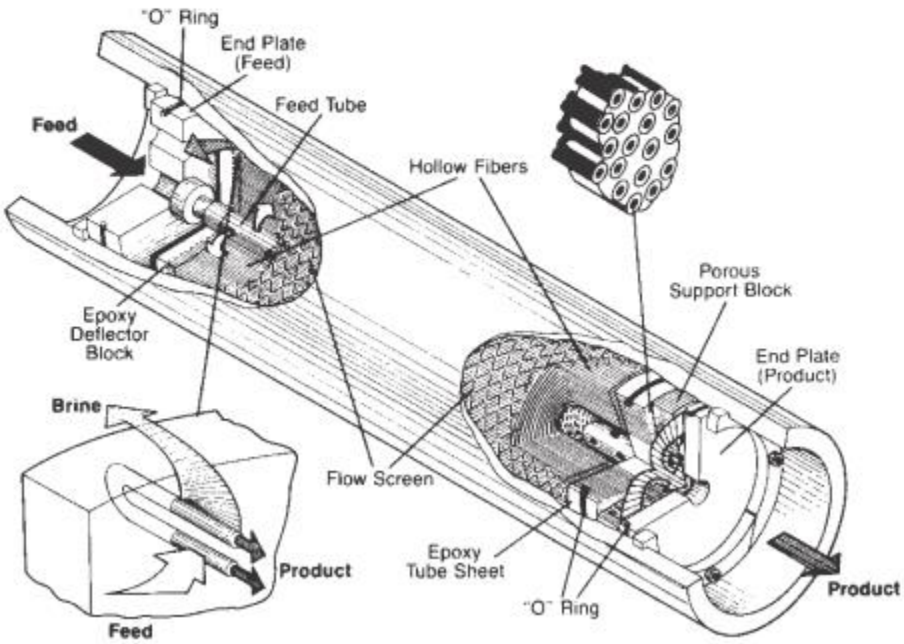


Figure 32: Hollow- fiber membrane configuration [16]

Spiral-wound membrane configuration dominates the market today, with the most widely used the 8-inch element. Their main limitations are the maximum feed water temperature at 45°C, the pH range between 3 and 10, the feed water pressure maximum 80 bars and that they are not tolerant to chlorine.

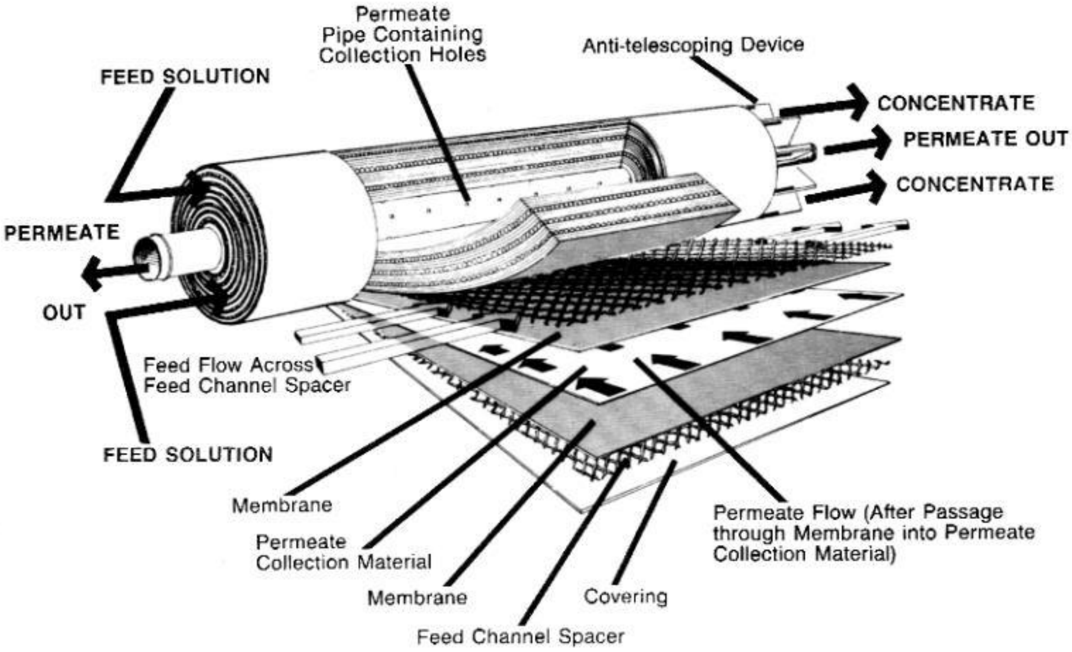


Figure 33:Spiral-wound membrane configuration [16]

Membrane performance tends to deteriorate over time and typically the RO membrane elements must be replaced every 3-7 years.

2.4 Membrane performance

The key parameters associated with the performance of RO units are the osmotic pressure of the water, the permeate recovery rate, the net driving pressure, the membrane salt passage and salt rejection, the membrane permeate flux, the specific membrane permeability and the concentration polarization factor [17,18].

a. Osmotic pressure

Osmotic pressure of a given saline water depends on the Total Dissolved Solids of the water and the temperature and it does not depend on the membrane. It is calculated by the following formula:

$$P_O = \mathrm{R} \times \mathrm{T} \times \Sigma \mathrm{x_i}$$

Where,

Po: the osmotic pressure, bars

R: the universal gas constant, R=0.082L*atm/mol*K

T: the temperature, Kelvin

Σxi: the sum of the molar concentrations of all constituents in saline water, mol/L

The “rule of thumb” often used in desalination processes is that for Seawater Reverse Osmosis, for every 100mg/L of salinity results in 0.07bars of osmotic pressure [18].

b. Permeate recovery rate

Recovery rate is the portion of the feedwater converted to fresh water flow and it is measured as a percent of the saline feed flow.

$$P_r = \left(\frac{\mathrm{Q_p}}{\mathrm{Q_f}}\right) \times 100\%$$

Where,

Pr: the permeate recovery rate

Qp: the permeate flow

Qf: the feedwater flow

Most seawater reverse osmosis plants (SWRO) are designed with a recovery rate around 50%.

The total dissolved solids of the concentrate can be calculated by the following formula:

$$TDS_c = \frac{TDS_f - \frac{P_r \times TDS_p}{100}}{1 - \frac{P_r}{100}}$$

Where,

TDSc: the total dissolved solids of the concentrate

TDSp: the total dissolved solids of the permeate

TDSf: the total dissolved solids of the feed water

Pr: the permeate recovery rate

c. Net driving pressure

Net driving pressure is the actual pressure that drives the transport of fresh water from one side of the membrane to the other. It is defined as a difference between the applied feed pressure of the saline water to the membrane minus all the other forces that counter the movement of the liquid through the membrane.

$$NDP = F_p - (O_{pfc} + P_p + 0.5 \times P_d)$$

Where,

NDP: the net driving pressure

Opfc: the average osmotic pressure on the feed/concentrate side of the membrane

Pp: the permeate pressure

Pd: the pressure drop across the feed/ concentrate side of the RO membrane

d. Membrane salt passage

Salt passage is defined as the ratio between the concentration of salt in the permeate and the concentration of salt in the feedwater.

$$S_p = \frac{\mathrm{TDS_p}}{\mathrm{TDS_f}} \times 100\%$$

Where,

Sp: the salt passage

TDSp: the total dissolved solids of the permeate

TDSf: the total dissolved solids of the feed water

e. Membrane salt rejection

Salt rejection is a measure of how much of the salt of the feedwater was retained by the membrane.

$$S_r = 100\% - S_p = (1 - \frac{\mathrm{TDS_p}}{\mathrm{TDS_f}}) \times 100\%$$

Salt rejection for most commercially available seawater reverse osmosis membranes is 99.6% to 99.85%.

f. Membrane permeate flux

Membrane flux is the permeate flow a membrane produces per unit membrane area.

$$F_p = \frac{\mathrm{Q_p}}{\mathrm{S}}$$

Where,

Fp: the membrane flux, in $L/m^2/h$ (lmh)

Qp: the flow rate of the permeate, in L/h

S: the total area of the membrane area of the element, m^2

The average membrane flux for a unit is calculated by dividing the total flow of the permeate by the total area of the membranes.

g. Specific membrane permeability

Specific membrane permeability characterizes the resistance of the membrane to the water flow. Usually membranes of lower specific permeability have higher salt rejection.

$$\mathrm{SMP} = \frac{\mathrm{F_p}}{\mathrm{NDP}}$$

Where,

SMP: the specific membrane permeability, lmh/bar

Fp: the membrane flux, lmh

NDP: the net driving pressure, bar

h. Concentration polarization factor

Concentration polarization is called the increase of salt concentration near the membrane surface, due to the water flows and the salts rejected.

$$\mathrm{CPF} = \frac{\mathrm{C_s}}{C_b}$$

Where,

CPF: the concentration polarization factor

Cs: the salt concentration at the membrane surface

Cb: bulk concentration

This can lead to greater osmotic pressure at the membrane surface, reduced water flow across the membrane, increased salt flow across the membrane and increased possibility that the precipitation causes membrane scaling.

For a given membrane, increase in permeate flux can lead to increase of the concentrate polarization, while increase in the feed flow can decrease it.

2.4.1 Mass transfer equations

a. Permeate and salt mass

The permeate and salt mass can be defined by the following equations:

$$Q_f = Q_p + Q_b \qquad M \rightarrow kg/s$$
$$C_f \times Q_f = C_p \times Q_p + C_b \times Q_b \qquad C \rightarrow kg/m^3$$

Where,

Mf: the mass flow of the feedwater

Mp: the mass flow of the permeate water

Mb: the mass flow of the bulk

Cf: the concentration of the feedwater

Cp: the concentration of the permeate

Cb: the concentration of the bulk

b. Water and salt transport rate

The water transport rate is given by the following equation:

$$Q_p = NDP \times A \times S \qquad m^3/s$$

Where,

Qp: the water transport rate

NDP: the net driving pressure, kPa

A: the water transfer coefficient, $m^3/(m^2*s*kPa)$

S: the surface area of the membrane, m2

The salt transport rate is given by the following equations:

$$Q_s = (C - C_p) \times B \times S \qquad (kg/s)$$

$$C = \frac{(C_f \times M_f + C_b \times M_b)}{M_f + M_b}$$

Where,

Qs: the salt transport rate

Cf: the concentration of the feedwater, kg/m^3

Cp: the concentration of the permeate, kg/m^3

Cb: the concentration of the bulk, kg/m^3

A: the salt transfer coefficient, $m^3/(m^2*s*kPa)$

S: the surface area of the membrane, m^2

From the equations above it is clear that for a specific membrane the water transfer rate through her is proportional to the pressure differential at her two sides, while the salt transfer rate through her is proportional to the concentration differential and does not depend on the pressure.

2.5 Factors that affect the membranes

The factors that affect the membrane operation are the feed pressure, the permeate recovery, the temperature and the salinity of the feedwater.

a. Pressure

From the equations above it is clear that for a specific membrane the water transfer rate through her is proportional to the pressure differential at her two sides.

b. Temperature

Warmer water reduces the viscosity, which increases the Net Driving Pressure and the membrane flux. However, warmer temperatures result in loosening up of the membrane, which lowers the salt rejection.

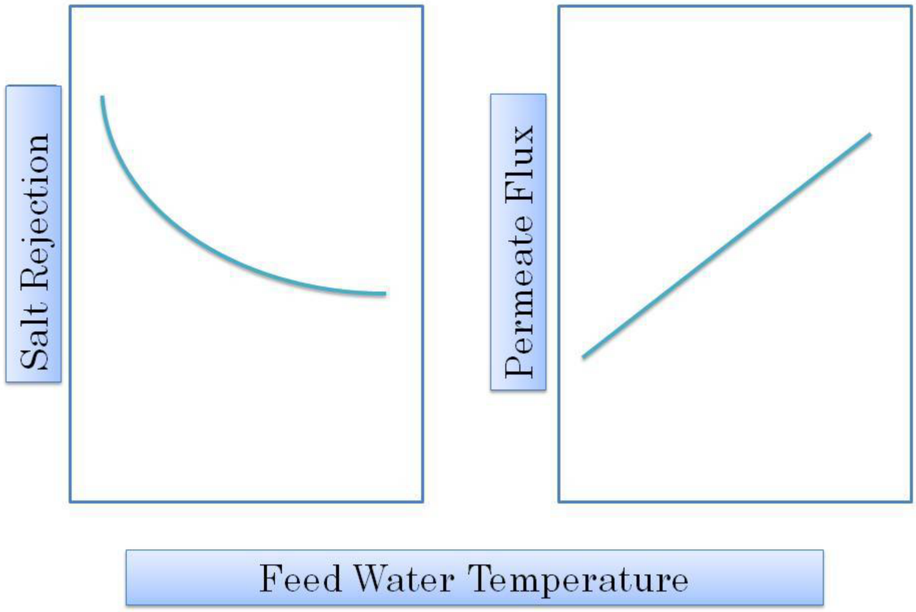


Figure 34: Effect of temperature in Reverse Osmosis desalination [18]

In RO plants, the flowrate is constant and the use of warmer water leads to lower feed pressure need, thus lower electricity consumption.

c. Salinity

Higher feedwater salinity reduces NDP and decreases the permeate flux, increases the salt concentration in the feed side and decreases salt rejection.

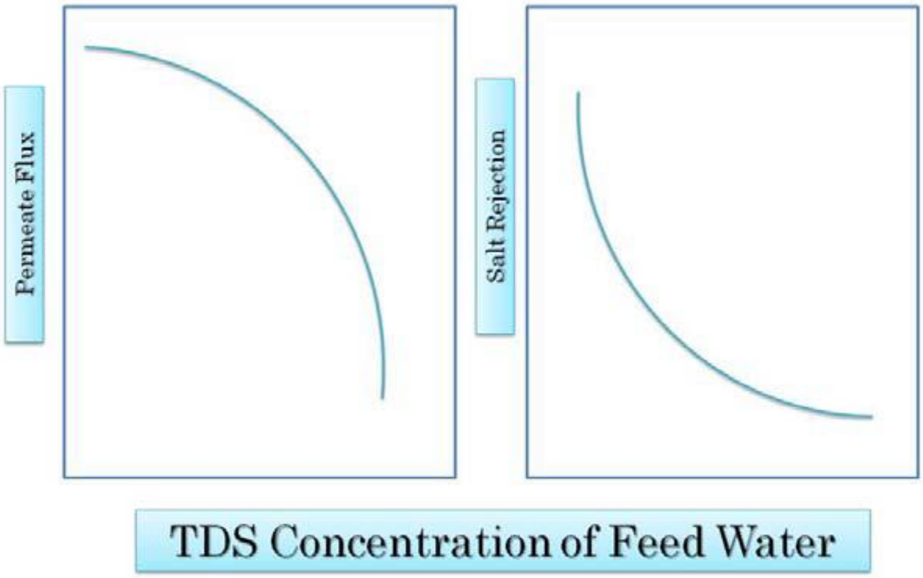


Figure 35: Effect of feedwater salinity in Reverse Osmosis desalination [18]

d. Recovery

Recovery has limited effect on permeate flux and salt rejection until it reaches high concentration polarization levels.

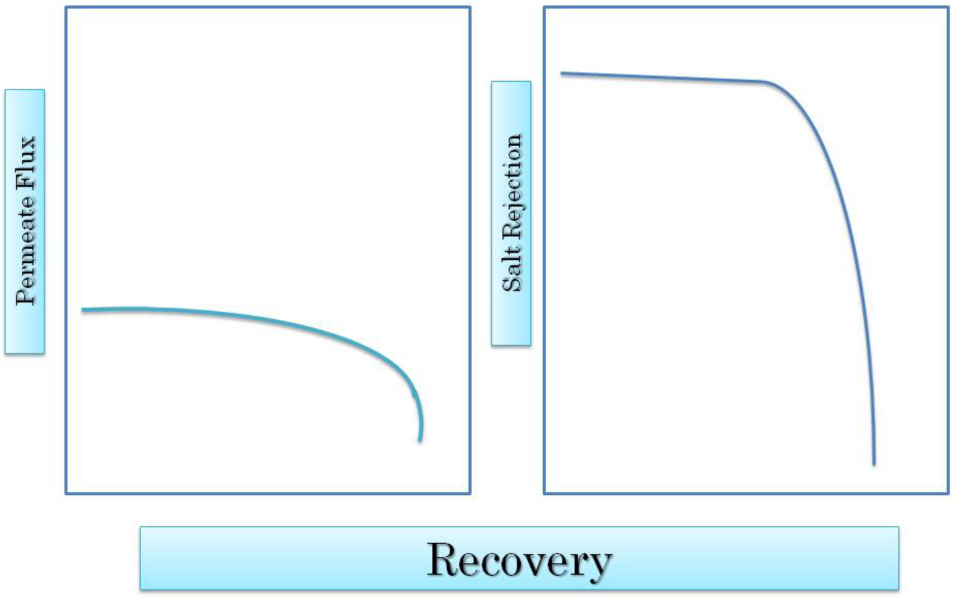


Figure 36: Effect of recovery in Reverse Osmosis desalination [18]

2.6 Energy recovery systems

Reverse osmosis desalination is an energy intensive process in which energy consumption is one of the largest contributors towards the total costs of water supply. In SWRO a large amount of energy is involved in pressurizing the feedwater.

In seawater systems, around 55-60% of the pressurized feedwater leaves the system in the form of the concentrate with about 60bar pressure. The disposal of highly pressurized brine is a major drawback of the system. This energy can be recovered by a recovery device to decrease the specific energy demand of the system and improve its efficiency.

The main function of an energy recovery device is to improve energy efficiency by harnessing the energy of the brine and delivering it back to the feed. This can be done by hydraulic to mechanical assisted pumping, hydraulically driven pumping in series or hydraulically driven pumping in parallel [19].

The concentrate is fed into the energy recovery device, which can be a Pelton wheel, a reverse turning turbine or a Piston type work exchanger, and it produces a rotating power output, which is used to assist the high-pressure pump.

The use of energy recovery systems can lead to energy savings up to 40%.

2.7 PV-RO system

Photovoltaic powered reverse osmosis desalination systems consist of many parts, like the reverse osmosis unit described before, the PV arrays, the charge regulator, the storage batteries and the DC motor, as shown in the diagram below.

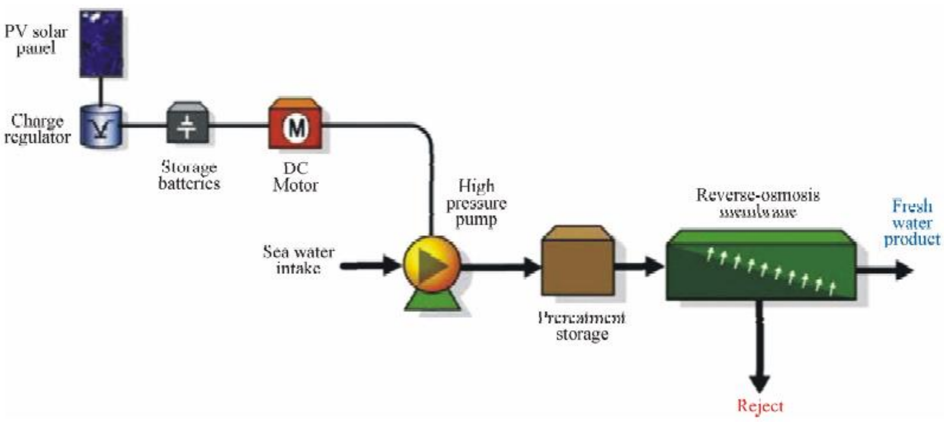


Figure 37: Schematic of a PV powered RO desalination system

Photovoltaics convert sunlight into electricity. PV equipment has no moving parts, thus it requires minimal maintenance and has a long life. PV cells are connected together to form a panel, which protects the cells and provides a usable operating voltage. PV panels are then combined to give the desired electrical output.

The extent at which the PV energy is competitive with conventional energy depends on the plant capacity, on the electricity grid and on the salt concentration of the feedwater, but PV-RO units have better socio-economic and environment benefits compared to diesel generated [5].

Chapter 3
Case study

Iraklia is a small Aegean island, part of small Kyklades, between Naxos and Ios. It has a population of 151 inhabitants, according to the last census of 2011 and its land area is $18km^2$ [20].

The island is not connected to the mainland electricity grid, it has some natural sources of water but most of its potable water is transferred by the mainland with tanker ships. In 2008 the annual transportation of water to Iraklia was $15700m^3$, with minimum monthly $600m^3$ and maximum $3000m^3$ [21].

In 2007, Idriada was placed in Iraklia, the first ever floating desalination unit in the world, supplied with a wind turbine and photovoltaic systems that produce the necessary energy to convert sea water into potable water. It was designed to remain still in the sea, under extreme conditions, and to produce up to $70m^3$ of water per day.

Unfortunately, Idriada wasn't exploited as it could and it was withdrawn from Iraklia. In 2017, the South Aegean District decided to call private companies to install a desalination plant in Iraklia, with total capacity of $300m^3$/day.

The goal of this case study is to design a RO desalination system that will cover the water needs, identify the energy required and the PV system needed to cover the required energy.

3.1 Reverse osmosis plant calculation

3.1.1 Choice of desalination method

Taking into consideration the small water demand of the island (300m^3/day), the abundant solar energy which can be exploited with Photovoltaics and the fact that in Greek islands the most mature technology is Reverse Osmosis, RO powered by PV is the system discussed.

Reverse Osmosis is a preferred desalination method, as it is easy to install and operate and the energy needed is low, especially in a seawater desalination reverse osmosis unit with energy recovery.

RO needs electricity to operate, which can be provided by Photovoltaics, especially in the case of Greek islands, where there is a lot of sunshine all year long and even more during the summertime, when the water demand peaks.

The RO unit has generally small size and, for the specific water demand it can be installed in a container. Furthermore, it is easily expandable in case the water demand grows.
It is generally easy to install and operate, which is very important in the case of a small and remote island.

Finally, it is a mature technology with a lot of experience in the design and installation of the units in Greek islands.

3.1.2 Calculation of membrane system

The heart of the reverse osmosis desalination unit is the membrane system, which is calculated by taking into consideration a lot of factors such as the fresh water demand and the feedwater quality.

The calculation of the reverse osmosis unit was done by following the steps described on the website of the company DOW and by using the software WAVE, provided by DOW [22].

STEP 1: Feed source, product quality and quantity determination

The feedwater is seawater from the Aegean Sea. The values used are from sampling from Milos water, which is close to Iraklia and it is a safe option, a temperature of 25^{o}C and pH of 8.2 are used [16].

The freshwater demand is 300m^3/day of potable water. According to World Health Organization (WHO), the permissible limit of salinity for potable water is 500ppm.

STEP 2: Flow configuration and number of passes

The standard flow configuration for water desalination is plug flow. In plug flow the water is passed once through the system. An RO system is usually designed for continuous operation, as shown in Figure 41.

Figure 38: Continuous Reverse Osmosis process [22]

Depending on the application, sometimes the batch operation mode is preferred. In the batch operation the feedwater is collected to a tank and the concentrate is recycled back to the tank, as shown in Figure 42.

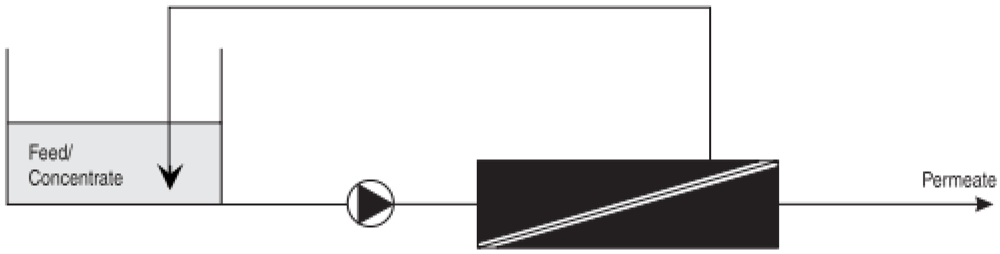


Figure 39: Batch Reverse Osmosis process [22]

A module consists of a pressure vessel with up to eight membrane elements that are connected in series. Single module systems are chosen when only a few membrane elements are needed. A single module system is shown in Figure 43.

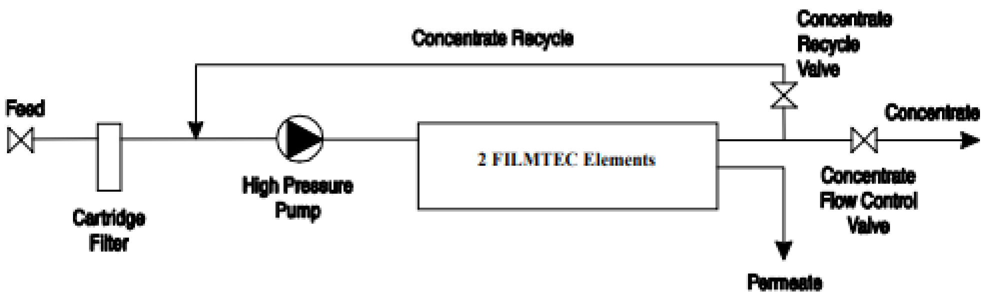


Figure 40: Single module Reverse Osmosis system [22]

In a single stage system, two or more modules can be arranged in parallel, as shown in Figure 44.

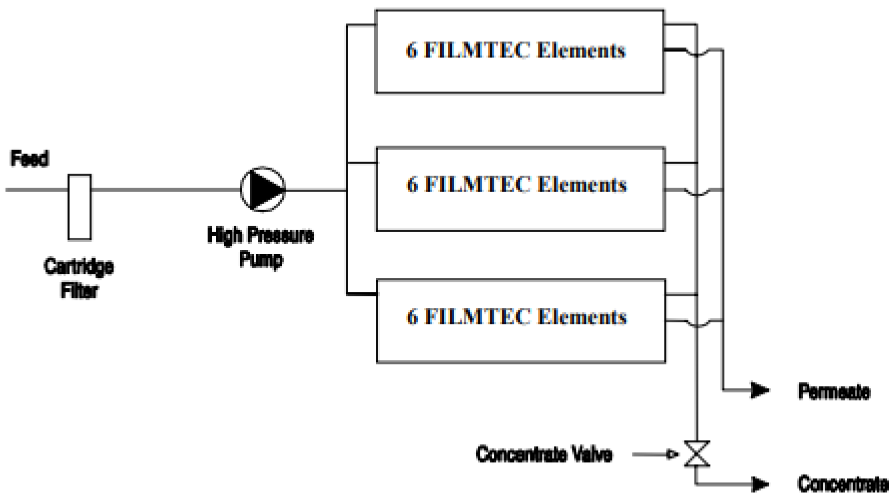


Figure 41: Single-stage, multiple module reverse osmosis system [22]

Systems with more than one stages are used for higher system recoveries, without exceeding the membrane element's recovery limits. An example of a multiple-stage system is shown in Figure 45.

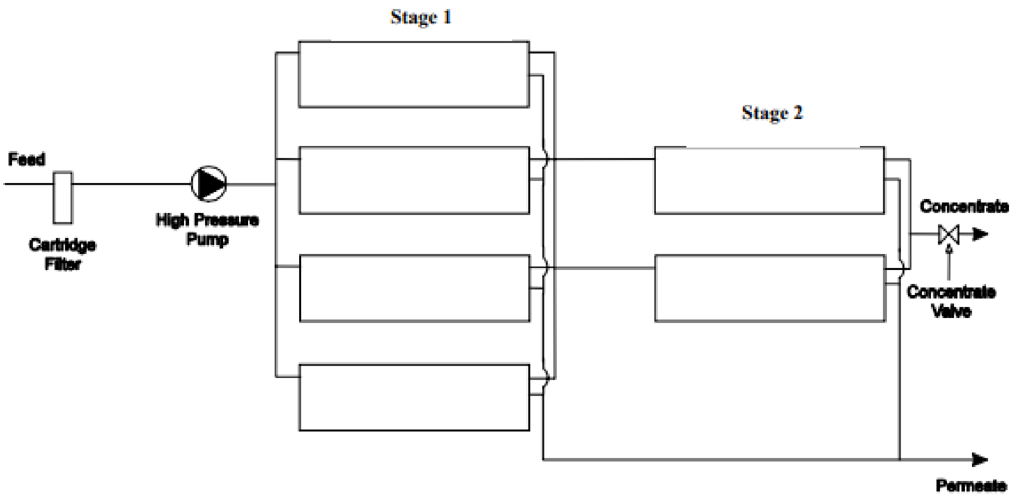


Figure 42: Two-stage reverse osmosis system [22]

A permeate staged systems may be considered for applications that require very high quality product, such as for medical use. Such a system is shown in Figure 46.

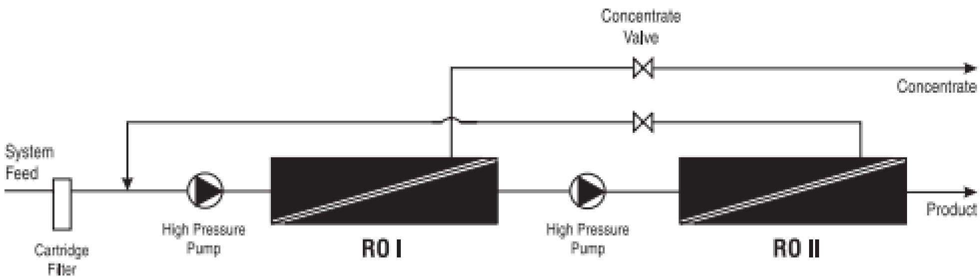


Figure 43: Permeate staged reverse osmosis system [22]

The choice of the appropriate method will be done with the help of the following steps. For reasons of simplicity and as the product demand is not very high, a single pass flow without energy recovery is chosen.

STEP 3: Membrane element determination

According to the company's proposals the membrane chosen for the specific application is a Seawater RO membrane, with high salt rejection, typically used for single pass seawater desalination.

The membrane chosen is SW30XHR-440i, and its specifications are shown in Table 12. It is 8-inches in diameter and 40 inches in length.

SW30XHR-440i	
Active area	40.9m^2
Pressure	55.2 bars
Flow	25m^3/day
Rejection	99.82%
Concentration	32000ppm
Salt	NaCl
Recovery	8%
Diameter	8 inches

Table 12: SW30XHR membrane specifications [22]

STEP 4: Average membrane flux

The average membrane flux is taken by the company's data and it is, for the membrane chosen, and seawater open intake with generic conventional pretreatment f =11.9-17 lmh.

STEP 5: Number of elements

In order to calculate the number of the elements we will use the following formula:

$$N_E = \frac{Q_p}{f \times S_E} = \frac{300/24}{15 \times 10^{-3} \times 40.9} = 20{,}37$$

Where,

NE: the number of elements needed

f: the average membrane flux

SE: the membrane surface area

The number of elements needed is NE=21

STEP 6: Number of pressure vessels

For large systems, 6-element vessels are standard, but vessels with up to 8 elements are available.

As we must have 21 elements we will be using 3 pressure vessels, each one with 7 elements.

STEP 7: Number of stages

The number of stages defines how many pressure vessels in series the feed will pass through until it exits the system.

The number of stages is a function of the planned system recovery, the number of elements per vessel and the feed water quality.

The company suggests the following table for seawater:

System recovery (%)	Number of serial element positions	Number of stages (6-element vessels)	Number of stages (7-element vessels)	Number of stages (8-element vessels)
35 - 40	6	1	1	—
45	7 - 12	2	1	1
50	8 - 12	2	2	1
55 - 60	12 - 14	2	2	—

Table 13: Number of stages of a seawater system [22]

For 50% recovery, and 7 element vessels, we have 2 stages.

STEP 8: Staging ratio

The relation of number of pressure vessels in subsequent stages is called the staging ratio, and it can be calculated by the following formulas:

$$R = [\frac{1}{1-Y}]^{\frac{1}{n}} = 1.414$$

$$R = \frac{N_v(i)}{N_v(i+1)} \;=>\; N_v(1) = 2,\; N_v(2) = 1$$

Where,

R: the staging ratio

Y: the recovery

N: the number of the stages

STEP 9: Balance the permeate flow rate

The permeate flow rate of the tail elements of a system is lower than of the lead elements. The goal of a good design is to balance the flow rate of elements in different positions.

The need for flow balancing and the method used can be determined after the analysis of the system by the software WAVE.

STEP 10: Analyze and optimize the membrane system

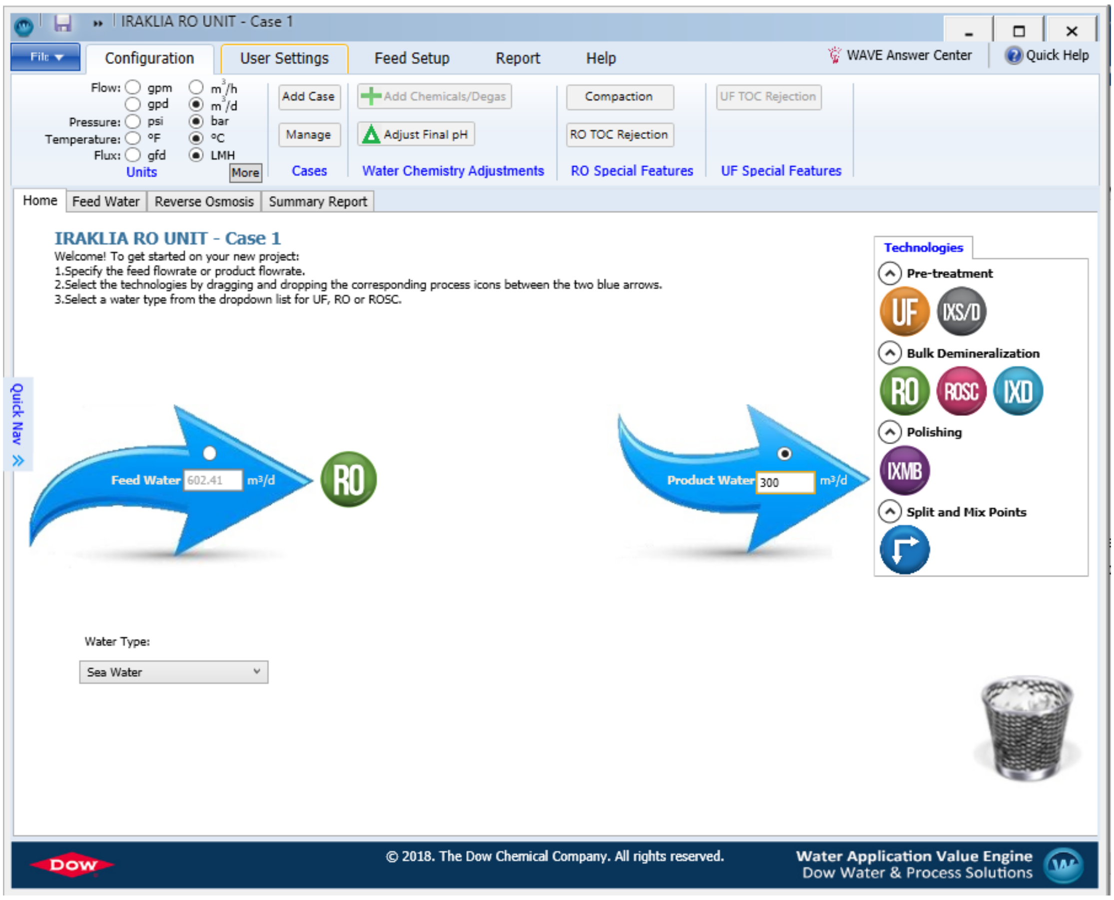
For the last step the system is simulated in the software WAVE, provided by the company DOW.

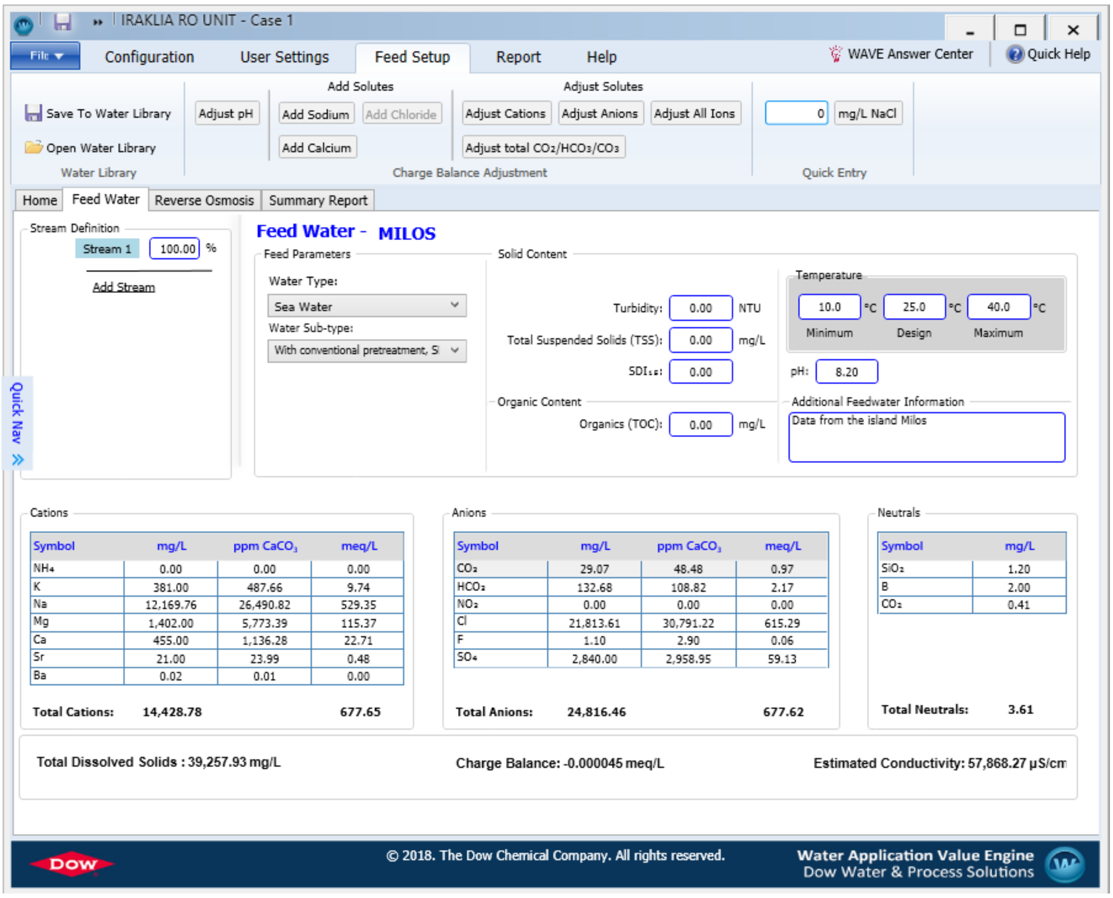
Water Application Value Engine (WAVE) is a modelling software program used to design and simulate the operation of water treatment systems, using Ultrafiltration, Reverse Osmosis and Ion Exchange Resins component technologies.

WAVE ANALYSIS

WAVE software consists of 4 tabs; Home, Feed water, Reverse osmosis, Summary report. The data entered are the feedwater analysis, the temperature and pH, the product flow, the membrane type, the number of elements, elements per vessel and the number of stages. The software has default data for the efficiency of the pump (80%).

The first three tabs, with the data inputs tabs are shown in the Figures below.




IRAKLIA RO UNIT - Case 1
File
Configuration
User Settings
Feed Setup
Report
Help
WAVE Answer Center
Quick Help
Save To Water Library
Open Water Library
Water Library
Adjust pH
Add Solutes
Add Sodium
Add Chloride
Add Calcium
Adjust Solutes
Adjust Cations
Adjust Anions
Adjust All Ions
Adjust total CO2/HCO3/CO3
Charge Balance Adjustment
mg/L NaCl
Quick Entry
Home
Feed Water
Reverse Osmosis
Summary Report
Stream Definition
Stream 1
100.00 %
Add Stream
Quick Nav
Feed Water - MILOS
Feed Parameters
Water Type:
Sea Water
Water Sub-type:
With conventional pretreatment, S
Solid Content
Turbidity: 0.00 NTU
Total Suspended Solids (TSS): 0.00 mg/L
SDI15: 0.00
Organic Content
Organics (TOC): 0.00 mg/L
Temperature
10.0 °C 25.0 °C 40.0 °C
Minimum Design Maximum
pH: 8.20
Additional Feedwater Information
Data from the island Milos
Cations
Symbol mg/L ppm CaCO3 meq/L
NH4 0.00 0.00 0.00
K 381.00 487.66 9.74
Na 12,169.76 26,490.82 529.35
Mg 1,402.00 5,773.39 115.37
Ca 455.00 1,136.28 22.71
Sr 21.00 23.99 0.48
Ba 0.02 0.01 0.00
Total Cations: 14,428.78 677.65
Anions
Symbol mg/L ppm CaCO3 meq/L
CO3 29.07 48.48 0.97
HCO3 132.68 108.82 2.17
NO3 0.00 0.00 0.00
Cl 21,813.61 30,791.22 615.29
F 1.10 2.90 0.06
SO4 2,840.00 2,958.95 59.13
Total Anions: 24,816.46 677.62
Neutrals
Symbol mg/L
SiO2 1.20
B 2.00
CO2 0.41
Total Neutrals: 3.61
Total Dissolved Solids : 39,257.93 mg/L
Charge Balance: -0.000045 meq/L
Estimated Conductivity: 57,868.27 µS/cm
DOW
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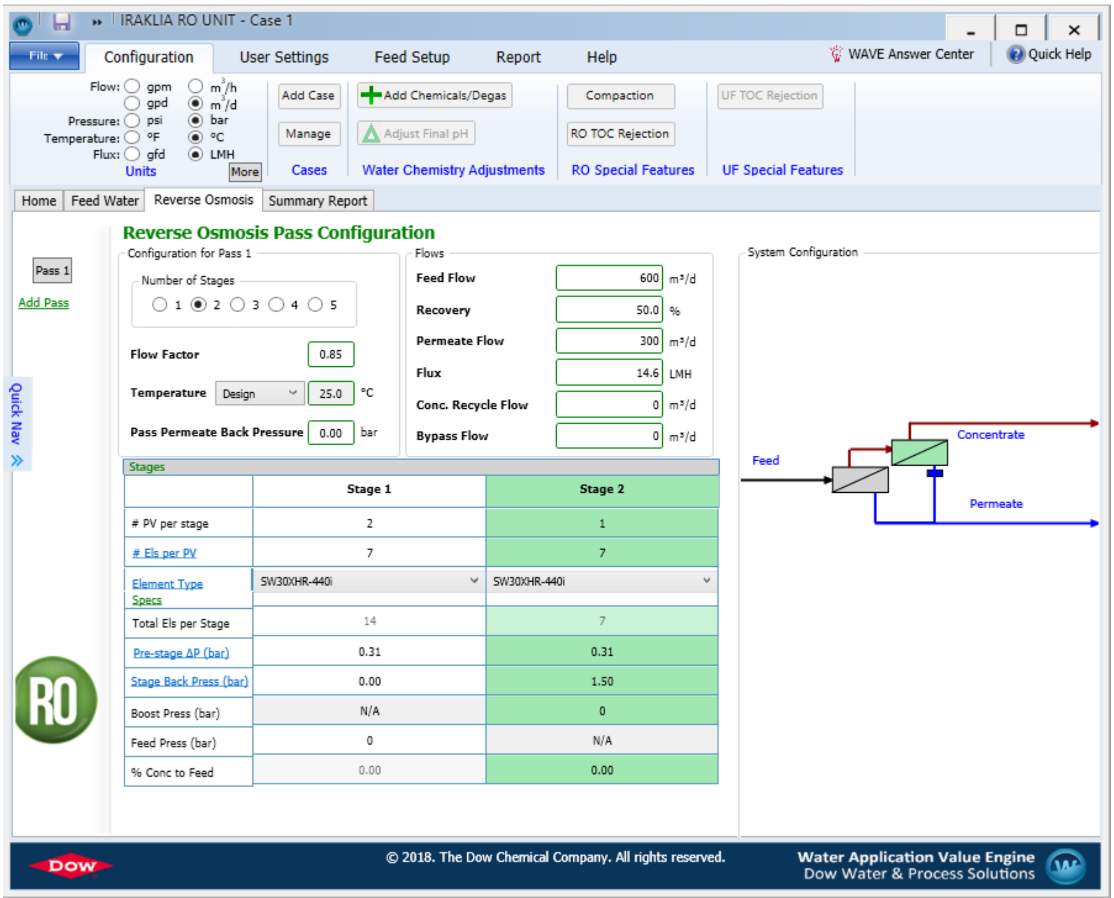
Water Application Value Engine
Dow Water & Process Solutions


IRAKLIA RO UNIT - Case 1
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gpd m³/d
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Temperature: °F °C
Flux: gfd LMH
Units
More
Add Case
Manage
Cases
Add Chemicals/Degas
Adjust Final pH
Water Chemistry Adjustments
Compaction
RO TOC Rejection
RO Special Features
UF TOC Rejection
UF Special Features
Home
Feed Water
Reverse Osmosis
Summary Report
Pass 1
Add Pass
Quick Nav
Reverse Osmosis Pass Configuration
Configuration for Pass 1
Number of Stages
1 2 3 4 5
Flow Factor 0.85
Temperature Design 25.0 °C
Pass Permeate Back Pressure 0.00 bar
Flows
Feed Flow 600 m³/d
Recovery 50.0 %
Permeate Flow 300 m³/d
Flux 14.6 LMH
Conc. Recycle Flow 0 m³/d
Bypass Flow 0 m³/d
System Configuration
Feed
Concentrate
Permeate
Stages
Stage 1 Stage 2
PV per stage 2 1
Els per PV 7 7
Element Type Specs SW30XHR-440i SW30XHR-440i
Total Els per Stage 14 7
Pre-stage ΔP (bar) 0.31 0.31
Stage Back Press (bar) 0.00 1.50
Boost Press (bar) N/A 0
Feed Press (bar) 0 N/A
% Conc to Feed 0.00 0.00
RO
DOW
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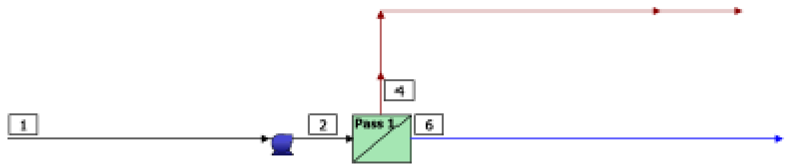
Water Application Value Engine
Dow Water & Process Solutions

The results of the simulation are shown in the Tables below.

RO System Flow Diagram



#	Description	Flow (m³/d)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to Pump	601.9	39,258	0.0
2	Net Feed to Pass 1	600.0	39,381	70.9
4	Total Concentrate from Pass 1	301.0	78,343	64.7
6	Total Permeate from Pass 1	300.0	149.7	0.0

Figure 44: RO system flow diagram

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	49.8 %
System Flow Rate	(m³/d)	Net Feed =	601.9	Net Product =	300.0		

Pass		Pass 1
Stream Name		MILOS
Water Type		Sea Water (With conventional pretreatment, SDI < 5)
Number of Elements		21
Total Active Area	(m^2)	858
Feed Flow per Pass	(m^3/d)	600.0
Feed TDS[a]	(mg/L)	39,381
Feed Pressure	(bar)	70.9
Flow Factor		0.85
Permeate Flow per Pass	(m^3/d)	300.0
Pass Average flux	(LMH)	14.6
Permeate TDS[a]	(mg/L)	149.7
Pass Recovery		50.0 %
Average NDP	(bar)	23.2
Specific Energy	(kWh/m^3)	4.95
Temperature	(°C)	25.0
pH		8.2
Chemical Dose		
RO System Recovery		49.8 %
Net RO System Recovery		49.8%

Table 14: RO system overview

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/d)	Recirc Flow (m^3/d)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/d)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/d)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30XHR-440i	2	7	600.0	0.00	70.5	0.0	338.2	68.5	2.1	262.7	19.1	0.0	105.3
2	SW30XHR-440i	1	7	338.2	0.00	68.2	0.0	301.0	64.7	3.4	37.3	5.4	1.5	462.4

Table 15: RO flow table

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)						
		Concentrate		Permeate		
	Feed	Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	381.0	677.0	759.8	1.35	6.10	1.94
Na^+	12,170	21,629	24,279	37.80	166.6	53.83
Mg^{+2}	1,402	2,494	2,802	1.02	4.34	1.43
Ca^{+2}	455.0	809.5	909.3	0.33	1.40	0.46
Sr^{+2}	21.00	37.36	41.97	0.02	0.06	0.02
Ba^{+2}	0.02	0.04	0.04	0.00	0.00	0.00
CO_3^{-2}	29.07	52.99	59.55	0.00	0.00	0.00
HCO_3^-	132.7	233.6	261.9	0.60	2.42	0.83
NO_3^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	21,814	38,773	43,527	62.15	273.7	88.48
F^-	1.10	1.95	2.19	0.00	0.02	0.01
SO_4^{-2}	2,840	5,054	5,677	0.81	3.40	1.13
SiO_2	1.20	2.13	2.39	0.01	0.03	0.01
Boron	2.00	3.39	3.72	0.22	0.75	0.28
CO_2	0.41	0.92	1.08	0.53	0.85	0.57
TDS*	39,258	69,784	78,343	105.3	462.4	149.7
pH	8.2	8.2	8.2	6.2	6.6	6.3

Table 16: RO solute concentrations

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/d)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/d)	Perm Flow (m^3/d)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30XHR-440i	9.2	300.0	70.5	39,380	272.4	27.7	28.2	56.52
1	2	SW30XHR-440i	9.1	272.4	70.1	43,362	247.8	24.7	25.2	68.95
1	3	SW30XHR-440i	8.7	247.8	69.8	47,666	226.2	21.7	22.1	85.31
1	4	SW30XHR-440i	8.2	226.2	69.4	52,204	207.7	18.6	18.9	107.0
1	5	SW30XHR-440i	7.5	207.7	69.2	56,849	192.2	15.6	15.9	136.2
1	6	SW30XHR-440i	6.7	192.2	68.9	61,435	179.4	12.8	13.1	175.5
1	7	SW30XHR-440i	5.8	179.4	68.7	65,794	169.1	10.3	10.5	228.3
2	1	SW30XHR-440i	2.4	338.2	68.2	69,782	330.0	8.20	8.4	290.0
2	2	SW30XHR-440i	2.1	330.0	67.6	71,501	323.0	7.03	7.2	343.6
2	3	SW30XHR-440i	1.9	323.0	67.1	73,043	317.1	6.00	6.1	408.1
2	4	SW30XHR-440i	1.6	317.1	66.6	74,412	312.0	5.10	5.2	485.7
2	5	SW30XHR-440i	1.4	312.0	66.1	75,615	307.7	4.32	4.4	579.0
2	6	SW30XHR-440i	1.2	307.7	65.6	76,662	304.1	3.64	3.7	691.4
2	7	SW30XHR-440i	1.0	304.1	65.2	77,567	301.0	3.06	3.1	827.0

Table 17: RO flow table

Product quality control		
	Permeate (mg/lt)	*Max. allowed (mg/lt)*
NH_4	0	0.5
K	1.94	12
Na	53.83	200
Mg	1.43	50
Ca	0.46	-
Sr	0.02	-
Ba	0	-
CO_3	0	-
HCO_3	0.83	-
NO_3	0	50
Cl	88.48	250
F	0.01	1.5
SO_4	1.13	250
SiO_2	0.01	-
B	0.28	1
CO_2	0.57	-
TDS	149.7	1500
pH	6.3	6.5-9.5

Table 18: Permeate quality control

As seen in Table 18 all the solid concentration are within the allowed limits. The pH value is lower, so there has to be fixed in the post-treatment.

The simulation gave a warning about the drop pressure at the second stage of the unit, so a permeate backpressure (1.5bars) was added to overcome the problem, since it is the lower system cost alternative.

3.2 Installation of a PV park to cover the needs of the RO units

A PV system design can be done by following 4 steps:

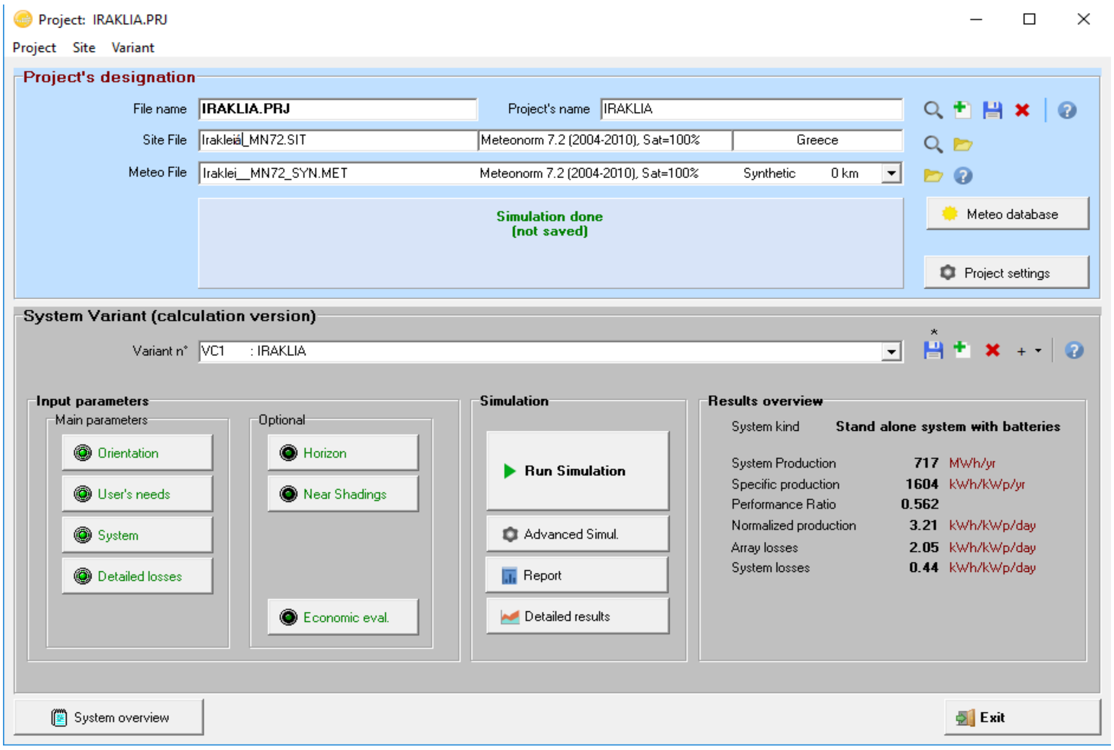
- Load estimation
- Estimation of PV panels
- Estimation of battery
- Estimation of cost

The specific energy required by the RO unit is 4.95kWh/m3, which means that for a 24h operation the load needed by the PV system is $E = \frac{4.95 \times 300}{24} = 61.875kW$.

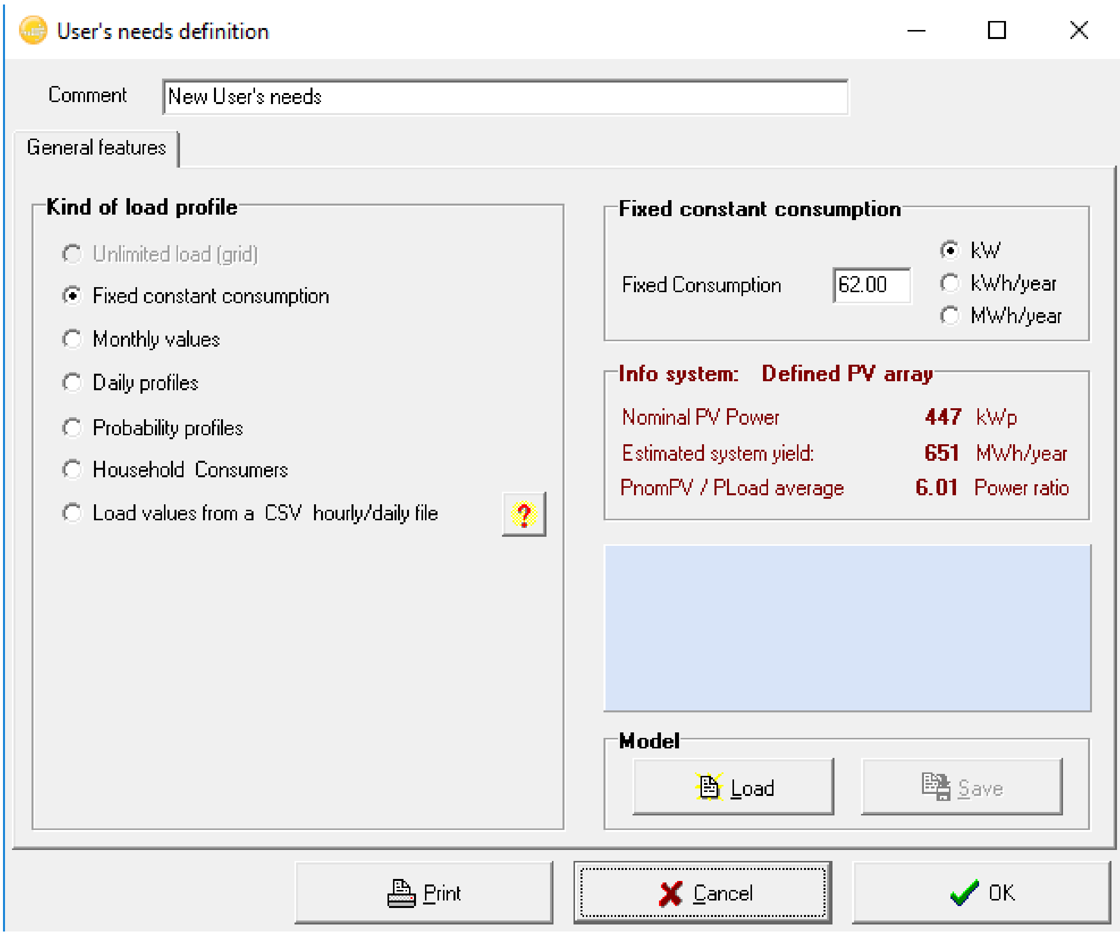
The actual power output of a PV panel depends on the peak power rating and the operating factor, and the combined efficiencies of the system.

The PV system needed to cover the Reverse Osmosis unit electricity demand will be calculated with the use of PVsyst software [23]. The tabs of the software are shown in the figures below.

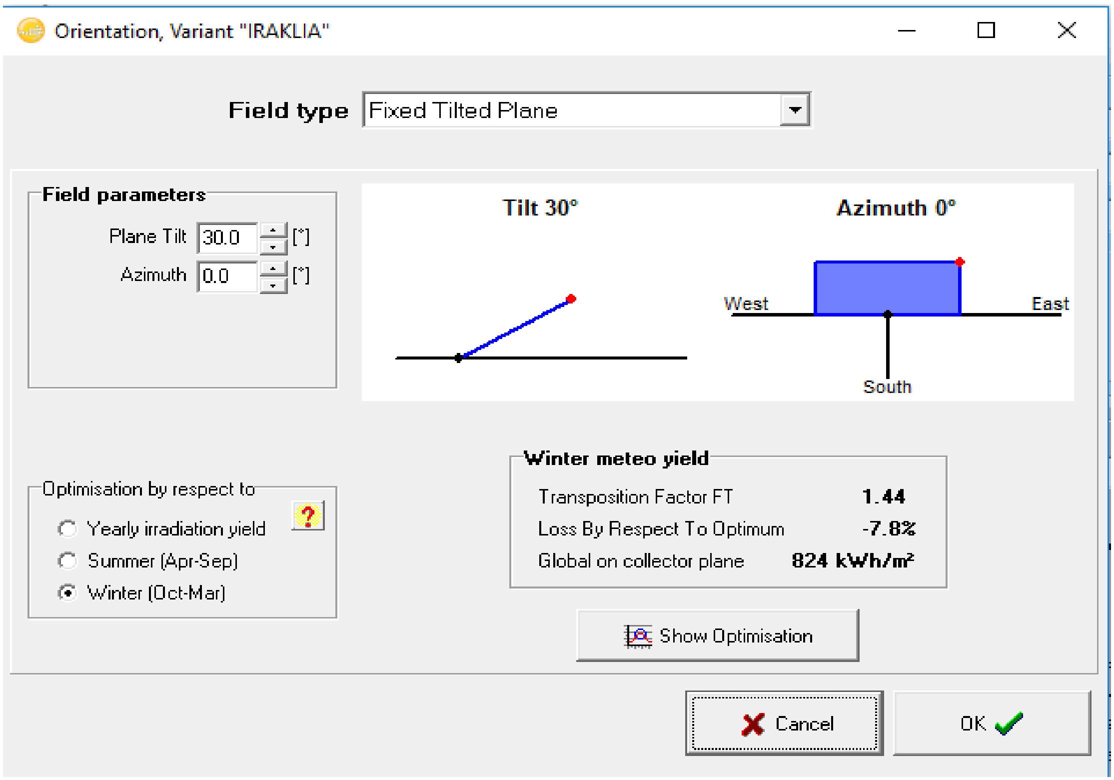
The system we are designing is a stand-alone PV system, set in the island of Iraklia, Kyklades. The meteorological data used are from the island of Naxos, which is about 30km away and is the safest option from the database.



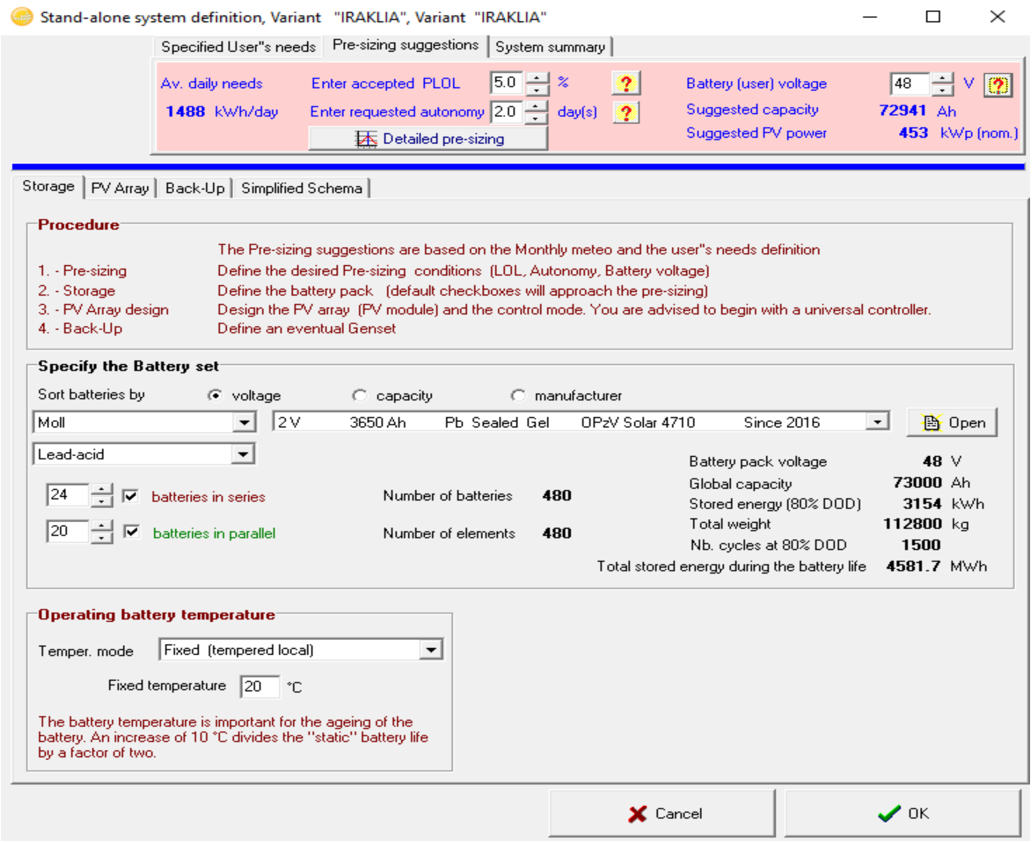
For reasons of simplicity, the system has a standard load of 62kW, operates 24h/day and we assume that the energy needs are the same throughout the year.



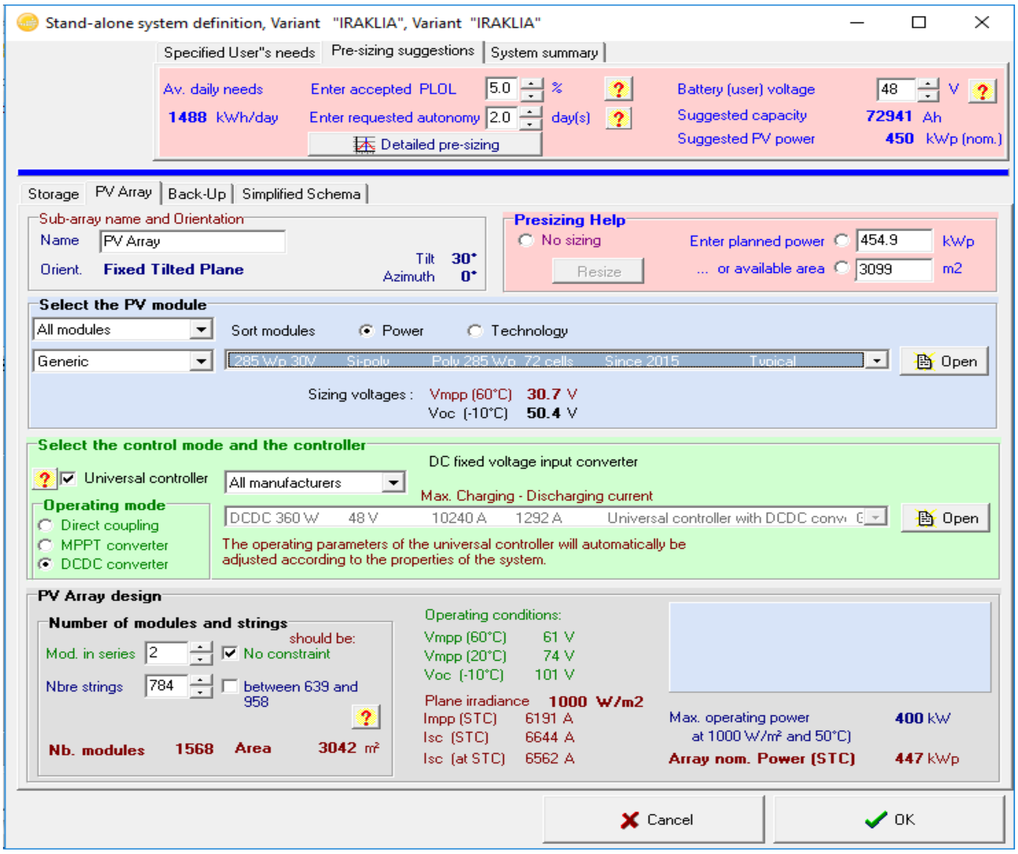
For Greece, the best orientation of the PV panels is 30º tilt and 0º azimuth. The optimization of the system is done by respect to winter. For lower cost and simpler installation fixed tilted panels are chosen.



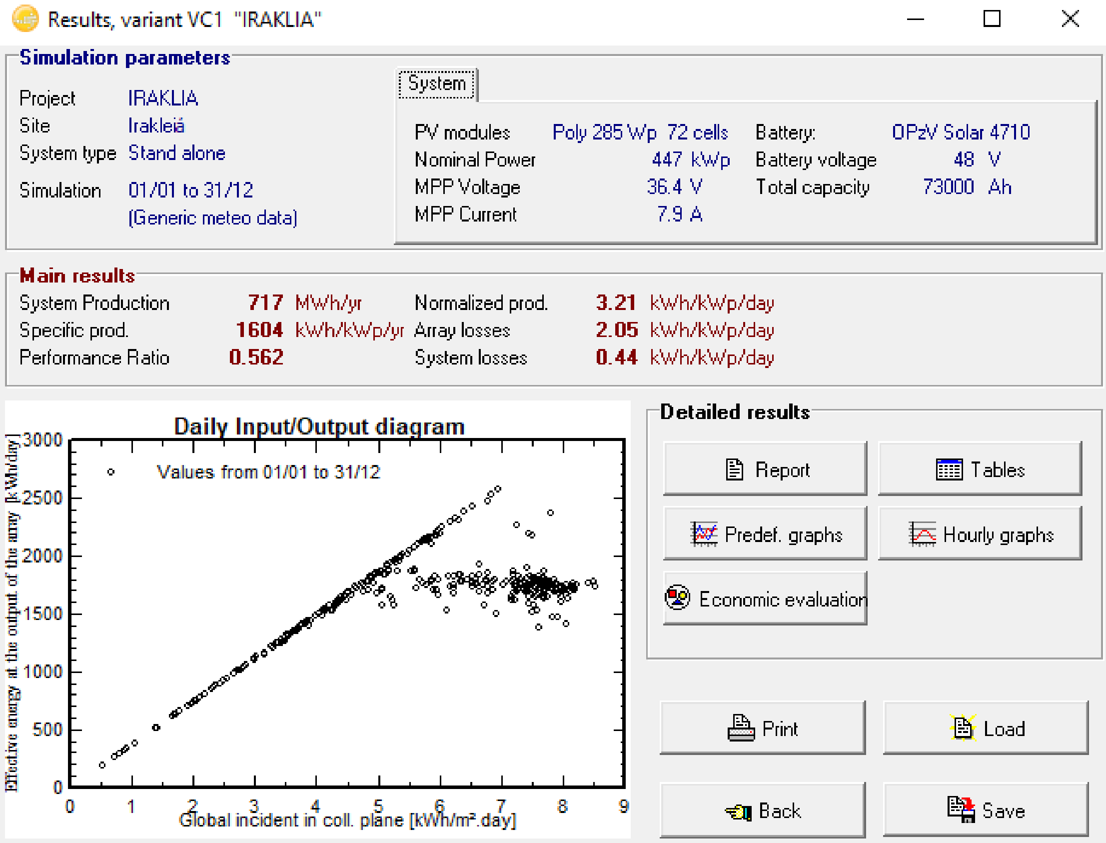
The autonomy needed by the batteries is estimated at 2 days. The battery voltage was chosen 48V, as the software recommends 48V for industrial use, and lower for domestic use. The battery type chosen was a 2V, 3650Ah, Lead-acid battery by OPzV Solar, from the database. The total number of batteries needed for our system is 480.



The PV module chosen is a generic 285Wp 30V, Si-poly module from the database. A simple DC-DC controller is used, as it is cheaper and the PV array results in 1568 modules covering an area of 3042m^2.



The main results are shown in the picture below.



No back-up generator is used, for reasons of simplicity. All the system's losses and efficiencies where calculated by default by the program.

For a more in depth analysis, the systems working hours, depending on the season could be identified, the performance ratio of a chosen PV panel, all the system's components' efficiencies, the exact temperature of the site, etc.

3.3 Evaluation of the system

In order for the PV-RO plant to be economically viable, the cost of the water produced must be lower than the cost of the water in the current status.

The water cost per m^3 can be calculated by the following formula:

$$WC = \frac{(IC_{RO} + IC_{EN}) \times R + OM + EC - ES}{WP}$$

Where,

IC_{RO}: the reverse osmosis installation cost

IC_{EN}: the photovoltaic system installation cost

R: the annuity factor, $R = \frac{i}{1-(1+i)^{-n}}$, i is the interest rate and n the duration of the investments

OM: the annual operation and maintenance cost that contains consumables, chemicals for pre- and post- treatment, membrane replacements, labor and insurance.

WP: the annual water production

EC: the annual cost of energy

ES: the income from energy sale

The data for the calculation of the water cost production were retrieved by bibliographical research [9,21].

The annual transportation of water in Iraklia for 2008 was 15700m^3 . Based on historical data on the water transportation needs, an assumed increase of 20% on water demand will be taken into account. So we consider WP=18840m^3.

The desalination unit installation cost for a unit of 300m^3 capacity is considered IC_{RO}=280000€.

The cost of the PV system was calculated as fixed price of 3000€/kWp, which in our case results in $IC_{EN} = 3000 \times 62 = 186000$€.

The cost for labor is considered fixed at 25000€/year.

The cost for chemicals is variable and depends on the water production. It is considered 0.065×WP=1225€/year.

The membrane cost is considered 0.15×WP=2826€/year.

The consumables and other costs are considered 0.04×WP=754€/year.

The insurance is considered 0.05×(IC_{RO}+IC_{EN}) = 81050€/year.

For i=7% and n=20 years, the annuity factor is $R = \frac{0.07}{1-(1+0.07)^{-20}} = 0.0944$.

The cost of water, when the desalination unit is powered by the PV system, is calculated:

$$WC = \frac{(IC_{RO}+IC_{EN})\times R+OM}{WP} = \frac{(280000+186000)*0.0944+25000+1225+2826+754+81050}{18840} = 8.22 \text{ €/m3}.$$

As there is no annual cost of energy and all the energy produced by the PV system is going to the desalination unit.

The cost of the produced water is very high, mainly due to the PV system, but it is still less than the cost of water transported to the island, which can reach 10€/m^3.

Alongside with the water cost, there are a lot of advantages at installing a PV-RO system, such as the security of daily water supply, the environmental benefits and the socioeconomic benefits for the area.

Without the renewable energy system the water cost is calculated by taking into consideration the annual electricity cost from the grid. The RO system needs 4.95kWh/m^3, which is 93258kWh/year for 18840m^3.

Considering the RO plant is an industrial installation and that the island is not connected to the mainland grid, and the power installation is diesel engines, the cost of electricity is 3.28*12++0.11529*93258=10791€.

The insurance cost is 0.05×(ICRO) = 14000€/year.

The water cost is then calculated:

$$WC = \frac{(IC_{RO}) \times R + OM + EC}{WP}$$
$$= \frac{280000 * 0.0944 + 25000 + 1225 + 2826 + 754 + 14000 + 10791}{18840}$$
$$= 4.3€/\mathrm{m3}$$

Chapter 4
Conclusions

The goal of this project was to study the possibility and technology available to deal with water stress around the world, by using seawater desalination powered by renewable energy sources.

The selection of the appropriate desalination system depends on a number of factors, such as the plant size, the feedwater quality, the product water demand, the technical infrastructure and the renewable energy source potential at the installation place.

There are a lot of available combinations of desalination systems with renewable energy sources. The appropriate combination of renewable powered desalination also depends on the quality and quantity of the product water and mainly at the local availability.

The most popular and commercial combination technologies are Reverse Osmosis with photovoltaics and Multiple Effect Distillation with thermal collectors.

Reverse osmosis powered by photovoltaics is a very good choice for district areas with a lot of sunshine, like the case of the Aegean islands. The technology of reverse osmosis plants is very mature, and the Greek islands have a lot of sun all year long.

The case study is about a PV powered RO plant in the island of Iraklia, Greece. The goal of the case study was to investigate the methodology used to calculate a Reverse Osmosis unit, focusing on the membrane assembly, and the power required for its operation.

Iraklia has relatively low water demand, is powered by diesel engines and has water transferred from the mainland by tanker ships.

The installation of a desalination plant is a necessity and since the island is not connected to the grid, due to the high cost of the electricity, the installation of a renewable energy park is a considerable choice, even though the PV park really increases the cost of the total installation.

The cost of water is very high when installing a PV- RO system, a lot higher than installing a RO system powered by the grid, but still lower than the cost of water transferred with tankerships by the mainland.

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