Renewable Energy Applications in Water Desalination

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Al-Karaghouli has served as a Technical Advisor and a Consultant on Renewable Energy at the United Nations Environmental Program in West Asia UNEP/ROA (2006-Dec. 2007). He was a professor of mechanical engineering and Director of the Energy Research Center at the University of Bahrain from 1998-2006. He has also served as the Director of the Energy and Environmental Research Center in Baghdad-Iraq (1997-1998), Director of the Solar Energy Research Center in Baghdad-Iraq (1993-1997), Director of the Regional Center for NSRE Information Network for the ESCWA Region (1990-1995), Chairman of Engineering Department at the Solar Energy Research Center (1988-1993), Chairman of Agriculture Applications Department at the Solar Energy Research Center (1983-1988), Design Engineer at Sun System Inc. Eureka, Ill, USA (1976-1978), and as a Design Engineer at the State Organization for Construction and Industrial Design- Ministry of Industry, Iraq (1968-1975).

Al-Karaghouli was a post-doctorate at Washington State University (Feb.-June, 1983) and has a PhD in mechanical engineering from Washington State University (1983). Other degrees include MS in mechanical engineering from Bradley University (1976), and BS in electrical engineering from the University of Mosel–Iraq (1968). He holds four patents, is the author of two books, and has more than ninety published papers in the field of renewable energy and energy conservation.

Relevant Papers

•Economic Analysis of a Brackish Water Photovoltaic-Operated (BWRO-PV) Desalination System *http://wrri.nmsu.edu/conf/conf11/economic_analysis_BWRO-PV.pdf*

•*Technical and economic assessment of photovoltaic-driven desalination systems http://wrri.nmsu.edu/conf/conf11/photovoltaic_desal_systems.pdf*

•*Renewable Energy Opportunities in Water Desalination http://wrri.nmsu.edu/conf/conf11/renewable_energy_water_desal.pdf*

•*Economic and Technical Analysis of a Reverse-Osmosis Water Desalination Plant using DEEP-3.2 Software http://wrri.nmsu.edu/conf/conf11/reverse_osmosis_deep.pdf*

•*Performance and Economic Analysis of a Medium-Size Reverse-Osmosis Plant using HOMER and DEEP-3.2 Software*

•*Solar and wind opportunities for water desalination in the Arab regions http://wrri.nmsu.edu/conf/conf11/solar_wind_desal_arab.pdf*

PowerPoint Presentation

http://wrri.nmsu.edu/publish/watcon/proc56/Al-Qaraghuli.pdf

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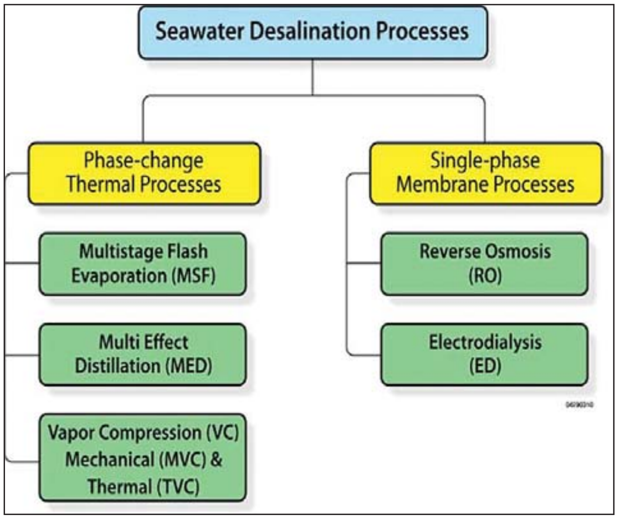

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Solar Water Desalination *(cont.)*

I-Phase-change processes

a. Multi-stage flash distillation (MSF).

b. Multi-effect distillation (MED).

c. Vapor compression (VC), thermal (TVC) and mechanical (MVC).

Other phase change desalination processes include **solar still distillation**, **humidification/ dehumidification, membrane distillation** and **freezing.**

II-Membrane Processes

a. Reverse Osmosis (RO).

b. Electrodialysis (ED & EDR).

There are also three other membrane processes which are not considered desalination processes but are relevant. These are: **Microfiltration (MF), Ultrafiltration (UF), and Nanofiltration (NF).** The **ion-exchange process** is also not regarded as a desalination process, but is generally used to improve water quality for some specific purposes.

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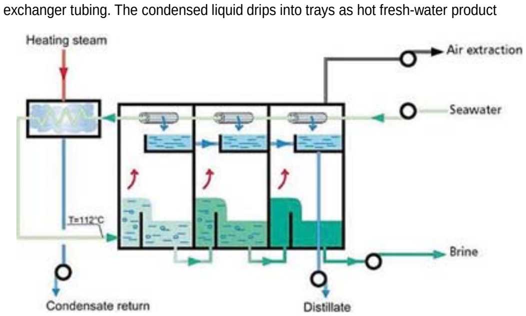
Distillation Processes *(cont.)*

Multi-stage flash distillation (MSF)

When the seawater is heated (90 to 110 C) and discharged into a chamber maintained at slightly below the saturation vapor pressure of the water, a fraction of its water content flashes into steam. The flashed steam condenses on the exterior surface of the heat-exchanger tubing. The condensed liquid drips into trays as hot fresh-water product



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MSF Power consumption and fresh water cost

Typical unit size: 50,000 to 70,000 m^3 /day

Top brine temperature: 90 C to 110 C

Typical gained output ratio (G.O.R) range between 6 to 8

G.O.R = kg of distillate/ kg of steam

Power consumptions:

Electrical energy: 4-6 kWh/ m^3

Thermal energy: 190 kj/kg (G.O.R =12.2) & 390 kj/kg (G.O.R =6)

Electrical equivalent for thermal energy: 9.5 to 19.5 kWh/ m^3

Total equivalent energy consumption: 13.5 to 25.5 kWh/ m^3

Cost range of product water: The average unit cost has fallen from about 9.0 $/$m^3$ in 1960 to about 1.0 $/$m^3$ at present.

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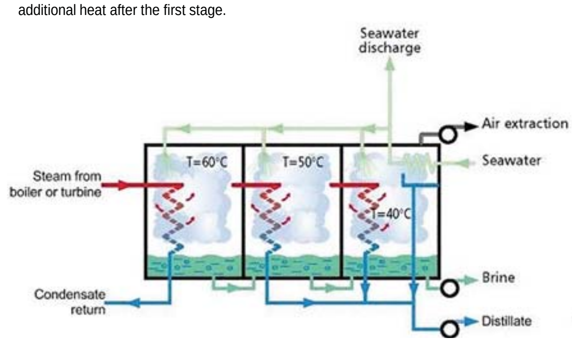
Distillation Processes *(cont.)*

Multi-effect distillation (MED)

MED units operate on the principle of reducing the ambient pressure at each successive stage, allowing the feed water to undergo multiple boiling without having to supply additional heat after the first stage.



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MED power consumption and fresh water cost

Typical unit size: 5,000 to 15,000 m^3 /day

Top brine temperature: 66 C to 72 C

G.O.R ranges between 8 and 12

Power consumptions:

Electrical energy: 1.5 to 2.5 kWh/ m^3

Thermal energy: 230 kj/kg (G.O.R =10) & 390 kj/kg (G.OR =6)

Electrical equivalent for thermal energy: 5.0 to 8.5 kWh/ m^3

Total equivalent energy consumption: 6.5 to 11.0 kWh/ m^3

Cost range of product water: The production cost of the MED process has fallen from 10.0 $/$m^3$ in the 1950's to about 1.0 $/$m^3$ today.

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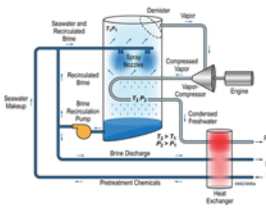
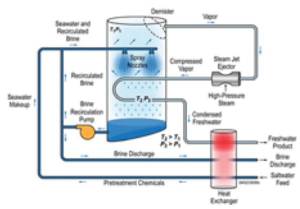
Distillation Processes *(cont.)*

Vapor-compression distillation

The heat for evaporating the water comes from the compression of vapor, rather than from the direct exchange of heat from steam produced in a boiler. Two primary methods are used to condense vapor so as to produce enough heat to evaporate incoming seawater: a mechanical compressor (MVC) or a steam jet (TVC).



MVC System



TVC System

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RO Process- Cont.

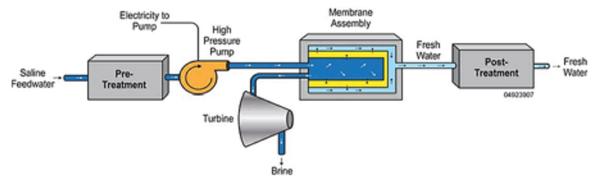
A typical RO system consists of four major subsystems:

Pretreatment: Removing suspended solids, adjusting the pH, and adding a threshold inhibitor to control scaling

Pressurization: Pump raises the pressure of feed water to an operating pressure appropriate for the membrane and the salinity of the feed water.

Separation: The permeable membranes inhibit the passage of dissolved salts while permitting the desalinated product water to pass through.

Stabilization: pH adjustment (from a value of about 5 to close to 7) and disinfection is employed to kill any bacteria, protozoa and virus that have bypassed the desalination process into the product water. Disinfection may be done by means of ultraviolet radiation, using UV lamps directly on the product, or by chlorination or chloramination (chlorine and ammonia).



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MVC and TVC Power consumption and fresh water cost

MVC Process
Typical unit size: 100 to 3000 m^3 /day
Top brine temperature: 74 C
Total equivalent energy consumption: 11.0 kWh/ m^3 based on 3000 m^3 / day capacity
TVC Process
Typical unit size: 10,000 to 35,000 m^3 **/day**
Top brine temperature : 70 C
G.O.R : 12
Power consumptions:
Electrical energy: 1.8 kWh/ m^3
Thermal energy: 187 kj/kg(G.O.R =12)
Electrical equivalent for thermal energy: 9.4 kWh/ m^3
Total equivalent energy consumption: 11.2 kWh/ m^3
Cost range of product water: The unit production cost ($/ m^3) of the VC process has also decreased considerably over time, from 5.0 $/$m^3$ in 1970 to about 1.0 $/$m^3$ at present .

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RO process - cont.

Membrane specifications:

RO membrane must be **freely permeable to water**, **highly impermeable to solutes**, and **able to withstand high operating pressures**. It should **ideally be tolerant of wide ranges of pH and temperature** and should be **resistant to attack by chemicals like free chlorine and by bacteria.**

Membrane materials:

Polymers of either **cellulose acetates** (cellulose diacetate, cellulose triacetate, or combinations of the two) , **or polyamide polymers**.

Membrane types:

Two types of RO membranes commonly used commercially are : **spiral-wound (SW) membranes and hollow-fiber (HF) membranes.** Other configurations, including tubular and flat plate-frame designs, are sometimes used in the food and dairy industries.

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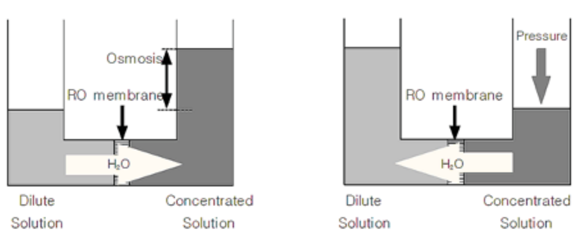
Membrane processes / Reverse Osmosis (RO) Process

Theory of Reverse Osmosis Membrane

When two water (or other solvent) volumes are separated by a semi-permeable membrane, water will flow from the volume of low solute concentration, to the volume of high solute concentration.
The flow may be stopped, or even reversed by applying external pressure on the volume of higher concentration. In such a case the phenomenon is called **reverse osmosis.**



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RO Power consumption and fresh water cost

Typical unit size: 24,000 m^3 /day

For Seawater RO (based on 41,500 ppm)
Electrical energy consumption: about 5 kWh/m^3

For brackish water RO (based on 5000 ppm)
Electrical energy consumption : 2.1 kWh/m^3
Water Production cost:
The average unit cost ($/$m^3$) of RO system have declined from 5.0 $/$m^3$ in 1970 to less than 1.0 $/ m^3 today. A decline in cost is reported, to $0.55/$m^3$ for a large RO project in Florida (USA).

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Energy requirements of the four main industrial desalination processes

	MSF	MED-TVC	MED	MVC	RO
Typical unit size $m^3 d^{-1}$	50,000 - 70,000	10,000 - 35,000	5,000 - 15,000	100 - 2500	24,000
Electrical Energy Consumption kWh m^{-3}	4 – 6	1.5 – 2.5	1.5 – 2.5	7 - 12	3 – 5.5
Thermal Energy Consumption kJ kg^{-1}	190 (GOR =12.2) – 390 (GOR =6)	145 (GOR =16) – 390 (GOR =6)	230 (GOR =10) – 390 (GOR =6)	None	None
Electrical Equivalent for Thermal Energy kWh m^{-3}	9.5 – 19.5	9.5 – 25.5	5 – 8.5	None	None
Total Equivalent Energy Consumption kWh m^{-3}	13.5 - 25.5	11 - 28	6.5 - 11	7 - 12	3 - 3.5

Source: WANGNICK CONSULTING (2010)

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Filteration

Microfiltarion (MF).

MF is ideal for removing: suspended solids and turbidity, bacteria and protozoa .Applied pressure operation is 30 to 500 kPa. Particle size removed 0.1-0.5 micron. Mostly used in the pharmaceutical industry.

Ultrafiltration (UF)

UF removes oils, colloidal solids , and other soluble pollutants and turbidity, and remove bacteria, protozoa and some viruses. Applied pressure operation is 30 to 500 kPa. The minimum particle size removed between 0.005 – 0.05 micron. Produced waters from the oil and gas industries can be effectively treated to remove oil and recycle the water.

Nanofiltration (NF)

NF membrane removes: turbidity , color , hardness , synthetic organic contaminant , sulfur , and virus . NF membrane operates under applied pressure between 500 to 1000 kPa. The minimum particle size removed between 0.0005- 0.001 microns. It is considered to be the state of the art in water purification.

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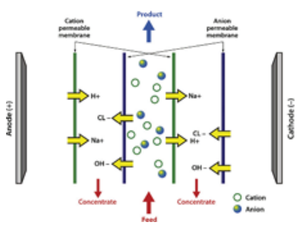
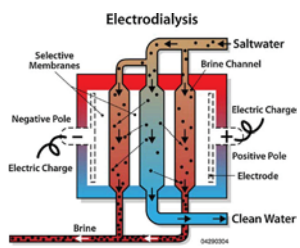
Membrane water desalination (cont.)

Electrodialysis (ED & EDR)

Electrodialysis (ED) is an electrochemical separation process that uses electrical currents to move salt ions selectively through a membrane, leaving fresh water behind.





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Combined heat and power (CHP) and hybrid desalination systems

Cogeneration or Combined heat and power (CHP):

It is the simultaneous production of electricity and the utilization of "waste" heat for water desalination or any other heating requirements.

Hybrid desalination systems: It is the use of more than one desalination process in one plant. A number of hybrid desalination systems have been proposed over the past years.

Examples are combination of:

- MSF, MED or VC with SWRO.
- RO, ED and UF.
- RO, UF and MSF or MED.
- VC with MSF or MED.

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ED power consumption and fresh water cost

For ED (based on brackish 2500ppm)

Electrical energy consumption: about 2.64 kWh/m^3

For ED (based on brackish 5000ppm)

Electrical energy consumption: about 5.5 kWh/m^3

Water production cost:

ED unit for brackish water desalination has gone down from 3.5 \$/m^3 in the 1960's to the average unit cost about 0.6 \$/m^3 at present.

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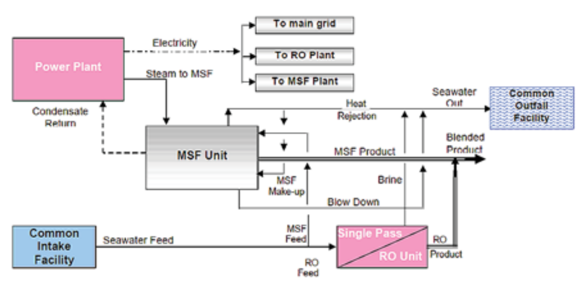
Combined heat and power plant



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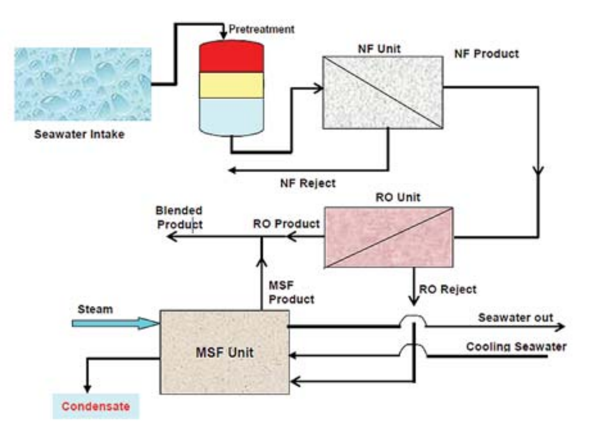
Hybrid system



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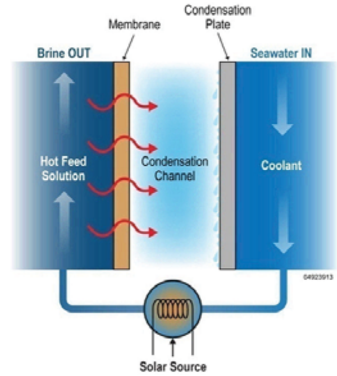
Other desalination processes / Membrane distillation (MD) Process

MD is a separation/distillation technique, where water is transported between hot and a cool stream separated by a hydrophobic membrane, permeable only to water vapor.



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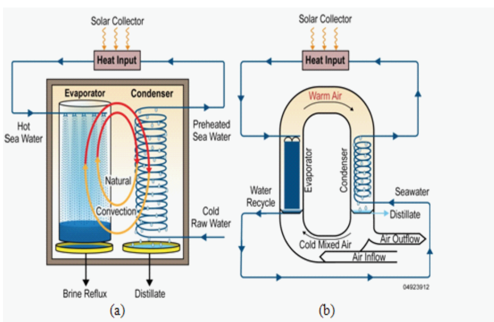
Other desalination processes / H-D System



Humidification-dehumidification systems: (a) open-water closed-air cycle, and (b) open-air closed-water cycle (modified from [64].

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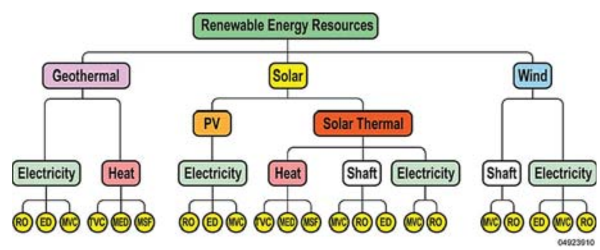
Renewable Energy Water Desalination

Desalination with renewable energy systems

Using desalination technologies driven by renewable energy sources (RES) is a viable way to produce fresh water in many locations today. As the technologies continue to improve—and as fresh water and cheap conventional sources of energy become scarcer renewable energy technology desalination will become even more attractive.



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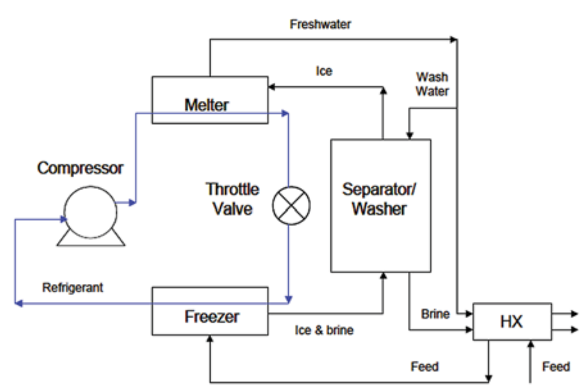
Other desalination processes / Freezing process

Freezing process depends on the fact that when ice crystal form, the dissolved salt is naturally excluded.



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Solar Water Desalination

Solar assisted desalination systems

Solar energy can drive the desalination units by either thermal energy and electricity generated from solar thermal systems or electricity generated by PV systems. The cost distribution of solar distillation is dramatically different from that of Reverse Osmosis and MSF. The main cost is in the initial investment. However, once the system is operational it is extremely cheap to maintain and the energy has little or even no cost. It is divided to two parts:

I- solar thermal assisted systems.

II-Solar photovoltaic assisted systems.

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Solar Water Desalination *(cont.)*

Solar thermal assisted systems

I-Direct solar thermal desalination system

The method of direct solar desalination is mainly suited for small production systems, such as solar stills, in regions where the freshwater demand is low. This includes:

▪simple solar still.

II-Indirect Solar thermal desalination

▪.Solar pond assisted desalination

▪Concentrated solar power (CSP) desalination

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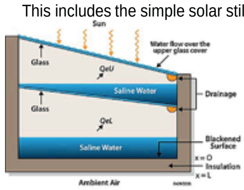
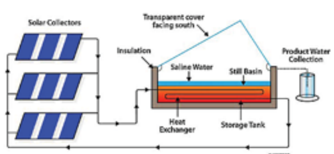
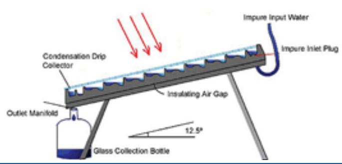
Solar Water Desalination *(cont.)*

I-Direct solar thermal desalination system

The method of direct solar desalination is mainly suited for small production systems, such as solar stills, in regions where the freshwater demand is low. This includes the simple solar still.







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Solar Water Desalination *(cont.)*

II-Indirect Solar thermal desalination

Indirect solar thermal desalination methods involve two separate systems: the collection of solar energy, by a conventional solar converting system, coupled to a conventional desalination method. This include:

- Solar ponds assisted desalination
- Concentration solar thermal (CSP) desalination

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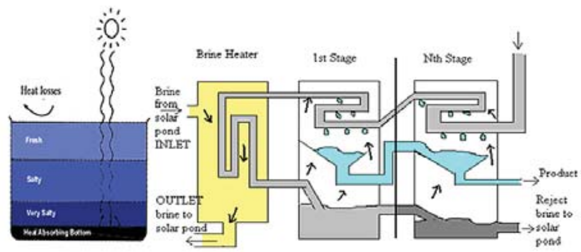
Solar Water Desalination *(cont.)*

Solar ponds assisted desalination

Salinity gradient solar ponds are a type of heat collector as well as a mean of heat storage. Hot brine from a solar pond can be used as industrial process heat (e.g. as a heat source for vaporizing feed water in MSF or MED desalination)



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Solar Water Desalination *(cont.)*

Concentration solar thermal systems

Concentrating solar thermal power technologies are based on the concept of concentrating solar radiation to provide high-temperature heat for electricity generation within conventional power cycles using steam turbines, gas turbines, or Stirling and other types of engines. The CSP plant consist of two parts: one collect solar energy and convert it to heat and another convert heat to electricity. For concentration, most systems use glass mirrors that continuously track the position of the sun.

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Solar Water Desalination/Concentrating Solar power systems

The four major concentrating solar power (CSP) technologies are:

- **Parabolic trough**
- **Fresnel mirror reflector**
- **Power tower**
- **Dish/engine systems.**


Trough System


Tower System


Dish System


Linear Fresnel System

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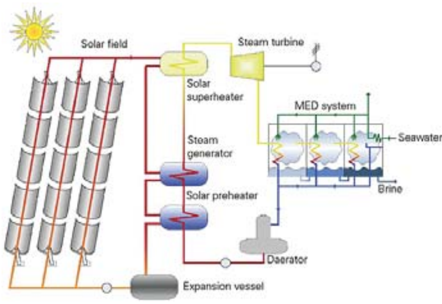
Solar Water Desalination/Concentrating Solar power systems

Concentration solar thermal (CSP) desalination

Parabolic trough coupled with MED desalination unit

A typical parabolic trough configuration combined with a MED system where steam generated by the trough (superheated to around 380ºC) is first expended in a non condensing turbine and then used in a conventional manner for desalination.



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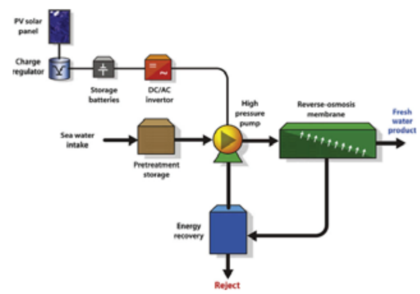
Solar Water Desalination/ Solar PV *(cont.)*

PV-RO systems applications

PV-powered reverse osmosis is considered one of the most promising forms of renewable-energy-powered desalination, especially when it is used in remote areas. Therefore, small-scale PV-RO has received much attention in recent years and numerous demonstration systems have been built. PV seawater RO production cost ranges from 3.9 to7.89 US$/m³ . Also for a PV/RO brackish-water desalination unit, a water cost of about 2.5 to 7.0 US$/m³.



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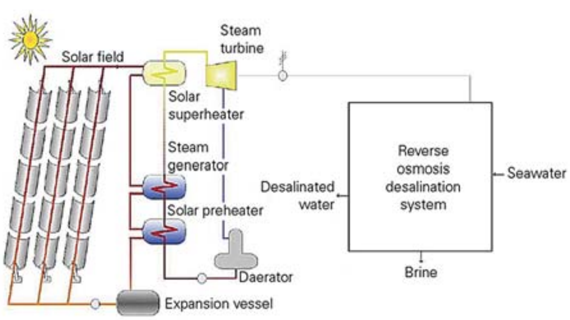
Solar Water Desalination/Concentrating Solar power systems

Parabolic trough coupled with RO desalination unit

In this case as well as in MED, the steam generated by the solar plant can be used through a steam turbine to produce the electric power needed to drive the RO pumps.



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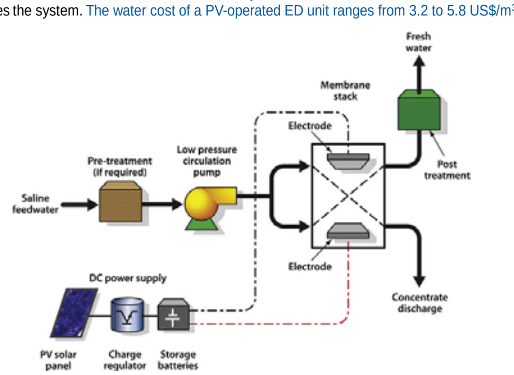
Solar Water Desalination/ Solar PV *(cont.)*

PV-ED applications

ED uses DC for the electrodes therefore the PV system does not include inverter which simplifies the system. The water cost of a PV-operated ED unit ranges from 3.2 to 5.8 US$/m³.



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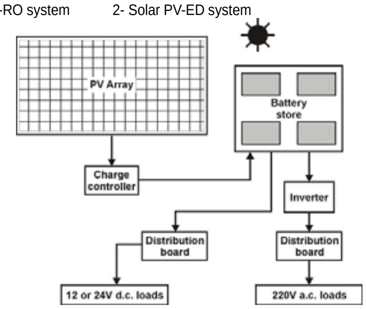
Solar Water Desalination *(cont.)*

Solar PV desalination system

Any photovoltaic system consists of a number of PV modules, or arrays. The other system equipment includes a charge controller, batteries, inverter, and other components needed to provide the output electric power suitable to operate the systems coupled with the PV system. PV system can be classified to:

1- Solar PV-RO system 2- Solar PV-ED system



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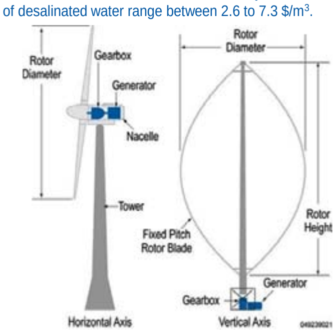
Wind/ Desalination systems

Wind turbines can be used to supply electricity or mechanical power to RO,VC and ED desalination plants. Like PV, wind turbines represent a mature, commercially available technology for power production. Wind turbines are a good option for water desalination especially in coastal areas presenting a high availability of wind energy resources.

Several small wind turbine to drive MVC , RO and ED systems existed today and the reported cost of desalinated water range between 2.6 to 7.3 $/m³.



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Geothermal / Desalination systems

The earth's temperature varies widely, and geothermal energy is usable for a wide range of temperatures from room temperature to well over 300°F. Geothermal reservoirs are generally classified as being either low temperature (<150°C) or high temperature (>150°C). Low temperature geothermal sources can be used in solar thermal desalination plant such as MED, whereas high-temperature geothermal fluids can be used to generate electricity to drive RO or ED plants.

Several geothermal /desalination system have been demonstrated. The reported cost of water from this system is about **$2.0/ m³.**

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Most common and promising RE/desalination technologies

System	Typical Capacity	Energy Demand	Potable Water Cost	Technical Development Stage
Solar still	< 0.1 m³/day	Passive solar	$ 2 to 8/ m³	mature
Solar MEH	1 to 100 m³/ day	Thermal: 100 kWh/ m³ Electrical: 1.5 kWh/ m³	$ 3 to 8/m³	Application and advanced R&D
Solar MD	0.15 to 10 m³/day	Thermal 150 to 200 kWh/ m³	$12 to 18/m³	Advanced R&D
Solar CSP/MED	>5000 m³/day	Thermal 60 to 70 kWh/ m³ Electrical 1.5 to 2 kWh/ m³	$2 to 3/m³ (prospective cost)	Advanced R&D
PV/RO	<100 m³/day	Electrical BW: 0.5 to 1.5 kWh/ m³ SW: 4 to 5 kWh/ m³	BW: $4 to 8/m³ SW: $6 to 10/m³	Application and advanced R&D
PV/EDR	<100 m³/day	Electrical: $3 to 4 kWh/m³	BW: $4 to 10/m³	Advanced R&D
Wind/RO	50 to 2000 m³/day	Electrical: BW: 0.5 to 1.5 kWh/m³ SW:4 to 5 kWh/m³	Units under 100 m³/day BW: $4 to 6/m³ SW: $6 to 8/m³ Unit of 1000 m³/day $2 to 5/m³	Application and advanced R&D
Wind/MVC	<100 m³/day	Electrical: SW: 12 to 15 kWh/m³	$5 to 8/m³	Basic research

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Recommendations

- Cost of desalinated water moved close to conventional water supply and expected to decrease the production cost in future.
- A number of technological upgrades and innovations in the past few years have resulted in reduced cost of desalted water to below $1.0/m3. Some RO plants reports a $0.52/ m3 cost.
- The hybrid desalination systems are proved to be technically feasible, economically attractive, and environmentally favorable.
- Renewable energy /desalination systems are currently economic and widely used in remote areas.
- The continuous increasing costs of fuel costs in recent years enhance the chance of using renewable energy in large capacity water desalination plants.
- Use of renewable energy sources including such as wind, solar and geothermal resources have a huge environmental impacts and should be considered as a sustainable fresh water source.

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