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Solar Energy for Water desalination

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Abstract

This paper presents the different solutions to the most commonly used desalination process (RO, MSF, MED), and solar energy production technology compatible with desalination. The goal is to assess the feasibility and profitability of the substitution of fuel energy used for desalination plants with renewable energy.
A review of various technologies will define broadly features associated to each technology and range of cost that are expected. Finally, a review of various projects will detail the practical aspects of floor space and actual production costs of fresh water.

Keywords : Desalination, RO, MSF, MED, Solar energy

Nomenclature

RO	Reverse Osmosis
MSF	Multi Stage Flash Distillation
MED	Multi Effect Distillation
PV	PhotoVoltaic
LFR	Linear Fresnel Reflector
CSP	Concentrating Solar Power

1. Introduction

It's true that freshwater scarcity is associated with large quantity of solar resource. It seems also logical and attractive to associate those two parameters for countries where grid electricity is not spread widely and with easy access to seawater or brackish water.

Solar desalination is not a new idea: it has been known for ages, antique sailors used to desalt water with simple and small sized solar stills.

It's also a fact that production of fresh water requires a large amount of energy: 1000 m3 of freshwater per day requires 10 000 tons of oil per year [1]. Though solar energy is often labelled as 'free energy', it's not so simple to evaluate feasibility and cost for solar desalination

Some technologies will not be taken in account in this paper: solar ponds, which are a direct desalination method, as well as desalination with electrodialysis (whose application is restricted to low salinity water).

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2. Desalination technologies

Desalination is by definition a process removing minerals and salts from saline water to produce freshwater, that can be used for human use or irrigation. It's applied to seawater and brackish water with different performances criteria.

It's normally considered that salinity below 500 ppm is suitable as drinking water. Basically, a complete desalination process includes 3-4 steps with, first pumping water (from sea, estuaries or saline aquifers), pretreatment of pumped water (filtration, chemical addition) desalination process 'stricto sensu' and last, a post treatment if necessary (in some case, adding few minerals).

There are different ways to produce freshwater with desalination technologies. More common technologies are:

- Reverse Osmosis
- Multi-stage Flash Process
- Multi Effect distillation.

As shown in table 1, those technologies have been developed worldwide with MSF and RO being dominant.

Table 1. Distribution of solar technologies in existing installations [2]

An example of a column heading	Total desalination plants (seawater + brackish water as feed in)	Desalination plants with seawater as feed in
Multi Stage Flash Process	43,5%	66,3%
Reverse osmosis	43,5%	22,4%
Multi effect distillation	~ 10%	
	Strong increase in worldwide installations	

2.1. Reverse Osmosis

The RO technology is based on the properties of semi-permeable membranes which can separate water from a saline solution, when excess of osmotic pressure is applied on the membrane systems. Pressure is applied with a high pressure pump (approximately 70 – 90 bars). Part of the flow (35 to 50%) goes through the membrane, with a salt concentration less than 500 ppm, rest of the flow called retentate (50 to 65%), containing high concentration of salts, doesn't pass through the membrane and is directly rejected at a high pressure.

RO can be applied to different types of water: seawater as well as brackish water, with the equivalent objectives depending on the pressure applied to the membrane

Reverse osmosis has known a great development over the last twenty years due to its easy and rather low cost technology and great improvement on membrane quality.

Key features of the RO process are the following:

- Low energy consumption
- Easy and ready to use : immediate stop and start
- Needs important pre-treatment : pre-filtration and chemical (anti-scalant) to avoid fouling on the membrane
- Outlet salt concentration around 500 ppm

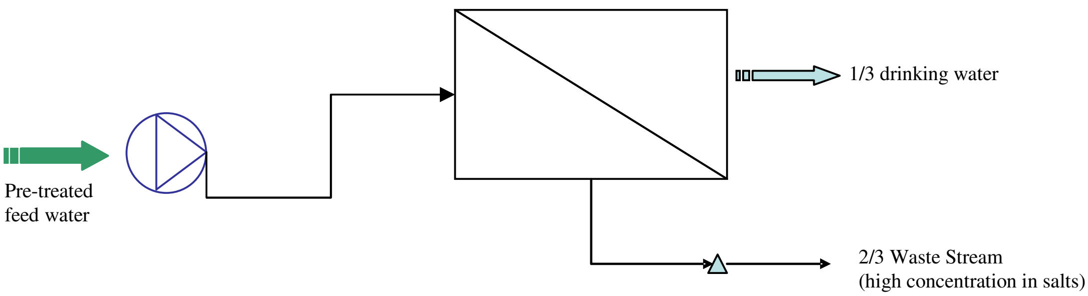

Fig. 1. Schematic of membrane RO systems

RO capacity has increased in the last 30 years to reach approximately 45 – 50 % of the desalinated total capacity.

Many developments contributed to the reduction of unit water cost (material, membrane module performances, reduction in energy consumption), with now a unit water price around 0,5 US$/m3

2.2. Multi Stage flash

In the MSF process, seawater is heated in a vessel called the brine heater, up to a temperature of 120°C, and then flows into another vessel, called a stage, where the ambient pressure is lower, causing water to boil. Steam is then condensed on a range of tubes passing through the vessel.

Low pressure ensures seawater cooling down to 40°C.

This well known technology has been used on large installations (more than 50 000 m3/day), with coupling of heat generation from a power plant, but MSF process can also be used with solar power.

Key features for MSF are the following:

- High reliability
- No need for complicated pre-treatment due to very limited scaling: simple filtration, and anti-scalant
- High investment cost
- High quality of produced freshwater (depending on the number of cells): salts concentration below 50 ppm
- Low running flexibility (low variation in flowrate)
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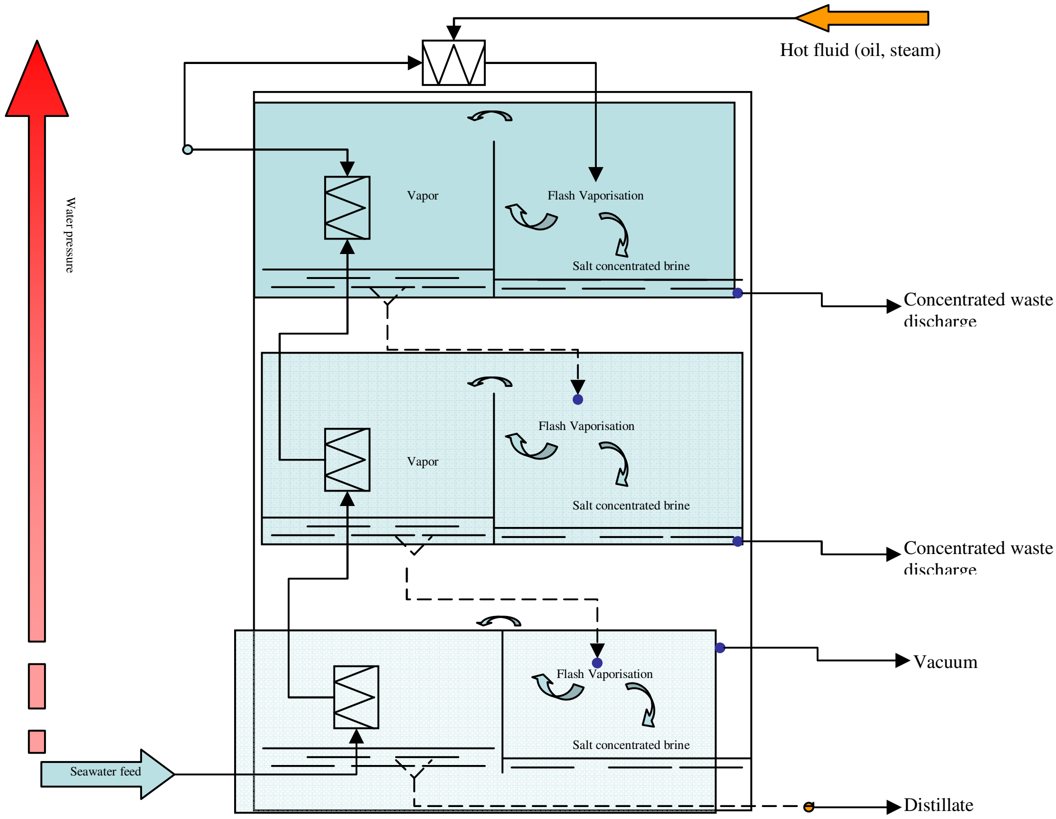

Fig. 2. Schematic drawing of MSF process

MSF plants are now installed worldwide, even though performance is not high and represent 40 – 45% of the total capacity in desalination.

Over the last 40 years, cost of desalinated water with MSF technology decreased by a factor 10 (from 10 $/m3 in 1960 down to less than 1 $/m3 in 2002) [3].

2.3. Multi Effect Distillation : MED

Multi Effect Distillation (MED) process is based on using latent heat of condensation of the vapor from the first cell to provide heat to a second cell. The evaporation takes place in cells where equilibrium temperature (Te) liquid / vapor is between 40 ° C and 68 ° C.

In the first cell, the steam produced is injected into the second effect, in order to ensure the evaporation and condensation at a lower temperature. This is then repeated in all following cells

In case of using solar source as heat source, hot water from the solar collector is introduced at the bottom tray, either directly or through a heat exchanger.

MED units with horizontal sprayed tubes are generally made with materials like, aluminum brass (AlBr) for tubes and stainless steel 316L for the casing. Sometimes, vertical heat exchanger can be used.

Key features for MSF are the following:

- High reliability, easy start of the system (less than 1 hour)
- High quality of produced freshwater (depending on the number of cells): salts concentration below 50 ppm
- No need for complicated pre-treatment due to very limited scaling: simple filtration, and anti-scalant
- Can be used on low temperature heat (from 60°C), which can be easily recovered as by-product in industrial plants.

MED is also suitable for small capacity installations and now represents more than 10% of the total capacity in desalination, with still promising developments. Use of coupling MED with Thermal vapor compression helped in decreasing running costs, as well as increase in unit capacity and heat transfer coefficients.

Water cost with recent MED is 0,7 US$/m3 which is close to RO [3].

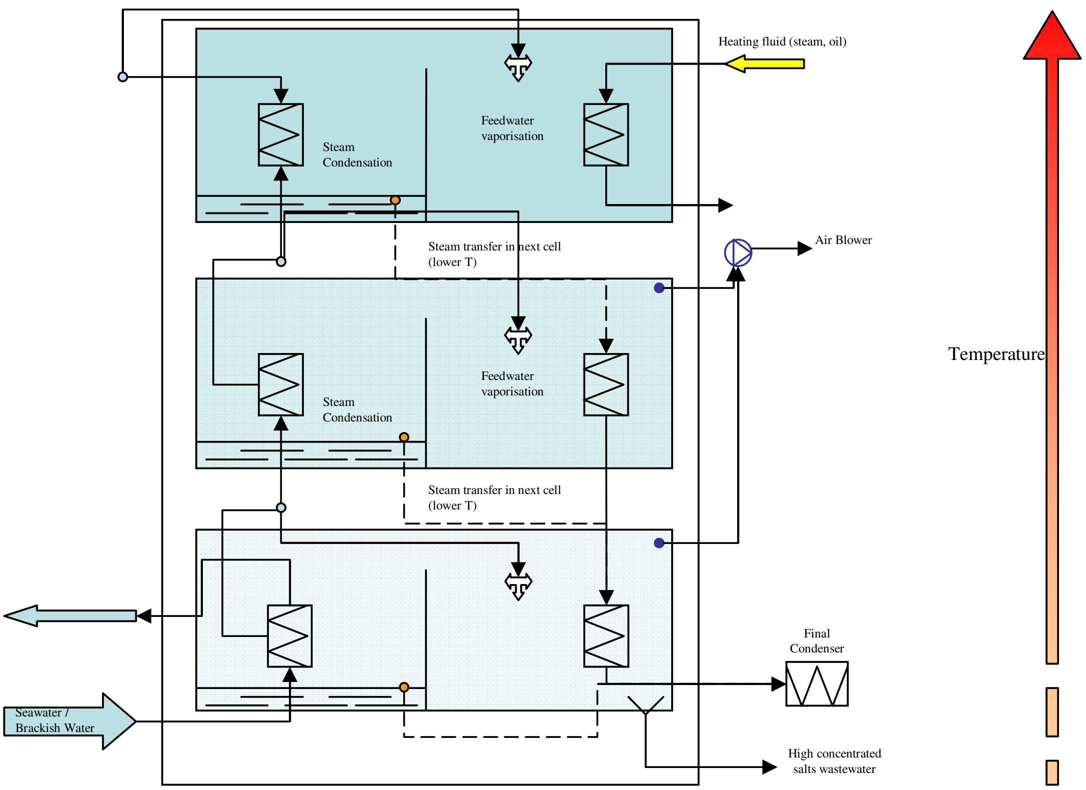

Fig. 3. Schematic drawing of MED process

2.4. Cost comparison of the different desalination technologies

As a brief outline, we can indicate energy consumption for the different desalting technologies above.

Table 2. Comparison of running cost in the different desalination technologies (per m3 of produced freshwater)

Consumption of desalination technologies	MSF	MED	RO
Heat power consumption	80 -120 kWth/m3	50 - 90 kWth /m3	N/A
Electricity power consumption	2.5 kWeh/m3	1 - 3 kWeh/m3	3 - 6 kWeh/m3

3. Solar Technologies

All desalination technologies described here mainly use thermal energy. Knowing that desalination needs are mainly in dry countries receiving huge intensity solar radiation, it comes as an evidence to use solar power for the running of the plants. Solar technologies can produce heat and thus electricity through a turbine (CSP), or directly electricity (PC and CPV). Growing interests and developments on CSP as well as PV tend to make those technologies more and more attractive

Parabolic troughs (NEP Solar)

Linear Fresnel (CNIM)

Central Tower (CNRS Promes)

Solar technologies can be divided in two categories: concentrating solar power (CSP) technology and photovoltaic (PV) technology.

Concentrating Solar Power Technologies mainly include
- Parabolic trough,
- Linear Fresnel reflector systems.
- Central tower receiver

These technologies concentrate solar radiation onto an absorptive pipe (receiver) which contains heat transfer fluid (water, oil or salt). When water is used, heat from the sun's radiation converts the water to steam by direct steam generation. In case of oil or salt, fluid acts as an intermediate thermal energy carrier, which passes through different heat exchanger converting water to steam.

These CSP systems generate power using a steam-driven turbine (with a Rankine cycle, for example)

Photovoltaic technology has been developed as flat-plate PV module, which is the most commonly used technology (PV), and concentrating photovoltaic (CPV) technology, which is a developing technology. The main difference between the two technologies is that CPV technologies use DNI as a solar source instead of Global Irradiation.

Recent developments in solar technology (material, geometry design of solar collector, sun tracking systems) helped increasing efficiency in performances of the global systems.

We'll go in more details on the different technologies, especially the most common ones which are parabolic trough, linear fresnel reflector system, as well as photovoltaic modules. On a practical point of view, each one of the different technologies will be selected and installed depending a list of criteria: technical, financial and site related constraints

3.1. Parabolic troughs

CSP parabolic troughs produce steam and electricity through the use of a parabolic reflecting surface that concentrates direct normal solar radiation (DNI) onto a receiving tube surrounded by a glass element.

The solar collectors track the sun from east to west during daytime, allowing the continuous focus of sun on the solar collectors. Thermal fluid is transferred through the receiving tube where it is heated to approximately 350 - 400°C. It is then used as heating fluid to the power plant for generation of high-pressure steam. Thermal storage (on sensible or latent heat) can be added to the system to ensure continuity during low solar radiation period (nighttimes or cloudy days).

Parabolic trough is the most developed of the CSP technologies and is now commercially available for industrial heat production purpose.

3.2. Linear Fresnel Reflectors Systems

A linear Fresnel reflector (LFR) technology uses thin segments of mirrors arranged in long parallel lines to reflect sunlight onto a fixed receiver, allowing thus to transfer energy through the absorber into some thermal fluid (water or oil). Concentration capacity of the mirrors is approximately 30 times sun's energy normal intensity. As for parabolic troughs, thermal storage can be added to the system.

The fluid then goes through a heat exchanger to power a steam generator, thus producing electricity and heat as a by-product.

LFR technology has great advantages on parabolic troughs and is the most promising technology in CSP. First, manufacturing process doesn't need high precision in bending mirrors, keeping Fresnel mirrors at a low cost, with manufacturing sites close to the installation location; then, structure and equipment are much lighter than parabolic troughs, which is another cost saving argument.

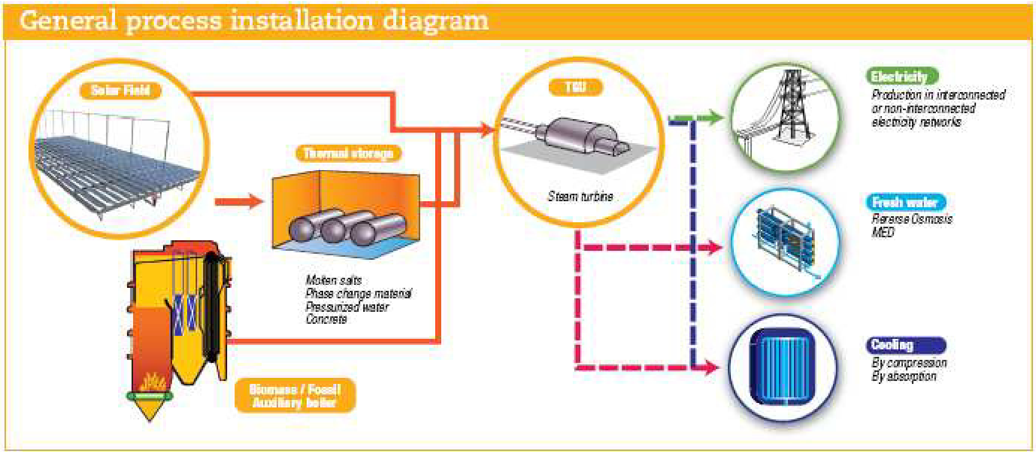

Fig. 4. Schematic drawing of LFR with different uses (CNIM)

Fig. 5. Details of LFR installation 0,7 MW (CNIM – F - La Seyne)

3.3. Flat Plate Photovoltaïc

Photovoltaic panels generate electrical power through the use of semiconductors, converting both DNI and diffuse irradiation into electricity. The most efficient photovoltaic technology is a flat-plate module with a core composed of mono- or polycrystalline silicon cells, which. A less efficient panel uses a thin film of cadmium telluride deposited onto a substrate. The cells or film absorb both direct and indirect solar radiation, which excite the electrons and induce an electric current. The panels are interconnected into a circuit to convert the direct current into an alternating current for the grid.

With diffuse collection, flat plate PV systems can operate effectively under conditions of light cloud cover

3.4. Concentrating Photovoltaic (CPV)

Almost similar to the Flat Plate PV, CPV technology is the most promising one with the following differences:

- CPV technologies use DNI as a solar source instead of Global Irradiation.
- CPV systems incorporate optical components such as mirrors combined with optical devices, to concentrate the DNI onto the photovoltaic cell, thus improving significantly the solar energy reaching the surface.
- CPV technology uses multi-junction cells designed to convert a whole spectral region of solar radiation to reach great efficiencies, almost double the efficiency of the conventional PV solar cell.
- CPV technology requires a highly accurate two-axis tracking system with tracker control units to continuously track the sun for a maximum DNI during daytime.

CPV technology may need cooling systems to disperse heat due to high concentration of solar radiation on cells.

4. Coupling solar energy and desalination

When coupling desalination methods and solar power, it can result in many combinations. In that part, we will describe and evaluate here projects already realised (mainly PV/RO, parabolic troughs/MSF, parabolic troughs/MED).

4.1. Photovoltaic / Reverse Osmosis

Many demonstration plants were carried out coupling RO systems with solar PV electricity. Most common way is to convert DC from PV panels through an inverter, to produce AC immediately used in pumps.

Some developments anyway were done on connecting panels to a brushless DC motor, powering a low pressure pump, thus allowing direct use from PV panel to pump [4].

Furthermore, battery banks are added to the system to store energy during night time to allow continuous running of RO operation.

PV-RO systems od capacities ranging form 0,5 to 50 m3/d have been installed as demonstrators.

Regarding costs, investment cost is higher than conventional RO, but also vary on location, quality of saline water and plant capacity.

In Ref [5] a complete table lists the different characteristics of PV coupled RO installations. Cost is extremely dependant from one location to the other, ranging from 30 US$/m3 down to 3 US$/m3

Cost reductions have been investigated, smartest approach is to eliminate storage battery (giving 15-20% of cost reduction) with varying flow of seawater through membrane with regards to available energy [6]

4.2. Parabolic troughs / MSF

The MSF process as a thermal process can also use solar power with parabolic troughs. Steam produced by parabolic troughs is used as heat source through a heat exchanger for MSF inlet. A thermal storage system can be added to the system to smooth variation of thermal energy supply and allow the continuous production of fresh water (during nighttime or low radiation period)

Demonstrator realised in Kuweit [7] showed a capacity of 10 m3/d, for a surface parabolic trough collector of 220 m². This corresponds to the average 10 – 60 l/m².day for solar powered MSF, as referenced in [8]

There are commercially available small-scale units combining MSF process with steam generating parabolic troughs, whose approximate costs is 7-9 US $/m3 of produced freshwater

4.3. Parabolic troughs / MED

We can find more installations of MED worldwide, coupled with solar energy from different technologies (tower, parabolic troughs, others…).

Water production cost for seawater desalination with MED coupled with a solar field has been proven to be quite dependant from plant capacity: for large planst (5000 m3/d), cost is around 2 US $/m3 and is increasing up to 3,2 US$/m3 for smaller plants (500 m3/d) [9].

Also as an example, Abu Dabhi installation ref [10], can run 85 m3/day of freshwater; in that case, heat source is water passing through evacuated-tube solar collectors (1862 m2). After several years of operation, critical point of the installation was maintenance of the pumps due to silt removal.

Some demonstrators were also realized to prove a total autonomy on energy with both thermal and electric energy (Parabolic troughs and PV panels), ref [11].

Aquasol is a hybrid project running with both gas and solar energy. Now in operation for several years, freshwater production is 3 m3/h of freshwater, combined to parabolic troughs with a surface of 500 m2, ref [12].

We can also point as an example, a project with combination of a tower with small scale MED producing 25 l/m2day for approximately 5 Wxh/m2d of solar radiation.

5. Conclusion

Solar MED and MSF, though appearing to be natural and tempting solutions, cannot be taken as proven technologies. More and more developments in both solar power and desalination technologies are expected to keep these solutions competitive compared to RO systems coupled with conventional power plant.

Somewhere, solution lies in combination: combination of heat sources and combination of processes. Recent developments present desalination systems including MSF combined with reverse osmosis, heat source being a thermal power plant, but coupling with solar resource can be imagined

Main advantage of that installation is that RO can run during nighttimes when electricity costs are low and MSF work during daytime with low running costs due to low pressure steam. Water storage offers flexible solution with energy consumption optimised. Addition of solar energy from start of the project (with parabolic troughs) would have low cost impact but no GHG emissions.

We can note that the range of possibilities is widely open in desalination. Need for fresh water will always be present, therefore desalination technologies must be enhanced to become cleaner, more efficient and more virtuous.

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