1. INTRODUCTION

Shortage of fresh water is a very important problem that is continuously increasing, due to population growth and changes in weather conditions, and affects many countries in the world. These countries usually have abundant seawater resources and a good level of solar radiation, which could be used to produce drinking water from seawater. Although everybody recognizes the strong potential of solar thermal energy to seawater desalination, the process is not yet developed at commercial level. The main reason for this is that the existing technology, although already demonstrated as technically feasible, cannot presently compete, on produced water cost basis, with conventional distillation and reverse osmosis technologies. Nevertheless, it is also recognized that there is still important room to improve desalination systems based on solar thermal energy. Among low capacity production systems, solar ponds represent the best alternative in case of both low fresh water demand and land price. For higher desalting capacities, it is necessary to choose conventional distillation plants coupled to a solar thermal system, which is known as indirect solar desalination [1]. Distillation methods used in indirect solar desalination plants are multi-stage flash (MSF) and multi-effect distillation (MED). MSF plants, due to factors such as cost and apparent high efficiency, pushed out MED systems in the sixties, and only small size MED plants were built. However, in the last decade, interest in multi-effect distillation has been significantly renewed and currently MED process is competing technically and economically with MSF technology [2]. Recent advances in research of low temperature processes have resulted in an increase of the desalting capacity and a reduction in the energy consumption of MED plants [3], providing long-term operation under remarkable steady conditions. Scale formation and corrosion are minimal, leading to exceptionally high plant availabilities of 94% to 96%.

2. THE PSA SOLAR DESALINATION EXPERIENCE

CIEMAT (Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, Spain) and DLR (Deutsche Forschungsanstalt für Luft- und Raumfahrt, Germany) decided in 1987 to develop an advanced solar thermal desalination system, thus initiating the so-called Solar Thermal Desalination (STD) Project carried out at the Plataforma Solar de Almería (PSA) until 1994 [4]. The following two project phases were scheduled and executed during this period aiming to achieve specific project objectives:

- Phase I: to study the reliability and technical feasibility of solar thermal technology application to seawater desalination.
- Phase II: to develop an optimized solar desalination system by implementing specific improvements in the system initially installed at the PSA, which could make it more competitive against conventional desalination systems.

Phase I was launched in 1988 and its evaluation finished in 1990. During this phase a solar desalination system was implemented at the PSA. This desalination system was composed of: i) a 14-effect Multi-Effect Distillation plant; ii) a solar parabolic-trough collector field; iii) a thermocline thermal energy storage tank.

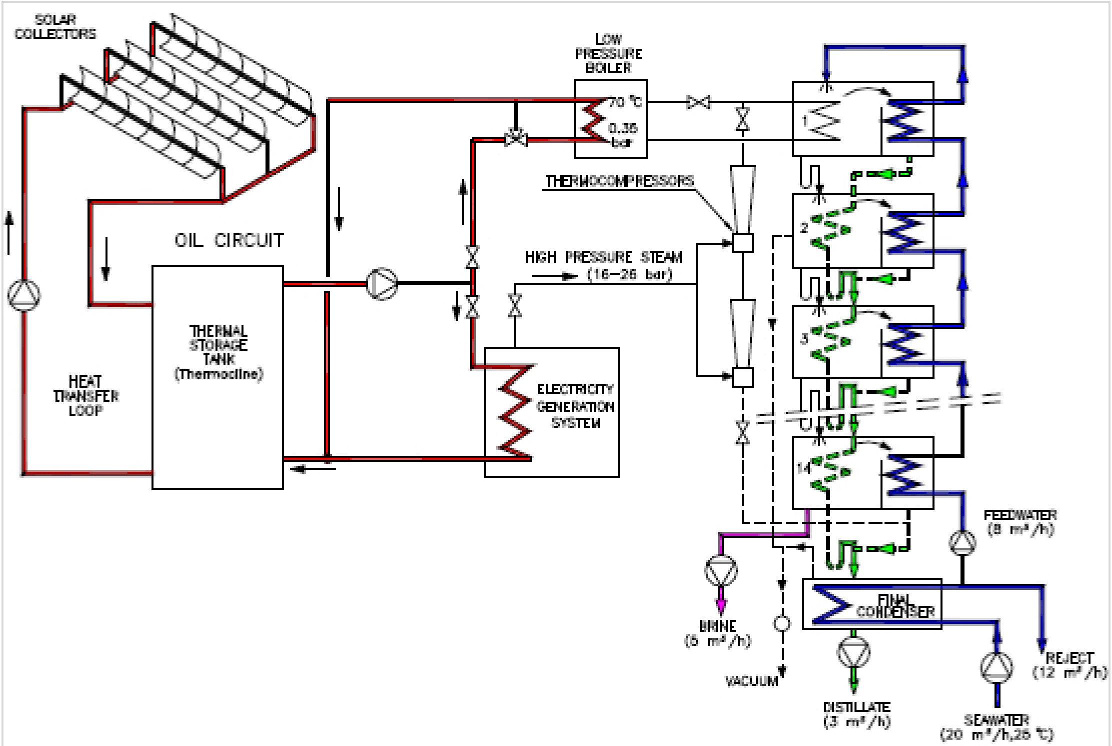

Figure 1: Schematic diagram of the solar MED system installed at PSA at Phase I of STD Project

These subsystems were interconnected as shown in Figure 1. The system operates with synthetic oil that is heated as it circulates through the solar collectors. The solar energy is thus converted into thermal energy in the form of sensible heat of the oil, and is then stored in the thermal storage tank. Hot oil from the storage system provides the MED plant with the required thermal energy. The desalination plant installed at PSA uses sprayed horizontal tube bundles for seawater evaporation, which must be limited to around 70°C to reduce scale formation. The MED plant is composed by 14 cells or effects at successively decreasing temperatures and pressures from cell (1) to cell (14). The seawater is preheated from cell to cell in the 13 preheaters. From cell (1), the seawater passes on from one cell to another by gravity before being extracted from cell (14) by the brine pump. Part of the seawater used to cool the condenser is rejected and the rest is used for the feedwater required to spray the cell (1) tube bundle. The fresh water is extracted from the condenser by means of the distilled water pump.

Table 1: Technical specifications of the PSA Desalination Plant

Nominal distillate production	3 m³/h
Heat source energy consumption	190 kW
Performance Ratio (kg distillate/2300 kJ heat input)	>9
Output salinity	50 ppm TDS
Seawater flow:	
At 10°C:	8 m³/h
At 25°C:	20 m³/h
Feedwater flow:	8 m³/h
Brine reject:	5 m³/h
Number of cells	14
Vacuum system	Hydroejectors (seawater at 3 bar)

The plant can also be fed with steam at 16-26 bar. High-pressure steam is produced in the PSA's Electricity Generation System to drive a small power plant. A small fraction of this steam can be used to feed the desalination plant, where it is sent to thermo-compressors, and mixed with steam produced in the fourteenth effect. This mixture is then ejected into the evaporator of the first cell to restart the desalination process. In this case, the MED plant consumption is lower. A vacuum system, composed of two ejectors (not shown in Figure 1) driven by seawater at 3 bar, is used to evacuate the air from the unit at startup and to compensate for the small amounts of air and gases released from feedwater and from small leaks through the gaskets. The most remarkable evaluation results obtained during Phase I were the following:

- High reliability of the system, as no major problem was observed in the coupling of the solar collector field with the MED plant.
- Low thermal inertia: it usually took 35 minutes to reach nominal production of distillate.
- Specific electricity consumption in the range from 3.3 to 5 kW_e h/m^3 of distillate.
- The plant showed a Performance Ratio (e.g. number of kg of distillate produced by 2300 kJ heat input) within the range of 9.4 to 10.4 when operating with low-pressure steam. Performance Ratio increases up to the range of 12 to 14 if high-pressure steam is used to feed the plant.

From the results obtained during Phase I, it was possible to identify potential relevant improvements that could be implemented in the MED solar system to increase its efficiency and competitiveness. This analysis concluded that:

- The plant electrical demand could be reduced by replacing the initial hydroejectorbased vacuum system with a steam ejector system.
- The plant thermal demand is 50% reduced by incorporating a double-effect absorption heat pump coupled to the MED plant.

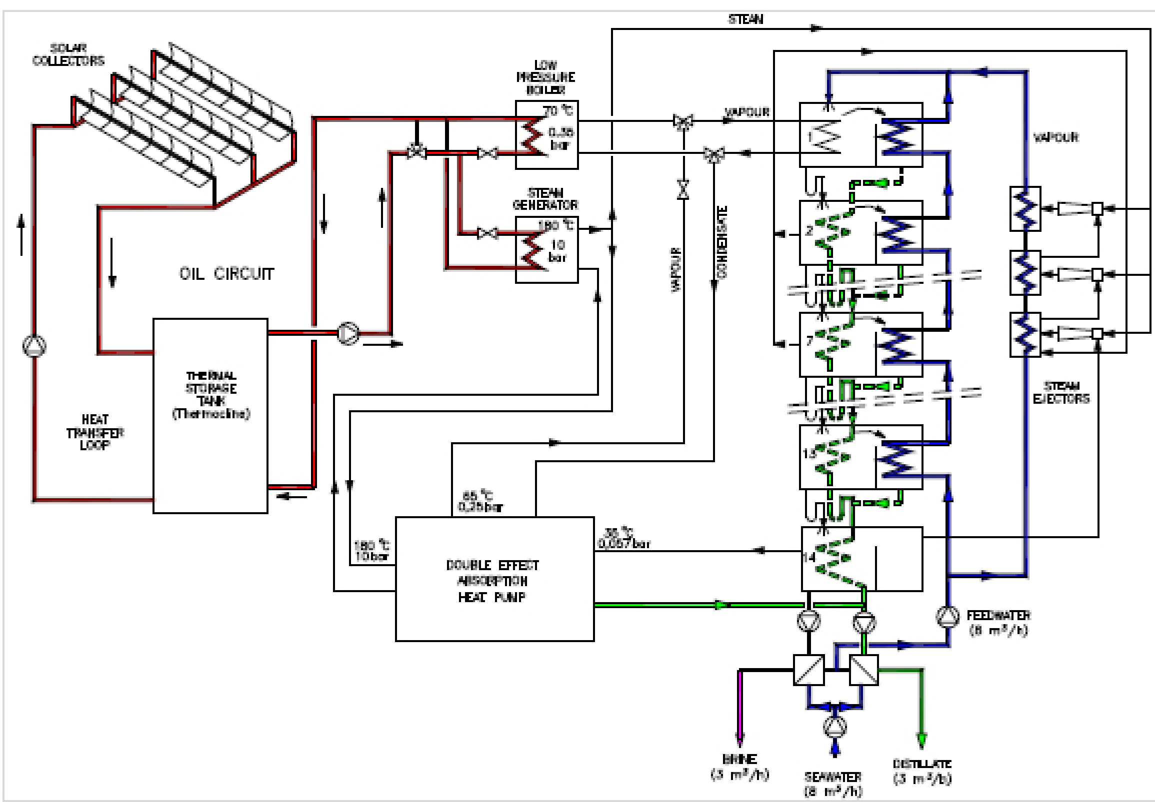

Figure 2: Improved Solar MED System (Phase II of STD Project)

Since these improvements would considerably reduce the specific cost of distillate produced by the optimized solar MED desalination system, it was decided to carry out the Phase II of the STD Project.

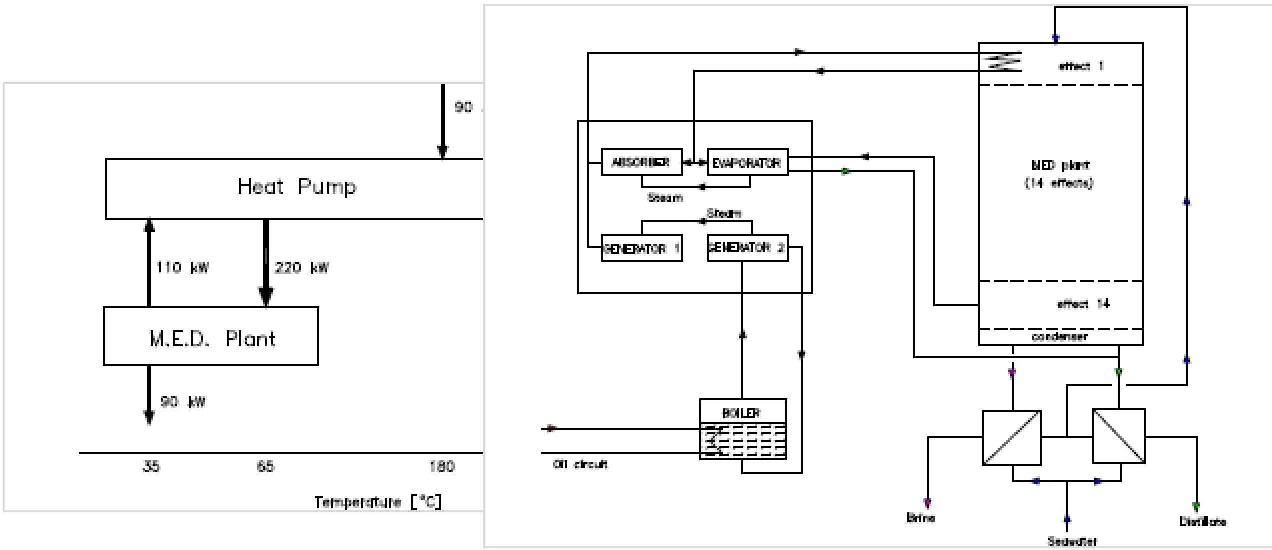

Figure 3: Conceptual scheme of Double Effect Absorption Heat Pump and its coupling within the Solar MED System

A schematic diagram of the improved desalination system in which an absorption heat pump was coupled to the MED plant can be showed in Figures 2 and 3. The heat pump delivers 200 kW of thermal energy at 65°C to the MED plant. The desalination process in the plant evaporator body uses only 90 of the 200 kW, while the remaining 110 kW are recovered by the heat pump evaporator at 35°C and pumped to usable temperature of 65°C. For this, the heat pump needs 90 kW of thermal power at 180°C. The energy consumption of the desalination system was thus reduced from 200 kW to 90 kW. The improvements implemented in the desalination system (i.e. absorption heat pump and steam-ejector based vacuum system) reduced the thermal energy consumption of the desalination system by 44%, from 63 to 36 kWh/m³ and electricity consumption by 12% from 3.3 to 2.9 kW e h/m³.

The project is focused in the technological development of three main specific technological aspects that are expected to significantly improve the present techno-economic efficiency of solar MED systems and therefore, reduce the cost of water production:

- Efficient incorporation of solar energy to the process by designing a static solar collector system, of CPC type (Compound Parabolic Concentrator), to supply heat at medium temperature (70ºC-100ºC). This solar collector system will be complemented by a thermal storage tank, and the overall system will be coupled with a gas-fired backup system to guaranty necessary operating conditions and permit 24-hours MED desalination plant operation (necessary to reduce capital costs).
- Development of a new Double Effect Absorption Heat Pump (DEAHP) optimized and fully integrated within the MED process to significantly reduce the overall energy input needed and to improve the overall energy efficiency of the process.
- Reduce to zero any discharge from the process by recuperating the salt from the brine. This process is intended to be accelerated by using advanced solar dryer systems specifically developed and designed. The elimination of the brine can provide an additional enhancement to the process economic figures.

The seawater system to be erected within the AQUASOL Project will be made up of:

- A multi-effect distillation plant with 14 cells in a vertical arrangement, with a nominal distillate production of 3 m^3 /h.
- A stationary CPC (Compound Parabolic Concentrator) solar collector field
- A thermal storage system based on water
- A double-effect ($LiBr-H_2O$) absorption heat pump.
- A smoke-tube gas boiler
- An advanced solar dryer for final treatment of the brine.

These subsystems are interconnected as shown in Figure 4. The system operates with water as heat transfer fluid, which is heated as it circulates through the solar collectors. The solar energy is thus converted into thermal energy in the form of sensible heat of the water, and is then stored in the tanks. Hot water from storage system provides the MED plant with the required thermal energy. In absence of solar radiation, the gas boiler feeds the heat pump, which is also fed with low temperature steam from MED plant in order to heat up water coming from first effect from 63.5ºC to 66.5ºC.

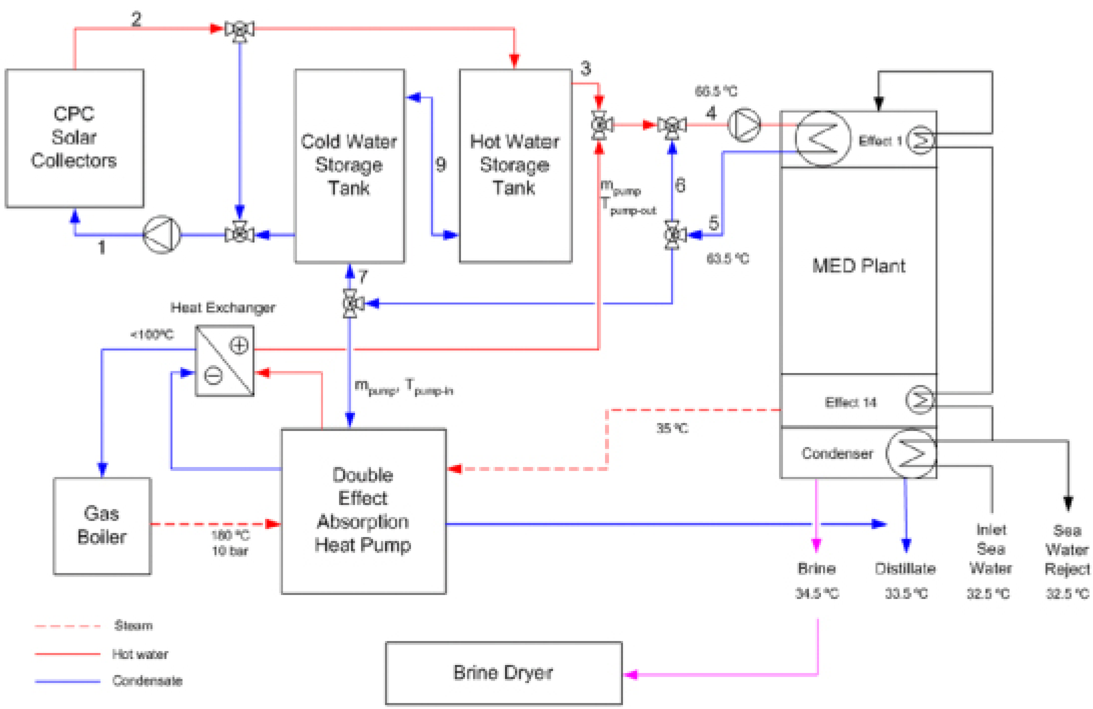

Figure 4. Configuration proposed for AQUASOL seawater desalination

The solar field consists of four rows of east-west-aligned stationary collectors (CPC Ao Sol 1.12x) tilted 35º with a total surface area of 499 m^2 (252 collectors). The thermal storage system has two 12-m^3 -capacity water tanks that are connected to each other. The total volume was based on the response time required by the gas boiler system and the heat pump during transient variations in solar radiation. The use of two tanks enables the solar contribution to be increased over the year as well as obtaining a certain temperature stratification necessary to avoid the heat pump water inlet temperature getting out of the permissible range (60ºC – 65ºC).

CPC devices have the best possible optic to provide thermal energy at medium range temperature as they are the only ones capable to achieve solar concentration without solar tracking devices. In addition, when specifically designed to desalination purposes, they will clearly have lower installation and maintenance cost than conventional alternative parabolic trough systems with sun tracking devices.

Also the project will design and install a new first effect for the PSA MED plant which will be fed with hot water from the thermal storage tanks in nominal operating conditions as shown in Table 3. This addition is an innovation over conventional MED plants in which low-pressure saturated steam is used as the heat transfer fluid.

Table 3. Estimated performance of the new first cell for PSA MED Plant

solar collector field double absorption heat pump	Desalination	driven by double effect
Power consumption	200 kW	150 kW
Inlet / outlet hot water temperature	75.0 / 71.0 ºC	66.5 / 63.5 ºC
Brine temperature	68 ºC	62 ºC
Hot water flow rate	12 kg/s	12 kg/s
Pressure drop	0.4 bar g	0.4 bar g

The concept of DEAHP was fully demonstrated by previous PSA experience, being a clearly important contribution to water-cost reduction in Solar-MED processes [4]. The double-effect absorption heat pump increases the energy efficiency of the distillation process by making use of the 35ºC saturated steam produced in the last MED plant effect, which would otherwise involve the loss of the energy in the evacuation of the cooling fluid used for its condensation, as the cold focus. To reach the temperatures required by the first MED plant effect, the pump generator must be fed with 180ºC saturated steam, temperature not possible to be achieved by the CPC solar field. Therefore, the heat pump will always have to be used with a gas smoketube boiler in order to produce steam that can adapt to the variable heat pump load.

Finally, zero discharge will enhance the overall process not only from the environmental point of view, but also from the economical as the salt obtained from each cubic meter of brine could even be more valuable than the distilled water itself. It is expected to, at least, double the present normal production rate at conventional salt pits.

3. MODELING SYSTEM

Real meteorological data from the PSA (longitude 2.36º W, latitude 37.10º N) was used to evaluate the behavior of the system over an entire year. The meteorological variables available were ambient temperature and global and diffuse solar radiation on a horizontal plane, all recorded at five-minute intervals. The solar radiation incident on the collector plane is easily calculated from expressions found in the literature [5]. The nominal flow rate provided by the field is 4.16 kg/s and the collector efficiency equation can be found with the following expression [6]:

$$\eta = 0.7 - 3.4 \frac{W}{m^2 \cdot {}^\circ C} \times \frac{(T_m - T_{amb})}{I_{col}} \quad (1)$$

Where T_m are the average collector inlet and outlet temperatures, T_{amb} is the ambient temperature and I_{col} is the solar radiation incident on the collector plane.

When modeling the stratification of the water tanks, a multi-node approximation [5], in which each of the two tanks is represented by two nodes or sections, was considered. The heat pump outlet temperature depends on the inlet temperature, the percent steam extracted from the last MED plant effect and the flow rate.

Two different configurations for subsystem connection were modeled. In the first of them (external mixing configuration) the hot water from the heat pump is mixed with water from the storage tank through a control valve which achieves the nominal operating conditions (m_4=1 2 kg , / sT_4 66.5º) C in the first MED plant effect. In the second configuration (internal mixing) the hot water from the heat pump enters the hot storage tank directly (see Figure 5).

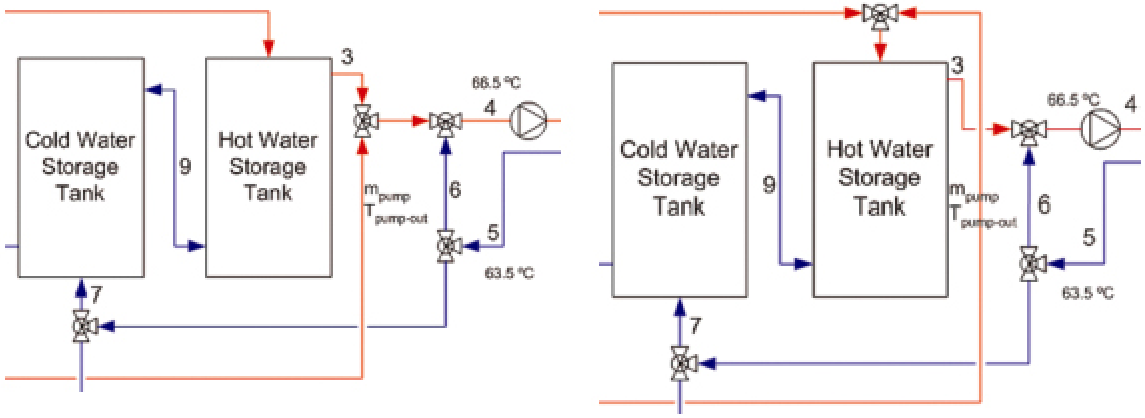

Figure 5. Both plant configurations analyzed: internal mixing (left) y external mixing (right)

Three desalination system-operating modes are possible depending on where the desalination unit energy supply comes from:

- Solar-only mode: energy to the first distillation effect comes exclusively from thermal energy from the solar collector field.
- Fossil-only mode: the double-effect heat pump supplies all of the heat required by the distillation plant.
- Hybrid mode: the energy comes from both the heat pump and the solar field. Two different operating philosophies were considered. In the first, the heat pump works continuously 24 hours a day with a 30% minimum contribution, while in the second, there is a pump startup or shutdown, depending on the availability of the solar resource.

4. RESULTS

After the analysis of the results obtained for the complete reference year, the external mixing configuration with heat pump startup and shutdown was shown a priori to be the most satisfactory configuration with regard to temperature and flow rate obtained. In the external mixing configuration with the pump always working, the water in the storage tanks reaches very high temperatures, even risking boiling. Furthermore, such high operating temperatures lead to a decrease in solar field efficiency. The solution to the problems of this configuration is given by being able to take one or more rows of the solar field out of operation.

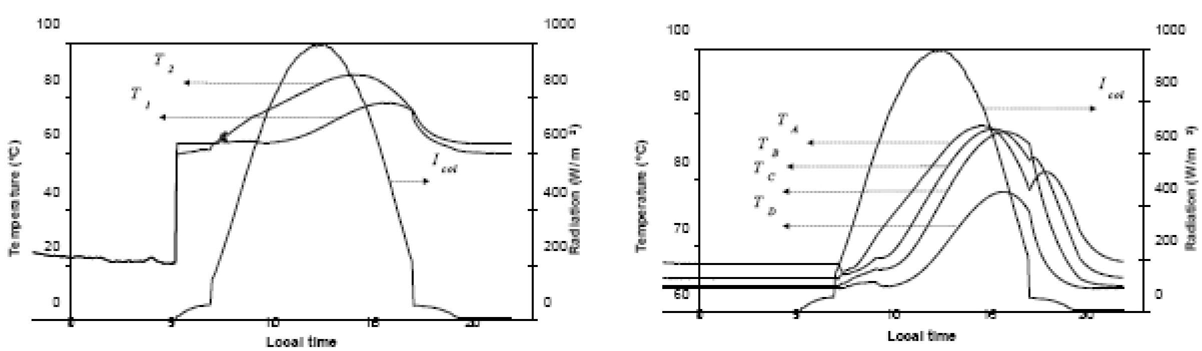

Figure 6. Solar field input/output (left) and storage tank nodes (right) temperature profiles for external mixing and DEAHP on/off configuration (July 27th)

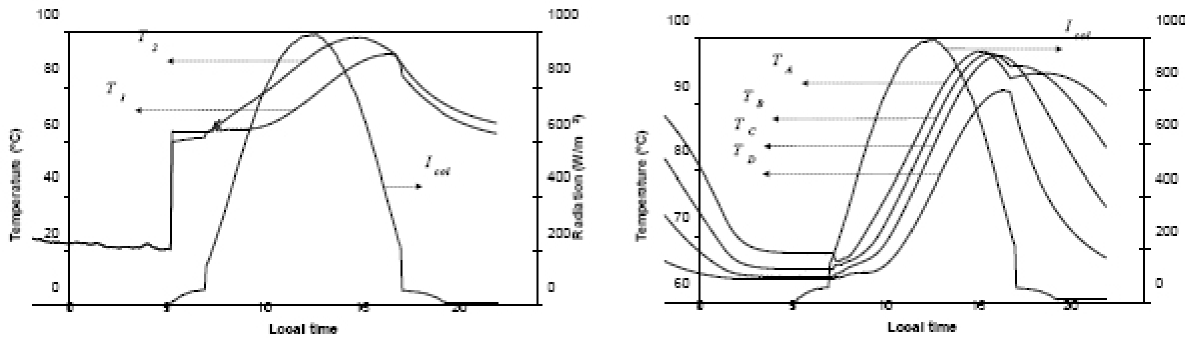

Figure 7. Solar field input/output (left) and storage tank nodes (right) temperature profiles for external mixing and DEAHP always on configuration (July 27th)

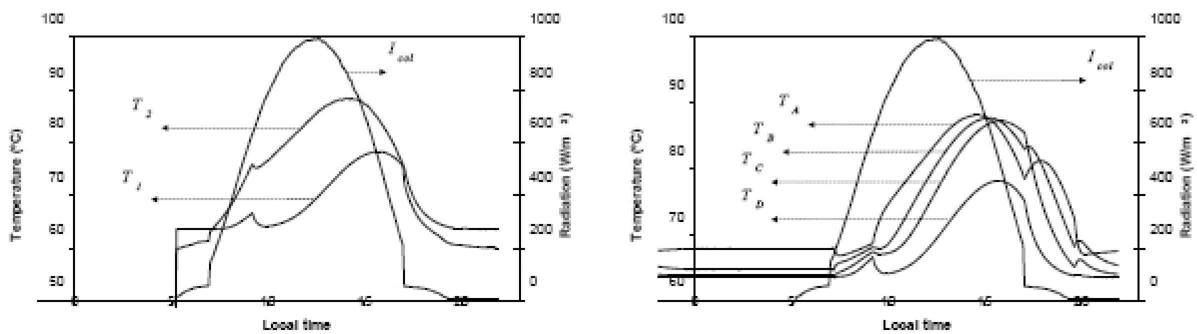

Figure 8. Solar field input/output (left) and storage tank nodes (right) temperature profiles for internal mixing and DEAHP on/off configuration (July 27th)

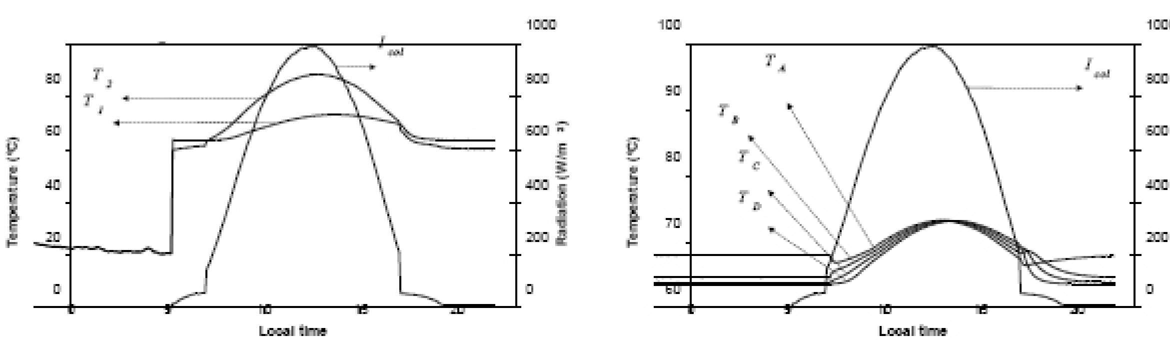

Figure 9. Solar field input/output (left) and storage tank nodes (right) temperature profiles for internal mixing and DEAHP always on configuration (July 27th)

In the internal mixing configuration with heat pump startup and shut down, there are several flow rates that vary quite a lot on days when the sky is clear, which can cause the flow rates reached to be outside of the piping design conditions. The internal mixing configuration with the pump always working has several different disadvantages. In this configuration, part of the heat pump feed water comes from the bottom of the cold tank and on days with high radiation, the temperature in that tank could be higher than the pump operating limits.

In Figures 6 to 9, several temperature profiles are shown for a completely clear summer day (July 27th) giving solar collector field inlet and outlet temperatures (T_1 , T_2), and the temperatures at each of the four nodes (T_A , T_B , T_C , T_D) considered in modeling the two thermal storage tanks. Figure 4 shows how water temperature within the tanks is near its boiling point. In Figures 8 and 9 temperature levels in the tanks are not very high but temperature in the lower part of the cold tank is over the maximum allowed by the heat pump.

5. DESALINATION COSTS

In the last years, a considerable reduction in fresh water cost from desalination plants has been achieved [7]; on the other hand, water produced in conventional treatment plants has raised due to over-exploitation of aquifers, contamination of ground water and saline intrusion. In countries such as the Persian Gulf region seawater desalination is, since many years ago, a fully competitive and used technique, and this situation is also increasingly close to become a reality in many other world areas due to continuously water demand increase and a parallel reduction in water availability due to previously mentioned reasons [7].

Table 4 shows capital and operating costs for the main technologies used in seawater desalination [8]: Multi-Stage Flash Distillation (MSF), Multi-Effect Distillation with Thermal Vapour Compression (MED-TVC), Mechanical Vapour Compression (MVC) and Reverse Osmosis (RO).

Table 4: Capital and operating costs for different desalination technologies [8]

	MSF	MED-TVC	MVC	RO[a]
Installation costs (**€/ m^3**/day)	1080 – 1690	780 – 1080	1020 – 1500	660 – 1200
Heat consumption (MJ/m^3)[b]	194 – 291	145 – 194	0	0
Power consumption (kWh/m^3)	3.5 – 4.0	1.5 – 2.0	9 – 11	3 – 4.5
Operation & maintenance (**€/m^3**)	0.05 – 0.07	0.04 – 0.07	0.05 – 0.08	0.05 – 0.10
Spare parts & chemicals (**€/m^3**)	0.02 – 0.04	0.02 – 0.03	0.02 – 0.04	0.02 – 0.05
Membranes replacement (**€/m^3**)	0	0	0	0.01 – 0.04

[a] Plant capacity between 10.000 – 100.000 m^3 /day
[b] GOR(MSF) = 8-12, GOR(MED-TVC) = 12-16

Wade [9] performed a comparison of water production costs by thermal distillation processes (MSF, MED) and reverse osmosis (RO, RO + Brine Booster). For this, he carried out a study with four plants with the same desalting capacity (31.822 m^3/day), operating in the Mediterranean area and with a fuel cost of 1.7**€GJ**. Results are shown in Table 5. Nowadays solar energy cannot yet compete with fossil fuel prices. To the achievement of such competitiveness, in the case of a hybrid solar-fossil fuel desalination facility, it is necessary to reduce the repercussion of the cost of the solar hardware to the final cost of the water in function of the cost of the fossil fuel energy. El-Nashar [10] calculated that for a fossil fuel cost of 11**€GJ**, a small MED plant fed only with solar energy from static solar collectors can obtain fresh water at a cost near to that of a conventional plant when the cost of the solar collector is 227**€/m^2** .

Table 5: Cost estimation of desalted seawater with different conventional technologies

MSF	1.18 **€ / m³**
MED	1.08 **€ / m³**
RO	0.93 **€ / m³**
RO + brine booster	0.85 **€ / m³**

Figure 10 shows a rough estimation of the equivalent solar hardware cost against fossil fuel cost to obtaining the same water. The target to be achieved with the proposed enhanced MED technology within the AQUASOL project is to approximate to these figures as much as possible. Particularly this result has been obtained for a typical commercial MED plant considering the following data: GOR = 7.5, production = 9600 m³/day, 90% availability, 15 years system lifetime and 50% solar fraction.

This means that, if the total achieved cost of the solar associated hardware (solar collector field, double effect absorption heat pump, brine dryer, etc.) is in the range of 90 to 155**€ / m²** (equivalent), the water cost from a hybrid solar-gas (50-50) MED plant would be the same than the one from a fully conventional MED plant (assuming mass production with large solar plants).

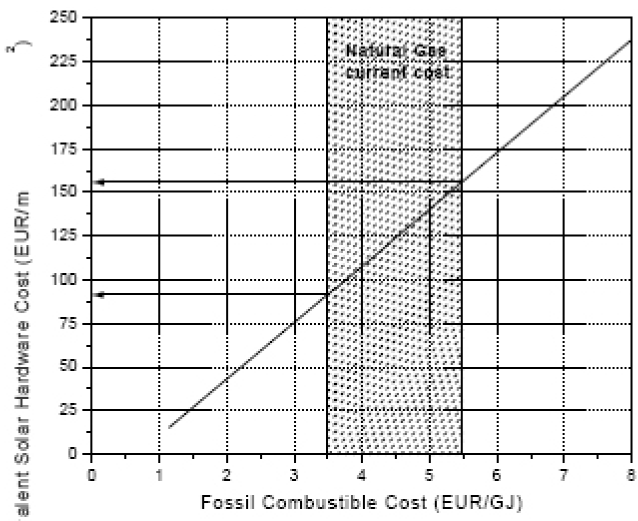

Figure 10: Estimated equivalent solar hardware cost versus fossil fuel cost to obtain the same cost than a conventional MED plant with a 50% solar contribution to the total plant energy requirement

6. CONCLUSIONS

Water scarcity is an increasing problem around the world and everybody agrees that seawater desalination can help to palliate this situation. Among the energy sources suitable to drive desalination processes, solar energy is one of the most promising options, due to the coupling of the disperse nature and availability of solar radiation with water demand supply requirements in many world locations. During the 90s, a Solar Thermal Desalination Project carried out at the Plataforma Solar de Almería, demonstrated the technical feasibility of solar thermal seawater desalination, through the coupling of a parabolic-trough solar collector field with a conventional Multi-Effect Distillation plant. Nevertheless, this technology cannot currently compete, from an economic point of view, with other conventional desalting technologies, without further improvements.

A new project, named AQUASOL, has been initiated in 2002 trying to improve the existing system. AQUASOL Project objective is the development of a least costly and more energy efficient seawater desalination technology based on Multi-Effect Distillation process with zero brine discharge. Specific proposed technological developments (new design of CPC collector and absorption heat pump, hybridization with natural gas and recovering of salt) are expected to both improve the energy efficiency of the process and process economy. The expected result would be an enhanced MED technology with market possibilities and suitable to be applied in the Mediterranean area and similar locations around the world. If a fuel cost (i.e. natural gas) of 4.5**€GJ** is considered, the needed cost of solar system (considering a solar contribution of 50% to the overall system and including solar collectors, absorption heat pump and brine dryer) to the achievement of the same economic competitiveness as conventional MED plant, is equivalent to around 125 **€/m²** of solar collector.

This paper also shows the results obtained in thermodynamic simulation of the AQUASOL desalination system. For this simulation, four different models representing the four possible operating configurations were implemented. Although the preliminary results show that one of these configurations (external mixing with startup and shut down of the heat pump) is the best, the simplicity of the model does not allow any of the other remaining figures to be discarded a priori. Therefore, during the demonstration phase of the AQUASOL project, these configurations will be implemented and evaluated in order to observe their behavior under real working conditions.