ELSEVIER

Desalination 122 (1999) 205–214

DESALINATION

www.elsevier.com/locate/desal

Thermo-economic analysis of a solar multi-effect distillation plant installed at the Plataforma Solar de Almeria (Spain)

L. García-Rodríguez[a]*, C. Gómez-Camacho[b]

[a]*Departamento de Física Fundamental y Experimental, Universidad de La Laguna, Tenerife, Canary Islands, Spain*
Tel. +34 (922) 31 83 03; Fax +34 (922) 25 69 73; email: mlgarcia@ull.es
[b]*Departamento Ingeniería Energética y Mecánica de Fluidos, Universidad de Sevilla, Sevilla, Spain*

Received 3 December 1998; accepted 28 February 1999

Abstract

A solar desalination plant was installed at the Plataforma Solar de Almería (PSA), Spain, and its first start-up took place in July, 1988. It is a multi-effect distillation (MED) system coupled to a one-axis tracking collector field and to a double-effect absorption heat pump. This plant was thermo-economically analyzed in some aspects, which complete the previous studies performed by the research team of the PSA. In this paper the influence on the product cost of some parameters was evaluated: thermal energy cost, number of effects, plant capacity and daily operation hours. In addition, the water costs of this solar MED plant were compared with a conventional energy source plant. Moreover, the effect on the competitiveness of the solar desalination system of the financial and fiscal politics parameters has been studied as well as the effect of the fuel and equipment cost evolution.

Keywords: Solar multi-effect distillation; Heat pump; Economics

---

1. Introduction

The Spanish research institution, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) and the Deutsche Forschungsanstalt für Luft- und Raum-fahrt e.V., Germany) (DLR) decided in January, 1987, to carry out the solar thermal desalination (STD) project to promote solar brackish and seawater desalination. The project was performed at the Plataforma Solar de Almería (PSA), a solar energy research center belonging to CIEMAT and DLR. PSA is located in southeastern Spain, near Almeria.

The main objective of phase I of the STD project was to study the reliability and feasibility of solar desalination. A 14-cell multi-effect

---

*Corresponding author.

PII: S0011-9164(99)00042-9

distillation (MED) plant was implemented at the PSA and connected to their solar facilities. The first start-up took place in July, 1988, and its evaluation finished in December, 1990 [1]. The plant, known as the "Sol-14 plant", is still in operation. The objective of Phase II [2] was the design and implementation of those improvements that could make solar thermal desalination more competitive. The initial vacuum system was replaced and a double-effect absorption heat pump (DEAHP) was coupled to the MED plant already installed at the PSA. In this paper, this solar desalination system is thermo-economically evaluated is some aspects.

The system analyzed consists of the following subsystems:

- The parabolic trough collectors (PTC) solar field. Thermal oil acts simultaneously as a heat transfer fluid and a heat storage medium. A computer program by C. Gómez-Camacho, briefly described in [3], was used for calculations of the solar field monthly production from some irradiance parameters at PSA previously evaluated from 1987 to 1991.
- Thermal storage, consisting of a single thermocline vessel.
- The boiler.
- The desalination plant is a 3 m^3/h MED unit.
- The DEAHP, which delivers 200 kW of thermal energy at 65 °C to the MED plant. The desalination process uses only 90 of the 200 kW, while the remaining 110 kW are recovered by the DEAHP at 35 °C and pumped to a usable temperature of 65 °C. For this, the DEAHP needs only 90 kW thermal power at 180 °C, thereby reducing the energy consumption of the desalination plant from 200 kW to 90 kW.

Results from previous studies of a generic solar PTC distillation system [3,4] have been taken into account:

- Calculations of monthly production from a given solar field at PSA.
- The most suitable design of a solar PTC desalination system. North–south solar field. The average temperature of solar field operation should be as low as possible.
- The capacity of the desalination plant should be the minimum one which allow the complete consumption of the energy delivered by the solar field. Therefore, the thermal storage capacity should be the minimum one for continious operation in the month of maximum energy production.
- At PSA, a solar PTC distillation system with minimum fresh water cost only could operate an annual average of 12 h/d — continuous operation only in the month of maximum production. If the desalination plant operates 24 h/d in winter, a great amount of energy is not consumed in summer due to the great difference between winter and summer energy production, and the product cost dramatically increases.

2. Solar desalination system

A MED solar desalination system was implemented at the PSA facilities. In this section, the description of the solar desalination system and the improvements performed in phase II are summarized from Zarza Moya [1,2]. A 14-cell MED plant was brought from the French company, Entropie, S.A., and connected to the PSA solar facilities. The initial solar desalination system implemented at the PSA facilities included a 14-cell MED plant, a boiler, a thermal storage system, and a PTC field.

Since PSA are 40 km from the sea, the desalination plant is operated in a closed circuit in which the distillate and brine are mixed in an open pool, producing the seawater which is again sent to the desalination plant.

The solar system operates with a synthetic oil heat transfer fluid (Santotherm 55), which is heated as it circulates through the solar collectors.

The heated oil is then stored in the thermal storage tank. The hot oil from the storage system goes to the boilers to generate the steam supply of the MED desalination plant.

The collector field consists of east–west aligned, one-track collectors with a total aperture area of 2,672 m^2 (Acurex, USA, model 3001). The size of the Acurex collector field is greater than that required by the Sol-14 desalination plant. Nevertheless, it was evidently more convenient to use the existing collector field at PSA than to erect a new, smaller collector field.

The desalination plant is connected to a single 115 m^3 thermocline vessel (Coupas, Greece) as a thermal storage system. The hot oil acts simultaneously as a heat transfer fluid and heat storage medium. The tank is insulated by 4.8m^3 of nitrogen.

The desalination plant uses sprayed horizontal tube bundles for seawater evaporation. The maximum temperature of evaporation is about 70 °C to limit scale formation. The plant evaporator body includes 14 cells at successively decreasing temperatures and pressures from cell (1) to cell (14). The external steam supply condenses in cell (1) tube bundle as it is sprayed by feedwater. The heat released evaporates part of this water at 67 °C, 0.28 bar. The steam thus produced goes on to cell (2) where it is also condensed in a tube bundle sprayed with feedwater. The latent heat produced by condensation of the vapour allows part of the feedwater entering the second cell to evaporate at the lower temperature/pressure of 64 °C/0.24 bar. The same condensation/evaporation process is repeated in cells (3) to (14). The vapor produced in cell (14) at 33 °C/0.05 bar is condensed in a final condenser cooled by seawater. The water condensed in each cell goes to the next one and finally to the condenser. The product water is then extracted from the condenser by means of the distilled water pump. The feedwater required to spray the cell (1) tube is part of the water coming out of the condenser.

Operation and maintenance experience with the solar desalination system has proven it to be highly reliable. Nevertheless, greater operating and maintenance requirements than a conventional MED desalination plant were due to the experimental nature of the plant, which had to be kept in perfect condition for testing and evaluation.

A conventional MED plant needs to cool the final condenser with seawater in order to condense the steam produced in the last effect. The amount of cooling water required by the condenser depends on the seawater temperature: the higher the temperature, the higher the flow rate required to keep the condenser at 35 °C. This cooling water is partially rejected back into the sea, thus wasting an important amount of 35 °C thermal energy. For a seawater temperature of 25 °C, the cooling flow required by the MED plant installed at the PSA was 20m^3/h. Only eight of the total 20m^3/h leaving the final condenser at 35 °C is used to feed the distillation process. The remaining 12 m^3/h are rejected to the sea, thus wasting more than 100 kW of thermal energy. This waste of energy can be eliminated by coupling a DEAHP unit at the final condenser.

The heat pump delivers 200 kW of thermal energy at 65 °C to the MED plant which devaluates this energy through its 14 effects. 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 thermal power at 180 °C. The energy consumption of the desalination system is thus reduced from 200 kW to 90 kW.

The ratio of the energy delivered by the heat pump (200 kW) to the primary energy received by it at 180 °C (90 kW) is called the coefficient of performance (COP), assumed to be 2.2 for this prototype. The MED plant feeds the steam produced in the last cell at 35 °C to the heat pump, instead of condensing it with cold seawater in the final condenser, thus avoiding wasting heat in the rejected cooling water. At the same time the heat

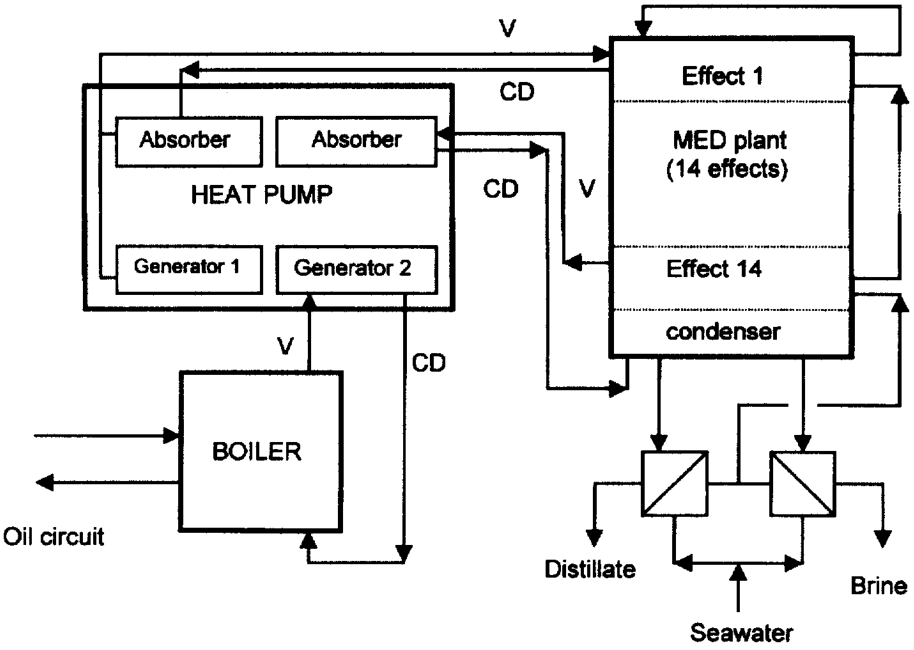

Fig. 1. MED plant connected to the heat pump. V, vapour; CD, saturated liquid.

pump was installed, two small plate heat exchangers were implemented in the MED plant distillate and brine circuits (Fig. 1). These two new heat exchangers connected in parallel preheat the seawater before entering the desalination plant by recovering sensible heat from the distillate and brine that leave the MED plant at about 35 °C.

At the conclusion of heat pump test evaluation, the main problem encountered was the randomly unstable operation of this equipment and the difficulty in achieving steady state conditions. In contrast to the operating problems, it should be pointed out that the theoretically assumed COP of 2.2 was not obtained during the testing, although some results were rather close. Some operative problems, normal with prototypes, may be avoided by implementing a proper control system. To sum up, the improvements imple-mented in the desalination system (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/m^3 and the electric consumption by 12% from 3.3 to 2.9 kWhe/m^3.

3. Influence of MED system parameters

The effect of the main parameters on the distilled water cost is given in Fig. 2 for the Sol-14 plant and for the Sol-14 plant coupled to the DEAHP where Pu_0 is the distilled water cost in reference conditions and Pu is the water cost at any other conditions. Those reference conditions are as follows:

- plant capacity, 3 m^3/h
- number of effects, 14
- plant availability, 95%
- boiler thermal losses, 5%
- thermal energy cost, 0.03 EUR/kWh
- cost of electricity, 0.09 EUR/kWh
- performance ratio, 10.5 for Sol-14 plant and 21 for Sol-14 coupled to DEAHP.

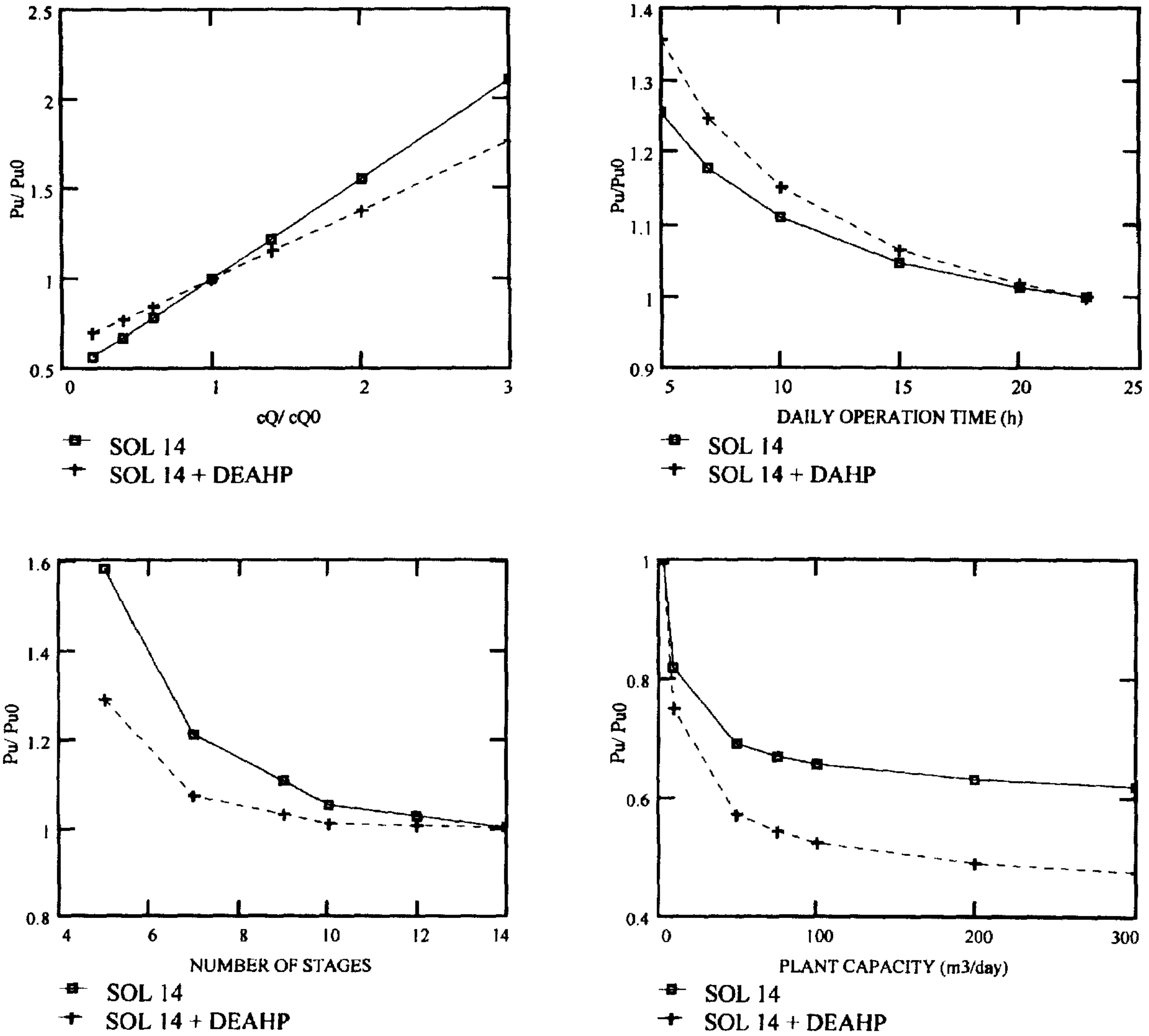

Fig. 2. Influence on distilled water cost (*Pu*) of thermal energy cost, daily operation time, number of stages and plant capacity.

3.30 EUR/m^3 and 2.36 EUR/m^3 are the respective product costs obtained for a MED and a MED–DEAHP systems in reference conditions. Algorithms for calculation of the plant equipment and operation and maintenance costs are given by Zarza Moya [2]. Basic assumptions of residual value, land cost, loan interest rate, system lifetime and general inflation are presented in Table 1. Fig. 2 shows the following results:

- The influence on the product cost of the thermal energy cost and the number of stages are lower for the MED–DEAHP system than for the MED plant.
- The number of cells of the distillation plant have little influence for a MED coupled to a heat pump.
- The decreasing of the product cost vs. the plant capacity is high for MED and MED–DEAHP

Table 1
Parameters for calculation of annual costs

Residual value of the system after its life time, %	10
Land cost, EUR/m^2	0
Boiler thermal losses, %	5
Loan interest rate, %	4.25
System lifetime, y	20
Basic solar collector price, EUR/m^2	149.6
O&M solar collector field, EUR/m^2/y	8.98
Cost of the boiler, % of the total solar field cost	10
General inflation, %	2.25

plants, specially at plant capacities below 100 m^3/h.

- Few variations of the thermal energy cost strongly influence the product cost. Since the cost of the energy consumption of the desalination plant depends on solar field and thermal storage subsystems, they should be carefully designed.
- The economic benefits of coupling the heat pump to the MED system, if the energy resource does not permit continuous operation, are lower than those in continuous operation.

3. Influence of solar field and thermal storage parameters

Fig. 3 shows the influence on the fresh water costs of the size of the solar field. In according to conclusions from previous solar desalination systems studies [4], the collector field connected to the desalination plant should be the biggest one which permits the total consumption of the energy delivered by the solar field. For solar fields larger than this, the fresh water cost increases because of an incomplete consumption of the solar energy available. This is because the desalination plant, in summer, is not able to consume the total production of the solar field in 24 h of operation. Nevertheless, for numbers of solar collectors lower than the optimum, the average of the daily operational hours are lower than the maximum. Therefore, the fresh water production is lower than the maximum that can be reached.

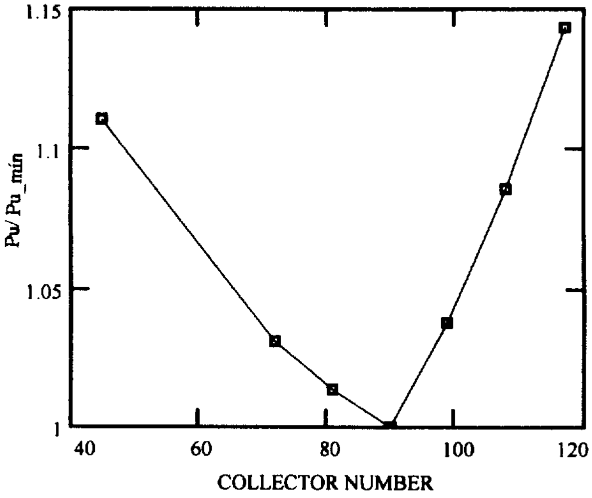

Fig. 3. Selection of the solar field size. Pu_{min} = 3.69 EUR/m^3.

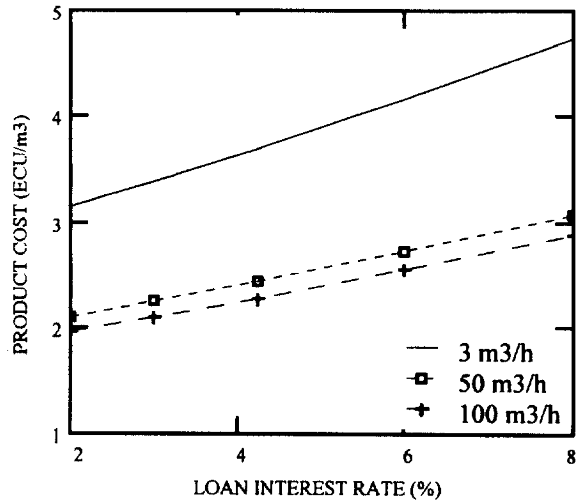

Fig. 4. Influence of the financial politics on the fresh water cost.

For an optimized solar field and thermal storage (see Table 2), the costs obtained are

Table 2
Main design and operation parameters for the equipment: solar collector field (CC), thermal storage (AT) and boiler (GV)

Equipment	Design and operation parameters		
Solar PTC field	Location	PSA	
	Collector	PTC: Solar Kinetics T700A; length = 6.1 m, width = 2.13 m	
	Thermal fluid	Santoterm 55	
	Axis height, °	0, horizontal collector	
	Azimuth of the axis, °	180, north–south	
	Azimuth of rows, °	0	
	Row distances, m	7	
	Column distances, m	7	
	Number of collectors:		
	MED + DEAHP	50	
	MED	90	
	Thermal fluid temperatures, °C:	MED	MED+DEAHP
	Inlet	$T_F = 110$	$T_F = 190$
	Outlet	$T_C = 190$	$T_C = 260$
Thermal storage	Thermal storage	Thermocline vessel	
	Thermal oil required, kg		
	MED	5.266×10^4	
	MED+DEAHP	2.606×10^4	
	Thermal losses	≈0	
Boiler	Fluids	Oil / saturated water	
	Inlet/outlet thermal oil temperatures, °C:		
	MED	$T_F = 110$, $T_C = 190$	
	MED + DEAHP	$T_F = 190$, $T_C = 260$	
	Steam temperature (T_v), °C:		
	MED	73	
	MED+DEAHP	180	
	Thermal energy delivered, kW:		
	MED	190	
	MED+DEAHP	90	
	Thermal losses, %	≈ 5	

3.69 EUR/m^3 for the Sol-14 plant and 2.86 EUR/m^3 for the plant coupled to the heat pump (Table 3), which is a 23% lower cost. Other required parameters are given in Table 1.

4. Financial and fiscal politics

Fig. 4 shows the influence of the financial politics on the solar distillation specific cost. Its influence decreases as the plant capacity increases.

Table 3
Product cost

System	Thermal energy consumption, kW	Thermal energy cost, EUR/kWh	Electric consumption, kWh/m^3	Hours of operation, h/d	Pu_0, EUR/m^3
MED	190	0.032	3.3	12.0	3.69
MED+DEAHP	90	0.038	2.9	11.7	2.86

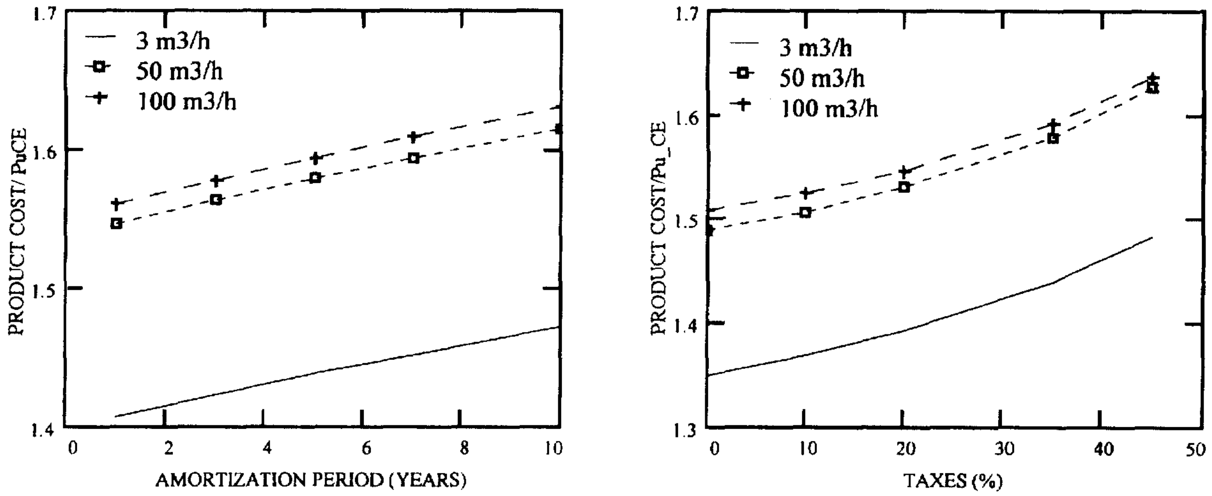

Fig. 5. Influence of fiscal politics on the competitiveness of the solar distillation where Pu_{CE} is the product cost of a conventional energy source MED plant.

Fig. 5 represents the cost of the solar MED divided by the cost of the water obtained by conventional energy ME distillation. The figures show the influence of the fiscal politics on the competitiveness of the use of solar energy. The influence is similar for different plant capacities.

5. Evolution of the cost of MED plants

Fig. 6 shows the influence on fresh water cost of the MED plant capital cost reduction for a solar MED system. The lower the plant capacity, the higher the cost reductions.

6. Evolution of conventional energy cost

m_r is the variation of the cost of conventional thermal energy source below or above inflation. Fig. 7 shows the effect on the distilled water cost by conventional energy cost vs. m_r and compares this evolution with the cost of solar ME distillation. As the short supply of fossil fuels will

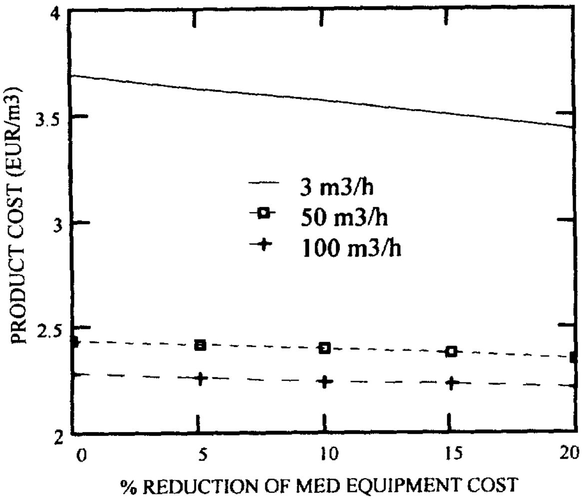

Fig. 6. Fresh water cost vs. the percentage of reduction of MED plant equipment cost for different plant capacities.

probably increase their cost, solar ME distillation will be more competitive in the future.

7. Conclusions

- The great increasing of the MED plant performance ratio due to the coupling of a heat pump makes DEAHP–MED plants suitable for solar applications as the cost of the energy delivered by the solar field is high.
- The coupling of a heat pump to a MED plant represents a significant reduction of the product cost. In addition, the higher the energy cost, the greater the product cost reductions of the MED–DEAHP system vs. a MED plant. These facts could facilitate the competitiveness of solar MED–DEAHP systems against conventional energy MED plants.
- The coupling of a heat pump offers an alternative of significant cost reductions for all desalination plant capacities. This fact is important especially for plant capacities below 100 m^3/h in which fresh water costs are higher than in larger ones.

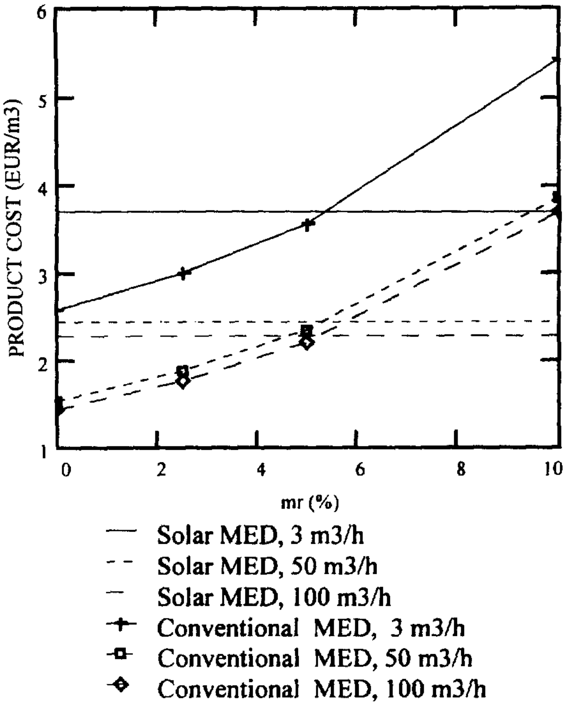

Fig. 7. Fresh water cost vs. m_r for different plant capacities.

- Since the lower the number of stages, the higher the product cost reductions of MED–DEAHP systems with respect to MED ones, heat pumps present an economical alternative of reducing the top temperature in MED systems without increasing product cost. This fact is interesting in the use of process heat in solar desalination as auxiliary energy.
- Since the lower the operation time of the MED plant, the lower the cost reductions due to the coupling of the DEAHP, in solar applications, the design of the system should permit continuous operation of the desalination plant. As in solar applications in southern Spain, the large difference between winter and summer production does not make minimum the fresh water cost in continuous operation, and the solar-fuel desalination may be more suitable than solar-powered plants. In addition, to

evaluate the possible economical advantages of coupling a heat pump to a solar MED system, special attention is required to evaluate the average of the operation time. For this evaluation, a detailed study of the available solar energy and irradiance transient month by month is necessary.

- The solar field size should be carefully designed since the cost of the fresh water is strongly influenced by it.
- Financial politics strongly influence the cost of fresh water production by solar energy. The lower the plant capacity, the higher the effects of financial politics.
- Special fiscal conditions would make the solar ME distillation more competitive. The influence of these conditions on the competitiveness are not dependent on plant capacity.
- As the cost of conventional energy sources probably increases in the future, and the cost of solar distillation should decrease due to improvements in the system, the solar ME distillation is an attractive option for high insolated coastal regions.

References

[1] E. Zarza Moya, Solar thermal desalination project: first phase results and second phase description. CIEMAT, Madrid, 1991.

[2] E. Zarza Moya, Solar thermal desalination project: Phase II results and final project report. CIEMAT, Madrid, 1995.

[3] L. García-Rodríguez and C. Gómez-Camacho, Desalination, 122 (1999) 195.

[4] L. García-Rodríguez and C. Gómez-Camacho, Desalination, 122 (1999) 215.