Desalination and Water Treatment
www.deswater.com

41 (2012) 9–25
March

1944-3994/1944-3986
doi: 10.1080/19443994.2012.664674

Taylor & Francis
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Techno-economic analysis of combined concentrating solar power and desalination plant configurations in Israel and Jordan

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Received 23 August 2010; Accepted 22 March 2011

ABSTRACT

Combined concentrating solar power (CSP) and desalination plants represent a realistic future option for the production of electricity and fresh water for countries of the world's sunbelt. In this paper, parabolic trough power plants for electricity production have been analysed in combination with multi-effect distillation (MED) and ultrafiltration/reverse osmosis (RO) desalination plants for two sites in Israel (Ashdod) and Jordan (Aqaba). Both RO and MED desalination plants were designed for a fresh water production capacity of 24,000 m^3/d. The power block of the CSP plant was selected to meet the steam consumption of the MED plant at the design point, which led to a gross electrical power generation capacity of the power block of 42 $MW_{el,gross}$. Due to the low availability and generally high cost of coastal land, the CSP + RO plant consists of two separate units. It was assumed that the CSP plant is located at an inland location where there is land available. The RO plant is located at the sea, while the MED plant is located at the CSP site. The pumping of the seawater and the water transmission system add about 0.2 \$/m^3 to the levelized water costs of the CSP + MED plant compared with a plant located at the sea. Three different sizes of high temperature heat storages (0 h, 6 h and 12 h of additional full load operation of the steam turbine) were applied to find the most economic setup. At current prices for heat storage units, systems with huge heat storage capacities become economic only at high feed-in tariffs for electricity and thus high revenues. The price of the electricity generated by the CSP plant was varied to show the influence of the feed-in tariff on the water generating costs. The levelized costs of water (LCOW) strongly depend on the electricity price. Water costs in Ashdod are higher than those in Aqaba due to the lower solar irradiance. For Aqaba, LCOW of about 1 \$/m^3 can be realized if a feed-in tariff of about 0.24 \$/kWh for electricity from renewable energy sources is established.

Keywords: Desalination; Solar energy; Reverse osmosis; Multi-effect distillation; Concentrating solar power; Costs of water

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1. Introduction

Recent studies have shown the potential of concentrating solar power (CSP) plants coupled with desalination plants to close the predicted gap in the energy and freshwater supply of the prospering Middle East and North Africa (MENA) region of the next decades [1–3].

In the framework of the research project "Concentrating Solar Power & Desalination for Communities in Israel and Jordan" (CSPD-COMISJO) the performance of an Andasol-type [4] CSP plant (parabolic trough receivers, oil as heat transfer medium, molten salt heat storage, Rankine steam power cycle) was modelled based on hourly time series of the irradiation conditions at an Israeli site at the Mediterranean Sea (Ashdod) and a Jordan site at the Red Sea (Aqaba). The Andasol-type CSP plants are coupled with different desalination technologies, namely multi-effect distillation (MED) plants and ultrafiltration (UF)/reverse osmosis (RO) plants.

The main criteria for comparison of the two evaluated concentrating solar power and desalination (CSPD) systems, CSP + MED and CSP + RO, are the levelized costs of water (LCOW). Details of the simulation, boundary conditions and results are given below.

2. General boundary conditions and design approach

The technical performance of a solar thermal power plant is closely related to the solar direct normal irradiance (DNI) available at its location. The hourly time series of the DNI at ground used for the performance evaluation of the CSP plants were derived from satellite data images of the Israeli and Jordan locations. DNI data from satellite images were collected for the years 2001–2005 [5]. The data of the reference year 2005 were used for the performance evaluation. In 2005 the average DNI at ground at Aqaba was 2,461 kWh/(m^2 y) and at Ashdod 1,984 kWh/(m^2 y). The feed waters to be desalinated at the Israeli and Jordan sites (seawater [SW] from the Mediterranean Sea and the Red Sea) were analysed in the laboratory. The requested salinity of the fresh water was fixed at 200 ppm with a constant freshwater output of each configuration of 24,000 m^3/d.

Natural gas for backup firing the MED units is available in Israel as well as in Jordan. The price for natural gas in Jordan is significantly higher than in Israel, while the electricity from the grid is cheaper in Jordan compared to Israel.

It was assumed that the CSP plant is located at an inland location where there is land available. In Aqaba, the site is 5 km away from the coast and 50 m above sea level. In Ashdod, the site is 2 km away from the coast and 10 m above sea level. The RO plant is located at the sea, while the MED plant is located upcountry at the CSP plant. The pumping of the SW and the water transmission system to an inland location, of course, add electricity and investment costs to an MED setup. This situation is roughly evaluated in this paper.

2.1. Water conditions and economic parameter set

The results of the feed water analysis used as input of the technical design and cost evaluation of the RO and MED systems as well as the main economic parameters used are shown in Table 1.

The salinity of the Red Sea water is slightly higher than that of the Mediterranean Sea water. The SW temperature gradient between summer and winter season is recognizably higher at the Mediterranean Sea. As a consequence, cooling water mass flow rates to the final condenser of the MED unit strongly vary over the seasons.

Two of the main parameters with major influence on the economics are the project duration and the investment interest rate which are fixed for this study at 20 years and 8% respectively. Another parameter with influence on the economics is the cost of labour, which is notably higher in Israel than it is in Jordan.

2.2. Performance and cost calculation approach

Both desalination plants, RO and MED, were designed for a fresh water production capacity of 24,000 m^3/d. It was assumed that the desalination units work at full load conditions. Part load operation was not considered due to economic and operational disadvantages applying part load operation. Consequently, the MED units were assumed to be co-fired with natural gas to obtain full load conditions (backup heat for MED is available from a gas burner). The MED plants for Aqaba and Ashdod were designed and simulated using the software IPSEpro (SimTech Simulation Technology, Austria). IPSEpro is an object-oriented model building and simulation software suited especially for power plant and desalination plant calculation. To design the two-stage, two-pass RO system, Reverse Osmosis System Analysis (ROSA) software (The Dow Chemical Company, USA) was used.

The power block of the CSP plant was selected to meet the steam consumption of the MED plant at the design point, which led to a gross electrical power generation capacity of the power block of

Table 1
Water conditions at Aqaba and Ashdod and economic parameters

City	Aqaba	Ashdod
General information		
Country	Jordan	Israel
Latitude, deg North	29.60	31.85
Longitude, deg East	35.03	34.67
Satellite data available	2001–2005	2001–2005
Selected reference year	2005	2005
Average annual DNI at ground, kWh/(m^2 y)	2,461	1,984
Population	80,000 Aqaba 60,000 Elat (I)	210,000
Fresh water end use	Drinking water	Drinking water
Available fossil fuel	Natural gas	Natural gas
Water parameter		
(A) Feed water		
Water source	Red Sea	Mediterranean Sea
Feed water resources, m^3/d	Unrestricted	Unrestricted
Feed water intake conditions	Open intake	Open intake
Feed water transport distance for MED, km	5	2
Height difference sea level-CSP + MED, m	50	10
Seawater temperature, high, °C	28	32
Seawater temperature, low, °C	20	18
pH	8.3	7.5
Total dissolved solids, ppm	42,555	40,512.6
Ammonium (NH_4^+), ppm	0.03	0
Potassium (K^+), ppm	490	515
Sodium (Na^+), ppm	13,100	12,870
Magnesium (Mg^{2+}), ppm	1,590	1,180
Calcium (Ca^{2+}), ppm	415	450
Strontium (Sr^{2+}), ppb	0	0
Barium (Ba^{2+}), ppb	0	0
Carbonate (CO_3^{2-}), ppm	7.065	7.191
Bicarbonate (HCO_3^-), ppm	144	163.34
Nitrate (NO_3^-), ppm	2	0
Chloride (Cl^-), ppm	22,834	22,143
Fluoride (F^-), ppm	0.97	0
Sulphate (SO_4^{2-}), ppm	3,239	3,145
Silica (SiO_2), ppm	2	5
Boron (B^{3+}), ppm	5.4	5.95
(B) Fresh water		
Fresh water salinity (required), ppm	<200	<200
Fresh water demand, plant design point, m^3/d	24,000	24,000
Economic parameter		
Project duration, years	20	20
Share of loan capital, %	100	100
Investment interest rate, %	8	8
Medium costs of labour, $/(person year)	5,220	24,800
Average electricity price, $/kWh$_{el}$	0.069	0.115
Costs for fossil fuel (natural gas), $/kWh	0.02	0.01
Rate of exchange, Dollar/Euro	1.4	1.4

42 MW_{el}. Accordingly, the gross electrical power generation capacity of the power block of 42 $MW_{el,gross}$ was chosen as the design point for the solar field and the heat storage system. It was assumed that the CSP plant is solar driven only. In power block part load operation, a natural gas burner delivers the shortage in exhaust steam for the MED units. No fossil co-firing for the power block was considered. Three different sizes of thermal storage were considered which allow for an additional full load operation of the steam turbine of 0 h, 6 h and 12 h. The design of the whole power block was done using the commercial power cycle simulation software EBSILONprofessional (STEAG KETEK IT GmbH, Germany).

To evaluate the techno-economic performance of the combined systems, annual calculations on an hourly basis were performed for the CSP + MED and CSP + RO systems for both locations Aqaba and Ashdod. Satellite-derived irradiance data and air temperature data from MeteoNorm (Meteotest, Switzerland) were used. Calculations were performed with an in-house built EXCEL tool with efficiency curves derived from detailed thermodynamic simulations in EBSILONprofessional.

The main results for the CSP + MED plant are the net and gross annual electricity production of the CSP plant, the process steam production for the MED plant and the required fossil co-firing to run the MED desalination plant during times when no heat (direct or stored) from the solar system is available. For the CSP + RO system, the main results of the annual calculation are the gross and net electricity production and the constant electricity consumption of the RO plant with 24,000 m^3/d. The electricity needed for the MED or the RO units is always considered to be bought from the local grid at the local tariff.

For economic evaluation, the LCOW were calculated by

$$\mathrm{LCOW} = \frac{C_{\mathrm{Inv}} + C_{\mathrm{el}} + C_{\mathrm{co-fi(MED)}} + C_{\mathrm{chem}} + C_{\mathrm{staff}} + C_{\mathrm{maint}} + C_{\mathrm{mem(RO)}} + C_{\mathrm{G\&A}} - \mathrm{REV_{el}}}{Q_{\mathrm{water}}}, \quad (1)$$

where, LCOW is the levelized costs of water, $\$/m^3$; C_{Inv} is the total annual investment costs of the CSP and the desalination plant, $/y; C_{el} is the annual costs of electricity required for operation of the desalination plant (RO or MED) if the electricity is bought from the grid, $/y; $C_{co-fi(MED)}$ is the annual fuel costs for co-firing (only for MED), $/y; C_{chem} is the annual costs for chemicals, $/y; C_{staff} is the annual costs for staff, $/y; C_{maint} is the annual maintenance and spare parts costs, $/y; $C_{mem(RO)}$ is the annual costs for membrane replacement (only for RO), $/y; $C_{G\&A}$ is the annual general and administrative costs (G&A), $/y; REV_{el} is the annual revenue from electricity sales, $/y; Q_{water} is the annual water production capacity, m^3/y.

3. Techno-economic performance of desalination units under full load conditions

3.1. RO units

By far the most widespread type of membrane-based desalination processes, RO is rapidly gaining shares of the desalination market due to the high energy efficiency of modern plants implementing energy recovery devices (ERDs) and to the possibility of scaling up plant size to capacities in the range of some 100,000 m^3 per day. Commercially available RO membranes can retain about 98–99.5% of the salt dissolved in the feed water [6] and typical operating pressures range between 10 and 15 bars for brackish water (BW) and between 55 and 65 bars for SW [7].

Smooth operation and stable long-term performance of RO membranes for SW desalination require high-quality feed water. In the presence of a poorly pre-treated feed, inorganic and organic matter may accumulate at the membrane surface causing membrane scaling and fouling, and strongly reducing or inhibiting mass transfer through the membranes. Conventional RO pre-treatment consists of both physical and chemical processes. Physical pre-treatment generally consists of mechanical filtering of the feed water by screening, cartridge filters and sand filters [7]. For chemical pre-treatment, scale inhibitors, coagulants, disinfectants and polyelectrolytes are added [7]. It is being increasingly realized, however, that integrated membrane systems—in particular with UF as pre-treatment step—offer improvements with respect to conventional pre-treatment due to their potential to prolong membrane life and thus reduce replacement costs and improve long-term performance of a desalination plant [8].

For such reasons, the simulation of the technical and economic performance of CSP + RO desalination plants at the selected case-study sites relies on a UF–RO configuration, which has been shown to provide significant advantages in the specific case of SW desalination in Ashdod [9]. For the design of the system, only well established technologies were considered, which are suitable to be installed in a desalination system of the required capacity (24,000 m^3 per day).

3.1.1. Technical setup and performance of RO units

An overview of the technical setup of the proposed UF–RO desalination plants in Ashdod and Aqaba is given in Table 2. The systems were designed

Table 2
Design data of the reverse osmosis units

	UF–RO unit	
	First pass	Second pass
General design information		
Water source	SW (open intake)	
Design permeate salinity, ppm	<200	
Operation time per day, h	24	
Number of passes	2	
Water recovery per pass, %	50	80
Pre-treatment		
Pre-treatment steps	Ultrafiltration	RO permeate
SDI after pre-treatment	<3	<1
RO membranes unit		
Membrane type	Dow Filmtec SW30HR-320	Dow Filmtec BW30LE-440
Element diameter, inch	8	8
Active area, m^2	29.7	40.9
Rejection, %	99.75	99.00
Design flux, lmh	12.5	16
Number of membrane elements per vessel	6	6

for continuous operation with constant permeate flow and constant system recovery. An operation time of 24 h/day and a plug-flow design (i.e. without concentrate recirculation) were assumed.

The feed water is pumped from an open SW intake to the pre-treatment unit, which consists of UF membranes such as the Zenon ZeeWeed® membranes, which are capable of achieving a Silt Density Index (SDI) equal to 3 or less in the RO feed. For the RO unit, standard pressure vessels containing six elements were considered and the membranes were chosen with the help of the online design tool ROSA provided by DOW Filmtec [10]. The number of membrane elements required is determined by the flux at which they are operated. Although it is tempting to operate at high flux in order to minimize the investment cost for the membranes, the flux that can be achieved in practical SW and BW desalination is determined by the fouling tendency of the feed water. Flux typically ranges between 12 and 17 lmh for SW desalination (11–17 lmh for open intake, and 13–20 lmh for well intake or microfiltration pre-treatment [11]) and between 25 and 30 lmh for BW desalination [12]. The CIIRDF project [9] investigated the economic feasibility of improving flux in a 20,000 m^3/day UF–RO SW desalination plant in Ashdod, and concluded that increasing flux from 12.5 to 16 lmh would result in economic benefits. For the present project, different configurations with fluxes ranging between 10 and 16 lmh were tested. Contrarily to the results of the CIIRDF project, it was found that operation at high fluxes would not result in economic advantages in Aqaba and Ashdod and therefore the more conservative flux of 12.5 lmh was assumed in the calculations.

As in many current SW-RO plants, the unit consists of two passes, the first with high rejection RO membranes (Dow Filmtec SW30HR-320) while the second consists of high flux BW RO membranes (Dow Filmtec BW30LE-440) to reduce salinity and remove boron to achieve drinking water standards. Within each pass, the membranes are configured into two stages, such that the second-stage RO membrane module components take the concentrate of the first-stage RO components. The staging ratio R between first and second stage is calculated as follows:

$$R = \sqrt{\frac{1}{1-r}} \tag{2}$$

where r is the recovery ratio of the considered pass. The system is designed that the permeate of the second stage of the first pass is the feed of the second pass since it has higher salinity than the permeate of the first stage of the first pass. The second pass is designed for BW desalination with high recovery ratio (80%).

An ERD of the type isobaric pressure exchanger was assumed to be used, which can operate with an efficiency of 96% [13]. An overall efficiency of the high pressure pump and electrical motors equal to 80% was assumed. The specific energy consumption E of the system including the ERD is calculated as follows [14]:

$$E = \frac{P_f Q_f \varepsilon_{\text{pump}}^{-1} - P_b Q_b \varepsilon_{\text{ERD}}}{Q_p}, \tag{3}$$

where P_{f} and Q_{f} are the pressure and flow rate of the RO feed, P_{b} and Q_{b} are the pressure and flow rate of the brine, Q_{p} is the permeate flow rate, and $\varepsilon_{\text{pump}}$ and ε_{ERD}, respectively, are the efficiency of the high pressure pump and of the ERD.

The results of the design calculations and performance expectations obtained with the ROSA software for the Ashdod and Aqaba sites are presented in Table 3. A flow sheet of the designed RO unit is shown in Fig. 3, see Section 4.3.

Table 3
Design data of the reverse osmosis units

	UF–RO Aqaba		UF–RO Ashdod	
	First pass	Second pass	First pass	Second pass
Design data				
Number of membranes in pass	2,721	186	2,748	195
Number of pressure vessels in pass	454	31	458	33
Stages in pass	2	2	2	2
Staging ratio, R	1.41	2.24	1.41	2.24
Number of pressure vessels in stage 1, $N_{v,11}$	266	21	268	23
Number of pressure vessels in stage 2, $N_{v,12}$	188	10	190	10
Permeate salinity, ppm	214.41	14.94	209	45
Final permeate salinity, ppm	190		188	
Overall water recovery ratio	49%		48%	
Pumps' efficiency and energy consumption (ROSA output)				
Feed pressure, bar	68.88	4.97	65.62	5.46
Concentrate pressure, bar	66.66	3.00	63.4	3.58
Concentrate flow rate, m^3/h	1,010	32	1,020	32
Energy consumption without ERD, kWh/m^3	4.78	0.22	4.56	0.24
Energy consumption with ERD, kWh/m^3	3.04	–	2.92	–
Overall energy consumption, kWh/m^3	*3.16*		*3.05*	

Based on the results summarized in Table 3, the UF–RO system in Ashdod has lower specific energy consumption than the one in Aqaba. This result is not surprising given the slightly higher salinity of the SW in the Red Sea compared to that of the Mediterranean Sea.

3.1.2. Economic performance

Table 4 shows the parameters that were used in the economic analysis of the UF–RO desalination plants to be coupled with the CSP systems. The economic parameters are the same for the two case-study sites with the exception of the staff costs, which are estimated to be 5,220 \$/(person year) in Aqaba and 24,800 \$/(person year) in Ashdod. The remaining economic parameters were assumed from the economic feasibility analysis in the CIIRDF project [9].

The results of the economic analysis for the Ashdod and Aqaba sites are presented in Table 5.

The main cost component in both systems is the capital cost for the first pass. Among operation and maintenance (O&M) costs, the largest share is taken by the electricity costs followed by the maintenance costs and the membrane replacement costs. If the energy requirements of the UF–RO desalination plants are met by grid electricity, the water costs of the two systems will amount to 0.905 $\$/m^3$ for Aqaba and 1.081 $\$/m^3$ for Ashdod.

Table 4
Parameters of the economic analysis of the reverse osmosis units

	Aqaba	Ashdod
Investment cost		
RO plant costs including brine disposal, UF pre-treatment, excluding second pass, product re-mineralization, intake, $\$/(m^3/day)$	1,283	
Second pass, $\$/(m^3/day)$	150	
Post-treatment plant, $\$ / (m^3/day)$	55	
Open seawater intake, $\$ / (m^3/day)$	217	
Project lifetime, years	20	
Investment interest rate, %	8	
RO plant availability, %	95	
Operation and maintenance costs		
Number of plant operators	8	
Staff cost, \$/(person year)	5,220	24,800
Maintenance cost, as percentage of investment on annual basis, %	1.5	
Membrane replacement rate per year, %	20	
Membrane element cost, \$	500	
Chemical cost, first pass, $\$/m^3$	0.03	
Chemical cost, second pass, $\$/m^3$	0.02	
G&A cost, as percentage of operating costs, %	10	
Electricity price from grid, \$/kWh	0.069	0.115

Table 5
Economic analysis of the reverse osmosis units

	UF–RO Aqaba		UF–RO Ashdod	
	Annual expenditure k$/year	Unit water price $/m^3	Annual expenditure k$/year	Unit water price $/m^3
Investment costs				
Capital cost, first pass, including seawater intake	3,703	0.454	3,740	0.455
Capital cost, second pass	45	0.005	47	0.006
Capital cost, post-treatment plant	132	0.016	133	0.016
Total investment costs	3,880	0.476	3,920	0.477
Operation and maintenance costs				
Staff cost	42	0.005	198	0.024
Maintenance cost	552	0.068	558	0.068
Membrane replacement cost	291	0.036	294	0.036
Chemical cost, first pass	258	0.032	260	0.032
Chemical cost, second pass	172	0.021	173	0.021
Cost of electricity if bought from grid	1,870	0.229	3,035	0.369
G&A costs, as percentage of O&M costs	318	0.039	452	0.055
Total operation and maintenance costs	3,502	0.429	4,970	0.604
Total costs		*0.905*		*1.081*

3.2. MED units

For selecting an appropriate thermal desalination system to be coupled with a CSP power plant, the following criteria were applied:

- The thermal desalination system is well-established.
- The desalination system is suited for the production of water in the order of magnitude of 24,000 m^3 per day.
- The major energy source of the thermal desalination system is thermal energy (steam).
- The top brine temperature is low to minimize efficiency losses of the steam turbine of the CSP power plant.
- The specific electrical energy consumption of the thermal desalination system is as low as possible.

MED was selected because it meets the aforementioned criteria best.

MED is widely and increasingly employed for SW desalination. In MED plants with horizontal tube falling film evaporators, water is evaporated on heat transfer tubing. Heating steam from an external source (here the exhaust steam of the steam turbine) is only needed in the first stage, also called effect. The vapour produced in the first effect is fed into the tubes of the next effect. It condenses inside the tubes, while a fraction of the SW on the shell side evaporates. The pressure subsequently decreases from effect to effect and is held at a constant level by a vacuum system.

3.2.1. Technical setup and performance of the MED units

Single-unit capacities of MED plants without thermal vapour compression are typically up to 15,000 m^3 of distillate per day. Therefore, two identical MED units, each producing 12,000 m^3/d, were selected for each site.

Ten-stage MED units with parallel feed water flow and separate pre-heaters were designed for summer and winter conditions in Aqaba and Ashdod. The flow sheet of the 10-stage plant, shown in Fig. 1, was built during system simulation. The optimal number of stages results from the overall temperature difference between heating steam temperature and SW temperature. While more stages lead to a higher efficiency of the plant, the driving temperature difference for each stage decreases with increasing number of stages and, thus, the heat transfer area increases.

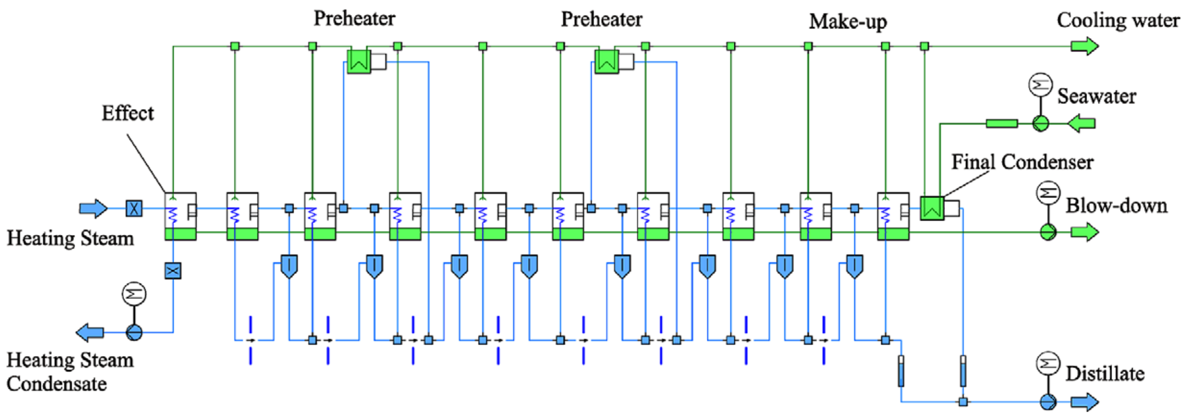

Fig. 1. IPSEpro flow sheet of the chosen MED plant (vacuum system not shown here).

Table 6
Design data of the MED units including vacuum system in Aqaba and Ashdod (data refer to one unit with 12,000 m^3/d)

	Aqaba		Ashdod	
	Summer	Winter	Summer	Winter
MED design data				
Seawater temperature, °C	28	20	32	18
Seawater salinity, g/kg	42.5		40.5	
Distillate mass flow rate, t/day	12,000		12,000	
Distillate salinity, ppm	<10		<10	
Number of stages	10		10	
GOR	8.35		8.52	
Concentration factor	1.5		1.6	
Top brine temperature, °C	65		65	
Heat transfer area of one stage, m^2	4,626		4,893	
Specific heat transfer area, m^2 s/kg	366		391	
Heating steam mass flow rate, kg/s	16.63		16.31	
Heating steam pressure at turbine outlet, bar	0.35		0.35	
Heating steam pressure at first stage, bar	0.278		0.276	
Temperature of heating steam condensate, °C	67.3		67.2	
Specific heat consumption, kWh/t	77.8		76.3	
Make-up water mass flow rate, kg/s	427		378	
Cooling water mass flow rate, kg/s	751	142	1,539	94
Total seawater mass flow rate to MED, kg/s	1,178	569	1,918	472
Specific electrical power consumption if MED is located at coast, kWh/t	1.7	1.2	2.4	1.0
Specific electrical power consumption if MED at inland location (distance 5/2 km), without ER, kWh/t	3.7	2.2	3.4	1.2
Specific electrical power consumption if MED at inland location (distance 5/2 km) with ER, kWh/t	2.9	1.9	–	–
Vacuum system				
Mass flow rate NC gas + steam extracted, kg/s	0.215		0.215	
Motive steam pressure for vacuum system at steam ejector inlet, bar	4		4	
Motive steam mass flow rate for vacuum system, kg/s	0.69		0.69	

In Table 6, the design data of a single MED unit with a production capacity of 12,000 m^3/d are listed for summer and winter operation for Aqaba and Ashdod.

The maximum process temperature is the temperature of the heating steam, which is some degrees higher than the top brine temperature in the first effect. The top brine temperature was set to 65°C because at higher temperatures scaling problems can become severe. To describe MED plant efficiency, the Gained Output Ratio (GOR) defined as

$$\mathrm{GOR} = \frac{\dot{m}_{\text{distillate}}}{\dot{m}_{\text{heatingsteam}}} \quad (4)$$

is used. For negligible salt concentration in the distillate, the concentration factor (CF) is

$$\mathrm{CF} = \frac{S_{\text{blow-down}}}{S_{\text{make-up}}} = \frac{\dot{m}_{\text{make-up}}}{\dot{m}_{\text{make-up}} - \dot{m}_{\text{distillate}}}. \quad (5)$$

At the final condenser, the make-up water temperature is kept constant over the seasons. A fraction of pre-heated SW is fed to the effects while the rest, which has been used as cooling water, is discharged to the sea. All temperatures and mass flow rates in the effects are constant during summer and winter operation. Only the required cooling water mass flow rate and consequently the SW mass flow rate depend on SW temperature and therefore vary with seasons. As electrical power consumption depends on water mass flow rates, it accordingly varies with seasons. The specific electrical power consumption was calculated for sites directly located at the sea and estimated for the inland sites chosen.

A vacuum system is necessary to extract non-condensable (NC) gases released from the evaporating brine as well as penetrated into the evaporator through leakages. In Fig. 1 no vacuum system is shown because it was designed separately from the plant. A typical layout of a two-stage steam ejector system was chosen and added to the overall CSP + MED system layout, as shown in Fig. 2. After estimating the NC gas and steam mass flow rates to be extracted, necessary motive steam pressure and mass flow rate for the steam ejectors can be calculated for a given pressure at the vent extraction point in the final condenser. In general, a high motive steam pressure of up to 16 bars leads to a lower necessary motive steam mass flow rate. Nevertheless, a low motive steam pressure of four bars is more suitable for coupling with CSP (see Section 4), leading to the mass flow rate of steam extracted at the turbine which is shown in Table 6.

3.2.2. Economic performance

Economic parameters for the MED plant are split in investment costs and O&M costs, as shown in Table 7. Investment costs of the MED units, the open SW intake, the post-treatment plant and the water transmission system to the inland location are based on information provided by suppliers of MED plants and components for water systems. The costs of the SW intake strongly depend on the coastal conditions and are site specific. A typical number for the open intake investment cost for MED plants was chosen. The same applies to cost data for the SW transmission system to the selected inland sites and the discharge (cooling water plus blowdown) transmission system from the inland sites back to the sea which include, e.g., pipelines, civil works and erection. For estimating the costs of the water transmission system, open country was assumed. The cost estimations for the desalination plant including the SW intake and for the water transmission system do not include land costs. By installing an ERD in the discharge pipeline in Aqaba, some of the pumping energy can be recovered. This energy recovery (ER) has been accounted for in the calculation of the specific power consumption for the inland site in Aqaba.

For O&M cost calculation, the number of plant operators and yearly staff costs, electrical energy costs from grid, maintenance and spare parts costs, chemical costs and G&A costs are considered. Estimating steam costs is most difficult, because steam is directly delivered from the power plant. In power plants coupled with MED plants, steam is not expanded in condensing turbines as in stand-alone power plants, but in backpressure turbines (to a pressure of 0.35 to 0.5 bars). The resulting power loss in a conventional power plant is about 3 kWh/m^3 [15]. The cost of steam for MED plants can be calculated by assuming that this lost power has to be bought from the grid. Using this approach, called "power credit method" [16] or "reference cycle method" [15], it is possible to calculate a unit water price for the designed MED plant in a conventional cogeneration scenario. The results of the economic analysis using the power credit method for the designed MED plant directly located at the sea and coupled with a conventional power plant are shown in Table 7. The economic analysis of the MED plant coupled with the CSP plant using the approach of LCOW based on Equation (1) is shown in Section 4.

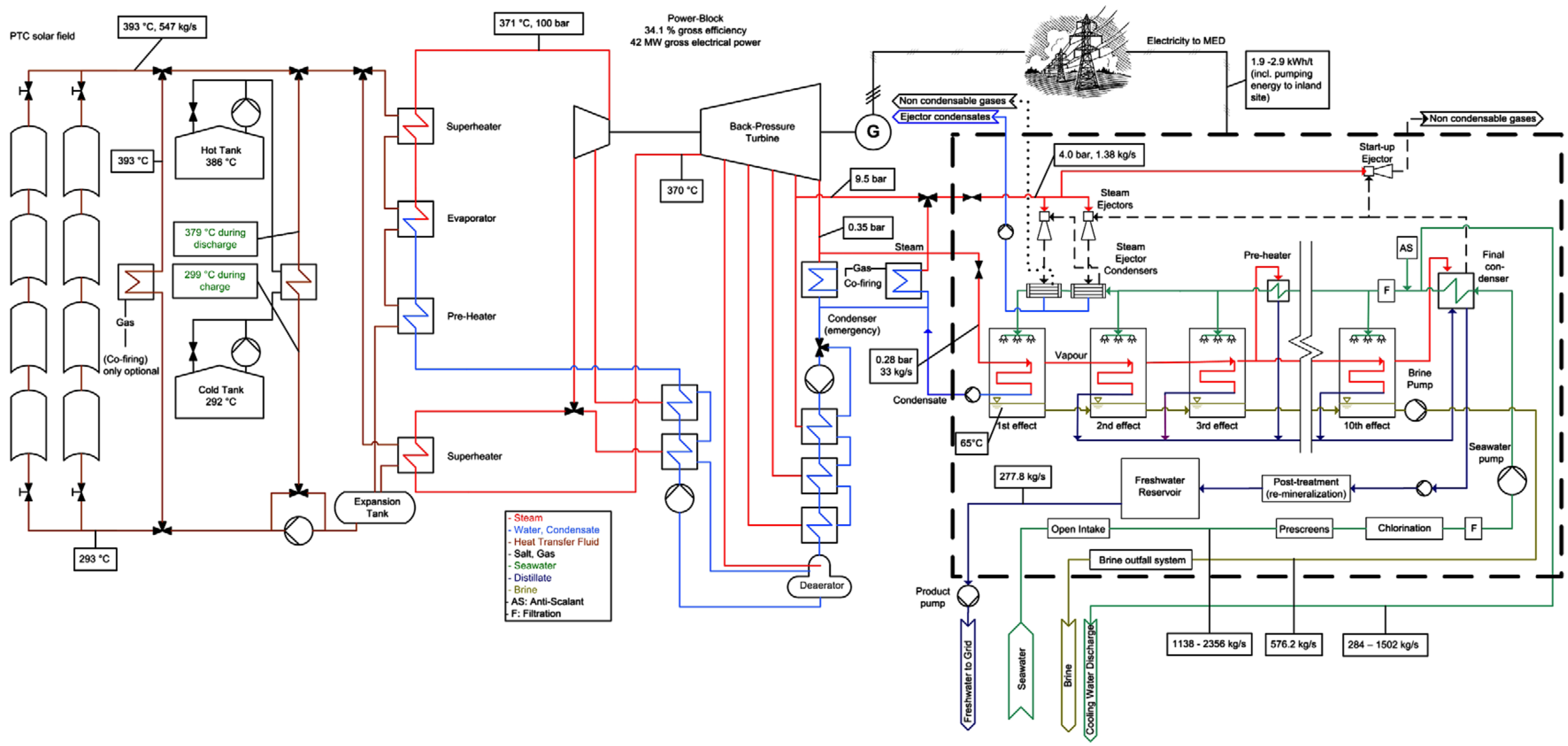

Fig. 2. Flow sheet of the CSP + MED system (only one MED unit is shown, but data refer to two MED units, all data refer to the inland site (5 km from coast and 50 m above sea level) in Aqaba).

4. Techno-economic performance of combined CSP and desalination plant configurations

The CSP systems evaluated in this study include a solar collector field, a thermal storage system and a conventional steam turbine power block.

4.1. Selection of CSP technology

As the desalination units, the CSP components are based on mature technology with available and reliable performance data. For the solar field, parabolic trough collectors with oil as heat transfer medium are chosen since such systems have been operated for over 20 years in the US [17]. These systems can be equipped with a two-tank thermal storage system, where molten salt is used to store the sensible heat. First plants with this technology recently went into operation in Spain (Andasol 1+2) with a peak electric power of 50 MW_{el} [4]. Transformation of heat into mechanical and electrical energy is done with a steam turbine power block (Rankine cycle). Industrial turbines (also designed for CSP applications) are available from several manufacturers today. A commonly used set of technical parameters has been used for all components of the CSP plant [18,19].

4.2. Technical setup of CSP + MED configuration

The flow sheet of the CSP + MED system is illustrated in Fig. 2, key performance parameters

Table 7
Economic performance of MED units in a conventional cogeneration scenario

	Aqaba	Ashdod
Economic parameters of MED		
Investment costs		
2 MED units each 12,000 m^3/day, \$/(m^3/day)	1,394	
Post-treatment plant, \$/(m^3/day)	55	
Open seawater intake, \$/(m^3/day)	217	
Water transmission system to inland location, \$/(m^3/day)	292	152
Energy recovery device for discharge pipeline, \$/(m^3/day)	29	–
Project lifetime, years	20	
Investment interest rate, %	8	
MED plant availability, %	95	
Operation and maintenance costs		
Number of plant operators (for both units)	6	
Staff cost, \$/(person year)	5,220	24,800
Electrical energy cost (buy from grid), \$/kWh	0.069	0.115
Power loss, kWh/m^3	3	
Maintenance and spare parts costs as percentage of investment costs on annual basis, %	1.5	
Specific chemical cost, \$/m^3	0.03	
G&A costs, as percentage of operation and maintenance costs, %	10	
Economic analysis for conventional cogeneration and MED location at the coast based on power credit method		
Specific investment costs for two MED units including seawater intake and post-treatment plant, \$/(m^3/day)	1,667	
Investment cost annual expenditure, \$/year	4,074,954	
Specific investment cost, \$/m^3	*0.490*	
Specific staff cost, \$/m^3	0.0038	0.0179
Specific electrical energy cost, \$/m^3	0.100	0.194
Specific steam cost, \$/m^3	0.207	0.345
Specific costs for maintenance and spare parts, \$/m^3	0.072	
Specific chemical cost, \$/m^3	0.030	
General & administrative costs, \$/m^3	0.041	0.066
Specific total operation and maintenance costs, \$/m^3	*0.454*	*0.725*
Total water cost, \$/m^3	*0.943*	*1.215*

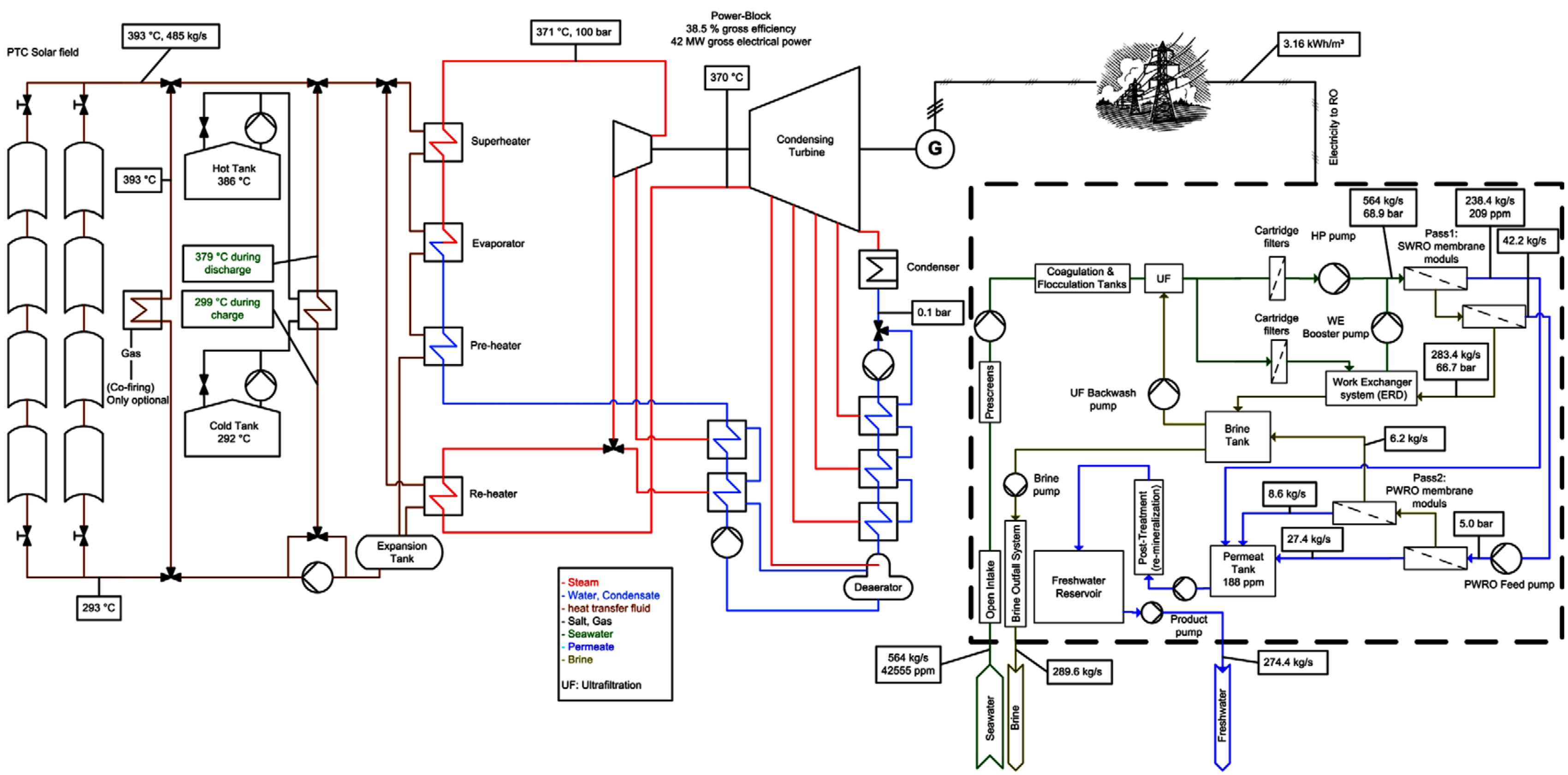

Fig. 3. Flow sheet of the CSP + RO system (data refer to the site in Aqaba).

Table 8
Design data of the CSPD systems

	CSP + MED		CSP + RO	
	Aqaba	Ashdod	Aqaba	Ashdod
Solar field				
Collector	Eurotrough		Eurotrough	
Absorber tube	PTR 70		PTR 70	
Peak optical efficiency	0.78		0.78	
Aperture area	Flexible		Flexible	
Nominal inlet temperature, °C	293		293	
Nominal outlet temperature, °C	393		393	
Thermal storage				
Storage efficiency, %	100		100	
Specific capacity, MWh/h	123		109	
Power block				
Turbine type	Backpressure turbine with controlled extraction		Condensing turbine	
Condenser type	MED		Wet cooling	
Gross capacity, MW	42		42	
Condenser pressure, mbar	350		100	
Gross efficiency of the steam turbine, %	34.1		38.5	
Desalination				
Steam mass flow rate to first MED effects, kg/s	33.26	32.62	–	
Steam pressure at turbine outlet, MED, bar	0.35		–	
Steam mass flow rate to vacuum system, kg/s	1.38		–	
Motive steam pressure at turbine extraction, vacuum system, bar	9.5		–	
Motive steam pressure at steam ejector inlet, bar	4.0		–	
Specific electricity consumption (MED located at inland CSP site), kWh/m^3	2.4	2.3	3.16	3.05

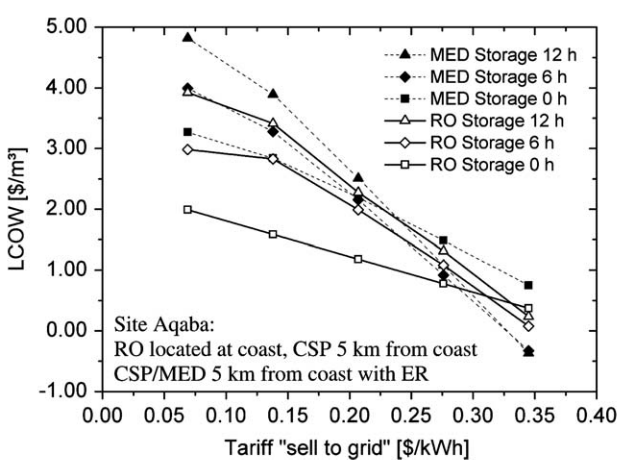

Fig. 4. LCOW for the CSPD configurations in Aqaba as a function of the feed-in tariff for the electricity produced.

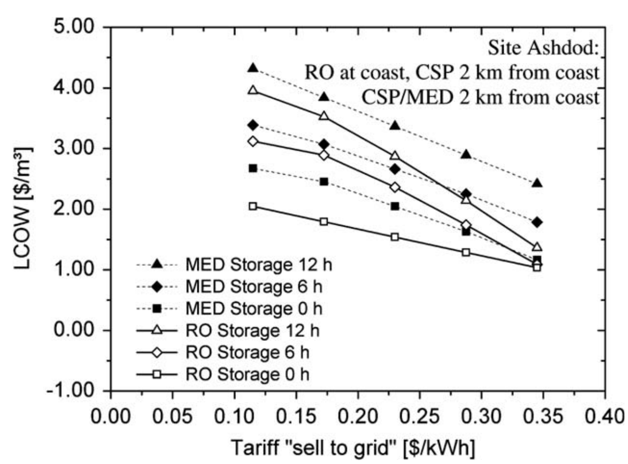

Fig. 5. LCOW for the CSPD configurations in Ashdod as a function of the feed-in tariff for the electricity produced.

can be taken from Table 8. In this configuration, the exhaust steam of the turbine is used to feed the first effects of the two MED units. For the MED design in this study, a mass flow rate of 33.26 kg/s steam at 0.35 bar is required. For this purpose a backpressure turbine is used that yields a constant exhaust pressure of 0.35 bar. The power block is designed such that at nominal load conditions the MED plant can fully be operated from the turbine exhaust steam. With the steam parameters fixed from the oil side, the isentropic efficiencies of the turbine stages pre-defined and the exhaust steam given with 33.26 kg/s the gross electric power results in 42 MW_{el}. In addition to the main steam supply of the MED plant the vacuum system needs a motive steam of 1.38 kg/s at a pressure of 4 bar. This steam is taken from the first extraction of the lower pressure turbine at nominal 9.5 bar. Selection of this extraction guarantees that the pressure does not fall below 4 bar even in turbine part load operation.

For the solar system, the field inlet temperature is fixed at 293°C, and the outlet temperature at 393°C. Depending on the field size (aperture area), the design oil mass flow rate of 547 kg/s is reached at different irradiation levels. A number of different field sizes were therefore simulated to find the economic optimum. For the storage system, three different capacities, 0 h, 6 h and 12 h of full load operation, are defined. Storage systems with higher capacity do not represent an economically feasible alternative.

In Fig. 2 only four effects of a single MED unit are drawn, while the overall system consists of two separate 10-stage MED units (see Fig. 1) with a production capacity of 12,000 m^3/d each. Numbers given in Fig. 2 correspond to the overall system consisting of the CSP plant and two MED units.

4.3. Technical setup of CSP + RO configuration

The CSP + RO plant, in effect, consists of two separate units, a conventional CSP plant for electricity production and the RO desalination plant. A combined plant at one site is not considered since the CSP + RO combination has the inherent advantage to place the RO unit close to the water source and the CSP plant at a location with low costs of land. The power block is applied with a condensing turbine and a wet cooling system. The condensing pressure is fixed at 100 mbar which corresponds to rather high cooling temperatures. The power block design point is chosen equal to the CSP + MED system with 42 MW_{el} gross output.

Due to the higher efficiency of the condensing turbine, less thermal energy (485 kg/s oil mass flow) is required at this operating point. Storage sizes are chosen to yield the same number of full load hours as in the CSP + MED configuration. Due to different thermal consumption, the storage capacity in terms of kWh is larger for the CSP + MED plant than for the CSP + RO plant. Fig. 3 shows the flow sheet of this configuration, key parameters are listed in Table 8.

4.4. Techno-economic performance of CSP + RO and CSP + MED configurations

The data used for the economic evaluation of the CSP + MED and CSP + RO systems in Aqaba and Ashdod are summarized in Table 9. The LCOW were calculated with Eq. (1). It has to be noted that it was assumed that the electricity required for the operation of the RO or MED plant, respectively, is bought from the grid. The steam for the MED plant is provided by the CSP plant and, thus, not included in the calculation of the LCOW.

Since the LCOW are closely linked to the price the owner gets for the produced electricity, the LCOW

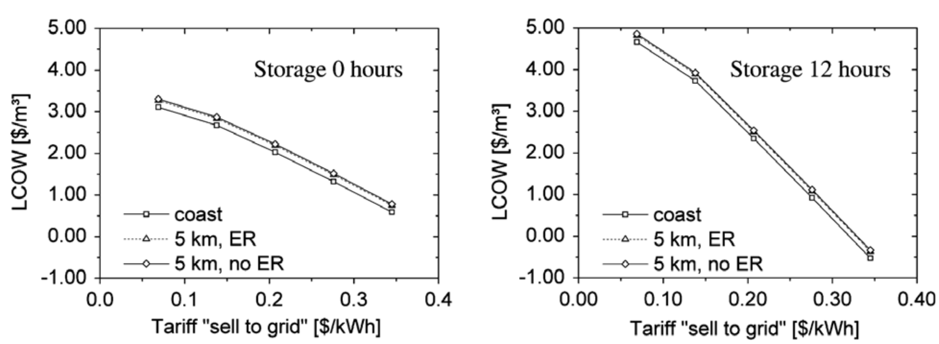

Fig. 6. LCOW of CSP + MED in dependence on the feed-in tariff for different locations (coast and inland) and configurations (with and without ER in discharge pipeline) in Aqaba.

Table 9
Cost data used for the economic evaluation of the CSP + MED and CSP + RO systems in Aqaba and Ashdod

City	Aqaba		Ashdod	
System	CSP + MED	CSP + RO	CSP + MED	CSP + RO
Investment costs				
Investment costs of CSP solar field, $/m^2	455	455	455	455
Investment costs of power block, $/kW	1, 092	1, 092	1, 092	1, 092
Investment costs of heat storage, $/kWh	72.8	72.8	72.8	72.8
Investment costs of desalination plant, inland, $/(m^3/d)	1, 988 (ER) 1, 959 (no ER)	– –	– 1, 819 (no ER)	– –
Investment costs of desalination plant, coast, $/(m^3/d)	1, 667	1, 705	1, 667	1, 705
Operation and maintenance costs				
O&M costs of solar field, $/m^2/year	11.2	11.2	11.2	11.2
O&M costs of power block, $/MWh/year	4.2	4.2	4.2	4.2
O&M costs of heat storage, $/MWh/year	70	70	70	70
O&M costs of desalination plant, inland without electricity and fuel costs for co-firing (only MED), $/m^3	0.133 (ER) 0.137 (no ER)	– –	– 0.158 (no ER)	– –
O&M costs of desalination plant, coast without electricity and co-firing (only MED), $/m^3	0.126	0.200	0.151	0.235
Energy costs				
Electricity price from grid, $/kWh	0.069	0.069	0.115	0.115
Fossil fuel price (natural gas), $/kWh	0.020	–	0.010	–
Economic parameter				
Project lifetime, year	20	20	20	20
Investment interest rate, %	8	8	8	8

were calculated for various electricity prices. For each price, the solar field size was varied to find the economic optimum in terms of LCOW. Fig. 4 shows the results for the site in Aqaba and Fig. 5 for Ashdod, both for storage capacities of 0 h, 6 h and 12 h of full load operation. The clear dependence of LCOW on the electricity price is obvious although some differences in the slope of curves exist between the two sites as well as between RO and MED systems. The differences in the slope of curves result from the dependency of the electricity generating costs of the CSP plant on the irradiation conditions and the CSP plant design concerning heat storage and solar field size. In general, it can be stated that the CSP + RO configuration results in lower LCOW than the CSP + MED system. As a second result, the systems without heat storage give lower LCOW than the systems including heat storage except at high feed-in tariffs. With increasing feed-in tariffs the electricity produced by the CSPD plants becomes more valuable, which from the economic point of view favours larger solar fields and larger solar thermal storage systems to generate more electricity than with non-storage concepts. The economic optimum was found for each tariff and storage size by variation of the solar field size, which leads to different amounts of electricity produced by the steam turbine and thus higher revenues. As a third result, it comes out that water generating costs in Ashdod are higher than those in Aqaba when the solar production is supported with reasonably high feed-in tariffs. The main driving factor is the better irradiance for the Aqaba site. For Aqaba, LCOW of about 1 $/m^3 can be realized if a feed-in tariff of about 0.24 $/kWh for electricity from renewable energy sources is established. Today's feed-in tariffs of about 0.35 $/kWh in Spain indicate that this is not an unrealistic scenario.

While in Jordan no fixed feed-in tariff is available at the moment (a new renewable energy & energy efficiency law has been inaugurated in 2010), in

November 2006 the Israeli Public Utilities Authority published a feed-in law for electricity produced by CSP plants. For CSP plants with an installed capacity larger than 20 MW_{el}, a payback of 0.163 $/$kWh_{el}$ is guaranteed for a 20-year period. The costs of the fresh water produced in Ashdod, Israel, with the CSPD set-ups excluding thermal storage systems described above would be 1.9 $/$m^3$ for CSP + RO and 2.5 $/$m^3$ for CSP + MED.

To reach the breakeven point with the conventional MED cogeneration scenario (for costs of water, see Table 7), the feed-in tariff in Jordan must be at least 0.27 $/kWh and in Israel about 0.34 $/kWh. The same comparison for RO systems (for costs of water, if the electricity is bought from the grid, see Table 5) leads to the minimum feed-in tariffs of 0.26 $/kWh in Jordan and 0.35 $/kWh in Israel.

At feed-in tariffs above 0.34 $/kWh in Aqaba and above 0.40 $/kWh in Ashdod, water can be produced even without any additional market price for the generated water, i.e. the generated water is fully subsidized by the revenues for the electricity.

Furthermore, the CSP + MED system in Aqaba located 5 km away from the coast and 50 m above the sea level and equipped with an ER system in the discharge pipeline (see Section 3.2.2) was compared with a CSP + MED system without ER in the discharge pipeline and with a CSP + MED system located at the coast.

Fig. 6 shows the LCOW for these three configurations. For the non-storage and 12 h storage option, it turns out that the LCOW are nearly the same for the system with and without ER, i.e. that the additional investment costs for the ER are more or less balanced by the savings in electricity consumption. Comparing the LCOW of the systems located inland and at the coast, it has to be noted that land costs were not considered. When moving the CSP + MED site towards the coast a reduction of LCOW by about 0.20 $/$m^3$ is obtained.

It has to be noted that the results strongly depend on the technical and economic input parameter sets. Therefore, results presented in this study have to be treated as a rough guideline for assessment of combined CSP and desalination plants. Water costs of a certain project can only be evaluated based on a detailed feasibility study considering all boundary conditions.

All the results concerning the economics in this study have to be treated with uncertainties. The given numbers result from the chosen set of technological data, site-specific data, economic boundary conditions and assumptions made.

5. Conclusion

The techno-economic performance of CSP + MED and CSP + RO plant configurations has been analysed for a site in Israel (Ashdod) and in Jordan (Aqaba). It was assumed that the CSP plant is located at an inland location where there is land available. The RO plant was considered to be located at the sea, while the MED plant is located upcountry at the CSP plant. State-of-the-art MED and UF–RO plants were designed for a constant fresh water production capacity of 24,000 m^3/d. The power block of the CSP plant was designed to meet the design point of the MED unit, which led to a gross electricity generation capacity of 42 MW_{el}. CSP setups with three different heat storage capacities were analysed that allow an additional full load operation of the steam turbine of 0 h, 6 h and 12 h.

In all of the evaluated CSPD configurations, the LCOW strongly depend on the price the owner gets for the electricity produced by the CSP plant. It can be stated that the CSP + RO setups show economic benefits in comparison to the CSD + MED configurations except for very high electricity prices.

The costs to produce water with CSPD plants are lower in Aqaba, Jordan, than in Ashdod, Israel, due to better irradiation conditions and lower national wages for the staff in Aqaba.

With increasing feed-in tariffs heat storage configurations become more and more economic than non-heat storage concepts. To reach the breakeven point with conventional cogeneration scenarios, the feed-in tariff for CSP + MED in Ashdod must be at least 0.34 $/kWh, in Aqaba 0.27 $/kWh and for CSP + RO in Ashdod 0.35 $/kWh and in Aqaba 0.26 $/kWh. Water without any additional price for the consumer can be produced with feed-in tariffs above 0.34 $/kWh in Aqaba and above 0.40 $/kWh in Ashdod.

When moving the CSP + MED site towards the coast, a reduction of LCOW by about 0.20 $/$m^3$ is obtained without consideration of land costs.

It has to be noted that the results strongly depend on the technical and economic input parameter sets. Water costs of a certain project can only be evaluated based on a detailed feasibility study considering all boundary conditions.

In summary, CSPD configurations can be a realistic economic future option for the fresh water production to meet the demand of the MENA region. With the implementation of national regulations concerning a feed-in tariff for electricity produced by CSP plants (like in Spain), CSPD configurations represent a realistic scenario today.

Acknowledgements

The authors would like to thank the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety for funding the project CSPD-COMISJO (Grant No. 0327559).

Symbols

C	—	annual costs, \$/y
CF	—	concentration Factor
DNI	—	direct normal irradiance, kWh/(m^2 y)
ε	—	efficiency
E	—	specific energy consumption, kWh/m^3
GOR	—	Gained Output Ratio
$\dot{m}$	—	mass flow rate, kg/s
P	—	pressure, Pa
Q	—	flow rate, m^3/s
R	—	staging ratio
r	—	recovery ratio
REV_{el}	—	annual revenue from electricity sales, \$/y
S	—	salinity, g/kg
SDI	—	Silt Density Index
LCOW	—	levelized costs of water, \$/m^3

Abbreviations

BW	—	brackish water
CSP	—	concentrating solar power
CSPD	—	concentrating solar power and desalination
ER	—	energy recovery
ERD	—	energy recovery device
G&A	—	general and administrative
MED	—	multi-effect distillation
MENA	—	Middle East and North Africa
NC	—	non-condensable
O&M	—	operation and maintenance
RO	—	reverse osmosis
SW	—	seawater
UF	—	ultrafiltration

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