Desalination and Water Treatment
www.deswater.com

51 (2013) 1887–1899
February

doi: 10.1080/19443994.2012.703388

Taylor & Francis
Taylor & Francis Group

Preliminary thermoeconomic analysis of combined parabolic trough solar power and desalination plant in port Safaga (Egypt)

J. Blanco*, P. Palenzuela, D. Alarcón-Padilla, G. Zaragoza, M. Ibarra

CIEMAT-Plataforma Solar de Almeria, Ctra. de Senés s/n, 04200 Tabernas, Almeria, Spain
Tel. +34 950 387 939; email: julian.blanco@psa.es

Received 20 March 2012; Accepted 12 June 2012

ABSTRACT

The development of society is strongly dependent on water and electricity. There is an increasing water and energy demand driven by population growth and rising industrial and agricultural production. The combination of concentrated solar power (CSP) and desalination processes has a huge potential for producing both energy and water in arid regions suffering from fresh water scarcity and facing the current energy challenge. One of the regions is Middle East and North Africa (MENA), where plans are currently under discussion to make possible large CSP plants developments. The integration of desalination (CSP+D) into solar power plants could make CSP technology even more attractive in such regions. The focus of this study is thermodynamic characterization and an economic evaluation of different configurations for coupling parabolic trough solar power plants and desalination facilities at a MENA location in Egypt chosen as reference for its Southern coast (Port Safaga). The desalination technologies considered for the combination with parabolic trough concentrating solar power plants (PT-CSP), are low temperature multi-effect distillation (LT-MED) and reverse osmosis (RO). Moreover, an additional concept of LT-MED has been evaluated: a LT-MED powered by the steam obtained from a thermal vapor compressor (TVC). In this case, unlike the conventional thermal vapor compression process (TVC-MED), the entrained vapor to be used in the ejector comes from the exhaust steam from the low pressure (LP) turbine instead of an effect of the MED unit. In order to optimize this latter concept (LT-MED-TVC), different configuration schemes have been studied. When thermodynamic efficiencies and costs are analyzed comparing the two more efficient configurations (PT-CSP/RO and PT-CSP/LT-MED), considering 58°C/0.18 bar of exhaust turbine steam conditions and 5.5 kWh/m^3 of RO power requirements, initial results are very similar.

Keywords: Power and water cogeneration; Concentrating solar power and desalination; CSP+D

1. Introduction

The typical geographical coincidence of water shortage and other water problems and high solar radiation is widely recognized [1], so the use of solar energy to simultaneously address water and power production is one of their most sustainable solutions. Therefore, integration of water desalination technologies in concentrating solar power plants is a relevant area of concentrating solar power (CSP) research, and

*Corresponding author.

Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain

if successful, will certainly accelerate the large-scale implementation of solar energy, especially in regions where fresh water is scarce. One of the regions is Middle East and North Africa (MENA), where the combination of significant population growth, expected to increase from 500 million people in 2000 to about 700 million in 2025 [2], strong energy demand, expected to increase from 1,300 TWh/year in 2000 to about 2,500 TWh/year in 2025 [2], and also high water demand, expected to increase from 300 billion m^3/year in 2000 to about 450 billion m^3/year in 2025 [2], anticipate problematic feasible scenarios in the coming years/decades due to the very limited renewable water sources and currently complete dependence on fossil fuels [3]. Considering the previous context in the specific case of MENA countries, it is difficult to imagine any adequate solution without a significant contribution of renewable energies, being solar energy the first obvious candidate to be introduced due to its very high potential in the region. Also, among different solar energy technologies, CSP has the highest potential [4], being this the reason why large solar development plans and projects, such as the Desertec Initiative [5] and the Mediterranean Solar Plan [6], are currently underway in the MENA region. Specific CSP projects are already been developed, such as the projects in countries like Morocco (Ain Beni Mathar), Algeria (Hassi-R'mel) or Egypt (Kuraymat), or projects under development (Abu Dhabi), also existing plans for large development of solar energy at defined countries, such as Algeria and Saudi Arabia. Even though the technology to make these developments possible is ready, the main problem is the funding till date [7].

If today, solar thermal technology for power production is available and the market ready, the next logical step to develop CSP technology even more efficient at regions such as MENA would be the integration of desalination (CSP+D) into solar power plants. The concept of combining CSP and desalination facilities is a very attractive solution due to the following reasons:

- At many locations with high solar potential, combined water power projects can be more attractive to local stakeholders than stand-alone power production projects.
- Technological synergies can be identified to potentially reduce the cost of combined power and water production relative to the independent production of the same items.
- Financial arrangements can also benefit, as water and power cost can be better adapted to the specific local conditions of the facility.
- Politically, the exportation of electricity to other countries can be justified (in many cases, this is the only reasonable way to make bankable the electrical projects) and, at the same time, the basic needs of the local population can be addressed by locally distributing the water, partially financed by the sale of power.

However, the concept has also some drawbacks:

- The CSP+D concept needs, obviously, facilities to be located near the sea, where land cost and availability can be a significant problem.
- Direct Normal Irradiation (DNI) is normally lower in the areas close to the sea.
- Some technological aspects are not yet solved, and specific research, development and demonstration activities are needed to define the best concepts and systems [8].

However, in addition to all the potential benefits of combined power and water production, desalination integration into CSP plants is not a straightforward issue yet, as there are several unsolved technological issues, which still need specific research, development and demonstration initiatives to define the best concepts and systems [8]. One of these issues is the definition of the best configuration when thermal desalination technologies coupled with a parabolic-trough (PT) solar power facility (using low grade steam from the turbine to feed a multi-effect distillation [MED] unit) compared with the reverse osmosis (RO) option (electricity from the power facility is used at RO plant either in the same or in different location).

Studies on different basic integrated power and desalination plants' configurations have been published, such as the description of the operation of low temperature multi-effect distillation (LT-MED) desalination plants using low grade steam from different power plants [9]. Other studies address the energy cost analysis to produce water from an integrated power plant into LT-MED and thermal vapor compression MED (TVC-MED) units [10], evaluate the benefits of integrating RO units with existing power/desalination plants in the Middle East [11], or perform thermoeconomic analysis of different configurations for the combination of a RO subsystem to produce drinkable water and a steam power plant to generate electricity [12]. Considering the specific case of CSP+D plants, some studies show the potential of CSP plants coupled with desalination systems (RO and MED) for MENA region [13] and techno-economically analyze the combination of PT power plants for electricity production with MED and ultrafiltration/RO plants [14,15].

2. Solar resource assessment and project site selection

The activity carried out described in this was partially financed by the SolarPACES (Solar Power and Chemical Energy Systems) Executive Committee and was a coordinated activity developed by CIEMAT (Spain), DLR (Germany) and NREA (Egypt), in the context of SolarPACES Task VI (Solar Energy and Water Processes and Applications). Presented results correspond to the phase 1 of the project, being the phase 2 currently under execution. The starting point to define the site project was the basic requirements of flat land availability and a good value of DNI. Solar radiation is a climatic variable measured only in few meteorological stations and during short and, on most occasions, discontinuous periods of time. Therefore, developers do not find appropriate historical databases with information available on solar resource for specific sites. Different approaches are available to characterize the solar resource of a specific site. The possible options are:

- Approximation by using data from nearby stations. This option can be useful for relatively flat terrains and for distances of less than 10 km from the site. In the case of complex terrain or longer distances, the use of radiation data from other geographical points is inappropriate.
- Interpolation of surrounding measurements. This approach can be used only for areas with a grid of measurement stations and for average distances between the stations of about 20–50 km [16,17].
- Solar radiation estimation from satellite images is currently the most suitable approach. It supplies the best information on the spatial distribution of the solar radiation and it is a methodology broadly accepted by the scientific community and with a high degree of maturity [18]. Nevertheless it is mandatory to have at least one reference weather station in the area to calibrate the satellite data.

Therefore, solar radiation assessment was done by estimating the solar resource potential in the Egypt coastal strip using satellite images (Irsolav, Spain). Yearly sums of global horizontal (GHI) and DNI are calculated in all Egypt coastal strip distributed with a mean distance of 5 km from the sea and separated between each other with a spatial resolution of 5 km. First filtering of possible suitable locations was made considering ground elevation above sea level to discard excessive land tilt. The establishment of the geographical coordinates of the points along the Egyptian coastal strip has been done with Google Earth software [19]. Fig. 1 shows the Mediterranean Sea coastal strip and Fig. 2 the elevation profile of the Mediterranean Sea coastal line selected. Fig. 3 shows the Red Sea coastal strip and Fig. 4 the elevation profile for the set of points selected on this coast.

Solar radiation calculated from satellite images is based upon the establishment of a functional relation-

Fig. 1. Egypt coastal strip at the Mediterranean Sea in red color (drawn by Google Earth).

Fig. 2. Elevation profile of the Egypt coastal strip at the Mediterranean Sea.

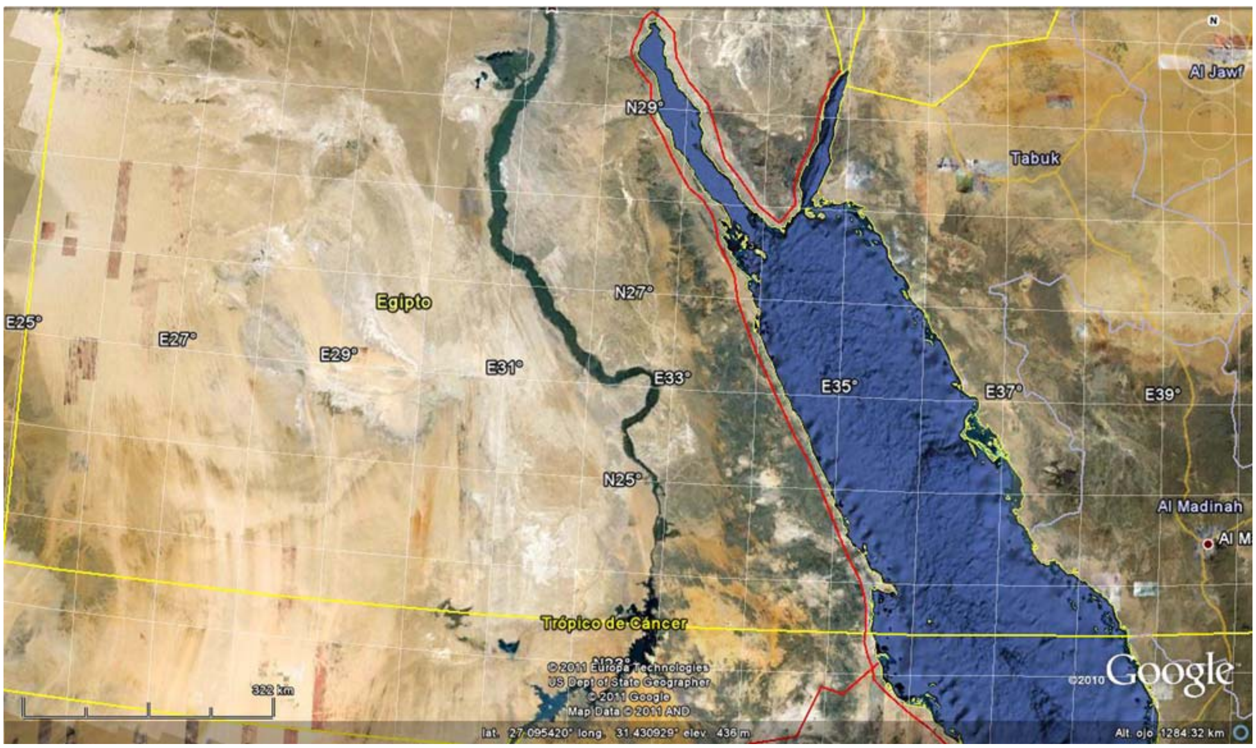

Fig. 3. Egypt coastal strip at the Red Sea, the red line inland corresponds to the Egypt border drawn by Google Earth.

ship between the solar irradiance at the Earth's ground surface and the cloud index estimated from satellite images. This relationship has been previously fitted using high quality ground data, in such a manner that the solar irradiance–cloud index correlation can be extrapolated to any location of interest. This way, solar radiation components (global, diffuse, and direct) can be calculated from satellite observations. Used methodology to the quantification of solar irradiation from satellite images is based upon the so called Heliosat-2 model, which has been modified and assessed by CIEMAT by using 30 ground stations in Spain. IrSOLaV has developed from the initial Heliosat-2 method, a new operational tool able to be applied to a database of images from 1995 until 2010. However, images from 2006 to 2010, which belong to Meteosat Second Generation, have been used in this study. The satellite images belong to the high resolution visible channel with a spatial resolution of about $1 \times 1\,km^2$. Used model was initially described in [20], and was later modified for a better estimation of solar radiation with clear sky, leading to an important improvement in the accuracy of the model [21,22].

Obtained results showed an interval of yearly average DNI values of 1,854–2,247 $kWh\,m^{-2}\,year^{-1}$, at the Egyptian Mediterranean coastal strip. In the case of the Red Sea, DNI values were higher, between 2,245 and 2,551 $kWh\,m^{-2}\,year^{-1}$. The higher variability (than in the Mediterranean coast) was due to the abruptness of the terrain. Based on these results, the

Fig. 4. Elevation profile of the Egypt coastal strip at the Red Sea.

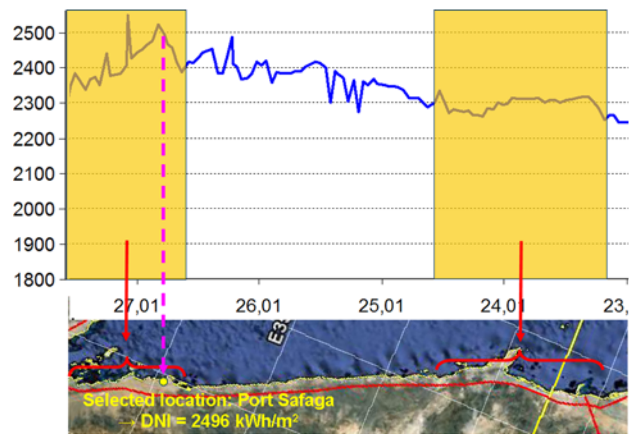

Fig. 5. DNI results (kWh m^{-2} $year^{-1}$) of the Egyptian coastal strip in the west side of the Red Sea and selected location (Port Safaga).

selected location was Port Safaga, in the west side of the Red Sea coast and with a yearly DNI of 2,496 kWh m^{-2} $year^{-1}$ (see Fig. 5).

The closeness of the sea does not have any effect on the ground albedo of the sites calculated, and therefore in the values of DNI estimated, due to the spatial resolution of the pixel of the satellite images and the considered distance from the sea (5 km). However, the arid soil cover (inland or coastline) can have an effect on the values of DNI estimated from satellite. In Egypt the terrain is highly reflecting and can have an effect on the estimations of the model achieving a lower precision and a subestimation of solar radiation (for both global and especially DNI). This effect is due to the fact that high reflectance is associated with cloudy conditions.

3. Solar power and water cogeneration plants: considered configurations

When the possible options to combine power production and desalination in dual purpose plants are analyzed, MED and RO are considered as the most suitable ones. This is due to the fact that both options are, respectively, the most efficient thermal and electrical desalination technologies. In the case of RO, the integration is a straightforward issue by simply using the produced electricity to feed the desalination unit. In addition, the power and desalination plants do not need to be physically close to each other, a fact that could impart a significant advantage due to the previously mentioned inconvenience that DNI is normally lower at the areas close to the sea. Thus, the solar power plant can be placed at better inland locations and the RO desalination plant can be just by the sea, minimizing seawater pumping requirements.

The second option, CSP and MED facilities, is based on the use of low grade steam from the power cycle (typically a Rankine one) to provide the thermal energy needed by the desalination process. This means that the MED unit needs to be physically located close to the steam turbine. The first, immediate inconvenience is that distance to the sea must be carefully analyzed to optimize and balance the global power and water production output (direct function of DNI potential), the pumping energy requirements, and the initial capital investment. On the other hand, this combination provides additional advantages such as reducing or eliminating the cooling requirements of the power cycle by using the desalination MED process to partially (or completely) replace the conventional cooler associated to the power block. In addition, challenging ambient conditions in specific regions, such as Middle East/Persian Gulf with seasonal high seawater temperatures and saline concentrations, imply the necessity to increase temperature level at turbine exhaust steam output to make cooling feasible. In these conditions, the penalty to power production that results from using steam to drive a MED process is substantially reduced; and it is, from a thermodynamic point of view, very attractive against the RO option, which is normally heavy penalized when high salinity water is used, from both the energy and maintenance points of view.

When integration of CSP and MED technologies is analyzed, two different types of configurations can been considered: using the exhausted steam from the

CSP plant as the source of the heat (LT-MED), and a novel system consisting of a LT-MED distillation plant powered by the steam produced from a thermal vapor compressor (TVC). In this case, unlike typical TVC-MED process, the vapor to be used in the steam ejector comes from the exhausted steam of the CSP plant instead of an intermediate effect of the desalination unit. This concept (LT-MED-TVC) has a strong potential since it is useful for the coupling of any thermal desalination process to a CSP plant, as different schemes can be considered depending on the quality (pressure) of the steam extracted from the low pressure (LP) turbine, to be used as the motive steam in the ejector. Figs. 1–3 show the systems under consideration:

- Configuration 1: LT-MED unit integrated into a PT-CSP plant (Fig. 6).
- Configuration 2: LT-MED-TVC unit integrated into a PT-CSP plant with steam extractions in the LP turbine (Fig. 7).
- Configuration 3: RO unit connected to a PT-CSP plant (Fig. 8).

The CSP plant consists of a PT (LS3 type) concentrating solar power (PT-CSP) plant based on a reheat Rankine cycle with water as the working fluid. In all configurations, the thermal energy from the solar field is transferred to a power conversion system consisting of a preheater, an evaporator, and a superheater. The resulting steam at 373˚C is sent to a high pressure (HP) turbine where after suffering an expansion process is extracted at 18.5 bar in order to reheat it. The reheated steam is left to its expansion through a LP turbine up to 70˚C in the first configuration and up to 58˚C in the others, producing electrical power. Due to the serious scarcity of fresh water in MENA regions, a dry cooling system is the most suitable option in this location. The configuration showed in Fig. 6 consists of an LT-MED unit integrated into a PT-CSP plant. In this option, the desalination plant is directly fed by the LT steam from the turbine outlet, with the MED unit acting as the cooler of the power plant.

In the second configuration (Fig. 7), a steam ejector is used to use part of the exhaust steam from the turbine to provide the energy needed by the MED unit. With this scheme, different possible configurations can be achieved, depending on the enthalpy of the steam extracted to be used as motive flow in the ejector. The resulting compressed vapor is injected into the first effect of the distillation unit. A dry cooling system is considered for condensing the remaining exhaust steam from the turbine. This cooling option is usually the one selected in arid areas, since typical wet cooling towers consume between two and three metric tons of water per MWh of produced electricity [23]. The use of seawater as cooling option (sensible heat) would imply a higher (than dry cooling) energy consumption, due to the large amount of water that would need to be pumped and the distance from the sea that the whole facility is likely to be located (from about 2–5 km). Finally, in the third configuration (Fig. 8), the RO plant is driven by the power output from the PT-CSP plant.

Operating conditions of the solar power plants shown in the previous configurations (Figs. 6–8), were taken from the power cycle of Andasol 1 plant [24], which was the first CSP commercial plant to introduce a molten salt thermal storage system.

A thermodynamic characterization of the configurations considered has been carried out. On one hand, a steady state model of each power cycle has been implemented in the Engineering Equation Solver (EES) software [25] in order to perform different simu-

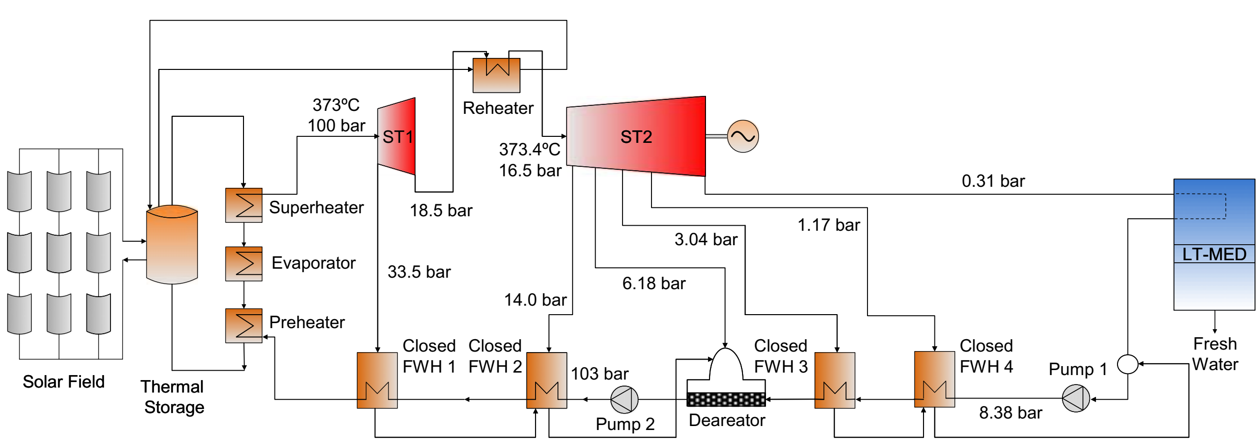

Fig. 6. Diagram of the LT-MED unit integration into a PT-CSP plant.

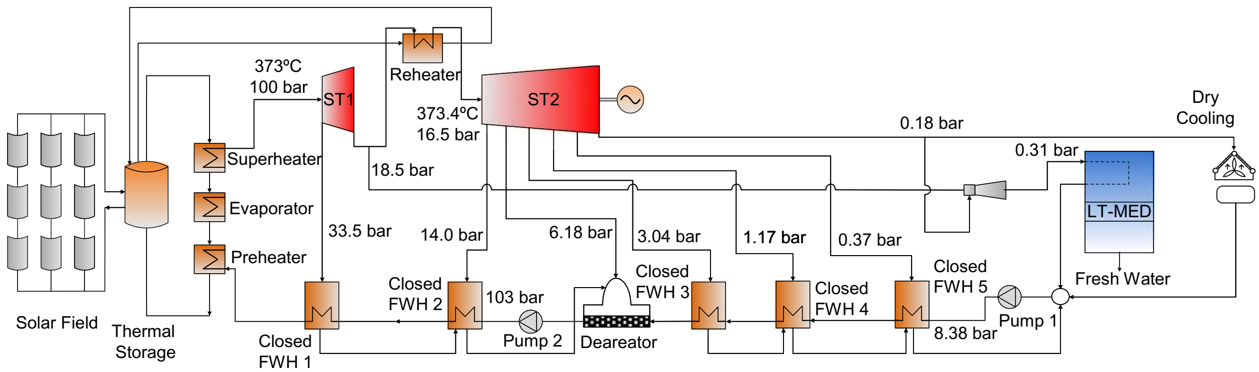

Fig. 7. Diagram of the LT-MED-TVC unit integration into a PT-CSP plant (one of the several possible configurations).

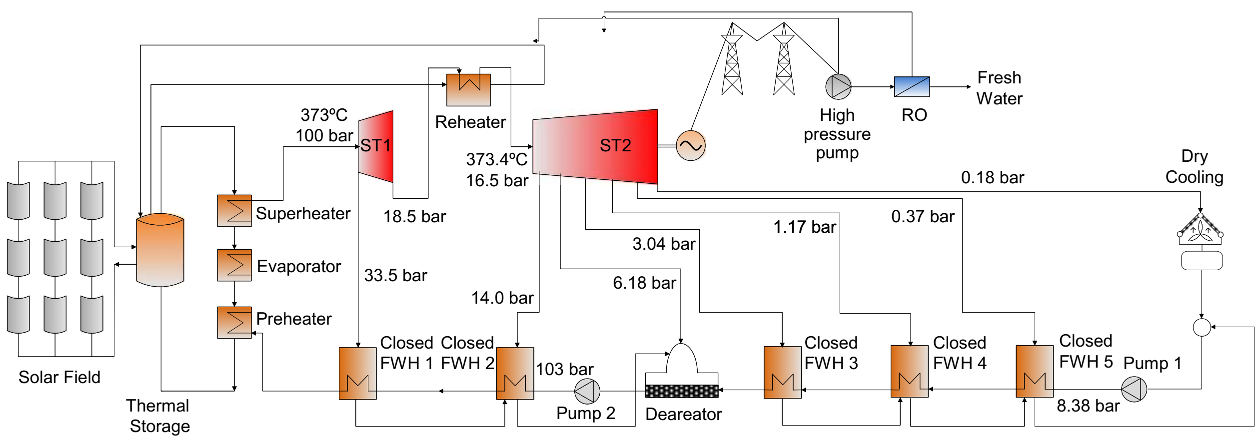

Fig. 8. Diagram of the RO unit integration into a PT-CSP plant.

lations varying parameters of the system (specific electric consumption, exhaust steam temperature, etc.); solar field size assessment has been determined by a computer model developed in MATLAB environment. On the other hand, the economic analysis of the four evaluated systems has been carried out by the assessment of the levelized electricity cost (LEC) and the levelized water cost (LWC).

4. Port Safaga case study

The first phase of the study was performed for the specific location of Port Safaga in Egypt (Fig. 9), which can be considered as a representative case in the Middle East and Persian Gulf region. As previously indicated, from satellite images, the DNI value of 2,496 kWh/m^2-yr was considered to this location. In all cases, a net CSP plant power production of 50 MWe was considered, since this is a typical size of most of existing solar plants. Therefore, all internal electrical consumptions (pumps, desalination unit, dry condenser, etc.) are considered and deducted to achieve the net production of 50 MWe.

Fig. 9. Possible theoretical location of the CSP+D cogeneration plant in Port Safaga.

To determine the efficiency of these different configurations, a thermodynamic analysis using a steady state computer model is needed. This can be done by assessing the net thermal output capacity (which is the thermal power required by the power cycle, provided by the solar field), the overall efficiency, and the cooling requirements. This yields a set of nonlinear, algebraic equations for each thermodynamic cycle and the steady flow energy equations of all the components associated with the power cycle (pump, reheater, heat exchanger, condenser, turbine, etc.).

With the specification of thermodynamic state points, a set of nonlinear, algebraic equations is generated for each cycle and the solution was obtained using the EES software. Each case solution yields the cycle unknown state points, along with its net output thermal capacity (thermal power to be provided by the solar field), overall efficiency, thermal power dissipated in the condenser, and its gross turbine output. Actual expansion and compression processes in the turbines and pumps, respectively, have been considered. An isentropic efficiency of 85% has been considered for all the turbines and pumps. Actual steam enthalpy at the outlet of the high and LP turbines of all the configurations proposed has been calculated through:

$$\eta_{\mathrm{st}} = \frac{h_{\mathrm{inlet}} - h_{\mathrm{oulet}}}{h_{\mathrm{inlet}} - h_{\mathrm{outlet,i}}} \tag{1}$$

where η_{st} is the isentropic efficiency, h_{inlet} is the enthalpy of the steam which enters the turbine, h_{outlet} is the actual enthalpy at the outlet of the turbine, and $h_{\mathrm{outlet,i}}$ is the ideal enthalpy of the steam which leaves the turbine. In the case that some steam is extracted from the turbine, the enthalpy of the extracted steam has been calculated with the assumption of linear condition line in the *h-s* diagram between the inlet and the outlet of the turbine:

$$\frac{h_{\mathrm{m}} - h_{\mathrm{outlet}}}{h_{\mathrm{inlet}} - h_{\mathrm{outlet}}} = \frac{s_{\mathrm{m}} - s_{\mathrm{outlet}}}{s_{\mathrm{inlet}} - s_{\mathrm{outlet}}} \tag{2}$$

where h_{m} and s_{m} are the enthalpy and the entropy at the point where the steam extraction has been done. In all case studies, the analysis has been carried out considering a net power production of the plant (P_{net}) of 50 MWe. The net power production of the plant is calculated as the gross turbine output (P_{turb}) minus the power required by the pumps (P_{pumps}) and minus the power required by the desalination plant (P_{desal}):

$$P_{\mathrm{net}} = P_{\mathrm{turb}} - P_{\mathrm{pumps}} - P_{\mathrm{desal}} \tag{3}$$

For the calculation of the power required by the desalination plant, a specific electric consumption of 2.11 kWh/m^3 has been considered in the case of the MED plant (this figure includes the pumping consumption of needed seawater, including MED cooling requirements) and 5.46 kWh/m^3 in the case of RO [13]. In both cases 24 h operation and a water production of 35,000 m^3/day have been taken into account. The steam flow required by the MED has been calculated by:

$$q_{\mathrm{steam}} = \frac{\mathrm{FWF} \times \rho}{\mathrm{GOR}} \tag{4}$$

where FWF is the fresh water production in m^3/day, ρ is the fresh water density in kg/m^3 (at 35℃ and 1 bar), and GOR is gained output ratio, which is defined as kilograms of distillate produced for every kilogram of steam supplied to the distillation unit. A GOR of 8.4 has been considered in all cases of MED technology. To calculate the steam ejector flow rates (both live steam and entrained vapor flow rates), a semi-empirical model developed by El-Dessouky [26] has been considered. The model makes use of the field data collected over 35 years by Power [27] for vapor entrainment ratios of steam jet ejectors. The entrainment ratio is the flow rate ratio of the motive steam and the entrained vapor and it can be calculated using:

$$Ra = 0,296 \frac{(P_{\mathrm{s}})^{1,19}}{(P_{\mathrm{ev}})^{1,04}} \left(\frac{P_{\mathrm{m}}}{P_{\mathrm{ev}}}\right)^{0,015} \left(\frac{\mathrm{PCF}}{\mathrm{TCF}}\right) \tag{5}$$

where P_{m}, P_{s}, and P_{ev} are the pressures of the motive steam, compressed vapor, and entrained vapor, respectively, PCF is the motive steam pressure correction factor and TCF is the entrained vapor temperature correction factor. Following equations were used to calculate PCF and TCF:

$$\mathrm{PCF} = 3 \times 10^{-7}(P_{\mathrm{m}})^2 - 0,0009(P_{\mathrm{m}}) + 1,6101 \tag{6}$$

$$\mathrm{TCF} = 2 \times 10^{-8}(T_{\mathrm{ev}})^2 - 0,0006(T_{\mathrm{ev}}) + 1,0047 \tag{7}$$

where P_{m} is in kPa and T_{ev} is in ℃. Finally, the overall efficiency has been calculated by:

$$\eta_{\mathrm{global}} = \frac{P_{\mathrm{net}}}{\mathrm{NOTC}} \tag{8}$$

where NOTC is the net output thermal capacity, which is given by:

$$\mathrm{NOTC} = P_{\mathrm{pcs}} + P_{\mathrm{RH}} \tag{9}$$

where P_{pcs} and P_{RH} are the power required by the power conversion system and the reheaters of the cycle, respectively. Considering the NOTC of the power block, the solar field size has been determined by a computer model developed in MATLAB. For this purpose, a model is used for the collector based on its thermal losses, its efficiency curve, and energy balances [28–30].

To summarize, the following parameters, assumptions, and boundary conditions have been taken into account in the computer model [31]:

- Plant location: Port Safaga (Egypt) (Longitude 33.81°E; Latitude 26.79°N).
- Design point: 27 September (radiation at solar noon 968.99 W/m^2, ambient temperature: 36.89°C).
- PT solar field based on the LS-3 type collector with peak optical efficiency of 76%.
- North–South orientation (of PT collectors). Main characteristics: 99.0 m longitude, 545 m^2 of aperture area, and 0.76 of peak optical efficiency.
- Distance to the sea of CSP+D facility: between 2 and 3 km.
- Thermal storage (molten salts) system for 24 h solar operation at design day. This implies an equivalent thermal storage capacity of about 13 h, with possibility to run 24 h from mid-spring to mid-autumn.
- Thermal oil (heat transfer fluid) type: Monsanto VP-1(properties determined using Monsanto software).
- Inlet temperature to the field: 295°C.
- Outlet temperature from the field: 390°C.
- Actual expansion and compression processes have been considered.
- An isentropic efficiency of 0.852 has been taken for the HP steam turbine, and an isentropic efficiency of 0.85 for the LP steam turbine.
- An isentropic efficiency of 0.75 has been taken for the pumps of the power cycle.
- Dry cooling is used to the power cycle steam condensing but seawater is used in the case of MED cooling. This is due to the large amount of seawater that would be needed to pump in the case of Rankine cycle which would significantly increase pumping energy consumption.
- Condensing conditions at LP turbine (configuration #1): 70°C (0.31 bar), as needed by the MED unit.
- Condensing conditions at LP turbine (configurations #2 and #3): 58°C (0.18 bar). This is a consequence of high ambient temperatures and the use of dry condensers [32].
- Condensing temperature of MED last effect: 40°C (seawater temperature at 30°C).
- The power required by the cooling unit has been taken from a study of a dry-cooled PT plant located in the Mojave Desert, which showed 5% less electric energy produced annually [23].
- When not all the steam from LP turbine is taken to the condenser, the energy consumption estimated by the dry cooling system is proportionally lower.

In all analyzed cases, nominal desalination plant production was $3.5 \times 10^4\,m^3$/day, an amount defined by the configuration PT-CSP+LT-MED (configuration #1) when all the steam from the turbine outlet at 70° C feeds the MED unit. With this data, several thermodynamic simulations have been performed for the LT-MED-TVC and RO configurations (configurations #2 and #3, respectively). In the case of configuration 2, the simulations have been performed using part of the steam that is extracted from the LP turbine (at pressures 1.17, 3.04, 6.18 and 14.0 bars) as motive steam. Table 1 shows the results of the thermodynamic analysis for all configurations, calculating the total thermal energy required by the integrated power and desalination facility (provided by the thermal storage system), cooling requirements, the solar field size needed according to the DNI potential of the selected location, and the overall combined facility efficiency, always considering the same net power and water production (50 MWe and $3.5 \times 10^4\,m^3$/day, respectively).

It can be observed that, with defined conditions, the integration of a LT-MED unit into a PT-CSP plant gets the best results, which means that the reduction of power production for this configuration due to the higher pressure of the exhaust steam is less than the extra power that the CSP must generate in configuration 3 for RO desalination process. In addition, no power plant cooling would be required in this configuration and therefore no condenser would (theoretically) be necessary.

LT-MED-TVC configurations show worse results than configurations 1 and 3, as it uses a high exergy steam to feed a steam ejector which provides the steam required by the MED desalination process. However, it has the advantage over the RO configuration of lower cooling requirements. In addition, when compared to the first configuration, the integration of a LT-MED into a PT-CSP plant by replacing the cooling unit has a major disadvantage in the fact that the desalination plant must be very close to the turbine since the exhaust steam has very low density and therefore pipes with very large diameters are needed to conduct the steam to the desalination plant. This is why the thermal compression of the steam (LT-MED-TVC) can also be considered as a feasible option.

5. Cost estimation

To estimate the power and water costs of the most efficient configurations from the previous case study described (PT-CSP/LT-MED and PT-CSP/RO), the following definition of LEC can be used [33]:

$$\mathrm{LEC} = \frac{\mathrm{crf} \times K_{\mathrm{invest}} + K_{\mathrm{O\&M}} + K_{\mathrm{fuel}}}{E_{\mathrm{net}}} \tag{10}$$

$$\mathrm{crf} = \frac{k_{\mathrm{d}}\,(1 + k_{\mathrm{d}})^{n}}{(1 + k_{\mathrm{d}})^{n} - 1} + k_{\mathrm{insurance}} \tag{11}$$

where:

- $K_{\mathrm{insurance}}$: annual insurance rate (typical value = 1%)
- K_{invest}: total investment of the plant
- K_{fuel}: annual fuel cost (not applicable in the case of solar energy without backup)
- k_{d}: real debt interest rate (value used = 8%)
- n: depreciation period in years (value used = 25 years)
- $K_{\mathrm{O\&M}}$: annual operation and maintenance costs
- E_{net}: annual net electricity delivered to the grid

Additional data used to calculate the cost of the solar power are the following:

- From a practical point of view, a CSP plant is considered with 13 h of thermal storage, working 24 h from mid-spring to mid-autumn, and also at nominal turbine capacity the rest of the year.
- Investment cost of the 50 MW PT-CSP plant without thermal storage: 4,620 €/kW-nominal.
- Investment cost of thermal storage: 56 \$/kWh-stored.
- About 200 hec of flat land needed.
- Plant availability: 96%.
- Consumption for the cleaning of the mirrors: 0.07 $\mathrm{m^3/MWh_e}$ [34].
- Land costs are not considered.

The same procedure will be used to estimate the LWC. Additional data to calculate the cost of the desalination plant:

- Investment cost of RO facility: 1,207 $\$/\mathrm{m^3}$ day installed (considered availability: 96%, the same of CSP plant) [35].

Table 1
Main data of different CSP+D configurations analyzed to Port Safaga (Egypt) case study (50 MWe and 35,000 $\mathrm{m^3}$/day in all configurations)

	Desalination system	Thermal energy consumption ($\mathrm{MW_{th}}$)	Cooling requirements (%)	Parabolic trough field area ($\mathrm{m^2}$)	CSP+D efficiency (%)
Conf. #1	LT-MED	161	0	733,570	31.1
Conf. #2	LT-MED-TVC (1,17 bar)	180	19	824,040	27.7
	LT-MED-TVC (3,04 bar)	191	27	872,000	26.2
	LT-MED-TVC (6,18 bar)	198	30	905,790	25.2
	LT-MED-TVC (14 bar)	208	34	948,300	24.1
Conf. #3	RO	175	100	798,970	28.6

Table 2
Comparative costs of power (50 MWe net production) and water (35,000 m^3/day net production) cogeneration with PT-CSP/RO and PT-CSP/LT-MED configurations. Values in USD

Cogeneration system	PT-CSP/RO	PT-CSP/LT-MED
Investment solar plant (M$)	612.76	554.83
Investment desalination plant (M$)	42.24	43.05
LEC (cts$/kWh)	27.20	24.75
LWC ($/m3)	0.70	0.75
Net power production (GWh-year)	307.30	307.30
Net water production (hm3—year)	8.96	8.96
Needed yearly power revenues to break-even power production costs (USD)	$83,587,409	$76,057,251
Needed yearly water revenues to break-even power costs (USD)	$6,279,081	$6,702,469

- Investment cost of MED facility: 1,230 $/$m^3$ day installed (availability: 96%, the same of CSP plant) [35].
- Specific electricity consumption by RO plant: 5.5 kWh/m^3 [13].
- Specific electricity consumption by MED plant: 2.4 kWh/m^3, which also considers the energy needed to MED feed and cooling water.
- Chemical consumption, manpower, membrane replacement, spare parts, and all other fixed and variable cost were also considered.

Main cost results are summarized within the Table 2.

As it can be appreciated, estimated power cost is slightly higher in the case of CSP-RO integrated plant, being the opposite in the case of desalinated produced water.

6. Conclusions

Solar thermal coproduction of water and electricity can only be made at large CSP plants, being RO and MED the two most reasonable options for desalination technology. The RO option would be the more efficient in most of cases, having also the advantage of not constraining the geographical location of the solar plant, potentially avoiding typical problems of land availability, and lower DNI levels close to seashore. However, when ambient temperatures drastically limit the expansion at steam turbines and the only reasonable solution to exhaust steam condensing is dry cooling, there is some room for a more energy efficient, and maybe even more economical, MED option. The results have shown that, at 0.18 bars in the turbine outlet conditions, the configuration that involves LT-MED is more efficient thermodynamically than the coupling of the CSP plant with a RO desalination plant and needs a smaller solar field for the same production of electricity. Moreover, this configuration has the advantage of not requiring any power plant cooling. The results obtained are valid for arid regions, where RO has higher specific electric consumption and dry cooling is used in CSP plants; and, coincidentally, nearly all locations in which thermal desalination technologies have an important market, (Middle East and Persian Gulf region) have these constraints.

Two types of LT-MED plants have been considered: a LT-MED plant, using the exhausted steam from the CSP plant as the source of the heat, and a novel system consisting of LT-MED plant powered by the steam produced from a TVC. In this case, unlike in the typical TVC-MED process, the entrained vapor to be used in the steam ejector comes from the exhausted steam of the CSP plant instead of an intermediate effect of the desalination plant. This new concept has a strong potential since is useful for the coupling of any thermal desalination process to a CSP plant. Within this concept (LT-MED-TVC), different schemes have been studied: a system that uses the high exergy steam at the HP turbine outlet as motive steam in the TVC, and others that use steam extracted at different pressures from the LP turbine as the motive steam in the ejector. Some main results are as follows: the integration of a LT-MED plant into a PT-CSP plant is the most efficient thermodynamically of all configurations proposed, besides no power cooling is required and therefore any condenser would be necessary. Although power production is reduced due to the higher pressure of the steam at the outlet of the turbine, the reduction is smaller than in other regions where the cold end temperature is lower. The integration of a LT-MED-TVC into a PT-CSP plant resulted in the smallest overall efficiency. However, when steam extractions from the LP turbine are carried out, the system is more efficient and the cooling requirements are lower compared to CSP+RO system. In addition to this, as opposed to the system CSP+LT-MED, this one does not depend on the load of the steam turbine, what can make it more convenient in some cases. When costs are analyzed, comparing the two more efficient configurations (PT-CSP/RO and PT-CSP/LT-MED), considering 58°C/0.18 bar of exhaust turbine steam conditions and 5.5 kWh/m^3 of RO power requirements, the results of final power + water costs, are very similar.

Nomenclature

CSP	–	concentrating solar power
CSP+D	–	concentrating solar power and desalination
DNI	–	direct normal irradiance
GOR	–	gain output ratio
k_d	–	real debt interest rate
K_{fuel}	–	annual fuel cost
$K_{insurance}$	–	annual insurance rate
K_{invest}	–	total investment of the plant
$K_{O\&M}$	–	annual operation and maintenance costs
LT-MED	–	low temperature multi-effect distillation
LT-MED-TVC	–	low temperature MED powered by thermal vapor compression
MED	–	multi-effect distillation
MENA	–	Middle East and North Africa
MSF	–	multi-stage flash distillation
n	–	depreciation period in years
PT	–	parabolic trough
PT-CSP	–	parabolic trough concentrating solar power
RO	–	reverse osmosis
SEGS	–	solar energy generating systems (California, USA, 1984–1991)
TVC	–	thermal vapor compression
TVC-MED		multi-effect distillation powered by thermal vapor compression

References

[1] J. Blanco, S. Malato, P. Fernandez-Ibañez, D. Alarcon, W. Gernjak, M.I. Maldonado, Review of feasible solar energy applications to water processes, Renew. Sustain. Energy Rev. 13(6–7) (2009) 1437–1445.

[2] MED-CSP, Concentrating Solar Power to the Mediterranean Region. Final Report. DLR—Institute of Technical Thermodynamics, 2005. Available from: http://www.dlr.de/tt/en/Portaldata/41/Resources/dokumente/institut/system/projects/MED-CSP_Full_report_final.pdf.

[3] UNDP, Human development report 2006. Beyond scarcity: Power, poverty and the global water crisis, United Nations Development Program, 2006.

[4] S. Olz, The global energy outlook—the key role of renewables, Alter Energy Convention 09, Dubai, October 27–29, 2009.

[5] Desertec Foundation, Red paper: An overview of the desertec concept, 2011. Available from: http://www.desertec.org/fileadmin/downloads/desertec-foundation_redpaper_3rd-edition_english.pdf.

[6] C. Hoyer-Klick, The Union for the Mediterranean and the Mediterranean Solar Plan. Mediterranean Solar Plan Workshop. Berlin, Germany, October 28, 2008.

[7] GEF, Assessment of World Bank/GEF strategy for the market development of concentrating solar power, Global Environmental Facility Program, World Bank, 2006.

[8] J. Blanco, D. Alarcon, G. Zaragoza, E. Guillen, P. Palenzuela, M. Ibarra, 2010, Expanding CSP research frontier: Challenges to be addressed by combined solar power and desalination plants, Proceedings of SolarPACES 2010 Conference, Perpignan, France, September 21–24, 2010.

[9] G. Kronenberg, F. Lokiec, Low-temperature distillation processes in single- and dual-purpose plants, Desalination 136 (2001) 189–197.

[10] L. Yang, S. Shen, Assessment of energy requirement for water production at dual-purpose plants in China, Desalination 205 (2007) 214–223.

[11] I. Kamal, Integration of seawater desalination with power generation, Desalination 180 (2005) 217–229.

[12] N. Bouzayani, N. Galanis, J. Orfi, Thermodynamic analysis of combined electric power generation and water desalination plants, Appl. Therm. Eng. 29 (2009) 624–633.

[13] F. Trieb, Concentrating solar power for seawater desalination, Aqua-CSP Study report, German Aerospace Center, Stuttgart, Germany, 2007. Available from: http://www.dlr.de/tt/en/desktopdefault.aspx/tabid-2885/4422_read-10813/.

[14] R. Olwig, T. Hirch, C. Sattler, 2010, Techno-economic analysis of combined concentrating solar power and desalination plant configurations is Israel and Jordan. Proc. EuroMed 2010 Desalination for Clean Water and Energy, Tel Aviv, Israel, October 3–7, 2010.

[15] M. Moser, F. Trieb, J. Kern, Combined water and electricity production on industrial scale in the MENA countries with concentrating solar power. Proceedings of EuroMed 2010 Desalination for clean water and energy. October 3–7, 2010, Tel Aviv, Israel.

[16] R. Pérez, R. Seals, A. Zelenka, Comparing satellite remote sensing and ground network measurements for the production of site time specific irradiance data, Sol. Energy 60 (1997) 89–96.

[17] A. Zelenka, R. Perez, R. Seals, D. Renne, Effective accuracy of satellite-derived hourly irradiances, Theoret. Appl. Climatol. 62 (1999) 199–207.

[18] L.J.B. McArthur, Baseline Surface Radiation Network (BSRN). Operations manual V1.0. Serie: World Climate Research Programme. Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1998.

[19] Google Earth software, 2011. Available from: http://www.google.com/earth/index.html.

[20] L.F. Zarzalejo, J. Polo, L. Martín, L. Ramírez, B. Espinar, A new statistical approach for deriving global solar radiation from satellite images, Sol. Energy 83 (2009) 480–484.

[21] J. Polo, L.F. Zarzalejo, L. Martin, A.A. Navarro, R. Marchante, Estimation of daily Linke turbidity factor by using global irradiance measurements at solar noon, Sol. Energy 83 (2009) 1177–1185.

[22] J. Polo, L.F. Zarzalejo, L. Ramirez, B. Espinar, Iterative filtering of ground data for qualifying statistical models for solar irradiance estimation from satellite data, Sol. Energy 80 (2006) 240–247.

[23] C. Richter, J. Dersch, Methods for reducing Cooling Water Consumption in Solar Thermal Power Plants. Proceedings of 15th SolarPaces CSP Symposium, Berlin, Germany, September, 15–18, 2009.

[24] A.M. Blanco-Marigorta, M.V. Sanchez-Henriquez, J.A. Pena-Quintana, Exergetic comparison of two different cooling technologies for the power cycle of a thermal power plant, Energy 36 (2011) 1966–1972.

[25] Engineering Equation Solver version v8.742. Available from: http://www.fchart.com.

[26] H. El-Dessouky, H. Ettouney, Fundamentals of Salt Water Desalination, Elsevier Science B.V, Amsterdam, 2002.

[27] B.R. Power, Steam Jet Ejectors for Process Industries, McGraw-Hill, New York, NY, 1994.

[28] E. Zarza, Generación Directa de Vapor con Colectores Solares Cilindro Parabólicos [Direct Steam Generation with Parabolic Troughs Solar Collectors], Proyecto Direct Solar Steam (DISS), CIEMAT, Madrid, 2004.
[29] F.P. Incropera, D.P. Dewitt, Fundamentals of Heat and Mass Transfer, Willey, New York, NY, 1996.
[30] González L., E. Zarza, L. Yebra, Determinación del Modificador por Ángulo de Incidencia de un colector solar LS-3, incluyendo las pérdidas geométricas por final de colector [Determination of Incidence Angle Modifier of an LS-3 Solar Collector, Including End Collector Geometric Losses]. Informe técnico [Technical Report] DISS-SC-SF-30. Plataforma Solar de Almeria, 2001.
[31] J. Blanco, D. Alarcon, P. Palenzuela, G. Zaragoza, C. Sattler, R. Olwig, K. Hennecke, R. El Navrawy, B. Rashed, Assessment of CSP+D potential in the Mena Area, SolarPACES Task VI Report, 2011. Available from: http://www.solarpaces.org/Library/library.htm.
[32] O.A. Hamed, H.A. Al-Washmi, H.A. Al-Otaibi, Thermoeconomic analysis of a power/water cogeneration plant, Energy 31(14) (2006) 2699–2709.
[33] W. Short, D.J. Packey, T. Holt, A manual for the economic evaluation of energy efficiency and renewable energy technologies. NREL/TP-462-5173, Golden, CO, 1995.
[34] US Department of Energy, Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation, Washington, DC, 2009. Available from: <http://www1.eere.energy.gov/solar/pdfs/csp_water_study.pdf>.
[35] Global Water Intelligence, Desalination Markets 2010 – Global Forecast and Analysis, UK, London, 2010.