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Integration between concentrated solar power plant and desalination

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ABSTRACT

Fresh water and electricity production in desert areas via the use of solar radiation represent examples of sustainability. The concentration of solar power by means of parabolic trough (PT-CSP) technology has a great potential not yet exploited in the realm of renewable energy production. A new technology for the solar energy section is being proposed by the authors which uses air as a working fluid. The use of air allows the cycle to be coupled with an inter-cooled compression section and a re-heated expansion section which is called Discrete Ericsson Cycle, (DEC-based plant). The paper presents an integration of such a CSP-DEC plant with desalination: where freshwater is produced according to a Low Temperature Multi Effect Distillation (LT-MED) technology. The LT-MED plant operates on the heat from the air coolers in the inter-stage cooling of the DEC-based plant. This heat is normally expelled to atmosphere. In fact, the heated air has the same temperature ranges required for the operation of the LT-MED desalination technology. This provides an efficient integration of energy for desert applications. The most important feature of this new solar energy plant is that the thermal needs of desalination in DEC-based plants do not interfere with the electricity production of the plant as is the case for current conventional PT-CSP plants which use diathermic oils as Heat Transfer Fluid (HTF). When the performance of the CSP DEC-based plants, integrated with the LT-MED technology, are compared to conventional CSP plants, they show an increased efficiency in terms of fresh water production per unit of energy produced. Thus, fresh water production can be considered as a valuable addition to the plant.

Keywords: Concentrated solar power; Parabolic trough; Desalination; LT-MED; Air as HTF

1. Introduction

Energy and water are two resources neither of which humanity can live without. Energy consumption per capita is often assumed to be an indicator of the level of social development. This represents a concern for developing countries trying to align their consumption to actual levels of developed countries.

Water consumption per capita is correlated with the quality of life. Fig. 1 shows that energy and water are often wasted in developed countries while their scarcity in developing countries (and even more in under-developed countries) results in many cultural and social problems in under-developed countries. Thus, energy and water are needed for basic needs and are thus generally in high demand but limited supply.

According to Fig. 1, the close relationship between water and energy makes them essential for basic life

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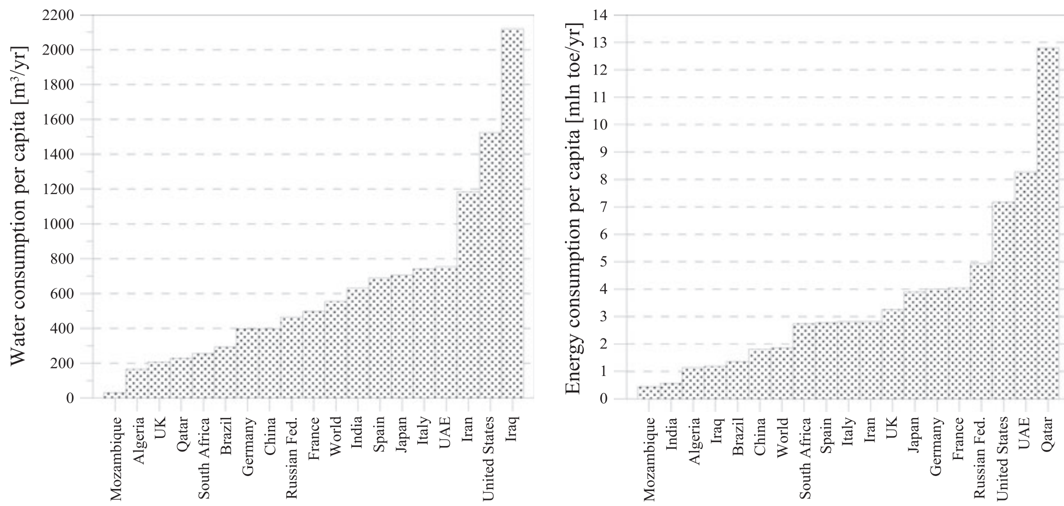

Fig. 1. Water consumption (left) and energy consumption (right) per capita [25,26].

necessities as well as a wide range of economic activities. The limited sources of water in many parts of the world, have raised much concern, especially in regions affected by drought. Even in areas with high precipitation and large river basins, there is over-use and mismanagement of water. More than a billion people lack access to clean, safe drinking water and are suffering poor health which reduces their quality of life. The problems are widespread and will most likely continue in the future due to the accelerated demands of fresh water arising from economic development. World-wide fresh water supply is therefore a challenge [1].

Another important challenge for the future is the balance between energy demand and energy production. It is known that almost 90% of overall energy consumption is based on fossil fuels. This is in contrast with the CO_2 commitments universally proposed by many countries. Renewable energy sources, apart from hydroelectric, biomass and landfill waste, still account for only 3% of the total energy consumption. The IPCC reference limits are 450 ppm for CO_2 in atmosphere. However, the actual concentration is equal to 403.2 ppm [2,3], and is considered by the authors too close to the IPCC limit. Therefore, a change in energy supply and use is required to help decrease the CO_2 concentration in the atmosphere. Moreover, the role of desalination is increasing and in the future, this technology will require even more energy as it is applied in desert areas where solar radiation is high.

The use of solar energy for desalination is not a novelty. And recent technological advances in concentrated solar power (CSP) plants offer a unique opportunity for desalination plants [4,5]. As such, it seems that CSP has the potential to make great steps forward in renewable energy production, in order to lower the use of fossil fuels for energy [6].

The CSP technology offers the lowest cost option of large, utility-scale solar energy today and it is expected that there will be a halt to incentives that were in place for the early commercial plants situated in locations with premium solar resources. As the cost of electricity from conventional generation technologies continues to rise due to the fluctuation of refined fossil fuel costs and the introduction of CO_2 taxation, there is increased interest in CSP as a viable alternative to other renewable technology options. With global warming on the increase, this has further increased the interest. As a matter of fact, large solar development plants and projects, such as the Desertec Initiative [7] and the Mediterranean Solar Plan, which consider the installation of CSP plants in the Mediterranean area, are currently under discussion. Among the technologies, the Parabolic Troughs (PT) are the most commonly used in commercial plants and their performance are continuing to attract energy sectors worldwide [8]. Unfortunately, CSP plants (mainly of PT type) have many drawbacks: reliability, high costs, financing problems, use of certain Heat Transfer Fluid (HTF)'s, use of special materials, temperature limits, pressure drops, components-pumps, sealing systems, valves, etc.

A simplification of CSP plant technology is expected to be discussed in literature, in order to address and recommend increased reliability, safety, decreased investment, and maintenance costs. This will help attract funds for investment in these plants.

CSP plants can offer power generation in remote locations, mainly in desert areas where development is marginal and under the minimum standards for an acceptable life. In these regions, 5% of the World's population has to survive on less than 1% of the world's available fresh water supply. Similar figures apply to the availability of energy. Access to fresh water is therefore a number one priority for governments in the Middle East and North Africa (MENA) regions, thus making desalination an attractive solution. It is similar for the availability of electrical energy.

Integrating CSP with this type of water treatment can reduce the costs and ensure both energy and water, match territorial needs and solar irradiation. A desalination (D) unit integrated with a CSP plant (CSP + D) appears to be the right choice. More generally, there are several renewable energy sources and desalination combinations that are being tested for innovative desalination processes. Detailed assessments of available and exploitable water resources have been carried out [9,10].

The CSP + D that use low or medium pressure steam from the power system, especially in combination with Parabolic Trough CSP (PT-CSP), has been already piloted in different locations. Those demonstrations carried out at the Plataforma Solar de Almeria (PSA) in Spain demonstrate the technical feasibility of solar thermal seawater desalination. The water shortage in MENA and also the need to move toward cleaner as well as sustainable electricity generation systems makes PSA a suitable case for cogeneration of power and water with solar thermal energy sources.

In this paper, the authors briefly discuss the characteristics of a new PT-CSP plant [11], in which air is considered as the HTF in conventional receivers. The solar conversion section of this new PT-CSP is represented by direct expansion of air inside a series of gas turbines. The air undergoes a series of inter-cooled compressions and it is heated in part via the recuperation of heat from the returning air after expansion. After this, it is further heated in the solar section where the solar heated air undergoes a series of inter-heated expansions. In this cycle (with numerous expansions), the authors want to get closer to theoretical Ericsson Cycle which, with heat fully recuperated, has the Carnot efficiency. The cycle obtained has been called in previews papers Discrete Ericsson Cycle (DEC). The DEC-based plant implies that there is thermal energy loss, represented by:

(1) The heat removed during inter-cooling of the initial stages of compression.
(2) The heat removed from the air after the recuperation phase as it returns to compression suction.
(3) The heat removed in the recuperation phase. The remaining heat is significant enough to be used for other thermal needs.

The most important aspect is that these energy losses (inter-cooling of the compressed air and heat recovery after the recuperation) are in the same temperature range which is suitable to produce freshwater by LT-MED technology. This desalination technology has been integrated with DEC-based CSP plants and specific performance parameters have been determined per unit of electricity produced. At a suitable pressure level, dry saturated steam for desalination is produced thus recovering heat losses in the plant. The desalination process is fed by this steam. This means that the thermal needs of the desalination plant are fully integrated with DEC-based plant. Namely, the steam is produced by recovering thermal energy which would be otherwise wasted. In fact, the main disadvantages of conventional (oil HTF-based) CSP + D are that the desalination integration is technologically intrusive with CSP. Namely that the LT-MED process decreases the net electric power of the CSP [12,13]. This is due to the steam extraction, usually from a low pressure (LP) turbine. The DEC-based plant recuperates the energy after the last expansion stage; which is then added to the air stream after the last stage of compression. In this way, the size (length) of the solar field is reduced. This exchange of heat is easily modifiable if freshwater production (m^3/kWh_{el}) is assumed as a goal.

2. Desalination technologies

In general, there are two major types of desalination technologies that can be broadly classified as either membrane or thermal. In the first process (membrane), water passes through a membrane without a phase change, and in the second one, water is involved in a phase change. Both technologies need energy to operate and produce freshwater.

Within these two main types, there are subcategories using different techniques. The major processes are identified in four techniques: Multi Stage Flash (MSF), Multi Effect Distillation (MED), Mechanical Vapor Compression (MVC), and Reverse Osmosis (RO). Table 1 presents the main energy requirements for all processes and efficiency issues. MSF and LT-MED both require thermal and electrical energy while MVC and RO require only mechanical or

Table 1
Comparison of desalination applied commercial technologies [2]

Process	MSF	LT-MED	MVC	RO
Energy used	Thermal	Thermal	Mechanical	Mechanical
Conversion freshwater/seawater (%)	10–25	23–33	23–41	20–50
Heat consumption (kJ/kg)	250–330	145–390	–	–
Electricity consumption (kWh/m^3)	3–5	1.5–2.5	8–15	2.5–7
Plant cost (\$/m^3/d)	1,500–2,000	900–1,700	1,500–2,000	900–1,500
Production unit capacity (m^3/d)	<76,000	<36,000	<3,000	<20,000
Max top brine temperature (K)	363–393	328–343	343	318
Product water quality (ppm)	<10	<10	<10	200–500

electrical energy. The combination of CSP with MED will be more effective than the combination of CSP and MSF desalination since MED is more efficient in terms of primary energy use and electrical consumption. In addition, its operating temperature is lower. Moreover, it has a lower plant cost. Among the mechanically driven desalination options, the much lower primary energy (electrical) consumption of RO and the slightly lower cost compared to LT-MED suggests that RO might be the preferred desalination technology [14].

In this paper, a feedforward multi effect LT-MED system is considered, making use of the availability of the thermal power that can be recovered in the CSP-DEC. This choice is also due to the lower thermal energy consumption per kg of fresh water produced with respect to MSF. The lower electricity consumption required by the multi effects LT-MED technology reinforces the choice of this technology. The low temperature of the saturated steam reduces its energy [15], leading to a more efficient desalination process. Technologies like MVC and RO need only electricity. But the higher electricity consumption with respect to the other technologies decreases the output of a conventional CSP plant.

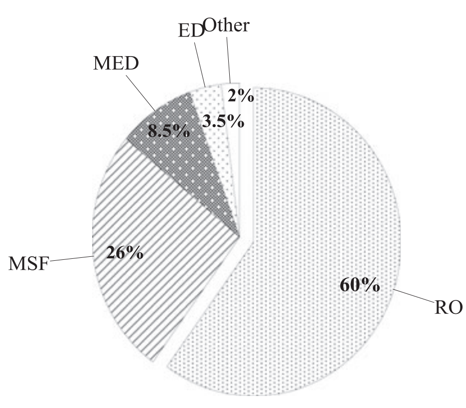

Fig. 2. Worldwide installed desalination capacities by technology for a total of 66.5 million m^3/d, 2011 [27].

Analyzing the global desalination capacity, MED and RO technologies account for about 68.5% (refer to Fig. 2). The RO technology, which is the more used desalination process, has some intrinsic advantages in respect to the others as it only requires the use of electrical energy and thus makes the energy needs easier to be fulfilled [16]. As such, RO is used for very large plants, and represents the most used technology.

3. Integration between DEC-based PT-CSP plants and desalination

3.1. DEC-based PT-CSP plants features

As previously stated, the discouraging results of the use of renewable technologies (except for large hydro) shows that about 3% of the global energy generation is based on renewable energy. This calls for new systems with greater potential and with a strong industrial feasibility.

The CSP technologies seem to have these properties and could represent, if duly supported, a replacement for fossil fuel-based power generation. Fig. 3 (l) shows the exponential growth of CSP installed power in spite of the economic crises which have occurred in major countries in the world. The PT technology (the most commercially developed and reliable) has a dominant role, Fig. 3 (r). Present plants use diathermic oil as a HTF which is heated to about 723.15 K as a maximum temperature. When MS are used, the maximum operating temperature is 823.15 K. Today, only one plant in Sicily (Italy) is using MS but many plants in the design and construction phase make reference to MS. In both cases, the HTF acts as thermal source used to feed thermoelectric power plants which are quite conventional in design. As such, the PT-CSP technology matches downstream conventional generation technologies having an upstream section for capturing concentrated solar energy.

However, this potential for this technology has not been followed by the industrial engineering world

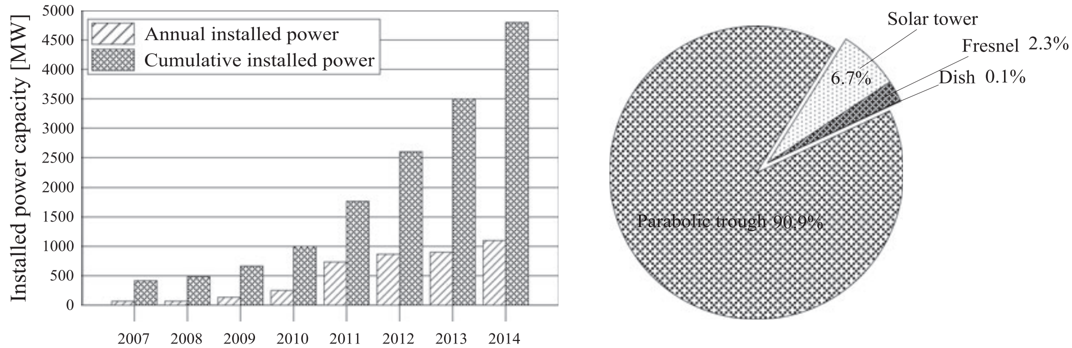

Fig. 3. The Worldwide CSP power installed capacity (l) and by technologies (r) [3].

[17,18]. It is believed that the main reason for this situation is the complexity of the overall plant (solar energy concentration and conversion section) and some challenges related to plant management (presence of a condensing section in desert areas, oil toxicity and flammability, weak reliability, high maintenance costs, not conventional components, etc.). When considering molten salts, a minimum temperature should be always guaranteed for the HTF to avoid solidification which occurs at high temperatures such at 200˚C.

A real breakthrough could be represented with the use of gases as HTF as discussed in [11,19]. During the last years, the authors focused their attention on a new solar conversion section based on the direct expansion of air (considered as a HTF) inside gas turbines [16]. In order to improve cycle efficiency, a sequence of inter-cooled compressions, as well as a series of inter-reheated expansions, have been proposed. The corresponding cycle has been named DEC.

This proposal aims at simplifying current solar concentration technology in terms of flexibility of power plant size, reliability of the working fluid (in this case gas) and the, level of plant operations.

The main concept of the DEC is that compressed air is heated inside solar collectors which have more or less the same technology than that already on the market. It is directly expanded inside turbines, which are also widely available. The reference thermodynamic cycle to convert thermal energy into mechanical is the Joule one, but, in order to improve efficiency, compression is done through a sequence of inter-cooled stages and expansion is done through a similar sequence of re-heated expansions. Please note that the compressors and turbines are coupled. The high temperature, which is achieved through the inter-reheated expansions, allows for a recuperation in which part of this enthalpy is used to heat compressed air after the last compression stage. The remaining heating stage of air, to reach the maximum fixed temperature, is done inside solar collectors. In addition, extra solar collectors are also used to re-heat the air in the inter-stages of expansion. The thermodynamic cycle of the air approaches the Ericsson cycle in a discrete mode (DEC) which would consider an infinite number of compressions and expansions which of course are not sustainable in reality. In the previous papers, the authors discussed the setup of the main thermodynamic parameters (maximum pressure and temperature, number of compressions and expansions, solar fields at different operating pressures, etc. [11,16,17]) and the main construction and financial aspects related to the overall solar collector length.

The main aspects of the DEC-based plant are: (a) the Parabolic Trough Collector (PTC) and (b) plant layout. Hereafter, a synthesis of the respective modeling and results are presented. Other details are available in the cited author’s literature.

3.1.1. PTC model

The PTC model represents the thermal behavior of an absorber metallic tube surrounded by a glass tube. The inner tube combines a high absorbance for the solar irradiation (short wavelengths) with low emissivity in the temperature range in which the surface emits radiation (long wavelengths). The external anti-reflective glass tube captures the long wavelengths emitted by the metallic tube. Inside it, the HTF represented by air, moves along the trough absorbing heat due to forced convection. The equilibrium of all the thermal states (inner and outer temperature of the glass and metallic tube and HTF) can be calculated by solving the conservation of energy equation for the two tubes, including the HTF, mass, and momentum. The equilibrium applies to all the longitudinal sections of the PTC. In the developed model, uniform properties are applied on the cross sections for all the variables the authors are modifying. This assumption uses a CFD approach for the HTF to consider cross section disuniformity due to the non-uniform irradiation on the metallic tube (from the Sun) and low HTF density. The characteristics of the concentrated solar power on the inner metallic tube of the PTC are evaluated taking into consideration the geometry of the existing parabolas and the optical properties of the glass tube and that of the metallic tube surface. The thermal processes have been described considering conventional irradiation and convection rules. A set of five non-linear equations have been derived and solved whose unknowns are the thermal state previously mentioned. Considering the high conductivity of the metallic tube and the considerably reduced thickness of the glass tube, a simplification has been done so that only three unknowns remain. They are represented by the temperature value for the inner metallic and glass tubes and for HTF. These temperature values vary along the length of the receiver, and describe the full heating process of the HTF. As the HTF temperature increases, the length of the metal tube increases as well, producing a decreasing efficiency of the PTC along its length because of the higher irradiation toward the environment. The real geometries of existing PTC's have been considered as well as typical values of all the optical and thermal properties of the tubes and of the fluid. When the radius of the inner tube and the inlet air mass flow rate have been fixed, all the thermo-fluid dynamics properties of the HTF can be predicted as a function of the PTC length. Also pressure losses are predicted according to known fluid flow rules for rough tubes.

By dividing the PTC into small discrete steps and evaluating in each element, all the properties of the HTF, the thermal receiver efficiency is defined as:

$$\eta_{\text{th}} = \frac{\dot{m}\, c_{\text{p}}\ \Delta T}{\dot{m}\, c_{\text{p}}\, \Delta T + \dot{q}'_{\text{heatloss}}} \quad (1)$$

The numerator is the real energy transferred to the HTF, while $\dot{m}$, c_{p}, ΔT are the HTF mass flow rate, specific heat at constant pressure and the overall temperature increase inside the PTC. The heat loss; $\dot{q}'_{\text{heatloss}}$ represents the thermal energy exchanged toward the environment due to radiation. The balance shows that the sum of these two terms is equal to the arriving solar power.

This model has been used as design tool when a specific HTF temperature increase is desired. Following the heating of the HTF, the efficiency decreases and reaches a nil value. From this point on the PTC doesn't transfer any heat. Considering that as the HTF increases in temperature and decreases in pressure, the density also decreases. This means that the speed of the fluid (air) tends to increase without any constraints. In order to limit it to a maximum allowable value to keep the working conditions safe, the flow rate is split by the model into PTC branches which operate in parallel when this limit is reached.

3.1.2. Plant layout

The plant layout follows the DEC's requirements. Compressors and expanders have been represented by suitable adiabatic efficiency values while heat exchangers that cool down the compressed air between compression stages have been represented by real approach temperatures and performance. The thermodynamic states of the two fluids involved have been calculated according to pinch point analysis. Having chosen the heat exchanger types as well as their main data, the design has been done according to NTU's classical rules.

A similar approach has been used for the recuperation phase when heat is exchanged between the low pressure HTF (leaving from the last turbine) and the high pressure air stream moving out from the last compressor. The hot air temperature returning to the compressor suction, and the air temperature leaving the compressor discharge, are such that they allow for this heat exchange. The net benefit is a greater cycle efficiency and a smaller HP solar field. Also, the recuperator design, and size come from basic engineering principles, having fixed suitable pinch points for the heat exchanger type.

According to a layout which considers three compression and expansion stages, the data reported in Table 2 shows the input data and the characteristics of the proposed plant. For the maximum assumed air temperature, the heating of the HTF inside the solar fields has been evaluated from the PTC model. Fixing the solar tube geometry (metallic and glass tubes), geometry and technology of the parabolas, the details of the three solar fields–at low (L), medium (M) and high (H) pressure (P)–have been calculated in terms of number of branches and all the relevant properties inside them. Fig. 4 shows the plant layout: ambient air enters three stages of inter-cooled compression (heat exchangers B and C), then recuperates heat from the returning air before entering the HP solar field.

Inside the solar field, it is heated until it reaches a fixed maximum temperature. Hot air, is then expanded inside three stages of inter-reheated expansion sections whose re-heating processes are also done inside two solar fields operating at MP and LP. During these

Table 2
Input of the proposed plant layout

Direct normal irradiance (W/m^2)	H	900
HTF inlet temperature (K)	T_{in}	313.1
HTF inlet pressure (bar)	P_{in}	1
HTF maximum temperature (K)	T_{max}	1,023.1
HTF maximum pressure (bar)	P_{max}	50
HTF maximum speed (m/s)	v_{max}	25
Air mass flow rate (kg/s)	$\dot{m}$	1
Pinch point at the inter-cooling heat exchanger (K)	$\Delta T_{pp,cool}$	20
Pinch point at the regeneration (K)	$\Delta T_{pp,regen}$	30
Number of turbines	N_{exp}	3
Number of compressors	N_{com}	3
Pressure ratio of each compressor	β	3.7
Compressor (adiabatic) efficiency (%)	η_{comp}	0.85
Turbine (adiabatic) efficiency (%)	η_{exp}	0.89
Ericsson cycle efficiency fully regenerated (Carnot) (%)	η_{eric}	0.66
Generator efficiency (%)	η_{gen}	0.95
PTC thermal efficiency (%)	η_{th}	0.44
DEC Cycle efficiency (%)	η_{DEC}	0.41
Plant efficiency (gross) (%)	η_{glo}	0.18

heating stages, the flow rate is split which guarantees that a maximum air speed is not reached inside PTC. A cooling section is done inside the regenerator and, finally, discharged into atmosphere. Different, and more flexible layouts, could be considered which separate the compression phases from the useful power production. The number of compression and expansion stages could also be changed.

An interesting alternative which is under study is the use of the high enthalpy of the air leaving the last turbine inside a thermal storage system which could give night-time continuity to the energy conversion (or a support during lower solar irradiation). In the presence of thermal storage, a larger HP solar heat collector section should be considered which is able to restore the thermodynamic characteristics in step “7”. When air is used as a HTF, it is assumed, at this time, that the most suitable thermal storage technology is based on a packed bed systems. During periods of low solar irradiation, air leaving the recuperator, crosses the storage system and heats up the thermal storage system until the maximum allowable temperature is reached.

In order to further simplify the CSP plant, with respect to what already presented [14,19,20], an open plant is here considered. Namely, the air is discharged to atmosphere and cooler ambient air is used for the compression suction. In the previous papers, the inlet temperatures of the first compressor were restored by passing through an air-cooled heat exchanger fed by external air or cooled by an another cooling medium. In reality, the air leaving the recuperator at ambient pressure could be simply expelled into the atmosphere as conventionally happens for gas turbine plants not combined with other recovery systems. The most important aspect of the DEC plant, though, is the receiver length of the solar fields; Table 3 reports this information. These results from PTC model have been fixed for the input and output temperature and present receiver technology [18]. Mass flow rate assumed inside the receivers is 1 kg/s.

The following observations and conclusions have been derived from the overall analyses of the unit:

(1) Number of branches operating in parallel increases when operating pressure inside the receiver decreases. This is due to the density reduction of the air and to the need of limiting the maximum air speed inside receivers (maximum speed is 25 m/s).
(2) Overall receiver length of the three sections remains almost constant (133 m, 131 m, 157 m for HP, MP and LP, respectively). This is due to the similar thermal efficiency of the receivers, even though it decreases when air temperature increases (due to the higher metal temperature which increases radiation losses): the overall solar collector area can be estimated at about 2,400 m^2. At a solar irradiation equal to 900 W/m^2, an overall solar power input is equal to 2.16 MW. The heating of the HTF requires 876.5 kW, therefore the averaged PTC thermal efficiency is equal to 44%. This value is lower than the one that characterizes conventional CSP plants. The main reason is due to the higher metal temperature of the receivers (with respect to the conventional plants) as a result of the higher HTF temperature. An improvement of the glass tube absorbance is envisaged. Net mechanical power of the plant is 388.4 kW when 1 kg/s of air crosses the receivers. Assuming a generator efficiency equal to 0.95, net electrical power is 369 kW. A total plant efficiency is about 18% (including the thermal efficiency of the receivers). It should be pointed out that conventional CSP plants have a higher averaged thermal efficiency (close to 65–70%) and a net efficiency of the solar conversion section close to 35%. An overall solar conversion efficiency is in the range of 24%, excluding storage section efficiency [21].
(3) Pressure losses inside the MP and LP solar fields are negligible considering that each branch consists of 1/3 (MP) and 1/30 (LP) of the overall mass flow rate.

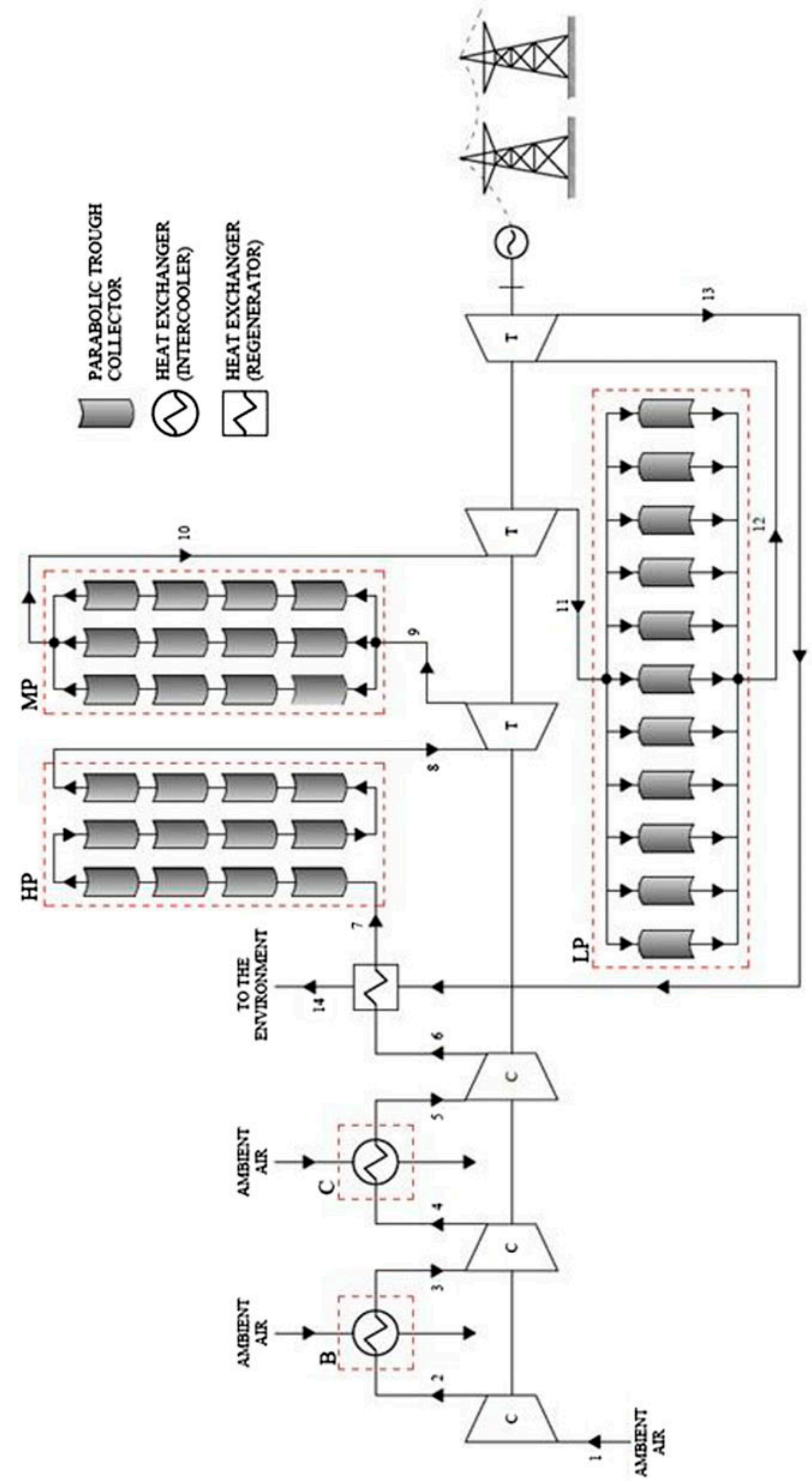

Fig. 4. DEC plant layout for three expansions and compressions [14,17,18].

Table 3
DEC-based solar field length

DEC	HP	MP	LP	Total length
Solar fields length (m)	133.1	43.5	14.3	421
Number of branches	1	3	11	

Fig. 5 shows the T-S plane of the DEC and Table 4 main thermodynamic data.

3.2. Thermal energy recovery and desalination integration

As previously observed, the DEC-based CSP plant needs three low temperature external sources.

The first two are required to cool down the compressed air (transformations “2–3” and “4–5” in Fig. 5; the third represented by the atmosphere, insures constant conditions at the first intake compression section. The three corresponding temperature ranges are: 333.1–480.5 K; 333.1–511.2 K; 313.1–541.2 K. It is evident how these temperature ranges fit properly into the thermal requirements of the LT-MED desalination technology.

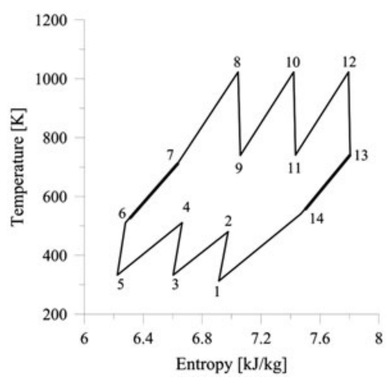

Fig. 5. T-s diagram of reference cycle for the conversion section.

Fig. 6 shows a plant layout which allows this heat recovery for desalination. Three streams of water flow into three heat exchangers in which air is cooled and the water is converted into dry saturated steam. The hot air after the recuperation section, that heat of which normally would have represented a thermal loss to atmosphere, is now used for a very useful process in the desalination unit, namely vaporization of the steam, a key thermal medium for desalination. Hence, air which was cooled inside the compression loop by heat exchangers “B” and “C” is now cooled in other exchangers in the desalination unit. A new heat exchanger “A” has been inserted after the recuperation phase see Fig. 4). The steam for desalination is at 0.31 bar, saturated temperature equal to 343.1 K.

Table 5 reports main thermodynamic data at the heat exchangers input and output.

Fig. 7 shows the layout of the LT-MED technology studied. Eleven (11) stages have been considered. In each stage, steam produces a partial vaporization of the salted water whose salinity increases as the number of stages increases too. The salinity increases when salted water moves from the first to the subsequent stages and this produces a partial boiling of the salted water at a temperature which is progressively lower. The temperature of the steam remains constant, until it is fully condensed.

In a typical conventional multi effects (stages) LT-MED unit, like the one considered, the top brine temperature in the last effect is in the range of 310 K (as result of continuously decreasing the pressure and thus the boiling temperature under partial vacuum).

Table 4
DEC thermodynamic properties

	Temperature (K)	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)
1	313.1	1.00	313.50	6.9134
2	480.5	3.64	483.25	6.9763
3	333.1	3.64	333.18	6.6034
4	511.2	13.40	514.47	6.6641
5	333.1	13.40	331.45	6.2242
6	511.2	50.00	513.07	6.2794
7	712.1	50.00	727.86	6.6335
8	1,023.1	49.06	1,076.10	7.0441
9	739.8	13.24	757.11	7.0593
10	1,023.1	13.24	1,073.90	7.4213
11	740.9	3.62	758.07	7.4340
12	1,023.1	3.62	1,073.30	7.7939
13	741.8	1.00	758.98	7.8048
14	541.2	1.00	546.06	7.4706

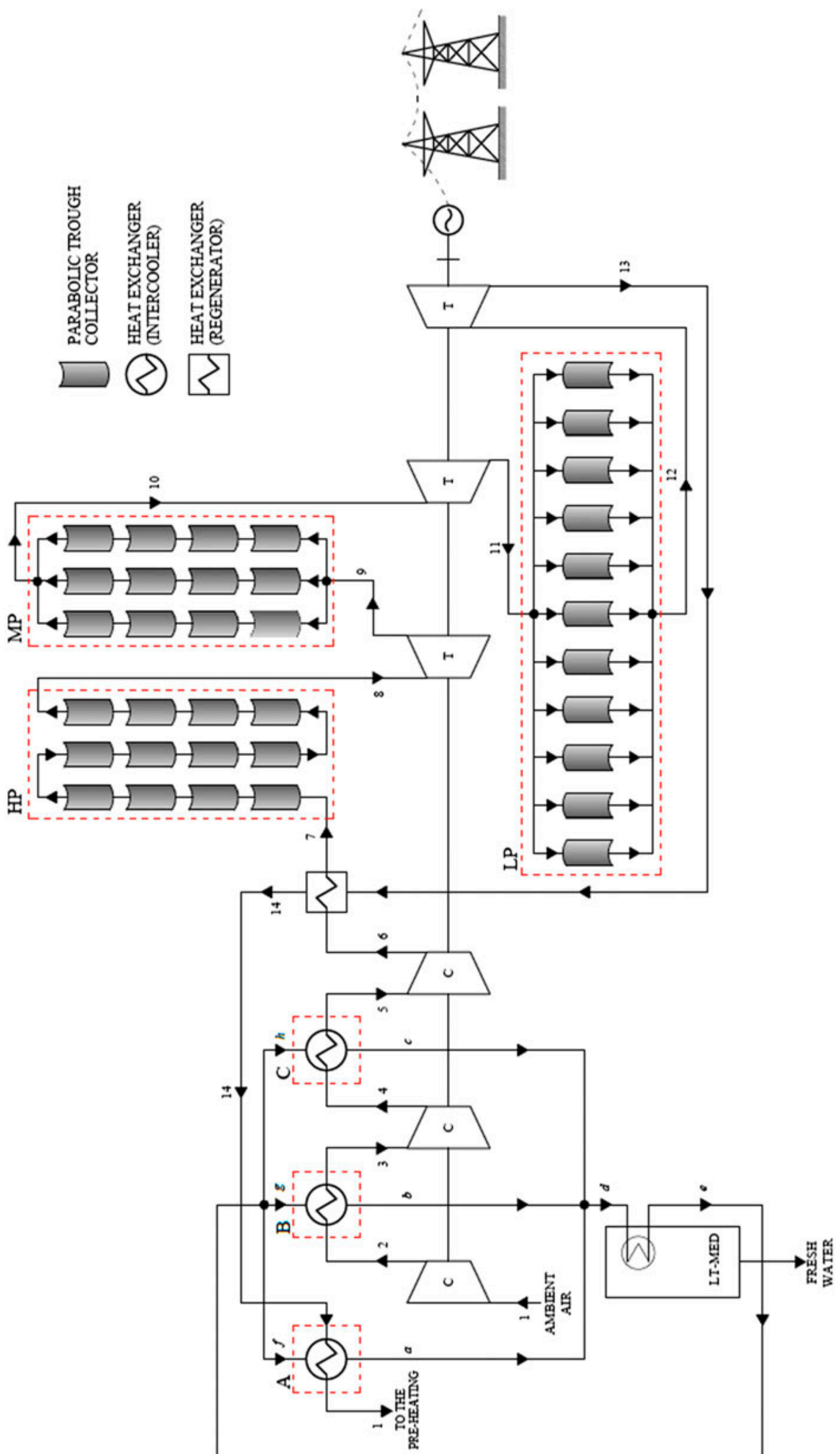

Fig. 6. LT-MED desalination unit integrated with the DEC plant.

Table 5
Temperature ranges of the three heat exchangers

	Water (Cold side)				Air (Hot side)			
	T_{in} (K)	h_{in} (kJ/kg)	T_{out} (K)	h_{out} (kJ/kg)	T_{in} (K)	h_{in} (kJ/kg)	T_{out} (K)	h_{out} (kJ/kg)
Heat exchanger A	343.1	292.4	343.1	2,626.0	541.2	546.1	313.1	364.0
Heat exchanger B	343.1	292.4	343.1	2,626.0	480.5	483.3	333.1	363.6
Heat exchanger C	343.1	292.4	343.1	2,628.0	511.2	514.5	333.1	362.2

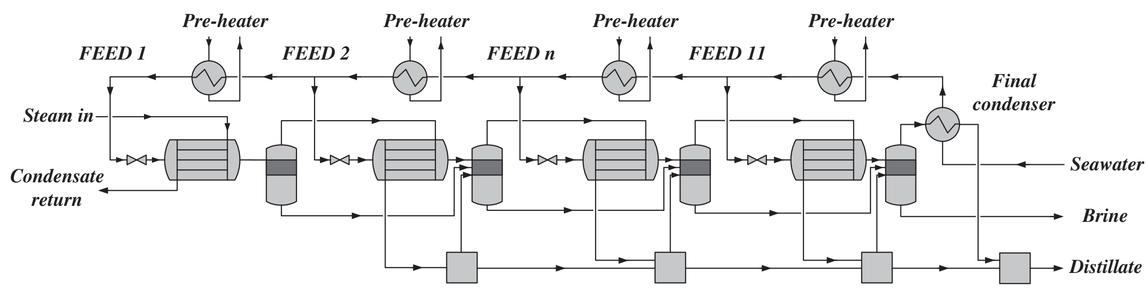

Fig. 7. LT-MED plant layout.

In the case of 11 (eleven) stages, a specific Gain Output Ratio (GOR) is equal to 9.8. The GOR reports the fresh water produced per unit mass of steam (kg_{fw}/kg_{steam}). The saturated dry steam is characterized by the given enthalpy (saturation temperature is 343.1 K). The GOR defines the thermal efficiency required by the LT-MED technology per unit mass of fresh water produced. For example, for a GOR of 9.8 (as it has been widely suggested in literature [20,22]), the energy required is 238.1 kJ. This corresponds to an enthalpy of 2,333 kJ/kg per unit mass of fresh water produced, at the vaporization temperature of 343.1 K.

Data from Table 5 demonstrate that 0.078 kg/s of steam can be produced at the heat exchanger "A", 0.050 kg/s of steam can be produced at the heat exchanger "B" and 0.065 kg/s from heat exchanger "C". Therefore, almost 0.2 kg/s of fully saturated steam can be produced as a result of the thermal recovery from the DEC-based plant whose data are reported in Table 2.

Thus, 0.2 kg/s of steam would be produced in the 11 (eleven) effects of the desalination plant (having a GOR = 9.8) and 1.96 kg/s of fresh water. This result is reached by preheating the stage in each effect. As previously mentioned, the extra heat comes from the air after it has been cooled by the recuperation section.

In order to compare the fresh water production with data presented in literature (for a 50 MW_{el} conventional CSP plant [12,13,19,20,23,24]), the scale up of the DEC plant offers a production rate equal to 22,100 m^3/d, for 24-h continuous plant operation. This result is much greater than that produced by a conventional CSP plant. In reference [13], for a plant producing electrical power close to 50 MW, the fresh water production is equal to 14,300 m^3/d having the same GOR (9.8) considered in this paper and the same thermodynamic conditions of the steam extracted (p_{sat} = 0.31 bar, T_{sat} = 70°C). In reality, in this conventional situation, the steam extracted from the LP turbine (16.91 kg/s) is probably limited by the electricity loss due to the steam extraction. In fact, in this situation, the electrical power of the plant (considering the steam extracted) is 50 MW_{el} while the same power if the extraction doesn't take place would be 51.84 MW_{el}. So an equivalent electrical loss close of 3.5% is due to the steam extraction that otherwise would have been used for electrical production.

In addition to the losses due to the reduced steam entering the turbines for electrical production, the conventional CSP plant also uses electricity directly. Elaborating on this electrical loss in the conventional CSP, the data reported in [13] can be estimated in the range of 1.8% when 1.5 kWh (electric) per m^3 of freshwater is assumed. In fact, for a 50 MW_{el} conventional CSP plant, 14,300 m^3/d of freshwater are produced requiring 21,460 kWh_{el}/d for desalination. In contrast, the DEC-based CSP plant only has a direct electrical loss (2.7% instead of the 3.5% of the conventional plant) which is simply subtracted from the DEC-CSP electricity production. In addition, this represents an additional direct "loss" which will not be the same (in absolute terms) for the two CSP (conventional and DEC-based) because of the different volumes of freshwater production.

When a DEC-based CSP plant is considered, the freshwater produced is greater than a conventional CSP plant having the same output electrical power. This performance is equal to 22,100 m^3/d with a consumption of 33,150 kWh_{el}/d for desalination. Therefore, 2.7% of the electric energy produced by the DEC-based CSP plant would be used for desalination.

In summary, when a LT-MED desalination plant is integrated with a CSP plant:

(1) If it is a conventional plant, then 3.5% of the electrical energy produced is lost due to the steam extraction and 1.8% is lost due to the electricity needs: equating to an overall loss equal to 5.3% of the electricity produced as a result of the desalination plant integration.
(2) If it is DEC-based, the only loss is due to the electricity needs of the desalination and this accounts for 2.7% of the electric energy produced by the plant.

The differences of the electrical efficiency obtained by the DEC justify the scientific attention of the integration of the CSP + D and call for the need of additional studies aimed at further optimizing the overall plant energy integrations.

A further advantage is obtained namely the ratio between freshwater (m^3) and net electricity produced (kWh) is equal to 0.0189 (m^3/kWh), while for a conventional CSP plant, this value is 0.0121 (m^3/kWh). Considering that the two "products" (electricity and freshwater) represent the payloads of the plant, some financial benefits of the DEC-based CSP plant should be expected when cost effective thermal storage solutions are used.

4. Conclusions

This paper has focused on the integration of LT-MED desalination units with PT-CSP plants having a novel design in respect to the conventional ones. They use a new conversion section in which air is considered as working fluid. As previously mentioned, the reference plant cycle is of the Ericsson type where compressions and expansions make use of a sequence of inter-cooled and inter-reheated stages. The role of the concentrated solar energy is to the bring maximum temperature to a fixed value (about 1,050 K) which is done during the reheating stages (between expansions) at maximum pressure. This occurs after a recuperation stage which recovers the heat in the returning air after last expansion to further heat up the hot air after the last compression.

DEC-based PT-CSP plants require two inter-cooling sections for the use of thermal energy to produce saturated dry steam for desalination purpose. Additional heat can be recovered after the recuperation stage. The LT-MED technology has been used considering that thermal energy needs have a temperature requirement which conveniently fits with the thermal sources previously mentioned; compressed air which must be cooled and hot air discharged into atmosphere after recuperation.

Considering an air mass flow rate in the DEC-based plant equal to 1 kg/s (which is according to the present solar receiver technology), the electrical power production is 382.6 kW with a net efficiency of about 0.20, including the receiver thermal efficiency. About 564 kW can be recovered as thermal power, at a 320–550 K temperature range and it is used to produce 2 kg/s of dry saturated steam (at 0.31 bar) which feeds the desalination plant. Also, 1.96 kg/s of fresh water can be produced (GOR = 9.8) from salt water in an 11th stage LT-MED plant.

Applying these results to a DEC-based plant having 50 MW_{el}, 22,100 m^3/d of freshwater can be produced using the waste heat recoverable by the plant. This datum depends on the full recovery of the waste heat inside DEC-based CSP plant. In addition, the electrical needs of the desalination unit, assuming 1.5 kWh_{el}/m^3_{fw}, are, 2.7% of the electrical energy produced by the plant. This represents the only energetic cost of the desalination.

When a conventional CSP plant (using thermal oil as working fluid) is considered and LT-MED is integrated with it (as in the literature is presented), 14,300 m^3/d of fresh water could be produced. This result matches present technology, with the same GOR and the same steam thermodynamic conditions for desalination. In this situation, freshwater production is limited by the constraints on the steam extraction from the LP turbine required to feed the heating needs of the desalination. This thermal (steam) extraction equates to an electrical loss equal to 3.5% of the total electricity production. In this situation, the direct electrical needs of the desalination plant accounts for 1.8% of the electricity produced by the conventional CSP plant.

In conclusion, DEC-based CSP plants appear suitable to be integrated with a desalination LT-MED plant. In the case of a conventional CSP plant, the desalination plant produces a total loss equal to 5.3% of the electricity produced. But this total loss is reduced to 2.7% in the case of DEC-based CSP plant.

Moreover, in the conventional CSP plant, the ratio between fresh water (m^3) and net electricity produced (kWh) is equal to 0.0121 while in the proposed integration in this paper, the same ratio is equal to 0.0189. Freshwater and electricity are the payloads of the plant, so some financial benefits of the DEC-based CSP plant should be expected.

From this point of view, an economic analysis would be needed in order to estimate the cost per kWh produced by a DEC-based CSP plant. A complete estimation is still unavailable but the greater simplicity of the plant proposed (assuming a cost effective thermal storage section) allows to conclude that the cost should be lower.

DEC-based plants could also operate without the recuperation stage. This will require a bigger solar capture section (and the relative cost increase) but would favor a further increase in the freshwater production considering that the energy exchanged inside the recuperate could be used for fulfilling the thermal needs of this additional freshwater. This opens the door to future economic optimization of fresh water and electricity production.

Nomenclature

CSP	—	concentrated solar power
CSP + D	—	desalination unit integrated to CSP plant
D	—	desalination
DEC	—	discrete ericsson cycle
GOR	—	gain output ratio
HP	—	high pressure
HTF	—	heat transfer fluid
LP	—	low pressure
LT-MED	—	low temperature multi effect distillation
MED	—	multi effect distillation
MENA	—	Middle East and North Africa
MP	—	medium pressure
MS	—	molten salts
MSF	—	multi stage flash
MVC	—	mechanical vapor compression
PT	—	parabolic trough
PTC	—	parabolic trough collector
RO	—	reverse osmosis

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