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# Modeling of Solar Polygeneration Plant

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**Abstract.** In this work, a exergoeconomic analysis of the joint production of electricity, fresh water, cooling and process heat for a simulated concentrated solar power (CSP) based on parabolic trough collector (PTC) with thermal energy storage (TES) and backup energy system (BS), a multi-effect distillation (MED) module, a refrigeration absorption module, and process heat module is carried out. Polygeneration plant is simulated in northern Chile in Crucero with a yearly total DNI of 3,389 kWh/m$^2$/year. The methodology includes designing and modeling a polygeneration plant and applying exergoeconomic evaluations and calculating levelized cost. Solar polygeneration plant is simulated hourly, in a typical meteorological year, for different solar multiple and hour of storage. This study reveals that the total exergy cost rate of products (sum of exergy cost rate of electricity, water, cooling and heat process) is an alternative method to optimize a solar polygeneration plant.

## INTRODUCTION

Chile has abundant renewable energy resources, such as, solar, wind, hydro, biomass and geothermal. Also, northern Chile has one of the highest rates of solar radiation in the world [1], where the potential for the development of solar technologies in this region is vast. On the other hand, in this zone is where most of the Chilean mining industries are located. Those industries require a continuous power, water, cold and heat supplies [2], [3]. Additionally, in the last years, solar technologies costs have experienced a significant reduction [4]. Under this scenario, northern Chile has the potential to generate power, fresh water, cold and heat through solar energy, to develop the sector sustainably and competitiveness.

Power, fresh water, cold and heat are feasible to be produces stand-alone system or in a polygeneration system. Polygeneration system is the integration of multiple utility outputs with one or more inputs for better performance. The better performance may again be assessed from different aspects, such as., thermodynamic, economic, enviromental, and social. Solar polygeneration systems have many advantages over stand-alone systems. Its advantages make polygeneration competitive technologies. The main advantages are in terms of energy efficiency, cost effective, alternative fuels and energy carriers, and emissions [5].

Exergoeconomic analysis combines economic and thermodynamic relations by applying the concept of cost (an economic property) to exergy (a thermodynamic property). Exergoeconomic assesses the cost of consumed resources, money and system irreversibilities in terms of the overall production process [5].

Concentrated solar power (CSP) with parabolic trough collector (PTC) has proven to be the most mature and lowest cost solar thermal technology in CSP technologies [6].

Multi-effect distillation (MED) is an efficient method to provide fresh water by desalination. MED is more attractive than multi-stage flash (MSF) because it has lower energy consumption, lower sensitivity to corrosion and scaling, and greater development potential [7]. The integration of CSP and desalination plants has been published in scarce studies [8]–[10].

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Absorption chiller is an important technology to produce industrial cooling [11], [12]. The absorption system uses thermal energy to drive the system. The technology solutions for absorption refrigeration device that are commercially available are mainly single effect cycle and double effect cycle [12]. The integration of solar technologies and absorption plants has been published in scarce studies in trigeneration scheme [13],[14].

Finally, a few studies have been made on exergoeconomic analysis of polygeneration systems with CSP plant but there is not study on exergoeconomic analysis with the current scheme polygeneration.

The solar polygeneration plant consists of a Concentrated solar power (CSP) with parabolic trough collector (PTC) with thermal energy storage (TES) and backup energy system (BS), a multi-effect distillation (MED) plant, a single effect absorption refrigeration system, and a countercurrent heat exchanger as process heat plant.

The aim of the present work is to do a thermoeconomic assessment of polygeneration plant for producing electricity, fresh water, cooling and heat in orden to optimize a solar polygeneration plant.

## MATERIALS AND METHODS

The methodology considers designing and modeling a solar polygeneration plant and applying exergoeconomic evaluations.

### Design and Modeling of a Polygeneration Plant

Solar polygeneration plant is configured according to the operating temperatures constraints imposed by each system, where the MED module has replaced the condenser of CSP plant, the refrigeration module is coupled in the sixth turbine extraction and process heat module is coupled between preheaters (Figure 1). The turbine back pressure is increased from 0.06 bar to 0.37 bar because the MED module must operate within a temperature range of 64 to 74 °C [15]. Additionally, the solar field aperture area is increased from 510,120 $m^2$ to 614,014 $m^2$ (20.4 %) [16] in order to maintain the same gross power. Main parameters of solar polygeneration plant are presented in Table 1.

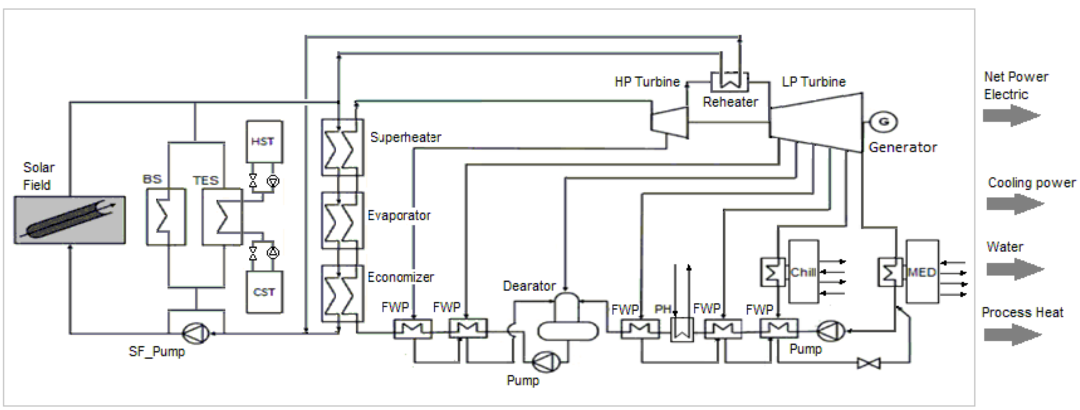



**FIGURE 1.** Polygeneration plant configuration. CSP/TES + MED + Chill + PH.

CSP-PTC plant is modeled considering a typical plant as Andasol 1 [17], [18] with a solar collector field with EuroTrough collector (Skal-et), Schott PRT-70 as absorber tube, thermal fluid Dowtherm A, 614,014 $m^2$ of aperture area, and 393 ºC as design temperature of solar field. The solar multiple (SM) is defined as 2.56. The power conversion unit consists of a regenerative Rankine cycle with reheat and six extractions, as suggested in Blanco-Marigorta et al. [19].

$$SM = \frac{\dot{Q}_{th,solar\ field}}{\dot{Q}_{th,power\ block}}_{design\ point} \quad (1)$$

Where $\dot{Q}_{th,solar\ field}$ is the solar thermal energy produced by the solar field at the design point, in kW, $\dot{Q}_{th,power\ block}$ is the solar thermal energy required by the power block at nominal conditions.

The TES is assumed as two tank indirect and molten salt (60% $NaNO_3$, 40% $KNO_3$) as storage media, and 95% of annual storage efficiency. The TES thermal capacity is defined as 12 hours of full load capacity.

$$TES_{th} = \frac{\dot{W}_{des.gross}}{\eta_{des}} t_{full\ load} \quad (2)$$

Where $TES_{th}$ is the equivalent thermal capacity of the storage tanks, in kWh, $\dot{W}_{des.gross}$ is gross power, in kWh, $\eta_{des}$ is efficiency of Rankine cycle in design point, and $t_{full\ load}$ is the number of hours of thermal energy delivered at the power block's design thermal input level, in hours.

The desalination plant is modeled with 12 effects parallel-cross feed MED plant with 11 feed preheaters, as suggested in Zak et al. [20]. The fresh water production is 37,341 $m^3$/day and 9.1 of gained output ratio (GOR). Main parameters of MED plant are presented in Table 1.

The refrigeration plant is configured with a single-effect LiBr-$H_2O$ absorption chiller, as suggested in Herold et al. [21] with 5 MW of cooling capacity and 0.7 of nominal COP. Main parameters of refrigeration plant are presented in Table 1.

Finally, a counter current heat exchanger is configured for the production of process heat, with 7 MW heating capacity. Main parameters of process heat plant are presented in Table 1.

The CSP-PTC plant is validated from Blanco-Marigorta et.al [19] and Software SAM [17]. The MED plant is validated from Zak et al. [20] and El-Dessouky et al.[22]. Finally, the cooling plant is validated from Herold et al. [21].

**TABLE 1.** Polygeneration plant design.

| TES | Value Unit |
|---|---|
| Type / Storage fluid | 2-tank / Molten Salt (60% $NaNO_3$, 40% $KNO_3$) |
| Tank temperature (cold/hot) / Annual Storage Efficiency | 292 °C / 386 °C / 95% |
| Full load hours of TES | 12 |
| Solar field | Value Unit |
| Parabolic trough collector model / absorber tube | EuroTrough (ET-150) / Schott PRT-70 |
| Solar Field inlet/outlet temperature | 293.0 °C / 393.0 °C |
| Aperture Area / Solar Multiple | 614,014 $m^2$ / 2.56 |
| Power conversion unit | Value Unit |
| Gross power | 55.0 MW |
| HP turbine inlet pressure/temperature | 103.57 bar / 373 °C |
| LP turbine back pressure/temperature | 0.37 bar / 73.9 ºC |
| HP turbine / LP turbine isentropic efficiency | 85.2% / 85.0% |
| Generator /motor / pumps efficiency | 98.0 % / 98% / 70% |
| Multi Effect Desalination | Value Unit |
| Feed seawater intake temperature / salinity | 25.0 °C / 0.042 kg/kg |
| Feed seawater after down condenser temperature | 35.0 °C |
| Maximum salinity in each effect / Top Brine Temperature | 0.072 kg/kg / 65.0 °C |
| GOR / Concentration factor | 9.07 / 1.71 |
| Single stage absorption chiller | Value Unit |
| Cooling capacity | 5.0 MW |
| Chilled water inlet / outlet temperature | 10.0 °C / 6 °C |
| Cooling water inlet/outlet temperature | 25.0 °C / 35.0 °C |
| Inlet temperature desorber / COP | 108.5 °C / 0.70 |
| Process Heat | Value Unit |
| Process heat capacity | 7.0 MW |
| Hex inlet / outlet temperature | 63.0 °C / 90.0 °C |

IPSEpro is used for the modeling and simulations. IPSEpro solves the flowsheet of the process using Newton-Raphson method, linearizing the non-linear equations at starting value. In order to obtain the dynamic system behavior IPSEpro has to be linked to Microsoft Excel. Matlab is used for modeling and simulating of TES behavior and for exergoeconomic assessment.

Polygeneration plant is hourly simulated step by step during a typical meteorological year (TMY). As a result, the hourly, monthly and annual production is obtained. The location considered for this plant is Crucero, in northern Chile, latitude -22.14°, longitude -69.3° and 3389 kW h/$m^2$/year of DNI [1].

For the purpose of analysis, the following assumptions are made: variations of kinetic energy, potential energy, and pressure drops in the lines were disregarded; startup and shutdown are not evaluated; CSP plant and MED plant are a base load station; fixed demand of cooling and process heat.

## Exergoeconomic Evaluations

The exergoeconomic methodology involves applying a thermodynamic, economic and exergoeconomic models [23]. First, aggregation level is selected allowing the delimitation of the boundaries analysis (Figure 2). Then, thermodynamic model is applying where are made mass balances, energy balances and exergy balances.

$$\sum(\dot{Q}\left(1-\frac{T_0}{T}\right))-\dot{W}+\sum(\dot{m}_{in}e_{in})-\sum(\dot{m}_{out}e_{out})-\dot{E}_D=0 \tag{3}$$

Where, $\dot{Q}$ is the thermal heat power, in kW, $T_0$ is the temperature of reference, in K, $\dot{W}$ is exergy rates of work, in kW, $\dot{m}$ is the mass flow, in kg/s, e is the exergy specific in kJ/kg, and $\dot{E}_D$ is the rate of exergy destruction, in kW.

The exergy rates from sun is calculated by

$$\dot{E}_{sun}=A\cdot DNI\cdot(1+\frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4-\frac{4}{3}\left(\frac{T_0}{T_{sun}}\right)) \tag{4}$$

Where A is the solar field aperture area, in $m^2$, $T_0$ is the temperature of reference, in K, and $T_{sun}$ is the sun temperature, taken as 6000 K.

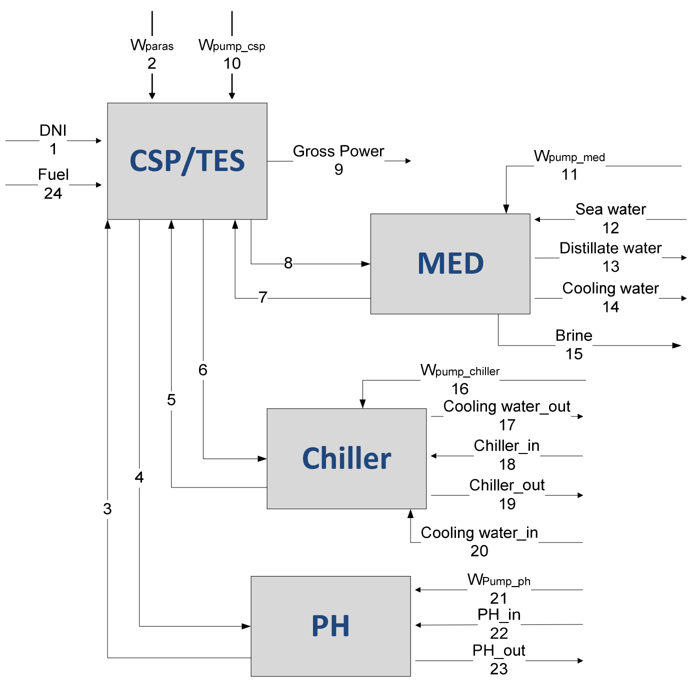



**FIGURE 2.** Aggregation level for exergoeconomic assessment in polygeneration plant.

By exergy balance costs are obtained the exergy unit cost $c_j$ and the exergy cost rate $\dot{C}_j$ for each stream and product, such as, exergy unit cost of electricity, in USD/kWh, exergy unit cost of water, in USD/kWh or USD/$m^3$, exergy unit cost of cooling, in USD/kWh, and exergy unit cost of heat, in USD/kWh.

$$\sum_{j=1}^{n}(c_j\dot{E}_j)_{k,in}+\dot{Z}_k^{CI}+\dot{Z}_k^{OM}=\sum_{j=1}^{m}(c_j\dot{E}_j)_{k,out} \tag{5}$$

$$\dot{C}_j = c_j \dot{E}_j = c_j(\dot{m}_j e_j) \quad (6)$$

Where, $c_j$ is the exergy unit cost, in USD/kWh, $\dot{C}_j$ is the exergy cost rate in USD/h, $\dot{E}$ is the exergy rate, in kW, $\dot{Z}_k^{CI}$ is the non-exergy-related cost rate associated with an investment cost, in USD/h, $\dot{Z}_k^{OM}$ is the non-exergy-related cost rate associated with an operation and maintenance cost, in USD/h.

Exergetic analysis considered reference temperature 25°C, reference atmospheric pressure 1.013 bar, and reference mass fraction LiBr 0.5542 kg/kg.

Investment cost MUSD (capex) and operating and maintenance cost MUSD/year (opex) considered are: 397.3 and 17.8 in CSP [6], [17], [4], [9], 59.5 and 1.8 in MED plant [7], [22], [24]–[26], 2.7 and 0.006 in Refrigeration plant [11], [27], and finally 0.3 and 0.0006 in process heat plant [28]. The fossil cost fuel is 0.0324 USD/kWh [29]. It has been considered a horizon of 25 years and a discount rate of 10%.

## Levelized Cost Calculated

The levelized cost is the total cost of installing and operating expressed in USD per unit of product generated by the system over its life. The levelized cost of each product is calculated, such as, levelized electricity cost (LEC), in USD/kWh, levelized water cost (LWC), in USD/m$^3$, levelized cooling cost (LCC), in USD/kWh, and levelized process heat cost (LCH), in USD/kWh. It is compared the total cost rate with the levelized cost.

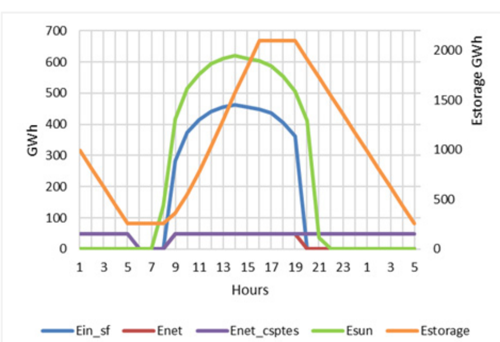
$$LC = \sum_{j=0}^{n} \frac{capex_j \cdot crf + opex_j + C_{fuel\,j}}{(1+i)^j} / (Annual\ Production_j) \quad (7)$$

Where LC is the levelized cost, in USD/kWh or USD/m$^3$, capex is the capital expenditure, in USD, opex is the operational expenditure or operation and maintenance cost, in USD/year, crf is the capital recovery factor, $C_{fuel}$ is the fuel cost (such as, fossil fuel, electricity, steam, other), in USD/year, i is the discount rate, in %, n is the number of time periods, in years, the Annual Production is the annual production of: electricity, in kWh, or water, in m$^3$, or cooling, in kWh, or process heat, in kWh, for LEC, LWC, LCC and LHC respectively.

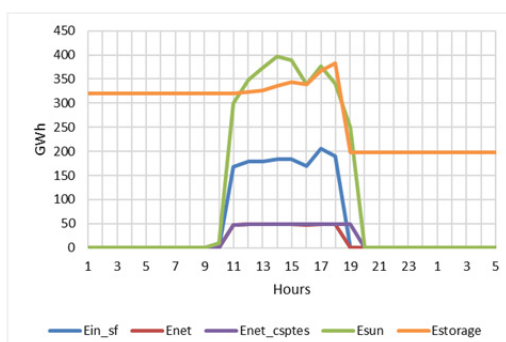
# RESULTS AND DISCUSSION

## Productions and Costs in Base Case

Hourly production is analyzed on a clear day on December 21 (Figure 3a) and on a partial day on June 19 (Figure 3b). In a clear day, energy collected by the solar collectors allows producing electricity at full load and charge the thermal energy storage (TES). In a partial day, energy collected by the solar collectors is not enough to operate at full load during the day but from TES or BS is possible to operate at full load or part load. The graph does not show the BS contribution.



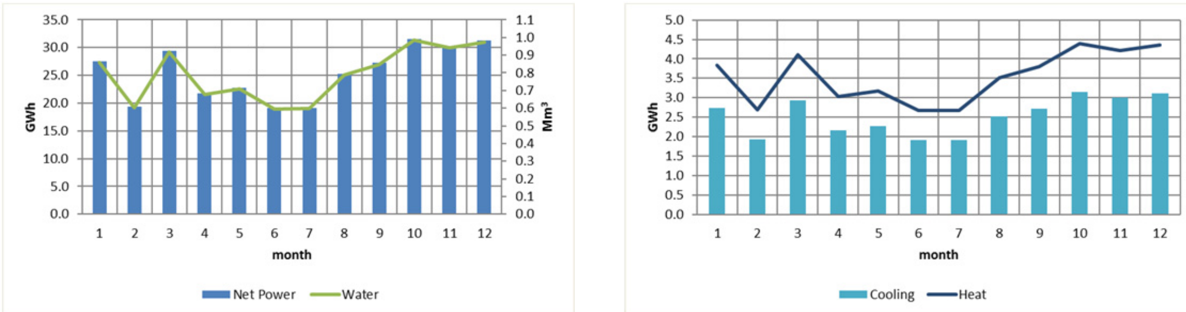

(a)




(b)

**FIGURE 3.** Production for base case: a) clear day, b) partial day. Ein_sf: Energy in SF, Enet: Energy net without TES, Enet_csptes: Energy net with TES, Esun: Energy from sun, Estorage: Energy storage.

In Figure 4 the monthly production for base case is presented. The capacity factor is 96% and the sun contributed with 71.6%.




(a) (b)

**FIGURE 4.** Monthly production a) net power and water; b) cooling and heat.

The annual productions in base case are: 463.1 GWh/year of gross power, 408.2 GWh/year of net power, 13.2 $Mm^3$/year of fresh water, 42.0 GWh/year of cooling, and 58.9 GWh/year of process heat.

The total exergy cost rate of products is 8,988.4 USD/h and the exergy unit costs are: 0.1056 USD/kWh, 1. 795 USD/$m^3$ (2.725 USD/$m^3$ considering pumping sea water for 70 km), 0.036 USD/kWh, and 0.024 USD/kWh of electricity, fresh water, cooling and process heat respectively. On the other hand, the levelized cost are: 0.140 USD/kWh, 0.8478 USD/$m^3$, 0.0078 USD/kWh and 0.00056 USD/kWh for LEC, LWC, LCC and LHC respectively. The difference in value between levelized cost and exergy unit cost is due to the form of cost allocation. Exergoeconomic uses the exergy as criteria to allocate the costs, then it is a rational cost allocations.

## Costs in Function of SM and Hours of TES

In figure 5 the minimum total exergy cost rate of products is presented. Results show that the minimum total exergy cost rate of product is 8,723 USD/h with a SM of 1.8 and a TES of 6 h. There is a difference of 2.9% between the base case and optimal configuration. However, there is relatively little difference between other configurations of SM and TES.

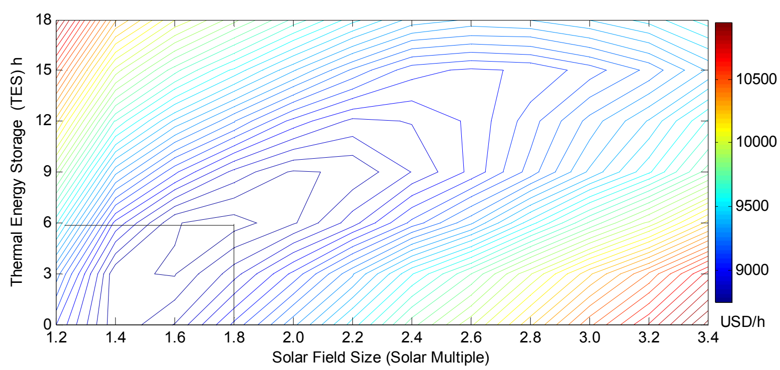



**FIGURE 5.** Total exergy cost rate of products USD/h in function of solar multiple (SM) and hours (h) of TES.

Regarding exergy unit costs, in Figures 6, the minimum exergy unit cost is presented. The minimum exergy unit costs are: 0.1021 USD/kWh, 1.756 USD/$m^3$, 0.035 USD/kWh and 0.023 USD/kWh of electricity, water, cooling and heat respectively.

(a)

(b)

(c)

(d)

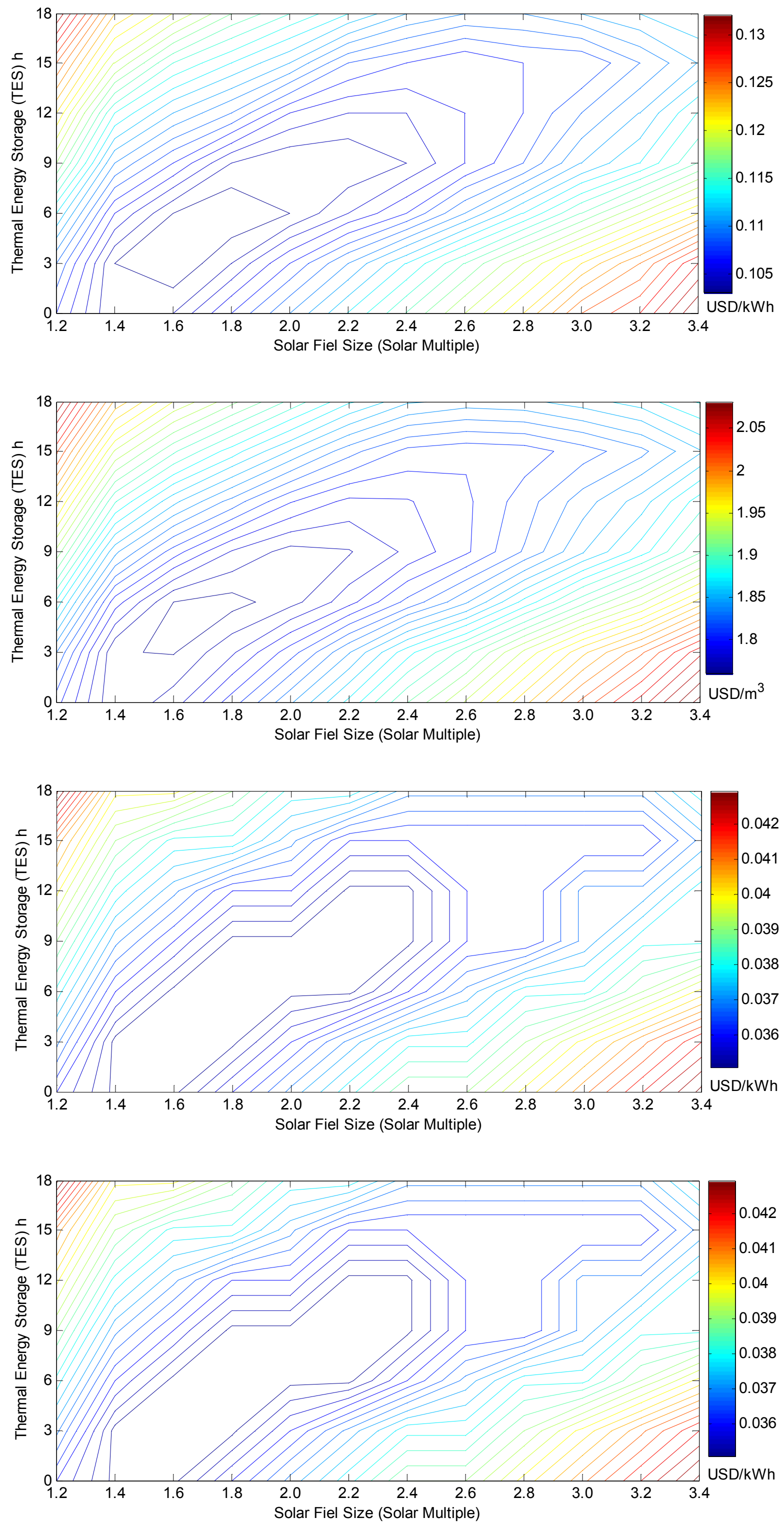



**FIGURE 6.** Exergy unit cost of a) electricity, b) water. c) cooling, d) heat.

In relation to levelized cost, the minimum levelized costs are: 0.140 USD/kWh, 0.8478 USD/$m^3$, 0.0078 USD/kWh and 0.00056 USD/kWh for LEC, LWC, LCC and LHC respectively (Figure 7). The difference in value between levelized cost and exergy unit cost is due to the form of cost allocation. In this case is not possible to sum different kind of products such as, electricity and water, because they have different units.

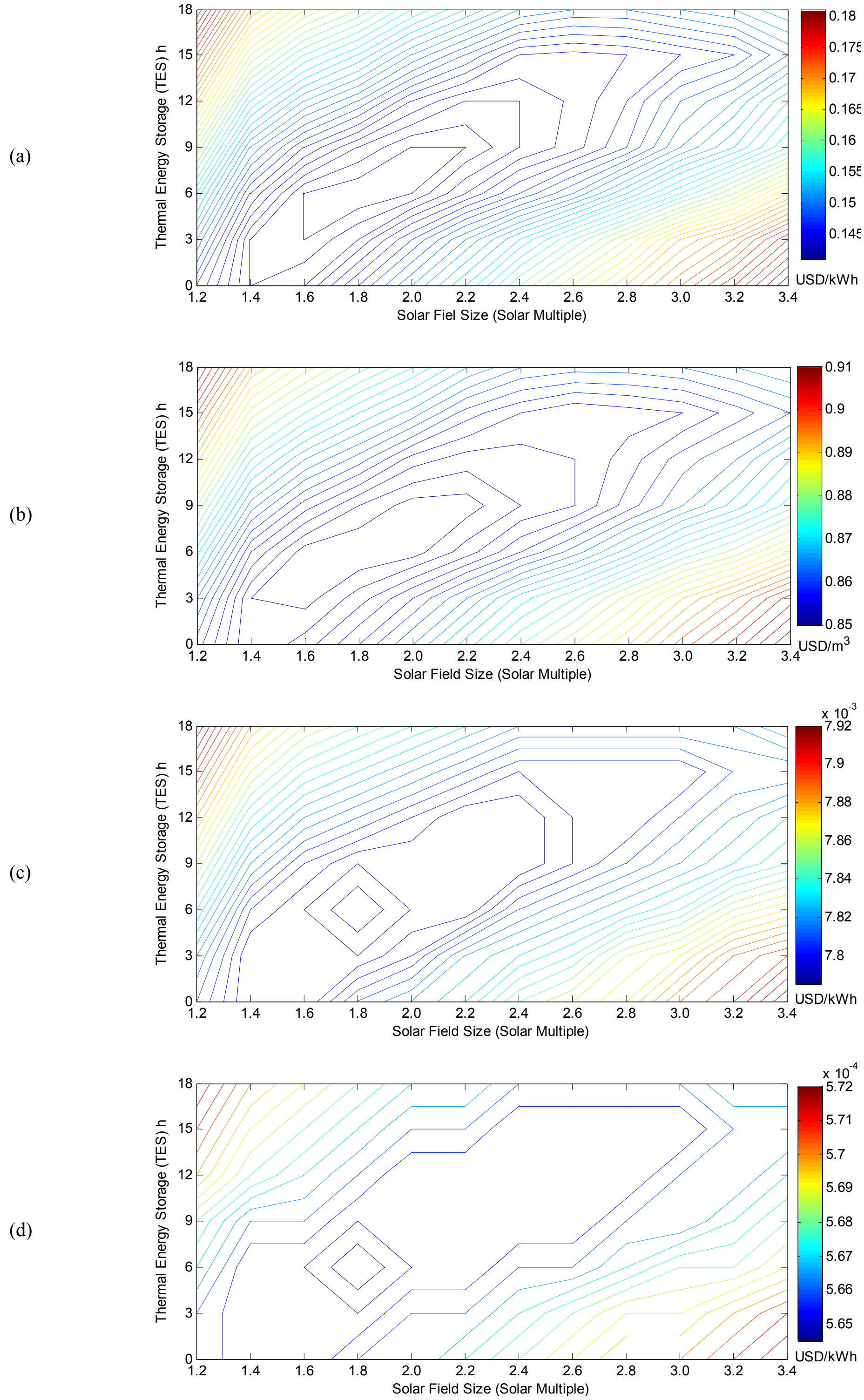



**FIGURE 7.** Levelized cost of a) electricity (LEC), b) water (LWC). c) cooling (LCC), d) heat (LHC).

An optimal solar field area should maximize the amount of time in a year that the field generates enough thermal energy to drive the power unit block at its rated capacity, minimize installation and operating costs, use TES and BS efficiently and cost effectively. The problem of choosing an optimal solar field area and storage capacity involves analyzing the tradeoff between a larger solar field and storage capacity that maximizes the system's electrical output and project revenue, and a smaller field and storage capacity that minimizes installation and operating costs [18]. That results in the lowest LEC. The LEC is a useful metric for optimizing the solar field size and storage capacity because it includes the amount of electricity generated by the system, the project installation costs, and the cost of operating and maintaining the system over its life. Thus, in CSP plant the criterion for selecting the optimal size of the plant is the minimum LEC [30], but in solar polygeneration plant is more interesting to use the minimum total exergy cost rate of products because exergoeconomic uses the exergy as criteria to allocate the costs, then it is a rational cost allocations. Also, total exergy cost rate of products includes exergy costs rate of fuels and non-exergy-related costs rate. Additionally, exergy cost rate of products allows sum different kind of products, such as, electricity, fresh water, cooling and process heat.

## CONCLUSIONS

The achievements of this work is the modeling of a solar polygeneration plant integrating a CSP/TES-PTC plant, a MED module, a simple effect absorption cooling module, and a heat exchanger module, simulated hourly during a year, and performed by an exergoeconomic analysis.

The exergy unit costs are: 0.1056 USD/kWh, 1.795 USD/$m^3$, 0.036 USD/kWh, and 0.024 USD/kWh of electricity, fresh water, cooling and process heat respectively, but the minimum levelized costs are: 0.140 USD/kWh, 0.8478 USD/$m^3$, 0.0078 USD/kWh and 0.00056 USD/kWh for LEC, LWC, LCC and LHC respectively. The differences in value between exergy unit costs and levelized costs are due to the form of cost allocation. Exergoeconomic method uses the exergy as criterion to allocate the costs and allows to perform an assessment considering the conversion efficiencies and economic benefits offered by the system. Hence, in the case of solar polygeneration plant is better to use exergoeconomic method.

The minimum total exergy cost rate of product is 8,723 USD/h with a SM of 1.8 and a TES of 6 h. The total exergy cost rate of products (sum of exergy cost rate of: electricity, water, cooling and heat) allows using only one parameter to get the minimum total exergy cost rate. At difference of levelized cost where it is not possible to sum LWC USD/$m^3$ with LEC, LCC and LHC USD/kWh.

As a prospective action should be done an exergoeconomic assessment with low aggregation level in CSP plant. The CSP plant at aggregation level of individual components, such as turbine, pump, solar field, and others.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

A : aperture area, $m^2$
capex : capital expenditure, USD
cf : fuel cost, USD/year
$\dot{C}_j$ : exergy cost rate, USD/h
$\dot{C}_{D,k}$ : exergy destruction cost rate, USD/h
$\dot{C}_{L,k}$ : exergy loss cost rate, USD/h
$\dot{C}_{F,k}$ : exergy fuel cost rate, USD/h
$\dot{C}_{P,k}$ : exergy product cost rate, USD/h
$c_j$ : exergetic unit cost, USD/kWh
cfr: capital recovery factor, %
COP: Coefficient of performance, -
D: exergy destruction, kWh
DNI: direct normal irradiance, $W/m^2$
e : exergy specified, kJ/kg
$\dot{E}$ : time rate of exergy or exergy rate, kJ/s
$\dot{E}_{heat}$ : time rate of exergy heat process, kJ/s
$\dot{E}_{sun}$ : time rate of exergy from sun, kJ/s
$\dot{E}_D$ : time rate of exergy destruction rate, kJ/s
$\dot{E}_{D,k}$ : time rate of exergy destruction rate of element k, kJ/s
$\dot{E}_{L,k}$ : time rate of exergy loss rate, kJ/s
$\dot{E}_{F,k}$ : time rate of exergy fuel rate, kJ/s
$\dot{E}_{P,k}$ : time rate of exergy product rate, kJ/s
i: discount rate, %
$f_k$ : exergoeconomic factor, %
GOR: gained output ratio, -
LCC : levelized cooling cost, USD/kWh
LEC : levelized electricity cost, USD/kWh
LHC : levelized process heat cost, USD/kWh
LWC : levelized water cost, $USD/m^3$
$\dot{m}$ : flow rate, kg/s
n: number of time periods, years
opex : operational expenditure or operation and maintenance cost, USD/year
$\dot{Q}_{th,power\ block}$ : thermal power demanded by the power block, W
$\dot{Q}_{th,solar\ field}$ : thermal power produced in the solar field, W
$r_k$ : relative cost difference, %
SM : solar multiple, -
T : temperature, °C
$T_0$ : ambient temperature, °C
TBT: top brine temperature, °C
$t_{full\ load}$ : hours of full-load hours of TES, h
$w_{des,gross}$ : power cycle thermal in design-point , kW
$y_{D,k}$ : exergy destruction ratio
$\dot{Z}_k^{CI}$ : capital investment cost rates, USD/h
$\dot{Z}_k^{OM}$ : operating and maintenance cost rates, USD/h

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