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Exergoeconomic Assessment of a Solar Polygeneration Plant

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Abstract

This paper shows the results of an exergoeconomic assessment of a solar polygeneration plant. Solar polygeneration plant consists of a concentrated solar power (CSP) type parabolic trough, a multi-effect desalination MED module, a refrigeration absorption module, and process heat module, in order to produce electricity, desalinated water, cooling and process heat respectively.

A solar polygeneration plant is justified due to the high demand for the products produced, where a CSP plant produces high residual heat (waste heat) that is possible to leverage through polygeneration.

The methodology allows coupling thermodynamic equations and economic relations in order to solve complex systems. Polygeneration plant was evaluated to be installed in Crucero, in northern Chile where the direct normal irradiance reaches values of 3,389 kW h/m^2/year.

The results indicate that the polygeneration plant has an energy efficiency of 62.8%, an exergy efficiency of 24.5%, products cost rate of 10,713.2 USD / h and a net present value (NPV) of 4.3 MUSD.

Keywords: *CSP, MED, CHP, cooling, polygeneration, exergoecononomic, thermoeconomic.*

1. Introduction

Concentrated solar power (CSP) produces electricity, but it can also be coupled with other technologies in a polygeneration scheme to produce other products, such as desalination water, industrial cooling and process heat (Serra et al., 2009), especially where those products are in short supply and when there is high solar irradiation. The combined production of products by polygeneration scheme permits to increase the thermodynamic efficiency of the consumed resources. Polygeneration can transform waste heat into useful heat to drive other processes. Exergoeconomic analysis combines both economic and thermodynamic analysis (1st and 2nd law of thermodynamics) by applying the concept of cost that is an economic property, and the concept of exergy that is a thermodynamic property. The main objectives of exergoeconomic analysis are: to identify the location, magnitude and sources of exergy destruction and losses in an energy system; to calculate the cost associated with these losses; to assess the production costs of each product in the energy conversion system, which has more than one output; to facilitate feasibility and optimization studies for energy system; to assist in decision-making procedures concerning plant operation and maintenance; and to compare technical alternatives (Tsatsaronis, 1993).

Concentrated solar power (CSP) technologies can be parabolic trough collector (PTC), central receiver (CR), linear fresnel (LF) or dish-Stirling (DS). CSP-PTC has proven to be the most mature and lowest cost solar thermal technology (IRENA, 2012). Multi-effect distillation (MED), multi-stage flash (MSF) and reverse osmosis (RO) represent the most reliable, commercially proven and efficient methods to provide fresh water by desalination, and can be coupled with the CSP plant (Palenzuela et al, 2011; Cipollina et al, 2009). Absorption and vapor compression are the most important technologies to produce industrial cooling (Infante

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and Kim, 2013; Hassan et al, 2012). Solar absorption systems utilize the thermal energy from solar collector to separate a refrigerant from the refrigerant/absorbent mixture. Solar absorption systems have been published in some studies (Sarbu and Sebarchievici, 2013; Ullah et al., 2013). Industrial process heat is used in different industrial processes. The thermal energy demand is below 300 °C (Fernández-García et al., 2010).

Finally, exergoeconomic analysis of polygeneration systems with fossil fuel as main energy source has been published in some studies. 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.

This work shows the results by using a model to simulate a polygeneration plant, which consists of a CSP-PTC, a MED desalination plant, a single effect LiBr/H2O absorption refrigeration plant, and a process heat plant for the production of four products: electricity, desalination water, industrial cooling and process heat.

2. Work description

2.1. Objectives and methodology

The objective of the present study is to evaluate exergoecomically a solar polygeneration plant producing power, desalinated water, industrial cooling and process heat. Figure 1 shows the polygeneration plant studied.

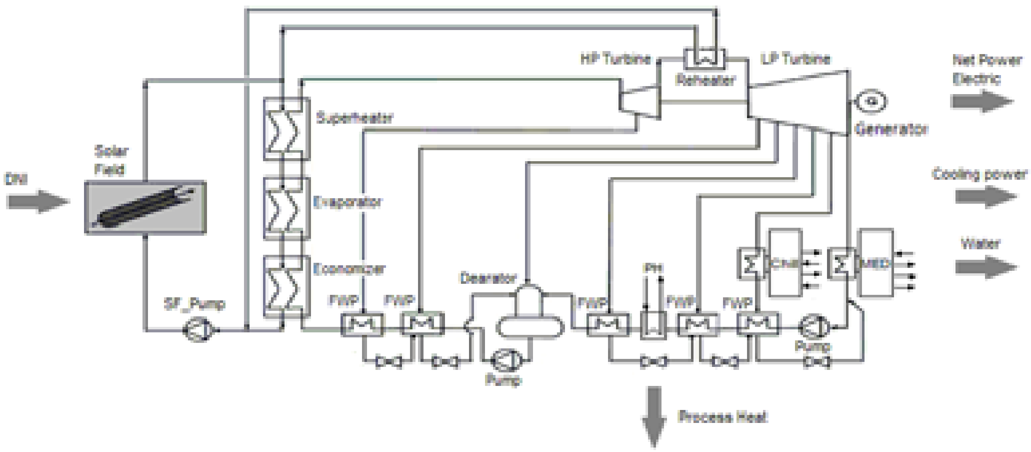

Fig. 1: Configuring solar polygeneration plant.

The methodology followed is presented in Figure 2. First, from preliminary design and modeling of CSP-PTC plant, multi-effect distillation (MED), absorption refrigeration plant, and a heat exchanger, different coupling points are evaluated to select the most appropriate in technical terms. After that, aggregation level is selected allowing the delimitation of the boundaries analysis (Figure 3). Then, a physical structure and productive structure is obtained and the fuels and products are determined. Subsequently, different models are defined: thermodynamic model (1st and 2nd law of thermodynamics), economic model (determination of investment costs, operation and maintenance), exergoeconomic model (Bejan et al, 1996) (determination exergetic unit cost USD/kWh, fuel cost rate, product cost rate, destruction cost rate, total cost rate USD/h, and exergoeconomic factors) and financial model. Finally, the system is solved.

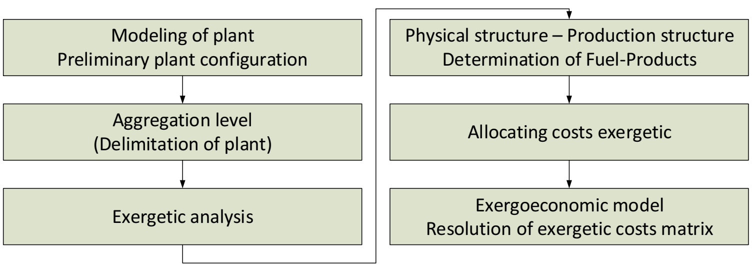

Fig. 2: Methodology.

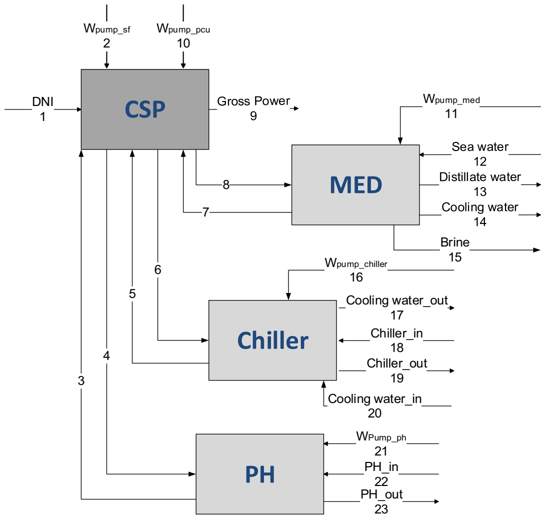

Fig. 3: Aggregation level for exergoeconomic assessment in polygeneration plant.

IPSEpro was used for the modeling and simulations of the system. This software allows to elaborate the flowsheet of a process using the components available in libraries or created by user. It then solves the flowsheet using Newton-Raphson method, linearizing the non-linear equations at starting value. Matlab and EES (equation engineering solver) were used to obtain characteristic parameters in each plant and to exergoeconomics assessment.

The polygeneration plant was evaluated to be installed in northern Chile, Crucero, latitude -22.14°, longitude -69.3°, DNI 3,389 kWh/m^2/year (Escobar et al, 2015).

2.2. Design problem.

Preliminary design and model plants were done separately and subsequently coupled so as to operate in a scheme polygeneration. The CSP-PTC plant is configured with a solar collector field with Skal-et, thermal fluid Dowtherm A and a power block of 55 MW of gross capacity. The power conversion unit consists of a regenerative Rankine cycle with reheat and five extractions. The CSP plant was modeled without thermal energy storage and without backup system. The desalination plant was modeled with 12 effects parallel-cross feed MED plant with 11 feed preheaters. The refrigeration plant was configured with a single-effect LiBr-H_2O absorption chiller with 5 MW of power cooling. As a final point, a heat exchanger was configured for the production of process heat, with 7 MW power heating.

Each plant was validated separately. There is no information about plants operating under this polygeneration scheme. The CSP-PTC plant was validated from Blanco et al. (2011), the MED plant was validated from Zak et al. (2012), and the refrigeration plant was validated from Herold et al. (1996).

2.2.1. Coupling of technologies.

Several coupling points were evaluated between CSP plant and other plants. The most appropriate point of coupling was selected (Figure 1) according to the technical constraints imposed by each system.

MED plant was coupled with CSP plant condenser. In the chosen configuration it was not possible to regulate the amount of water produced. Given that MED plant must operate within a temperature range of 64 to 74 °C (Al-Karaghouli et al, 2013), it was necessary to increase LP turbine backup pressure from 0.06 bar to 0.37 bar (see Table 1). Therefore, electric power was reduced to increase this pressure.

The solar field aperture area must increase to maintain electrical power, but it will increase investment cost and LEC. Polygeneration plant should increase solar field aperture area from 294.534 m^2 to 356,063.7 m^2 equivalent to increase aperture area in 20.9 %.

Desorber of the absorption refrigeration plant required operating temperature within 80 to 110°C (Srikhirin et al, 2001). Absorption refrigeration plant is coupled to the LP turbine 5th extraction where temperature is 108.3°C (see table 1).

Main parameters of polygeneration plant are presented in Table 1.

Tab.1: Polygeneration plant design.

Solar field	Value Unit
Irradiance at design day, SM=1.4	1010.0 W/m^2
Solar Field inlet/outlet temperature	293.0 °C / 393.0 °C
Collector efficiency	0.68
Aperture area	356,063.70 m^2
Power conversion unit	Value Unit
Gross power production	55.55 MW
HP turbine inlet pressure/temperature	103.57 bar / 373 °C
HP turbine extraction pressure/temperature	30.6 bar / 234.9 ºC
LP turbine 1st extraction pressure/temperature	12.77 bar / 341.6 ºC
LP turbine 2nd extraction pressure/temperature	6.18 bar / 259.6 ºC
LP turbine 3rd extraction pressure/temperature	5.99 bar / 256.2 ºC
LP turbine 4th extraction pressure/temperature	2.63 bar / 175.9 ºC
LP turbine 5th extraction pressure/temperature	1.17 bar / 108.3 ºC
LP turbine back pressure/temperature	0.37 bar / 73.9 ºC
HP turbine / LP turbine isentropic efficiency	85.2% / 85.0%
Generator and Motor mechanical and electrical efficiency	98.0 %
Pumps isentropic efficiency	70.0 %
Multi Effect Desalination	Value Unit
Feed seawater intake temperature	25.0 °C
Feed seawater intake salinity	0.042 kg/kg
Feed seawater after down condenser temperature	35.0 °C
Maximum salinity in each effect	0.072 kg/kg
Top Brine Temperature (TBT)	65.0 °C
GOR	9.07
Fresh water production	37,341 m^3/day
Concentration factor	1.71
Single stage absorption chiller	Value Unit
Cooling power	5.0 MW
Chilled water inlet / outlet temperature	10.0 °C / 6 °C
Cooling water inlet temperature (absorber)	25.0 °C
Cooling water outlet temperature (condenser)	35.0 °C
Inlet temperature desorber	108.5 °C
COP	0.70
Process Heat	Value Unit
Heating power	7.0 MW
Hex inlet / outlet temperature	63.0 °C / 90.0 °C

2.2.2. Decision variables.

Decision variables used are: LP turbine back pressure, LP turbine 5th extraction pressure, isentropic efficiency of turbine and of pump. LP turbine back pressure varies between 0.28 to 0.40 bar, it influences the inlet temperature to the first effect of the multi-effect desalination module. LP turbine 5th extraction pressure varies between 1.00 to 1.30 bar, it influences the desorber inlet temperature of the cooling system. Isentropic efficiency varies between 80% to 90% in turbine and between 65% to 75% in pump.

2.2.3. Exergoeconomic and economic parameters.

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: 241.13 and 4.0580 in CSP (IRENA, 2012; NREL, 2013), 22.85 and 1.2587 in MED plant (Li et al., 2013; Verdier et al., 2011; Trieb eta al., 2009; Trieb et al., 2008; IEA-ETSAP and IRENA, 2012), 3.15 and 0.0069 in Refrigeration plant (Mokhtara et al., 2010; Lazzarin, 2013; Misra et al., 2003, Infante and Kim, 2013.), and finally 0.197 and 0.0004 in process heat plant (Turton, 2012). It has been considered a horizon of 25 years and a discount rate of 10%.

For financial evaluation, sales prices of each product were considered: electric energy 0.12 USD/kWh (CNE, 2015), electric power: 9.5 USD/kW/month (CNE, 2015), desalinated water: 3.5 USD/m^3 (Wood Mackenzi, 2014), cooling: 0.1 USD/kWh (CDEC-SING, 2014; Demir et al, 2008), process heat: 0.08 USD/kWh (CDEC-SING, 2014; Kecebas et al, 2013). Chile has an imposition rate on the utility of 21% (SII, 2015). A constant depreciation over the plant lifetime is chosen here.

In the model, variations of kinetic energy, potential energy, and pressure drops in the lines were disregarded.

2.3. Models developed.

The exergoeconomic assessment involves applying a thermodynamic model where are made mass balances (eq. 1), energy balances (eq. 2) and exergy balances (eq. 3). For determining the exergy specified (eq. 4) the potential and kinetic exergy were disregarded. It is calculated the different kind rates of exergy, such as, exergy work rates (eq. 5), exergy process heat rates (eq. 6), exergy physical rates (eq. 7), exergy chemical rates (eq. 8), and exergy rates from sun (eq. 9). Thereby thermodynamic properties and rates of exergy in each stream are determined.

$$\sum(\dot{m}_{in} - \dot{m}_{out}) = 0 \quad \text{(eq. 1)}$$

$$\sum(\dot{m}_{in} h_{in}) - \sum(\dot{m}_{out} h_{out}) - \dot{W} + \dot{Q} = 0 \quad \text{(eq. 2)}$$

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

$$e = e_{ph} + e_{ch} + e_p + e_k \quad \text{(eq. 4)}$$

$$\dot{E}_{work} = \dot{W} \quad \text{(eq. 5)}$$

$$\dot{E}_{heat} = \left(1 - \frac{T_0}{T}\right)\dot{Q} \quad \text{(eq. 6)}$$

$$\dot{E}_{ph} = \dot{m} e_{ph} = \dot{m}((h - h_0) - T_0(s - s_0)) \quad \text{(eq. 7)}$$

$$\dot{E}_{ch} = \dot{m} e_{ch} = \dot{m}\left(-\Delta G + \left(\sum_p n e_{ch} - \sum_R n e_{ch}\right)\right) \quad \text{(eq. 8)}$$

$$\dot{E}_{sun} = A \cdot DNI \cdot (1 + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T_{sun}}\right)) \quad \text{(eq. 9)}$$

Additionally, It is calculated the energy efficiency in power plant (eq. 10), coefficient of performance (COP) in Single stage absorption chiller (eq. 11), energy efficiency in process heat (eq. 12), energy efficiency in MED (eq. 13), utilization factor of polygeneration plant (eq. 14), gained output ratio (GOR) in MED (eq. 15), exergy efficiency (eq. 16), and solar multiple (SM) (eq. 17).

$$\eta_{CSP} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \quad \text{(eq. 10)}$$

$$\eta_{PH} = \frac{\dot{Q}_{out}}{\dot{Q}_{in} + \dot{W}_{pump}} \quad \text{(eq. 11)}$$

$$COP_{abs} = \frac{\dot{Q}_{chiller}}{\dot{Q}_{desorb} + \dot{W}_{pumps}} \quad \text{(eq. 12)}$$

$$\eta_{MED} = \frac{\dot{m}_{distillate} h_{distillate}}{\dot{Q}_{in\_med} + \dot{W}_{pumps}} \quad \text{(eq. 13)}$$

$$\eta_{polygeneration} = \frac{\dot{W}_{net} + \dot{m}_{distillate} h_{distillate} + \dot{Q}_{chiller} + \dot{Q}_{out}}{\dot{Q}_{in}} \quad \text{(eq. 14)}$$

$$GOR = \frac{\dot{m}_{distillate}}{\dot{m}_{steam\ 1st\ effect}} \quad \text{(eq. 15)}$$

$$\varepsilon = \frac{\dot{E}_{out}}{\dot{E}_{in}} = 1 - \frac{\dot{E}_D}{\dot{E}_{in}} \quad \text{(eq. 16)}$$

$$SM = \frac{\dot{Q}_{th,solar\ field}}{Q_{th,power\ block}}_{design\ point} \quad \text{(eq. 17)}$$

The economic model is then applied. This is quantifying the capital investment cost rates (eq. 18), the operating and maintenance cost rates (eq. 19), and the total cost rates (eq. 20).

$$\dot{Z}_k^{CI} = \frac{CC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad \text{(eq. 18)}$$

$$\dot{Z}_k^{OM} = \frac{OMC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad \text{(eq. 19)}$$

$$\dot{Z} = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \quad \text{(eq. 20)}$$

Later it is developed the exergoeconomic model. By exergy balance costs (eq. 21) it is obtained exergy cost unitary c_j and exergy cost rate $\dot{C}_j$ (eq. 22) for each stream.

$$\sum_{j=1}^{n} (c_j \dot{E}_j)_{k,in} + \dot{Z}_k^{CI} + \dot{Z}_k^{OM} = \sum_{j=1}^{m} (c_j \dot{E}_j)_{k,out} \quad \text{(eq. 21)}$$

$$\dot{C}_j = c_j \dot{E}_j = c_j (\dot{m}_j e_j) \quad \text{(eq. 22)}$$

With these results it is calculated the exergy destruction cost rate (eq. 23), exergy destruction ratio (eq. 24), relative cost difference (eq. 25), and exergoeconomic factor (eq. 26).

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \quad \text{(eq. 23)}$$

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \quad \text{(eq. 24)}$$

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{c_{F,k}(\dot{E}_{D,k} + \dot{E}_{L,k}) + (\dot{Z}_k^{CI} + \dot{Z}_k^{OM})}{c_{F,k} \dot{E}_{P,k}} \quad \text{(eq. 25)}$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}(\dot{E}_{D,k} + \dot{E}_{L,k})} \quad \text{(eq. 26)}$$

For evaluating economic, it is calculated the levelized cost (eq. 27) of energy (LEC), of water (LWC), of cooling (LCC), and process heat (LHC). crf is the capital recovery factor (eq. 28).

$$LC = \sum_{j=0}^{n} \frac{capex_j crf + opex_j + Cf_j}{(1+i)^j} / (Annual\ Production_j) \quad \text{(eq. 27)}$$

$$crf = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \text{(eq. 28)}$$

Finally, it is calculated the net present value (NPV) (eq. 29) and internal rate of return (IRR) (eq. 30).

$$NPV = \sum_{j=0}^{n} \frac{Cash\_in_j - Cash\_out_j}{(1+i)^j} \quad \text{(eq. 29)}$$

$$0 = \sum_{j=0}^{n} \frac{Cash\_in_j - Cash\_out_j}{(1+IRR)^j} \quad \text{(eq. 30)}$$

3. Results and discussion.

3.1. Monthly production, production in clear day and production in partial day.

Polygeneration plant receives 968.6 GWh/year from the sun, of which 666.03 GWh/year are transferred to the power conversion unit. Consequently, gross electric energy produced is 186.9 GWh/year, net electrical energy is 179.5 GWh/year, water produced is 5.32 Mm^3/year, power cooling is 16.9 GWh/year and power heating is 23.7 GWh/year. Average monthly net electrical energy is 14.9 GWh/month, water is 0.44 Mm^3/month, power cooling is 1.41 GWh/month, and power heating is 1.97 GWh/month (Figure 4).

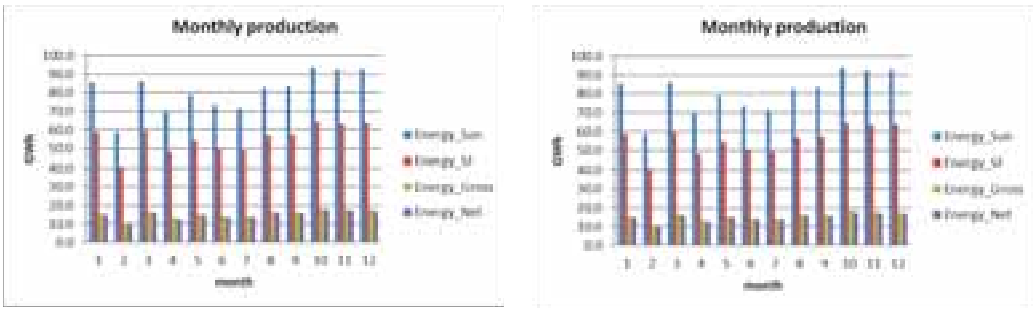

Fig. 4: Monthly production of: a- energy sun, energy solar field (SF), energy_gross (electricity), energy_net (electricity). b- energy_net (electricity), energy_ cooling, energy process heat (ph) and water volume.

In Figure 5 the monthly exergy destruction is presented. Average monthly exergy destruction is 50.7 GWh/month for polygeneration plant, 47.1 GWh/month in CSP plant, 3.2 GWh/month in MED plant, 0.3 GWh/month in cooling plan, and 0.1 GWh/month in heating plant.

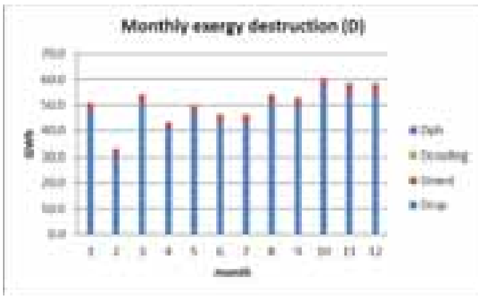

Fig. 5: Monthly exergy destruction in CSP plant, MED plant, Cooling plant and Process Heat plant (ph).

Production was analyzed on a clear day on December 21 (Figure 6a) and on a partial day on June 19 (Figure 6b). Some collectors in the solar field must be out of focus (partial defocusing) on clear day from 10:00 to 18:00 to maintain maximum production of plant design. Thermal energy storage could return this extra energy to power conversion unit.

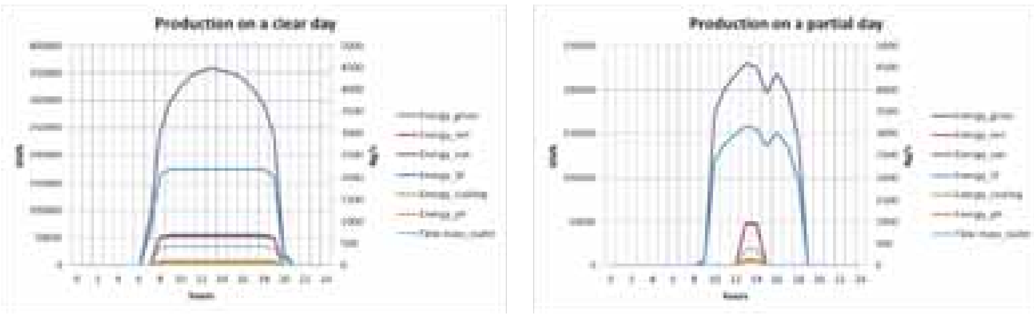

Fig. 6: Production on a: a- clear day, b- partial day.

In a partial day, such as in Figure 6b, energy collected by the solar collectors is insufficient to operate at full load and it must operate at partial loads. Consequently, polygeneration plant produces less energy. A backup system could improve polygeneration plant production.

3.2. Exergoeconomic assessment results.

In relation to the exergoeconomic assessment: exergy destruction cost rate plus total cost rates (capital investment plus operating and maintenance) are 9332.0, 1156.3, 123.9 and 32.8 USD/hour for CSP plant, MED plant, cooling plant and heating plant respectively. Relative cost differences are 99.0%, 99.0%, 92.8% and 46.5%. Exergoeconomic factors are 97.6%, 97.0%, 84.9% and 43.2 10% for CSP plant, MED plant, cooling plant and heating plant respectively. According to these indicators, it is recommended to optimize

CSP plant. This requires reducing total cost rates (capital investment plus operating and maintenance) in demerit of equipment efficiency. Effects of cooling plant and heating plant are marginal, although the location of these plants affects performance of CSP plant.

Operating on a clear day or partial day has a direct impact on exergetic unit cost and product cost rate, as shown in Figure 7.

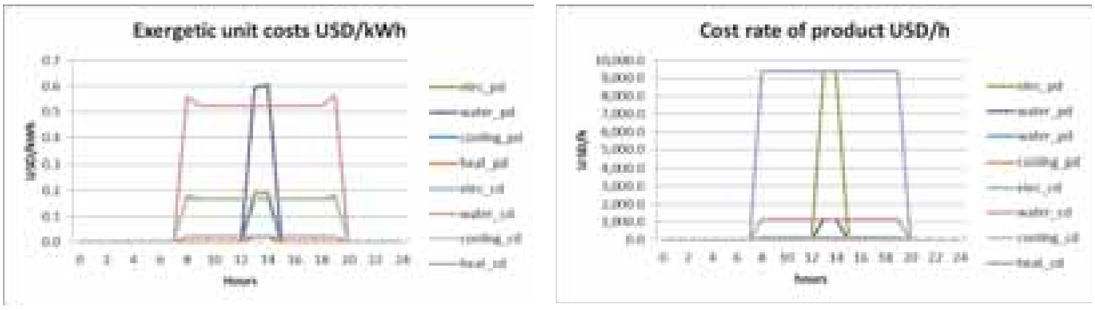

Fig.7: a- Exergetic unit costs USD/kWh. b- Total product cost rate of USD/h. (pd: partial day, cd: clear day)

3.3. Solar multiple results.

Minimum total cost rate of products (electricity + water + cooling + heat process) and minimum total levelized cost (LEC + LWC + LCC + LHC) is reached at solar multiple of 1.3 (see Figures 8 and 9). Minimum total product cost rate is 10713.3 USD/h, the minimum LEC is 0.168 USD/kWh and the minimum LWC is 0.734 USD/m^3 for annual production.

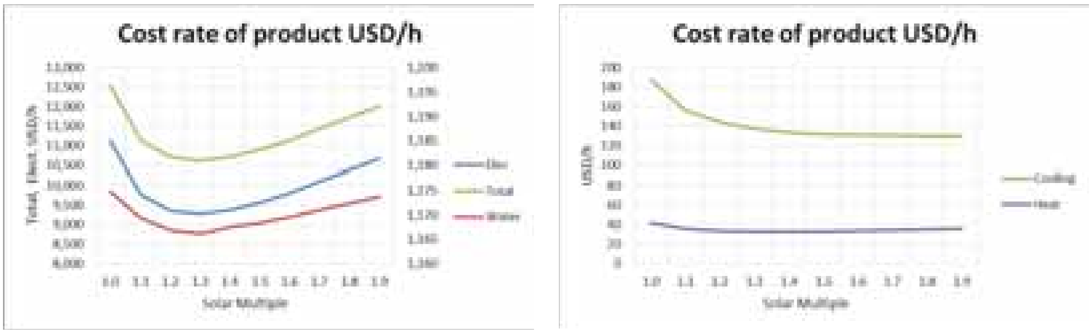

Fig.8: Product cost rate of: a- Total, electricity and water. b- Cooling and heat process.

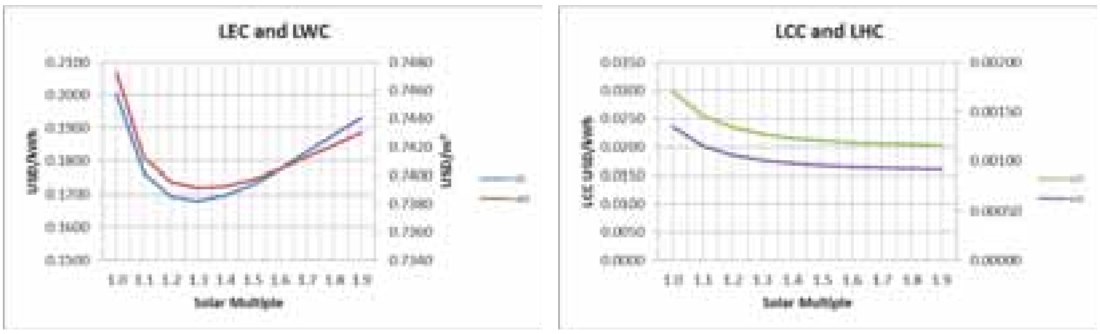

Fig. 9: a- Levelized energy cost (LEC) USD/kWh and Levelized water cost (LWC) USD/m3. b- Levelized cooling cost (LCC), Levelized heating cost (LCH) USD/kWh.

The production of each of the products is raised by increasing the solar multiple, see Figure 10, but also increases investment costs, operation and maintenance costs. Thus, the criterion for selecting the optimal size of the plant in CSP plant is where the minimum LEC is reached (Montes et al., 2009). In the case of polygeneration plant the criterion for selecting the optimal size of the plant is where the minimum total product cost rate is reached that matches with minimum LEC, minimum LWC and minimum total levelized cost.

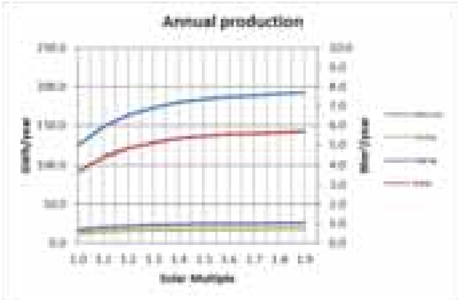

Fig.10: Polygeneration plant production.

3.4. Decision variables.

The results are presented in Figures 11 and 12. Minimum product cost rate is produced at a pressure of 0.28 bar but the maximum NPV occurs at 0.4 bar by varying LP turbine backup pressure. On the other hand, minimum cost rate of product is produced at the same pressure of maximum NPV by varying LP turbine 5th extraction pressure.

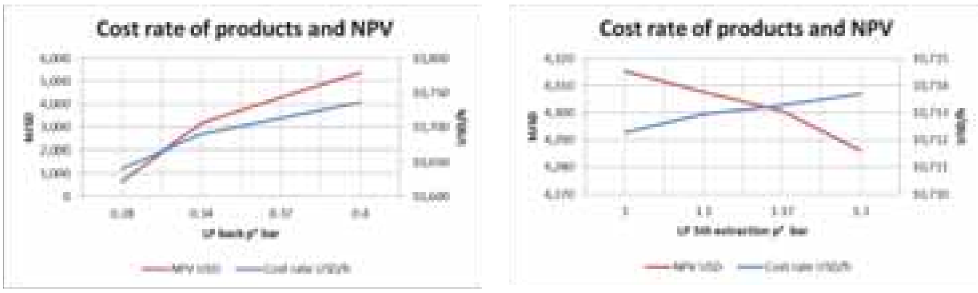

Fig.11: Effects of: a- LP turbine backup pressure, b- LP turbine 5th extraction pressure.

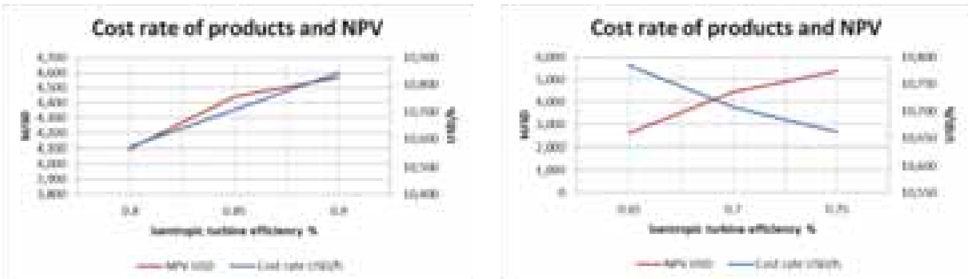

Fig.12: Effects of Isentropic efficiency in: a- turbine, b- pump.

3.5. Energy efficiency.

In Figure 13 Sankey diagram of polygeneration plant is presented. Utilization factor of polygeneration plant is 62.78%. The efficiencies are: 68.8% in solar field, 30.6% in the power conversion unit, 20.9% in CSP plant, 89.9% in MED plant, 99.98% in heating plant and a COP of 0.7 in cooling plant.

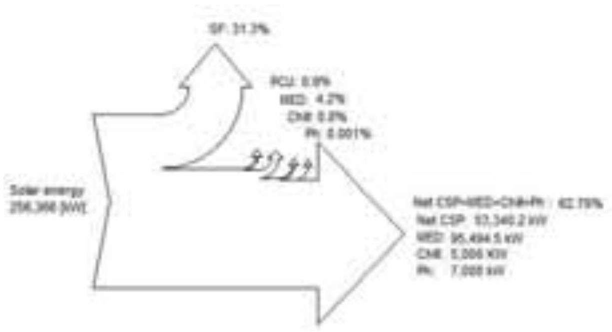

Fig. 13: Sankey diagram of polygeneration plant.

3.6. Exergetic efficiency and exergy destruction.

In Figure 14 Grassmann diagram of polygeneration plant is presented. The exergetic efficiencies are: 24.5% in polygeneration plant, 57.1% in solar field, 52.7% in power conversion unit, 24.7% in MED plant, 66.9% in heating plant, and 33.9% in cooling plant.

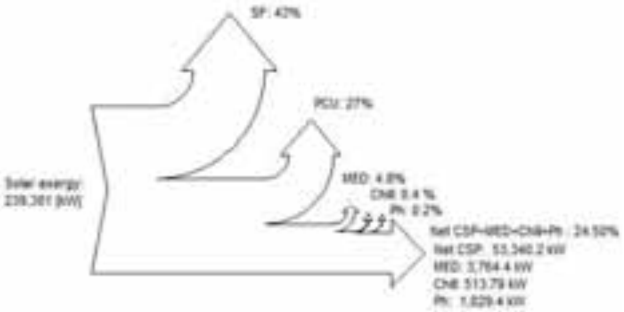

Fig. 14: Grassmann diagram of polygeneration plant.

In Figure 15 exergetic efficiency and exergy destruction in each subsystem are presented and evaluated. Exergy destruction are the following: 43.0% in solar field, 27.0% in power conversion unit, 77.6% in CSP plant, 4.8% in MED plant, 0.4% in cooling plant, 0.2% in heating plant, and 75.4% in polygeneration plant. Figure 14 shows that the effect on the destruction of exergy in cooling plant and heating plant is marginal.

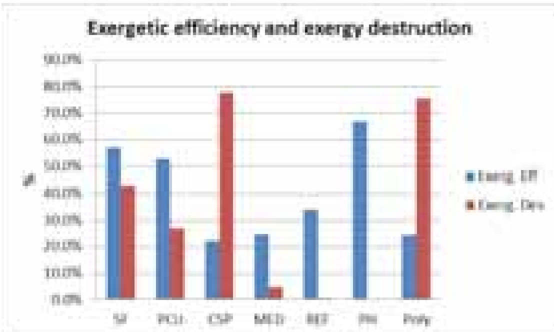

Fig.15: Exergetic efficiency and exergy destruction in polygeneration plant.

In Figure 16 exergetic efficiency is presented in each component of CSP plant. The main components where exergy destruction occurs are: solar collectors (43.0%), evaporator (11.4%), reheater (4.8%), economizer (3.8%), superheater (2.2%), LP turbine (1.8%), generator (1.0%), HP turbine (0.9%) and CFWP3 preheater (0.4%).

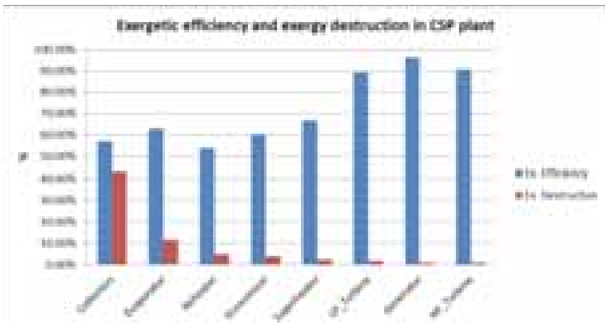

Fig. 16: Exergetic efficiency and exergy destruction in main components of CSP plant.

In Figure 17 exergetic efficiency in main components of MED plant is presented. The main components where exergy destruction occurs are: Effect 1 (1.11%), condenser (0.75%), and second to twelfth effects (from 0.24% to 0.16%).

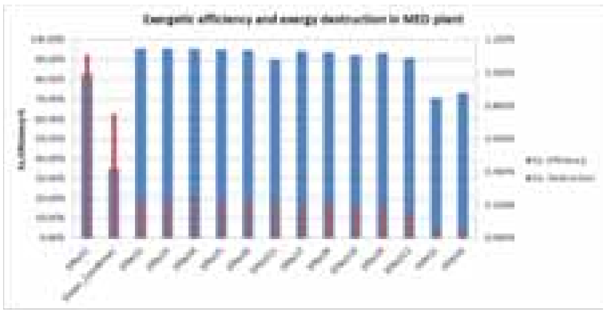

Fig. 17: Exergetic efficiency and exergy destruction in main components of MED plant.

In Figure 18a exergetic efficiency in main components of cooling plant is presented. Main components where exergy destruction occurs are: absorber (0.44%), desorber (0.06%), condenser (0.05%), and evaporator (0.05%).

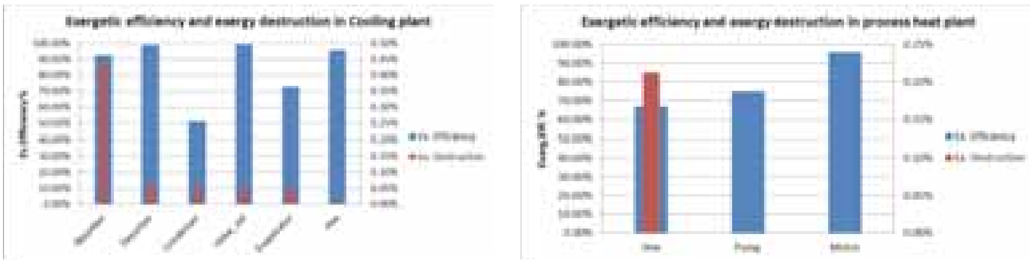

Fig. 18: Exergetic efficiency and exergy destruction of a- cooling plant. b- process heat plant

Finally, in Figure 18b exergetic efficiency in process heat plant is presented. The component where most exergy destruction occurs is the heat exchanger (0.21%).

4. Conclusions

The achievements of this work are the design and simulation of a solar polygeneration plant for the production of electricity, desalinated water, industrial cooling and process heat, using a CSP-PTC plant, a MED plant, a simple effect absorption cooling plant, and a heat exchanger for process heat, simulated hourly, and performing an exergoeconomic analysis.

In terms of energy efficiency, a polygeneration plant that operates individual plants has more efficiency. Polygeneration plant has a utilization factor of 62.7% (20.8% CSP, 89.9% MED, 0.701 refrigeration and 99.9% process heat) meanwhile CSP plant has an efficiency energy of 20.9%.

In terms of exergy efficiency and exergy destruction, polygeneration plant exergetic efficiency is 24.5%. In CSP plant the highest exergy destruction is produced in solar field and power conversion unit. The second highest is produced in MED plant. Destruction of exergy in cooling plant and heating plant is marginal. The main components where exergy destruction occurs in CSP plant are solar collectors (43.0%), evaporator (11.4%), reheater (4.8%), economizer (3.8%), and superheater (2.2%).

A production on clear day generates surplus energy, which can be stored in thermal energy storage. Thermal energy storage could return this extra energy to power conversion unit and raise the plant availability.

According to the exergoeconomic assessment, it is recommended to optimize CSP plant since CSP plant has the biggest total cost rate. This requires reducing total cost rates (capital investment plus operating and maintenance) in demerit of equipment efficiency.

Regarding solar multiple, the minimum LEC and LWC occurs with a solar multiple of 1.3. LEC varies from 0.17 to 0.20 USD/kWh, LWC ranges from 0.739-0.747 USD/m^3, LCC varies from 0.02 to 0.03 USD/kWh, and LHC varies from 0.001 to 0.0013 USD/kWh. The criterion for selecting the optimal size of the plant is where the minimum total cost (product cost rate) is reached.

When it comes to varying the decision variables, the main results in polygeneration plant are a product cost rate of 10,713.2 USD/h and NPV of 4.3 MUSD. LP turbine backup pressure, LP turbine 5th extraction pressure, temperature effects condenser outlet in MED plant, and temperature effects condenser in cooling plant are evaluated. Minimum product cost rate is produced at a pressure of 0.28 bar but the maximum NPV occurs at 0.4 bar by varying LP turbine backup pressure.

As future actions the study should incorporate a thermal energy storage (TES) and backup, as well as, apply optimization tools.

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Nomenclature

A : aperture area, m^2
a_i: coefficients for collector efficiency, -
Cash_in: Cash inflows, USD/year
Cash_out: Cash outflows, USD/year
capex : capital expenditure, USD
cf : fuel cost, USD/year
$\dot{C}$: cost rate associated with exergy transfer or exergy cost rate , USD/h
$\dot{C}_j$: 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 : cost per unit of exergy or exergetic unit cost, USD/kWh
$c_{F,k}$: cost per unit of exergy fuel, USD/kWh
$c_{P,k}$: cost per unit of exergy product, 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
e_{ch} : chemical exergy specified, kJ/kg
e_k : kinetic exergy specified, kJ/kg
e_p : potential exergy specified, kJ/kg
e_{ph} : physical 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
$\dot{E}_{ch}$: time rate of exergy chemical, kJ/s
$\dot{E}_{sun}$: time rate of exergy from sun, kJ/s
$\dot{E}_{ph}$: time rate of exergy physical, kJ/s
$\dot{E}_{work}$: time rate of exergy work, 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, %
E_{anual} : annual electricity, kWh/year
E_{th_an} : annual heat, kWh/year
f_k : exergoeconomic factor, %
G: Gibbs function, kJ
G_b: direct normal irradiance, W/m^2
GHI: global horizontal irradiance, W/m^2
GOR: gained output ratio, -
h : enthalpy, kJ/kg
IRR: internal rate of return, %
LC: levelized cost, USD/kWh o USD/m^3
LCC : levelized cooling cost, USD/kWh
LEC : levelized energy cost, USD/kWh

LHC : levelized heat cost, USD/kWh
LWC : levelized water cost, USD/m^3
$\dot{m}$: flow rate, kg/s
n: number of moles (eq. 8), kmol
n: number of time periods, years
NPV: net present value, USD
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
$\dot{Q}$: heat rate, kJ/s
r_k : relative cost difference, %
SM : solar multiple, -
T : temperature, °C
T_0 : ambient temperature, °C
TBT: top brine temperature, °C
$\dot{W}$: work rate, kJ/s
$y_{D,k}$: exergy destruction ratio
$\dot{Z}_k^{CI}$: capital investment cost rates, USD/h
$\dot{Z}_k^{OM}$: operating and maintenance cost rates, USD/h
$\dot{Z}$: total cost rates, USD/h

Greek symbols

ε : exergetic efficiency
η : efficienccy
τ : average annual time of plant operation at nominal capacity

Abbreviations

CFWP: condensate feed water preheater
Chill: chiller
CHP: combined heat and power
CDEC: centro de despacho económico de carga
CNE: comisión nacional de energía
CR: central receiver
CSP: concentrated solar power
DS: dish Stirling
EES: Engineering equation solver
FWP: feed water preheater
G: generator
HEX: Heat exchanger
HP: high pressure
LF: linear fresnel
LiBr/H_2O : Lithium bromide / water
LP : low pressure
MED: multi-effect desalination
MSF: multi stage flash
OCR: organic rankine cycle
P: Products
PCU: Power unit convertion
PH: process heat
PHH: Preheater
PTC: parabolic trough collector
R: reactants
RO: reverse osmosis
SF: solar field
SGFWP: steam generator feed water preheater
SII: servicio de impuestos internos
SING: Sistema interconectado del norte grande