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Exergoeconomic and techno-economic analysis of a solar multi-generation plant with thermal energy storage

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Abstract.

A exergoeconomic and techno-economic analysis of integrating multi-effect distillation, absorption refrigeration and process heat plants in a concentrated solar power plant is carried out. A solar multigeneration plant is modeled to simultaneously produce electricity, desalinated water, cooling, and process heat. The methodology considers modeling a multi-generation plant, applying exergoeconomic method and levelized cost method. The solar multi-generation plant is simulated in a typical meteorological year, with one hour time-step and a yearly total DNI of 3,389 kW h/m^2/year, considering the demand of a specific mining company located in northern Chile. The analysis of simulation shows that the levelized cost method overcharges electricity and undercharges water, cooling and process heat with respect to the exergoeconomic method. The exergoeconomic method is a robust method of cost allocation for applying in a solar multi-generation plant.

Keywords: *multi-generation, exergoeconomic, CSP, multi-effect desalination, absorption refrigeration.*

1. Introduction

The demand for electricity, water, cooling and process heat has been growing increasingly in Chile [1], especially due to the mining requirements. Consequently, electricity, water, and fuel prices have reached high levels, which negatively impact the competitiveness of companies. According to Chilean Energy Ministry [2], in 2014, 37% of electricity generated in Chile was consumed by the mining industry, other industries consumed 31%, the residential sector 17%, while the commercial and public sectors accounted for 14% of the electricity consumption. On the one hand, Chile has high availability of renewable energy resources, such as solar, wind, hydro, biomass and geothermal energy. Within these sources, solar energy is an important resource due to high rates of radiation existing in northern Chile, considered as the highest worldwide [3]. On the other hand, in the north of Chile there are several mining facilities, which demand a large amount of electricity, fresh water, heat process, and cooling [1], [4], utilities that are feasible to be delivered by multi-generation systems or stand-alone systems.

Multi-generation or polygeneration is defined as the concurrent production of two or more energy services and/or manufactured products that, benefiting from the energy integration of the processes, extracts the maximum thermodynamic potential of the resources consumed [5]. A multi-generation scheme has comparative advantages over stand-alone systems, since it allows reducing both primary energy consumption and emissions of greenhouse gasses displacing fossil fuels, as well as decreasing energy dependency at the country level, contributing to the diversification of energy sources. Multi-generation scheme is a process of

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integration of different technologies by which is possible to increase the thermodynamic efficiency and decrease the consumed resources [5]. This integrated process can be evaluated either by an levelized cost analysis or exergoeconomic analysis. Levelized cost analysis considers the first law of Thermodynamics and economic principles to determine the present value of the total cost of building and operating of a productive plant over its economic life, converted to equal annual payments. Costs are levelized in USD per unit of annual production. Key inputs to calculate levelized cost include capital expenditure, operational expenditure, fuel costs, and revenues from the sales of by-products, such as, carbon credits [6]. However, a conventional economic analysis, as levelized cost, does not provide criteria for apportioning the carrying charges, fuel costs, and operational expenses to the various products generated in the same system [7]. On the other hand, exergoeconomic or thermoeconomic analysis considers the second law of Thermodynamics and economic principles for determining the unit exergy costs and exergy cost rate of each product. According to Tsatsaronis [8], exergoeconomics is defined as the branch of engineering that appropriately combines, at the level of system components, thermodynamic evaluations based on an exergy analysis with economic principles, in order to provide the designer or operator of a system with information that is useful to the design and operation of a cost-effective system, but not obtainable either by regular energy, or exergy analysis, or economic analysis. Exergoeconomic assesses the cost of consumed resources, money and system irreversibilities in terms of the overall production process [5].

For the reasons mentioned above, a solar multi-generation system is configured and simulated in order to produce electricity, desalination water, industrial cooling and process heat required by the mining sector in northern Chile. The solar multi-generation plant proposed herein consists of a concentrated solar power (CSP) parabolic trough collector (PTC) field with thermal energy storage (TES) and backup system (BS), a multi-effect distillation (MED) plant, a single-effect absorption refrigeration system (Ref), and a countercurrent heat exchanger as process heat plant (PH), the last three plants use thermal energy to drive the processes.

CSP-PTC could be integrated into multi-generation system so as to deliver different products, such as electricity, fresh water, process heat and refrigeration [9], different studies have focused on cogeneration configurations [10]–[16] and trigeneration schemes [14], [17], [18]. However, there are studies which considered the levelized cost method and others the exergoeconomic one to evaluate the benefits of the integration, but both methods are unlike and produce different results. For this reason, the aim of the present work is to apply an exergoeconomic method and levelized cost method in a multi-generation plant to compare the unit costs of each product.

2. Materials and methods

The methodology considerers modeling a solar multi-generation plant and applying an exergoeconomic method and levelized cost method.

2.1. Multi-generation plant

The solar multi-generation plant is depicted in Figure 1, the CSP-PTC plant is configured and modeled considering a typical CSP plant as Andasol-1 power plant [19], [20]. The solar field (SF) consisting of EuroTrough collectors (ET-150), Schott PRT-70 absorber tubes, Dowtherm A as heat thermal fluid (HTF). The design temperature of SF is 393 ºC and the outlet temperature is 293 ºC. The irradiance and solar efficiency at design point are 1,010 W/m^2 and 0.72, respectively. The solar multiple (SM) is defined as 2.56 with 614,014 m^2 of aperture area. The solar multiple is a measure of the solar field aperture area as a function of the power block's nameplate capacity, and it is expressed as:

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

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

The power block (PB) consists of a regenerative Rankine cycle with reheat and six extractions, as suggested in Blanco-Marigorta et al. [21]. The TES is assumed as a two-tank indirect system using molten salts (60% $NaNO_3$, 40% KNO_3) as storage media, 95% of annual storage efficiency, and the design temperature in the hot tank is 386 ºC and 292 ºC for the cold tank. TES_{th} is the equivalent thermal capacity of the storage tanks, it is defined as:

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

where, $\dot{W}_{des.gross}$ is gross power, η_{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. It is assumed 12 hours of full load capacity.

The BS supplies thermal energy directly to the HTF in the PB. Other assumptions are made: SF outlet temperature has been kept constant [22]; startup and shutdown are not evaluated; the capacity factor is assumed as 96%; and CSP plant is a base load power station.

In the CSP plant, the point of coupling of MED, Ref and PH plants is selected according to the operating temperatures constraints imposed by each technology and to cause the minimum penalty for power production. Therefore, the MED plant replaces the CSP plant condenser, the Ref plant is coupled to the fifth turbine extraction, and the PH plant is coupled between feed water preheaters (FWP). It is not possible to regulate the amount of water produced because the MED plant is driven by the heat rejected from the power cycle. The production from Ref plant and PH plant can be regulated per the demand.

The desalination plant is modeled with 12 effects parallel-cross feed MED plant with 11 feed preheaters, as suggested in Zak et al. [23]. The fresh water production is 37,341 m^3/day and 9.1 of Gained Output Ratio (GOR).

The refrigeration plant is configured with a single-effect LiBr-H_2O absorption chiller, as suggested in Herold et al. [24] with 5 MW_{th} of cooling capacity and 0.7 of nominal coefficient of performance (COP).

Finally, a counter current heat exchanger is configured to produce process heat, with 7 MW_{th} heating.

The sizing chosen for each plant was selected according to the demand of a specific mining company located in northern Chile.

Each stand-alone system is modeled and validated. Then, the multi-generation plant is the combination of the validated stand-alone systems. The CSP-PTC stand-alone plant is validated from Blanco-Marigorta et.al [21] and SAM software [19]. The MED plant is validated from Zak et al. [23] and El-Dessouky et al.[25], and the cooling plant is validated from Herold et al. [24].

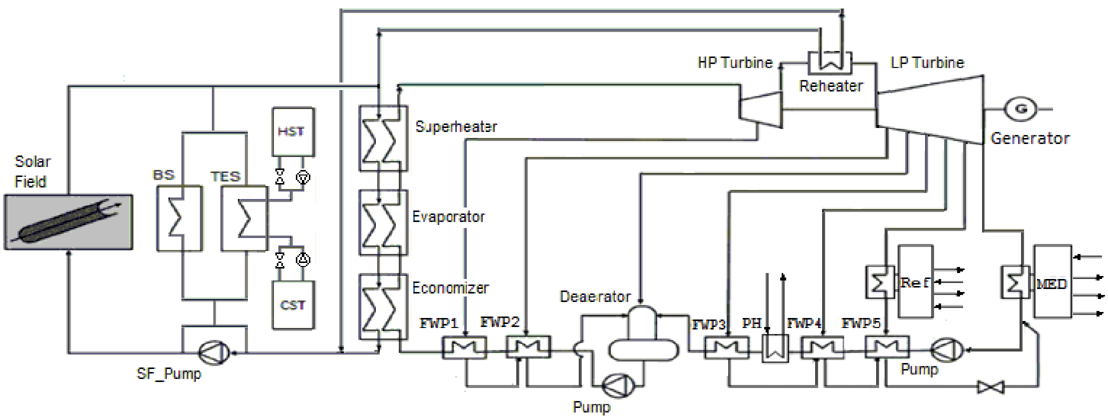


Fig. 1: Multi-generation plant configuration. CSP/TES + MED + Ref + PH.

Table 1 shows the main parameters of solar multi-generation plant.

Tab. 1: Main parameters of multi-generation plant at design point.

Property	Value Unit
TES	
Type / Storage fluid	2-tank / Molten Salt
Tank temperature (cold/hot) / Annual Storage Efficiency	(292 °C / 386 °C) / 95%
Full load hours of TES	12 h
Solar field (SF)	
Parabolic trough collector model	EuroTrough collector (Skal-et)
Solar Field inlet/outlet temperature	293.0 °C / 393.0 °C
Aperture area	614,014 m^2
Solar Multiple	2.56
Power block (PB)	
Gross power production	55.0 MW_e
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 (MED)	
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-effect absorption chiller (Ref)	
Cooling power	5.0 MW_{th}
Chilled water inlet / outlet temperature	10.0 °C / 6.0 °C
Cooling water inlet/outlet temperature	25.0 °C / 35.0 °C
Inlet temperature desorber / COP	108.5 °C / 0.70
Process Heat (PH)	
Process heat capacity	7.0 MW_{th}
Heat exchanger temperature inlet / outlet	63.0 °C / 90.0 °C

The software IPSEpro [26] was used for the modeling and simulations of the multi-generation plant and each stand-alone plant. IPSEpro can calculate mass and energy balances and simulate different kind of processes. IPSEpro solves the flowsheet of the process using Newton-Raphson method. IPSEpro provides only steady state solutions. In order to obtain the dynamic system behavior, IPSEpro has to be linked to Microsoft Excel by IPSEpro-PSExcel, where the solar multi-generation plant is simulated over a one-year period in time steps of one hour. Finally, MATLAB software is used for modeling and simulating TES behavior and for thermoeconomic and techno-economic assessment.

The multi-generation plant was evaluated to be installed in northern Chile, in Crucero, latitude -22.14°, longitude -69.3° and 3389 kW h/m^2/year of DNI [3].

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

2.2. Exergoeconomic method

A exergoeconomic evaluation is applied using Bejan et al. method [7]. Figure 2 depicts the delimitation of the boundaries analysis. The fuels and products are established, and mass, energy and exergy balances are applied. The exergy balance equation take the form:

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

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

The exergy rates from sun [27] is defined as:

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

where A is the solar field aperture area, and T_{sun} is the sun’s surface temperature, taken as 6000 K.

For each system component is applied the economic balance in order to determine the unit exergy cost c_j and exergy cost rate $\dot{C}_j$ of each stream. The economic balance is expressed by:

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

where, c_j is the exergy unit cost, $\dot{E}$ is the exergy rate, $\dot{Z}_k^{CI}$ is the non-exergy-related cost rate associated with an investment cost (or capex), $\dot{Z}_k^{OM}$ is the non-exergy-related cost rate associated with an operation and maintenance cost (or opex).

The exergy cost rate is expressed as function of unit exergy cost by:

$$\dot{C}_j = c_j\dot{E}_j = c_j(\dot{E}_{ph} + \dot{E}_{ch} + \dot{E}_p + \dot{E}_k) \quad \text{(eq. 6)}$$

where the subscripts ph, ch, p, and k are physic, chemical, potential and kinetic, respectively.

The total cost rate of product $\dot{C}_p$ is the sum of total cost rate of fuel $\dot{C}_f$ and non-exergy-related cost rate $\dot{Z}$.

The exergy analysis considered a reference temperature of 25°C, a reference atmospheric pressure of 1.013 bar, a reference mass fraction of LiBr of 0.5542 kg/kg, and a reference mass fraction of water salinity of 0.042 kg/kg.

Investment cost in MUSD, and operating and maintenance cost in MUSD/year considered are: 397.3 and 17.8 in CSP [11], [19], [28], [29]; 59.5 and 1.8 in MED plant [25], [30]–[33]; 2.7 and 0.006 in Refrigeration plant [16], [34]; and finally 0.3 and 0.0006 in process heat plant [35], respectively. The fossil cost fuel is 0.0324 USD/kWh [36]. It has been considered a horizon of 25 years and a discount rate of 10%.

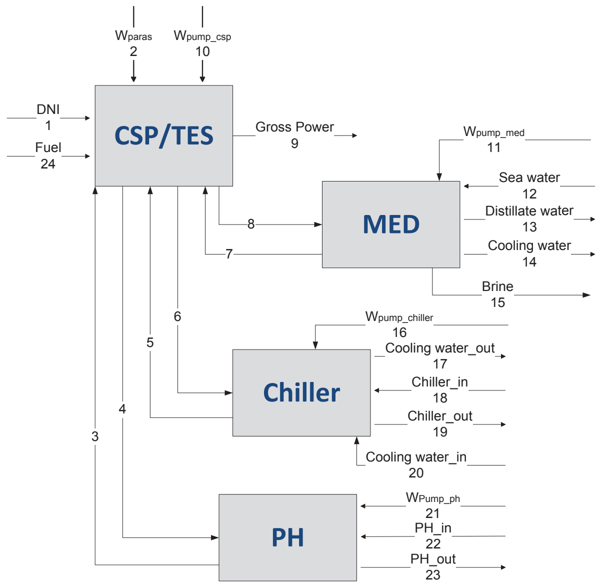


Fig. 2: Aggregation level for exergoeconomic assessment in multi-generation plant.

2.3. Levelized cost method

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 [11], [22], [37].

The levelized electricity cost (LEC), in USD/kWh, is defined by:

$$LEC = \sum_{j=0}^{n} \frac{capex_j crf + opex_j + C_{fuel\,j}}{(1+i)^j} / (E_{elect\_an\_j}) \qquad \text{(eq. 7)}$$

where $capex$ is the capital expenditure, $opex$ is the operational expenditure, crf is the capital recovery factor, C_{fuel} is the annual fuel cost, i is the discount rate, n is the number of time periods, $E_{elect\_an\_j}$ is the annual production of electricity provided by the generator minus the parasitic loads of CSP plant. Fuel cost is calculated by:

$$C_{fuel} = c_{ff} \frac{Q_{\text{th,power block\_BS}}}{\eta_{\text{boiler}}} \qquad \text{(eq. 8)}$$

where c_{ff} is the fossil fuel cost, in USD/kWh, $Q_{\text{th,power block\_BS}}$ is the thermal energy required by the power block from BS, in kWh/year, and η_{boiler} is the boiler efficiency, assumed as 0.9.

A similar procedure was used for the other levelized costs estimation. The levelized water cost (LWC), in USD/m^3, is defined by:

$$LWC = \sum_{j=0}^{n} \frac{capex_j crf + opex_j + C_{fuel\,j}}{(1+i)^j} / (V_{water\_an\_j}) \qquad \text{(eq. 9)}$$

where $V_{water\_an\_j}$ is the annual production of water, in m^3/year, and C_{fuel} is the fuel cost, in USD/year. Fuel cost in the case of MED, refrigeration and process heat plants is the cost associated with electric consumptions, and it is calculated by:

$$C_{fuel} = LEC\ \text{En}_{\text{pumps}} \qquad \text{(eq. 10)}$$

Where En_{pumps} is the annual energy consumption from pumps, in kWh/year.

The levelized cooling cost (LCC), in USD/kWh, is defined by:

$$LCC = \sum_{j=0}^{n} \frac{capex_j crf + opex_j + C_{fuel\,j}}{(1+i)^j} / (E_{cooling\_an\_j}) \qquad \text{(eq. 11)}$$

where $E_{cooling\_an\_j}$ is the annual production of cooling, in kWh/year.

The levelized process heat cost (LHC), in USD/kWh, is defined by:

$$LHC = \sum_{j=0}^{n} \frac{capex_j crf + opex_j + C_{fuel\,j}}{(1+i)^j} / (E_{heat\_an\_j}) \quad \text{(eq. 12)}$$

where $E_{heat\_an\_j}$ is the annual production of process heat, in kWh/year.

3. Results and discussion.

3.1. Production and cost in the base case.

The monthly production of electricity, fresh water, cooling and process heat, in the solar multi-generation plant without BS, is presented in Figure 3. At the location, there is a seasonality of DNI, with shorter days and lower values of DNI in the winter season. Hence, the solar multi-generation plant shows a seasonal variation, presenting a lower production of electricity, fresh water, cooling and process heat during the winter (June and July). However, in February, the production decreases by the Altiplanic Winter which moistens the air coming from the east (where Bolivia is located) bringing unsettled weather and clouds.

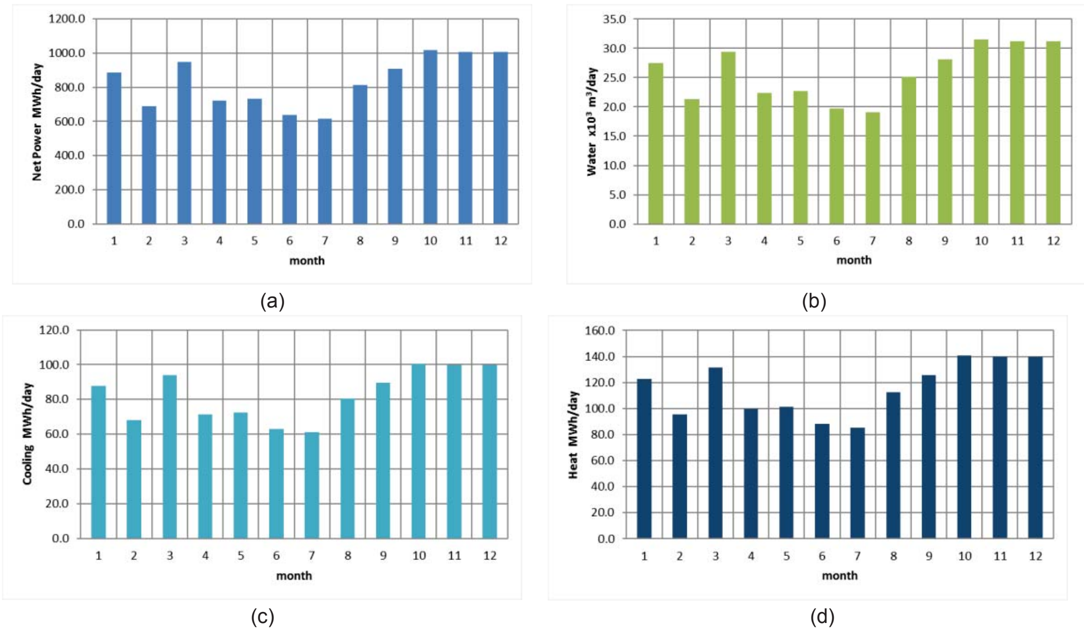


Fig. 3: Monthly productions from the solar: a) Net power. b and water. c) Cooling. d) Heat.

Figure 4a depicts the monthly capacity factor without BS, which is largest in the summer due to the seasonal variation in DNI available for collection. Figure 4b shows the monthly exergy destruction, which is greater in the CSP plant with an 89.4%. In the CSP plant, the SF is the most critical component in terms of exergy destruction. It is important to point out that exergy input of SF is derived solely from the sun which does not affect the consumption of fossil fuel. The second largest exergy destruction is in the MED plant with 9.6% of the total exergy input. In the case of cooling and process heat plants, the exergy destruction is less than 1%.

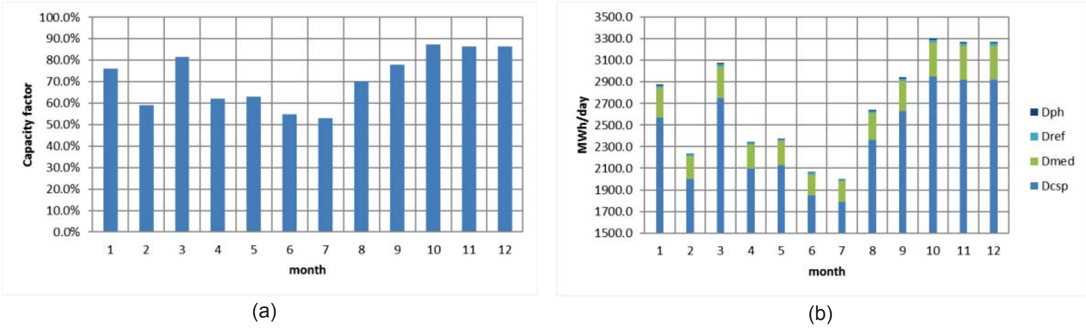


Fig. 4: a) Monthly capacity factor without BS. b) Monthly exergy destruction without BS.

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 unit exergy costs (UEC) and levelized costs (LC) are presented in Figure 5. Two cases are considered in the case of water cost, without and with the cost of pumping the seawater to the plant location (about 70 km). The difference in value between UEC and LC is due to the form of cost allocation. Exergoeconomics uses the exergy as criterion to allocate the costs, and it is considered as a rational cost allocation. The levelized cost method overcharges electricity and undercharges water, cooling and process heat.

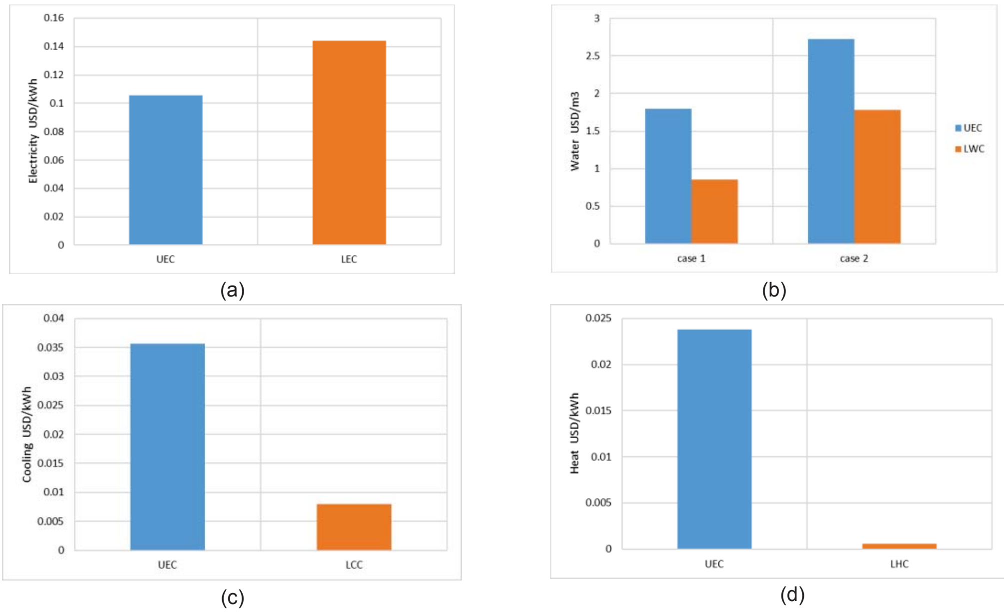


Fig. 5: Comparison between the levelized cost method and exergoeconomic method. Specific cost (UEC and LC) of: a) electricity, b) water, c) cooling, d) process heat.

If a system produces only one product, there are no problems to calculate the levelized cost because it is not necessary to use an allocation criterion of costs. However, if a system produces more than one product as in a multi-generation system, then, it is needed to establish an allocation criterion of costs in order to calculate the products cost. Conventional economic analysis does not provide criteria for apportioning the carrying charges, fuel costs, and opex to the various products generated in the same system [7]. Exergoeconomics provides criteria for apportioning the costs, therefore, exergy is the appropriate variable to use in this case.

On the other hand, the total exergy cost rate of products is 8,988.4 USD/h, which is distributed in 64.7% in electricity, 31.3% in fresh water, 2.2% in cooling, and 1.8% in process heat. In a process of optimization, the variable to be minimized is the total exergy cost of products.

3.2. Production and cost as functions of sizing SM and TES.

The solar multi-generation plant was hybridized with fossil fuel in order to fix the capacity factor in a 96%. Chile does not have restrictions to use fossil fuel in CSP plants. In contrast, Spain limits the use of fossil fuel in CSP plants. A solar multi-generation plant will be more dispatchable by coupling the solar multi-generation plant with BS. This also allows a more flexible generation strategy to maximize the value of the products generated. Figure 6 shows the capacity factor in the multi-generation plant without BS in which the capacity factor is increased with the SM and the hours of TES. This latter one allows storing excess energy collected by the SF when it is not used in the PB, and discharges that energy later when the DNI is lower, such as in cloudy days or at night. Consequently, the annual production of each product is increased too, as seen in Figure 7.

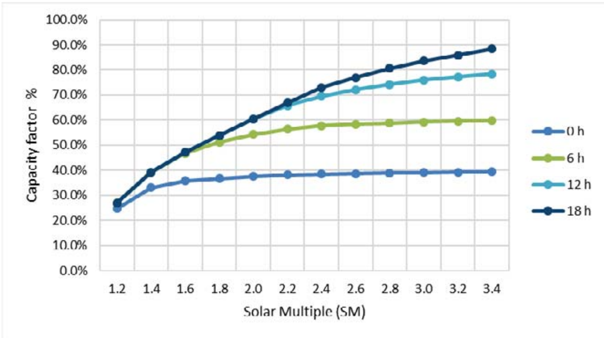
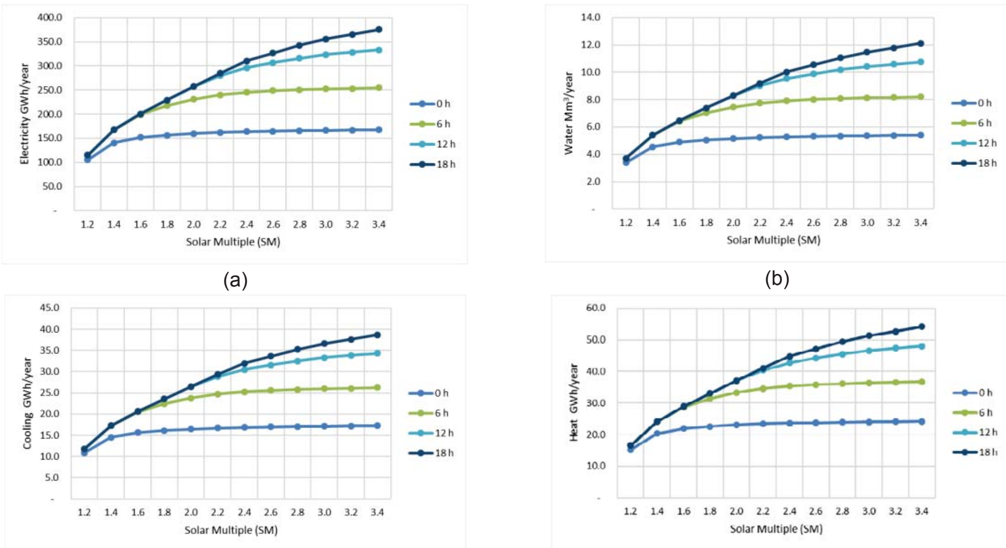


Fig. 6: Capacity factor in the multi-generation plant without BS.



(c) (d)

Fig. 7: Annual production of: a) electricity, b) water, c) cooling, d) process heat.

Figure 8 presents the unit exergy cost (UEC) and levelized cost (LC) of each product (electricity, fresh water, cooling, and process heat) as a function of SM, and with a TES of 12 hours. It is observed that UEC and LC are different, but the minimums UEC and LC are produced at the same SM, with an SM of 2.2. In a multi-generation plant, there are common costs associated with the products concerned, and it is necessary to determine the share of costs attributable to one or another product. So, the allocation cost needs an additional rational analysis to prevent allocation from being arbitrary. Regarding the levelized cost method, the fuel cost for MED, refrigeration and process heat plants only corresponds to the cost associated with electric consumptions and does not consider the steam cost because this latter one is assumed as an internal cost. On the other hand, allocation of costs based on exergoeconomic method equitably charges each product with the appropriate share of capex and opex that are involved in operating such component according to its exergy rate. Hence, the exergoeconomic method is more appropriate to multi-generation plant than levelized cost method.

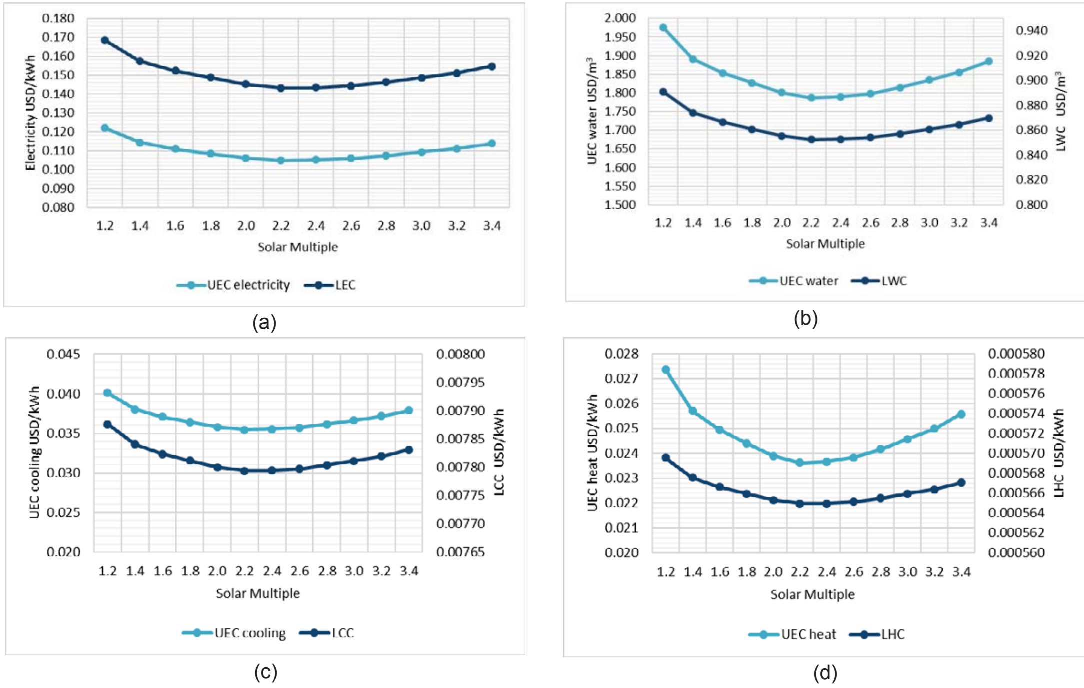


Fig. 8: Specific cost (UEC and LC) as a function of SM. a) electricity, b) water, c) cooling, d) process heat.

An optimal sizing of SF and TES should minimize installation and operating costs, and maximize the amount of time in a year to drive the power cycle at its nominal capacity. This point is reached with the minimum levelized cost and unit exergy cost. The unit cost in the solar multi-generation plant is dominated by the investment cost of CSP plant. The unit cost varies significantly, depending on the capacity factor, which in turn depends on the DNI, hybridization (BS) levels, and sizing of SF and TES.

4. Conclusions

The levelized cost method and the exergoeconomic method were applied to a solar multi-generation plant to compare the unit costs of each product. The solar multi-generation plant was made up of concentrated solar power plant, multi-effect distillation, absorption refrigeration, and process heat plants. The solar multi-generation plant was simulated hourly during a typical meteorological year.

The levelized cost method overvalues the electricity cost and undervalues the water, cooling, and process heat costs because the allocation cost does not charge all internal cost to MED, Ref and PH plants.

The exergoeconomic method is more appropriate than levelized cost method since the allocation cost is based on the second law of Thermodynamics and economic principles. Then, there is an equitable distribution of the appropriate share of non-exergy-related cost rate and exergy cost rate in each product.

The minimums UEC and LC happened at the same sizing of SM and TES, however, the unit costs have different values. Hence, independently of the method used, in a process of optimization of sizing of SM and TES, it is obtained the same sizing.

In terms of exergy destruction, the highest exergy destruction of the CSP plant is produced in SF and PB. The second highest is produced in the MED plant, but in the case of Ref and PH plant, the exergy destruction is about 1%.

In future studies, it is recommended that an exergoeconomic analysis and life cycle analysis be done in the solar multi-generation plant in order to use the cost accounting in the environmental evaluation. Likewise, another research line could be to evaluate different schemes of solar multi-generation plant coupled with other technologies, such as reverse osmosis desalination and vapor compression refrigeration systems.

Finally, an exergoeconomic evaluation with low aggregation level in CSP plant should be done at the level of individual components, such as the turbine, pump, solar field, and so on.

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Nomenclatures

A : aperture area, m^2
BS: backup system
Capex : capital expenditure, USD
Cf_j : fuel cost, USD/year
$\dot{C}_j$: exergy cost rate, USD/h
$\dot{C}_{D,k}$: exergy destruction 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 : unit exergy cost, USD/kWh
cfr: capital recovery factor, %
CSP: concentrated solar power
CST: cold storage tank
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
$\dot{E}_{ph}$: time rate of physical exergy, kJ/s
$\dot{E}_{ch}$: time rate of chemical exergy, kJ/s
$\dot{E}_D$: time rate of exergy destruction 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, %
FWP: feed water preheater
GOR: gained output ratio, -
HTF: heat thermal fluid
HST: hot storage tank
HP: high pressure
LC: levelized cost
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
LP: low pressure
$\dot{m}$: flow rate, kg/s
MED: multi-effect distillation
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, kW
$\dot{Q}_{th,solar\ field}$: thermal power produced in the solar field, kW
SM : solar multiple, -
Ref: refrigeration
PB: power block
PH: process heat
T_0 : ambient temperature, °C
TBT: top brine temperature, °C
TES: thermal energy storage
$t_{full\ load}$: hours of full-load hours of TES, h
UEC: unit exergy cost
$w_{des,gross}$: power cycle thermal in design-point , kW
$\dot{Z}$: Non-exergy-related cost rate, USD/s
$\dot{Z}_k^{CI}$: capital investment cost rates, USD/h
$\dot{Z}_k^{OM}$: operating and maintenance cost rates, USD/h