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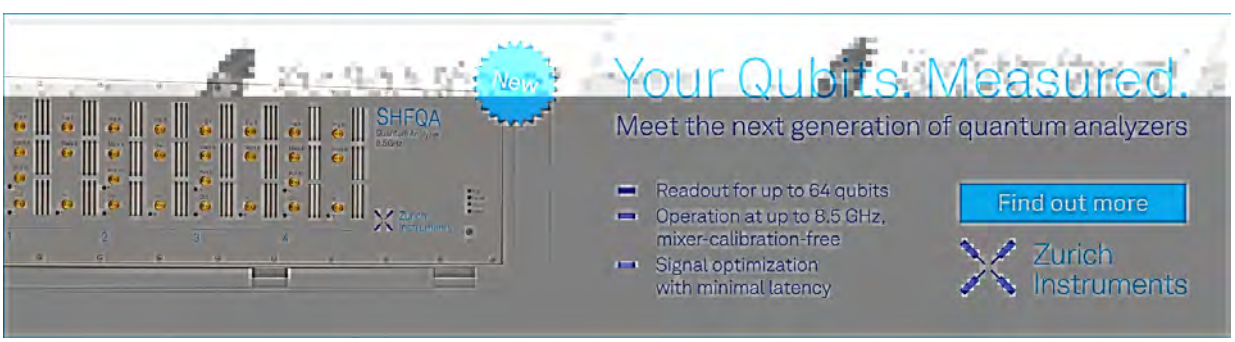

Exergy Cost Assessment of Solar Trigeneration Plant Based on a Concentrated Solar Power Plant as the Prime Mover

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Abstract. An exergy cost assessment of solar trigeneration plant to generate electricity, fresh-water, and heat is carried out in order to study the process of exergy cost formation, to determine the key components that contribute to the cost of each product, and to establish the best configuration in term of unit exergy cost. The solar trigeneration plants evaluated consist of a concentrated solar power (CSP), a multi-effect distillation plant, and a process heat module, in which the CSP plant is the prime mover. The methodology includes modeling and evaluating the performance of standalone and trigeneration plants using the symbolic exergoeconomic methodology. Results show that the best configuration, in terms of exergy cost, is when the multi-effect distillation plant replaces the power cycle condenser. Regarding the costs formation, the key components which could be improved in their design are: solar collectors, evaporator, re-heater, dissipative systems, and productive subsystems.

INTRODUCTION

The mining industry in zones with high direct normal irradiation conditions, such as in northern Chile, presents a high demand of electricity, fresh-water, and process heat [1]. These products are feasible to produce in standalone plants that consume mainly fossil fuels. However, given the advantages offered by operating in a multigeneration scheme, it is interesting to consider the evaluation of a multigeneration plant to produce these products. A multigeneration or polygeneration system is an integration process that produces more than one product from one or more natural resources [2], whose advantages are: allowing to reduce both primary energy consumption and CO_2 emissions, avoiding the waste heat, reducing the transmission and distribution network and other energy losses, as well as decreasing energy dependency at the country level, and contributing to the diversification of energy sources [3]. Note that trigeneration and cogeneration are the integration of three and two utility outputs, respectively, with one or more inputs for better performance. On the other hand, in zones with high availability of solar irradiation the Concentrated Solar Power (CSP) plant could be a cost-effective option to produce electricity because this type of plant allows operating directly from solar energy, storing the thermal energy captured, and operating in hybrid form using a fossil fuel backup, which allows to operate in stable and constant conditions, and thus does not to affect the performance of plants that are integrated into the multigeneration scheme. Therefore, CSP plants have the potential to play an important role in the production of electricity from non-conventional renewable energies, which constitute an opportunity for sustainable development. At the same time, considering that the power block, in the CSP plant, rejects heat to the environment, this heat could be recovered by technologies driven by thermal energy. Therefore also, a CSP plant is feasible to integrate it with other technologies to produce other products, such as process heat, steam, hot water, fresh-water, cooling, and any other [4].

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Given the above, in this article, it is proposed analyzing the integration of a CSP plant operating in trigeneration schemes as the prime mover. Note that the prime mover, which turns thermal or chemical energy into power, is the heart of any polygeneration system [3]. The technologies are driven by thermal energy for producing desalted water and process heat consist of a multi-effect distillation plant and a countercurrent heat exchanger module, respectively.

Due to the complexity of dealing with many energy flows in multigeneration schemes, the integration and assessment of such technologies should be evaluated applying a rational method. A method for the allocation of resources and products allows solving this problem, considering all input and output from the system, as well as the production units of each product. For solving this problem, several methods have been proposed in the literature, which in general are classified in thermodynamic, economic, and thermoeconomic methods (or exergoeconomic). Nevertheless, the thermoeconomic methods are based on the Second Law of the Thermodynamics and economic principles [2], [5], [6]. Its main property is the exergy that indicates the maximum work that a flow or a system might produce while interacting with the environment, and it is very useful for the analysis of multigeneration systems. The exergy cost of flow represents the units of exergy flow used to produce it [7]. Exergy cost is a conservative magnitude that increases in every process according to the irreversibilities of the processes. The process of cost formation provides vital information for the designer and evaluator can improve the design [8].

Few articles reported in the literature have applied thermoeconomic assessment to solar multigeneration systems, considering a concentrated solar power plant as prime mover [1], [4], [9]–[11]. In that context, CSP could be integrated into polygeneration schemes [4]. However, such those studies do not consider the evaluation of the process of exergy cost formation and the decomposition of each cost in order to compare trigeneration schemes and find out the key components to improve the design. Therefore, two solar trigeneration schemes and standalone systems are analyzed through the symbolic exergoeconomic method to study the process of exergy cost formation, to determine the key components that contribute to the cost of each product, and to establish the best configuration in terms of unit exergy cost.

MATERIAL AND METHODS

The methodology considers modeling standalone plants. Then, according to technical restrictions, the standalone systems are integrated in two solar trigeneration configurations. After that, the symbolic exergoeconomic methodology [12]–[14] is applied, which is a technique based on the exergy cost theory [15], and provides information on the irreversibilities generated in each component, the exergy cost formation of each component, the malfunction and dysfunction, and the fuel impact.

The plants were simulated at the design point by considering meteorological data [16] of a representative zone with high level of direct normal irradiance. The software IPSEpro [17] and MATLAB were used for the simulation of the different systems. The exergoeconomic evaluation was conducted using MATLAB, and the ExIO module [18], that is a complement of the Microsoft Excel. The main parameter to analyze is the unit exergy cost of product, which represents the amount of exergy required to get a unit of exergy of the product.

The standalone CSP plant is composed of the solar field, thermal energy storage, backup system, and power block, configured similarly to Andasol-1 power plant [1], [11]. The solar field consists of EuroTrough collectors, Schott PTR-70 absorber tubes, and Dowtherm A as heat transfer fluid. Its design temperature is 393 ºC and 293 ºC as the outlet and inlet values. The direct normal irradiance considering is 1 010 W/m^2 at the design point, and the collector optical efficiency is 72 % [1]. The aperture area is 510 120 m^2 and a solar multiple of 2.56. The thermal energy storage system has two-tank indirect system using molten salts; its capacity is 12 h of full peak. The power block consists of a regenerative Rankine cycle with reheat and six extractions. The gross power production is 55.0 MW$_e$, the high-pressure turbine inlet pressure is 100.0 bar and the low-pressure turbine backpressure is 0.06 bar.

The MED desalination plant considers 12 parallel-cross feed effects and 11 feed preheaters [1]. The feed seawater intake temperature is 25 °C, the feed seawater temperature after down condenser is 35 °C and the maximum salinity in each effect is 0.072 kg/kg. The top brine temperature is 65 °C, the fresh water production is 37 168 m^3/day, and the amount of distillate produced per unit mass of the input thermal energy is 9.1. The concentration factor is 1.7, the specific heat consumption is 245.2 kJ/kg, and the specific electricity consumption is 1.5 kWh/m^3.

The process heat plant (PH) is configured by a counter-current heat exchanger [1] and its nominal thermal load is 7 MW$_{th}$. The heat exchanger inlet and outlet temperatures are 63 °C and 90 °C, respectively.

Each standalone system was validated against data reported in the literature; therefore, the trigeneration plant model is the combination of validated models. The CSP plant was validated by comparing the results between the

IPSEpro/Matlab model and the case study (Andasol-1) of SAM software [19]. Regarding the MED plant, it was validated considering the data reported by Zak et al. [20] and from El-Dessouky et al. [21].

The solar trigeneration plants are depicted in Figure 1. First, in Trigen 1 the MED plant replaces the power cycle condenser and the PH plant is coupled to the fifth turbine extraction, in which the low-pressure turbine back-pressure is modified to 0.37 bar, since the MED plant must operate within a specific temperature range. Second, in the case of Trigen 2, the MED plant and the PH plant is coupled to the sixth and fifth turbine extraction, respectively. The low-pressure turbine back-pressure is not modified. Finally, the aperture area of Trigen 1 and Trigen 2 are 607 282 m^2 and 585 151 m^2, respectively. Note that the aperture areas were modified to develop the same gross power of the standalone CSP plant.

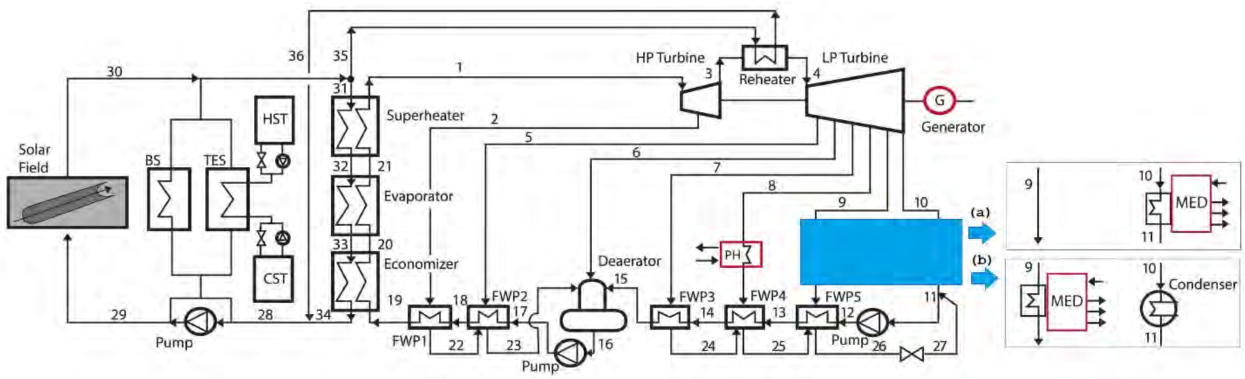

FIGURE 1. Configuration of solar trigeneration plants. (a) Trigen 1, (b) Trigen 2.

The symbolic exergoeconomic methodology [12]–[14] provides information on the irreversibilities generated in each component, the exergy cost formation of each component, the malfunction and dysfunction, and the fuel impact. The system is described by a physical structure and a productive structure. The physical structure depicts the devices that constitute the system, while the productive structure is built according to the purpose of each component and shows the origin of the resources (named Fuel) of each component and its product. It is not necessarily equal to the physical structure of the system. The productive structure depends on the fuel and product definitions, and the disaggregation level selected. First, the productive structure is composed of n components connected by flows characterized by its exergy flow. Each component consumes resources from other components (named Fuel), to produce useful effects for other components (named Product). Fuel is transformed into product and irreversibility. Second, the disaggregation level in this study, considerer the CSP plant at level of components, and the MED and PH plant at level of a unique subsystem each one, as can see in Figure 1. Finally, the mathematical formulation of the symbolic exergoeconomic methodology is described in Torres et al. [13] and in a previous article of the authors [8].

The energy systems generally have productive and dissipative components. The productive components provide functional products, fuel to other processes, and residues. Likewise, the dissipative components are required to reduce or eliminate the environment impact of residues, to maintain the operation conditions of the system, and to improve the efficiency of the system [8]. The CSP plant and MED plant have productive and dissipative components, in which the dissipative components are condensers, while the PH plant only has productive components.

The unit exergy cost of the product is decomposed into two parts: the unit production cost due to irreversibilities of the components, and the unit production cost due to the residues. The unit exergy cost is expressed in kW/kW. The process to assess the cost of the flow streams and processes helps to understand the process of cost formation, from the input resources to the final products. Note that the production costs can also be broken down into three contributions: the cost of the resources needed to obtain it, the investment and operation costs, and the costs associated with the allocation of the residues. Then, the unit exergy cost is expressed in USD/kWh. This analysis was already done in previous studies conducted by the authors [1], [11].

RESULTS AND DISCUSSION

Figure 2 shows the results of the cost decomposition of the components that contribute to the cost formation of each product in every plant evaluated. Electricity, fresh-water, and heat are produced in the Generator of the CSP plant, the MED module, and PH module, respectively. The main components that contribute to the cost formation of electricity, in standalone and trigeneration plants, are the solar collectors, evaporator, and reheater. In the case of fresh-water, in trigeneration plant, are the solar collectors, dissipator_MED, MED module, and evaporator. For the process heat are the solar collectors, PH module, and evaporator. Finally, for the other standalone plant (MED and PH plants), the main contribution comes from the boiler, that has the higher exergy destruction because it is the highest heat source.

The unit cost of product is integrated by the sum of the irreversibility contributions of the components and the residues allocation. The solar collector has the highest share in the unit exergy cost in the standalone CSP and trigeneration plants, that it is attributable to the irreversibilities related with the temperature difference between the sun and the collector work fluid. On the other hand, the dissipative components, as power cycle condenser and dissipator_MED, allow reducing the environmental impact of residues, which are charged proportionally to the cost of products dissipated.

In order to reduce the unit exergy cost of each product (electricity, fresh water, and process heat), the solar collector, evaporator, reheater, dissipator_MED, MED module, and PH module should be analyzed in depth in an optimization process.

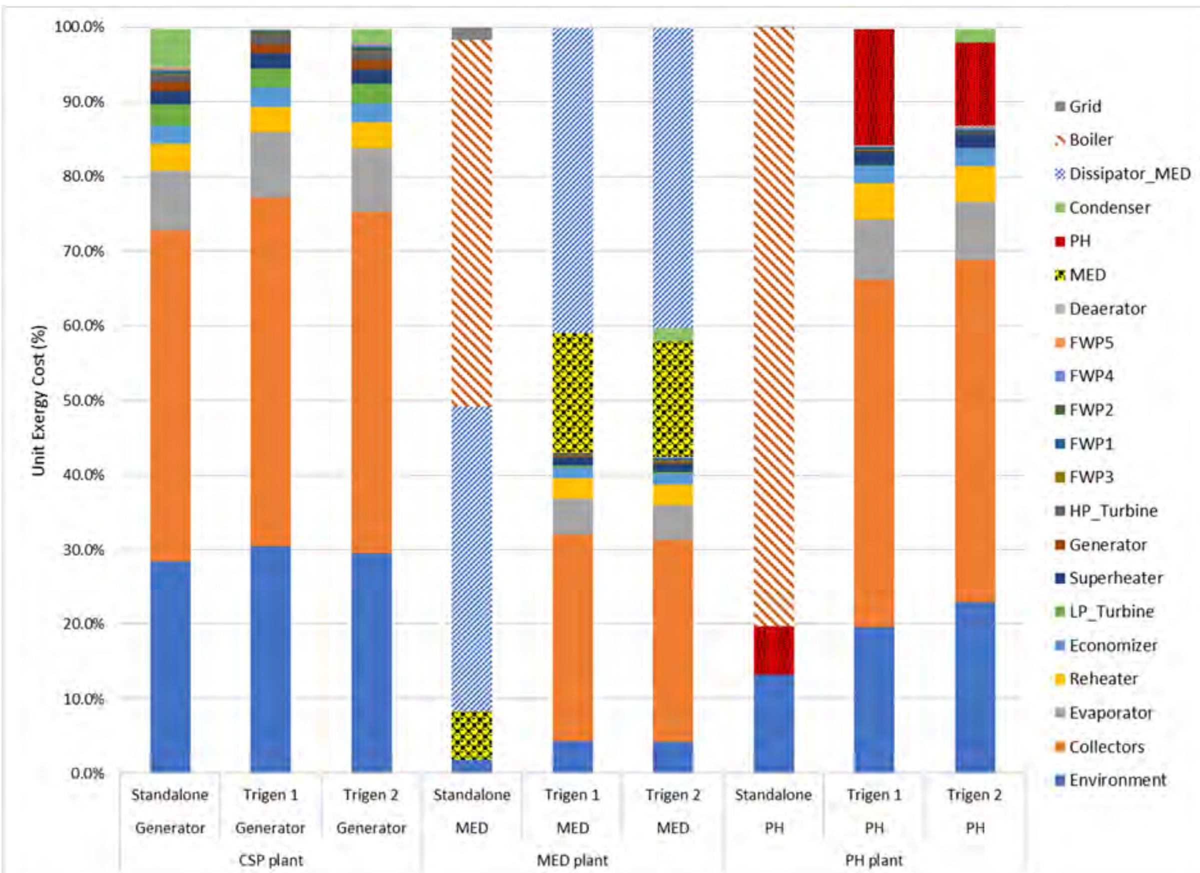

FIGURE 2. Cost decomposition of Generator, MED, and PH in standalone and trigeneration plants.

Regarding the comparison of these plants, the results are presented in Figure 3. According to the results, a solar trigeneration plant is more cost effective than stand-alone systems, and Trigen 1 is better than Trigen 2. In term of unit exergy cost, the best configuration is Trigen 1 that is when the MED plant replaces the condenser of the power cycle; however, only the process heat can be regulated to the demand but is not possible to regulate the fresh-water production independently of the power production, since the MED plant is driven by the heat rejected from the power cycle condenser. For this reason, any problem, as a failure event or maintenance stop in the MED plant or in the CSP plant, will affect both productions. Conversely, in Trigen 2, both the fresh water and process heat can be regulated according to the demand independently of the power production.

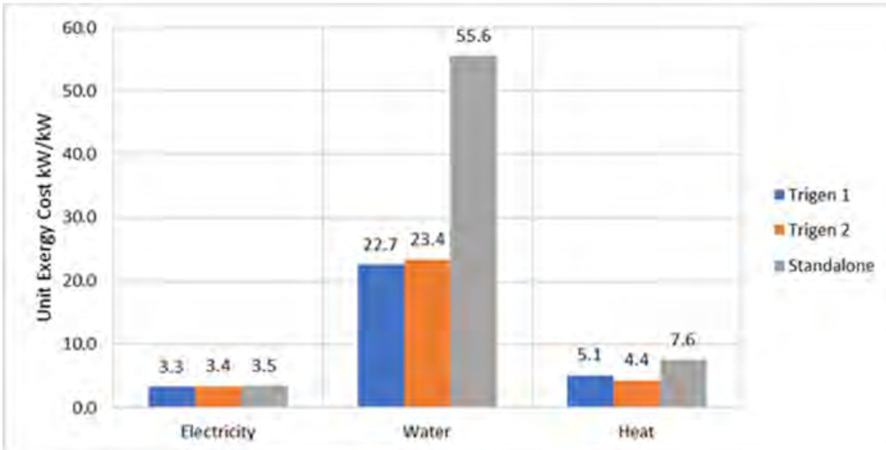

FIGURE 3. Unit exergy cost of electricity, water, and heat.

CONCLUSIONS

The symbolic exergoeconomic methodology was applied to solar trigeneration schemes and standalone plants to compare and analyze the process of cost formation in term of unit exergy cost. The configurations analyzed include a concentrated solar power as the prime mover, a multi-effect distillation plant, and a process heat module. The solar trigeneration plants were simulated to satisfice a large demand for energy and fresh water in zones with high irradiation conditions and scarcity of water.

Symbolic exergoeconomic methodology delivers crucial information to the design and optimization process of complex systems such as trigeneration schemes. It constitutes a rational method to assess a CSP-trigeneration plant since it is based on the quality of energy assessed. It provides a general criterion that enables to assess the efficiency of trigeneration systems and rationally explains the process of cost formation of products, in which to decompose the production costs into the contributions of the components irreversibilities and residues cost.

The best configuration is when the MED plant replaces the condenser of the power cycle. That plant was the most cost-effective configuration.

Results show that the main components that contribute to the costs formation of electricity are: solar collectors, evaporator, and reheater. In the case of fresh water are: solar collectors, MED's dissipative, MED module, and evaporator. Finally, in the process heat are: solar collectors, PH, and evaporator. Those components are the key equipment, on which the design should be improved in order to reduce the unit exergy cost of each product.

The solar trigeneration plants are more cost-effective than stand-alone systems, therefore they are a promising alternative for the supply of electricity, fresh-water, and process heat for a zone with high irradiation conditions, scarcity of water, and a short distance to consumption centers.

In future studies, a thermoeconomic diagnosis of the operation of a CSP-trigeneration plant should be conducted to determine the malfunction and dysfunction of a process. Also, it might be considered studies of different configurations of solar multi-generation plants (cogeneration, trigeneration, and polygeneration schemes) through different coupling points in a concentrated solar power plant.

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NOMENCLATURE

BS: backup system
CSP: concentrated solar power
CST: cold storage tank
FWP: feed water preheater
G: generator
HP: high pressure
HST: hot storage tank
LP: low pressure
MED: multi-effect distillation
PH: process heat
Trigen: trigeneration
TES: thermal energy storage

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