Exergy cost decomposition and comparison of integrating seawater desalination plant, refrigeration plant, process heat plant in a concentrated solar power plant

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Abstract

A thermoeconomic analysis of a solar polygeneration plant for the joint production of electricity, fresh water, cooling, and process heat is carried out, in order to analyze in depth the process of exergy cost formation and comparing with standalone systems. The solar polygeneration plant consists of a concentrated solar power as prime mover, and a multi-effect desalination, a refrigeration absorption, and a process heat plants. Results show that the main components that contribute to the costs formation are: solar collectors, evaporator, re-heater, economizer, turbine, and super-heater. Also, a solar polygeneration plant is more cost effective than stand-alone systems, which produces the lower unit exergy cost of electricity, water, cooling and heat.

Keywords: polygeneration, symbolic thermoeconomic, exergy cost theory, concentrated solar power, multi-effect distillation, refrigeration.

1. Introduction

Polygeneration is the integration of multiple utility outputs with one or more inputs for better performance. The better performance may be assessed from different aspects, such as, thermodynamic, economic, environmental, and social, in which the main advantages are in terms of the improvement of energy efficiency and cost-effectiveness, use of alternative fuels and energy carriers, and reduction of emissions. Its advantages make polygeneration competitive technologies [1]. In a topping cycle polygeneration system [2], fuel is used in the prime mover, typically in a power cycle such as Rankine, Brayton or Diesel cycles, that generates electricity, and the prime mover's hot exhaust is used to supply thermal energy to other technologies driven by heat, like thermal distillation, process heat (industrial heating, production of synthetic fuels, and other), and absorption cooling. The concentrated solar power (CSP) as a prime mover is an interesting alternative to analyze the operation of a polygeneration scheme since it produces electricity fueled by solar energy, and could be helped by a thermal energy storage or the hybridization with a fossil fuel or a biofuel. This allows continuous operation, with a capacity factor similar to a conventional plant to better match supply with demand, and additionally, rejects thermal energy from the power cycle that it is feasible to couple it with technologies driven by thermal energy. In order to evaluate the integration in a polygeneration scheme there are several methods [1], [3], [4], however the thermoeconomic (or exergoeconomic) method [5] is recommended because provides compact matrix-based formulation for the detailed analysis of complex systems such as polygeneration systems, where the Second Law of Thermodynamics provides its physical roots [6]. Exergy 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 this system because it allows measuring in the same physical unit resources of very different nature, for instance electricity, energy, water, cooling, heat, resources, and waste. The exergy cost of mass and/or energy flow represents the units of exergy used to produce it, i.e. the exergy cost of a flow is the amount of resources expressed in exergy consumed for producing this flow [7]. The unit exergy cost allows analyzing and identifying integrations because it is possible to determine the potential for resources savings. Exergy cost is a conservative magnitude that increases in every process according to the irreversibility involved in that process. So, in an integrated process, it is interesting to study in depth how exergy costs are being formed, therefore the process of cost formation

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provides vital information for the designer and evaluator that allows a better design and performance analysis, respectively.

CSP could be integrated into polygeneration schemes [8] and different studies have focused mainly on the final cost of each product [9]–[12]. However, such those studies do not consider the evaluation of the process of exergy cost formation and the decomposition of each cost. For the reasons mentioned above, a solar polygeneration system is analyzed by applying the symbolic exergoeconomic method to study the process of exergy cost formation and to determine the main components that contribute to the cost formation of each product, so that find out new opportunities for savings. The solar polygeneration scheme considered in this work is composed of a concentrated solar power, a multi-effect desalination plant, a single-effect refrigeration absorption module, and a process heat module.

2. Methodology

The methodology consists first of the modeling of a solar polygeneration plant and stand-alone plants. Secondly symbolic exergoeconomic methodology [6], [13], [14], which is a technique based on the exergy cost theory [15], was then applied.

The solar polygeneration plant is depicted in Figure 1, this consists of a concentrated solar power [16], [17] type parabolic trough with thermal energy storage (TES) and backup system (BS), a multi-effect desalination (MED) plant [18], a single-effect refrigeration absorption (REF) plant [19], and a process heat (PH) module. The configuration and validation of the solar polygeneration plant and the stand-alone systems are described as Poly 1 and stand-alone plants in a previous study of the authors [11].

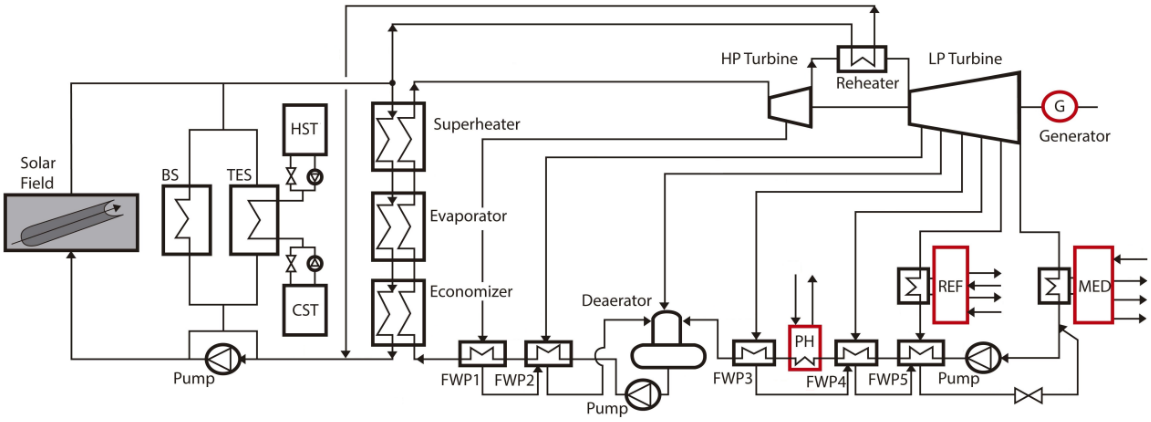

Fig.1. Configuration solar polygeneration plant. CST: cold storage tank, FWP: feed water preheater, G: generator, HP: high pressure, HST: hot storage tank, LP: low pressure.

The main characteristics of those plants are shown in the Table 1.

Tab. 1: Main characteristics of the polygeneration plant and the stand-alone plants.

Property	Polygeneration	Stand-alone
CSP		
TES, storage fluid	Two tank, molten salt	
Tank temperature (cold/hot), °C	292 / 386	
Full load hours of TES, h	12	
Parabolic trough collector model	EuroTrough	
Absorber tube	Schott PTR-70	
Heat transfer fluid	DowTherm A	
Collector optical efficiency, %	72.073	
Irradiance at design day, W/m^2	1 010	
Solar Field inlet temperature (inlet/outlet), °C	293 / 393	
Aperture area, m^2	616 650	510 520

Solar Multiple	2.56	
BS efficiency	90 %	
Capacity factor	96 %	
Gross power production, MW_e	55.0	
HP turbine inlet pressure, bar	100.0	
LP turbine back pressure, bar	0.37	0.06
MED		
Feed seawater intake temperature, °C	25	
Feed seawater intake salinity, kg/kg	0.042	
Feed seawater after down condenser temperature, °C	35	
Maximum salinity in each effect, kg/kg	0.072	
Top brine temperature, °C	65	
Gained Output Ratio, kg/kg	9.07	
Fresh water production, m^3/day	37 168	
Concentration factor	1.7	
Specific heat consumption, kJ/kg	245.2	
Specific electricity consumption, kWh/m^3	1.5	
REF (single stage absorption chiller)		
Cooling capacity, MW_{th}	5	
Chilled water temperature (inlet/outlet), °C	10 / 6	
Cooling water temperature (inlet /outlet), °C	25 / 35	
Inlet temperature desorber, °C	108.49	
Coefficient of Performance (COP)	0.70	
PH (countercurrent heat exchanger)		
Process heat capacity, MW_{th}	7	
Heat exchanger temperature (inlet/outlet), °C	63 / 90	

The solar systems were simulated at the design point by considering an hourly meteorological year [20]. The software IPSEpro [21] and MATLAB were used for the simulation of the different systems. The exergoeconomic evaluation was conducted using MATLAB, and the ExIO module [22] as a complement of the Microsoft Excel.

The exergy cost theory (ECT) provides a general criterion that enables to assess the efficiency of energy systems and rationally explains the process of cost formation of products. Thus, it is a cost accounting methodology that propose methods to determine the number of resources required for getting a product. As a numerical technique, cost values could be assessed. And with the help of the symbolic exergoeconomic method, the causes of the cost formation process can be easily obtained by using matrix algebra. The ECT requires that the system be described by a physical structure and a productive structure, the last structure is built according to the purpose of each component, and shows the origin of the resources of each component and its product. Each plant has only one physical structure to describe the physical relations between the process units, but various productive structures can be defined depending on the fuel and product definitions as well as the disaggregation level selected. The disaggregation level is interpreted as the degree of accuracy of the analysis. Each subsystem can be a part of an equipment, an equipment, or a group of equipment. The productive diagram is a graphic representation of the thermoeconomic model of the plant, in which the inputs of a component are its resources, and the outputs of a component are its products. This structure is composed of n components connected by flows characterized by its exergy. Each component consumes resources from other components or from an environment (those resources are named Fuel), to produce useful effects for other components or for the environment (those useful effects are named Product). Fuel (F) is partially transformed into product (P) and partially destroyed as irreversibility (I). A flow from component i to component j is represented by the exergy flow, then, the Fuel and Product is defined as

$$F_i = P_i + I_i = \sum_{j=0}^{n} E_{ji} \quad \text{(eq. 1)}$$

$$P_i = F_i - I_i = \sum_{j=0}^{n} E_{ij} \quad \text{(eq. 2)}$$

where E_{ij} is the exergy flow, the subscripts i and j are generic components.

The fuel-product presentation is the adjacency matrix of the productive graph, that allows getting all flows within the productive structure, and is based on distribution coefficients y_{ij} which indicate the proportion of the production of the j-th component used as resource for the i-th component: it shows how the product of a component is distributed among the other components and the environment.

$$y_{ij} = \frac{E_{ij}}{P_j} \quad \text{(eq. 3)}$$

Expressing the Equation 1 as function of y_{ij}, it yields:

$$F_i = E_{0i} + \sum_{j=1}^{n} E_{ji} = E_{0i} + \sum_{j=1}^{n} y_{ij} \cdot P_j \quad \text{(eq. 4)}$$

The previous equation in matrix notation is:

$$\boldsymbol{F} = \boldsymbol{F}_e + \langle \boldsymbol{FP} \rangle \cdot \boldsymbol{P} \quad \text{(eq. 5)}$$

where $\boldsymbol{F}$ and $\boldsymbol{P}$ are vectors of all fuels and products, $\boldsymbol{F}_e$ is the vector of external resources, and $\langle \boldsymbol{FP} \rangle$ is a matrix composed of elements y_{ij}.

Similarly, with the same procedure, it is obtained:

$$\boldsymbol{P} = (\boldsymbol{K}_D - \langle \boldsymbol{FP} \rangle)^{-1} \cdot \boldsymbol{F}_e \quad \text{(eq. 6)}$$

where $\boldsymbol{K}_D$ is a diagonal matrix containing the unit exergy consumptions of all components (k_i), defined as

$$k_i = \frac{1}{\psi_i} = \frac{F_i}{P_i} \quad \text{(eq. 7)}$$

where ψ_i is the exergy efficiency.

Equation 6 allows to calculate the products of all components starting from the external resources consumed by the plant ($\boldsymbol{F}_e$) and using the parameters that define the components (unit exergy consumptions and distribution coefficients).

The thermoeconomic analysis of energy systems, such as a polygeneration plant, has productive and dissipative components. The productive components provide functional products, fuel (resources) to other processes, and residues and waste disposals. Likewise, the dissipative components are required to reduce or eliminate the environment impact of residues and waste, to maintain the operation conditions of the system, and to improve the efficiency of the system.

According to the cost model, the exergy cost of the product is defined as

$$C_{P,i} = C_{F,i} + C_{R,i} \quad \text{(eq. 8)}$$

where C is the exergy cost, and the subscripts P, F, and R mean product, fuel, and residues, respectively.

The costs of the external resources are known values as

$$C_{e,i} = E_{0i} \quad \text{(eq. 9)}$$

and the cost of each flow making up the product is proportional to its exergy

$$C_{ij} = c_{P,i} \cdot E_{ij} \quad \text{(eq. 10)}$$

where $c_{P,i}$ is the unit exergy cost of the product of i-th component.

The exergy cost of residues allocated to each productive unit is

$$C_{R,i} = \sum_{r\epsilon V_D} C_{ri} = \sum_{r\epsilon V_D} \beta_{ir} \cdot C_{P,r} \qquad \text{(eq. 11)}$$

where C_{ri} is the exergy cost of the residues dissipated in the r-th component that has been generated by the i-th productive component, β_{ir} is the residue cost distribution ratio, V_D is the set of the dissipative system components. The residue cost distribution ratios represent the portion of the cost of the residue dissipated in the r-th component which has been generated in the i-th productive component.

The exergy cost of the product is decomposed into two parts

$$\boldsymbol{C}_P = (\boldsymbol{C}_e + \boldsymbol{C}_R) \cdot (\boldsymbol{U}_D - \langle \boldsymbol{FP} \rangle)^{-1} = \boldsymbol{C}_P^e + \boldsymbol{C}_P^r \qquad \text{(eq. 12)}$$

where $\boldsymbol{C}_P^e$ is the exergy cost due to irreversibilities of the components, $\boldsymbol{C}_P^r$ is the exergy cost due to the residues allocation, and $\boldsymbol{U}_D$ is the identity matrix.

In the same form, the unit exergy cost of the product is decomposed into two parts

$$c_p = c_P^e + c_P^r \qquad \text{(eq. 13)}$$

where c_P^e is the unit production cost due to irreversibilities of the components, c_P^r is the unit production cost due to the residues, they are calculated by

$$c_P^e = (\boldsymbol{U}_D - \langle \boldsymbol{FP} \rangle)^{-1} \cdot \boldsymbol{c}_e \qquad \text{(eq. 14)}$$

$$c_P^r = (\boldsymbol{U}_D - \langle \boldsymbol{FP} \rangle)^{-1} \cdot \boldsymbol{c}_R \qquad \text{(eq. 15)}$$

where $\boldsymbol{c}_e$ is the unit exergy cost of the external resources, $\boldsymbol{c}_R$ is the unit exergy cost of the residues.

In summary, the process to assess the cost of the flow streams and processes in a polygeneration plant helps to understand the process of cost formation, from the input resources to the final products.

Note that in this analysis different levels of disaggregation were taken: in the case of the CSP plant, is considered at the level of components, but in the case of the systems to provide the other products, there are considered at the level of a unique subsystem. Finally, nominal conditions of both alternatives have been used estimates this exergy cost analysis.

3. Results and discussion

3.1. Stand-alone plants

The results about the costs decomposition for the stand-alone CSP plant are depicted in Figure 2 and shows how the unit cost of product is obtained as the sum of the irreversibility contributions of the other devices which are preceeding this product. The main components that contribute to the costs formation of electricity cost (in the generator), in descending order of importance, are: solar collectors, evaporator, condenser, reheater, low-pressure turbine, economizer, and superheater. In the solar collectors is produced the most significant exergy destruction, that it is attributable to the irreversibilities associated with the large temperature difference between the sun and the heat transfer fluid. Furthermore, it can be seen that this exergy cost is charged to the rest of components according to a topping cycle scheme. On the other hand, the condenser is a dissipative component, that is allocated to all productive units. It interacts with other components, in the sense is that the device allowing to close a thermodynamic power cycle. As its operating temperature is quite low, from the point of view of the Second-Law of Thermodynamic, its contribution to exergy costs is not so high, being the steam generator (or solar collectors in this case) the main inefficient components.

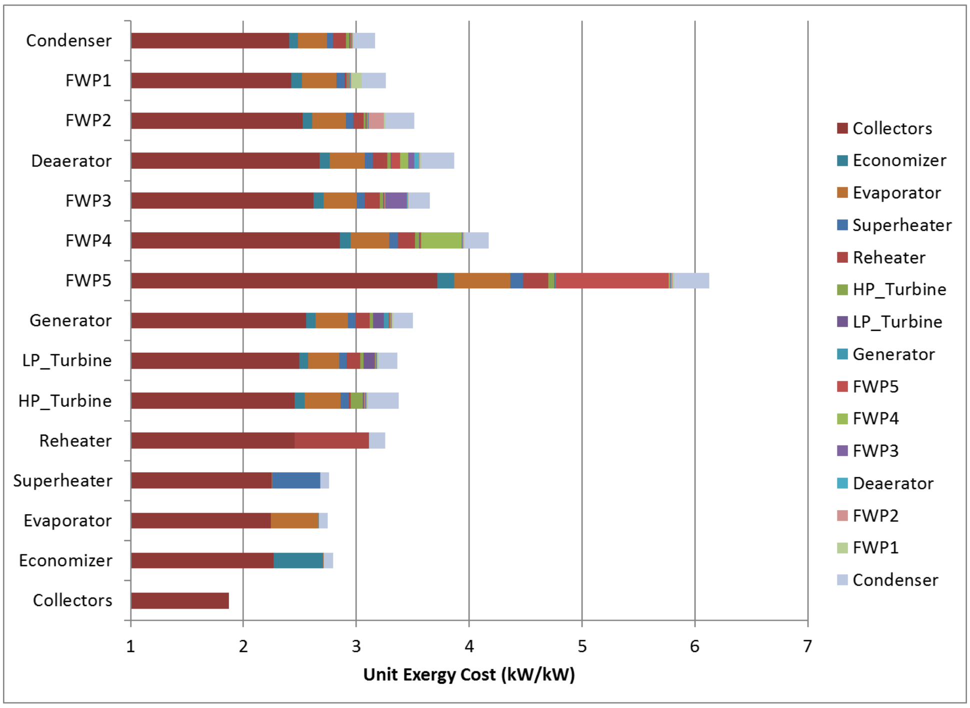

Fig. 2: Cost decomposition in stand-alone CSP plant.

In the case of other stand-alone plants, the main contribution in the cost of each product comes from the boiler, being the higher heat source and then having the higher exergy destruction. Note that since both the MED plant and the REF plant include a dissipative component to operate, they participate in the costs formation. Figures 3, 4 and 5 show the costs decomposition in the other stand-alone plants. In the case of the PH major exergy costs comes from the boiler and a residual additional cost comes from the heat exchanger to accommodate the heat supply.

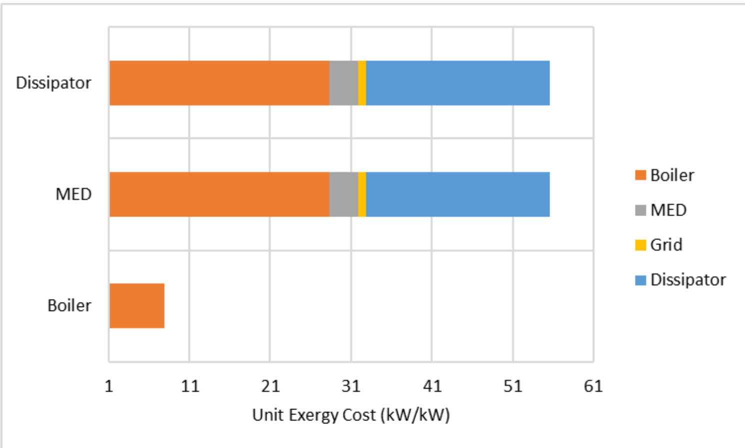

Fig. 3: Cost decomposition in stand-alone MED plant.

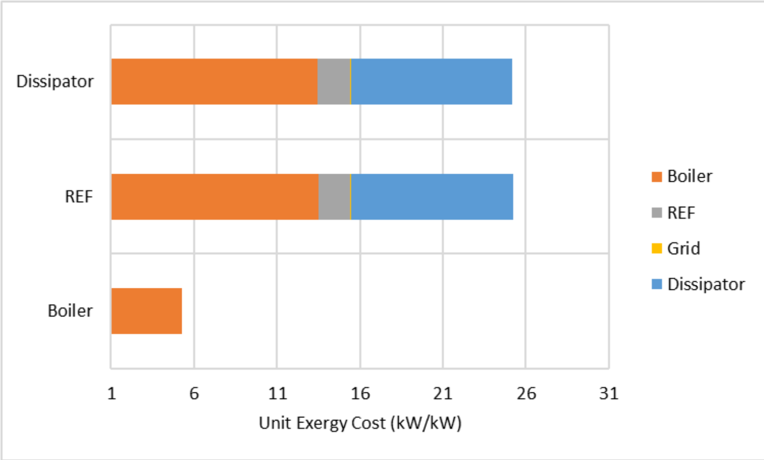

Fig. 4: Cost decomposition in stand-alone REF plant.

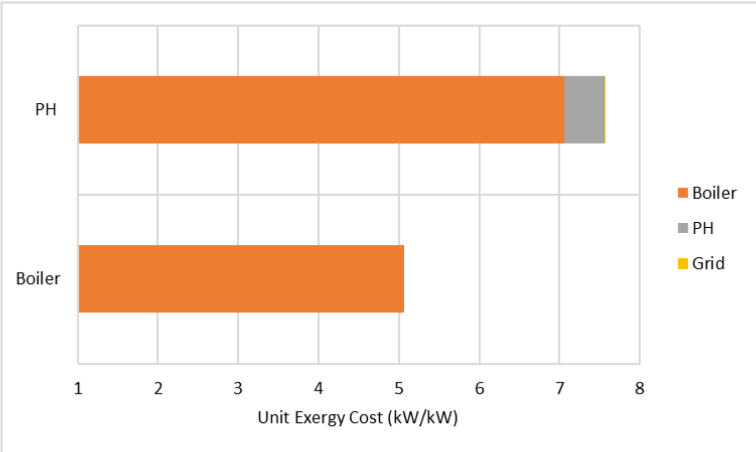

Fig. 5: Cost decomposition in stand-alone PH plant.

3.2. Polygeneration plant

The costs decomposition in the solar polygeneration plant is depicted in Figure 6. The products such as electricity, fresh water, cooling, and head are produced in Generator, MED, REF and PH, respectively. The main components that contribute to the costs formation of electricity are: solar collectors, evaporator, reheater, economizer, low-pressure turbine, and superheater. In the case of water, these components are: MED's dissipative, solar collectors, MED, evaporator, reheater, economizer, and superheater. In the case of cooling, the devices are: REF's dissipative, solar collectors, REF, evaporator, reheater, economizer, and superheater. Finally, in the case of process heat, they are: solar collectors, PH, evaporator, reheater, feed water preheater (FWP4), economizer, and superheater. In order to reduce the costs of products, it is necessary to first consider these components in an in-depth process of analysis and optimization.

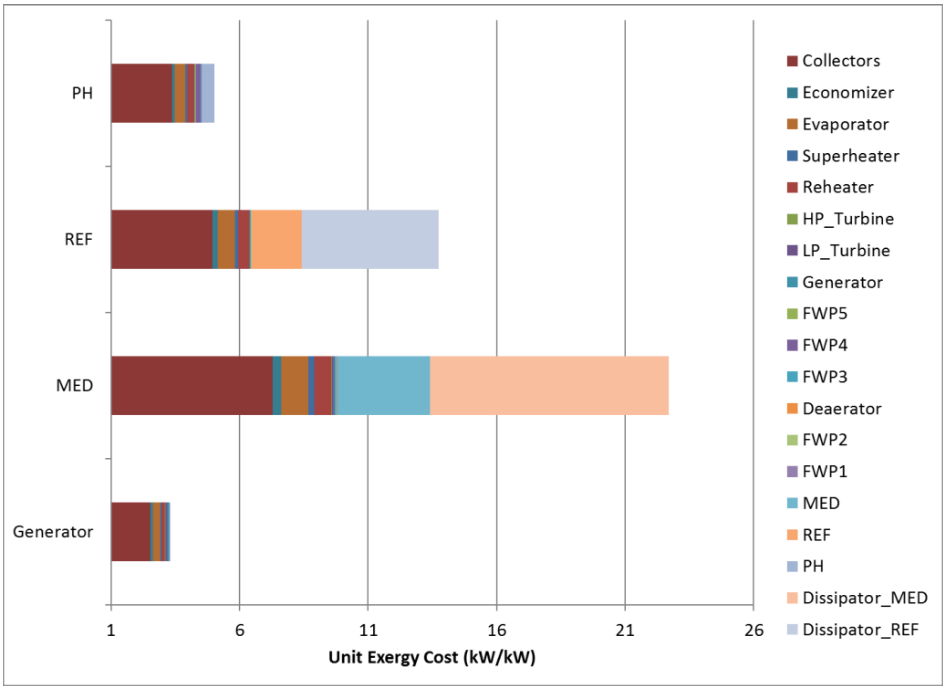

Fig. 6: Cost decomposition in polygeneration plant.

3.3. Comparison between polygeneration plant and stand-alone systems

Regarding the comparison between polygeneration plant and standalone systems, the results are presented in Figure 7. According to these results, a solar polygeneration plant is more cost-effective than stand-alone systems, since a lower unit exergy costs of electricity, water, cooling and process heat has found with respect to the stand-alone scheme. Remember that the unit exergy cost represents the amount of exergy required to get a unit of exergy of the product, i.e. the resources required to carry out the production. For instance, a unit of exergy cost of electricity of 3.3 kW means that 3.3 kW of exergy of resources is needed for producing 1 kW of electricity. The unit exergy cost is possible to express in USD/kWh also, but in this case, is necessary to consider the investment and operation costs. Anyway, this analysis was already done in a previous study conducted by the authors [11].

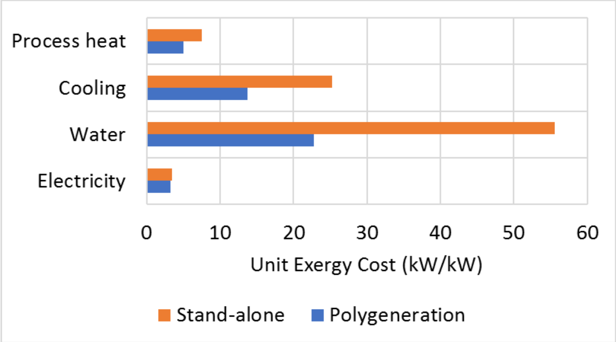

Fig. 7: Unit exergy cost of each product.

4. Conclusions

The exergy cost theory was applied to a solar polygeneration plant and stand-alone plant to analyze the process of exergy cost formation in this complex and integrated scheme, as it is a solar polygeneration plant using a concentrated solar power as prime mover, a multi-effect desalination, a refrigeration absorption, and a process heat plants. The solar polygeneration plant was simulated in a location with high direct normal irradiations.

Symbolic thermoeconomic provides a method to decompose the production costs into the contributions of the components irreversibilities and residues cost, thus it determines the cost formation process in a solar polygeneration scheme. This method delivers information that is crucial to the design and optimization process of those complex schemes.

Results show that the main components that contribute to the costs formation of electricity in a solar polygeneration plant are: solar collectors, evaporator, reheater, economizer, low-pressure turbine, and superheater. In the case of stand-alone CSP plant is similar, but includes the condenser, the order is: solar collectors, evaporator, condenser, reheater, low-pressure turbine, economizer, and superheater. On the other hand, the main components that contribute to the costs formation of water are: MED's dissipative, solar collectors, MED, evaporator, reheater, economizer, and superheater. In the cooling are: REF's dissipative, solar collectors, REF, evaporator, reheater, economizer, and superheater. Finally, in the process heat are: solar collectors, PH, evaporator, reheater, feed water preheater (FWP4), economizer, and superheater. To sum up, it is noted that ECT allows finding some interactions between different plant components that are not necessarily very close one from the other.

The analysis shows that the integrated solar polygeneration plant is more cost-effective than stand-alone systems since it produces the lower unit exergy cost of electricity, water, cooling and heat.

Nevertheless, the ECT applied here should be enlarged in future studies to different configurations of solar multi-generation plants (cogeneration, trigeneration, and polygeneration schemes) through different coupling points in a concentrated solar power plant. Also, it might be considered other alternative technologies to provide desalted water and cooling.

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Nomenclature

A: solar field aperture area
BS: backup system
C : exergy cost
$\boldsymbol{C_P}$: exergy cost of the product
$\boldsymbol{C_P^e}$: exergy cost of product due to irreversibilities of the components
$\boldsymbol{C_P^r}$: exergy cost of product due to the residues allocation
c : unit exergy cost
$\boldsymbol{c_e}$: unit exergy cost of the external resources
$\boldsymbol{c_R}$: unit exergy cost of the residues
COP: coefficient of performance
CSP: concentrated solar power
CST: cold storage tank
E : exergy flow
ECT: exergy cost theory
FWP: feed water preheater
F: fuel
$\boldsymbol{F_e}$: vector of external resources
$\langle \boldsymbol{FP} \rangle$ matrix composed of distribution coefficients
G: generator
HP: high pressure
HST: hot storage tank
I: irreversibility
$\boldsymbol{K_D}$: diagonal matrix of unit exergy consumptions
k : unit exergy consumptions
LP: low pressure
MED: multi-effect distillation
P: product
PH: process heat plant
Poly 1: Polygeneration 1
REF: Refrigeration plant
SF: solar field
TES: thermal energy storage
$\boldsymbol{U_D}$: identity matrix
V_D : dissipative system components
y : distribution coefficients

Greek symbols

ψ : exergy efficiency
β_{ir} : residue cost distribution ratio