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Comparison of the levelized cost and thermoeconomic methodologies – Cost allocation in a solar polygeneration plant to produce power, desalted water, cooling and process heat

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ABSTRACT

The present work shows a comparison between the levelized cost and the thermoeconomic methods in their application to assess the performance of a solar polygeneration plant. The aim is to analyze the costs allocation process, the unit specific costs of each product, as well as the energy and exergy efficiencies, which allows to identify the main advantages of both the evaluated methods. The methodology is applied in a case study configured by a concentrated solar power with thermal energy storage and backup system, combined to a multi-effect distillation plant, an absorption refrigeration plant, and a process heat module. The present study reveals that through the levelized cost method, the cost associated to the electricity generation is higher than it is by applying the thermoeconomic method, whereas the costs of water, cooling and process heat are significantly lower. Those differences represent an increase of about 35.1% in the case of the electricity, and a reduction in the cost associated to the water, cooling, and heat production by around 34.4%, 78.1%, and 97.6%, respectively. Results show that the thermoeconomic method is an equitable and rational cost allocation method which is suitable for a solar polygeneration plant. This method is recommended when a more precise analysis is required to assess the proper costs of different products, and for assessing the benefits of a polygeneration plant, when compared to stand-alone plants. However, the levelized cost method is a simple and fast method, and a deep knowledge of thermodynamics is not required, being recommended when in need to perform a first approach of the costs of each product.

1. Introduction

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, seeking to extract the maximum thermodynamic potential (maximum thermodynamic efficiency) of the resources consumed [1]. In general, if a multi-generation system generates two products, it is named as a cogeneration system, such as Combined Heating and Power (CHP), Combined Cooling and Power (CCP), and Combined Water and Power (CWP) for example. Correspondingly if a multi-generation system generates three products, it is named as a trigeneration system, such as Combined Cooling, Heating and Power (CCHP). Finally, if a multi-generation system generates more than three products, it could be named generically as polygeneration system; however, in order to avoid any confusion, the term polygeneration is used in this paper to represent any scheme of a multi-generation system. The basic elements of a polygeneration plant is the prime mover or engine, which provides the mechanical motive power; the electrical power generator, and the heat recovery equipment including cooling, water distillation, and/or other subsystems. The typical prime mover can be a Rankine, a Brayton, a Diesel or a combined cycle.

Polygeneration systems are commonly classified as topping or bottoming cycle systems [2]. In a topping cycle, the priority is power production, i.e. the supplied fuel is first used to produce power and then thermal energy. In contrast, in a bottoming cycle, the priority is for heat production, i.e. high temperature thermal energy is the primary product delivered and the heat rejected from the process is recovered to

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Nomenclature

A	aperture area, m^2
BS	backup system
capex	capital expenditure, USD
Cf_j	fuel cost, USD/a
$\dot{C}_j$	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
EPC	Engineering, Procurement, and Construction
GOR	Gained Output Ratio, $kg_{distillate}/kg_{steam}$
i	discount rate, %
FWP	feed water preheater
HTF	heat transfer fluid
HST	hot storage tank
HP	high pressure
LC	levelized cost
LCC	levelized cooling cost, USD/kWh
LEC	levelized electricity cost, USD/kWh
LHC	levelized heat cost, USD/kWh
LWC	levelized water cost, USD/m^3
LP	low pressure
MED	multi-effect distillation
n	number of time periods, years
opex	operational expenditure or operation and maintenance cost, USD/a
$\dot{Q}_{th,power\ block}$	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
PH	process heat
T_0	ambient temperature, °C
TES	thermal energy storage
$t_{full\ load}$	hours of full-load of TES, h
UEC	unit exergy cost
$w_{des,gross}$	power cycle thermal in design-point, kW
$\dot{Z}$	total investment and operating and maintenance cost rate, or non-exergy-related cost rate, USD/h
$\dot{Z}_k^{CI}$	capital investment cost rates, USD/h
$\dot{Z}_k^{OM}$	operating and maintenance cost rates, USD/h

generate power. Polygeneration plants have been extensively employed within the industrial sector, where large concurrent heat and power demands are present [3]. A polygeneration scheme has comparative advantages over stand-alone systems, since it allows reducing both primary energy consumption and emissions of greenhouse gasses displacing fossil fuels, avoiding waste heat, reducing transmission and distribution network and other energy losses, as well as decreasing energy dependency at the country level, contributing to the diversification of energy sources [2]. According to the International Energy Agency [4] in 2014, the conversion of total primary energy supply to end use energy, in the world, was of 1.7% and 18.1% from CHP plants and electricity plants, respectively.

The average energy efficiency (First-Law of Thermodynamics) of fossil-fuelled power generation is about of 35–37%, whereas for polygeneration schemes it is around 75–80%, and up to 90% in the most efficient plants [3]. This means that about two-thirds of the primary energy input, which is the overall lost in traditional power generation, could be exploited leading to a significant reduction on both energy costs and CO_2 emissions [3]. Regarding the use of fuels in polygeneration schemes, fossil resources currently predominate. Renewable energies also have been used as primary energy sources in polygeneration schemes, allowing to generate electricity by delivering an input of thermal energy; in that context, biomass, geothermal and concentrated solar technologies [5] have been implemented in polygeneration schemes.

In order to integrate and properly assess a polygeneration plant, in which two or more goods are produced from one or more natural resources, it is necessary to determine the production cost of each product. Due to the complexity of dealing with many energy flows in polygeneration 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, investments, operation and maintenance costs, as well as the production units of each product. To solve this problem, several cost allocation methods have been proposed in the literature, which in general are classified in thermodynamic, economic, and thermoeconomic methods (or exergoeconomic). The thermodynamic methods are based on the First-Law and/or Second-Law of Thermodynamics [6–9], including several methodologies, such as the energy balance, work flow, kW equivalence, enthalpy drop, heat discount, weighting, entropy change, and exergy methods. The economic methods are similar to thermodynamic ones depending on whether lowering power or heat costs are in priority [8,10]. Among the available methods that exist are the proportional method, the equal distribution method, and the benefit distribution method. Finally, the thermoeconomic methods are based on the Second-Law of Thermodynamics and economic principles [1,11,12], which include algebraic and calculus methods. The algebraic methods use algebraic balance equations and auxiliary cost equations for each component, focus mainly on the cost formation process and determine average costs. The calculus method use differential equations, such that the system cost flows are obtained in conjunction with optimization procedures based on the method of Lagrange multipliers, and it is used to determine marginal costs [13].

1.1. Solar polygeneration plant

The use of the solar energy as main resource in a polygeneration system for producing energy and water is an opportunity for sustainable development. Solar energy can be captured and concentrated by Concentrated Solar Power (CSP) technologies to provide the heat required to generate electricity through a power cycle. Hence, a CSP plant could be the prime mover in a polygeneration scheme, operating as a topping cycle system, and other technologies could be integrated to generate by-products, such as desalted water, cooling and process heat. CSP is one of the promising options for electricity supply as demonstrated in some areas such as, Spain, USA, and North Africa [14]. CSP plants require abundant direct normal irradiation for producing