Energy Conversion and Management 168 (2018) 215–229

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

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

Roberto Leiva-Illanes[a,b,*], Rodrigo Escobar[a], José M. Cardemil[c], Diego-César Alarcón-Padilla[d]

[a] Escuela de Ingeniería, Pontificia Universidad Católica de Chile, Santiago, Chile
[b] Departamento de Mecánica, Universidad Técnica Federico Santa María, Viña del Mar, Chile
[c] Departamento de Ingeniería Mecánica, Universidad de Chile, Santiago, Chile
[d] CIEMAT-Plataforma Solar de Almería, Almería, Spain

ARTICLE INFO

Keywords:
Polygeneration
Thermoeconomic
Concentrated solar power
Multi-effect distillation
Absorption refrigeration

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

* Corresponding author at: Departamento de Mecánica, Universidad Técnica Federico Santa María, Av. Federico Santa María 6090, Viña del Mar, Chile, and Escuela de Ingeniería, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Santiago, Chile.
E-mail addresses: roberto.leiva@usm.cl, rleivaillanes@puc.cl (R. Leiva-Illanes).

https://doi.org/10.1016/j.enconman.2018.04.107
Received 22 January 2018; Received in revised form 20 April 2018; Accepted 28 April 2018
Available online 09 May 2018
0196-8904/

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 electricity to be economically attractive, limiting the regions of interest for deploying CSP systems to areas of high direct normal irradiation conditions, which are in general hot and dry regions. Moreover, the development of CSP plants requires availability of flat land and proximity to consumption centers. CSP can integrate thermal energy storage (TES) in order to increase the capacity factor and to provide dispatchable electricity to the grid, and could capture peak market prices. Additionally, CSP can be hybridized with a backup energy system (BS), which supplies thermal energy to maintain the plant's power generation at design conditions when there is a lack of solar radiation and/or thermal energy from TES.

The current CSP market is dominated by parabolic trough collector technologies, comprising around 85% of cumulative installed capacity [14]. CSP is considered a promising multi-purpose technology for electricity, heat and district cooling production, and water desalination [5], as it is easily integrated to thermal driven cycles that can produce fresh water, refrigeration and process heat. Within the industrial thermal desalination technologies, multi-effect distillation (MED) is considered the most attractive option due to its lower energy consumption (compared to the rest of the thermal technologies as multi-stage flash and solar stills), low sensitivity to corrosion, low presence of scaling, high development potential, and the possibility of operating at temperatures lower than 100 °C [15]. In the line of refrigeration systems driven by thermal energy, the single-effect absorption cycle is driven at low temperatures, between 80 and 110 °C [16], and is available in the market, making it a good alternative to be considered in a polygeneration scheme. Each technology can be integrated into the CSP plant taking into account its technical restrictions and the demand of each product. The size of the plants has been established to satisfy a large-scale supply from the mining industry (northern Chile, Australia, and North Africa), which operates continuously and presents a constant demand. The CSP plant has been chosen considering the already existing commercial plant, called Andasol 1, due to the technical data of this plant is available in different technical reports. The electric power is produced in the CSP plant and the heat rejected from the power production is then used to produce the other products (desalted water, cooling and process heat), whose production is limited by the availability of the heat rejected from the CSP plant. This also limits the size of the desalination, cooling, and process heat plants.

For the aforementioned, a solar polygeneration system is configured and simulated in order to produce electricity, desalted water, industrial cooling and process heat. The solar polygeneration plant proposed herein consists of a concentrated solar power parabolic trough collector field with thermal energy storage and backup system as prime mover, integrated to a multi-effect distillation plant, a single-effect absorption refrigeration system, and a counter-current heat exchanger as process heat plant. This solar polygeneration scheme was previously analysed by the authors in a recent work [17], in which a thermoeconomic assessment was performed considering that the plant operates in high direct normal irradiation conditions. The present work constitutes the continuation of that research, where its main contribution is a comparison between the levelized cost and the thermoeconomic methods applied to a solar polygeneration plant. The aim of that evaluation is to determine and compare the different unit costs of each product obtained by each method, such as levelized costs and unit exergy costs (electricity, water, cooling and heat); the cost allocation process; and the energy and exergy efficiencies.

1.2. Assessment of a solar polygeneration plant

CSP plants as the prime mover could be easily integrated into polygeneration systems, as demonstrated in [5,18]. Due to the potential of such systems, the integration of a CSP plant and desalination, refrigeration and process heat technologies has been analysed in several studies as described below, focusing mainly in cogeneration and trigeneration schemes. Nonetheless, currently there is only one CSP plant configured in a polygeneration system, the "Aalborg CSP-Brønderslev CSP with organic Rankine cycle project" [19] located in Denmark, a solar cogeneration plant for generating heat and power of 16.6 MW.

Two assessment methodologies have been intensively employed for analysing solar polygeneration plants: the levelized cost method [20] and the thermoeconomic method [11]. Both methodologies allow estimating separately the costs of each product generated by the system. The first method determines the present value of the total cost of investment, maintenance and operation, fuels, and revenues from the sales of by-products (such as carbon credits) of a productive plant over its economic life, considering equivalent annualized payments [21], levelized in monetary units per unit of annual production. The levelized cost (LC) allows alternative technologies to be compared considering different scales of operation or different investment and operating periods. In this context, several studies have focused on assessment of CSP-polygeneration systems using the levelized cost method. Olwig et al. [22] carried out a techno-economic analysis of integrated CSP and desalination plants, including MED and reverse osmosis (RO) systems. The authors determined the levelized water cost (LWC), considering a cash flow that includes the total investment costs (CSP and desalination plants), the fuel for backup, the maintenance and operation cost associated to desalination, while the annual revenues due to electricity sales were subtracted from the costs. Later, Moser et al. [23] developed a techno-economic model for the assessment of desalination plants, driven by renewable energies, based on CSP plant, MED and RO technologies. The model considers a detailed method for cost allocation to determine the LWC and levelized electricity cost (LEC), considering capital and operational costs. The operational cost includes fixed and variable operating costs, where the last one was determined using the reference-cycle method, in which the evaluation of heat cost is approached based on the comparison of steam turbine performances in two cases (MED case and reference case). The reference cycle is defined as a power block with standard cooling such as once-through or evaporative tower. Heat cost is defined as the cost needed to compensate the missing income that would be generated in the reference case, that constitutes the consistency in the allocation method employed.

Fylaktos et al. [24] carried out an economic analysis of an electricity and desalinated water cogeneration plant in Cyprus. Three different CSP schemes were examined: a CSP stand-alone plant, CSP-RO, and CSP-MED. They calculated the LEC for the whole plant using the kWh-equivalent method that consist in converting the revenues from water and from selling CO_2 allowances into equivalent electricity production units (kWh). Through this approach the plant is considered as an electricity-only system, and all the production is added and expressed in terms of the LEC. The estimation of the levelized cost was based on the substitution method, consisting in separate the LEC and LWC. In this context, for determining separately the LWC, it assumed that the difference of possible revenue streams between a CSP stand-alone plant and the cogeneration plant has occurred because of the integration of the desalination subsystem. Recently, Palenzuela et al [25] carried out a techno-economic analysis of different CSP-MED systems and compared them with a CSP-RO configuration, based on the assessment of the LEC and LWC. LEC contemplates the total investment cost of the CSP plant, the annual operation and maintenance costs, the annual fuel cost due the backup system, and the annual net electricity delivered to the grid. While LWC considers the investment, operation and maintenance cost, and the fresh water production. The steam energy cost and the electricity consumption by the MED were considered as internal costs, therefore neglected. In other recently study, Mata et al. [26] carried out an investigation on solar polygeneration for electricity production and desalination, considering two configurations of CSP-MED plants in two potential locations. Regarding the economic analysis, it is based on the LEC and LWC, where the annual fuel cost was only assigned to the LEC, since water is extracted as an additional product from the CSP plant and does not represent an additional fuel cost. At the same time, the electric and steam costs of the MED plant were considered as internal costs of the plant.

The main feature of the thermoeconomic method is that it proposes a cost balance equation applying the unit exergy cost to the exergy balance equation according to specific principles and rules [12] and at the same time, it allows to understand the cost formation process and the flow of costs in the system. Only a few studies have focused on thermoeconomic evaluation of CSP-polygeneration plants. In this context, Al-Sulaiman et al. [27,28] carried out an thermoeconomic optimization of three trigeneration systems using organic Rankine cycle for power, cooling and heating production. One of those trigeneration systems is a solar-trigeneration system, which consist of a CSP plant (including a parabolic trough collector field, TES, and an Organic Rankine Cycle as power block), and the heat recovery system composed of a steam generator and a single-effect absorption chiller. They used the specific exergy costing (SPECO) method as the thermoeconomic approach. This method is based on the notion that exergy is the only rational basis for assigning costs to the interactions that a thermal system experiences with its surroundings and to the sources of inefficiencies [11]. Along the same lines, Calise et al. [29] carried out an exergy and exergoeconomic analysis of a novel hybrid solar geothermal polygeneration system that produces energy and water, based on a hybrid system equipped with an organic Rankine cycle driven by a parabolic trough collector solar field and a geothermal well, a multi-effect distillation unit, and an absorption chiller. They applied an accounting of exergoeconomic costs in order to establish a monetary value to all material and energy flows, providing a reasonable basis for cost allocation. Recently, Ortega et al. [30] carried out a thermoeconomic comparison of the joint production of electricity and fresh water in a parabolic trough CSP plant, MED and RO units. The authors applied the largely used thermoeconomic method developed by Bejan et al. [11]. The thermoeconomic methodology was selected in order to assess the actual cost of the steam consumption of the distillation process, which allows assessing the cost of production for each asset and the services used to generate them so that these costs can be properly charged. Finally, in a recent publication by the authors Leiva-Illanes et al. [17] carried out a thermoeconomic assessment of the joint production of electricity, fresh-water, cooling and heat from a solar polygeneration plants. Three configurations were investigated, two CSP-polygeneration schemes and one considering stand-alone systems. The authors applied the same thermoeconomic method developed by Bejan et al. [11] and evaluated the plants in terms of the total exergy cost rate of products and unit exergy costs. This method allowed to determine the cost of each product using cost allocation rules, allocating the resources consumed to the useful product of each component, and distributing its costs proportionally to the exergy flow. The present work constitutes the continuation of this research were a comparison between the unit exergy cost and the levelized cost is deeply analysed.

As described above, different studies have been focused on assessment of CSP-polygeneration systems by the levelized cost method [20] and other by the thermoeconomic method [11]; however, the results from each method are unlike and produce significant differences. Hence, the present work aims to deliver insights about which method is more appropriate for assessing a solar polygeneration plant. For that reason, it is proposed an analysis in a CSP-polygeneration plant, in which the levelized cost method and the thermoeconomic method are applied, allowing to compare the costs allocation method used, the unit specific costs of each product, and the efficiencies according to the First-Law and Second-Law of Thermodynamics. Therefore, the main advantages of each method are determined in terms of the complexity of calculations, rules and rationality of cost allocation, and the applicability to compare between stand-alone plants and polygeneration plants. The results give relevant information for decision-makers to evaluate CSP-polygeneration systems and could constitute a guide to understand these methods.

2. Methodology

The methodology considers modelling stand-alone plants, and the integration of those plants in a solar polygeneration scheme. The solar polygeneration plant is modelled using a computational simulation platform, allowing the application of both evaluation methods: the levelized cost [20] and the thermoeconomic method [11]. The solar polygeneration plant is configured as a topping cycle, in which the priority is the production of electricity, and the by-products are generated according to the availability of thermal energy in the power cycle.

The software IPSEpro [31] was employed for modelling and simulating the solar polygeneration and stand-alone plants, without TES/backup-system. Three modules of IPSEpro were employed: IPSEpro-MDK, IPSEpro-PSE, and IPSEpro-PSXLink. IPSEpro-MDK is a model development kit that offers all the capabilities required to define and build new component models and to translate them into a form that can be used by IPSEpro-PSE. IPSEpro-PSE is a process simulation environment that allows establishing mass and energy balances, simulating different kinds of processes, through iterative Newton-Raphson method. IPSEpro-PSE provides only steady state solutions, so in order to assess the transient behavior of the system, IPSEpro-PSE is linked to Microsoft Excel through the IPSEpro-PSXLink tool. Using this module the input data, such as direct normal irradiance [32], the collector optical efficiency of solar field [33,34], and the demand for products, are modified for each time-step. The polygeneration plant is simulated considering an hourly resolution meteorological database [32]. The partial results are the solar field thermal input/output, and the production level of the solar field. Afterward, the simulation of the TES and backup system behavior was implemented using MATLAB software. Hence, the total production of each product is the sum of the production from the solar field, TES, and backup system. This approach allows to simulate the polygeneration plant over a one-year period using an hourly time step, and apply the levelized cost and the thermoeconomic method on an annual basis.

The polygeneration plant is evaluated disregarding the variations of kinetic energy, potential energy, and pressure drops in the lines, and considering the environmental conditions of the Atacama Desert in northern Chile. The Atacama Desert has one of the highest solar resources in the world; this region has flat and unused terrains, and it is close to consumption centers, such as mining facilities, that have high energy and water demands in the country. In particular, the simulation considered the meteorological conditions of the vicinity of Crucero substation (22.14 °S, 69.3 °W, 1 146 m above sea level), considered as one of the most relevant places for CSP development in Chile, due to the 3 389 kWh/(m^2 a) of annual direct normal solar irradiation [32].

2.1. Design parameters

A CSP plant is based on a number of sub-systems, such as solar thermal loop (composed of the solar field, thermal energy storage, and backup system), and a power block. Fig. 1 shows the CSP plant, that is configured considering the configuration of Andasol-1 power plant [33,34], located in southern Spain. The solar field (SF) consists of EuroTrough collectors aligned in a north-south orientation, Schott PTR-70 absorber tubes, and synthetic oil type Dowtherm A as heat transfer fluid. The design temperature of the SF considers 393 °C and 293 °C as the outlet and inlet values, correspondingly. The collectors track the sun from east to west during the day. The design point was considered as the 21st December at solar noon for Crucero (in the southern hemisphere), where the direct normal irradiance is 1 010 W/m^2 and the collector optical efficiency is 72% [34]. The solar multiple (SM) is a measure of the solar field aperture area as a function of the power

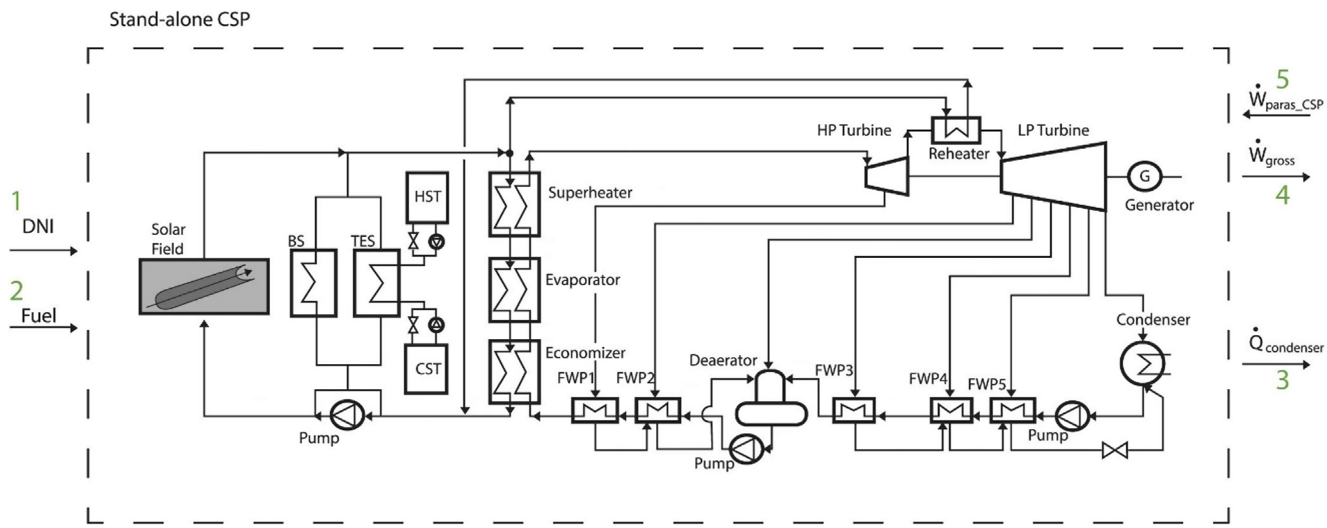

Fig. 1. Stand-alone CSP plant. DNI: direct normal irradiance, CST: cold storage tank, FWP: feed water preheater, G: generator, HP: high pressure, HST: hot storage tank, LP: low pressure.

block's nameplate capacity. This parameter is very important because allows sizing the SF and it is expressed as:

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

where $\dot{Q}_{th,solar\ field}$ is the thermal energy delivered by the solar field at the design point and $\dot{Q}_{th,power\ block}$ is the thermal energy required by the power block at nominal conditions. The solar multiple (SM) is assumed as 2.56, according to the design point of Andasol-1. That SF represents an area of 510 120 m^2. This is the aperture area that collects solar insolation, not include any reduction due to angle of incidence effects, shadowing or end losses.

The TES is assumed as a two-tank indirect system using molten salts as storage media. It presents 95% of annual storage efficiency [35], and the design temperature is 386 °C and 292 °C for the hot and cold tanks, respectively. TES_{th} is the equivalent thermal capacity of the storage tanks and is defined as:

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

where, $\dot{W}_{des.gross}$ is the gross power, η_{des} is the efficiency of Rankine cycle at design point, and $t_{full\ load}$ is the number of hours of thermal energy delivered at the power block's design thermal input level, being assumed as 12 h. $t_{full\ load}$ is a key parameter since it allows sizing the TES, i.e. determines the system's maximum storage capacity.

A natural gas heater is considered as a backup system, supplying thermal energy directly to the heat transfer fluid used in the SF. The capacity factor is assumed as 96%, as suggested in [25], considering that the solar polygeneration plant does not have restriction on the consumption of fossil fuel.

The power block consists of a regenerative Rankine cycle with reheat and six extractions, as described in Blanco-Marigorta et al. [36]. 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 high and low-pressure turbines present isentropic efficiencies of 85.2% and 85.0%, respectively. The generator efficiency is 98.0%, and the pumps isentropic efficiency is 70.0%.

Fig. 2 shows the MED desalination plant, that considers 12 parallel-cross feed effects and 11 feed preheaters, as described in Zak et al. [37]. The feed seawater intake temperature is 25 °C and its salinity is 0.042 kg/kg, the feed seawater temperature after down condenser is 35 °C whereas 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 Gained Output Ratio (GOR) is 9.1, which is defined as the amount of distillate produced per unit mass of the input thermal energy (steam from CSP plant). The concentration factor is 1.7, while the specific heat consumption is 245.2 kJ/kg, and the specific electricity consumption is 1.5 and 5 kWh/m^3 at the MED and the seawater pumping system [38], respectively.

Fig. 3 shows the refrigeration plant (REF), that is configured with a single-effect LiBr-H_2O absorption chiller, as described in Herold et al. [39]. It has a cooling capacity of 5 MW_{th} (1 421.73 tons) and a nominal coefficient of performance of 0.7. The chilled water inlet temperature is 10 °C and is discharged at 6 °C. The nominal cooling water temperature inlet and outlet are 25 °C and 35 °C, respectively. Moreover, the desorber inlet temperature is 108.49 °C.

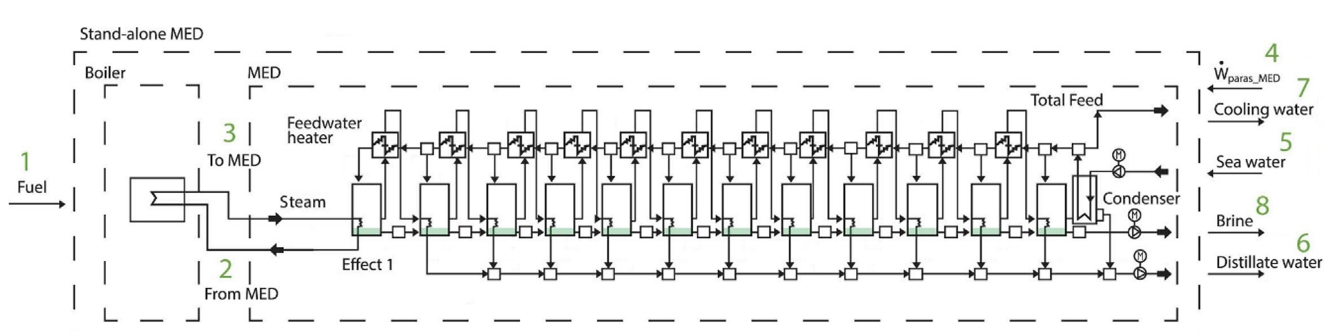

Fig. 2. MED plant.

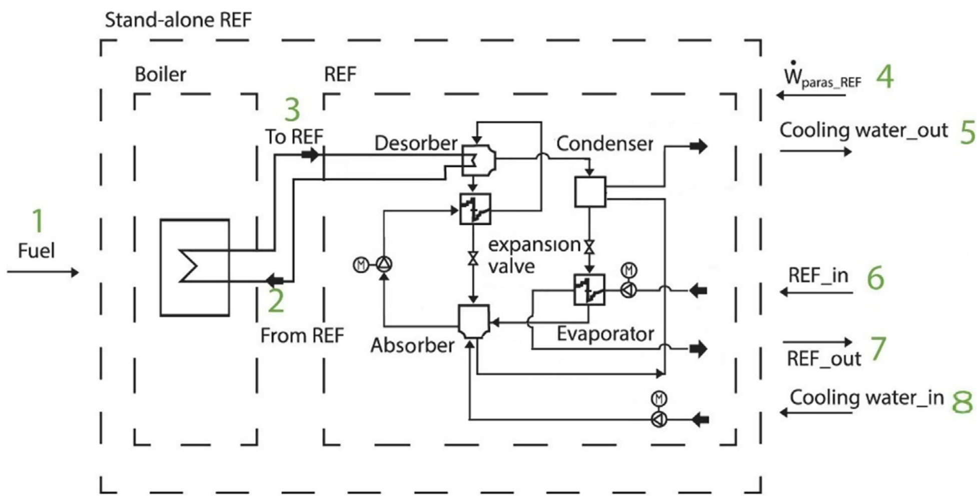

Fig. 3. Refrigeration plant.

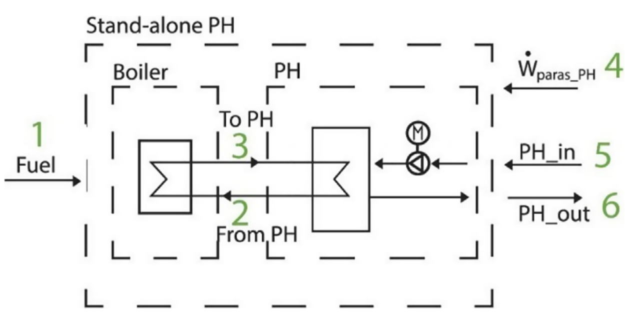

Fig. 4. Process heat plant.

Fig. 4 shows the process heat plant (PH), configured by a counter-current heat exchanger, which delivers process heat at nominal thermal load of 7 MW_{th}. The heat exchanger inlet and outlet temperatures are 63 °C and 90 °C, respectively.

The solar polygeneration scheme considers the integration of the desalination, refrigeration, and process heat plants, into the CSP plant, where this last one is the prime mover. Fig. 5 shows the configuration of the CSP polygeneration plant, in which the MED plant replaces the condenser of the power cycle, the REF plant is coupled to the sixth turbine extraction, and the PH plant is coupled between feed water preheaters (FWP3 and FWP4). The coupling point of each plant was selected considering the operating temperatures constraints of each technology, aiming to cause the minimum performance penalty on the SF aperture area for the same power production. Those constraints produce changes at the design point parameters of the CSP plant. For this reason, the low-pressure turbine back-pressure is modified to 0.37 bar, since the MED plant must operate within a temperature range of 64 °C–74 °C [15], and the sixth extraction pressure is modified to 1.17 bar, considering the operating constraints of the refrigeration plant, which must operate within a temperature range of 80 °C–110 °C [16]. Additionally, in order to develop the same gross power of the stand-alone CSP plant, the aperture area of the SF was modified to 616 650 m^2, i.e. a 20.9% larger than a stand-alone CSP plant.

In this CSP-polygeneration configuration is not possible to regulate the production of desalted water because the MED plant is driven by the heat rejected from the power cycle. Hence, the production of desalted water is linked to the production of electricity; if the electricity production decreases then the production of desalted water decreases too and vice-versa. The desalted water production depends on the mass flow rate of the exhaust steam from the outlet of the low-pressure turbine. Unfortunately, any problem, as a failure event or maintenance stop in the MED plant or in the CSP plant, will affect both productions, since the MED plant replaces the condenser of the power cycle. The presence of the MED plant allows closing the thermodynamic cycle through the condensation of the exhaust steam from the turbine for reuse in the cycle, then any problem in the MED plant consequently represents a problem in the condenser of the power cycle. On the other hand, the production from REF plant and PH plant can be regulated according to the demand. The output of cooling and process heat depends on the operating parameters of the rest of the plant. When process heat and cooling production are jointly or individually reduced, the power cycle needs less input thermal energy to generate electricity at the nominal rate. Thus, the control system could either reduce the energy input to the power cycle by partial defocusing solar collectors, or reduce the thermal energy output from TES and/or backup system.

For validating the polygeneration plant it was necessary to validate each stand-alone system, because currently there is no solar polygeneration plant of this characteristics in operation. Therefore, the polygeneration plant model is the combination of the validated model for each stand-alone system. The power cycle was validated at the design point using the nominal data of Andasol-1 reported by Blanco-Marigorta et al. [36]. Furthermore, the CSP plant was validated by comparing the results between the IPSEpro/Matlab model and the case study (Andasol-1) of SAM software [34]. The results indicate differences of 3.6% in terms of annual net electricity, and 1.5% regarding the thermal efficiency. Regarding the MED plant, it was validated considering the data reported by Zak et al. [37] and from El-Dessouky et al. [40]. The results show no differences in the total distillate water production, 5.46% error in terms of specific heat transfer area, and 7.81% regarding the GOR, that are considered as having good accuracy, as stated in [41]. Finally, the thermodynamic model of the PH plant was validated using the data reported by Herold et al. [39]. The results show differences lower than 2.6% in terms of the cooling capacity and COP.

A constant demand for electricity, water, cooling and process heat was assumed in order to meet the demand profile in the mining industry, which requires continuous operation and energy supply. Therefore, the power cycle, the desalination, the refrigeration, and the process heat units operate at full-load condition. The thermal energy storage and backup system allow to operate in periods of low solar radiation, delivering full-load steady state generation, even on cloudy days or during the night, assuring predictable dispatchability. The transient state conditions affect the solar field, the thermal energy storage, and the backup system. Those subsystems can operate at part-load conditions although the solar thermal loop provides thermal power at rated condition. In this study, the part-load condition of the solar

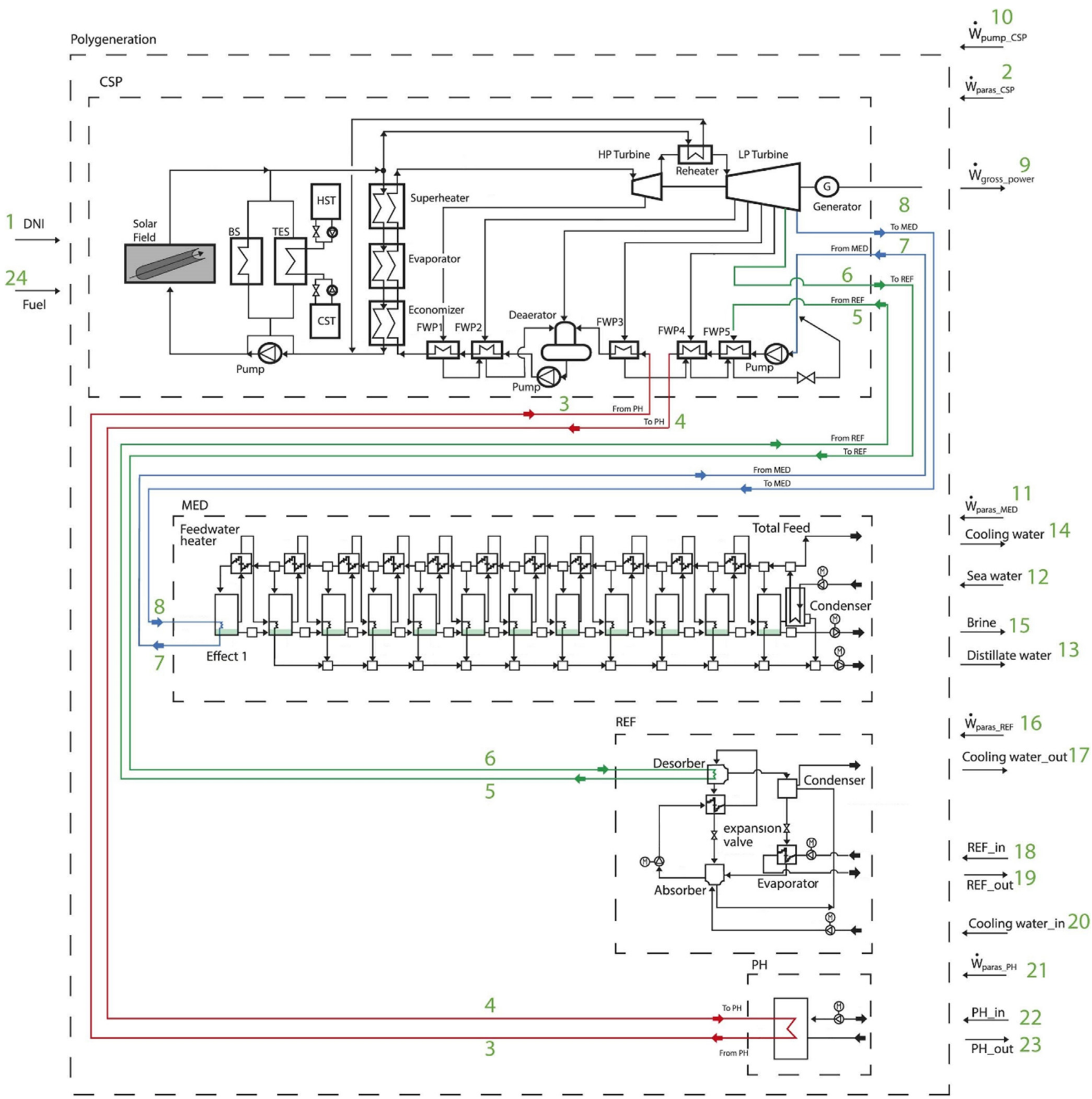

Fig. 5. CSP polygeneration plant.

thermal loop was simulated considering a variable efficiency of solar field, in terms of the direct normal irradiance, aperture area, optical efficiency, and the incidence angle [17]. Finally, start-up and shutdown procedures were not evaluated.

2.2. Economics considerations

The main economic considerations for the CSP plant are summarized in Table 1.

The main economic considerations for the other plants are listed in Table 2. In the case of MED plant, it includes the costs associated to the transportation of sea water to the plant location.

In the economic evaluation, a horizon of 25 years and a discount rate of 10% have been considered.

2.3. Energy and exergy evaluation

In order to evaluate the cost allocation in stand-alone and polygeneration plants, it was defined an adequate aggregation level, which allows delimiting the boundaries of the system. Figs. 1–5 show the boundaries of each system, with dashed lines, in which the fuels and products of each subsystem are established. The fuels are defined as the resources expended to generate the product; it could be any input that constitutes a resource, for example, seawater, steam, and electricity in a MED plant. Conversely, the products represent the desired result produced by the system or the purpose of the system. The relations between resources and products for each subsystem are detailed in Leiva-Illanes et al. [17]. Subsequently, First-Law and Second-Law of Thermodynamics are applied, as follows:

Table 1
Specific cost for CSP plant.

Cost	Value	Unit	Reference
Direct capital cost			
Site improvements	28	USD/m^2	[34]
Solar field	200	USD/m^2	[14]
Heat transfer fluid system	78	USD/m^2	[34]
Storage	35	USD/kWh_{th}	[25]
Fossil backup	60	USD/kW_e	[34]
Power plant	850	USD/kW_e	[34]
Balance of plant	105	USD/kW_e	[34]
Contingency	7	%	[34]
EPC and owner cost	11	% of total direct capital cost	[34]
Total land costs	2	% of total direct capital cost	[34]
Sales of tax applies of direct cost	4	% of total direct capital cost	[34]
Operational and maintenance costs			
Fixed cost by capacity	66	USD/(kW a)	[34]
Variable cost by generation	3	USD/MWh	[34]
Fossil fuel cost	0.0324	USD/kWh	[42]

Table 2
Specific cost for a MED plant, refrigeration plant, process heat plant and boiler.

Cost	Value	Unit	Reference
MED plant			
Direct capital cost MED			
Infrastructure and construction	1 500	USD/(m^3 day)	[26]
Contingencies (%)	10	%	[26]
Total	1 650	USD/(m^3 day)	
Operational and maintenance costs MED			
Chemical	0.025	USD/(m^3 a)	[26]
Maintenance	0.1	USD/(m^3 a)	[26]
Labor	2	% annualized total direct capital cost	[26]
Sea water transportation			
capex of piping	736	USD/m	[38]
capex of pumping	3.75	MUSD	[38]
Specific electricity consumption (pumping)	5	kWh/m^3	[38]
Distance from the coast to the plant location	70	km	
Location altitude	1 146	meters above sea level	
Refrigeration plant			
Direct and indirect capital cost	548.0	USD/kW_{th}	[43]
Operational and maintenance cost	2	%	
Process heat plant			
Direct and indirect capital cost	583.3	USD/kW_{th}	[44]
Operational and maintenance cost	2	%	
Boiler			
Direct and indirect capital cost	76.8	USD/kW_{th}	[44]
Operational and maintenance costs	2	%	

$$\sum_{in}(\dot{m}_{in}\cdot h_{in})-\sum_{out}(\dot{m}_{out}\cdot h_{out})-\dot{W}+\dot{Q}=\frac{dEn_{cv}}{dt} \tag{3}$$

$$\dot{E}_Q-\dot{E}_W-\dot{E}_D+\sum_{in}(\dot{m}_{in}\cdot e_{in})-\sum_{out}(\dot{m}_{out}\cdot e_{out})=\frac{dE_{cv}}{dt} \tag{4}$$

where $\dot{m}$ is the mass rate, h is the specific enthalpy, $\dot{W}$ is the rate of work, $\dot{Q}$ is the heat power, dEn_{cv}/dt is the energy change rate in the control volume, $\dot{E}$ is the rate of exergy, e is the specific exergy, and dE_{cv}/dt represent the exergy change rate in the control volume. Both dEn_{cv}/dt and dE_{cv}/dt are null in steady-state conditions. The subscripts in, out, cv, Q, W, and D are inlets, outlets, control volume, heat transfer, work, and destruction, respectively.

The exergy rate of heat ($\dot{E}_Q$) and work ($\dot{E}_W$) that cross the boundaries of a control volume (j) are defined as follows

$$\dot{E}_Q=\left(1-\frac{T_0}{T_j}\right)\cdot\dot{Q}_j \tag{5}$$

$$\dot{E}_W=\dot{W}_j \tag{6}$$

where T_0 is the temperature of reference, in K. The reference environment assumed in this study is $T_0 = 25\,^{\circ}C$ and $P_0 = 1.013$ bar, respectively. Additionally, the reference mass fraction of LiBr and water salinity is considered of 0.5542 kg/kg and 0.042 kg/kg, respectively.

The specific exergy is defined as follows

$$e=e_{phy}+e_{che}+e_{Pot}+e_{kin} \tag{7}$$

where the subscripts phy, che, pot, and kin are related to physical, chemical, potential, and kinetic portion of exergy, respectively. In this study, the potential and kinetic exergy rates are neglected. The physical and chemical exergy are defined by

$$e_{phy}=(h-h_0)-T_0\cdot(s-s_0) \tag{8}$$

$$e_{che}=-\Delta G+\left(\sum_{Pr}n\cdot e_{che}-\sum_{Re}n\cdot e_{che}\right) \tag{9}$$

Table 3
Energy and exergy efficiencies.

Polygeneration	
η	$\frac{\dot{W}_{net\,polygen}+\dot{m}_{distillate}\cdot h_{distillate}+\dot{Q}_{REF}+\dot{Q}_{PH}}{\dot{Q}_{in\,polygeneration}} = \frac{(\dot{E}n_9-\dot{E}n_2-\dot{E}n_{10}-\dot{E}n_{11}-\dot{E}n_{16}-\dot{E}n_{21})+\dot{E}n_{13}+(\dot{E}n_{18}-\dot{E}n_{19})+(\dot{E}n_{23}-\dot{E}n_{22})}{\dot{E}n_1+\dot{E}n_{24}}$
ψ	$\frac{\dot{E}_9+\dot{E}_{13}+(\dot{E}_{19}-\dot{E}_{18})+(\dot{E}_{23}-\dot{E}_{22})}{\dot{E}_1+(\dot{E}_2+\dot{E}_{10}+\dot{E}_{11}+\dot{E}_{16}+\dot{E}_{21})+\dot{E}_{12}+\dot{E}_{24}}$
Stand-alone CSP	
η	$\frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{E}n_4-\dot{E}n_5}{\dot{E}n_1+\dot{E}n_2}$
ψ	$\frac{\dot{E}_4}{\dot{E}_1+\dot{E}_2+\dot{E}_5}$
	Stand-alone MED
η	$\frac{\dot{m}_{distillate}}{\dot{Q}_{steam\,1st\,effect}} = \frac{\dot{m}_{distillate}}{\dot{E}n_3-\dot{E}n_2}$
ψ	$\frac{\dot{E}_6}{\dot{E}_1+\dot{E}_4+\dot{E}_5}$
Stand-alone REF	
η	$\frac{\dot{Q}_{REF}}{\dot{Q}_{in\,boiler}+\dot{W}_{pumps}} = \frac{\dot{E}n_6-\dot{E}n_7}{\dot{E}n_1+\dot{E}n_4}$
ψ	$\frac{\dot{E}_7-\dot{E}_6}{\dot{E}_1+\dot{E}_4}$
Stand-alone PH	
η	$\frac{\dot{Q}_{PH}}{\dot{Q}_{in\,boiler}+\dot{W}_{pump}} = \frac{\dot{E}n_6-\dot{E}n_5}{\dot{E}n_1+\dot{E}n_4}$
ψ	$\frac{\dot{E}_6-\dot{E}_5}{\dot{E}_1+\dot{E}_4}$
Stand-alone systems	
η	$\frac{\dot{W}_{net\,CSP}+\dot{m}_{distillate}\cdot h_{distillate}+\dot{Q}_{REF}+\dot{Q}_{PH}}{\dot{Q}_{in\,CSP}+\dot{Q}_{in\,MED}+\dot{Q}_{in\,REF}+\dot{Q}_{in\,PH}} = \frac{(\dot{E}n_4-\dot{E}n_5)_{CSP}+\dot{E}n_{6\,MED}+(\dot{E}n_6-\dot{E}n_7)_{REF}+(\dot{E}n_6-\dot{E}n_5)_{PH}}{(\dot{E}n_1+\dot{E}n_2)_{CSP}+(\dot{E}n_1+\dot{E}n_4)_{MED}+(\dot{E}n_1+\dot{E}n_4)_{REF}+(\dot{E}n_1+\dot{E}n_4)_{PH}}$
ψ	$\frac{\dot{E}_{4\,CSP}+\dot{E}_{6\,MED}+(\dot{E}_7-\dot{E}_6)_{REF}+(\dot{E}_6-\dot{E}_5)_{PH}}{(\dot{E}_1+\dot{E}_2+\dot{E}_5)_{CSP}+(\dot{E}_1+\dot{E}_4+\dot{E}_5)_{MED}+(\dot{E}_1+\dot{E}_4)_{REF}+(\dot{E}_1+\dot{E}_4)_{PH}}$

where s is the specific entropy, G is Gibbs function for the reaction, n is the number of moles, the subscripts Pr and Re denote the products and the reactants of the reaction, respectively. However, in the case of the exergy rates from the fossil-fuel it is calculated with the following simplification [45]

$$\dot{E}_{ff} = \dot{m}_{ff}\cdot\xi\cdot LHV \tag{10}$$

where ξ is an experimental correlation [45], LHV is the lower heating value of the fossil-fuel. The subscript ff denotes fossil-fuel.

$$\xi = 1.033 + 0.0169\cdot\frac{y}{x} - \frac{0.0698}{x} \tag{11}$$

where x and y are the composition C_xH_y in a general gaseous fuel. In the present work, the natural gas is considered as methane (CH_4), in which ξ is close to unity.

Regarding to the exergy rates of solar radiation, the Petela equation is considered [46] which is one of the most cited models in the literature and few differences are observed against other models. For example, between Petela's and Spanner's models the difference is about 0.0002%, and between Petela's and Jeter's is about 1.8%, for temperatures of 298 K and 6 000 K.

The First-Law or energy efficiency (η) defined as the ratio between energy output and energy input, and the Second-Law or exergy efficiency (ψ) defined as the ratio between the exergy rate of product and the exergy rate of fuel, are determined through the following equations,

$$\eta = \frac{\dot{E}n_{net}}{\dot{E}n_{in}} \tag{12}$$

$$\psi = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\sum\Delta\dot{E}_{out}}{\sum\Delta\dot{E}_{in}} \tag{13}$$

where $\dot{E}n$ is the energy rate, $\dot{E}$ is the exergy rate, the subscript P, and F mean products and Fuel, respectively. Note that the energy efficiency applied to a polygeneration plant is known as utilization factor, also. In the case of the stand-alone MED, it is used the GOR as the indicator of energy efficiency considering that its product is a mass (fresh-water).

Table 3 summarizes the expressions for these performance parameters applied to the boundaries considered in each subsystem.

2.4. Levelized cost method

The levelized cost is the total cost of installing and operating the plant, expressed in monetary unit per unit of product generated by the system over its life [20,25]. Therefore, the levelized electricity cost, in USD/kWh, is defined by:

$$LEC = \frac{capex\cdot crf + opex + C_{fuel}}{En_{el}} = \frac{\dot{Z}\cdot\tau + C_{fuel}}{En_{el}} \tag{14}$$

where $capex$ is the capital expenditure, $opex$ is the operational expenditure, crf is the capital recovery factor, C_{fuel} is the annual fuel cost, En_{el} is the annual production of net electricity delivered by the CSP plant, considering the parasitic loads (Note that the polygeneration plant does not include electric consumption of MED, REF, and PH), $\dot{Z}$ is the non-exergy-related cost rate, τ is the annual average time of the plant's operation at nominal capacity, in h/a. Fuel cost is calculated by:

$$C_{fuel} = c_{ff}\cdot\frac{Q_{\text{th,power block}_{\text{BS}}}}{\eta_{\text{boiler}}} + c_{sun}\cdot\frac{Q_{\text{th,power block}_{\text{solar}}}}{\eta_{\text{collector}}} \tag{15}$$

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/a, and η_{boiler} is the boiler efficiency, assumed as 0.9, c_{sun} is the sun fuel cost, in USD/kWh, $Q_{\text{th,power block solar}}$ is the thermal energy required by the power block from Solar (SF and TES), in kWh/a, and $\eta_{\text{collector}}$ is the collector optical efficiency. The cost of solar energy is neglected.

The total investment and operating and maintenance cost rate is defined by

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM} = \frac{capex\cdot crf + opex}{\tau} \tag{16}$$

where $\dot{Z}^{CI}$ is the investment cost rate, $\dot{Z}^{OM}$ is the operation and maintenance cost rate (not include fossil-fuel cost).

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

$$LWC = \frac{capex\cdot crf + opex + C_{fuel}}{V_w} = \frac{\dot{Z}\cdot\tau + C_{fuel}}{V_w} \tag{17}$$

where V_w is the annual production of water, in m^3/a, and C_{fuel} is the fuel cost, in USD/a. Fuel cost in the case of MED, refrigeration and process heat plants is the cost associated with electric and thermal consumptions supplied from the CSP plant (in the case of the stand-alone plant is from the grid and boiler, respectively), and the sea water cost. The last cost applies only to the MED plant. In a polygeneration scheme, the thermal energy cost is considered as an internal cost (it is assumed by the power cycle because it is considered waste heat), and the sea water cost is assumed null too. Additional discussions about cost allocation can be found in the literature [47–49]. Fuel cost is calculated by:

$$C_{fuel} = LEC\cdot\text{En}_{\text{pumps}} + C_{thermal}\cdot En_{thermal} + C_{sw}\cdot V_w \tag{18}$$

where En_{pumps} is the annual energy consumption from pumps, in kWh/a, $C_{thermal}$ is the thermal energy cost, in USD/kWh, $En_{thermal}$ is the annual thermal energy consumption, in kWh/a, and C_{sw} is the sea water cost.

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

$$LCC = \frac{capex\cdot crf + opex + C_{fuel}}{En_c} = \frac{\dot{Z}\cdot\tau + C_{fuel}}{En_c} \tag{19}$$

where En_c is the annual production of cooling, in kWh/a. Finally, the levelized process heat cost (LHC), in USD/kWh, is defined by:

Table 4
Unit exergy cost of electricity, water, cooling and heat.

c	Polygeneration plant	Stand-alone plant
Electricity	$c_9 = \frac{\dot{C}_1 + \dot{C}_{24} - (\dot{C}_4 - \dot{C}_3) - (\dot{C}_6 - \dot{C}_5) - (\dot{C}_8 - \dot{C}_7) + \dot{Z}_{csp}}{\dot{E}_9 - \dot{E}_2 - \dot{E}_{10}}$	$c_4 = \frac{\dot{C}_1 + \dot{C}_2 - \dot{C}_3 + \dot{Z}_{csp}}{\dot{E}_4 - \dot{E}_5}$
	$c_1 = 0, c_2 = c_9, c_3 = c_4, c_5 = c_6, c_4 = c_5, c_7 = c_8, c_7 = c_6, c_{10} = c_9, c_{24} = c_{ff}, c_3 = c_9$	$c_1 = 0, c_2 = c_{ff}, c_3 = 0, c_5 = c_4$
Water	$c_{13} = \frac{(\dot{C}_8 - \dot{C}_7) + \dot{C}_{11} + \dot{C}_{12} - \dot{C}_{14} - \dot{C}_{15} + \dot{Z}_{med}}{\dot{E}_{13}}$	$c_6 = \frac{\dot{C}_1 + \dot{C}_4 + \dot{C}_5 - \dot{C}_7 - \dot{C}_8 + \dot{Z}_{med} + \dot{Z}_{boiler}}{\dot{E}_6}$
	$c_7 = c_8, c_{11} = c_9, c_{12} = 0, c_{14} = 0, c_{15} = 0$	$c_1 = c_{ff}, c_2 = c_3, c_2 = c_3, c_4 = P_{elect}, c_5 = 0, c_7 = 0, c_8 = 0$
Cooling	$c_{19} = \frac{(\dot{C}_6 - \dot{C}_5) + \dot{C}_{16} + (\dot{C}_{20} - \dot{C}_{17}) + \dot{Z}_{ref}}{\dot{E}_{19} - \dot{E}_{18}}$	$c_7 = \frac{\dot{C}_1 + \dot{C}_4 + (\dot{C}_8 - \dot{C}_5) + \dot{Z}_{ref} + \dot{Z}_{boiler}}{\dot{E}_7 - \dot{E}_6}$
	$c_5 = c_6, c_{16} = c_9, c_{17} = 0, c_{18} = c_{19}, c_{20} = 0$	$c_1 = c_{ff}, c_2 = c_3, c_2 = c_3, c_4 = P_{elect}, c_5 = 0, c_6 = c_7, c_8 = 0$
Process Heat	$c_{23} = \frac{(\dot{C}_4 - \dot{C}_3) + \dot{C}_{21} + \dot{Z}_{ph}}{\dot{E}_{23} - \dot{E}_{22}}$	$c_6 = \frac{\dot{C}_1 + \dot{C}_4 + \dot{Z}_{ph} + \dot{Z}_{boiler}}{\dot{E}_6 - \dot{E}_5}$
	$c_3 = c_4, c_{21} = c_9, c_{22} = c_{23}$	$c_1 = c_{ff}, c_2 = c_3, c_2 = c_3, c_4 = P_{elect}, c_5 = c_6$

$$LHC = \frac{capex \cdot crf + opex + C_{fuel}}{En_h} = \frac{\dot{Z} \cdot \tau + C_{fuel}}{En_h} \tag{20}$$

where En_h is the annual production of process heat, in kWh/a.

It should be noted that the fuel costs are part of the operating and maintenance costs. However, because of the importance of fuel costs in thermal systems, fuel costs are considered separately from the *opex* in this research work. Other revenues, such as selling carbon credits and selling renewable credits conforming with the renewable energy quota established by Chilean legislation, are not considered in this study.

2.5. Thermoeconomic method

A thermoeconomic evaluation was also applied, considering the method proposed by Bejan et al. [11]. The economic balance is applied in order to determine the unit exergy cost c_j and the exergy cost rate $\dot{C}_j$ of each stream. That economic balance is expressed by:

$$\sum_{in} (c_{in} \cdot \dot{E}_{in})_k + \dot{Z}_k^{CI} + \dot{Z}_k^{OM} = \sum_{out} (c_{out} \cdot \dot{E}_{out})_k \tag{21}$$

where, c is the unit exergy cost. The subscript k, in, and out denote the kth component, inlets, and outlets, respectively. This equation can be expressed as the sum of total cost rate of fuel $\dot{C}_f$ and non-exergy-related cost rate $\dot{Z}$, equivalent to the total cost rate of product $\dot{C}_p$.

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

$$\dot{C} = c \cdot \dot{E} = c \cdot \dot{m} \cdot e \tag{22}$$

For each subsystem, the fuel, product, and auxiliary equations are defined in order to apply the economic balance for the polygeneration and stand-alone plants. More details are stated in the previous study conducted by the authors [17]. Table 4 summarizes the equations of those balances and report the auxiliary equations.

where P_{elect} is the electricity price from the grid for industrial use, which is assumed to be 0.098 USD/(kWh) (Tariffs BT4 and AT4) [50].

3. Results and discussion

3.1. Production and cost in the base case

The CSP-polygeneration plant receives 2 039.3 GWh/a and 399.6 GWh/a from the solar field and the backup system, respectively. Consequently, the annual productions are 463.1 GWh/a of gross power, 408.5 GWh/a of net power, 13.2 Mm^3/a of fresh water, 42.0 GWh/a of cooling, and 58.9 GWh/a of process heat. The plant is hybridized with natural gas. In Fig. 6 the Sankey and the Grassmann diagrams of the polygeneration plant are presented, in which the width of the arrows is shown proportionally to the flow of energy and exergy rate, respectively. The Sankey diagram shows energy inputs and outputs, as well as energy efficiency. However, when resources and products of different energy nature (such as water) are present the Sankey diagram is limited. A partial solution is using an appropriate definition, in terms of energy, of those resources and/or products. Therefore, it is not appropriate to express the energy efficiency for the overall system in a polygeneration plant that generates non-energy products. This problem does not occur when using the Grassmann diagram (and the Second-Law or exergy efficiency), because it is based on the exergy rate. The exergy flows and irreversibilities are represented in the Grassmann diagram, in which each component represents a graphical exergy balance and shows how part of the exergy input is lost in the successive transformation processes. As observed in the Sankey diagram, the energy input is transformed into useful energy in a ratio of 53.7%, that is distributed with respect to the energy input as 16.7%, 32.8%, 1.7%, and 2.4% in electricity, water, cooling, and process heat, respectively. On the other hand, the Grassmann diagram shows that the exergy input is transformed into useful exergy flows in about 27.1%, distributed as 25.4%, 1.0%, 0.1%, and 0.5% in electricity, water, cooling, and process heat, respectively, while the main irreversibilities or exergy destruction are in the solar thermal loop. The high exergy destruction is explained due the large temperature difference between the source temperature (sun) and the heat transfer fluid, while exergy destruction in the power block is mainly due to the large temperature differences between the hot and cold fluids. The main reason for the high exergy destruction in the BS (combustion chamber) are the chemical reactions and heat exchange between streams with large temperature differences. Note that in a conventional steam power plant, the boiler is the main source of irreversibility.

Table 5 shows the energy and exergy efficiencies of each subsystem. The polygeneration plant is more efficient than the overall stand-alone systems in terms of both energy and exergy efficiencies, due to the fact that there is a better utilization of the resources. Exergy analysis provides more information for a better understanding of the process, to quantify sources of inefficiency, and to distinguish quality of energy used. Energy analysis provides only partial information, because it does not provide a measure of how close is to ideal processes, and losses of energy could be large but with low quality (thermodynamically insignificant). On the other hand, the product of the MED plant is a mass and the efficiency of a stand-alone MED plant, in terms of consumed energy, is usually measured for any of the following indicators: GOR ($kg_{distillate}/kg_{steam}$), the Performance Ratio ($kg_{distillate}/kJ_{steam}$), the Specific Heat Consumption ($kWh_{steam}/m^3_{distillate}$), or the Unit Operating Cost ($USD/m^3_{distillate}$). In this study the GOR is used as indicator. Note that the energy efficiency, defined as the ratio between energy output and energy input, is not an appropriate indicator since the product is not an energy but a mass (fresh-water).

If a system produces more than one product, as in a polygeneration system, an allocation criterion of costs is needed in order to determine each product cost. In this context, the allocation procedure using unit exergy costs (UEC) and levelized costs (LC) is presented in Table 6. For the polygeneration plant, the UEC of electricity is lower than the LEC, conversely, the UEC of water, cooling and heat are higher than LWC,

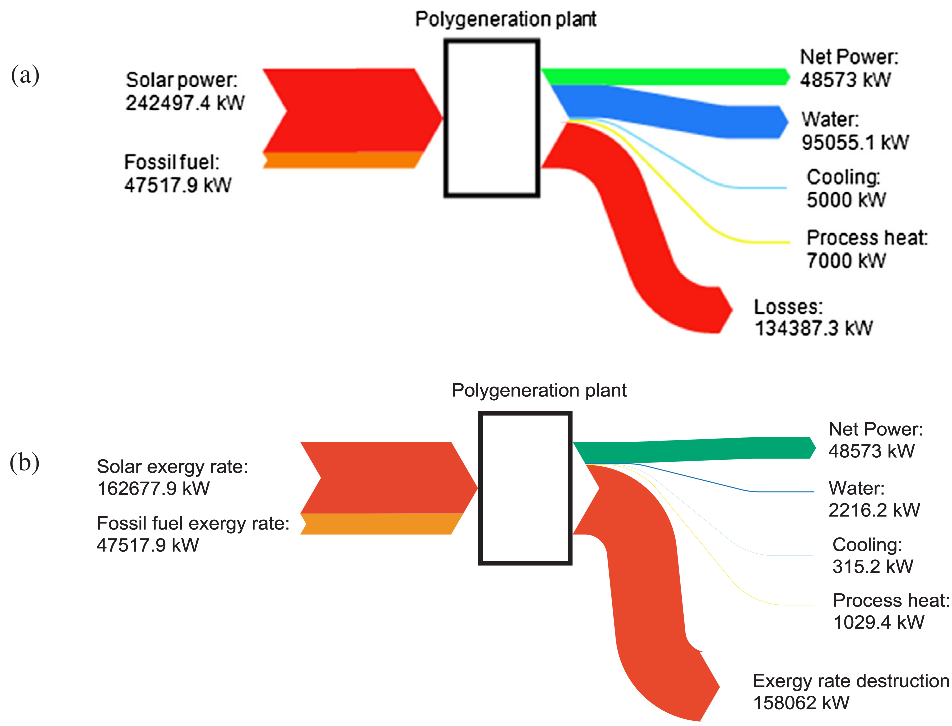

Fig. 6. Polygeneration plant. (a) Sankey diagram. (b) Grassmann diagram.

Table 5
Energy and exergy efficiencies.

	Energy efficiency %	Exergy efficiency %
Polygeneration	53.7	27.1
Overall stand-alone systems	41.6	18.7
Stand-alone CSP	21.5	30.9
Stand-alone MED	–	1.9
Stand-alone REF	63.0	4.0
Stand-alone PH	90.0	13.2

Table 6
Unit exergy costs and levelized costs.

Item	Polygeneration plant		Stand-alone plants
	UEC	LC	UEC and LC
Electricity, USD/kWh	0.1058	0.1429	0.122
Water, USD/m^3	2.746	1.804	4.036
Cooling, USD/kWh	0.036	0.008	0.060
Heat, USD/kWh	0.0238	0.0006	0.038

LCC, and LHC, respectively. The numeric difference between unit exergy cost and levelized cost is due to the form of cost allocation. Through the levelized cost method, the thermal energy cost is considered as an internal cost, so the thermal energy cost is assumed completely by the electricity production. Hence, the $\dot{Z}_{csp}$ is completely allocated to the electricity cost, since the LEC equation (see Eq. (14)) does not consider the cost of the other product generated by the CSP plant in this scheme, i.e. thermal energy. In contrast, by applying the thermoeconomic method, the thermal energy cost is shared with MED, REF and PH plants and is distributed according to its exergy rate. Consequently, the $\dot{Z}_{csp}$ is allocated to the electricity cost and the thermal energy cost, in such a way that the $\dot{Z}_{csp}$ is allocated to the electricity, water, cooling and process heat costs (see Equations on Table 4). For that reason, the thermoeconomic method is considered as a rational cost allocation method. The levelized cost method overestimates the cost of electricity and underestimates the costs of the by-products and induce a bias that could lead to a misevaluation of the project; for instance, if the LEC calculated is higher than the selling price of the grid. Conventional economic analysis, as the levelized cost method, does not provide a rational criteria for apportioning the carrying charges, fuel costs, and *opex* to the several products generated in the same system [11].

Regarding stand-alone plants, both methods give the same results because each plant produces only one product, and it is not necessary to allocate any cost between products.

By comparing the result between polygeneration and stand-alone plants, the unit exergy cost of each product is lower in polygeneration schemes, therefore, when the thermoeconomic method is used, the results show that the polygeneration plant is more cost-effective than stand-alone systems. However, comparing by levelized cost, the LEC in the polygeneration plant is higher than in the stand-alone plant, and the other costs (LWC, LCC, and LHC) are lower. These results are explained by the increase in the solar field aperture area, which increases the *capex* and *opex*, that is allocated to the LEC and also the fact that the cost of the steam (consumed by the MED, REF, and PH plants) is considered as an internal cost. In this case, it is not possible to establish which scheme is better, whether the polygeneration plant or the stand-alone systems, considering that electricity and water are the priority in the mining industry. Thus, additional metrics are needed to discriminate which scheme is more attractive. For example, the overall cost of products or the total exergy cost rate could be used, whose values in the polygeneration plant are lower than in the case of stand-alone plants. The total exergy cost rate of products, calculated using the thermoeconomic method [11], is 10 504.4 USD/h for polygeneration plant, which is distributed in 55.4% in electricity, 41.1% in fresh water, 1.9% in cooling, and 1.6% in process heat, while in the stand-alone systems is 13 630.0 USD/h, which is distributed in 49.3% in electricity, 46.6% in fresh water, 2.2% in cooling, and 1.9% in process heat. It can be concluded that the polygeneration scheme offers a more attractive solution than the stand-alone systems.

The monthly production of electricity, fresh water, cooling and process heat, in the solar polygeneration plant, follows the same trend

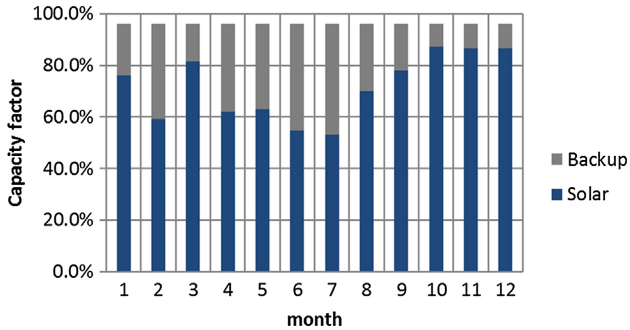

Fig. 7. Monthly capacity factor in polygeneration plant.

of capacity factor as shown in Fig. 7, which unfolds the contribution from the solar (SF and TES) and from the backup system. The contribution from the solar is largest in the summer due to the seasonal variation in direct normal irradiation available for collection, although in summer there is a significant decrease in February, due to a local meteorological phenomenon called "Altiplanic Winter", which is characterized by an increase on the air moistens coming from the east, bringing unsettled weather and clouds. Thus, the consumption of fossil fuel is higher in February, June, and July, reaching 38.3%, 43.0%, and 44.6%, respectively.

The monthly specific cost of products, such as unit exergy cost and levelized cost of electricity, fresh water, cooling, and process heat, in the polygeneration plant, are shown in Fig. 8. The specific cost of the products, calculated through both methods follows the same trend, reaching high values in winter and decreases during summer (except in February). Considering that the capacity factor is fixed, then when the fossil fuel consumption is increased, the costs of products increased too. Consequently, the costs of products are higher in February, June, and July. It should be noted that, in stand-alone plants, the specific costs of the product vary only in the CSP plant as this is driven by solar radiation and fossil-fuel, while for the other plants the specific cost remains constant, since they are driven only by fossil fuel. Regarding the comparison of both methods, the levelized cost method gives a higher cost of electricity, lower cost of fresh water, cooling, and process heat compared with the thermoeconomic method, as observed before.

The advantages of using the levelized cost method are that the cost of steam is considered as an internal cost and it is not necessary to develop an additional assessment, which saves time and reduces the complexity of calculations. Therefore, the evaluator does not require to develop a deep thermodynamic analysis. However, through this approach, the cost of electricity seems more expensive relative to the cost of other products, leading to a distortion in the evaluation, because the allocation of costs does not obey physical parameters as the exergy, which gives the allocation some arbitrariness. Therefore, this method is recommended when it is necessary to perform a first approximation of the costs of each product, but comparing between a polygeneration plant and the stand-alone plants could lead to significant inaccuracies, as the case discussed above.

On the other hand, the advantages of using the thermoeconomic method are that it applies a rational allocation of resources that is not arbitrary since it is based on the exergy, requiring, however, a thorough knowledge of thermodynamics to determine the different exergy flows, which makes the process complex and laborious. Therefore, this method is recommended when a more precise analysis of the costs of each product is needed, and specifically for comparing between polygeneration and the stand-alone schemes.

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

Fig. 9 shows the variation of the capacity factor, in the polygeneration plant, as a function of the solar multiple, the hours of

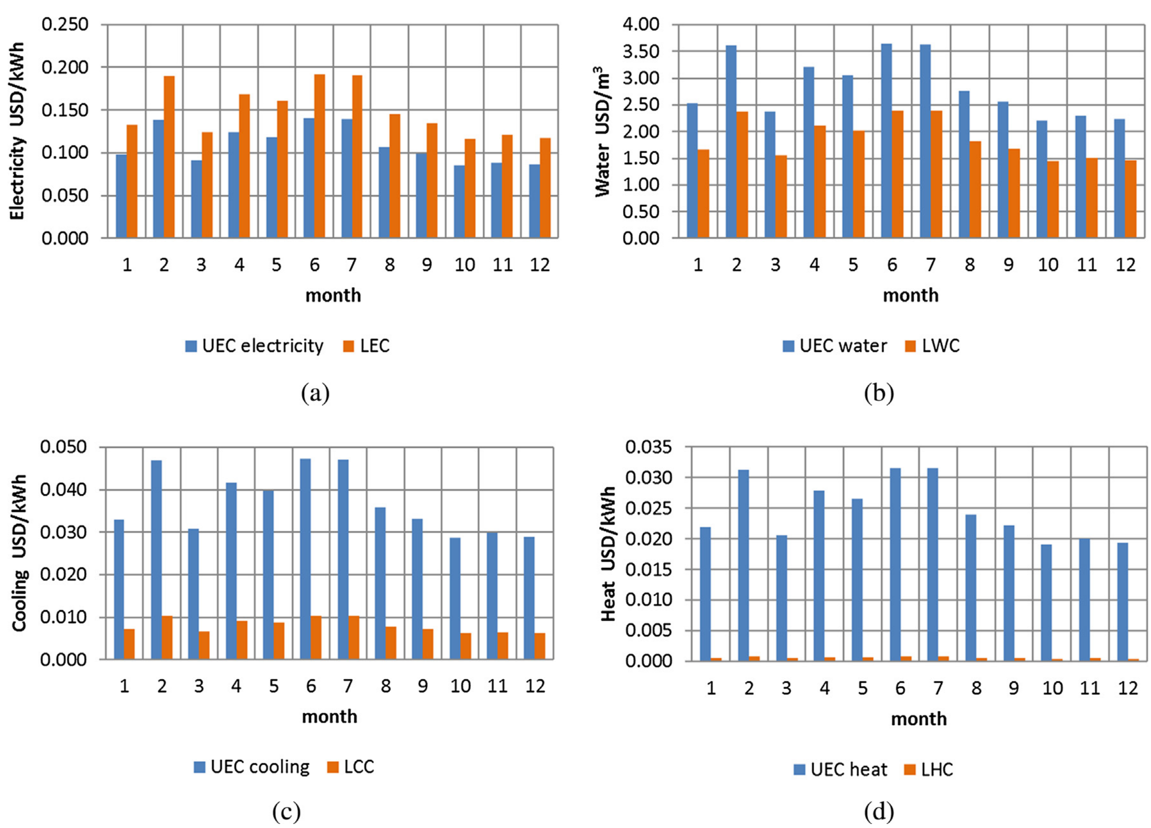

Fig. 8. Comparison between the levelized cost method and thermoeconomic method in polygeneration plant. Monthly UEC and LC of: (a) electricity, (b) water, (c) cooling, (d) process heat.

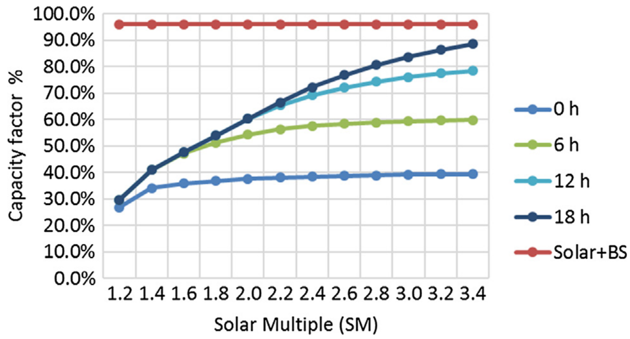

Fig. 9. Capacity factor in the polygeneration plant.

storage, and the hybridization through the BS. An important point that contributes to increasing the capacity factor is the direct normal irradiation. This variable depends on the location (latitude) between other factors, although in this work is not considered a variation on the location. The SM is larger than one to guarantee that the power block is effectively used during the year. The TES allows storing excess energy collected by the SF when it is not used in the power block, and discharges that energy later when the direct normal irradiance is lower. The solar polygeneration plant presents higher dispatchability when hybridized, coupling a backup system. This also allows a more flexible generation strategy to maximize the value of the products generated. Consequently, the annual production of each product is increased too, following the same trends of Fig. 9.

On the other hand, the trade-off between the incremental costs of the increased SF, TES, and BS must be balanced against the increase in the production by the rise of the capacity factor. In this context, Fig. 10 presents the unit exergy cost and levelized cost of each product (electricity, fresh water, cooling, and process heat) as a function of SM and hours of TES of the polygeneration plant. The minimum values of the unit exergy cost and the levelized cost are different in value, but occur at the same points regarding SM and TES.

Regarding the values of minimum UEC and LC that are different, the lowest UEC of electricity and LEC are 0.1020 USD/kWh and 0.1405 USD/kWh, respectively. In the levelized cost method, the electricity cost supports both the *capex* and *opex* of the CSP plant and the fossil fuel cost, whereas in the thermoeconomic method, these costs are shared by the exergy flows which connect the CSP plant with the MED, REF and PH plants. While the lowest UEC of water and LWC are 2.705 USD/m^3 and 1.798 USD/m^3, respectively. The LWC is lower than the UEC of water, because the water cost bears the *capex* and *opex* of the MED plant and its own consumption of electricity, but does not consider the thermal cost from CSP plant. In the case of the REF plant, the lowest UEC of cooling and LCC are 0.035 USD/kWh and 0.0078 USD/kWh, respectively. The LCC is lower than the UEC of cooling, for the same reason that in the case of the water cost. Similarly, the minimums UEC of process heat and LHC are 0.023 USD/kWh and 0.00056 USD/kWh, respectively.

Concerning to the points of the lowest UEC and LC, they occur at the same point in terms of SM and TES, 1.4 and 3 h, respectively. Therefore, the same plant size (SF and TES) is reached by applying both methods. However, the difference in the unit exergy cost between an SM and TES of 1.4 and 3 h, and base case (2.56 and 12 h) is 3.8%, 1.6%, 3.1%, and 3.7% for electricity, water, cooling, and heat, respectively. In the case of levelized cost, the difference is about 3.8%, 0.5%, 0.2%, and 0.2% for electricity, water, cooling, and heat, correspondingly. The minima UEC and LC coincide at the same plant size because the polygeneration plant is dominated mainly by the solar field size and the thermal energy storage capacity. The variations on the investment cost of SF and TES produce similar variations in both methods, keeping only differences in the magnitude. An optimal solar field area should maximize the time in a year that the field generates enough thermal energy to drive the power cycle at its rated capacity, minimize *capex* and *opex*, and use TES and backup system efficiently and cost effectively.

Regarding to the stand-alone CSP plant, the minimum UEC of electricity and LEC have the same value and it also occur at the same SM and TES (1.8 and 6 h). Nevertheless, when the stand-alone CSP plant is integrated in the CSP-polygeneration plant, the SM and TES are reduced from 1.8 and 6 h to 1.4 and 3 h respectively, due to the modification of the turbine extraction pressures and the back pressure in the CSP plant to couple the MED, REF, and PH plants.

An optimal sizing of SF and TES should minimize installation and

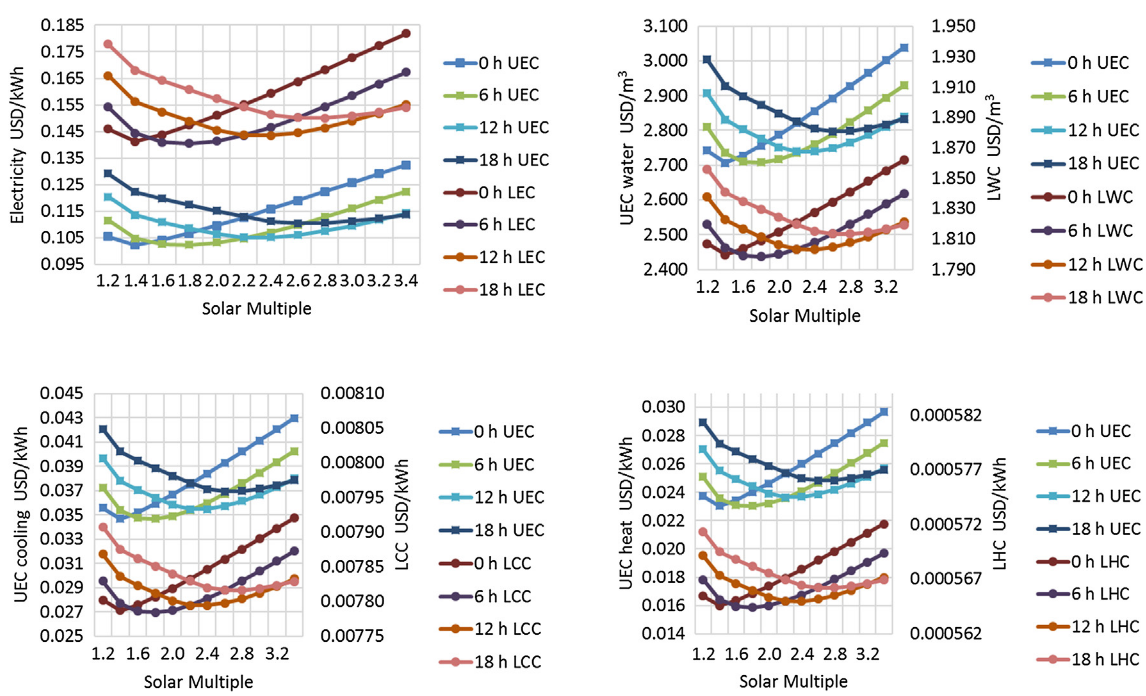

Fig. 10. Unit exergy cost (UEC) of electricity, water, cooling and heat, versus Levelized electricity cost (LEC), Levelized water cost (LWC), Levelized cooling cost (LCC), and Levelized heat cost (LHC).

operating costs, and maximize the amount of energy delivered throughout the year. This point is reached with the minimum levelized cost and unit exergy cost. The unit cost in the solar polygeneration plant is dominated by the investment cost of CSP plant, therefore the unit cost varies significantly depending on the capacity factor, which in turn depends on the direct normal irradiation, hybridization (BS) levels, and sizing of SF and TES. According to the thermoeconomic method, in an optimization process, the variable to be minimized is the total exergy cost of products, which includes the exergy costs and non-exergy costs of the polygeneration plant. This method allows measuring in the same unit resources and products of very different nature, such as electricity, water, cooling, process heat, resources, and waste. For this reason, the thermoeconomic method is recommended for assessing polygeneration plants.

4. Conclusions

The levelized cost method and the thermoeconomic method were applied to a solar polygeneration plant to analyze and compare the cost allocation process, the unit specific costs of products, the energy and exergy efficiencies, as well as the main advantages of each method employed. The solar polygeneration plant consists of a concentrated solar power plant, a multi-effect distillation, an absorption refrigeration, and a process heat plants.

When it is generated only one product by each stand-alone system, it is not necessary to allocate any cost between products, and both methods give the same results. Yet, when more than one product is generated 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 cost allocation procedure needs an additional rational analysis to prevent allocation from being arbitrary. In this context, the levelized cost method and the thermoeconomic method are used extensively in the evaluation of this kind of plants, in which levelized cost method is a simple and fast method, and deep knowledge of thermodynamics is not required. In the absence of a detailed knowledge of the plant, the level cost method is a good alternative and presents reasonable results. Therefore, this method is recommended when it is necessary to perform a first approximation of the costs of each product, but comparing between polygeneration plant and the stand-alone plants could lead to inaccurate conclusions. On the other hand, the thermoeconomic method is an equitable distribution of the appropriate share of non-exergy-related cost rate (*capex* and *opex*) and exergy cost rate in each product. It is based on the Second-Law of Thermodynamics and the Economics, in which all costs from resources consumed are charged to its useful products. This method is recommended when it is required to perform a more precise analysis of the costs of each product, and for assessing the benefits of polygeneration schemes, compared to the stand-alone plants. The disadvantages of the thermoeconomic method are its complexity and additional knowledge about the internal parameters of the plant, which could not be available.

Results show that the electricity cost calculated through the levelized cost method is higher than the estimated by the thermoeconomic method. In contrast, the water, cooling, and process heat costs are lower since in the levelized cost method, the cost allocation does not charge all internal cost to MED, REF and PH plants. The allocation of costs based on thermoeconomic 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 thermoeconomic method constitutes a rational method to assess a CSP-polygeneration plant, since it is based on the quality of energy assessed.

The analysis shows that the lowest unit exergy and levelized costs happened at the same sizing of SM and TES, however, the unit costs have different values. Hence, independently of the method employed, in an optimization process for sizing of SM and TES, the same results are delivered. Nevertheless, the thermoeconomic method allows measuring resources and products of very different nature, such as energy and water, using the same unit.

In the case of a polygeneration scheme, it is common to use as indicator the utilization factor, which is based on the First-Law of Thermodynamic relating the energy outputs (work, electricity, heat, cooling, heat supplied to the desalting plant, or other) to the energy inputs (sun, fossil fuel, heat, or others). This indicator does not discriminate between the high-quality energy as work or electricity, and low-quality energy as heat. Additionally, when resources and products of different energy nature (as water) are presented, the indicator is limited. A partial solution is to use an appropriate definition, in terms of energy, of those resources and/or products. For that reason, the utilization factor provides a false high-performance impression of the polygeneration plant. Therefore, a better indicator for polygeneration plant is the exergy efficiency.

In future studies, a thermoeconomic assessment with a low aggregation level in the CSP plant should be applied to individual components, such as turbines, preheaters, solar field, among others, in order to identify the thermodynamic improvements for the polygeneration schemes.

Acknowledgments

The authors wish to express their gratitude to CONICYT-PCHA/Doctorado_Nacional/año2013-folio21130634, and also appreciate the support from CONICYT/FONDAP 15110019 “Solar Energy Research Center“- SERC-Chile and the project Fondecyt N° 1130621.

References

[1] Serra LM, Lozano M-A, Ramos J, Ensinas AV, Nebra SA. Polygeneration and efficient use of natural resources. Energy May 2009;34(5):575–86.
[2] Al Moussawi H, Fardoun F, Louahlia-Gualous H. Review of tri-generation technologies: Design evaluation, optimization, decision-making, and selection approach. Energy Convers Manage 2016;120:157–96.
[3] IEA. Co-generation and Renewables; 2011.
[4] IEA. Key World Energy Statistics 2016; 2016.
[5] Modi A, Bühler F, Andreasen JG, Haglind F. A review of solar energy based heat and power generation systems. Renew Sustain Energy Rev 2017;67:1047–64.
[6] Ye X, Li C. A novel evaluation of heat-electricity cost allocation in cogenerations based on entropy change method. Energy Policy 2013;60:290–5.
[7] Tereshchenko T, Nord N. Uncertainty of the allocation factors of heat and electricity production of combined cycle power plant. Appl Therm Eng Feb. 2015;76:410–22.
[8] Gochenour C. Regulation of heat and electricity produced in combined heat and power plants; 2003.
[9] Beretta GP, Iora P, Ghoniem AF. Allocating resources and products in multi-hybrid multi-cogeneration: What fractions of heat and power are renewable in hybrid fossil-solar CHP? Energy 2014;78:587–603.
[10] Nuorkivi A. Allocation of fuel energy and emissions to heat and power in CHP. Energy-AN Consulting; 2010 [Online]. Available: http://era17.fi/wp-content/uploads/2012/02/Report-Nordic-CHP-Allocation_Energy-AN-Consulting_2010-9-7.pdf [Accessed: 24-Aug-2017].
[11] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. 1 edition John Wiley & Sons; 1996.
[12] Abusoglu A, Kanoglu M. Exergoeconomic analysis and optimization of combined heat and power production: a review. Renew Sustain Energy Rev Dec. 2009;13(9):2295–308.
[13] Baghernejad A, Yaghoubi M. Exergoeconomic analysis and optimization of an Integrated Solar Combined Cycle System (ISCCS) using genetic algorithm. Energy Convers Manage May 2011;52(5):2193–203.
[14] IRENA. Renewable Power Generation Costs in 2014 : An Overview; 2015.
[15] Al-Karaghouli A, Kazmerski LL. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. Renew Sustain Energy Rev 2013;24:343–56.
[16] Sarbu I, Sebarchievici C. General review of solar-powered closed sorption refrigeration systems. Energy Convers Manage 2015;105:403–22.
[17] Leiva-Illanes R, Escobar R, Cardemil JM, Alarcón-Padilla D. Thermoeconomic assessment of a solar polygeneration plant for electricity, water, cooling and heating in high direct normal irradiation conditions. Energy Convers Manage 2017;151(May):538–52.
[18] Fernández-García A, Zarza E, Valenzuela L, Pérez M. Parabolic-trough solar collectors and their applications. Renew Sustain Energy Rev 2010;14(7):1695–721.
[19] NREL. Aalborg CSP-Brønderslev CSP with ORC project. SolarPACES, 2017 [Online]. Available: https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=8316 [Accessed: 06-Jul-2017].
[20] Short W, Packey D, Holt T. A manual for the economic evaluation of energy

efficiency and renewable energy technologies. Univ Press Pacific 1995;2(March):120.
[21] IEA-NEA. Projected costs of generating electricity 2015; 2015. p. 16.
[22] Olwig R, Hirsch T, Sattler C, Glade H, Schmeken L, Will S, et al. Techno-economic analysis of combined concentrating solar power and desalination plant configurations in Israel and Jordan. Desalin Water Treat 2012;41(1–3):9–25.
[23] Moser M, Trieb F, Fichter T, Kern J, Hess D. A flexible techno-economic model for the assessment of desalination plants driven by renewable energies. Desalin Water Treat 2014;3994(October):1–15.
[24] Fylaktos N, Mitra I, Tzamtzis G, Papanicolas CN. Economic analysis of an electricity and desalinated water cogeneration plant in Cyprus Desalin Water Treat 2014;3994(September 2015):1–18.
[25] Palenzuela P, Alarcón-Padilla D, Zaragoza G. Large-scale solar desalination by combination with CSP: Techno-economic analysis of different options for the Mediterranean Sea and the Arabian Gulf. Desalination 2015;366:130–8.
[26] Mata-Torres C, Escobar RA, Cardemil JM, Simsek Y, Matute JA. Solar polygeneration for electricity production and desalination: Case studies in Venezuela and northern Chile. Renew Energy 2017;101:387–98.
[27] Al-Sulaiman FA, Dincer I, Hamdullahpur F. Thermoeconomic optimization of three trigeneration systems using organic Rankine cycles: Part I – formulations. Energy Convers Manage May 2013;69:199–208.
[28] Al-Sulaiman FA, Dincer I, Hamdullahpur F. Thermoeconomic optimization of three trigeneration systems using organic Rankine cycles: Part II – applications. Energy Convers Manage May 2013;69:209–16.
[29] Calise F, d'Accadia MD, Macaluso A, Piacentino A, Vanoli L. Exergetic and exergoeconomic analysis of a novel hybrid solar–geothermal polygeneration system producing energy and water. Energy Convers Manage 2016;115:200–20.
[30] Ortega-Delgado B, García-Rodríguez L, Alarcón-Padilla D. Thermoeconomic comparison of integrating seawater desalination processes in a concentrating solar power plant of 5 MWe. Desalination 2016;392:102–17.
[31] SimTech GmbH. IPSEpro Process Simulation Environment, Rev 5.0. SimTech Simulation Technology; 2011.
[32] Escobar RA, Cortés C, Pino A, Pereira EB, Martins FR, Cardemil JM. Solar energy resource assessment in Chile: Satellite estimation and ground station measurements. Renew Energy Nov. 2014;71:324–32.
[33] Wagner MJ, Gilman P. Technical manual for the SAM physical trough model. Contract 2011;303(June):275–3000.
[34] NREL. System Advisor Model (SAM) Case Study: Andasol-1. 2013. p. 1–10.
[35] Houda J, Trieb F, Scharfe J, Kern J, Nieseor T, Cottret N, Glueckstern P. Combined Solar Power and Desalination Plants : Techno-Economic Potential in Mediterranean Partner Countries and Desalination Configurations (MED-CSD); 2009.
[36] Blanco-Marigorta AM, Victoria Sanchez-Henríquez M, Peña-Quintana JA. Exergetic comparison of two different cooling technologies for the power cycle of a thermal power plant. Energy 2011;36(4):1966–72.
[37] Zak G, Mitsos A, Hardt D. Master Thesis. Thermal desalination : structural optimization and integration in clean power and water. Massachusetts Institute of Technology; 2012.
[38] COCHILCO. Proyecciones del consumo de agua en la minería del cobre al 2026. COCHILCO, Comisión Chilena del Cobre. DEPP 16/2015; 2015 [Online]. Available: https://www.cochilco.cl/Listado Temtico/Proyeccion_de_consumo_de_agua_2015_al_2026.pdf #search = precio del agua en el norte. [Accessed: 21-Nov-2017].
[39] Herold K, Radermacher R, Klein S. Absorption chillers and heat pumps. 1st ed. CRC Press; 1996.
[40] El-Dessouky HM, Ettouney HM. Fundamentals of salt water desalination. Elsevier; 2002.
[41] Palenzuela P, Hassan AS, Zaragoza G, Alarcón-Padilla D-C. Steady state model for multi-effect distillation case study: Plataforma Solar de Almería MED pilot plant. Desalination 2014;337:31–42.
[42] CNE. Informe de Proyección de precios de combustibles 2015-2030. CNE, Comisión Nacional de Energía, Chile; 2015 [Online]. Available: https://www.cne.cl/wp-content/uploads/2015/11/ResEx541_2015_Comb-informe-final-Informe-Proyecciones-Precios-Combustibles.pdf [Accessed: 21-Nov-2017].
[43] Noro M, Lazzarin RM. Solar cooling between thermal and photovoltaic: An energy and economic comparative study in the Mediterranean conditions. Energy Aug. 2014;73:453–64.
[44] Turton R, Bailie R, Whiting W, Shaeiwitz J, Bhattacharyya D. Analysis, synthesis, and design of chemical processes. 4th ed. Prentice Hall; 2012.
[45] Ahmadi P, Dincer I, Rosen MA. Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants. Energy Oct. 2011;36(10):5886–98.
[46] Petela R. Engineering thermodynamics of thermal radiation for solar power utilization. 1 ed. McGraw-Hill Education; 2010.
[47] Wang Y, Lior N. Fuel allocation in a combined steam-injected gas turbine and thermal seawater desalination system. Desalination 2007;214(1):306–26.
[48] Wang J, Mao T. Cost allocation and sensitivity analysis of multi-products from biomass gasification combined cooling heating and power system based on the exergoeconomic methodology. Energy Convers Manage 2015;105:230–9.
[49] Piacentino A. Application of advanced thermodynamics, thermoeconomics and exergy costing to a multiple effect distillation plant: in-depth analysis of cost formation process. Desalination 2015;371:88–103.
[50] ELECDA. Tarifas actuales de suministro electrico. ELECDA; 2016 [Online]. Available: http://www.elecda.cl/wp-content/uploads/2016/10/Tarifas-de-Suministro_ELECDA_-Noviembre-2016.pdf [Accessed: 21-Nov-2017].