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Thermoeconomic assessment of a solar polygeneration plant for electricity, water, cooling and heating in high direct normal irradiation conditions

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ABSTRACT

A thermoeconomic assessment of the joint production of electricity, fresh-water, cooling and heat for a solar polygeneration plant is carried out. The aims are to assess the actual cost of each product, to conduct a sensitivity analysis of investment, fuel cost and demand, and to evaluate the effects of solar field size and the sizing of thermal energy storage, for a polygeneration plant located in an area with high solar irradiation conditions and where there is demand for its production. The solar polygeneration plant is configured by a concentrated solar power (CSP) parabolic trough collector field with thermal energy storage and backup system, multi-effect distillation (MED) module, single-effect absorption refrigeration module, and process heat module. The solar polygeneration plant is simulated in a transient regime, in a representative location with high irradiation conditions, such as in northern Chile. Three configurations are investigated: two polygeneration schemes and one considering stand-alone systems. This study reveals that a solar polygeneration plant is more efficient and cost-effective than stand-alone plants for a zone with high irradiation conditions and proximity to consumption centers, such as mining industries, which require continuous operation and energy supply with fundamentally constant demand. Furthermore, according to northern Chilean market, solar polygeneration configurations are competitive regarding electricity, fresh-water, cooling and heat productions. Additionally, solar polygeneration plants can increase the economic profit by selling carbon credits and credits of renewable-energy quotas based on the Kyoto Protocol and Chilean legislation, respectively.

1. Introduction

Energy and fresh water are scarce in many places, especially in locations presenting high irradiation conditions, such as desert and arid zones, thus, the use of solar energy for producing energy and fresh water is an opportunity for economic development, energy security and climate change mitigation. Northern Chile, North-Africa and Australia are places with high irradiation conditions, availability of flat terrain, and with high consumption centers such as mining industries. Northern Chile is a good example for analysis, where its scarcity of energy and water, combined with the large mining facilities in the area, have pushed the demand for electricity, water, cooling and industrial process heat at competitive costs [1,2]. In fact, electricity, water and fuel prices have reached historical highs, negatively affecting the competitiveness of companies operating in the region. According to the Chilean Energy Ministry [3], in 2015, 17% and 34.4% of final energy consumption and electricity generated in the country respectively was consumed by the mining industry, while other industries account for 23% and 24.4% respectively. Chile has a geography that provides an extraordinary variety of climatic conditions and availability of water resources and solar energy. Chile extends 4 270 km from north to south. The north is mostly arid desert, the central zone having a more Mediterranean and the south being temperate and wet. The mining is mainly concentrate in the north regions where minerals are more abundant. The arid Atacama Desert in northern Chile contains great mineral wealth, principally copper. So, the energy consumption in northern Chile is mostly related to mining industries, which require continuous operation and energy supply with fundamentally constant demand. The main sources of energy supply for mining are electricity and fuels. The demand for electricity in 2015 was 18.7 TWh and 12.8 TWh in northern Chile and the cooper mining industry, respectively. At regional level, the electricity demand of the cooper mining industry was 11.0 TWh in Antofagasta

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Nomenclature

A	solar field aperture area, m^2
BS	backup fossil fuel energy system
capex	capital expenditure, USD
c_{ff}	fossil fuel cost, UD/(kWh)
$\dot{C}$	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	unit exergy cost, USD/(kWh)
cfr	capital recovery factor, %
COP	Coefficient of performance, –
COCHILCO	Chilean Cooper Commission
CSP	concentrated solar power
DNI	direct normal irradiance, W/m^2
e	exergy specified, kJ/kg
$\dot{E}$	time rate of exergy or exergy rate, kJ/s
$\dot{E}_{sun}$	exergy rate from sun, kJ/s
$\dot{E}_D$	exergy destruction rate, kJ/s
$\dot{E}_{F,k}$	exergy fuel rate, kJ/s
$\dot{E}_{P,k}$	exergy product rate, kJ/s
$\dot{E}_{L,k}$	exergy loss rate, kJ/s
EPC	Engineering, Procurement, and Construction
FWP	feed water preheater
G	generator
HP	high pressure
i	discount rate, %
f_k	exergoeconomic factor, %
$LiBr/H_2O$	Lithium bromide/water
LP	low pressure
LCC	levelized cooling cost, USD/(kWh)
LEC	levelized electricity cost, USD/(kWh)
LHC	levelized process heat cost, USD/(kWh)
LWC	levelized water cost, USD/m^3
MED	multi-effect distillation
n	number of time periods, years
opex	operational expenditure or operation and maintenance cost, USD/a
P_{elect}	electricity selling price in the grid for industrial use, USD/(kWh)
PH	process heat plant
Poly	Polygeneration
$\dot{Q}$	heat rate, kJ/s
REF	Refrigeration plant
RO	reverse osmosis
r_k	relative cost difference, %
SAM	system advisor model software
SF	solar field
T_0	reference temperature, °C
TES	thermal energy storage
$\dot{W}$	work rate, kJ/s
$\dot{Z}$	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

Greek symbols

ψ	exergy efficiency
τ	average annual time of plant operation at nominal capacity

region [1]. Similarly, the demand for process heat and cooling in northern Chile is almost exclusively associated with mining activity. According to Chilean Cooper Commission (COCHILCO) [4], the demand for fuels in 2015 was 21.2 TWh in the copper mining industry, of these 16.7 TWh was used in ore transportation trucks, and 4.5 TWh in mining processes that requiring process heat such as smelting, refineries, leachable mineral treatments, and services. Of these processes, the leachable mineral treatments, and services require low temperatures, and its process heat demand was about 1.15 TWh. At the regional level, the fuel demand for copper mining industry was 12.1 TWh in Antofagasta region, and the demand of the leachable mineral treatments, and services was about 0.6 TWh. On the other hand, Chile in terms of water, agriculture accounts 77.8%, industry accounts for 9.1%, mining for 7.2% and drinking water for 5.9%. The proportions vary greatly between regions depending upon the climatic regions. The water consumption of the copper mining industry in 2015 was of 15.8 m^3/s, which is forecast to increase to around 21.5 m^3/s by 2026 due to the development of new projects and reduced ore concentration. At a regional level, the freshwater consumption of the copper mining industry in 2015 was of 5.7 m^3/s in Antofagasta region [1]. In contrast, Chile presents high availability of solar energy, especially in the northern region, which stands out as one of highest solar radiation rates worldwide. In this area, the annual average of daily global horizontal irradiation reaches levels higher than 8 kWh/m^2 and the daily average of direct normal irradiation presents values higher than 10 kWh/m^2 [5]. Hence, considering the large demand for electricity, fresh water and process heat, among other utilities, in northern Chile, and the high solar energy availability, we propose to analyze the potential for implementing polygeneration schemes, driven by solar energy.

A polygeneration scheme is an integrated process, which has three or more outputs that include energy flows, produced from one or more natural resources. Polygeneration systems can be classified as either topping, or bottoming cycle systems [6]. In a topping cycle, the priority is power production, i.e. the supplied fuel is first used to produce power and then thermal energy. It is the most popular and widely used method of polygeneration. In contrast, in a bottoming cycle, the priority is heat production, i.e. high temperature thermal energy is the primary product produced by the process and the heat rejected from the process is recovered to generate power. A polygeneration scheme has comparative advantages over individual stand-alone systems, since it allows for reduction in both the primary energy consumption and the emissions of greenhouse gasses by displacing fossil fuels. A polygeneration scheme allows for the integration of different technologies, maximizing the rational use of resources. Due to the complexity of dealing with several energy flows, the integration of such technologies could be evaluated through a thermoeconomic approach, which combines both economic and thermodynamic relations, aiming to reduce the total exergy cost rate of the products. That approach allows performing a complete assessment, considering the conversion efficiencies and economic benefits offered by the system [7].

1.1. Polygeneration technologies

Concentrated solar power (CSP) systems generate solar power by using mirrors to concentrate a large area of sunlight onto a small area. Electricity is generated when the concentrated light is converted to heat, which drives a power cycle that is usually a Rankine cycle. CSP technologies can be classified into four categories: CSP parabolic trough collector, central receiver (solar tower), linear Fresnel and dish-Stirling. Within the CSP technologies, CSP parabolic trough collector is considered as the most mature, accounting for 85% of the cumulative installed capacity; and presenting the lowest cost [8]. CSP parabolic trough collector allows for a simple integration of thermal energy storage (TES) and a backup system allowing to operate in periods of low