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Thermo-economic design optimization of parabolic trough solar plants for industrial process heat applications with memetic algorithms

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HIGHLIGHTS

- A thermo-economic optimization of a parabolic-trough solar plant for industrial process heat applications is developed.
- An analysis of the influence of economic cost functions on optimal design point location is presented.
- A multi-objective optimization approach to the design routine is proposed.
- A sensitivity analysis of the optimal point location to economic, operational, and ambient conditions is developed.
- Design optimization of a parabolic trough plant for a reference industrial application is developed.

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ABSTRACT

A thermo-economic design optimization of a parabolic trough solar plant for industrial processes with memetic algorithms is developed. The design domain variables considered in the optimization routine are the number of collectors in series, number of collector rows, row spacing, and storage volume. Life cycle savings, levelized cost of energy, and payback time objective functions are compared to study the influence on optimal design point location. Furthermore a multi-objective optimization approach is proposed to analyze the design problem from a multi-economic criteria point of view. An extensive set of optimization cases are performed to estimate the influence of fuel price trend, plant location, demand profile, operation conditions, solar field orientation, and radiation uncertainty on optimal design. The results allow quantifying as thermo-economic design optimization based on short term criteria as the payback time leads to smaller plants with higher solar field efficiencies and smaller solar fractions, while the consideration of optimization criteria based on long term performance of the plants, as life cycle savings based optimization, leads to the reverse conclusion. The role of plant location and future evolution of gas prices in the thermo-economic performance of the solar plant has been also analyzed. Thermo-economic optimization of a parabolic trough solar plant design for the reference industrial process heat application at a southern Mediterranean country considered in this work shows a levelized cost of energy of 5 c€/kW h.

1. Introduction

1.1. State-of-the-art

Currently there is a worldwide pressure on fossil fuel consumption, due to the combined effects of the increasing primary energy demand, limitations in available sources, and the environmental awareness of anthropogenic carbon dioxide emissions impact on global warming [1]. These factors constitute an important driving force behind a progressive introduction of clean and viable alternatives in all energy consuming sectors.

The industrial sector has been identified as a potential and still largely unexplored application for solar thermal, since it represents a significant part of total primary energy consumption [2,3]. In the past decades several solar industrial process heat plants were constructed, however, due to the unstable progression of oil prices, their market penetration has been slow and difficult. Nevertheless, recent oil prices, and improvements on the state-of-the-art of medium temperature collectors are bringing back the attention to this area, as shown by the recent studies done by [4–8]. Previous assessments conducted by [3] identified the most relevant

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Nomenclature

A	solar field collector area, m^2
a_0	coefficient of thermal efficiency curve
a_1	coefficient of thermal efficiency curve, W/m^2 K
a_2	coefficient of thermal efficiency curve, W/m^2 K^2
A_a	absorber cross-sectional area, m^2
A_c	collector aperture area, m^2
$A_{e,i}$	exterior area of storage *i*th segment, m^2
A_g	solar field gross area, m^2
b_1	incidence angle modifier curve coefficient
b_2	incidence angle modifier curve coefficient
C	collector concentration ratio
C_a	collector cost per unit area, €/m^2
C_f	fixed costs of the plant, €
C_l	land cost per unit area, €/m^2
$C_{p,i}$	storage specific heat capacity at constant pressure of *i*th segment, J/kg K
C_{pi}	piping cost per unit length, €/m
C_{sp}	solar plant total cost, €
C_v	storage cost per unit volume, €/m^3
D	absorber diameter, m
Eff	solar plant efficiency
E_{p1}	electric power consumed by pump of solar circuit, W
E_{p2}	electric power consumed by pump of load circuit, W
E_t	annual thermal energy produced by the plant, J
f	friction factor
f_{bs}	fraction of shaded area
F_s	solar fraction
g	gravitational acceleration, m/s^2
$G_{b,n}$	normal direct irradiance, W/m^2
K_d	market discount rate
K_{fuel}	annual cost of backup fuel, €
K_{ins}	insurance tax
K_{inv}	plant total investment, €
$K_{o\&m}$	plant operational and maintenance costs, €
k_θ	incidence angle modifier
L	piping total length, m
L_C	collector length, m
L_p	spacing between rows, m
LCCc	life cycle cost of a conventional fuel system only system, €
LCCs	life cycle cost of a solar plus auxiliary energy system, €
LCS	life cycle savings, €
$\dot{m}_L$	mass flow rate on load circuit, kg/s
$\dot{m}_s$	mass flow rate on solar circuit, kg/s
n	plant lifetime, years
N_p	number of collectors in parallel
N_s	number of collectors in series
Q_{aux}	auxiliary power, W
Q_i	input irradiance power on the solar field, W
Q_p	industrial process demanded power, W
$Q_{u,i}$	useful power from solar field *i*th segment, W
Re_D	Reynolds number
T_a	ambient temperature, °C
T_i	storage temperature of *i*th segment, °C
$T_{f,i}$	fluid average temperature of the solar field *i*th segment, °C
T_{in}	solar field inlet temperature, °C
T_{out}	solar field outlet temperature, °C
T_p	process temperature, °C
T_r	process return temperature, °C
U	storage overall heat transfer coefficient, W/m^2 K
V	storage volume, m^3
V_i	volume of the storage *i*th fluid segment, m^3
V_w	absorber tube water velocity, m/s
$\bar{x}$	design variables vector
X	design domain
W	collector aperture width, m
β	collector tracking angle, °
Δp	pressure differential, Pa
ΔT_p	process temperature differential, °C
ε	absorber tube inner absolute roughness, m
η_i	efficiency of the solar field *i*th segment
θ	incidence angle, °
ρ_i	density of the storage *i*th fluid segment, kg/m^3
v	piping design velocity, m/s

Abbreviations

AR	aspect ratio
CRF	capital recovery factor
DNI	direct normal irradiance
E–W	East–West
GA	genetic algorithm
IEA	International Energy Agency
LCOE	levelized cost of energy
LCS	life cycle savings
N–S	North–South
PBT	payback time
PTC	parabolic-trough collector
TMY	typical meteorological year

temperature ranges and industrial thermal demand consumers, concluding that a significant part of these demands are situated at temperature levels between 100 °C and 250 °C. At this temperature level standard stationary non-concentrating collectors present large thermal losses that reduce their efficiency, hence the use of tracking concentrating technology should be considered. Furthermore, industrial processes are frequently located on places where buildings are densely packed and there is small available area [4,8], so it is relevant that the collectors also allow rooftop installation. These requirements justify the recent developments of new concentrating collector designs that are modular and lightweight, such as small parabolic troughs [9–11]. Efforts have been made in the past to assess the potential of parabolic trough collectors for industrial applications. A study performed by [4] reported that parabolic trough collectors reached energy costs ranging from 0.04 €/kW h to 0.08 €/kW h, depending on the industrial process temperature, and considering favorable solar irradiance conditions. These values were substantially higher than typical thermal energy costs in industry, hence this technology was still not able to reach competitiveness without significant subsidies. Another study performed by [8] reaches similar conclusions and evaluates the subsidies intensity necessary to achieve competiveness with other energy sources, for typical investor profile requirements. In a general way, although all recent studies point in the same direction and identify a large potential for solar thermal energy in the industrial sector, further research efforts are still required to increase its economic performance, in order to be able to compete with cheaper fossil fuel energy sources without the need of public subsidies.

In this paper the design of a parabolic-trough solar plant for industrial process heat applications is optimized by thermo-hydraulic model simulation in order to improve its economic performance. Although there are well defined and established methods for designing low and high-temperature solar plants [1,35], there are at present few studies that address the particular