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Thermoeconomic optimization of Solar Heating and Cooling systems

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ABSTRACT

In the paper, the optimal thermoeconomic configuration of Solar Heating and Cooling systems (SHC) is investigated. In particular, a case study is presented, referred to an office building located in Naples (south Italy); for such building, three different SHC configurations were analyzed: the first one is based on the coupling of evacuated solar collectors with a single-stage LiBr–H_2O absorption chiller equipped with a water-to-water electrical heat pump, to be used in case of insufficient solar radiation; in the second case, a similar layout is considered, but the capacities of the absorption chiller and the solar field are smaller, since they are requested to balance just a fraction of the total cooling load of the building selected for the case study; finally, in the third case, the electric heat pump is replaced by an auxiliary gas-fired heater. A zero-dimensional transient simulation model, developed in TRNSYS, was used to analyze each layout from both thermodynamic and economic points of view. In particular, a cost model was developed in order to assess the owning and operating costs for each plant layout. Furthermore, a mixed heuristic–deterministic optimization algorithm was implemented in order to determine the set of the synthesis/design variables able to maximize the overall thermo-economic performance of the systems under analysis. For this purpose, two different objective functions were selected: the Pay-Back Period and the overall annual cost. Possible public funding, in terms of Capital Cost Contributions and/or feed-in tariff, were also considered. The results are presented on monthly and weekly basis, paying special attention to the energy and monetary flows in the optimal configurations. In particular, the thermoeconomic analysis and optimization showed that a good funding policy for the promotion of such technologies should combine a feed-in tariff with a slight Capital Cost Contribution, allowing to achieve satisfactory Pay-Back Periods.

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1. Introduction

The basic principle of Solar Heating and Cooling (SHC) systems lies in the use of high efficiency solar collectors producing hot water all over the year. During the heating season, the solar energy can be obviously used to provide heat and/or sanitary hot water to the building. During the cooling season, the solar thermal energy can feed an absorption chiller to provide refrigerated water; in this way, a significant increase of the annual utilization factor of the solar collectors can be achieved, even in cases in which the demand for sanitary hot water is low or absent. Obviously, the most interesting peculiarity of SHC systems regards the cooling operation. Usually, the maximum demand for cooling coincides with the maximum availability of solar radiation, whereas conventional electric-driven systems have the problem of providing their minimum capacity in the hottest day hours [1]. In addition, the use of solar energy in refrigeration can be very useful in order to limit the growth of the electric energy demand in summer and for sustaining the development of technologies based on renewable energy sources.

Many institutions are presently involved in R&D and demonstration activities on this field: for example, in 1998 the International Energy Agency (IEA) launched a program ("Solar Heating and Cooling, SHC") aimed at improving the conditions for a market introduction of solar assisted cooling systems. This program promoted a reduction of primary energy consumption and electricity peak loads due to air conditioning and thereby developed an environmentally friendly way for air conditioning (IEA, Task 38, formerly Task 25) [2]. Nowadays, dozens of SHC pilot plants have been installed all over the world, experimenting different technologies of solar collectors and absorption/adsorption chillers. Among them, the most promising technology is based on the use of evacuated-tube solar collectors and single-stage H_2O–LiBr absorption chiller, showing the best compromise between system efficiency and costs.

In this framework, a lot of research work has been done in the last few years, also in the field of the numerical analysis of SHC

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Nomenclature

c_{NG}	natural gas cost (€/Sm^3)
c_{EE}	electric energy cost (€/kW h)
c_{ft}	feed-in tariff (€/kW h)
c_p	constant pressure specific heat (kJ/kg K)
c_v	constant volume specific heat (kJ/kg K)
f	design factor
$\dot{m}$	mass flow rate (kg/h)
t	temperature (°C)
A	area (m^2)
AF	annuity factor (years)
C	cost (€)
COP	coefficient of performance
E_{el}	electric energy (kJ)
F_{sol}	solar fraction
J	component capital cost (€)
LHV	natural gas lower heating value (kW h/Sm^3)
M_i	mass of the TK1 *i*th segment (kg)
OF	objective function (€/year)
$\dot{P}$	mechanical power (kJ/h)
PE	primary energy (kJ)
PES	primary energy saving
Q	thermal energy (kJ)
$\dot{Q}$	heat flow (kJ/h)
$\dot{Q}_{B,lsm}$	building max cooling load (kJ/h)
Q_{SC}	useful solar collector energy gain (kJ/h)
SPB	simple pay back (year)
$T_{off,ACH}$	ACH shut-down temperature (K)
U	trasmittance (kJ/h m^2 K)
UA	overall trasmittance (kJ/h K)
V	volume (m^3)
η_{el}	conventional efficiency in thermoelectric conversion
η_{motor}	motor efficiency
$\eta_{pumping}$	pump efficiency
η_{SC}	solar collector efficiency
η_{AH}	AH efficiency
η_{comb}	combustion efficiency
α_{SC}	SC slope (°)
ϑ	time (h)
β_i	power coefficient
ρ	density (kg/m^3)
γ	control function
φ_{P2}	mass flow rate per SC area (kg/h m^2)
Δt_n	nominal temperature difference (°C)
Δt_{TK1}	ACH re-activation set temperature (°C)
ΔC	operating costs savings

Subscripts

H	TK1 top
L	TK1 bottom
amb	ambient
c	cooling
cap	capital
h	heating
in	inlet
n	nominal
out	outlet
op	operating
opt	optimal
rated	at nominal conditions
req	required
rej	rejected
s	summer
set	set by the controller
tot	total
w	winter

systems, mainly aiming at developing transient simulation codes for their design analysis. In particular, a very accurate study was performed by Eicker et al., investigating SHC systems for an office building [3] for different European climates. The authors also performed a cost analysis, showing that Southern European locations with higher cooling energy demand lead to significantly lower costs. In particular, for long operation periods, the unit cost of cooling energy are around 200 €/MW h, rising up to 280 €/MW h for buildings with lower internal gains and shorter cooling periods. For a Southern German climate, the costs are more than two times higher. However, this study considers only a simplified system layout consisting only of a solar field, a stratified storage tank, a controller and a back-up heater. In addition, the system is only externally coupled with the building, using a building load file. Finally, the authors of this study do not suggest any specific design modification to improve the system economic profitability [3]. Florides et al. developed a very interesting TRNSYS simulation model for a Cypriot building [1,4]. Such model was based on the use of several built-in components: thermostats, auxiliary boilers, tanks, pumps absorption refrigerator, house load and different types of solar collectors: flat plate collectors, evacuated tube collectors, CPC collectors. The system was simulated, varying the main design parameters – storage tank volume, collector area, etc. – and the results were analyzed from energetic, economic and environmental points of view. In this work, the authors also performed a parametric optimization aiming at improving system energetic performance. However, the system layout adopted in this work is very simple since the auxiliary energy is provided only by a gas-fired heater, not considering the possibility of using more efficient devices, such as electric heat pumps. In addition, the above mentioned optimization was not implemented in order to assess the set of operating/design parameters minimizing system cost.

A similar work was also performed for a Malaysian building by Assilzadeh et al. [5], using the same procedure and the same simple system layout shown in references [1,4]. The above described simulation tool allowed to establish the optimal collector area and slope. A sensitivity analysis was also included, varying: collector slope, pump flow, boiler set-point temperature, storage tank volume and collector area. This sensitivity analysis did not aim at determining the optimal set of design parameter, adopting a rigorous optimization procedure. The same simplified system layout was analyzed in a paper by Gaddhar et al. [6]. This work, unfortunately based on an out-to-date energy market, also implements a more detailed economic optimization procedure for a solar cooling prototype located in Beirut [6]. Other works available in literature, are mainly focused on the development of accurate mathematical models of the overall system, paying special attention to the absorption chiller. On the other hand, such papers are scarcely interested to the economic aspects of the system. For example, Atamaca and Yigit performed the analysis for the city of Antalya (Turkey), implementing a complex mathematical model for LiBr–H_2O absorption chiller [7]. A very detailed mathematical model was also implemented by Ardheali et al. [8] and Joudi et al. [9,10], for the Iranian and Iraqi climates respectively.

As for experimental analysis, an interesting work was performed by Hammad et al., for a Jordan building [11]. The authors described the performance of a 1.5-ton solar cooling prototype, paying special attention to the variation of the coefficient of perfor-

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