Energy and Buildings 70 (2014) 207–223

Contents lists available at ScienceDirect

Energy and Buildings

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

Economic evaluation of solar thermal and photovoltaic cooling systems through simulation in different climatic conditions: An analysis in three different cities in Europe

Ursula Eicker[a], Antonio Colmenar-Santos[b,*], Lya Teran[b,1], Mariela Cotrado[a], David Borge-Diez[b,1]

[a] Hochschule für Technik Stuttgart, Schellingstr. 24, 70174 Stuttgart oder, Postfach 101452, 70013 Stuttgart, Germany
[b] Departamento de Ingeniería Eléctrica, Electrónica y de Control, UNED Juan del Rosal, 12 – Ciudad Universitaria, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 4 June 2013
Received in revised form
27 September 2013
Accepted 18 November 2013

Keywords:
Domestic hot water
Heat transfer coefficient
Photovoltaic solar cooling system
Primary energy
Sun protection
Thermal solar cooling system

ABSTRACT

Since several processes working with solar energy are available, a study to know which technology is more suitable considering the primary energy consumption and economy is necessary. This paper has as objectives the primary energy analysis and economic evaluation of solar thermal and photovoltaic cooling systems used for the air conditioning in office buildings applying simulation systems. Due to the climatic conditions influence on the performance of these two systems, the comparison is made for three different climates corresponding to Palermo, Madrid and Stuttgart. For each climate the same geometry and dimensions of a building are considered but with different user profiles and construction, consequently different heating and cooling loads, in total 12 cases are taken into consideration. The consumption of electricity is favored with the electricity produced by the photovoltaic modules, which covers in some of the studied cases almost the half of the total energy demand, therefore the relative primary energy savings reaches 50%, while in the case of the solar thermal system, the relative primary energy savings reaches 37% in Palermo, 36% in Madrid, and 29% in Stuttgart. Hence, simulations to determine the best work parameters in each place are suggested for the reduction of energy demands and a sensitivity analysis is presented.

1. Introduction

The increasing demand of energy and the effort to reduce the concentration of greenhouse gases in the atmosphere leads to the searching not only of environmental friendly technologies but also ways for the improvement of the already existing clean technologies in order to make them economically competitive.

The present work has as objectives the primary energy analysis and economic evaluation of two systems which fulfill the requirement of cooling with low CO_2 emissions [1]. Since the high cooling loads and solar gains occur in the same months, the application of solar energy for air conditioning is a logical option [2], the first system is a compression cooling machine fed with electricity provided by photovoltaic (PV) modules and if required from the public grid. If the electricity produced by the PV is higher than the electricity demand, the surplus can be fed into to the public grid depending on the case and the second system is an absorption cooling machine operated with heat provided by solar collectors, the thermal solar cooling system is composed of a solar collector field, for the different simulations are considered flat plate collectors (FPC) and compound parabolic concentrators (CPC).

At the moment, there are some studies for the comparison of these two systems, in some cases these comparisons are made just considering a defined place, period of the year or in other cases considering the performance only of the cooling machines showing that although absorption chillers are more ecological because they consume lower primary energy, their investment cost are still expensive to compete with compression chillers [3]. Therefore, in order to know in which place the application of these systems is more suitable, it is interesting to make a comparison of these two systems for different climates, countries and electricity price [4–12]. In the present work the simulations are made for three different climates corresponding to Stuttgart, Madrid and Palermo. Finally, the results are evaluated considering primary energy and economy parameters described in Task 25 [5,13]. The analysis is developed with results of annual simulations using the programs TRANSOL EDU 3.0 [14], which is used for the simulation of a thermal solar cooling system, and INSEL 7.0 for the simulation of an electrical PV solar cooling system and also for the system used as a reference [15].

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* Corresponding author. Tel.: +34 913 987 788/913 986 476; fax: +34 913 986 028.
E-mail address: acolmenar@ieec.uned.es (A. Colmenar-Santos).

[1] Tel.: +34 913 986 476; fax: +34 913 986 028.

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http://dx.doi.org/10.1016/j.enbuild.2013.11.061

Nomenclature

ACM	absorption cooling machine
CL	cooling load
CPC	compound parabolic concentrators
CSTB	French Scientific Center for Building Physic
COP	coefficient of performance
DHW	domestic hot water
FPC	flat plate collectors
HL	heating load
IEA	International Energy Agency
PE	primary energy
PV	photovoltaic
TRNSYS	TRaNsient Systems Simulation Program
VFD	variable-frequency drive

Symbols

PCT	energy consumed by the cooling tower (kWh)
PCM	energy consumed by the electrical chiller used as a back-up in the thermal solar cooling system (kWh)
Q_1	annual radiation on solar collectors (kWh)
Q_2	annual heat produced by solar collectors (kWh)
Q_3	annual required heat for cooling by the absorption cooling machine (kWh)
Q_4	annual heat removed from the absorption cooling machine by the cooling tower (kWh)
Q_5	annual cooling produced by the absorption cooling machine (kWh)
Q_6	annual cooling produced by the electrical chiller used as a back-up in the thermal solar cooling system (kWh)
Q_7	annual overall cold production by absorption cooling (kWh)
Q_8	annual cooling demand (kWh)
Q_9	annual heating demand (kWh)
Q_{10}	annual heat demand for domestic hot water (kWh)
Q_{11}	annual heating provided by the back-up of the thermal solar system (kWh)
Q_{12}	annual heating provided by the solar collectors (kWh)
Q_{13}	annual heat for domestic water provided by the back-up of the thermal solar system (kWh)
Q_{14}	annual heat for domestic hot water provided by the solar collectors (kWh)
U	heat transfer coefficient (W/m^{2}K)

Table 1
Cases for the calculation of electricity cost of the photovoltaic cooling system.

Case	Photovoltaic cooling system		Thermal solar cooling system	
	Remaining electricity from PV is exported to the public grid	Feed in tariff for electricity (€/kWh)	A benefit for heating and DHW is considered	Tariff of gas (€/kWh)
A	No	–	No	–
B	Yes	Germany: 0.2455 Italy 0.2085 Spain 0.1855	Yes	Germany 0.0572 Italy 0.0542 Spain 0.0506
C	Yes	Germany 0.42 Italy 0.33 Spain 0.4	–	

2. Methodology

2.1. Description of the compared solar systems

In the present work, the comparison of two solar systems is carried out using two different programs. The program TRANSOL EDU 3.0 is used for the simulation of a thermal solar cooling system and the program INSEL 7.0 for the simulation of an electrical PV solar cooling system and also for the system used as a Ref. [16]. The simulations are developed for an office building, which is considered to be in three different places: Palermo, Madrid and Stuttgart.

2.1.1. Reference system

This system is composed of a vapor compressor cooling machine of 30 kW, 40 kW and 50 kW depending on the cooling demand and a cooling storage tank of 1.5 m^3 as shown in Fig. 1. It is assumed that all the electricity demand is covered by the public grid [17]. It is considered that the consumption of energy correspond to the condensers fan, vapor compressor, controller and pumps. A vapor compression cooling chiller model was written in Fortran and implemented as a user-written DLL INSEL block.

2.1.2. Photovoltaic cooling system

The system is similar to the reference system but the energy demand is covered by the electricity obtained by the photovoltaic (PV) modules and if required from the public grid. If the electricity produced by the PV is higher than the electricity demand, the surplus can be fed into to the public grid depending on the case (for the calculation of the energy produced and consumed three cases are considered, see Table 1). The photovoltaic system was modeled in INSEL. The system is composed of two inverters and one hundred modules, which is the maximal number of modules to be installed in the roof buildings area because of the space limitation. In Table 9 is shown the data corresponding to the dimensions of the components of the photovoltaic cooling system.

2.1.3. Thermal solar cooling system

This system is simulated using the system SCH601 given by the program TRANSOL 3.0 as shown in Fig. 2. Although, this figure shows a system including domestic hot water (DHW) production, space heating and cooling, only the elements corresponding to cooling are considered for the comparisons in the present work [18–24]. Energy production used for space heating and DHW production is accounted as an additional economic saving, but not in the cooling system overall analysis.

The thermal solar cooling system is composed of a solar collector field. For the different simulations are considered flat plate collectors (FPC) and compound parabolic concentrators (CPC). The solar collector field exchanges energy with a solar storage tank through an external heat exchanger joined to a primary pump and a secondary pump on the side of the solar collector field and on the side of the solar storage tank correspondingly. Solar thermal heat storage tank is used intended for combined heat storage for heating demand, DHW production and cooling system. Solar collector thermal mass is considered in the model. The primary loop is controlled by radiation. In the first loop the pump is turned on as a function of the incident radiation in the plane of the solar field. The secondary loop control works interlocked with the primary loop control. The pump flow rate is constant. The system stops the pumps if the temperature in the tank or in the solar collector exceeds the maximum security value. An absorption cooling machine (ACM) is directly connected to the solar storage tank, the ACM is turned on when cooling is required and the temperature of the solar tank is over a set point temperature. The flow rate through the generator is constant, so the fluid at the inlet is mixed with the outlet fluid in order to adjust the power of the device. The heat coming from the absorber and condenser is released by