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Adsorption chiller operation by recovering low-temperature heat from building integrated photovoltaic thermal collectors: Modelling and simulation

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A B S T R A C T

This work focuses on a dynamic simulation model for the energy, economic and environmental analysis of an innovative polygenerative system layout based on a building integrated photovoltaic thermal system coupled to an adsorption chiller and to an electricity storage system. The thermal energy of building integrated photovoltaic thermal collectors is exploited in order to produce solar space heating and cooling and domestic hot water. Auxiliary electric air-to-water heat pumps/chillers and a gas-fired condensation boiler are included in the system model in order to integrate the demands of heating, cooling and domestic hot water production. The electricity produced by building integrated photovoltaic thermal collectors is used to satisfy the building needs. The eventual extra-production is delivered to the grid or stored in lead-acid batteries.

By means of the developed dynamic simulation model (implemented in TRNSYS environment) the energy system performance on the whole building can be analysed in terms of heating/cooling energy, electricity and domestic hot water demands. In particular, both the passive and active energy effects of the investigated collectors can be assessed. The model includes a suitable tool for the comparison of the innovative system layout vs. traditional reference building-plant systems. For energy, economic and environmental impact optimization purposes, sensitivity analyses can be performed by varying the main system design parameters with respect to the value of reference case ones.

In order to show the potentiality of the developed simulation model, several new case studies are developed. They refer to a 3-floor office building located in four different Italian weather zones. Simulation results show that the obtained SPBs, the primary energy saving for electricity and domestic hot water production, and the equivalent carbon dioxide avoided emissions range between 10.6–11.3 years, 58.5–68.8% and 76.3–90.2%, respectively.

1. Introduction

The exploitation of solar source is today one of the most effective option for increasing building energy efficiency and savings [1]. In European Union Countries, for the next generation of new and renovated buildings, the Building Integrated Solar Thermal Systems (BISTS) will be strongly recommended or mandatory. BISTS technologies also include Building Integrated PhotoVoltaic - Thermal (BIPVT) collectors, capable to simultaneously produce electricity and provide useful low temperature thermal energy [2]. Such heat can be suitably exploited in different ways, as for example: (i) for supplying Solar Heating (SH) [3], Solar Cooling (SC) [4] and Solar Heating and Cooling (SHC) systems [5]; (ii) for preheating heat pumps water-sources [6]; (iii) for Domestic Hot Water (DHW) preparation [7].

In cooling dominated climates, SC technology is very promising, since during the summer season cooling energy demands are typically simultaneous to the solar radiation. In SC systems, in order to achieve cooling energy, the collected solar thermal energy is supplied to a heat-driven chiller. For this purpose, absorption [8], adsorption [9] or desiccant evaporative [10] systems can be adopted according to the level of the obtained solar collector outlet temperatures. The most common SC system configurations are based on absorption chillers, most commonly used in combination with high temperature solar collectors [11], capable to provide relatively low (80–95 °C) [12] or high (>130 °C) [13] driving temperatures. Low temperatures (45–65 °C) can be obtained by

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Nomenclature

A	area, m^2
c	specific heat, J/(kg K)
C	cost, €
COP	coefficient of performance
E	energy, kWh
Eff_T	temperature efficiency modifier, °C^{-1}
Eff_G	radiation efficiency modifier, m^2/W
EER	energy efficiency ratio, adim
j	specific cost-price, €/kWh
$\dot{m}$	flow rate, kg/h
PE	primary energy, kWh
P	electric power, kW
Q	thermal power, kW
SPB	simple pay back, years
T	temperature, °C or K
U	heat transfer coefficient, W/(m^2 °K)
V	volume, m^3

Greek symbols

ε	long wave emissivity, –
λ	conductivity, W/m K
η	efficiency, –
ρ_s	solar reflectance, adim

Subscripts and superscripts

ADS	referred to adsorption chiller
aux	auxiliary
$cell$	referred to photovoltaic cell
$cool$	cooling
CB	condensation boiler
chw	chilled water
cw	cooling water
DHW	domestic hot water
el	electric
E	energy
EX	exchange
HE	heat exchanger
$heat$	heating
HP	referred to heat pump
hw	hot water
i	i-th time step of the simulation
I	referred to inverter
IS	referred to innovative system
in	input
LAB	referred to lead-acid battery
NG	natural gas
out	output
PES	primary energy saving
$pump$	referred to pump
PVT	PVT solar collectors
R	referred to regulator
RS	referred to reference system
RF	referred to radiant floor
SC	solar collectors
tot	total
th	thermal
y	year

PhotoVoltaic - Thermal (PVT) collectors [14], which can drive adsorption chillers [15], increasing the range of applications of SC systems [16].

Recently, the system combination of PVT solar collectors and adsorption chillers has gained an increasing attention in literature [17]. As an example, the energy and economic performance of an innovative system layout, including PVT collectors, a solar assisted heat pump, an adsorption chiller and electrical energy storage technologies, have been investigated in [18]. Here, for two case studies related to a fitness center and on office space, the utilization factor of the adsorption chiller was estimated about 79% and 98%, with an average Coefficient of Performance (COP) efficiency of 0.58. Similarly, the performance of two solar cooling systems, based on electrical adsorption heat-driven systems (including one driven by PVT collectors), were compared in [19]. Here, promising system efficiencies for the weather of Athens are calculated, e.g. solar COP around 0.47.

The building envelope integration of solar collectors, used to drive adsorption chillers, have been analysed by very few authors, from both numerical [20] and/or experimental [21] points of view. From the numerical point of view, the results of a SC system consisting of building integrated flat-plate solar thermal collectors (driving an absorption chiller) and of building integrated photovoltaic thermal panels (for a DC-driven vapour compression refrigeration system) are compared with the results obtained on a system equipped by stand-alone solar collectors, conventionally installed on the roof of a building located in Hong Kong [22]. Similarly, a study concerning the energy performance of façade BIPVT and integrated solar thermal collectors, installed on a building located in a Spanish warm and temperate weather zone, is presented in [23]. Here, BIPVT collectors are used to preheat winter cold air for heating purposes, whereas the heat obtained by the integrated solar thermal collectors is exploited to feed an adsorption chiller, balancing 93% of the building cooling demand.

At the best authors' knowledge, very few works are today available in literature concerning solar cooling systems obtained through BIPVT collectors with water working fluid coupled to low temperature heat-driven chillers (i.e. adsorption chillers). A rare example concerns a pilot scale experimental set-up consisting of novel roof BIPVT water collectors combined to a liquid desiccant enhanced indirect evaporative cooling system [4]. The recent experimental results showed that the system is capable to provide 3 and 5.2 kW of heating and cooling power, respectively, and to supply 10.3 MWh/year of electricity.

The production of electricity obtained by BIPVT suggests the investigation of the potentiality and benefits (operational, economic and environmental) connected to the use of an electrical storage system [24]. As well known, a less grid-dependent system allows diminishing losses on the electric grid distribution system [25]. The use of electrical storage systems also enhance the economic feasibility of the system, particularly if an optimized management of the electrical flows, from and to the grid, is implemented as a function of the electricity selling prices and/or funding policy [26].

The impact of an electrical storage on the increase of the PV technology in the building sector has been investigated by several authors [24]. As an example, a study on the effect of the electricity storage on building overall energy and economic performances, obtained by shifting the electrical loads from on-peak to off-peak periods, was investigated in [27]. Here, authors developed different strategies applied to a typical residential building with the aim to optimally manage its energy resources as well as to promote self-consumption of energy. A method to reduce the viability of energy storage systems, for balancing the building electrical loads and the