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ScienceDirect

Solar Energy 117 (2015) 59–73

SOLAR ENERGY

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Parametric study and cost analysis of a solar-heating-and-cooling system for detached single-family households in hot climates

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Received 28 December 2014; received in revised form 29 March 2015; accepted 21 April 2015
Available online 16 May 2015

Communicated by: Associate Editor Yanjun Dai

Abstract

A solar-heating-and-cooling (SHC) system, consisting of a flat-plate solar collector array, a hot water storage tank, and an absorption chiller unit is designed and modeled to satisfy thermal loads (space heating, domestic hot water, and space cooling). The system is applied for Nicosia, Cyprus, a location with prolonged summer-like conditions, where heating demand is moderate, while space cooling demand is comparatively very high. The study investigates the potential of a solar system installed and operated onsite in a detached single-family household to satisfy all necessary thermal loads. The hot water storage tank is also connected to an auxiliary heater (diesel-fired boiler) to supplement solar heating, when needed. The main purpose of the study is to model the overall system and contact a parametric study that will determine the optimum economic system performance in terms of design parameters. The system is compared, through a cost analysis, to an electric heat pump (EHP) system. It is found that the optimum system combination of solar collector area and volumetric capacity of the hot water storage tank is 70 m^2 and 2000 L, respectively. The total annualized cost (in USD) for the optimum SHC system is $3,719. The sensitivity analysis showed that the SHC system would be unfavorable to compete with EHP technology, if the solar collector cost is above $360/m^2.

Keywords: Absorption chiller; Solar collector; Solar heating and cooling; Solar air-conditioning; Parametric study; Cost analysis

1. Introduction

In locations with hot climates, most buildings require space cooling, space heating, and domestic hot water. These three thermal demands can be satisfied with different types of equipment and system configurations. Numerous methods and options exist, which can be broadly categorized based on: type of fuel, thermal or refrigeration cycle, renewable- or non-renewable-based energy source. Fossil fuel-dependent systems typically include some, or a combination, of the following equipment: (a) oil/gas-fired boiler used to produce heat, (b) electric vapor-compression heat pumps running on electricity grid-imported from a centralized power plant fueled with fossil fuels, (c) waste heat-operated equipment, where waste heat was generated as a by-product of a fossil fuel–fueled power plant. Refrigeration cycles are used to generate useful heating and/or cooling, and can be operated by electricity (e.g. vapor-compression heat pump), or driven by heat (e.g. absorption chiller). The thermal loads can also be satisfied fully, or partly, by equipment running on renewable energy sources, like photovoltaic (PV) technology, which generates electricity to run, for example, an

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http://dx.doi.org/10.1016/j.solener.2015.04.024
0038-092X/

Nomenclature

A	heat transfer area (m^2)
A_c	solar collector area (m^2)
c	unit cost (\$/kW h, \$/m^3)
C	cost (\$)
f	solar fraction (–)
f_a	annuity factor (–)
h	specific enthalpy (J/g)
$\bar{H}$	average daily irradiation (MJ/m^2)
I_{TC}	monthly average daily energy above the critical level (W/m^2)
$\bar{K}_T$	monthly average daily clearness index (–)
L	load (J)
LHV	lower heating value (GJ/m^3)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
q	vapor quality (–)
Q	heat transfer (J)
$\dot{Q}$	heat transfer rate (W)
T	temperature (K, °C)
U	overall heat transfer coefficient (W/(m^2 K))
V	volume (L, m^3)
VA	volume-area ratio (m^3/m^2)
X	percentage of LiBr (%)
X'	modified dimensionless loss ratio (–)
Y	dimensionless absorbed energy ratio (–)
Z	component cost (\$)

Greek symbols

Δt	time step (s)
η	efficiency (–)
$\bar{\theta}_b$	average beam incidence angle (degrees)
$\bar{\theta}_d$	average effective incidence angle of isotropic diffuse radiation (degrees)
$\bar{\theta}_g$	average effective incidence angle of isotropic ground-reflected radiation (degrees)
$(\overline{\tau}\overline{\alpha}/\tau\alpha)_n$	ratio of average monthly transmittance–ab sorptance product to normal-incidence transmit tance–absorptance product (–)
ϕ	monthly average daily utilizability (–)

Subscripts/superscripts

a	average
ach	absorption chiller
ah	auxiliary heating
anl	annual (average value)
c	cooling, Collector
ct	cooling tower
dhw	domestic hot water
$diesel$	diesel fuel
e	evaporator
ee	electricity
EHP	electric heat pump
h	heating
hs	household
$hwst$	hot water storage tank
m	monthly
max	maximum value
min	minimum value
r	rated value
s	storage
sc	space cooling
sh	space heating
st	storage tank
TE	thermal energy
TL	tank losses
tot	total value

Abbreviations

CDD	cooling degree days
COP	coefficient of performance
HDD	heating degree days
SHC	solar heating and cooling

electric heat pump. Also solar energy harnessed by means of solar collectors is a promising alternative option, especially in locations with abundant solar energy. In this case, accumulated heat, in the form of hot water, is used to satisfy thermal demands directly, in the case of space heating and domestic hot water, or indirectly, through hot-water activated technology, e.g. absorption chiller systems, to generate useful cooling for space cooling and refrigeration applications.

In colder countries the need for space cooling is usually scarce and generally not treated in residential applications. However in regions with prolonged summer-like conditions, where temperatures exceed 25 °C for almost six months every year, and may even exceed 40 °C, there is an unavoidable necessity for space cooling. Since space cooling loads are continuously very high, if the option selected for cooling is electrically-operated equipment, the running cost will be very high. Therefore there exists an urgent need to develop system options with minimum, or ideally, no use of both fossil fuels and electricity. Fortunately high space cooling demand coincides with high solar energy availability (Ali et al., 2008), which provides an opportunity to harness solar energy and convert it to useful cooling through a heat-activated technology. Even if a solar heating and cooling (SHC) system cannot fully satisfy thermal demands, it can contribute to a significant reduction in running costs of electric equipment and/or fossil fuel-fired boilers. Additionally use of solar energy limits