Energy and Buildings 65 (2013) 75–83

Contents lists available at ScienceDirect

Energy and Buildings

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

Performance analysis of a rooftop wind solar hybrid heat pump system for buildings

Qin-Yi Li, Qun Chen, Xing Zhang *

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 14 March 2013
Received in revised form 26 May 2013
Accepted 27 May 2013

Keywords:
Rooftop renewable energy system
Wind solar hybrid
Heat pump
Exergy analysis
Environmental benefit

ABSTRACT

Utilization of wind and solar energies coupled with heat pumps is a promising technology for energy conservation and emission reduction. This paper describes a rooftop wind solar hybrid heat pump system for building hot water, heating and cooling loads and presents energy and exergy analyses as well as an environmental benefit assessment. The system consists of a shrouded wind-lens turbine subsystem, a flat-plate solar thermal subsystem and a water/air source heat pump subsystem, where the wind and solar subsystems are compactly installed on the rooftop. The solar collector heats water for supplying domestic hot water and increasing the heat pump evaporation temperature for room heating. Heat pumps are used for room heating and cooling and auxiliary heating domestic hot water. Wind power contributes to satisfying the heat pump power demand. Energy and exergy analyses show that the solar thermal subsystem is exergetically inefficient and thus a better design of the solar collector can improve the system exergy efficiency. Wind power can provide 7.6% of the yearly heat pump power demand to satisfy the thermal loads of a 198 m^2 residential building in Beijing. The system can yearly reduce 31.3% carbon dioxide emission compared with conventional energy systems.

1. Introduction

Renewable energy utilizations for buildings are important ways toward zero energy consumption and zero emission buildings [1]. As common renewable energies, wind and solar energies can be combined for complementary use because wind energy is richer in winter than in summer while solar energy is the opposite. Therefore, wind solar hybrid utilization for building heating and cooling is a promising technology for sustainable development.

As another common technology for energy saving, heat pumps can be coupled with renewable energy to improve the system efficiency [2]. Kilkis [3] theoretically analyzed a wind-geothermal heat pump system which utilized a 6 kW wind turbine to drive a geothermal source heat pump and the results showed that the system could satisfy a 100 m^2 residential building heating and cooling loads. Ozgener [4,5] set up an experimental system of a solar assisted geothermal heat pump together with a 1.5 kW wind turbine for a greenhouse heating load and found that the wind power could supply 3.13% of the heat pump yearly power demand. Chow et al. [6] designed a solar assisted heat pump system for indoor swimming pool space and water heating, and found that the system coefficient of performance (COP) could reach 4.5 and the energy saving ratio was 79% compared with conventional energy systems. Tagliafico et al. [7] presented a steady state model of a water-to-water heat pump coupled with flat plate solar collectors for swimming pool water heating in various Italian sites and found that the degree-days index was the main independent variable for the energy saving assessment of the systems. Caglar and Yamali [8] analyzed a solar assisted heat pump with an evacuated tubular collector for domestic heating and the system COP could reach 6.38. Moreno-Rodriguez et al. [9] designed a direct-expansion solar assisted heat pump for domestic hot water and the acquired COP could reach 2.9. However, as the reason that the wind turbines used in the existing systems are lowly efficient and occupy much room detached from the building, there are very few studies on the wind power/solar thermal hybrid heat pump system for residential building thermal loads.

Further, several researchers analyzed the performance of renewable energy utilization systems using the irreversible thermodynamic theory [10–15]. Koroneos and Tsarouhis [10] assessed independent solar heating, absorption cooling, electric assisted water heater, and photovoltaic systems using exergy and lifecycle assessment theories and concluded that the exergy efficiencies of solar based systems were relatively low and should be improved. Al-Sulaiman et al. [11] analyzed a solar driven trigeneration system with parabolic through solar collectors and an organic Rankine cycle for cooling, heating and electricity generation and pointed out that the solar collectors and organic Rankine cycle evaporators were the main sources of exergy destructions.

* Corresponding author. Tel.: +86 10 62772668; fax: +86 10 62772668.
E-mail address: x-zhang@tsinghua.edu.cn (X. Zhang).

0378-7788/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2013.05.048

Nomenclatures

A	area (m^2)
c_p	water specific heat at constant pressure (J/(kg K))
D	thermal load (MJ)
Ex	exergy (W)
I	intensity (W/m^2)
(KA)	thermal conductance of building (W/K)
N_{per}	number of residents
Q	heat transfer rate (W)
T	temperature (K)
U	wind speed (m/s)
(UA)	thermal conductance of heat exchanger in heat pumps (W/K)
V_{per}	needed hot water volume per person per day (l/day/person)
W	work (W)
η	efficiency
ρ	density (kg/m^3)

Subscripts

0	ambient
a	air
ab	absorbed
c	condensation
cool	cooling process, cooling capacity
cw	compressor work
d	destruction
dr	destruction ratio
e	evaporation
elec	electricity
equiv	equivalent
ex	exergy
grid	grid power
heat	heating process, heat quantity
hp	heat pump
hw	hot water
in	inlet
indoor	indoor condition
out	outlet
s	solar
sc	solar collector
sub	subsystem
sys	system
T	wind turbine
tank	tank condition
therm	thermodynamic
w	water, wind
wm	water main

Superscripts

′	heat source condition

Abbreviations

COP	coefficient of performance

This paper describes a rooftop wind solar hybrid heat pump system for residential building hot water, heating and cooling loads and presents energy and exergy analyses as well as an environmental benefit assessment. Firstly, the thermal loads of a two story building in Beijing are simulated for the application of the system. Secondly, the system is described in detail and the energy conservation and exergy balance equations are solved to analyze the system performance according to the meteorological data of Beijing and the building thermal loads. Finally, the environmental benefits are analyzed compared with conventional energy systems.

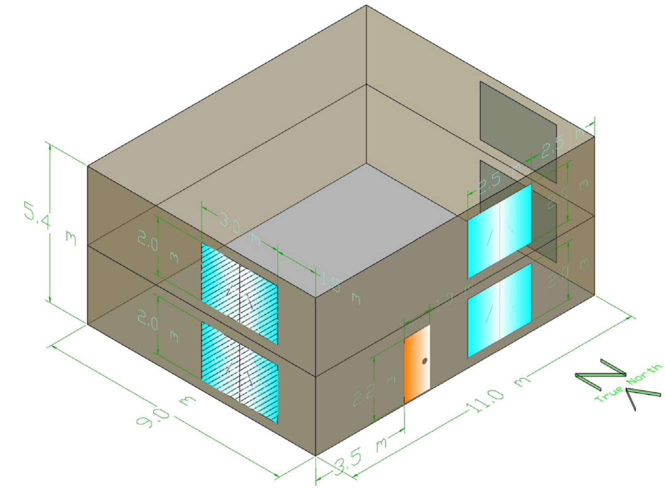

Fig. 1. Schematic of the residential building geometry.

2. Thermal load modeling of a residential building in Beijing

A two story residential building in Beijing is studied for the application of the wind solar hybrid heat pump system. Fig. 1 shows the schematic of the residential building model. The building is located in suburban terrain and facing south. The total architecture area is 198 m^2, with each story being 11 m long, 9 m wide and 2.7 m high. The dimensions of the envelope materials are taken from actual building materials based on market investigations. The walls are made of 9 mm thick wood siding outside, 66 mm thick fiberglass quilt in the middle and 12 mm thick plaster board inside. The roof is made of 19 mm thick wood siding outside, 111.8 mm thick fiberglass quilt in the middle and 10 mm thick plaster board inside. The floors are made of HF-C5. The south door is 2.2 m high and 1 m wide made of fiberglass quilt. Each story has three windows respectively in the east, south and west wall, with the east and west windows being 3 m × 2 m and the south window being 2.5 m × 2 m. Each window is made of two layers of 6 mm thick glass with 3 mm thick air in between. Table 1 lists the thermophysical properties of the architecture materials, Table 2 lists the indoor design parameters of the building and Table 3 lists the lighting power and human released heat variations during a day.

The all-year hourly heating and cooling loads of the building were simulated using the popular building energy simulation software *EnergyPlus* based on the typical all-year hourly meteorological data of Beijing [16]. The software can output hourly heating and cooling loads of a building when the building envelope geometry and materials, the indoor design parameters, the daily schedule of indoor loads and the meteorological data are input as boundary conditions. Although the software is highly precise for hourly simulation, it should be pointed out that the simulation results may deviate from the practical situations because the realistic boundary conditions may vary from the set values in practice, especially for the meteorological data and indoor loads. The daily hot water demand D_{hw} was estimated using the following equation [2]:

$$D_{hw} = N_{per} V_{per} \rho_w c_p (T_{hw} - T_{wm}), \quad (1)$$

where N_{per} is the number of residents in the building, V_{per} is the needed hot water volume per person per day estimated as 40 l/day/person, ρ_w is the water density (1000 kg/m^3), c_p is the water specific heat at constant pressure (4180 J/(kg K)), T_{hw} is the