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Optimal management proposal for hybrid water heating system

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ABSTRACT

This paper presents the dynamic modeling of a domestic hybrid water heating system. The system is composed of a solar collector, a heat pump water heater, a wind turbine, a battery and a hot water storage tank. Both air-source and geothermal-heat pumps are investigated. Detailed mathematical dynamic models of the individual components are presented and validated. Simulations for typical days in summer and winter for Beirut and Cedars, two Lebanese locations with different meteorological and demographic conditions, are conducted using Matlab software. A renewable coverage factor (RCF) is defined, representing the renewable energy share with respect to the total delivered energy. Results reveal that the proposed hybrid system is capable of securing all hot water needs in all case studies and RCF is always above 63%. Furthermore, an energetic, economic optimal management model is developed for the proposed hybrid system. It is applied to the considered case studies, where results illustrate the optimum size of each of the system components as well as the optimum energy-flow distributions among them over two investigated time periods, five and ten years. It is noticed that the initial cost of the hybrid system is acceptable and important annual savings are obtained.

1. Introduction

Life is facing three major problems, which are negatively affecting health, peace and security. They are: (1) the dramatic increase in the energy demand corresponding to the global population evolution as well as the development of living standards, (2) the great consumption increase of the current primary energy source-the non-renewable fossil fuels and (3) the aggravation of global warming and environmental pollution as a result of the preceding two stated problems.

Lebanon is a developing country that meets the majority of its energy needs from oil imports. The country suffers a huge shortage in the electricity generation which is compensated through thousands of backup self-generators that are estimated to represent up to 30% of all electricity generated [1]. Thus, end use electrical energy management is dispensable in this country, because it can participate in minimizing the energy consumption and consequently, reduce the operating expenditure and the local environmental pollution.

Water heating is a major energy consumer all around the world. For instance, its share of the total residential energy consumption is about 11% in USA [2], 14% in Europe [3], 22% in Canada [4], 25% in Australia [5], 25% in Russia [6], 30% in Japan [7], 29% in Mexico [8], 27% in China [9], 32% in South Africa [10], etc. Although no clear statistics for energy consumption corresponding to the domestic water heating in Lebanon, it is known that the country almost has $4010 per capita GNI (Gross National Income) [11], which reflects the good standards of living and consequently the large energy demand. This fact together with the illustrated worldwide statistics reveal that the residential hot water production constitutes an important portion of the total consumed energy in Lebanese homes. Furthermore, 75% of residents rely on electric heaters for domestic hot water production [12], which add an unsustainable burden on the Lebanese electricity sector. Therefore, an important portion of the residential electrical consumption may be saved by the proper choice and management of the domestic water heating system.

This paper presents the detailed numerical modeling of a proposed hybrid water heating system. The performance of this system is investigated for two case studies in Lebanon, where one is located in the capital-Beirut, a coastal metropolitan city, and the other is in Cedars, a mountainous town. The main reason for choosing

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Nomenclature

A	area [m^2]
a	thermal diffusivity [m^2/s]
C	battery capacity [Wh]
C_b	bond conductivity [W/mK]
COP	coefficient of performance
C_p	specific heat [J/kgK]
D	diameter [m]
dt	time step [s]
E	electrical energy [kWh]
$\dot{E}$	electrical capacity [W]
g	gravitational acceleration [m/s^2]
$g(t)$	hot water flow rate from storage tank [kg/s]
h	enthalpy [J/kg]
H	height/ground heat exchanger depth[m]
$h(t)$	domestic hot water demand profile [kg/s]
I	solar radiation [W/m^2]
k	thermal conductivity [W/mK]
L	length [m]
L_c	characteristic length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [Pa]
P	power [W]
Q	heat energy [kWh]
$\dot{Q}$	heat capacity [W]
R	thermal resistance [m^{2}K/W]
r	radius [m]
T	temperature [K or °C]
t	time
U_t	overall loss heat transfer coefficient from the top of collector [W/m^{2}K]
U_{bp}	loss heat transfer coefficient from the bottom of the absorber plate [W/m^{2}K]
U_{bw}	loss heat transfer coefficient from the bottom of the tube wall [W/m^{2}K]
U_{pw}	overall heat transfer coefficient between absorber plate and tube-wall [W/K]
u	velocity [m/s]
V	volume [m^3]
W	width [m]
x, y, z	spatial coordinates
Z_0	surface roughness length [m]
a	absorptance of coating
α	convective heat transfer coefficient [W/m^{2}K]
α'	radiative heat transfer coefficient [W/m^{2}K]
α''	combined-convective and radiative-heat transfer coefficient [W/m^{2}K]
β	coefficient of thermal expansion [1/K]
δ	thickness [mm]
ε	emittance
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
σ	Stefan–Boltzmann constant
τ	transmittance of glass cover

Subscripts

1,2,3	1st, 2nd, 3rd region
a	air
b	borehole
bat	battery
c	condenser
consume	consumed water
d	downward
cs	cross section
e	evaporator
eq	equivalent
gr	grout
HP	heat pump
HTF	heat transfer fluid
i	in, inside
L	load
l	lower part
o	out
p	absorber plate
r	refrigerant
s	soil
st	storage
tap	tap water
u	upper part/upward
w	wall
WB	wind-battery system
wat	water in storage tank

Dimensionless numbers

Symbol	Explanation	Relation
Gr	Grashof number	$Gr = \frac{L_c^3 g \rho^2 \beta \lvert \Delta T \rvert}{\mu^2}$
Nu	mean Nusselt number	$Nu = \frac{\alpha D}{k}$
Pr	Prandtl number	$Pr = \frac{\mu C_p}{k}$
Ra	Rayleigh number	$Ra = Gr \cdot Pr$
Re	Reynolds number	$Re = \frac{\rho u D}{\mu}$

these case studies is the evaluation of the proposed system in different climatic and demographic conditions, which represent the extreme conditions of the country. Furthermore, an optimal management model for the presented system is suggested and solved for these two case studies. The main objective of this model is the optimization of: the energy-flow distributions among the system components, the size of each component and system cost.

2. Literature review

A Taiwanian research group presented and studied an integral-type solar assisted heat pump water heater (ISAHP) [13–17]. In this design, the storage tank and the Rankine cycle units were integrated together to make a more compact size and a thermosyphon loop was used to transfer heat from the condenser to the water storage tank. Furthermore, the condenser was of tube-in-sheet, unglazed type and the solar collector was itself the evaporator. The ISAHP absorbs energy from solar radiation and ambient air simultaneously. It was found that the thermal performance of an ISAHP is marginally influenced by the variation of ambient temperature. Guoying et al. [18] performed a simulation study of solar-air source heat pump water heater with a specially designed flat-plate heat collector/evaporator with spiral-finned tubes. The designed collector/evaporator was exposed directly to both ambient air and solar radiation and hence, it could collect solar energy through the plate and ambient-air energy through the natural convection between the tubes and the ambient. It was proved that this system could produce 55 °C-hot water all around the year, overcoming the problem of direct expansion solar assisted heat pump (DX-SAHP) that fails in rainy days. Anderson and Morrison [19] studied a solar-boosted heat pump heater with flat unglazed aluminum solar evaporator panels to absorb solar and ambient energy. A wrap-around condenser coil on the outside of the water