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Optimization of combined cooling, heating and power generation by a solar system

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ABSTRACT

In this paper energy, exergy and economic optimization of a combined cooling, heating and power (CCHP) solar generation system equipped with conventional photovoltaic (PV), concentrated photovoltaic/thermal (CPVT), and evacuated tube (ET) collectors is presented. Optimization was performed to achieve the highest values of relative net annual benefit (RNAB) and exergy efficiency as two objectives. Decision or design parameters were the number of CPVT collectors, the number of ET collectors, the number of PV collectors as well as the capacity of batteries and the size of hot water storage tank. Optimum values of design parameters with maximizing objective functions were performed by NSGA-II multi-objective optimization technique. LINMAP method was used to select one optimum point among many others which had constructed the Pareto front curve. The chosen point used only 3 CPVT collectors and specific water storage tank volume without any battery. Sensitivity analysis of effects of changes in fuel and electricity prices as well as equipment investment costs on optimum values of design parameters were also investigated. Finally the equipment selection results for a full CPVT solar energy system connected to the grid and disconnected to the grid (remote area) were also compared and reported.

1. Introduction

Photovoltaic thermal (PVT) systems not only produce solar electric energy but also deliver solar thermal energy as the byproduct. Several research works are devoted to study solar combined production of heating and power (CHP) systems. Kalogirou and Tripanagnostopoulos [1] used TRNSYS software to study and simulate PVTs for domestic electrical and thermal applications. Aste et al. [2] studied PVTs to find the optimum solar fraction (the amount of energy produced by the solar technology divided by the total energy required) for electrical and thermal loads [1,2]. With PVTs being commercial, even expensive highly efficient concentrated cells (CPVTs) became economical as far as a lower number of these cells (in comparison to usual PV systems) are required in a solar system. CPVTs are in two groups of low concentration cells (for which cooling mechanism is not necessary) and high concentration cells (which need an active or a passive cooling mechanism) [3]. Mittelman et al. [4] stated that the operational temperature of usual PV (low concentrated) cells is about 40 °C–60 °C while for high concentrated ones (CPVTs with III-V semiconductor materials) this temperature can be as high as 240 °C. Therefore, with cooling CPVT system, thermal energy at relatively high temperature can be obtained for heating applications. The extracted thermal energy from CPVT systems can be also used in generator of an absorption chillers with temperatures above 100 °C [4,5]. However, more studies are required to explore the capabilities and benefits of CPVT systems especially in comparison with the other types of collectors, these systems are employed for desalination application as well [6].

In addition, solar-powered absorption chillers have become popular due to the fact that cooling capability increases favorably in summer days as the sunlight gets more intense and more energy is available. Koroneos et al. [7] emphasized the effect of using these systems on reducing environmental pollution (due to lower fossil fuel consumption). Similarly, Calise [8] presented energy and economic analysis of solar heating and cooling systems in order to use them at school buildings. Molero-Villar [9] stated that its marketing introduction still represents challenge, due to the higher investment cost, although the features of an absorption chiller promises a good combination with a solar energy system in order to eco-friendly serve the energy loads of a building.

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Nomenclature

A	Surface area (m^2)
AC	Annual cost ($/year)
ASV	Annualized salvage value
C	Specific heat (J/(kg.°C))
CCHP	Combined cooling, heat and power
Con	Concentration
CPV	Concentrated photovoltaics
CPVT	Concentrated photovoltaic thermal
D	Crowding distance
ET	Evacuated tube collector
Ex	Exergy (W)
EUAC	Equivalent uniform annual cost
f	Value of objective function
Hour	Solar hour of the day
h	Heat transfer coefficient (W/(m^2.°K))
i	Interest rate
K	Incident angle modifier
k	Thermal conductivity (W/(m.°K))
L	Life of system (year)
LHV	Lower heating value (J/kg)
M	Maintenance
m	Mass (kg)
$\dot{m}$	Mass rate (kg/s)
N	Number
NAC	Net annual cost
Nu	Nusselt number
n	Unit vector form the earth to the sun
P	power (W)
Pr	Prandtl number
PV	Photovoltaics
PVT	Photovoltaic Thermal
Q	Power (W)
RNAB	Relative net annual benefit
Re	Reynolds number
RMSE	Root mean square error
Sp_{CO2}	Specific Co_2 emission (kg/kWh)
SV	Salvage value
T	Temperature (all in °C except from Stefan Boltzmann which is in °K)
TMY2	Typical meteorological year, version 2
U	Overall heat transfer coefficient (W/(m^2.°K))
u_{wind}	Wind speed (m/s)
V	Volume (m^3)
$\dot{V}$	Volumetric flow rate (m^3/s)
X	LiBr mass fraction in solution

Subscript

abs	Absorber
amb	Ambient
annu	Annualized
b	Bought electricity from the grid
coo	Cooling
c	Cold
con	Condenser
conv	Convection
d	Characteristic length (m)
day	Referring to the number of day
dir	Direct or beam radiation
ET	Evacuated tube
el	Electrical
eva	Evaporator
ext	External
f	Fuel
gen	Generator
gl	Glass
HP	Heat pump
HW	Hot water
h	Hot
heat	Heat need
INC	Incident radiation
ini	Initial
int	Internal
l	Longitudinal
liq	Liquid
load	Load of the building
los	Losses
m	Mean
NOCT	Nominal operating cell temperature
nom	nominal power (kW)
opt	Optical
part	partial power (kW)
par	Parasitic consumption
pl	Plate which is the wall of cooling channel in CPVT
pv	Photovoltaic
rad	Radiation
ref	Refrigerant
s,strg	Strong solution
s,weak	Weak solution
s	Sold electricity to the grid
stor	Water storage tank
sun	Related to sun
t	Transversal
tank	Hot water storage tank
tot	Total (thermal and hot water loads)
trad	Traditional system of providing loads
vap	Vapor
WH	Water heater
w	Water
x	X direction in X-Y-Z coordinate
y	Y direction in X-Y-Z coordinate
z	Z direction in X-Y-Z coordinate

Greek letters

τ	Time interval (1 h)
ζ	Capital recovery factor
γ	Surface azimuth angle (degree)
β	Slope (degree)
ω	Hour angle (degree)
λ	Site latitude (degree)
δ	Declination angle (degree)
θ	Incident angle (degree)
η	Efficiency
μ	Dynamic viscosity (pa.s)
ε_{Ex}	Exergy efficiency
ε	Emissivity
ε_{HE}	Solution heat exchanger effectiveness
Δt	Time difference (s)
ρ	Density (kg/m^3)
φ	Price factor ($/kwh)
ψ_{CO2}	Pollutant emission factor ($/$kg_{Co2}$)
σ	Stefan Boltzmann constant (J/(s m^2 K^4))