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Comparative study of indirect photovoltaic thermal solar-assisted heat pump systems for industrial applications

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HIGHLIGHTS

- Two indirect PVT solar-assisted heat pump systems integrated in a paper mill are proposed.
- Mathematical model is used to investigate the performance of these systems.
- The systems are compared for different values of the supplied hot water.
- Increasing the supplied hot water temperature leads to a decrease of the performance factors.
- The best solution in economic terms is a PVT system with a steam ejector heat pump.

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ABSTRACT

In this paper, a comparative study of indirect photovoltaic thermal solar-assisted heat pump systems for water heating in industry is presented. The solutions to achieve a system with a steam ejector heat pump and a system with a mechanical compression heat pump integrated in a paper mill are proposed. The mathematical models are developed and used to evaluate the performance of these systems for the Bacau, Romania climatic conditions. A numerical study highlights the energy, exergy and economic efficiency of each system for the different operating hot water temperatures supplied. The obtained results show that an increase in the hot water temperature leads to a decrease in the energy, exergy and economic performance and that in an industrial company with continuous operation, the best solution is a photovoltaic thermal system with a steam ejector heat pump.

1. Introduction

A photovoltaic thermal (PVT) system integrates a PV module and a conventional solar thermal system in a single piece of equipment in order to generate electricity and thermal power simultaneously.

The electrical efficiency of PV system decreases rapidly as the PV module temperature increases. Therefore, the PV module is cooled with a fluid in a PVT system, thus obtaining more electricity and useful heat.

Theoretical research and practical applications of PVT technologies have been carried out. Thus, Tyagi et al. [1] give the trends of development and technological advancement for the useful applications of PVT in hybrid systems like solar heating, water desalination, solar greenhouse, solar still, photovoltaic-thermal solar heat pump/air-conditioning system, building integrated photovoltaic/thermal (BIPVT) and solar power co-generation.

Air-based PVT is one of the most commonly used PVT technologies and has been developed into commercial units and used in many engineering practices. Amori et al. [2] evaluate experimentally the performance of different conceptual designs of hybrid PVT collectors. They manufactured and tested four types of air based hybrid PVT collectors. First model consists of two PV modules in parallel connection with no cooling and the other three models are hybrid PVT collectors that differ in the number of ducts and passes of cooling air. A quantitatively comparative study of these designs has been carried out to achieve good cooling of the solar modules in order to minimize the cells operating temperature and to maximize the collector thermal efficiency. The obtained results show that the combined efficiency of collector model with double duct and single pass is higher than the other models, in Iraq especially.

The air PVT collectors are generally less efficient than liquid ones. Water-based PVT is a commonly used technology, too. Compared to the air-based system that can achieve maximum

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Nomenclature

B_{se}	monthly benefit of the PVT-SEHP system (EUR/month)
C_{se}	monthly cost of the PVT-SEHP system (EUR/month)
$c_{p,g}$	heat capacity of glycol (J/kg °C)
$c_{p,w}$	heat capacity of water (J/kg °C)
D_g	glycol mass flow rate (kg/s)
$D_{v,se}$	vapor mass flow rate in the SEHP (kg/s)
$D_{v,c}$	vapor mass flow rate in the MCHP (kg/s)
D_s	motion steam mass flow rate (kg/s)
$D_{w,se}$	water mass flow rate in the SEHP (kg/s)
$E_{c,se}$	exergy consumed to produce motion steam monthly (kWh/month)
$E_{u,se}$	useful exergy of hot water supplied monthly (kWh/month)
E_{pvt}	useful exergy produced by PVT system (W)
EPF_{se}	energy performance factor for the PVT-SEHP system
$ExPF_{se}$	exergy performance factor for the PVT-SEHP system
G	global irradiance on a cell surface (W/m^2)
$h_{a,se}\ldots h_{f,se}$	refrigerant fluid specific enthalpy in the characteristic points in SEHP (J/kg)
$h_{a,c}\ldots h_{d,c}$	refrigerant fluid specific enthalpy in the characteristic points in MCHP (J/kg)
h_{ge}	outlet glycol specific enthalpy of the evaporator (J/kg)
h_{gi}	inlet glycol specific enthalpy in the evaporator (J/kg)
hr	time of day (hour)
$I_{c,i}$	current in the cable i (A)
i	order number of the cable
j	order number of the PVT panel
k	order number of the inverter
$kt_{cp,p}$	overall heat transfer coefficient from the connecting pipeline p to air (W/m^2 °C)
n_c	number of cables
n_{cp}	number of connecting pipeline
n_i	number of inverters
n_p	number of PVT panels in a row
n_r	number of rows of PVT panels
n_z	number of days in the month
p	order number of connecting pipeline
$P_{c,c}$	compressor power (W)
$P_{c,cd}$	condensate circulation pump power (W)
$P_{inv,k}$	electrical power in the inverter (W)
P_p	glycol circulation pump power (W)
P_{pvt}	useful electrical power produced by PVT system (W)
pr_e	electricity price (EUR/kWh)
pr_q	heat price (EUR/kWh)
$R_{c,i}$	ohmic resistance of the cable i (Ω)
R_{se}	monthly revenue of the PVT-SEHP system (EUR/month)
$Q_{c,se}$	heat consumed to produce motion steam monthly (kWh/month)
Q_{pvt}	useful heat produced by PVT system monthly (kWh/month)
$Q_{u,se}$	useful heat produced by PVT-SEHP system monthly (kWh/month)
S	cell surface (m^2)
$S_{cp,p}$	surface of connecting pipeline p (m^2)
s_{ge}	outlet glycol specific entropy of the evaporator (J/kg °C)
s_{gi}	inlet glycol specific entropy in the evaporator (J/kg °C)
ssc	motion steam specific flow (kg steam/kg vapor)
t_{aer}	ambient air temperature (°C)
$t_{c,j}$	cell temperature in the PVT panel j (°C)
$t_{ge,j}$	outlet glycol temperature of the PVT panel j (°C)
$t_{gi,j}$	inlet glycol temperature in the PVT panel j (°C)
$t_{gcd,p}$	average temperature of glycol in the connecting pipeline p (°C)
$t_{gv,i}$	inlet glycol temperature in the evaporator (°C)
$t_{g,np}$	outlet glycol temperature of the last PVT panel (°C)
T_o	reference temperature for exergy calculus (K)
t_{we}	outlet water temperature of the condenser (°C)
t_{wi}	inlet water temperature in the condenser (°C)
t_r	reference temperature for the PVT panel
W_{pvt}	useful electricity generated by the PVT monthly (kWh/month)
$W_{p,g}$	electricity consumed by the pump glycol monthly (kWh/month)
$W_{p,w}$	electricity consumed by the pump water monthly (kWh/month)
$W_{p,cd}$	electricity consumed by the pump condensate monthly (kWh/month)
W_{contr}	electricity consumed by the controller monthly (kWh/month)

Greek letters

β	panel efficiency correction coefficient
$\Delta\Phi$	heat flux loss from connecting pipelines to air (W)
ΔH	pressure loss (Pa)
ΔP	electrical power loss (W)
ρ_g	glycol density (kg/m^3)
$\Phi_{c,se}$	heat flux consumed to produce motion steam (W)
Φ_{pvt}	useful heat flux produced by PVT system (W)
$\Phi_{u,c}$	useful heat flux produced by PVT-MCHP system (W)
$\Phi_{u,se}$	useful heat flux produced by PVT-SEHP system (W)
η_{burn}	combustion burner efficiency
η_{cd}	condenser efficiency
$\eta_{e,r}$	electrical efficiency reference for the PVT panel
$\eta_{inv,k}$	efficiency of inverter k
η_m	pump motor efficiency
η_{cm}	overall efficiency (compressor and motor)
η_{pm}	overall efficiency (condensate pump and motor)
η_{power}	efficiency of the conventional power plant
η_v	evaporator efficiency
τ_i	time when solar radiation appears
τ_f	time when solar radiation disappears
$\tau_{p,i}$	time the heat pump starts
$\tau_{p,f}$	time the heat pump stops

electrical efficiency of around 8% and thermal efficiency of around 39%, the water-based system could improve the electrical efficiency of the PVs up to around 9.5% and increase the solar thermal energy utilization up to around 50% [1]. Dubey et al. [3] evaluate the performance of partially covered flat plate water collectors connected in series. They developed a theoretical model and a computer program based on the energy and exergy balance equations. After a detailed analysis, they concluded that the partially covered collectors are beneficial in terms of annualized uniform cost if the primary requirement of the user is thermal energy yield and that fully covered collectors are beneficial when the primary requirement is electrical energy yield. Fudholi et al. [4] determined the electrical and thermal performance of photovoltaic thermal (PVT) water collectors with the spiral flow absorber. They found that, for a solar radiation level of 800 W/m^2 and a mass flow rate of 0.041 kg/s, the spiral flow absorber produced a PVT efficiency of approximately