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Investigation of a solar-biomass polygeneration system

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A B S T R A C T

The objective of this work is the investigation of a polygeneration system which is driven by solar energy and a biomass boiler. Parabolic trough solar collectors coupled to a storage tank are used in order to produce useful heat at high-temperature levels (~350 °C). The system includes an organic Rankine cycle and a vapor compression cycle in order for electricity and cooling to be produced respectively. Moreover, useful heat is produced at two temperatures levels (50 °C and 150 °C) and so there are totally four useful energy outputs. The system is optimized in steady-state conditions and then the most suitable design is investigated in dynamic conditions for all the year period. According to the final results, the yearly energetic efficiency of the system is 51.26% while the yearly exergetic efficiency is 21.77%. The net present value is found 165.6 k€, the payback period 5.13 years, the internal rate of return 21.26%, while the yearly CO_2 avoidance to 125 tn. Finally, the results of this work indicate that the suggested configuration can provide various useful outputs with high efficiency and the total investment is characterized as viable due to the suitable financial index values.

1. Introduction

The increasing energy demand [1], the fossil fuel depletion [2] and the global warming [3] are the most important issues of the energy domain in the recent years. Renewable energy sources constitute an answer in the alternative energy sources for substituting conventional fossil fuels [4]. Solar energy, wind energy, biomass and geothermal energy are the most important renewable energy sources for covering the energy needs of the building and the industrial sector [5].

Solar energy is an abundant energy source [6] and it can be converted directly into useful heat or electricity [7]. These facts make it a suitable energy source for exploitation in various applications such as refrigeration, heating production, desalination, chemical processes and electricity production [8]. The concentrating solar systems (parabolic trough collector, linear Fresnel reflector, solar dish and solar tower) are promising systems for useful heat production at high-temperature levels. These systems can be easily coupled to biomass boilers to provide a constant heat input in the examined application.

In this direction, different systems have been investigated in the literature with the use of solar or/and biomass utilization. Among these systems, the cogeneration, trigeneration and polygeneration systems are the most attractive choices because of the high system performances that they achieve [9]. Practically, the simultaneous production of more useful outputs makes possible the exploitation of waste heat streams. So, these systems transfer heat between various subsystems and so lower amounts of heat are rejected to the ambient; the fact that increases the overall system performance.

In the literature, there are various polygeneration systems which are driven by renewable energy sources. Among them, the studies with parabolic trough solar collectors (PTC) have a significant part in the literature because the PTC can produce useful heat in high-temperature levels with high thermal efficiency. Firstly systems with solar energy as the heat input are given. Leiva-Illanes et al. [10] examined a solar-driven polygeneration system for electricity, heating, cooling and water production. They used PTC coupled to a conventional Rankine power cycle and their results show that the exergy efficiency of the stand-alone system is 18.7%.

Bellos and Tzivanidis [11] optimized a system with Organic Rankine Cycle (ORC), absorption chiller and PTC for cooling, heating and electricity production. They found the maximum exergy efficiency to be 29.42% with toluene. In Ref. [12], it is found that this configuration (with pure thermal oil as working fluid) is a viable investment with a payback period of 5.3 years and internal rate of return (IRR) close to 20%. Furthermore, Bellos and Tzivanidis [13] examined a trigeneration system driven by PTC which includes a generator, an ejector, a condenser, a turbine and an evaporator. This configuration is a compact system which can produce heating, cooling and electricity. They found that this system is suitable for high heat amounts production, while it is financially viable with a payback period of around 5 years. The exergy efficiency of this system is found to be 11.26% and the energy efficiency

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Nomenclature

A_a	collector net area, m^2
CF	cash flow, €/year
c_p	specific heat capacity under constant pressure, J/kg K
C_0	capital cost, €
F	optimization objective function, –
f	solar cover, –
$f_{y,all}$	yearly solar cover for all the days, –
$f_{y,sun}$	yearly solar cover for only the sunny days, –
G_b	solar direct beam irradiation, W/m^2
Hu	lower heating values of the biomass, kJ/kg
IRR	internal rate of return, %
K	incident angle modifier, –
K_B	biomass cost, €/kWh_{th}
K_{el}	electricity cost, €/kWh_{el}
K_{cool}	cooling cost, €/kWh_{cool}
K_h	cost of the heat, €/kWh_{th}
m	mass flow rate, kg/s
m_B	biomass mass consumption, kg/s
M_{CO2}	yearly avoidance of carbon dioxide, tones
MW	molecular weight, kg/kmol
N	project lifetime, years
NPV	net present value, €
p	pressure, bar
Pel	net electricity production from all the system, kW
PP	payback period, years
PR	pressure ratio parameter, -
Q	energy rate, kW
Q_{c1}	heat rejection from the Organic Rankine Cycle condenser, kW
Q_{c2}	heat rejection from the Vapor Compression Cycle condenser, kW
Q_e	cooling production in the evaporator, kW
Q_{h1}	low-temperature heat production, kW
Q_{h2}	high-temperature heat production, kW
r	discount factor, %
s	specific entropy, kJ/kg K
SPP	simple payback period, years
T	temperature, °C
t	time, s
U_T	tank thermal loss coefficient, W/m^2 K
W_{pump}	organic fluid pump work demand, kW
WT	turbine work production, kW
V	storage tank volume, m^3
Y	yearly energy production/consumption, kWh

Greek symbols

δ	solar declination angle, °
Δt	time step, s
η_B	boiler efficiency, –
η_{en}	energy efficiency, –
$\eta_{en,y}$	yearly energy efficiency, –
η_{ex}	exergy efficiency, –
$\eta_{ex,y}$	yearly exergy efficiency, –
η_g	generator efficiency, –
$\eta_{is,T}$	turbine isentropic efficiency, –
$\eta_{is,com}$	compressor isentropic efficiency, –
η_m	mechanical efficiency, –
η_{motor}	motor efficiency, –
$\eta_{th,c}$	thermal efficiency of the solar collector, –
θ	solar incident angle, °
θ_z	Zenith angle, °
π_c	pressure ratio in the compressor, –
ρ	density, kg/m^3
φ	local latitude, °

Subscripts and superscripts

am	ambient
aux	auxiliary
B	boiler
c	collector
com	compressor
crit	critical point
c,in	collector inlet
c,out	collector outlet
e	evaporator/cooling
el	electrical
h	heat
h1	heat at low temperature
h2	heat at high temperature
HRS	Heat Recovery System
l	source to the heat recovery system
loss	storage tank thermal losses
l,in	sourse inlet to the heat recovery system
l,out	source outlet to the heat recovery system
loss	thermal loss of the tank
max	maximum
min	minimum
new	new moment
o	organic fluid
old	old moment
r	refrigerant
s	solar
st	stored in the tank
sun	sun
u	useful
y	yearly
0	reference

Abbreviations

COP	coefficient of performance
GWP	global warming potential
HRS	heat recovery system
ODP	ozone depletion layer
ORC	organic Rankine cycle
O&M	operation and maintenance
PP	Pinch point – Temperature difference
PTC	parabolic trough collector
VCC	vapor compression cycle
2D	two-dimensional depiction

of 87.39%.

The combination of a polygeneration system with geothermal and solar energy has been performed by Calise et al. [14]. This system was designed for producing heating, cooling, electricity and fresh water. The core of the examined system is an ORC which is fed by the heat sources. The authors of this work found the exergy efficiency to be up to 50% in the thermal recovery mode, up to 20% in the cooling mode and the simple payback period to be close to 5 years. Matta-Torres et al. [15] studied a system with PTC and backup boiler for electricity production and desalination. They examined a Rankine cycle with a multi-effect distillation system after the low-pressure turbine for the locations of Chile and Venezuela. Their results proved that this system can