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Exergy analysis of a Combined Cooling, Heating and Power system integrated with wind turbine and compressed air energy storage system

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ABSTRACT

Utilizing renewable energies is the promising solution to the environmental problems which are brought about due to fossil fuel consumption. The fact that these kinds of energies are intermittent can be overcome with using energy storage systems. Wind energy coupled with compressed air energy storage systems is one of the best candidates in this respect. The main objective of this paper is to study the integration of this system with a Combined Cooling, Heating and Power cycle comprised of a gas turbine, an organic Rankine cycle and an absorption refrigeration system. Energy and exergy analyses are applied to the system and the effect of key parameters on the system performance are analyzed. The results show that under design condition, the system can generate 33.67 kW electricity, 2.56 kW cooling and 1.82 ton per day hot water with a round trip energy efficiency of 53.94%. Also exergy analysis reveals that wind turbine, combustion chamber and compress air storage system have the highest amount of exergy destruction respectively. Finally, sensitivity analysis shows that parameters related to gas turbine are the most prominent parameters of the system which can change performance of the system considerably.

1. Introduction

During the last two centuries, energy consumption has increased rapidly due to population growth and technology improvements. Based on data published by DOE [1], almost 16% of total energy is consumed in residential and commercial sectors for cooling, heating and lighting purposes. Consumption of this amount of energy has many consequences, on the top of them environmental and economic problems. Combined cooling, heating and power (CCHP) systems are the promising solution to reduce energy consumption in these sectors [2].These systems also reduce energy losses in energy transmission system.

Many researchers have studied CCHP systems. Hanafizadeh et al. [3] defined three different scenarios for a CCHP system in an office building with different prime movers and studied them economically and environmentally. Chen et al. [4] studied coupling of a CCHP based on PEM fuel cell and absorption refrigeration system in steady state. They showed that efficiency of the system can reach to70.1% in summer and 82% in winter. Ma et al. [5] coupled an ammonia-water mixture with a SOFC-GT system and evaluated performance of the total system. They showed that the proposed system can reach to thermal efficiencies higher than 80%. Zhao et al. [6] analyzed a cascade system which is comprised of a SOFC, a gas turbine, a steam turbine and a Li-Br absorption refrigeration cycle to provide simultaneous power, heat and cooling. They also performed a sensitivity analysis on the most important parameters of the system. Li and Hu [7] performed exergetic comparison between an absorption refrigeration system and an electric compression chiller in a CCHP system which uses a combined cycle of gas turbine and steam turbine as prime mover. They showed that the selection between these two types of refrigeration is heavily dependent on the distance between the power station and refrigeration system, in a way that when the distance is lower than 5 km, absorption refrigeration system is more effective. Ebrahimi et al. [8] performed exergy analysis on a CCHP system which uses a steam and air heat exchanger to provide heating and a steam ejector condenser to provide cooling. They also optimized the plants performance using genetic algorithm. Gao et al. [9] analyzed the effect of gas composition on the performance of a gas engine which drives a CCHP system. They performed their study under both design and off-design conditions. Chen et al. [10] carried

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Nomenclature

A	area (m^2)
COP	coefficient of performance
c_p	power coefficient
C_p	specific heat at constant pressure (kJ/kg K)
Ex	exergy (kW)
ex	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat (kW)
r_p	pressure ratio
R_p	total pressure ratio of compression train
RTE	round trip efficiency (%)
s	specific entropy (kJ/kg K)
T	temperature (C)
t	time (h)
V	volume (m^3)
$\dot{W}$	power (kW)
x	mass fraction
y	molar fraction

Greek symbols

γ	specific heat ratio
η	efficiency (%)
ξ	chemical exergy/energy ratio
ρ	density (kg/m^3)
υ	velocity (m/s)
ε	effectiveness (%)

Subscripts

a	Air
CC	combustion chamber
ch	chemical
comp	compressor
f	fuel
g	flue gas
GT	gas turbine
ph	physical
tur	turbine
w	water
WT	wind turbine

out energy and exergy analyses on a CCHP system including a micro gas turbine and an absorption chiller. They also added a heat exchanger to produce hot water from gas turbine exhaust flow. Moya et al. [11] carried out an experimental analysis on a CCHP system consisting of a micro gas turbine, an air cooled absorption chiller and a heat exchanger to compute its efficiency. They also performed economic analysis to analyze feasibility of the system. Ochoa et al. [12] performed energy and exergy analyses on a cogeneration system consist of a micro turbine, single-effect LiBr/H2O absorption chiller and a heat exchanger. They showed that energy and exergy efficiency of the system are equal to 50% and 26%. Yang et al. [13] studied off-design performance of a CCHP system driven by gas turbine and discussed different definitions of CCHP efficiencies. Kong et al. [14] used linear programming to find out the optimal strategy for minimizing total cost of energy in CCHP systems. They showed that the optimal solution is heavily dependent on the load conditions.

One of the problems of using gas turbines is that their outlet temperature is high and this leads to a huge energy loss. Utilizing a bottom cycle to recover this energy can considerably boost the system efficiency. ORC cycles are good candidates for this purpose due to their low critical temperature. Borunda et al. [15] proposed a novel configuration for coupling ORC and parabolic trough collector. They used the proposed cycle for providing energy in a textile factory as a CHP system. They showed that using this configuration, the size of the thermal storage could be reduced. Pantaleo et al. [16] performed a techno-economic comparison between a gas turbine and a steam turbine as top cycle for a CHP system. To increase performance, they coupled an ORC cycle to both of these cycles. Fang et al. [17] proposed a new configuration of CCHP-ORC system which has the capability of adjusting electricity to thermal energy output ratio through changing electric chiller and ORC system load. Javan et al. [18] used an ORC cycle, an ejector refrigerator system and a water heater as a CCHP system to recover waste heat from internal combustion engine and used optimization process to maximize exergy efficiency and minimize total cost of the system. They also tried to find the best working fluid for ORC cycle. Kim and Perez-Blanco [19] used an organic Rankine cycle and a vapor compression cycle to produce simultaneous power and refrigeration. They also performed a sensitivity analysis on the key parameters of the system, including turbine inlet temperature, turbine inlet pressure, and the flow division ratio. Ebrahimi and Ahookhosh [20] combined a micro gas turbine, an ORC cycle and a steam ejector refrigeration cycle to provide power, heating and cooling simultaneously and defined an objective function based on energy and exergy analyses to optimize the plant. Li et al. [21] analyzed a CCHP system in terms of energy, economic and environment and used weighting method and fuzzy optimum selection theory to optimize the system. They showed that if the system couples with renewable energies and thermal storage systems, performance of the plant increases considerably in all mentioned criteria. Boyaghchi and Heidarnejad [22] performed a thermoeconomic analysis on a solar CCHP system and optimized the plant based on thermal efficiency, exergy efficiency and total product cost rate. Wang et al. [23] integrated a PV-wind system with an internal combustion engine and analyzed the system and provided optimal operation strategy. They also considered the effect of fuel price on the optimal dispatch strategies. Xia et al. [24] coupled solar powered ORC cycle and wind energy to drive a RO system to provide fresh potable water. Cetin et al. [25] studied combination of photovoltaic, wind and fuel cell systems to generate electricity for residential application. Hughes [26] used off-the-shelf electric thermal storage system to provide required heating demand with wind energy. Cavallo [27] showed that utilizing integrated wind-CAES is an affordable strategy for wind generators. Lund and Salgi [28] analyzed the role of CAES system integrated with renewable energies in the future sustainable energy system. They performed their study for Denmark. Kim and Favrat [29] performed energy and exergy analysis on a micro-CAES system coupled with air cycle heating and cooling system. They showed that CAES systems are good candidates for distributed generation systems. Hartmann et al. [30] calculated energy efficiency of different configurations of adiabatic CAES system in a full charge-discharge cycle.

Energy and exergy analyses can be used to provide more information about performance of the system. Ifaei et al. [31,32] proposed two new configurations to reduce water losses in natural draft wet cooling towers in steam power plants. These two configurations are based on integration of steam power plant with vapor compression refrigeration and absorption heat pump. They studied