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Energy, exergy, and economic evaluations of a CCHP system by using the internal combustion engines and gas turbine as prime movers

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ABSTRACT

In this paper, a combined cooling, heating and power (CCHP) system has been designed under an electric charge supply strategy for a residential complex in Iran.

The aim of this research is energy, exergy and economic analyses of the CCHP system with using different prime mover arrangements and presenting appropriate condition of its operation according to these viewpoints.

For this purpose, three types of gas engine, diesel engine, and gas turbine as prime movers have been presented and analyzed separately and simultaneously at six different scenarios and the appropriate scenario has been proposed for the CCHP system. In addition, the performance of system has been estimated at various part load conditions. The system is modeled and simulated using thermodynamic and economic relationships by using a computer code in the MATLAB software. The results show that the CCHP system under the electricity supply strategy with the simultaneous combination of two prime movers has significant advantages over one of them.

The CCHP efficiency with two prime movers increases up to 10% compared to that of a single prime mover as well as the exergy efficiency. Additionally, scenario 4 by combining the gas engine and diesel engine is selected as the best scenario. It has 87% energy efficiency, 62.8% exergy efficiency, and operating cost reduction of about 80%. Also, the payback period is 6.3 years by taking interest rate into account and 1.36 years regardless of it.

1. Introduction

By rise of the world's population, the need for energy supply is also increasing. On the other hand, due to increasing the pollutants and environmental hazards and low efficiency of power plants, the researchers seek new ways to supply energy [1]. Combined cooling, heating and power (CCHP) systems can significantly increase the energy efficiency by generating electricity on site and recovering hot flue gas for heating, cooling or dehumidification [2].

Wee [3] identified natural gas (CH4) as the cleanest source of energy among fossil fuels, following renewable energies such as hydroelectric power, solar energy, and etc. In order to reduce greenhouse gas emissions, he studied the hybrid systems of gas turbine and molten carbonate full cell as distributed energy sources. This hybrid system was considered due to higher power efficiency and by using molten carbonate fuel cells, a higher quality of electricity with efficiency of about 47% could be achieved. Chahartaghi and Alizadeh-Kharkeshi [4] investigated the performance of a CCHP system in a research that their prime mover was the proton exchange membrane (PEM) fuel cell. Their results illustrated that the energy and exergy efficiencies, and fuel energy saving ratio (FESR) were 81.55%, 54.55% and 45%, respectively.

Ebrahimi and Majidi [5] presented a combined cooling heating and power system with gas turbine as prime mover and the energy, exergy and environmental analyses were performed in their study. In addition a sensitivity analysis was presented to estimate the effect of main operating parameters on the system performance.

Jradi et al. [6] examined all the prime movers and cooling systems that were capable for operating in a combined systems. They also studied a variety of recent strategies to optimize the performance of the CCHP system and to increase energy efficiency. Also, Roman et al. [7] studied three prime movers for a combined system and performed energy, economic, and environmental analyses of the internal combustion engine, microturbine and fuel cells. They showed that the internal combustion engine and microturbine were suitable for the CCHP system. Their results for the CCHP system indicated a reduction in pollutant emissions and energy savings of more than 8% for both generators.

Kim et al. [8] also explored the characteristics of gas turbine performance under part load conditions. Their results illustrated that by

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Nomenclature

A	annual income
CC	capital cost
CCHP	combined cooling, heating and power
CHP	combined heating and power
CF	financial process income
COP	coefficient of performance
CR	cost reduction
DE	diesel engine
E	electricity demand
Ex	exergy
F	fuel
FESR	fuel energy saving ratio
GE	gas engine
GT	gas turbine
h	enthalpy
I	interest rate
ICE	internal combustion engine
LHV	low heating value
$\dot{m}$	mass flow
M	maintenance
N	lifetime of the equipment
NC	capacity of each component
NPV	net present value
NPWB	net present worth benefit
NPWC	net present worth cost
P	power
PB	payback period
PL	part load
PM	prime mover
$\dot{Q}$	heat transfer rate
R	reduced costs
S	entropy
SV	salvage value
T	temperature
$\dot{W}$	power
Z	altitude

Subscript

ab	absorption chiller
b	electricity buying
c	cooling load
Ch	chiller
ex	exergy
exh	exhaust
Exp	exporting electricity to the network
f	fuel
h	heat
in	inlet flow
nom	nominal
oil	oil cooling
out	outlet flow
pgu	power generator unit
rec	recovery
req	request
s	electricity selling
SP	separate production
y	year

Greek symbols

η	efficiency
μ	electricity sell from the grid factor
τ	time period

rising the input temperature of the turbine, the overall efficiency of the system was increased.

Ebrahimi [9] presented thermodynamic, economic, and environmental analyses of a combined system including cooling, heating, power, and process heat. In his study, effect of some parameters such as the remaining lifetime of the gas turbine, ambient temperature, altitude, relative humidity, interest rate, and exchange value were considered. The results showed that using this combined production systems led to reduction of fuel consumption, and pollutant emissions compared to conventional systems. Also, Ebrahimi and Keshavarz [10] studied a CCHP system with internal combustion engine, micro turbine and Stirling engine as prime movers for different climates. Their results showed the strong impact of ambient conditions on performance of prime movers. Li et al. [11] optimized the CCHP system for hotels, offices and residential buildings in China. The fuel of their prime movers was liquefied natural gas. Their results showed that the hotels had the largest contribution of energy savings up to 40% and in their system the performance of gas engine was better than gas turbine.

Jiang et al. [12] developed a thermodynamic model, experimental validation, and performance analysis of a novel CCHP system integrated with dehumidification system. Their prime mover was an internal combustion engine. The comparison between this system and the conventional CCHP systems was performed and energy and exergy analyses were presented.

Kang et al. [13] presented a CCHP system integrated with an organic Rankine cycle (CCHP-ORC) and a ground source heat pump. The energy, economic and environmental performances of the system were analyzed, and appropriate operation conditions were presented.

Javan et al. [14] developed a comprehensive technical-economic modeling and multi-purpose optimization of a combined system for residential applications. Their prime mover was a diesel engine and the system was combined with an organic Rankine cycle (ORC) that recovered heat from the cooling jacket and exhaust gases of the engine. The total cost rate was considered as objective function, including equipment investment costs, fuel costs, and environmental effect costs. Their results indicated that the capacity of the diesel engine and part load and full load operations had significant effect on the objective function.

In another study, Sanaye et al. [15] investigated and optimized the capacity of the prime movers of a combined heat and power (CHP) system. The prime movers included gas engine, diesel engine and gas turbine, which operated under nominal and part load conditions. They considered the recovered heat including the heat from the exhaust gases and the engine coolant jacket. In addition, the system performance was analyzed at nine different modes with all three prime movers. Their objective function was real annual profit. Accordingly, the best capacities for gas turbine, gas engine, and diesel engine were 1.3, 3.6, and 3.2 MW, respectively.

Tavakoli et al. [16] used energy, economic and environmental analyses to optimize the nominal capacity of the equipments for the combined cooling, heating and power system. Their prime mover was a gas engine that provided the needs of a water sports complex. They studied the operation of the prime mover under two scenarios of selling the electricity to the grid and without it. The results indicated that the capacity of 150 kW for electricity selling mode, and 120 kW for the mode of not selling to the grid were the best capacities.

Ahmadi et al. [17] presented thermodynamic modeling and exergy and environmental analyses of a CCHP system with a gas turbine as prime mover. They analyzed system performance and showed that combustion chamber and heat exchanger were the two main sources of