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# Thermodynamic analysis of a trigeneration system proposed for residential application

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An CCPP-based trigeneration system is proposed that would aid in harnessing the energy from stack and gas turbine exhaust gasses for meeting the heating and cooling demands of residential buildings. The system is investigated to exhibit the influence of various operating parameters on performance, $CO_2$ emissions reduction, and exergy destruction in three modes of operation, i.e., power and heating (P&H), power heating and cooling (PH&C) and power and cooling (P&C), which is followed by optimization. The results show that the system capacity may reach to 80 MW space heating and 30 MW water heating in P&H-mode while in P&C-mode the available space cooling is 43 MW. On the other hand, in PH&C-mode 40 MW space heating, 15.5 MW water heating and 21 MW of space cooling is estimated. The results further reveal that the generator of vapor absorption chiller contributes a maximum share of exergy destruction amongst the heating and cooling components followed by the space heating air conditioning unit. According to the optimization results, a maximum energy efficiency of 90% is obtained in P&H-mode while 54% exergy efficiency in all modes corresponding to the maximum power outputs.



## 1. Introduction

The simultaneous production of heating, cooling, and electricity from a common energy source is known as trigeneration. In trigeneration plants, waste heat and heat from various locations of main power plant are utilized to produce heating and cooling. As trigeneration systems produce three products from a single primary fuel, it results in a lower environmental impact and a greater efficiency than producing the same separately. The greater availability and wider choice of suitable technology have made trigeneration an attractive and practical offer for a broad range of applications. The process industries, buildings, and district energy schemes are major applications where considerable heating and cooling demands usually prevail. During the power generation in thermal power plants, a substantial amount of heat is wasted mainly through the stack. In parallel, the increasing depletion trend in fossil fuels, combined with the introduction of strict environmental regulation have led to a higher energy production cost. Therefore, the demand for reclamation of waste heat is continuously growing. One of the most promising ways of waste heat utilization is the simultaneous production of power, heating, and cooling in the trigeneration power plants.

One of the major applications of trigeneration is district energy, in which hot and cold streams are supplied to individual buildings for space heating, domestic hot water heating, and air conditioning. The district energy has been widely considered to be more cost-effective and environmentally optimal method for meeting the heating and cooling needs of buildings in the residential, commercial and industrial sectors. Different actions and policies have been introduced in various countries to encourage the implementation of trigeneration technology in various application areas. In the UK, there has been a progressive increase in the installed CHP capacity from 3 to 6 $GW_e$ in the recent years, where 68% of the plants run on natural gas [1]. The total CHP systems capacity installed in the European Union (EU) countries in 2010 have surpassed 105 GW where Germany leads with 22% followed by Poland and Denmark with 9% of the overall capacity. In Denmark, more than 50% of the electricity generation is provided by CHP systems, with 40% in Finland and 30% in Latvia and Netherlands [2]. In Japan and China, various government measures to promote CHP technologies have resulted in a greater use of technology in the total capacity. In the less developed countries, like Brazil, Iran, India, Mexico, and Turkey, various measures and policies have been devised to promote the deployment of trigeneration systems [1,3].

Numerous researchers have demonstrated the importance of cogeneration and trigeneration systems via energy and exergy methods for development of strategies towards efficiency

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**Nomenclature**

| | |
|---|---|
| EnE | energy efficiency [%] |
| ex | specific exergy flow [kJ/kg] |
| $\dot{E}x$ | exergy transfer rate [kW] |
| ExE | exergy efficiency [%] |
| h | specific enthalpy [kJ/kg] |
| $\bar{h}$ | specific enthalpy (molar) [kJ/kmol] |
| j | number of carbons [–] |
| k | number of hydrogens [–] |
| $\overline{LHV}$ | molar lower heating value [kJ/kmol] |
| M | molar mass [kg/kmol] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $\dot{N}$ | molar flow rate [kmol/s] |
| $\dot{Q}$ | heat transfer rate [kW] |
| $\dot{Q}_{CCPP}$ | natural gas heat required for electricity production in CCPP [kJ/h] |
| $\dot{Q}_{cooliing}$ | natural gas heat required for cooling production [kJ/h] |
| $\dot{Q}_{heating}$ | natural gas heat required for heating [kJ/h] |
| $\dot{Q}_{in,TCCPP}$ | natural gas heat required for trigeneration [kJ/h] |
| s | specific entropy [kJ/kg K] |
| U | overall heat transfer coefficient [kW/m$^2$ K] |
| $\dot{V}$ | volume flow rate [m$^3$/s] |
| $\dot{W}$ | power [kW] |
| $\dot{W}_{CCPP}$ | power produced by CCPP [kW] |
| $\dot{W}_{TCCPP}$ | power produced by trigeneration plant [kW] |
| $\dot{W}_{mup}$ | power required to pump the makeup water [kW] |
| $\dot{W}_{GTnet}$ | net power out of the topping GT-cycle [kW] |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | mole fractions of chemical species |
| $\beta$ | mass fractions of chemical species |
| $\gamma$ | specific heat ratio |
| $\varepsilon$ | effectiveness of heat exchanger |
| $\zeta$ | fraction of hot gasses supply for heating and cooling |
| $\eta$ | efficiency or isentropic efficiency |
| $\lambda$ | fraction of hot gasses available |
| $\bar{\lambda}$ | fuel-to-air ratio (molar) |
| $\psi$ | fraction of gas turbine exhaust |
| $\omega$ | specific humidity |

*Abbreviations*

| | |
|---|---|
| ABS | absorber |
| AC | air Compressor |
| CC | combustion chamber |
| CCHP | combined cooling heating and power |
| CCPP | combined cycle power plant |
| CIT | compressor inlet temperature |
| CND | condenser |
| CP | condensate pump |
| CHP | combined heating and power |
| COP | Coefficient of Performance |
| DE | deaerator |
| DHMDFR | dehumidifier |
| EVP | evaporator |
| FWP | Feedwater Pump |
| GEN | generator |
| GHG | green house gasses |
| GT | gas turbine |
| GTIT | gas turbine inlet temperature |
| GTPP | gas turbine power plant |
| GTPS | gas turbine power station |
| HL | heat loss |
| HMDFR | humidifier |
| HPD | high-pressure drum |
| HPE | high-pressure economizer |
| HRSG | heat recovery steam generator |
| Hx | heat exchanger |
| LF | load factor |
| LHV | lower heating value |
| LMTD | log-mean temperature difference |
| LPE | low-pressure economizer |
| P&C | power and cooling |
| P&H | power and heating |
| PH&C | power heating and cooling |
| PP | pinch point |
| PR | pressure ratio |
| RG | regenerator |
| RV | refrigerant valve |
| RXDR | Relative Exergy Destruction Ratio |
| SCAHTR | space cooling air heater |
| SH | superheater |
| SHAHTR | space heating air heater |
| SHHx | space heating heat exchanger |
| SHx | solution heat exchanger |
| SP | solution pump |
| ST | steam turbine |
| SV | solution valve |
| TCCPP | Trigeneration Combined Cycle Power Plant |
| VAR | vapor absorption refrigeration |
| WAC | winter air conditioning |
| WHHx | water heating heat exchanger |

improvement, environmental protection, and sustainability. In this regard, various trigeneration aspects are addressed including prime movers, cooling technologies, fuels, renewable resources employed and operating strategies implemented. Rosen et al. [4] have applied the energy and exergy concepts on a design for a cogeneration-based district energy system. The results have shown a great importance of the exergy analysis of cogeneration systems due to variable nature of quality of the energy products. Balli et al. [5] have carried out the exergetic performance analysis of a gas turbine-based cogeneration power plant located in Turkey. The exergy efficiency of the existing plant is calculated as 38% in which combustion chamber causes highest exergy consumption among the components. Authors have suggested some modifications to the plant which yield an increase in the exergy efficiency by nearly 3%. Ahmadi et al. [6] have considered a trigeneration system for exergy and environmental analyses. The trigeneration system described in this study includes a gas turbine cycle, a steam turbine cycle, and an absorption chiller. Khaliq [7] has carried out an exergy analysis of a gas turbine-based trigeneration system, as well as a parametric study of the effects of various operating parameters on energy and exergy efficiencies, electrical/thermal energy ratio and exergy destruction of the system. Ahmadi et al. [8] have performed a thermodynamic modeling of a trigeneration system with gas turbine as topping cycle and organic Rankine and absorption chiller as two bottoming cycles. For commercial and office buildings in Iran, Hanafizadeh et al. [9] have investigated a trigeneration scheme. In this paper, a greater emphasis is given to the economic facet of the trigeneration scheme operated in different configurations. A comparative analysis of the various configuration schemes is demonstrated with the help of basic economic indices. Ahmadi and Dincer [10] have presented an exergy, environmental analyses and optimization of a cogeneration plant. In this paper,