Energy Conversion and Management 169 (2018) 371–382

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Design and performance investigation of a biogas fueled combined cooling and power generation system

Farkhondeh Jabari[a], Behnam Mohammadi-ivatloo[a,b,*], Mohammad-Bagher Bannae-Sharifian[a], Hadi Ghaebi[c]

[a] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
[b] Roshdiyeh Higher Education Institute, Tabriz, Iran
[c] Department of Mechanical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

ARTICLE INFO

*Keywords:*
Biogas
Compressionchillers
Building cooling and power (BCP) system
Mixed integer non-linear programming (MINLP)
Plug-in electric vehicles (PEVs)

ABSTRACT

Nowadays, different renewable sources and energy storages are attracting world attention due to the major concerns about the excessive emissions and the global energy crisis. Hence, this paper studies design and performance investigation of a biogas fueled building cooling and power system, which comprises of an air compressor, an air preheater, a combustion chamber, a gas turbine, some compression chillers and aggregated plug-in electric vehicles. In the proposed coproduction facility, biogas is used as an alternative fuel to reduce the total greenhouse gas emissions and increase the economic saving in the consumption of fossil fuels. The feasibility and robust performance of this microgrid is evaluated under extremely-hot summer days. Three compression chillers are installed to satisfy total cooling demand of a large hotel building located in Ahwaz, Iran. Moreover, the total energy requirement of chillers and building electricity demand is supplied through the biogas driven gas turbine cycle. A mid-high temperature waste heat is recovered from the exhaust gases of gas turbine to be used in the air preheating stage. A comprehensive thermodynamic analysis is developed to solve a mixed integer non-linear programming problem with the aim of minimizing total electricity procurement cost of the proposed zero-emission cogeneration micro-plant taking into account the operational constraints of gas turbine cycle, compression chillers, and electric drive vehicles.

## 1. Introduction

During extremely hot weather or transient heat waves, air-conditioners are the most common energy consumers in residential, commercial, industrial, and administrative buildings especially in tropical regions. Therefore, use of energy storages and renewables in building cooling and power systems are rapidly gaining popularity due to the major concerns about the ecological problems and global energy crisis [1]. Moreover, the exhausted gases from the electricity generation cycles such as Brayton contains a significant amount of high quality heat, which can be used in building heating applications in cold regions. In a Brayton cycle, mid or high temperature waste heat can be recovered from flue gases of micro-gas turbine in order to be used in satisfying building heating demand, air preheating before entering the combustion chamber, generate electricity and alleviate emissions [2].

In recent years, studies on renewables based BCP plants have attracted an enormous attention. In this context, Oh et al. [3] introduced a long-term electricity usage forecasting model for cooling Singapore's residential buildings by an integrated adsorbent dehumidifier and evaporative cooler. Accounting for 30% of total electricity consumption as the cooling demand, the presented air-conditioning technology reduces 9,491,264 metric tons of $CO_2$ emissions and increases the electricity savings up to 21,096 GWh for 2014–2030. Ref. [4] developed a simple linear programming model for a novel cooling system composed of an ice storage and a hybrid electric-absorption chiller. The presented model has distinctive potentials of load shifting and great energy-saving. The energy, exergy, and environmental analysis of a hybrid solar-natural gas and a biomass-solar driven BCP system are investigated under uncertain operating conditions such as variable electrical demand, solar irradiance, and the installation ratio of photovoltaic panels. Mehrpooya et al. [5] proposed an innovative BCP grid which comprises of a molten carbonate fuel cell, a Stirling engine and a double effect $LiBr/H_2O$ absorption chiller. The exhausted heat from the Stirling cycle is recovered to supply the energy requirement of the absorption chiller.

Yao et al. [6] utilized both diabatic and adiabatic types of

* Corresponding author at: Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran.
*E-mail addresses:* f.jabari@tabrizu.ac.ir (F. Jabari), bmohammadi@tabrizu.ac.ir (B. Mohammadi-ivatloo), sharifian@tabrizu.ac.ir (M.-B. Bannae-Sharifian), hghaebi@uma.ac.ir (H. Ghaebi).

https://doi.org/10.1016/j.enconman.2018.05.026
Received 9 October 2017; Received in revised form 2 May 2018; Accepted 8 May 2018
0196-8904/ 

**Nomenclature**

*Air compressor*

$P_1$ ambient air pressure [MPa]
$T_1 = T_{amb}$ ambient air temperature [K]
$P_2$ compressed air pressure [MPa]
$T_2$ compressed air temperature [K]
$T_{2,s}$ temperature of pressurized air after isentropic compression process [K]
$k = 1.4$ specific heat ratio of ambient air
$\eta_{comp}$ compressor efficiency
$h_1$ specific enthalpy of ambient air [kJ/kg]
$h_2$ specific enthalpy of compressed air [kJ/kg]
$h_{2,s}$ specific enthalpy of pressurized air after isentropic compression process [kJ/kg]

*Air preheater*

$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_{Air}$ mass flow rate of air [kg/s]
$\dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_{C.P}$ mass flow rate combustion products [kg/s]
$C_{p,air}$ specific heat capacity of air [kJ/kg K]
$T_3$ temperature of preheated air entering the combustion chamber [K]
$P_3$ pressure of preheated air entering the combustion chamber [MPa]
$T_6$ temperature of gas turbine flue gases [K]
$\eta_{APH}$ efficiency of air preheater
$\Delta P_{APH}$ percentage of pressure drop in air preheating process

*Combustion chamber*

$\dot{n}_{Air}$, $\dot{n}_{B.G}$ and $\dot{n}_{C.P}$ molar flow rate of air, biogas and combustion products, respectively [kmol/s]
$\chi_{B.G-Air}$ biogas-air molar ratio
$\bar{h}$ sensible enthalpy at specified state [kJ/kmol]
$\bar{h}_f^0$ enthalpy of formation at standard reference state of 25 °C and 1 bar [kJ/kmol]
$\bar{h}^0$ sensible enthalpy at standard reference state of 25 °C and 1 bar [kJ/kmol]
$\dot{Q}_{Loss}$ heat loss in the combustion chamber [kW]
$\Delta P_{C.C}$ percentage of pressure drop in combustion chamber
$M_{B.G}$ and $M_{Air}$ molar mass of biogas fuel and air, respectively
$T_5$ temperature of combustion products [K]
$P_5$ pressure of combustion products [MPa]
$C_{p,gas}$ specific heat capacity of exhaust gases [kJ/kg K]

*Gas turbine*

$h_6$ entropy of gas turbine flue gases [kJ/kg]
$P_6$ pressure of exhausted gas from gas turbine [MPa]
$T_{6,s}$ temperature of exhausted gas from isentropic gas turbine [K]
$h_{6,s}$ specific enthalpy of high-pressure air leaving an isentropic gas turbine [kJ/kg]
$\eta_{GT}$ efficiency of gas turbine

*Compression chillers*

$P_{Chill}^t$ total electrical power consumed by all compression chillers at time $t$ [kW]
$N_{Chill}$ number of chillers
$U_i^t$ a binary decision variable that will be equal to 1, if chiller $i$ is on; otherwise it will be 0
$\alpha_i,\beta_i,\gamma_i,\xi_i$ coefficients related to the operating characteristic of chiller $i$
$PLR_i^t$ partial load ratio (PLR) of chiller $i$
$RT_i$ cooling capacity of chiller $i$ at operating time interval of $t$ [RTs]
$CL^t$ total cooling demand at time $t$ [kW]

*Plug-in electric vehicles*

$E_{t,i}^{PEV}$ electricity requirement for transportation of PEV $i$ [kW]
$P_{t,i}^{PEV_{ch}}$,$P_{t,i}^{PEV_{dis}}$ charge/discharge power of PEV $i$ [kW]
$SOC_t^{PEV_i}$ state of charge of PEV $i$ at time $t$
$SOC_{PEV_i}^{min}$,$SOC_{PEV_i}^{max}$ minimum/maximum state of charge level for PEV $i$ [kWh]
$U_{t,i}^{PEV_{ch}}$,$U_{t,i}^{PEV_{dis}}$ binary variable, "1" if charging/discharging of PEV $i$, otherwise 0
$\chi$,$\eta$ charging/discharging efficiency

*Optimization problem*

$\lambda_t$ net energy price at time $t$ ["$"/kWh]
$P_{grid}^t$ purchased electrical power from local power grid [kW]

compressed air energy storages (CAES) in a BCP system to maximize annual cost saving by storing excess generation during off-peak hours and releasing it for on-peak periods. In [7], a solar cooling system consists of evacuated tube collectors and a single effect absorption chiller is optimized from energetic, exergetic and financial viewpoints in the city of Athens, Greece. The optimum case is 450 $m^2$ of solar collectors coupled with a storage tank of 14 $m^3$ for 100 kW cooling capacity. Ref. [8] investigates a solar heating and cooling system for an office building located in Southern Italy. Thermo-economic performance of the proposed system is also evaluated considering the different operating conditions such as flat-plate and evacuated-tube solar panel technologies, tilt angles (10–70°), collecting areas (30–60 $m^2$), hot and cold storage capacities, reference emission factors, hourly electricity and natural gas prices. Compared to the conventional air-conditioners, this solar cogeneration plant has the primary energy saving and $CO_2$ emission reduction more than 23%. In [9], a combined cooling and heating system was designed and simulated to supply high cooling demand using solar and geothermal energy sources for an office buildings in sub-tropical climate regions. Solar energy is utilized in absorption cooling and water heating, while geothermal energy is used by a high-temperature chiller for radiant cooling systems. It is found that use of solar and geothermal energies results in 44.4% annual primary energy saving in comparison with the traditional systems. Thermodynamic and economic analyses of an off-grid solar cooling system which consists of photovoltaic cells and a vapor compression refrigeration cycle is investigated by Ozcan and Akyavuz [10]. Due to the intermittent nature of solar irradiance, a hydroelectric energy storage pumps water from a lower elevation reservoir to an upper reservoir during low-cost or off-peak electricity hours and utilizes it to produce hydro power at on-peak periods. Ref. [11] introduces an interesting old type of building cooling system in Bam city which is similar to a Baud-Geer or wind tower. In this system, an underneath channel called Naghb is excavated that uses the ground humidity to cool the inlet air. During hot-summer days, warm ambient air enters Baud-Geer, passes through the Naghb, and evaporation cooling makes it cooler.

Some scholars focused on optimal design and scheduling, economic and environmental analysis, performance assessment and comparisons of different BCP strategies. Yan et al. [12] designed a compound cold storage system that combines a heat pipe-based seasonal ice storage unit with a chilled water storage tank. This seasonal ice storage system