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Economic analysis of heat and electricity production in combined heat and power plant equipped with steam and water boilers and natural gas engines

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ABSTRACT

This paper deals with the cost and energy efficiency for heat and electricity production. The operation of the medium size Combined Heat and Power plant, located in Poland, with diverse production units: steam boilers, water boilers and gas engines is studied. The analysis is performed for spring-autumn season, characterized by relatively low and variable heat power demand. Due to such mutable conditions production units are forced to operate out of the nominal efficiencies. The analysis is performed for heating and electric energy production on: steam boilers and turbo-generator, water boilers, steam boiler and gas engines; and water boiler and gas engines. To reflect the actual situation, a mathematical model for the complete installation is developed. The model calculates energy balance for a given heating power demand profile. The model is based on the actual parameters, including all technical aspects and equipment's limitations. The developed tool enables to select the mode of operation for each production unit separately or in combined mode. As a result, the energy balance in one hour operation period is calculated. Such approach allows to compare the energy production efficiency and cost in each system at every hour.

Due to the fact, that nowadays heat and electricity production business, is strongly affected by legal regulations, the analysis of gas engines profitability with and without subsidy for natural gas based co-generation is performed.

1. Introduction

The energy production efficiency and fossil fuels availability are mainstream subjects in the power engineering. Worldwide energy policy is focused on energy production improvement and energy sources diversification. Recently many studies are performed on the energy efficiency growth and reduction of operational costs of Combined Heat and Power Plants.

Zhang et al. [1] developed a model to optimize the design of a biomass-fueled Combined Heat and Power Plants (BCHP) with energy storage. They used a receding horizon optimization to dispatch the BCHP components to obtain the minimum cost. The model application provides a means to determine optimal BCHP configuration with varying demands and utility tariff rates. Bartela et al. [2] studied the two cases of CHP units, one with Stirling engine and other without. The raw gas from the waste of biomass gasification is used as a heat source for Stirling engine. The authors identified the break-even unit investment costs for Stirling engine. They suggested that the expected drop of Stirling engines prices will allow the future use the proposed system. Zareh et al. [3] studied a cogeneration cycle with co-firing of biogas and natural gas. They evaluated the cycle in terms of exergo-economic at different mixing ratios. They found that the irreversibility of the anaerobic digester at low mixing ratios is high and irreversibility of combustion chamber at all mixing ratios is the highest value, as well as the total cost rate of the system is increased in the case of the pure biogas. Zhang et al. [4] proposed a novel CCHP system based on biomass, natural gas and geothermal energy. They performed a thermodynamic and economic evaluation of proposed system and studied the effects of gas mass ratio and split ratio on integrated system. Also, they performed a sensitivity analysis of economic factors on system performance. They found that the introduction of natural gas contributes to improve the reliability of energy supply system, and increase the energy density of inputs in prime mover. Zhu et al. [5] developed an advanced model for a free-piston Stirling engine micro-CHP system. Their model includes acoustic impedance matching and nonlinear thermodynamics. They compared their model results with experimental data and noticed the highest deviation of 10%. They found that the micro-CHP system exhibits high efficiency over a large temperature lift. Di Fraia et al. [6] proposed an integrated system for sewage sludge drying and electricity production. The system is powered by biogas from sewage sludge

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Nomenclature

c_p	specific heat capacity (kJ/(kg·K))
$\dot{E}_5$	electric power in co-generation (MW)
$\dot{E}_6$	electric power in condensation (MW)
E	energy (MWh)
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (t/h)
T	temperature (°C)
p	pressure (bar)
$\dot{F}$	mass flow rate of fuel (t/h)
C_f	chemical energy cost (EUR/GJ)
C_{CHP}	chemical energy cost for electricity production in co-generation [EUR]
C_{Cond}	chemical energy cost for electricity production in condensation [EUR]
S	subsidy in EUR to 1 MWh of electric energy produced in natural gas engines CHP (EUR/MWh)
η	energy efficiency
$\dot{Q}$	heat flow rate (GJ/h)
Q	thermal energy (GJ)
$\dot{Q}_{Chem5}$	chemical energy stream for heat production in co-generation
NCV	net calorific value [GJ/t]
x_{CHP}	chemical energy ratio on 1 MWh production in co-generation (GJ/MWh)
x_{Cond}	chemical energy ratio on 1 MWh production in condensation (GJ/MWh)
uC_{CHP}	the unit cost of 1 MWh production in co-generation (EUR/MWh)
uC_{Cond}	the unit cost of 1 MWh production in condensation (EUR/MWh)
C_{Heat5}	cost of thermal energy production in co-generation [EUR/GJ]
x_{el23}	chemical energy ratio on 1 MWh production in gas engines (GJ/MWh)
uC_{el23}	the unit cost of 1 MWh production in gas engines (EUR/MWh)
C_{el23}	chemical energy cost for electricity production in gas engines [EUR]

digestion and solar energy. They performed an energy, environmental and economic analysis for a real case study. They found that the use of renewable energy sources leads to a primary energy saving of about 15%. Arabkoohsar et al. [7] investigated the cost-effectiveness of employing CHP in power productive gas stations. They proposed a techno-economic criterion determining which station can efficiently host a CHP unit. They found the optimal CHP units and turbo-expanders for several case studies. The results shows that a power productive gas station with a relative heating demand of greater than 0.35 is a suitable host, while the minimum relative heating demand for making a simple gas station a suitable host is of 0.23. Arsalis et al. [8] studied a small scale a 1 MW gas turbine/0.5 MW photovoltaic cogeneration system. They used an electrolyzer coupled to convert excess renewable electricity to hydrogen. They found that the system is fully autonomous and satisfies the load profile of 1500 households. The results show the annual average primary energy ratio of the system is 0.806 while the lifecycle cost is 11.12 million USD, with an electricity cost at 0.06 USD/kWh. Sadaghiani et al. [9] proposed a new power generation plant to convert the trapped energies of geothermal hot water and Liquid Natural Gas streams to useful power. The combined power plant consists of 7 units, which each unit includes three discrete cycles of Kalina and two Organic Rankine power generation cycles to produce power from its heat sources. The results of energy and exergy analysis shown that the system is amended to maximize the exergy efficiency. After implementing modifications, the exergy efficiency of the system increased to 32.15%. Also, the net power output of each unit increased to 2485 kW after modifications. Kwan et al. [10] performed an exergetic and temperature analysis of a fuel cell-thermoelectric device hybrid system for the combined heat and power application. The authors proposed fuel cell and thermoelectric combined heat and power (FC-TE-CHP) system The novel system idea is to use the thermoelectric device to further improve the exergetic and temperature performance of the conventional fuel cell based combined heat and power (FC-CHP) system. The results show that the FC-TE-CHP improves the exergetic efficiency of FC-CHP by up to 2%, and that the optimal operation can be controlled by the water flow rate and fan speed. Wang et al. [11] proposed a CCHP system coupled with thermal energy storages according to energy level. They developed thermodynamics models and presented the coordinative strategies for operation of TES. They also compared the energy performance and adjustable area of building loads of two types TES. Jiang et al. [12] proposed a novel combined cooling, heating and power (CCHP) system integrated with trigenerative compressed air energy storage (T-CAES). The comparison of thermodynamic and economic analysis between the novel CCHP system and conventional CCHP system are carried out in application of office building. The primary energy rate of novel CCHP system is 85.57%, the primary energy saving ratio of novel CCHP system is 26.87%, and the total cost saving ratio of novel CCHP system is 30.55%. The authors found that their novel system is superior to conventional CCHP system. Yan et al. [13] studied the application of a gas-fired CCHP for solving the seasonal shortages of electricity and gas. They found that the revenue of Gas-fired CCHP system is greatly influenced by fuel price and electricity price. Also the results show that a reasonable energy efficiency sharing ratio will help to the recovery of investment in Gas-fired CCHP. Kang et al. [14] studied the performance of a biogas-fired gas turbine and performed the economic analysis of CHP systems with different heat demands. The net present value of the cash flow and the payback period were estimated by authors by using the investment and running costs of the entire facilities and the prices of electricity and heat, and economic indices such as the annual gross margin. The authors found a strong dependence of project economics on heat sales revenue. They also found that at moderate heat demand, the CHP system is more economical than the combined-cycle (CC) system. Bartela et al. [15] proposed the use of Stirling engine in CHP system that allows a growth in electricity production. They found that their system can be useful for municipal heating, however for further implementation the lower prize of Stirling engines is required. Zhang et al. [16] studied the performance of four CCHP systems with different cooling modes. CCHP system used the water–LiBr absorption chiller to meet the cooling demand. The authors compared exhaust-gas-and-hot-water-driven absorption chiller (AC) and another three cooling modes, including AC combined with electric chiller (EC), AC combined with gas-fired absorption chiller (GFC), and AC combined with ground source heat pump (GSHP). The authors proposed the optimization models for the four CCHP systems following the electric load (FEL) and following the thermal load (FTL). The evaluation criteria include primary fossil energy saving rate (PFESR), carbon dioxide emission reduction rate (CDERR) and annual total cost saving rate (ATCSR) compared with the separation production (SP) system. For optimization the authors used the Genetic algorithm (GA). The hypothetical commercial building in Shanghai was used for case study. Results show that the CCHP system with GSHP under FEL strategy has the best comprehensive performance, with PFESR of 0.2990, CDERR of 0.5278 and ATCSR of 0.1582. Yao et al. [17] proposed a novel tri-generation based compressed air