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Economic analysis of heat production in existing medium size combined heat and power plant, with respect to the CO_2 allowances purchasing cost

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A B S T R A C T

This paper presents mathematical modeling and economic analysis of a medium size combined heat and power (CHP) operation, installed in Poland. The plant is equipped with steam boilers, extraction condensing turbine, and the grade type water boilers. The paper determines the most efficient mode of CHP operations. The economic efficiency analysis is performed for transient seasons, characterized by low demands for heating, which obliged production units to operate out of its nominal conditions at a lower efficiency. The developed method is also suitable for analyzing complex power plants, with a few energy equipments.

The developed mathematical model for simulating CHP performance gives the possibility to select the boiler type, and assess the probability and efficiency of each configuration. The dedicated tool calculates the selected operation mode, heating power demand, and enables models comparison. The algorithm includes real equipment operational parameters, technical limitations, actual energy prices and costs regarding energy law acts. The performed analysis is up-to-date, due to a few aspects: permanently increased fossil fuels costs, low electric energy prices, growing costs of CO_2 emission allowances, and high electricity production cost on turbine's condensing section at steam parameters of $T = 435\ ^{\circ}C$ and $p = 34$ bar. A detailed cost analysis is performed on each product separately: thermal energy, electric energy from cogeneration and electric energy from condensation, during every hour, frequently. The calculation is carried every an hour for a period of 24 h, the energy balance is ensured during the calculation. The most important result of this study is a comparison of CHP to water boiler operation profitability, also including the net profit comparison. Furthermore, the cost of the CO_2 emission is studied, for the production profitability in two scenarios, as the price increases from 7 EUR/tone to 15 EUR/tone and 30 EUR/tone.

1. Introduction

The thermal energy is used for many different applications and purposes, such as in residential and industrial buildings, workshops, and in production processes, which requires certain temperature conditions. Each application has different nature of consumption and requires different production units. A particular example covers both, production for district heating grid and thermal energy needed in the industry.

In the countries with a comparable climate to Poland, which characterize long winter season, a significant part of the heat is produced in Combined Heat and Power plants (CHP). The CHP technology is known for decades, and so far was well examined and developed. Karlson et al. [1] studied CHP plant owned and operated by Karlskoga Energi och Miljö AB in Sweden. The life-cycles of the fuels used by the CHP – household/industrial waste, bio-oil, light fuel oil, wood waste, wood chips, a slaughterhouse-waste-derived product and peat to generate 202,222 MWh of heat, 119,234 MWh of steam and 28,220 MWh of electricity have been studied. Also, the carbon footprint of the plant was calculated for year-2016. Havukainen et al. [2] conducted life cycle analysis (LCA) for energy production from forest biomass in small scale CHP plant. Their study used the LCA for two purposes. The first aim was to quantify the environmental impacts of the energy production of a small-scale, combined heat and power production plant utilizing different forest biomasses. The second aim was to estimate the changes in the environmental impacts on the district heat production from natural gas when partially replacing it by heat from the Combined Heat and Power plant. Havukainen et al. [2] results indicated that by using forest biomass instead of natural gas in energy production, the global climate impacts are reduced when biogenic carbon is excluded, while the local effects are higher (acidification potential and eutrophication potential). Hu et al. [3] studied a phase-change heat storage facility in CHP integrated with renewable energy sources, wind energy. They analyzed an integrated thermal and power system with phase-change heat

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Nomenclature

c_p	specific heat capacity, kJ/(kg·K)
$\dot{E}_5$	electric power in co-generation mode, MW
$\dot{E}_6$	electric power in condensation mode, 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
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, GJ/h
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}	unit cost of 1 MWh production in co-generation, EUR/MWh
uC_{Cond}	unit cost of 1 MWh production in condensation, EUR/MWh
C_{Heat5}	cost of thermal energy production in co-generation, EUR/GJ

storage (HS) facility to improve the flexibility of the system, where the heat released from the extraction steam does not match the heat load. They used thermal resistance in modeling the heat storage system. The operation plan of the integrated system is optimized by the linear programming (LP) method to minimize the wind energy loss. Zhang and Kang [4] studied the effects of the distribution density of a biomass combined heat and power plant network on heat utilization efficiency in village–town systems. They obtained an optimal biomass CHP plant network using geographical information system (GIS) tools. They calculated the optimal value of the heat transmission threshold through a multi-scheme comparison. Wang et al. [5] by using the EES (Engineering equation solver) and Ebsilon Professional 13, studied the direct air-cooled, high-pressure heat supply power units. The characteristics of heat transfer and supply of cold-end between typical temperature range in winter time was analysed. In quality and quantity regulations, the cold-end heat transfer characteristics with different fans in isolation, the coal consumption, and the net power were investigated. The authors determined the optimal operation mode and energy saving effect of heating and air-cooled systems.

Haakana et al. [6] presented a methodology to promote the operation of CHP plant in the liberalized energy markets. The methodology considered a combination of marketplaces available to the power plant for its end products heat and electrical power, with a particular reference to electricity reserve market opportunities. The methodology proposed by the authors was tested with price data of the respective energy and power markets between years 2013 and 2015. Guo et al. [7] assessed the eco-efficiency of coal-fired CHP plants in Chinese eco-industrial parks. By a sensitivity analysis, they indicated that consideration of freshwater consumption and capital depreciation would have a significant impact on eco-efficiency.

Zhao et al. [8] proposed a flue gas recovery system for natural gas CHP plant with distributed peak-shaving heat pumps. The system has many benefits, such as improve network transmission and distribution capacity, provide energy savings, and reduce the emission. Vögelin et al. [9] performed economic optimization of CHP plant. The proposed optimization algorithm is robust. It has the ability to optimize at different power, storage and operational systems. Also, Vögelin et al. [10] performed a design analysis of gas engine CHP for building and industrial heat demand with varying price structures. They conducted optimization of plant power, heat storage size and operating strategy. Kalina [11] studied alternative configurations of heat recovery process in small and medium scale combined gas and steam cycle power plants. He considered the combined the CHP with Organic Rankine Cycle (ORC) and performed the energy and exergy efficiency analysis of the heat recovery process. Gustavsson and Hulteberg [12] studied the co-production of gasification-based biofuels in existing CHP. They analyzed the production capacity and integration potential of those CHPs. They found that there is a significant potential for biofuel production by utilizing existing Fluidized Bed Boilers as well as the utilization of waste heat and tail gases enable high overall efficiency. The results of Gustavsson and Hulteberg [12] revealed that integrated biofuel production decreases power generation from a CHP plant. Nelson et al. [13] modeled a solarized 100 kWe/165 kWt microturbine for CHP application. They found that the fuel use is reduced by 26.0% compared to the traditional microturbine at maximum power output. Salman et al. [14] studied the impact of retrofitting existing CHP with polygeneration of biomethane. The authors performed a comparative techno-economic analysis of integrating three different gasifiers and evaluated the operational limits of CHP by process integration with gasification. Salman et al. [14] compared technical performance of integrated gasifiers with CHP and performed economic analysis and sensitivity analysis by varying various parameters of the power plant. Kim and Edgar [15] used mixed-integer nonlinear programming to determine the optimal scheduling of combined heat and power plants in the wholesale energy market. The authors optimized the power production and maximized it during on-peak hours. The maximum profit was realized by committing more efficient generating units. The authors found that the less efficient generating units can be brought online due to operating constraints. Oreggioni et al. [16] assessed of biomass gasification CHPs with absorptive and adsorptive carbon capture units in Norway. The authors used LCA analysis of gasification CHP plants with absorptive and adsorptive CCS technologies. They found that CHP with pressure-vacuum swing adsorption (PVSA) cycles exhibit better environmental performance than CHP with installed MEA unit. Lee et al. [17] conducted modeling and optimization of an integrated wastewater treatment plant with a combined heat and power generation system. Thermal, environmental and economic aspects were considered. The proposed system was optimized (using the non-dominant sorting genetic algorithm-II (NSGA-II)) via the thermo-environ-economic method. Authors found that the total cost rate and environmental impact decreased by 16.9% and 5.3%, respectively. Also, the total required heat and 47% of electricity demand were covered after optimization. Zhong et al. [18] performed an optimization of solar aided coal-fired CHP based on changeable integrate mode under different solar irradiance. The authors optimized the operation strategy and used MINLP model to optimize the heat exchanger area and the integrated mode. Ziębik et al. [19] performed a thermodynamic evaluation of CHP integrated with installation of coal gasification. They found that the relative energy savings of IGCC-CHP are near the result of a gas and steam CHP and that the COHP (coefficient of heat performance) can help to divide fuel between heat fluxes. The higher COHP values in the case of heat recovery, the lower thermal parameters are obtained. Amirante et al. [20] proposed a novel, cost-effective configurations of CHPs for a small-scale cogeneration from biomass. The authors proposed a novel approach in