Energy and exergy evaluation of tri-generation system based on natural gas fired micro-turbine – a case study

Ocena energetyczna i egzergetyczna systemu tri-generacyjnego opartego o mikroturbinę gazową – studium przypadku

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The need of significant reduction of energy supply to building sector joined with new European Union regulations, known as *Green Deal*, requires application of energy and exergy efficient solutions of energy production and distribution. One of the feasible options is use of co-generation and tri-generation energy systems in the small scale.
The article presents the study on application of natural gas fired tri-generation system based on gas fired micro-turbine. The system consists of natural gas fired micro-turbine and heat exchanger which produces heat for space heating and ventilation and for cooling energy production in single stage absorption water chiller. The system operates whole year providing fixed electricity production – electrical power N_{El}, and heating/cooling energy production varying depending on building requirements. As a case study small office building of 1632 m^2 useable area has been chosen. Energy and exergy models of evaluated system have been presented.
It has been found that annual average energy and exergy efficiencies of the system are low – 0,339 and 0,247 respectively. It is due to the limited utilization of enthalpy and exergy of flue gas in heat exchanger.
Keywords: energy and exergy analysis, CHCP systems

Konieczność znaczącego ograniczenia potrzeb energetycznych budynków związana z najnowszą strategią Unii Europejskiej znaną jako Zielony Ład, wymaga stosowania efektywnych energetycznie rozwiązań w zakresie produkcji i dystrybucji energii. Jedną z możliwych do realizacji opcji jest wykorzystanie systemów ko-generacyjnych i tri-generacyjnych małej mocy.
W artykule przedstawiono studium zastosowania układu tri-generacyjnego małej mocy opartego o mikroturbinę gazową. Układ składa się z mikroturbiny gazowej z wymiennikiem ciepła dostarczającym ciepło do układu ogrzewania i wentylacji budynku oraz absorpcyjnej jednostopniowej wytwornicy wody lodowej. Układ pracuje przez cały rok zapewniając stałą produkcję mocy elektrycznej – N_{El}, i produkcję mocy cielnej/chłodniczej zależną od potrzeb budynku. Jako studium przypadku przyjęto mały budynek biurowy o powierzchni użytkowej 1632 m^2. Dla potrzeb analizy stworzone zostały modele energetyczny i egzergetyczny układu.
Wyniki analizy wykazały niską średnioroczną sprawność energetyczną i egzergetyczną układu – odpowiednio 0,339 i 0,247. Jest to związane z ograniczonym wykorzystaniem entalpii i egzergii spalin przepływających przez wymiennik ciepła.
Słowa kluczowe: analiza energetyczna i egzergetyczna, systemy CHCP

Introduction

The global energy economy faces two key tasks. First, it is essential to increase the share of renewable energy sources in the economy. A complete transition to renewable energy sources in countries where energy production is mainly based on the use of fossil fuels is a long-term process and impossible to achieve in the next few decades. Therefore, in parallel to a gradual transition to renewable energy sources, the second task – increasing the energy and exergy efficiency of fossil fuel use, has to be considered. The ideal way to make better use of non-renewable energy sources such as oil, natural gas, coal is combined production of electricity, heat and cooling energy.

Climate change, but also an increase in the requirements for climatic comfort in buildings, has resulted in substantial increase in energy consumption for the production of cooling energy. Most of the cooling demand in buildings is met by electricity-powered systems. The greatest demand for cooling occurs during summer periods, which coincides with the lowest availability of electricity. The use of absorption chillers powered by waste heat from electricity generation is an alternative to electricity-powered compressor chillers. The production of chilled water in a tri-generation system makes it possible to reduce the demand for electricity and further support the electricity system during the months with the highest demand. The use of tri-generation micro-systems in office buildings and production facilities

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deconcentrates the national energy system. The de-concentration of the electricity system is an ideal solution to the low efficiency of electricity transmission and relieves the burden on traditional coal-fired power plants, which should gradually be phased out. The use of waste heat generated during electricity generation, to heat buildings in winter periods and to power chilled water generators in summer periods is an ideal solution for economies in temperate climate zones. Tri-generation – the combined production of electricity, heat and cooling energy, leads to the most efficient use of primary energy.

Tri-generation systems are used in a variety of public facilities. Qiong Wu et al. analyzed the influence of building type and climate conditions on the energy, economic and environmental performance of tri-generation system [1]. They have focused on four representative categories of commercial buildings: hotel, hospital, shop and office located in six major climate zones in Japan. Using multi-criteria approach they have found that tri-generation system is the best suited for hotels and hospitals.

A very interesting approach to tri-generation was presented by Jialong Wang et al. [2]. They analyzed tri-generation system operating in combined CCH cooling and heating mode, where all the electricity produced is used to power the HVAC system. Waste heat from the gas engine is recovered to heat the building or to power a single-stage absorption chiller. They compared this type of solution with a traditional HVAC system powered entirely by grid electricity. The authors concluded that a CCH system operating even at low loads is more efficient than a traditional grid-powered HVAC system.

Zeynab Seyfouri, in paper [3], presented an analysis of a tri-generation system powered by a geothermal source. They have proved that low-temperature heat source of 133.3 °C, which consists of a hybrid GAX (HGAX) cycle and an organic Rankine cycle (ORC) coupled by a condenser, is capable of producing cooling energy at very low temperature (-50 °C). The authors have used ammonia-water mixture as the working fluid of the system. An exergy analysis showed that with simultaneous production of 1897 kW of electricity and 1000 kW of cooling, the exergy efficiency of such a system is 42.81%.

Antonio M. Pantaleo analyzed a dual-fuel system with an electrical output of 100 kW powered not only by natural gas, but also by biomass [4]. In the thermo-economic assessment, author compared different biomass/natural gas fuel ratios and the different climatic conditions under which the system operates, in order to evaluate the trade-off between lower energy conversion efficiency and higher investment costs when increasing the biomass input rate. The analysis showed that the best trade-off between energy efficiency, investment costs and bonuses for electricity generated from gaseous fuels and biomass is a 50 per cent natural gas-biomass mix.

A major challenge for tri-generation system designers is to match the system to the peaks in demand for the various forms of energy. Very often, peak electricity demand does not coincide with peak heat demand. Zhan Liu et al. [5] presented a novel tri-generation system based on adiabatic storage of compressed air energy for efficient allocation and utilization of compression heat. The CCHP system operates in off-peak charging mode. Excess electricity from the power grid is consumed by the compressors. In this process, the high-pressure air generated is finally stored in an air accumulator (ACC). The stored air is first removed from the ACC and then used to generate electricity.

Leonard L. Vasiliev [6] presented a novel idea of combining a hydrogen cell-powered CCHP system with a sorption heat pump system. Developed and tested system configuration offered the possibility of saving 15-20% of primary energy for cooling, heating and electricity production.

Hozhabr Adhami presented an example of micro-tri-generation that can be used in military applications [7]. He proposed a new portable tri-generation system that uses several energy sources. The author presented the novel use of renewable energy sources in the proposed systems for locations without access to energy sources. The weight of the suggested tri-generation systems varies according to the different drives and ranges from 5.66 kg to about 37.5 kg for single systems, respectively.

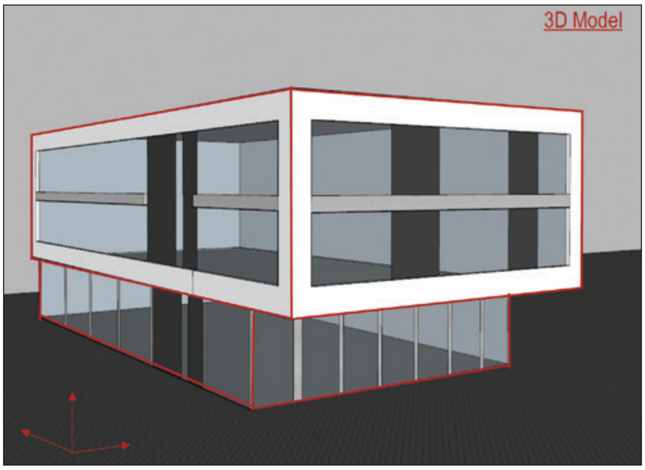
The article presents the study on application of natural gas fired tri-generation system based on natural gas fired micro-turbine. The system consists of natural gas fired micro-turbine and heat exchanger which produces heat for space heating and for cooling energy production in single stage absorption water chiller. The system operates whole year providing fixed electricity production – electrical power N_{El}, and heat production varying depending on heat requirements.

Case study description

Analyzed office building is 3-storey building with useable floor area of 1632 m^2 and useable volume of 13 382 m^3, located in Poznań, Poland – 2nd climatic zone.

The architectural drawings of concerned building have been entered into SketchUp graphics software in order to create 3D model for TRNSYS building energy analysis – figure 1.

Fig. 1.
Visualization of analyzed office building
Rys. 1. Wizualizacja analizowanego budynku biurowego



The following building features have been assumed for simulation in TRNSYS 17 software [8]:

- building is equipped with an water based HVAC system,
- internal temperatures are $t_{e,W}$ = 20°C in winter period and $t_{e,S}$= 23°C in summer period,
- occupation standard in office area is 8 m^2/person,
- building is occupied 8 hours a day,
- there are heat gains from people, lighting and equipment when the building is in use.

Multi-zone building model of TRNSYS 17 software has been used, which allowed for the dynamic analysis based on assumed utilization profile and climatic conditions for the city of Poznań. Using TRNSYS 17 software building's heating and cooling loads for each hour of the year have been calculated. Heating load calculations included space heating requirements and mechanical ventilation requirements. Cooling load calculations included heat gains through solid and transparent partitions, internal heat gains (people, computers, lighting) and mechanical ventilation requirements. The average daily values of cooling and heating loads have been the input for the calculation model of the tri-generation system. It has been assumed that the analyzed system completely covers heating and cooling demand of office building. The electricity produced by the micro-turbine is transferred to electricity grid. Average daily heating load distribution is shown in figure 1 and average daily cooling load distribution in figure 2.

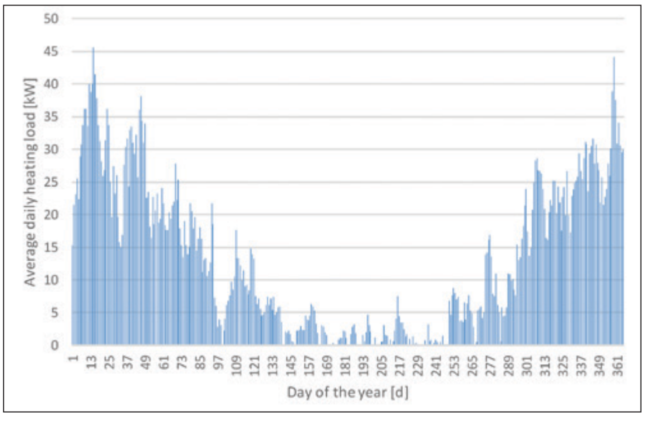


Fig. 2. **Average daily heating load of analyzed office building connected [8]**
Rys. 2. Średnie dobowe zapotrzebowanie na moc cieplną analizowanego budynku biurowego [8]

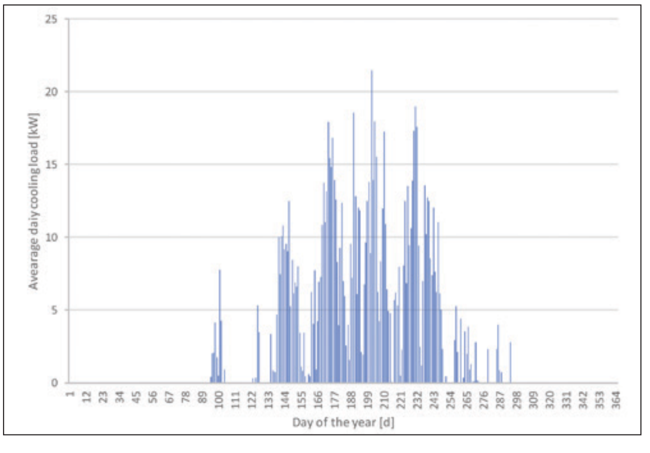


Fig. 3. **Average daily cooling load of analyzed office building [8]**
Rys. 3. Średnie dobowe zapotrzebowanie na moc chłodniczą analizowanego budynku biurowego [8]

Annual heating demand (Q_H) and annual cooling energy demand (Q_C) of analyzed office building have been calculated on the basis of average daily heating load ($Q_{H,i}$) and average daily cooling load ($Q_{C,i}$) distributions using the following equations:

$$Q_H = 24 \cdot \sum_{i=1}^{365} \dot{Q}_{H,i} \qquad (2)$$

$$Q_C = 24 \cdot \sum_{i=1}^{365} \dot{Q}_{C,i} \qquad (3)$$

In order to evaluate the annual heating demand (Q_C^{heat}) required for cooling energy production in single stage absorption water chiller (AWC) the seasonal energy efficiency ratio (*SEER*) of the chiller has been used [9].

$$Q_C^{heat} = \frac{Q_C}{SEER} \qquad (4)$$

The results of annual heating and cooling energy demand are presented in table 1.

Table 1. Annual heating and cooling energy demand of an office building
Tablica 1. Roczne zapotrzebowanie na ciepło i chłód budynku biurowego

Parameter	Unit	Value
Annual heat demand	[kWh a^{-1}]	112045
Annual cooling energy demand	[kWh a^{-1}]	1120
Annual heat demand for cooling energy production	[kWh a^{-1}]	2050

As it has been mentioned above micro-turbine operates whole year with priority of electricity production, thus the annual electricity production can be derived using formula:

$$E_{El} = 24 \cdot \sum_{i=1}^{365} N_{El,i} \qquad (5)$$

Energy and exergy models of evaluated system

Energy analysis is based on the first law of thermodynamics and helps in determination of energy efficiency of the system. Energy model of a natural gas fired micro turbine as the crucial element of tir-generation system has been presented in figure 4 [10]. The model consists of two main components: natural gas fired micro-turbine covered by control volume CV1 and heat exchanger covered by control volume CV2. The basic technical data of gas fired micro-turbine are presented in table 2.

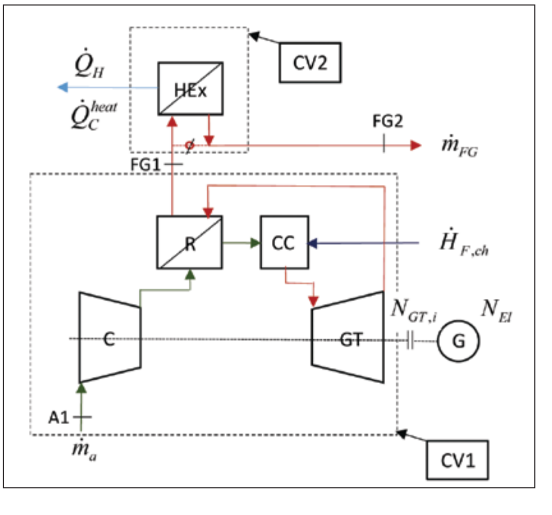
Table 2. Basic technical data of gas fired micro-turbine
Tablica 2. Podstawowe dane techniczne mikroturbiny gazowej

Parameter	Unit	Value
Electrical power output	[kW]	30
Electrical energy efficiency	[%]	23,6
Maximum energy efficiency	[%]	90
Flue gas mass flow	[kg s^{-1}]	0,31
Flue gas temperature (FG1)	[K]	548

Depending on current building requirements system can operate in three modes: heating, cooling and simultaneous heating and cooling. The heating capacity of heat exchanger (HEx) is controlled by the damper, changing the mass flow of flue gas through the heat exchanger.

Using energy balance analysis for two control volumes annual energy efficiency of the system can be derived.

Fig. 4. **Energy balance model of a natural gas fired micro turbine**
Rys. 4. Model energetyczny mikroturbiny gazowej



$$\eta_{e,MGT} = \frac{Q_H + Q_C^{heat} + E_{El}}{H_{F,ch}} \qquad (6)$$

Exergy analysis allows for the evaluation of irreversibility of all processes joined with the system operation as well as exergy efficiency of the system [11,12,13]. Exergy model of natural gas fired micro-turbine as the crucial element of tir-generation system, has been presented in figure 5 [8,10]. The flux of the internal exergy loss of that system is the sum of the exergy flux losses of two system elements: gas fired micro-turbine covered by control volume CV1 and heat exchanger covered by control volume CV2.

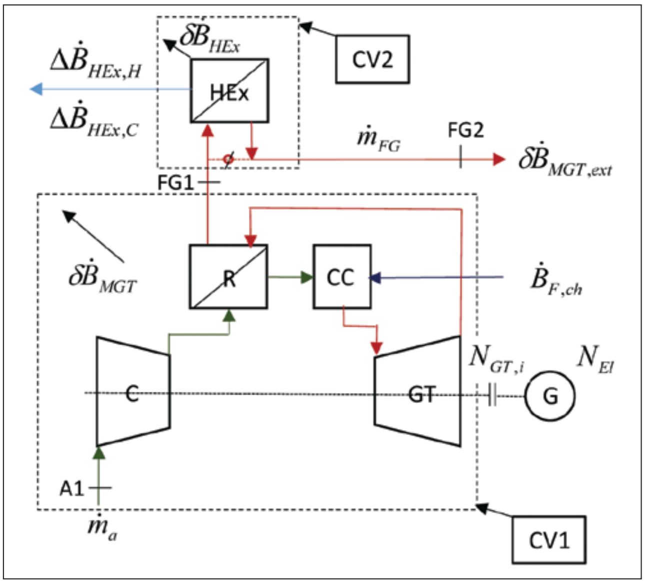


Fig. 5.
Exergy balance model of a natural gas fired micro turbine
Rys. 5. Model egzergetyczny mikroturbiny gazowej

Using exergy balance analysis for two control volumes annual exergy efficiency of the system can be derived.

$$\eta_{b,MGT} = \frac{\Delta B_{HEx,H} + \Delta B_{HEx,C} + E_{El}}{B_{F,ch}} \qquad (7)$$

where:
$\Delta B_{HEx,H}$ – exergy change of external heat source (heating installation) during heating season, [kWh a^{-1}],
$\Delta B_{HEx,C}$ – exergy change of external heat source (generator of AWC) during cooling season, [kWh a^{-1}].

Taking into account average temperatures of water flowing through the heat exchanger in heating ($T_{HEx,H}$) and cooling ($T_{HEx,C}$) modes equation (6) can be reformulated to the following form:

$$\eta_{b,MGT} = \qquad (8)$$

$$= \frac{Q_H \cdot \left(1 - \frac{T_{0,H}}{T_{HEx,H}}\right) + Q_C^{heat} \cdot \left(1 - \frac{T_{0,C}}{T_{HEx,C}}\right) + E_{El}}{B_{F,ch}}$$

where:
$T_{0,H}$ – average temperature of surroundings in heating mode, [K],
$T_{0,C}$ – average temperature of surroundings in cooling mode, [K].

Results and discussion

The results of energy and exergy balancing of the natural gas fired turbine are presented in tables 3 and 4.

Energy efficiency of co-generated heat and power production of natural gas fired micro turbine is low due to the limited utilization of enthalpy of flue gas in heat exchanger. Increase of useable heat production in heat exchanger can improve energy performance of such a system. It requires increase of heat demand for such a system by connection of other heat and cooling energy users.

Exergy efficiency of co-generated heat and power production of natural gas fired micro turbine is low due to the internal exergy losses joined with:
- diffusion – mixing of fuel (natural gas) and oxidant in combustion chamber,
- combustion process – chemical reaction between natural gas and oxygen introduced to the combustion chamber with compressed air,
- mechanical friction in gas turbine and compressor,
- hydraulic friction in pipe connections and heat exchanger,
- heat exchange between flue gas and water flowing through heat exchanger (high temperature difference).

Significant influence on low exergy performance has also external exergy loss joined with the limited utilization of flue gas exergy. Increase of flue gas exergy recovery can improve system operation. It requires increase of heat demand for such a system by connection of other heat and cooling energy users.

Calculated energy and exergy efficiencies of analysed system have been compared with reference energy system used in office buildings for covering their heat and cooling energy needs. The reference system is based on heat production in natural gas fired condensing boiler with seasonal energy efficiency $\eta_{e,H}$=0.94 and cooling energy production in electricity driven compressor water chiller with seasonal energy efficiency ratio $SEER_C$=3.65. It has been assumed that for reference system amount of electricity produced in evaluated micro-turbine based system has been produced and delivered to the grid from condensing power plant fired with hard coal, with total energy efficiency $\eta_{e,PP}$=0.33. The chemical energy and

Table 3. Energy balance analysis results
Tablica 3. Wyniki analizy energetycznej

Parameter	Unit	Value	Comment
Q_H	[kWh a^{-1}]	112045	Eq. (2)
Q_C^{heat}	[kWh a^{-1}]	2050	Eq. (4)
E_{EL}	[kWh a^{-1}]	262 800	Eq. (5)
$H_{F,ch}$	[kWh a^{-1}]	1112520	Manufacturer data
$\eta_{e,MGT}$	[-]	0,339	Eq. (6)

Table 4. Exergy balance analysis results
Tablica 4. Wyniki analizy egzergetycznej

Parameter	Unit	Value	Comment
Q_H	[kWh a^{-1}]	112045	Eq. (2)
Q_C^{heat}	[kWh a^{-1}]	2050	Eq. (4)
E_{EL}	[kWh a^{-1}]	262 800	Eq. (5)
$T_{HEx,H}$	[K]	353	
$T_{HEx,C}$	[K]	343	
$T_{0,H}$	[K]	278	
$T_{0,C}$	[K]	293	
$B_{F,ch}$	[kWh a^{-1}]	1157021	Manufacturer data
$\eta_{e,MGT}$	[-]	0,247	Eq. (8)

Table 5. Energy and exergy evaluation of reference system
Tablica 5. Ocena energetyczna i egzergetyczna systemu referencyjnego

Parameter	Unit	Value
Q_H	[kWh a^{-1}]	112045
Q_C	[kWh a^{-1}]	1120
E_{EL}	[kWh a^{-1}]	262800
$H_{F,ch,H}$	[kWh a^{-1}]	119197
$H_{F,ch,C}$	[kWh a^{-1}]	307
$H_{F,ch,el}$	[kWh a^{-1}]	796364
$H_{F,ch,ref}$	[kWh a^{-1}]	915868
$B_{F,ch,H}$	[kWh a^{-1}]	116527
$B_{F,ch,C}$	[kWh a^{-1}]	1023
$B_{F,ch,el}$	[kWh a^{-1}]	876000
$B_{F,ch,ref}$	[kWh a^{-1}]	993550

chemical exergy needs for reference system have been listed in table 5.

It can be seen that tri-generation system based on natural gas fired micro-turbine has worse energy and exergy performance with respect to the reference system for analysed office building. It is due to the low utilization of energy and exergy of flue gas leaving micro-turbine resulting in low energy and exergy efficiencies of that system.

The sensitivity analysis of application of such a system has been presented in figures 6 and 7 as the functions of chemical energy and chemical exergy use versus energy and exergy efficiency.

Conclusions

Tri-generation systems based on natural gas fired micro-turbines can be attractive alternative for typically used separated production of heat, electricity and cooling energy. The most important issue referred to application of such system is proper sizing of the system allowing for the most effective utilization of energy and exergy of flue gas living the turbine.

For analysed system covering heat and cooling energy needs of a small office building expected energy and exergy efficiencies should be higher than 0,412 and 0,289 respectively. It can be achieved by better sizing of the system.

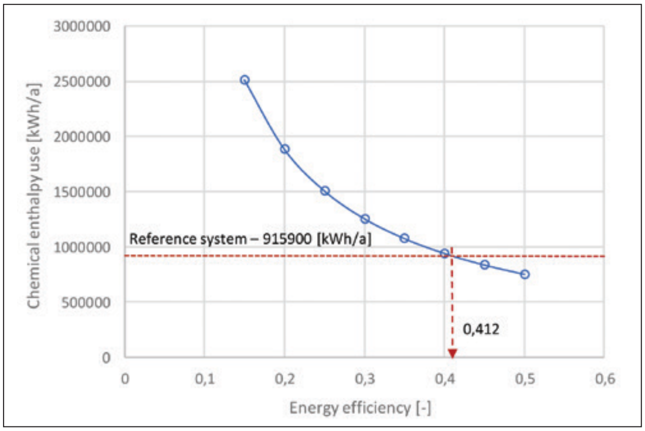


Fig. 6. Sensitivity analysis – energy performance
Rys. 6. Analiza wrażliwości – ocena energetyczna

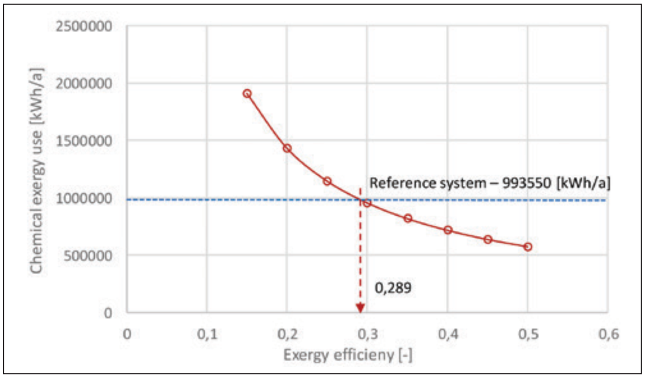


Fig. 7. Sensitivity analysis – exergy performance
Rys. 7. Analiza wrażliwości – ocena egzergetyczna

Sensitivity analysis performed shows that expected energy and exergy efficiencies for analysed system should be higher than 0,421 and 0,289 respectively. It can be achieved by better utilization of energy and exergy of flue gas leaving micro-turbine.

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