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Economic effectiveness evaluation of the free piston Stirling engine-based micro-combined heat and power unit in relation to classical systems

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Abstract In this article, a comparison of economic effectiveness of various heating systems dedicated to residential applications is presented: a natural gas-fueled micro-cogeneration (micro-combined heat and power – μCHP) unit based on a free-piston Stirling engine that generates additional electric energy; and three so-called classical heating systems based on: gas boiler, coal boiler, and a heat pump. Calculation includes covering the demand for electricity, which is purchased from the grid or produced in residential system. The presented analyses are partially based on an experimental investigation. The measurements of the heat pump system as well as those of the energy (electricity and heat) demand profiles in the analyzed building were conducted for a single-family house. The measurements of the μCHP unit were made using a laboratory stand prepared for simulating a variable heat demand. The overall efficiency of the μCHP was in the range of 88.6–92.4%. The amounts of the produced/consumed energy (electricity, heat, and chemical energy of fuel) were determined. The consumption and the generation of electricity were settled on a daily basis. Operational costs of the heat pump system or coal boiler based heating system are lower comparing to the micro-cogeneration, however no support system for natural gas-based μCHP system is included.

Keywords: Heating systems; Cost analysis; Stirling engine, Micro-cogeneration

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1 Introduction

Stirling engines, patented over 200 years ago, have been forgotten because of the dynamic development of the internal combustion engines. In recent years growing interest of this type of engines can be noticed because of the potential application in micro-cogeneration (micro-combined heat and power, μCHP) – the simultaneous production of electricity and heat in domestic scale. The development of micro-cogeneration is related to the energy policy which leads to increase of the significance of distributed generation. It is postulated that one of the priorities for the energy infrastructure is the need to invest in smart, efficient, and competitive power grid solutions based on decentralized sources including, primarily, renewable sources and μCHP sources. In particular, μCHP units, dedicated for residential applications, are intended to be a remedy for reducing the load of centralized energy systems and enabling the active participation of final consumers (called prosumers) in energy management [1,2]. One of the ways to generate heat and power in a single family-house is a Stirling engine-based CHP system. Stirling engines, known for an excellent operation culture and reliability, are classified into two basic categories as follows [3]: 1) Engines that use the reciprocating motion of the power piston for the rotating motion through the crankshaft and variable working mechanisms. The displacer is moved by a mechanical system. 2) Free piston engines, characterized by no rotating parts. The displacer is moved by changing the pressure, and power is generated using a linear alternator located on the power piston [4]. Modern version of the free piston Stirling engine (FPSE) has multiple advantages: quiet operation, various fuels available, long and maintenance-free operation. These aspects made FPSEs a potential solution for distributed generation. Scheme of the FPSE is presented in Fig. 1. The most popular engines are produced by Microgen, and they are basic machinery of μCHP units by major gas boilers companies: Viessmann, Baxi, Vaillant, and Remeha. The stages of investment in this solution were described in detail in [5]. The main parameters of the Microgen engine [6]: nominal electrical output 1000 W_{el}; characteristics of electrical output – nominal 230 V, frequency – 50 Hz or 60 Hz; working gas – helium at 2.3 MPa charge pressure.

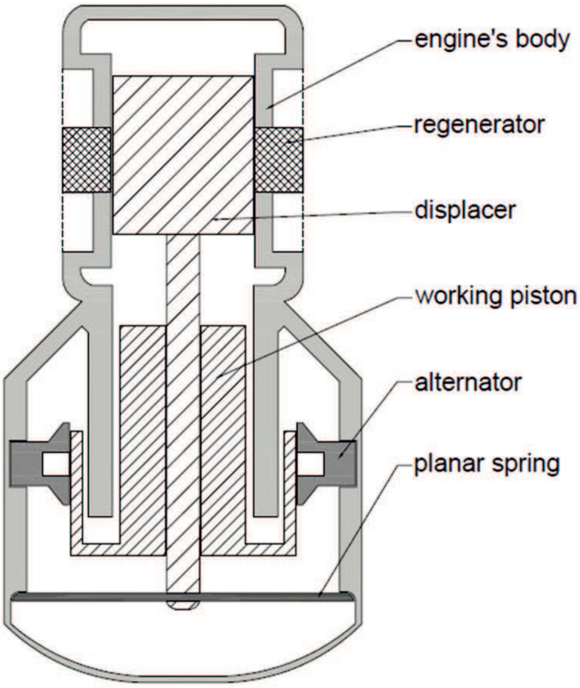

Figure 1: Scheme of the FPSE.

2 Free piston Stirling engine based micro-cogeneration unit

Analysis of the engine combined with other parts of the μCHP unit is sufficient for considering the micro-cogeneration advantages. The laboratory stand equipped with the Viessmann Vitotwin 300-W module (which consists of the Microgen engine and auxiliary burner) is part of the infrastructure of the Institute of Power Engineering and Turbomachinery in Gliwice. The analyzed natural gas fueled unit is characterized by thermal power up to 26 kW$_{th}$ (5.7 kW$_{th}$ obtained in the engine, and additional heat is produced by the auxiliary burner). It is prepared to produce heat for heating system as well as hot tap water. The laboratory stand is equipped with an independent measurement system which allows to estimate the effectiveness parameters of the whole installation. The scheme of the installation is presented in Fig. 2. Both systems are described in detail in [7].

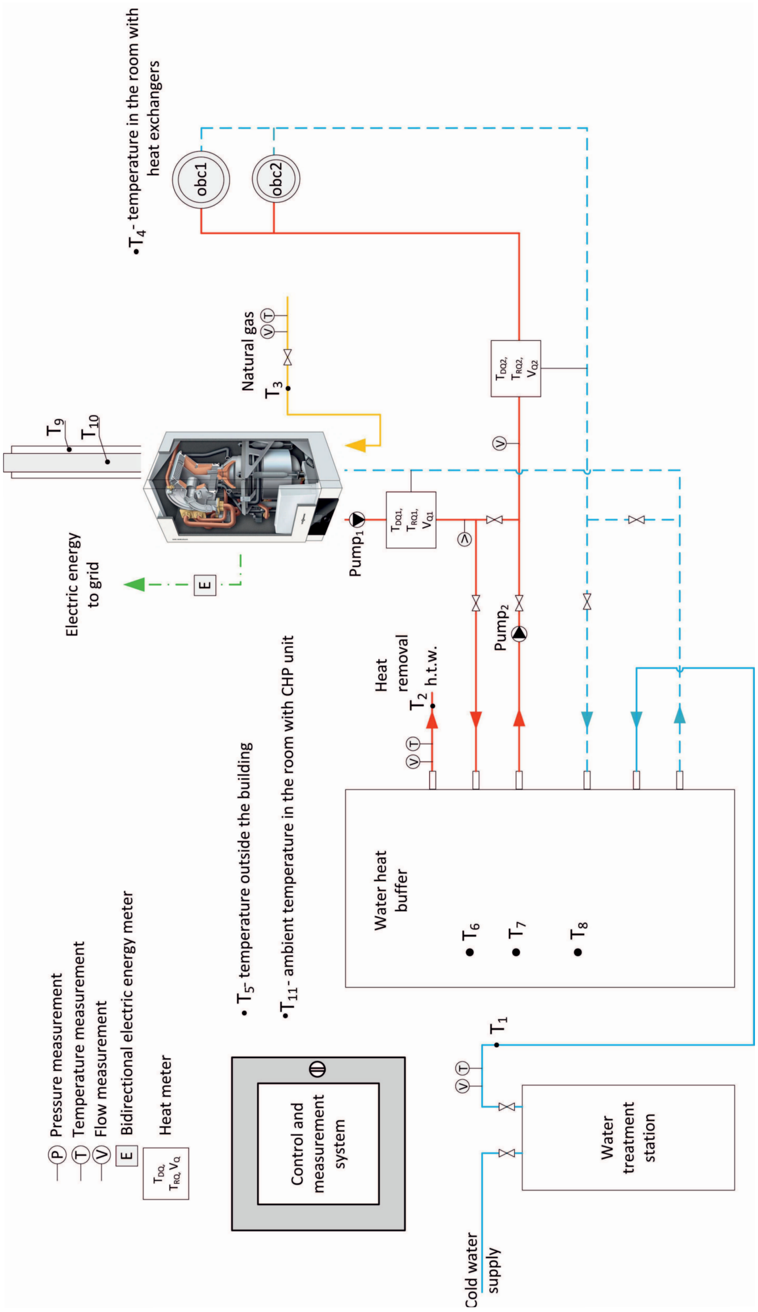

Figure 2: Scheme of the laboratory stand of the μCHP unit where: T_i – temperatures – measurement with thermocouple at the points $i = 1, \ldots, 10$, T_{DQi}, T_{RQi}, V_{Qi} $(i = 1, 2)$ – delivery temperature, return temperature and water flow – data from heat meter, E – bidirectional electric energy meter, Pump$_1$ – internal μCHP unit pump, Pump$_2$ – additional pump for buffer-heaters cycle, obc$_i$ $(i - 1, 2)$ – fan heaters.

The long-term measurements of the micro-cogeneration module were conducted. Three operating modes (OM1, OM2, OM3) were recognized. The selected parameters of each operating mode are presented in Tab. 1. The use of each operating mode is controlled by the internal device controller which considers few factors: temperature of the return water, temperature of water in the heat buffer, the actual heat demand and the ambient temperature. The highest efficiency η_{el_av} of the net electricity generation was obtained for the OM2 operating mode and was equal to $\eta_{el\_av\_OM2} = 12.7\%$ at the net electric power of $N_{el\_av\_OM2} = 0.93$ kW$_{el}$, which indicates that the primary burner of the Stirling engine operated at maximum load. The thermal power for OM2 was $Q_{(W1)\_av\_OM2} = 5.56$ kW$_{th}$. The highest efficiency of heat generation was obtained for the OM3 operating mode; i.e., with the peak load burner also running, it was equal to $\eta_{q\_av\_OM3} = 83.1\%$. The highest overall efficiency was obtained for OM1 and was equal to $\eta_{el+q\_av\_OM1} = 92.4\%$, at the lowest power output, which is also related to the lowest operating temperature of the unit. It allows to recover more heat from the exhaust gases as the device operates as a condensing boiler. It is obvious that presented modes are not the only ones as the device's thermal power is up to 26 kW$_{th}$. However, these modes were switched on by the controller if the instantaneous heat demand did not exceed 10 kW$_{th}$. The heat dispersion by the heat fan air heaters obc$_i$ $(i = 1, 2)$ is strictly limited by the air temperature in the room and the fan speed.

Table 1: Average values of selected parameters for each operating mode.

Parameter	Unit	Operating modes		
		OM1	OM2	OM3
$Q_{(W1)\_av\_OMi}$	kW	4.34	5.56	10.58
$N_{el\_av\_OMi}$	kW	0.67	0.93	0.93
$\eta_{el\_av\_OMi}$	–	0.123	0.127	0.072
$\eta_{q\_av\_OMi}$	–	0.801	0.758	0.831
$\eta_{el+q\_av\_OMi}$	–	0.924	0.886	0.903

3 Assumptions for μCHP operation analysis

The exemplary operating modes of the micro-cogeneration unit were recognized. This allows to calculate the effectiveness of μCHP for given profile of energy demand. The calculations of energy streams concerning whole year of operation of the μCHP, as well as the system with heat pump, were performed. It allowed to compare these heating systems with classical heat sources as coal boiler or gas boiler.

The analyzed year (2011/2012) refers to moderate climate. The studied building is located in the south-western part of Poland and its heating system is currently based on the heat pump. The analyzed residential building is a detached house having a total surface area of 266 m^2, occupied by four people. The heat demand profile (Q_d), electricity demand profile (E_{el_d}) as well as the electricity consumption by the heat pump system (E_{el_hp}) are based on experimental data described in detail in [8], and they are expressed in kilowatt-hour per day. The extensive, long-term measurements of the average daily ambient temperature (t_{amb}) were also conducted and they are described in [9]. The temperature characteristics for the studied year is shown in Fig. 3. The heat demand profile as well as the heat pump energy consumption is presented in Fig. 4. The electricity demand for municipal purposes are assumed to be linear (as a function of the average daily ambient temperature), and it is described by following formula:

$$E_{el\_d} = -0.1175 t_{amb} + 15.95 . \quad (1)$$

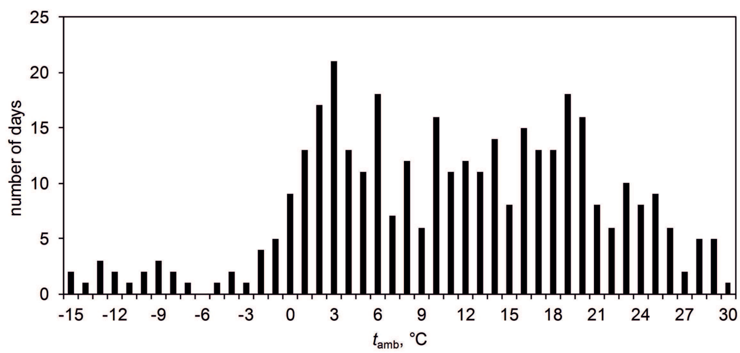

Figure 3: Number of days according to the 24-h average ambient temperature.

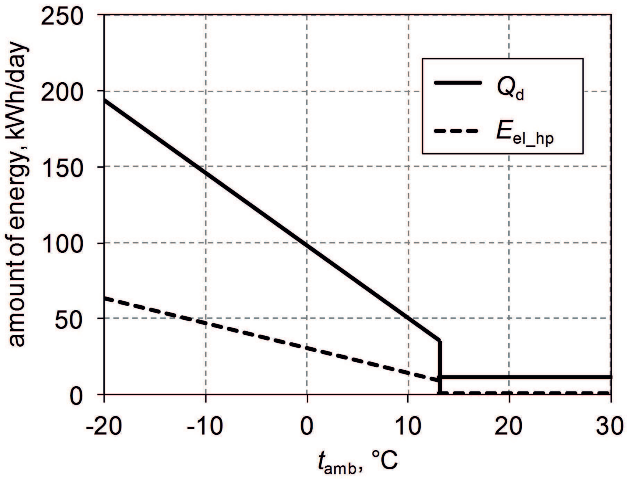

Figure 4: Heat demand (Q_d) and electricity consumption (E_{el_hp}) in the heat pump system as a function of the 24-h average ambient temperature.

4 Results of analysis

Experimental determination of the reference operating modes is intended to allow for a computational analysis of the micro-cogeneration system operation. Recognized load levels (operating modes) of the μCHP module while the heat demand is continuously changing (with the maximum instantaneous heat demand is approximately 10 kW$_{th}$ in this case) allow to calculate the total fuel consumption. The demanded amount of heat is produced by controlling the operating time of each mode.

A computational simulation of the micro-cogeneration system operation was performed for the analyzed year. It was assumed that the μCHP unit operates according to the priority of the heat demand coverage. The produced electric energy is a by-product. It is obvious, that total operation time of the μCHP device cannot exceed 24 hours per day, and the heat demand has to be covered. Controller of the device switch (for demanded time) the burners into particular operating mode. What is more, controller tries to maximize the efficiency of the module by maximizing the operation time of the mode characterized by the highest efficiency. The transition point to OM2 is determined by the ambient temperature and the heating curve implemented in the controller (dependency of the water supply temperature as a function of ambient temperature). When the daily heat demand (Q_d) exceeds the production capabilities of the OM2, the difference between the demand and the OM2 production capacity is covered by switching on (and appropriate operating time) the OM3 mode. The operating schedule as a function of the average daily ambient temperature is presented in Fig. 5.

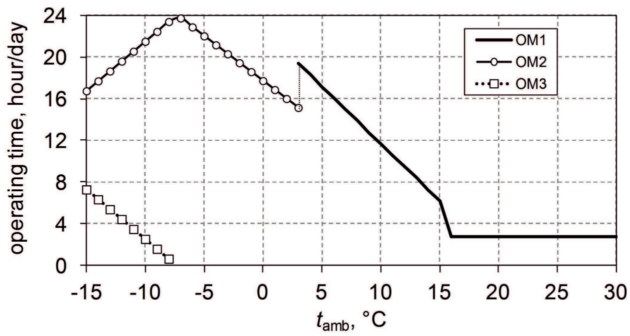

Figure 5: Operating time of each mode as a function of the 24-h average ambient temperature.

An assumption was made that the electric energy generated in the μCHP unit is maximally used for domestic purposes in daily settlement. Comparison of the daily electricity consumption and the electricity generation in the μCHP unit allowed to characterize the difference between them as a function of the ambient temperature, as presented in Fig. 6.

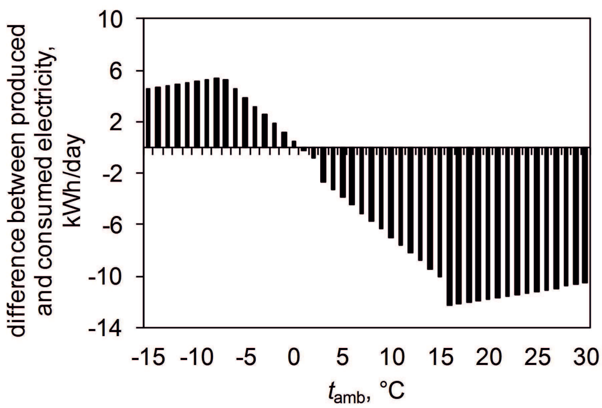

Figure 6: Difference between the electricity generated in the μCHP unit and the daily electricity consumption.

The analysis of the obtained data reveals that electricity production exceeds the demand in months when the daily average ambient temperature is not higher than 0 °C. During this period, the electric energy surplus is sold to the grid. When the ambient temperature exceeds 0 °C, the deficit of electricity is purchased from the grid. As described earlier the electric energy was settled on a daily basis with priority for household consumption. The total electricity demand exceeds production, although the daily settlement assumption causes some part of the generated electricity to be sold to the grid. The calculations results concerning the whole year of operation of the μCHP unit as well as heat pump are presented in Tab. 2: Q is the total amount of heat produced in each analyzed heating system, E_{el_demand} is the total electricity demand in the analyzed building, $E_{HP\_el\_cons}$ is the total amount of electricity consumed by heat pump, $E_{\mu\text{CHP}\_el\_p}$ is the total amount of electricity purchased from grid when the μCHP unit is installed, $E_{\mu\text{CHP}\_el\_s}$ is the total amount of energy sold to the grid, $E_{\mu\text{CHP}\_ch\_cons}$ is the total amount of chemical energy consumed by the μCHP unit throughout the analyzed year. Here $E_{\mu\text{CHP}\_ch\_cons}$ already takes into account various efficiencies and operating times of different modes.

Table 2: Total amounts energy produced/consumed in μCHP system and heat pump system.

Quantity	Value, kWh
Q	18473
$E_{HP\_el\_cons}$	5175
$E_{\mu\text{CHP}\_ch\_cons}$	23559
$E_{\mu\text{CHP}\_el\_s}$	116
$E_{\mu\text{CHP}\_el\_p}$	2555
E_{el_demand}	5333

5 Operating costs

Analysis of the heating systems operation and determination of the amounts of produced/consumed energy allows for the operating costs estimation. At this stage of analysis, the classical heating systems – gas boiler and coal boiler – were also taken into account. The efficiencies of the gas (η_{GB}) and coal (η_{CB}) boilers were assumed to be 0.9 and 0.8, respectively. The lower heating values (LHV) of the fuels were also assumed to be LHV_{coal} = 25 MJ/kg; LHV_{gas} = 35 MJ/m^3_n. It should be emphasized that all the heating systems operate in a way to ensure the same amount of heat (Q) for the analyzed building. The potential increase in the electricity demand when classical systems are used, related to the circulation pumps supply or other devices of these systems, is neglected because it seems to be relatively low compared to the total household consumption. The unit prices of the media concerned in the cost analysis are summarized in Tab. 3, mostly based on [9], where: c_{el_p} – unit price of purchased electricity, c_{el_s} – unit price of electricity sold to the grid, c_{gas} – unit price of purchased gas, c_{coal} – unit price of purchased coal.

Table 3: The media prices considered in the cost analysis.

Quantity	Unit	Value
c_{el_p}	PLN/kWh	0.6
c_{el_s}	PLN/kWh	0.15
c_{gas}	PLN/m^{3}n	2.2
c_{coal}	PLN/ton	900
PLN/EUR		4.3

The total cost of operation of the house equipped with a heat pump system (K_{HP}) consists of the cost of electricity to cover the household demand (K_{el_demand}) and the cost of electricity consumed by the heat pump (K_{HP_el}). It is described by the following equation:

$$K_{HP} = K_{HP\_el} + K_{el\_demand} = (E_{HP\_el\_cons} + E_{el\_demand})c_{el\_p}\,, \qquad (2)$$

where $E_{HP\_el\_cons}$ and E_{el_demand} are the total electricity consumed demand, respectively, and c_{el_p} is the unit piece of purchased electricity.

The cost of operation of the house equipped with a μCHP module ($K_{\mu\text{CHP}}$) consists of the cost of purchased gas ($K_{\mu\text{CHP}\_gas}$) and the cost of electricity for household demand, when the latter exceeds production ($K_{\mu\text{CHP}\_el\_p}$) it is reduced by the revenue from the sale of the surplus electric energy to the grid ($K_{\mu\text{CHP}\_el\_s}$; daily settlement). The following equation was used:

$$K_{\mu\text{CHP}} = K_{\mu\text{CHP}\_gas} + K_{\mu\text{CHP}\_el\_p} - K_{\mu\text{CHP}\_el\_s}$$
$$= E_{\mu\text{CHP}\_ch\_cons}\frac{3.6}{\text{LHV}_{gas}}c_{gas} + E_{\mu\text{CHP}\_el\_p}c_{el\_p} - E_{\mu\text{CHP}\_el\_s}c_{el\_s}\,. \tag{3}$$

The cost of operation of the house equipped with a classic gas boiler (K_{GB}) consists of the cost of the purchased gas (K_{GB_gas}) and the cost of electricity for household demand. It is described by the following formula:

$$K_{GB} = K_{GB\_gas} + K_{el\_demand} = \frac{Q}{\eta_{GB}}\frac{3.6}{\text{LHV}_{gas}}c_{gas} + E_{el\_demand}c_{el\_p}\,. \tag{4}$$

The cost of operation of the house equipped with a classic coal boiler (K_{CB}) consists of the cost of the purchased coal (K_{CB_coal}) and the cost of electricity for household demand. It is described by the formula:

$$K_{CB} = K_{CB\_coal} + K_{el\_demand}$$
$$= \frac{Q}{\eta_{CB}}\frac{3.6}{\text{LHV}_{coal}}\frac{c_{coal}}{1000} + E_{el\_demand}c_{el\_p}\,. \tag{5}$$

The results of the cost analysis are presented in Fig. 7. Analysis of the results reveals that the lowest operating costs could be achieved by the heating system fueled by coal which would probably not meet the ecological standards of the other systems. However, introducing the μCHP module would bring the positive cost effect of approximately 15% comparing to the gas boiler-based heating system. The lower operating costs results mostly from the avoided cost of electricity. The total surplus of the electric energy (that can be sold to the grid) produced by the FPSE is low as the consumption of this energy is the priority. Operation of the heat pump system is about 8% more cost effective. According to the Polish legal and economic environment, there is no support mechanism for natural gas-based μCHP included. Introducing fixed, more favorable prices of electricity purchase from prosumers or another type of support mechanism could significantly increase the profitability of such microplants.

6 Summary

In this article, a comparison of operation costs of various heating systems was presented. Analysis concerned the systems based on the free piston

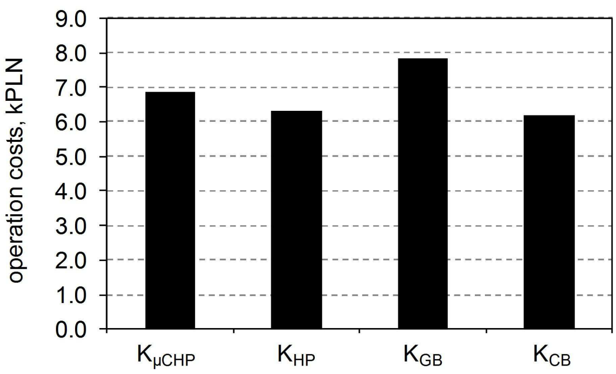

Figure 7: One-year operating costs of the analyzed heating systems including electricity demand coverage.

Stirling engine-based micro-cogeneration unit, heat pump, gas boiler and finally the coal boiler. For this purpose multiple experimental tasks were carried out: determination of the exemplary operating modes of the μCHP module and its efficiencies, long-term measurements of the energy demand profile in detached residential building, and measurements of the average daily ambient temperature throughout the year. Three operating modes determined for the given heat demand profile are characterized by various thermal and net electric powers. Based on the experimental research, the amounts of the produced/consumed energy (electricity, heat, chemical energy of fuel) were determined. The consumption and the generation of electricity were settled on a daily basis. In the daily settlement of electricity consumption for household needs, the reduction in the amount of energy imported from the grid is 52.1% when the μCHP is used. The operating cost analysis was performed. Operational costs of the heat pump system or coal boiler based heating system are lower comparing to the micro-cogeneration, however no support system for natural gas-based μCHP systems is included.

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