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Evaluation of a biomass based district heating system integrated with a Stirling engine

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Abstract

District heating (DH) systems in the European Union—in common with other energy generation systems—are subject to various regulatory and political pressures to be energy efficient and, to the extent possible, based on renewable energy sources (RES) out of environmental concerns. This paper proposes an innovative cogeneration configuration for a DH network, consisting of a biomass gasification unit, heat recovery system, high temperature purification unit and a Stirling engine for electricity generation. The system produces heat from biomass and generates the electricity that is needed for the purposes of auxiliary equipment and to cover pressure losses in the system. As such, the network may be 100% based on renewable energy source. This paper presents a thermodynamic analysis of the proposed solution. A detailed mathematical model of the system was built to carry out the analyses and calculate basic thermodynamic evaluation indices.

Keywords: Biomass gasification; Stirling engine; district heating system

1. Introduction

The energy sector is facing serious constraints. Due to requirements of the European Union (EU) energy systems have to include renewable and unconventional energy sources. This applies to both the generation of electricity and the production of heat. District heating (DH) systems in many European countries contribute to the provision of a significant amount of heat; e.g. in Poland this is around 50%, and the energy policy of the EU has factored in an important increase in the share of DH [1]. A strong emphasis is placed on increasing their efficiency, increasing the use of renewable energy sources (RES) and significantly lowering parameters of the water in the networks. Taking into account the energy policy conditions, new solutions for district heating should be proposed.

In countries where the use of renewable energy sources such as solar or geothermal is limited due to unfavorable climatic and geophysical conditions, biomass is one of the most promising energy sources. Biomass can be used for the production of heat in centralized, small or large scale district heating networks, harnessing locally available, often waste fuel.

One of the methods central to the use of biomass is gasification, i.e., thermochemical conversion of solid fuel into a combustible gas. The process consists of reactions of a gasifying agent with flammable substances contained in the fuel. As gasification agents, air, oxygen, water vapor or a mixture of them can be used. The main components of the gas resulting from gasification in air (process gas) are: carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen. The composition of the process gas can be influenced. The type of gasification medium has a significant impact on the content of flammable compounds in the gas, which also determines its further use. The main applications of the resulting gas are co-combustion in power boilers, gas turbines and, most frequently, gas piston engines, and use as a reburning fuel [2, 3, 4].

An interesting use of biomass is presented in [5]. A biomass gasifier is combined with a Stirling engine. This solution enables the combined production of electricity and heat. Currently, there are two basic categories of Stirling engines [6]. The first group consists of 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. The second category includes 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 [7]. Stirling engines are reliable and enjoy an excellent operation culture. Due to the characteristics of the gasification process and the cleaning methods available, the emission of gaseous pollutants into the atmosphere can be very low – considerably lower than dur-

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ing the combustion process of the same fuel. Gasification also provides far greater feedstock flexibility than combustion. Combining the advantages of the gasification process with the advantages of the Stirling engine creates synergies: possibility of harnessing a wide variety of thermal energy, especially renewable energy (including heat from waste and biomass gasification); separation of the combustion process from the energy conversion process.

In this paper, a novel solution for a district heating system is proposed. The main purpose of the analysis was to evaluate the proposed solution of a CHP source and a district heating system. A detailed mathematical model of the system was built for this purpose.

2. Model description and main assumptions for calculations

In this paper, a novel concept of a source for a district heating system, based on fuel gasification and Stirling engine is proposed. The main advantages of this solution is that it can use low grade fuels (waste biomass, residual wastes, low calorific fuels) to produce heat and electricity, mainly to cover auxiliary power of the DH system. By selecting appropriate parameters a system can be built that is self-sufficient in terms of electricity needs. The structure of the proposed system is presented in Fig. 1. It consists of an atmospheric gasifier (GG), a process gas cooler (GC 1°), combustion chamber (CC), high temperature purification unit (GCI) preceded by a gas cooler (GC 2°) cooling the medium to the temperature required in that process, a Stirling engine (SE) and gas coolers (and GC 3°), mounted in the flue gas stream after the engine. Since the Stirling engine is the external combustion-type, the requirements concerning purity of gas are much less strict than in internal combustion engines. This means existing hot-gas purification methods can be used, which reduces the cost of the purification system.

In the gasifier biomass is converted into combustible gas, the gas is cooled and the heat is used to produce hot water for district heating purposes. Then the gas is burned in the combustion chamber. High temperature exhaust gases are cooled to the temperature required in the high temperature gas removal installation and are directed to the Stirling engine. The high enthalpy of the exhaust gas is used to produce electricity and heat in the Stirling engine. Much of the heat contained in the exhaust gases is usefully used and transferred to the district heating system. Cooling in the Stirling engine occurs with re-entry of the agent from the DH system. It was assumed in the calculations that heat obtained within the system heats water in the network with parameters 90/70°C and thus only part of the heat obtained can be usefully exploited.

The assumptions for the analysis of the gasification process were derived primarily from the experimental studies on the GazEla gas generator, conducted at the Institute for Chemical Processing of Coal in Zabrze [2, 8]. Based on those results, it was assumed that cold gas efficiency η_{GG}, i.e., the ratio of chemical energy of the process gas to the chemical energy of the fuel, is 63% and the temperature of the gas leaving the gas generator is 950°C. The composition of the process gas is the following: H_2 = 5.9%, CH_4 = 1.7%, CO = 19.8%, CO_2 = 7.5%, N_2 = 44.3%, H_2O = 20.8%, and its lower heating value is 3.307 MJ/kg (3.743 MJ/m_n^3).

Electricity demand in a DH system results mainly from the auxiliary power of machines and devices operating in the system (in a heat source) and circulation pumps forcing the flow of water in pipelines. In the proposed solution electricity is generated in the Stirling engine, which uses the high enthalpy of flue gas from the combustion chamber to drive the generator. The efficiency of the engine is defined as the ratio of generated electric power (N_{SE}) to heat supplied to the engine ($\dot{Q}_s$):

$$\eta_{el,SE} = \frac{N_{SE}}{\dot{Q}_s} \tag{1}$$

The efficiency of electricity (η_{el}) and heat generation (η_q) in the whole system, and the overall efficiency of the entire system can be calculated based on the following relationships:

$$\eta_q = \frac{\sum \dot{Q}}{\dot{E}_{ch,b}}, \tag{2}$$

$$\eta_{el} = \frac{N_{el}}{\dot{E}_{ch,b}}, \tag{3}$$

$$\eta_{el+q} = \eta_q + \eta_{el} \tag{4}$$

where $\dot{E}_{ch,b}$ is chemical energy of biomass supplied to the system, Nel is electric energy generated by the engine and $\sum \dot{Q}$ is the sum of heat that can be usefully utilized, defined by the equation:

$$\sum \dot{Q} = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_{SE} \tag{5}$$

where $\dot{Q}_1$, $\dot{Q}_2$, $\dot{Q}_3$ is the heat obtained in gas cooler GC 1°, GC 2° and GC 3°, respectively (Fig. 1), while $\dot{Q}_{SE}$ is heat obtained in the Stirling engine.

The Stirling engine in the proposed system plays the important role of producing the electricity needed to cover the auxiliary power demand of the system. In this paper the assumptions for the Stirling engine are based on the detailed model of the Stirling engine presented in [9]. The efficiency of electricity generation of the engine is significantly dependant on the degree of cooling of the gas leaving the Stirling engine's heat exchanger. This degree of cooling, i.e., the temperature difference, is defined by the formula (denotations according to Fig. 1):

$$\Delta T_{SE} = T_{32} - T_{33} \tag{6}$$

The equation describing the relationship between efficiency and temperature difference is expressed as [10]:

$$\eta_{el,SE} = -2 \cdot 10^{-8} \cdot \Delta T_{SE} - 5 \cdot 10^{-5} \cdot \Delta T_{SE} + 0.2921 \tag{7}$$

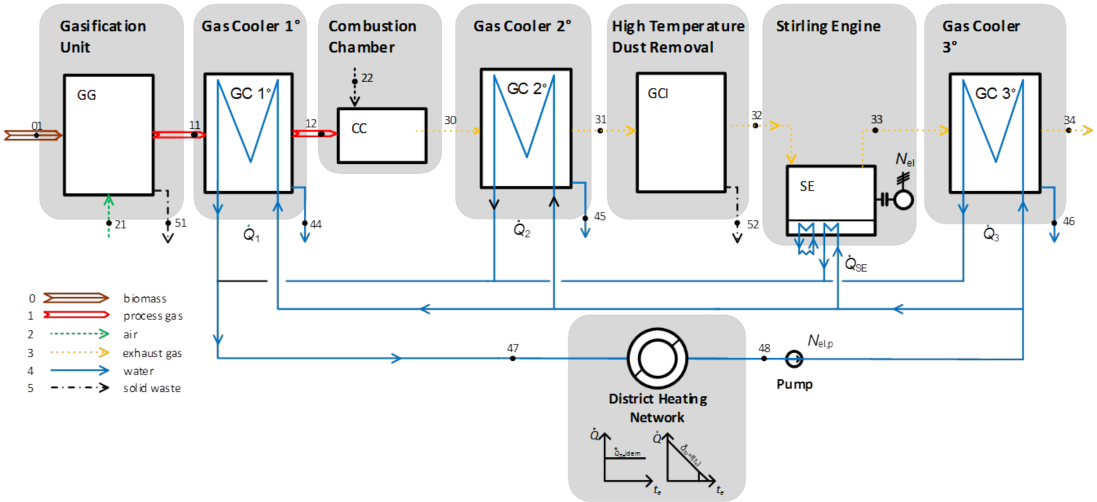

Figure 1: A schematic diagram of a DH system integrated with biomass gasification and Stirling engine; Denotations: GG—gas generator, GC—gas cooler, GCl—gas cleaning unit, SE—Stirling engine

Table 1: Characteristic parameters of the DH system with biomass gasification and Stirling engine

Parameter	Symbol	Value	Unit
Cold efficiency of the process gas generator	η_{GG}	63	%
Gas temperature at the outlet of generator	t_{11}	950	°C
Gas lower heating value	LHV_g	3.743	MJ/m_n^3
Gas temperature at the inlet to combustion chamber	t_{12}	140	°C
Efficiency of combustion chamber	η_{CC}	99	%
Efficiencies of gas coolers	η_{GC}	95	%
Temperature of flue gas after gas cooler 2°	t_{31}	700	°C
Temperature of flue gas after gas cooler 3°	t_{34}	100	°C
Efficiency of heat delivery to Stirling engine	η_s	95	%
Degree of heat recovery from Stirling engine cooling	$\eta_{q,SE}$	25	%

Table 2: Thermodynamic evaluation of the system with biomass gasification and Stirling engine

ΔT_{SE}	100	200	300	400	500	600
E_{chb}, kW	1000	1000	1000	1000	1000	1000
N_{el}, kW	13.7	26.6	38.6	49.6	59.8	68.9
Q_1, kW	202.4	202.4	202.4	202.4	202.4	202.4
Q_2, kW	317.4	317.4	317.4	317.4	317.4	317.4
Q_3, kW	220.7	174.1	128.6	84.5	41.6	0.0
Q_{SE}, kW	11.9	23.6	35.0	46.0	56.7	67.1
$\sum Q$, kW	752.4	717.4	683.3	650.2	618.1	586.8
η_{el}	0.014	0.027	0.039	0.050	0.060	0.069
η_q	0.752	0.717	0.683	0.650	0.618	0.587
η_{el+q}	0.766	0.744	0.722	0.700	0.678	0.656

The higher the degree of cooling, the higher the heat flux directed to the Stirling engine working space and the lower the average temperature of the supplied heat. As a consequence, the electric power of the engine is higher and the efficiency of electricity generation is lower. In the analyses presented in this paper, the degree of cooling was assumed to be in the range of 100 K to 600 K.

The heat produced in the source is transferred to the district heating network, distributing heat to the end users. Circulation of water is forced by electrically driven pumps located at the source. The recipients of heat in the network can be both industrial and individual consumers who use it for heating, ventilation and water production for utility and technological purposes.

The main assumptions for the analyzed system are presented in Table 1 and are largely based on [8, 11].

3. Results

This section presents the key results of the thermodynamic analysis. Included are, firstly, the calculations used to evaluate the system with biomass gasification and a Stirling engine (subsection 3.1) as a source of heat and electricity. Then, a thermodynamic assessment of the district heating system is made (subsection 3.2).

3.1. Thermodynamic analysis of the CHP system based on a Stirling engine

In the first step of the analysis the proposed system was evaluated in terms of its thermodynamic potential. For that purpose a system with 1.0 MW in biomass chemical energy was assumed. Exemplary results (based on the evaluation indices defined in subsection 2 and according to the denotations presented in Fig. 1) for the selected temperatures difference are presented in Table 2. The analyses were made for various values of ΔT_{SE}, which is an important parameter influencing the production of electricity and heat, thus, in consequence, the efficiencies.

The results of the analysis show the significant dependence of the system production capability as well as the efficiency on the degree of cooling in the Stirling engine. The amount of products vary with the degree of cooling in the engine with constant biomass chemical energy supplied to the gasification reactor; the higher ΔT_{SE}, the lower the heat production and overall efficiency of the system and the higher the electricity generation. For 1.0 MW in biomass chemical energy, when ΔT_{SE} changes from 100 to 600 K, the electric power ranges from 13.7 to 68.9 kW$_{el}$ and heat power ranges from 752.4 to 586.8 kW$_{th}$. The overall efficiency η_{el+q} is in the range 76.6 to 65.6%.

3.2. DH system based on biomass gasification and Stirling engine

Thermodynamic analyses show that the proposed solution has the thermodynamic potential to produce heat and electricity from biomass. As the cogeneration ratio (the ratio of electric power to heat) is very low in the system, it is mostly suitable for installations in which demand for heat is much higher than the demand for electricity. Thus, it is a solution suitable for most district heating networks. In this section, analyses are performed for an exemplary district heating system, as presented later in the paper.

3.2.1. Heat demand in the system

To define heat demand in the network it was assumed that there are two main types of demands of the end-user. The first type represents a group of needs changing during the course of the year $\dot{Q}_{\mathrm{TD}}$ (e.g., heat for heating purposes and ventilation) and the second represents a group of demands that are constant during the year $\dot{Q}_{\mathrm{TI}}$ (e.g., domestic hot water and technological purposes). Heat demand $\dot{Q}_{\mathrm{TD}}$ is dependent on the outside air temperature t_e (and assumed inside air temperature t_i, here equal to 20°C) and for a given outside temperature $t_{e,x}$ can be calculated according to the equation:

$$\dot{Q}_{\mathrm{TD,x}} = \dot{Q}_{\mathrm{TD,m}} \frac{t_{\mathrm{i}} - t_{\mathrm{e,x}}}{t_{\mathrm{i}} - t_{\mathrm{e,c}}}, \tag{8}$$

where $\dot{Q}_{\mathrm{TD,m}}$ is the maximum heat demand for heating and ventilation purposes (calculated for computational air temperature $t_{e,c}$). In Polish conditions the outside air temperature is assumed based on the climatic zone. In this paper this temperature was assumed at $t_{e,c} = -20$°C. For the whole year an exemplary temperature distribution curve was adopted from [9]. Heat demand for hot water production (for domestic use and technological purposes) is in general independent of air temperature and here it was assumed to be constant throughout the year.

While maximum heat demand in the network is the sum of heat demand $\dot{Q}_{\mathrm{TD,m}}$ and $\dot{Q}_{\mathrm{TI}}$, minimum heat demand in the whole DH system results from the need to produce hot water for technological purposes $\dot{Q}_{\mathrm{TI}}$. Since the characteristics of a district heating system may be very diverse, to make the analyses universal, a parameter α was introduced, showing the share of heat demand that is temperature dependant to the total heat demand in the system, according to the equation:

$$\alpha = \frac{\dot{Q}_{\mathrm{TD,m}}}{\dot{Q}_{\mathrm{TD,m}} + \dot{Q}_{\mathrm{TI}}} = \frac{\dot{Q}_{\mathrm{TD,m}}}{\dot{Q}_{\mathrm{T}}} \tag{9}$$

For the analysis, a district heating network with a maximum heat requirement of 1 050 kW was assumed (with the following demands: 400 kW heating, 250 kW ventilation, 150 kW technological purposes 250 kW domestic hot water). The nominal value of $\dot{Q}_{\mathrm{TD,m}}$ is 650 kW and for $\dot{Q}_{\mathrm{TI}}$ it is 400 kW. The heating network is a water network with a total pipeline length of 3 km and nominal supply/return parameters of 90/70°C, respectively.

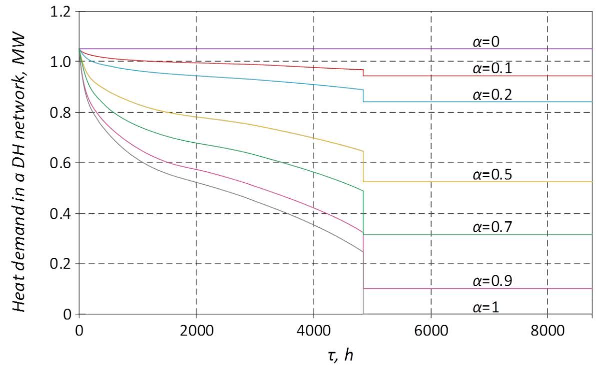

Figure 2: The annual ordered heat demand curve in the analyzed network as a function of coefficient α

Based on the annual outside air temperature distribution and the heat demand in the analyzed network, an ordered heat demand curve was generated as a function of the α parameter. The curves for the selected values of α are presented in Fig. 2.

The shape of the heat demand curve depends significantly on the value of parameter α—for the value of α equal zero, the heat demand in the DH network is constant throughout the year (regardless of the outside air temperature), for α equal to 1 heat demand occurs only during the heating season (assumed for outside air temperature lower than 12°C, which is for about 4800 h per year).

The annual heat demand in the analyzed network ($Q_{a,d}$) varies with the α value according to the linear equation:

$$Q_{\mathrm{a,d}} = -6818.8\alpha + 9204.3\,. \tag{10}$$

The maximum value of heat demand is 9204 MWh (33136 GJ) for $\alpha = 0$ and 2386 MWh (8588 GJ) for $\alpha = 1$.

3.2.2. Electricity demand in the system

Electricity demand in the district heating network is a result of the energy need for driving the circulating pumps ($N_{AUX,p}$) and the auxiliary power of the heat source ($N_{AUX,HS}$) which, in the analyzed case, consists of the gasification unit and cooling section and high-temperature gas purification units. As part of the auxiliary power requirements of the heat source module the authors consider: multistage biomass feeding system, drives for gas and air fans, drives for the reactor equipment (valves engines, grate drives), drives for the biomass dryers, and drives for the circulation pumps as well as the automatic control system. The auxiliary power coefficient (electricity demand to electricity production ratio) of the gasification systems is about 10% [12, 13] which, if compared to biomass chemical energy, is usually in the range 2.5–3.5%. In this paper it was assumed to be 3%.

The energy expenditure by the circulation pumps $N_{AUX,p}$ results from forcing the flow of the medium (overcoming friction resistance) by circulating pumps in the network. Its value is directly proportional to the flow of water and the pressure drop in the network Δp:

$$N_{\mathrm{AUX,p}} \cong \dot{V}\Delta p\,. \tag{11}$$

The pressure drop is caused by linear and local losses which can be calculated based on the detailed equations presented e.g. in [14] or with the use of simplified methods, as shown e.g. in [15]. The linear pressure losses are often calculated with the use of a unit pressure drop, denoted as R and expressed in Pa/m. Its value depends on the type of pipeline and medium, and the character of the fluid movement. In real networks it most commonly takes values ranging from over a dozen to more than several hundred Pa/m [14, 15].

The value of the local losses is often assumed as a certain part of the linear resistance value A, being the dimensionless coefficient of the local resistance values in the network relative to the linear losses, which may vary depending on the size of the network. It is usually in the range of 0.3–0.5 [14]. The formula for pressure loss calculations can thus be written as:

$$\Delta p = (1 + A)Rl\,. \tag{12}$$

The analyzed district heating network is relatively small (length $l = 3$ km), thus it was assumed that the value of A is 0.5. The coefficient of linear resistance R was assumed to be 150 Pa/m.

As was mentioned at the start of this section, the electricity demand consists of two components: the energy needed for pumping the heating medium and auxiliary power of the heat source. As the electricity needed for driving the circulating pumps is constant for given characteristics of the district heating network, the auxiliary power depends on the degree of cooling in the Stirling engine (ΔT_{SE}). This is due to the impact of the ΔT_{SE} on the efficiency of the whole CHP system (presented in Section 2). For given DH network characteristics (α, given heat demand) the biomass chemical energy supplied to the CHP system differs according to ΔT_{SE}. For a given heat demand, if ΔT_{SE} is higher, the efficiency of heat generation is lower and thus the chemical energy of fuel increases. The auxiliary power, as described earlier, is calculated directly on the basis of the biomass chemical energy. This results in changing electricity demand for various ΔT_{SE}. The authors assumed a similar auxiliary power coefficient if the additional system of heat production is used (3% of the fuel chemical energy).

Based on the assumptions made, analyses were conducted determine the electricity required to run the DH system with biomass gasification and a Stirling engine. The functions describing the annual demand for electric energy in the DH system are presented in Fig. 3.

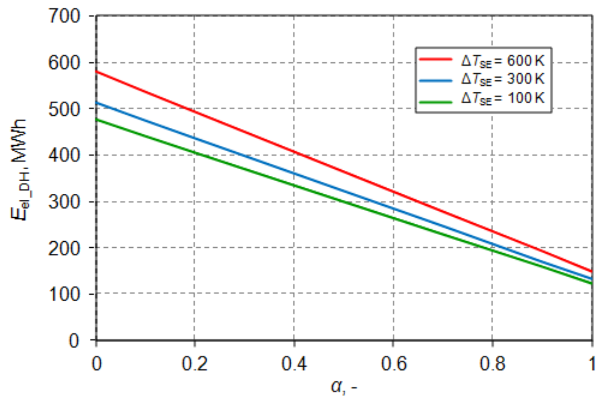

Figure 3: The annual demand for electricity in the analyzed district heating network for various values of ΔT_{SE}

3.2.3. Analysis of the CHP system with a Stirling engine

In order to produce the required amount of heat in the DH system, it is necessary to choose a heat source of an appropriate size (power). Asoperation of the source (gasification unit) may be limited by technical factors as well as by the availability of biomass, different scenarios can be taken into account. In this analysis it was assumed that the gasification unit can work for a certain period of time covering the heat demand in this period, with the rest of the heat demand being delivered from an additional source (e.g., biomass boiler, solar collectors, etc.). An exemplary diagram showing the heat demand coverage by the CHP source (Q_{CHP}) and additional heat sources (Q_{AB}) for the value of $\alpha = 0.5$ is shown in Fig. 4.

When the CHP system is able to operate for the whole year (Fig. 4a) it produces 9204 MWh of heat. If the time is 1084 h (Fig. 4c), only 1139 MWh of heat is produced. For other values of coefficient α and different operating times (selected values are marked in Fig. 4 with green points) the heat production is shown in Fig. 5. The operating times indicate the occurrence of several levels of temperature, i.e. higher than $-20°$C, $-3°$C, $1°$C, $5°$C and $11°$C, respectively.

Production of electricity in the system depends mainly on the values of the quantity ΔT_{SE}, and annual operation time, and varies from 20 kW$_{el}$ to 167.8 kW$_{el}$ ($\Delta T_{SE} = 100$ K) and from 133.8 kW$_{el}$ to 1081.2 kW$_{el}$ ($\Delta T_{SE} = 600$ K). Electricity production for three values of ΔT_{SE} as a function of annual operation time is shown in Fig. 6.

For the DH network, the ratio of annual heat produced in the CHP system to the heat demand resulting from the characteristics of the network is very important. To evaluate the ratio of covering the heat demand curve with the heat produced in the CHP system the β indicator was introduced, and this represents the ratio of the amount of heat produced in the CHP system (Q_{CHP}) to the total heat consumed in the DH network (Q_{DH}) according to the following formula:

$$\beta = \frac{Q_{\mathrm{CHP}}}{Q_{\mathrm{DH}}} = \frac{Q_{\mathrm{CHP}}}{Q_{\mathrm{CHP}} + Q_{\mathrm{AB}}} \tag{13}$$

where Q_{AB} is the amount of heat produced in the addi-

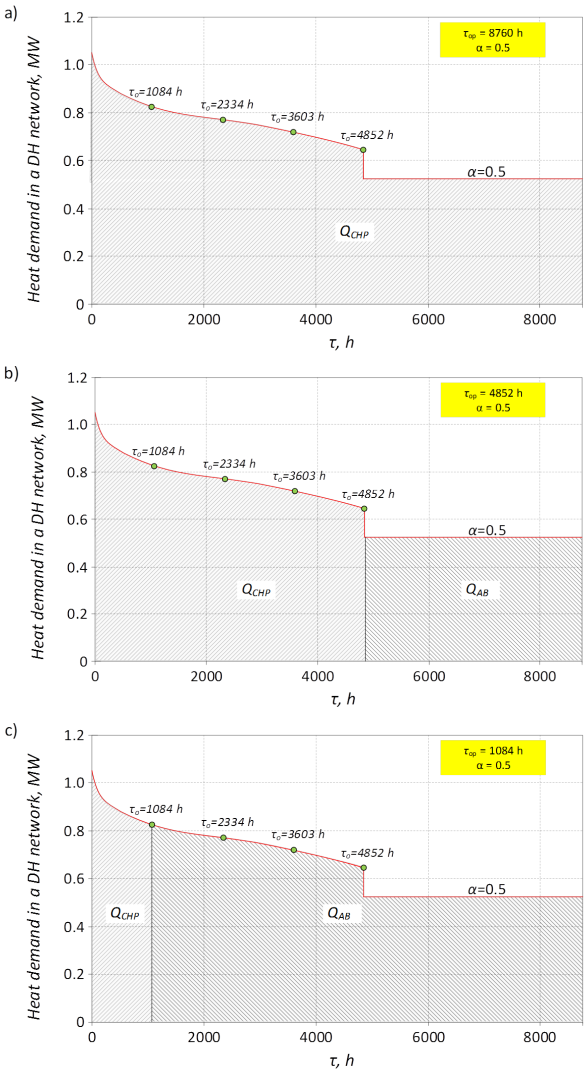

Figure 4: Distribution of heat demand over the network for CHP (Q_{CHP}) and additional heat source (Q_{AB}) for $\alpha = 0.5$ and various annual operating time

tional heat source. In this study, the selection of this source is not analyzed in detail; instead, it was merely assumed that it is a renewable energy source.

Indeed, the β indicator represents the ratio of covering the head demand curve with heat produced in the system integrated with biomass gasification and a Stirling engine (see Fig. 7). According to this definition $\beta = 1$ describes a network with all the heat produced in a CHP system and $\beta = 0$ describes a network where all the heat is produced in the additional heat source. The value of the β indicator depends on the α indicator and the operating time. The relationship between the α and β indicators is presented in Fig. 7.

Analysis of the presented results shows that the highest values of β are reached for the highest operating times (8760 h), where the entire heat demand can be covered by the CHP unit. For shorter operation time, the lower the α value, the lower the β, thus, the higher the share the additional boiler has in the heat production.

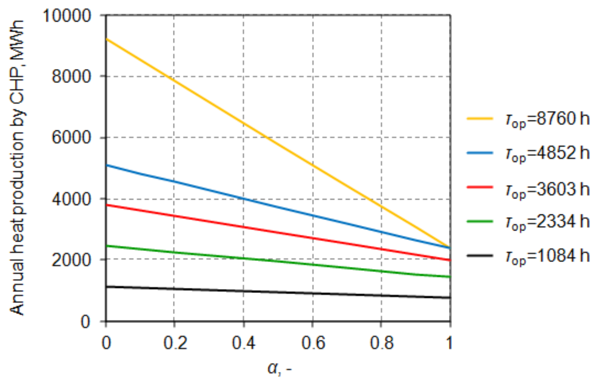

Figure 5: Annual heat production as a function of α

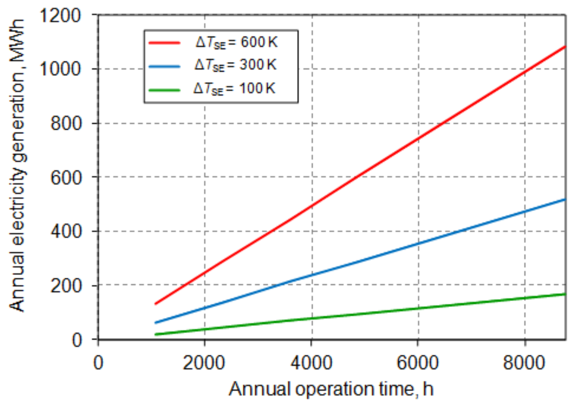

Figure 6: Annual electricity generation as a function of operation time

4. Summary and Conclusions

The system configuration proposed in this paper produces heat for a district heating network based on biomass gasification and a Stirling engine. The main advantage of the system is that it produces electricity that can be used to satisfy the electricity demand. Compared to a gas piston engine the use of a Stirling engine simplifies the purification step and opens the way to using high temperature cleaning. Moreover, due to the characteristics of the Stirling engine and the system as a whole, this also allows the use of waste and contaminated biomass.

Based on the conducted thermodynamic analysis it can be stated that the proposed solution for the CHP source integrated with a Stirling engine shows the potential for its use in DH systems. Annual production of heat and electricity in a DH network strongly depends on the type of network (parameter α), the assumed manner of operation of the CHP source and its operating time (τ_{op}). Through appropriate selection of the source, the DH system can potentially be self-sufficient in terms of energy requirements. If waste biomass is used as a fuel, the system may also become economically viable, but detailed analyses would have to be conducted to confirm this statement. This will be the subject of future research.

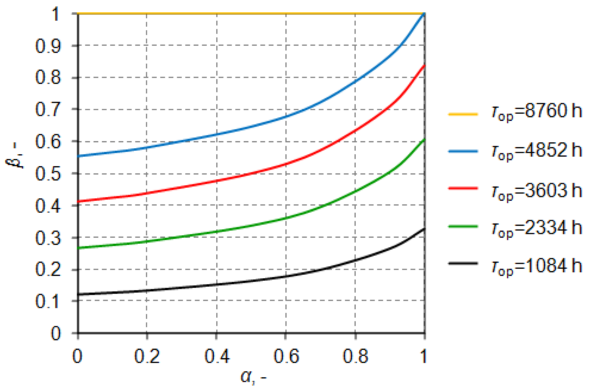

Figure 7: The relationship between β and α coefficients for various CHP system configurations

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