Chapter

Exploitation of Excess Low-Temperature Heat Sources from Cogeneration Gas Engines

Darko Goričanec and Danijela Urbancl

Abstract

The chapter presents an innovative technical solution for the use of low-temperature excess heat from the combined heat and power (CHP) of gas engines using gas or liquid fuel for district heating, building heating or industry. The primary fuel efficiency of CHP gas engines for heat production can be significantly increased by using the low-temperature excess heat of the exhaust gasses and the cooling system of the CHP gas engine, which are released into the environment thereby also reducing CO_2 emissions. District heating hot water systems generally work with higher temperatures of the heating water, which is transported to the heat consumer via the supply line, and the cooled heating water is returned to the CHP gas engine via the return line. In order to make use of the excess low-temperature heat of the exhaust gasses and the cooling system of the CHP gas engine, a condenser must be installed in the exhaust pipe in which the water vapor contained in the exhaust gasses condenses and a mixture of water and glycol is heated, which later leads to the evaporator of the high-temperature heat pump (HTHP). The cooled heating water is returned from the heat consumer via the district heating return pipe to a condenser of one or more HTHPs connected in series, where it is reheated and then sent to a CHP gas engine, where it is reheated to the final temperature. The Aspen plus software package is used to run a computer simulation of one or more HTHPs connected in series and parallel to the district heating system and to demonstrate the economics of using the excess heat from the exhaust gasses and the cooling system of the CHP gas engine.

Keywords: Rational use of energy, Low-temperature energy sources, CHP gas engine, High-temperature heat pump, District heating, Economic analysis

1. Introduction

More efficient energy consumption, and thus reduced consumption of non-renewable energy sources, can significantly reduce energy costs, mitigate climate change, improve the quality of life and reduce the EU's dependence on imported oil and gas. To achieve these goals, energy efficiency must be improved throughout the energy chain, from production to final consumption. EU action therefore focuses on sectors where savings can be greatest, such as energy consumption for heating and cooling buildings. In 2007, the EU set three main targets: a 20% reduction in greenhouse gas emissions (compared to 1990 levels), 20% of energy consumption from renewable sources in the EU and a 20% improvement in energy efficiency.

The 20% energy efficiency target was adopted with the adoption of Energy Efficiency Directive 2012/27/EU in 2012 [1].

The development of energy consumption since 2014 shows that the EU's energy consumption targets for 2020 have not been met. The crisis of COVID has severely affected the economy, reducing energy consumption in 2020. However, unless the European economy becomes more energy efficient, the subsequent economic recovery will lead to a resurgence of energy consumption. EU Member States have set up a working group to discuss with stakeholders the reasons for the increase in energy consumption in 2014 and 2017 and possible measures to address the problem.

The new edition of the Energy Efficiency Directive (EU) 2018/2002 entered into force in December 2018. The directive contains several new elements and some updates to previous directives. The EU's main goal is to achieve 32.5% energy efficiency by 2030 (compared to forecasts of expected energy consumption in 2030), with a clause on a possible upgrade by 2023. In accordance with the Energy Union and Climate Action Regulation (EU) 2018/1999, each Member State must draw up an integrated national energy and climate change plan (NECP) for the period 2021–2030, covering a 10-year period from 2021 to 2030 and describing how it intends to contribute to the objectives for 2030 in terms of energy efficiency, use of renewable energy sources and greenhouse gas emissions [1].

Moreover, increasing the efficiency of new or existing heat generation plants is one of the priorities in line with the EU's commitments to reduce GHG (greenhouse gases) emissions and achieve several environmental goals [1].

With the development of techniques and the growing demand for energy, more emphasis is now being placed on the use of renewable energy sources, in line with EU directives and the adoption of new legislation. The focus is on the rational use of energy and energy self-sufficiency of commercial and public buildings with all types of energy (electricity, heating and cooling).

There are only a few studies dealing with the coupling of heat pumps and CHP (combined heat and power) engines. An experimental study was conducted to increase the heating capacity of an electric heat pump using heat recovered from the generator of a gas engine [2]. Mancarella presented an approach for energy and CO2 emission modeling of CHP systems coupled with electric heat pumps [3], Blarke and Dotzauer [4] developed a novel CHP concept with a compression heat pump and cold storage using exhaust heat. Similar concepts were presented in [5], where Blarke compared an electric boiler and heat pumps with respect to decentralized CHP in West Denmark. Capunder et al. [6] presented an optimization model to evaluate the techno-economic and environmental characteristics of different multi-generation options.

The objectives for the use of surplus low temperature energy sources in CHP gas engines are:

- to implement a new l solution for the use of surplus low-temperature heat sources generated by the operation of CHP gas engines,
- to enable the smooth operation of new or existing CHP gas engines in heat generation for district and high temperature heating systems,
- to generate a greater amount of usable heat with the same consumption of primary fuel for the needs of high temperature heating,
- to maximize the overall fuel efficiency of CHP gas engines,
- selecting the technologically and economically optimal number of high-temperature heat pumps.

The purpose of using redundant low- temperature sources of CHP gas engines is:

- the need for a more efficient use of energy in heat production for district or high temperature heating systems, as today's energy efficiency is mainly limited to the insulation of pipes in district heating and the efficient use of energy by the end user,
- the need to use the excess low-temperature heat from CHP plants to increase the efficiency of the primary fuel,
- surplus low-temperature energy sources from CHP gas engines are used by high-temperature heat pumps to heat the return pipe water,
- the need to reduce CO_2 emissions to the environment while making major economic savings,
- the requirement to comply with EU recommendations and requirements concerning energy efficiency and environmental protection.

2. Operating the conventional CHP device

The CHP plant enables the simultaneous production of heat and electricity within one unit. The unit converts the chemical energy of the fuel by means of a steam turbine, gas turbine or internal combustion engine into mechanical energy, which is driven by a generator via a shaft, which converts the invested mechanical energy into electrical energy. A byproduct of this process is also the useful heat for high-temperature heating and the low-temperature waste heat, which is released into the environment via the cooling system and the exhaust system [6, 7].

The need for operation of the CHP plant is influenced by the season, the outdoor temperature and the specific needs of the end users. The mode of operation changes accordingly and adapts to the current demand for useful heat and electricity. In relation to the amount of usable heat and electricity, a proportional share of excess low-temperature heat is also produced.

3. Exploitation of excess low-temperature heat sources from CHP gas engines

When operating CHP gas engines, many low-temperature heat sources are generated, which are released into the environment via the cooling and exhaust system of the gas engine. These low- temperature heat sources are too low to be used directly to heat the return water of the district heating system. To be able to use this low-temperature heat source of the CHP gas engine, it is necessary to raise the temperature to the required temperature level using a high-temperature heat pump or several high-temperature heat pumps connected in series.

The principle of using surplus low-temperature heat sources of the CHP gas engine with built-in high-temperature heat pump is shown in **Figure 1**, where they are shown and marked: drive unit for combined heat and power (CHP), gas engine (ICE) with internal combustion, generator (G) for electricity generation, heat exchangers (HE1 - HE3), high-temperature heat pump (HP), piping system (P1 - P19) for heat distribution, heat consumer (HC), valves (V1 - V3), dampers

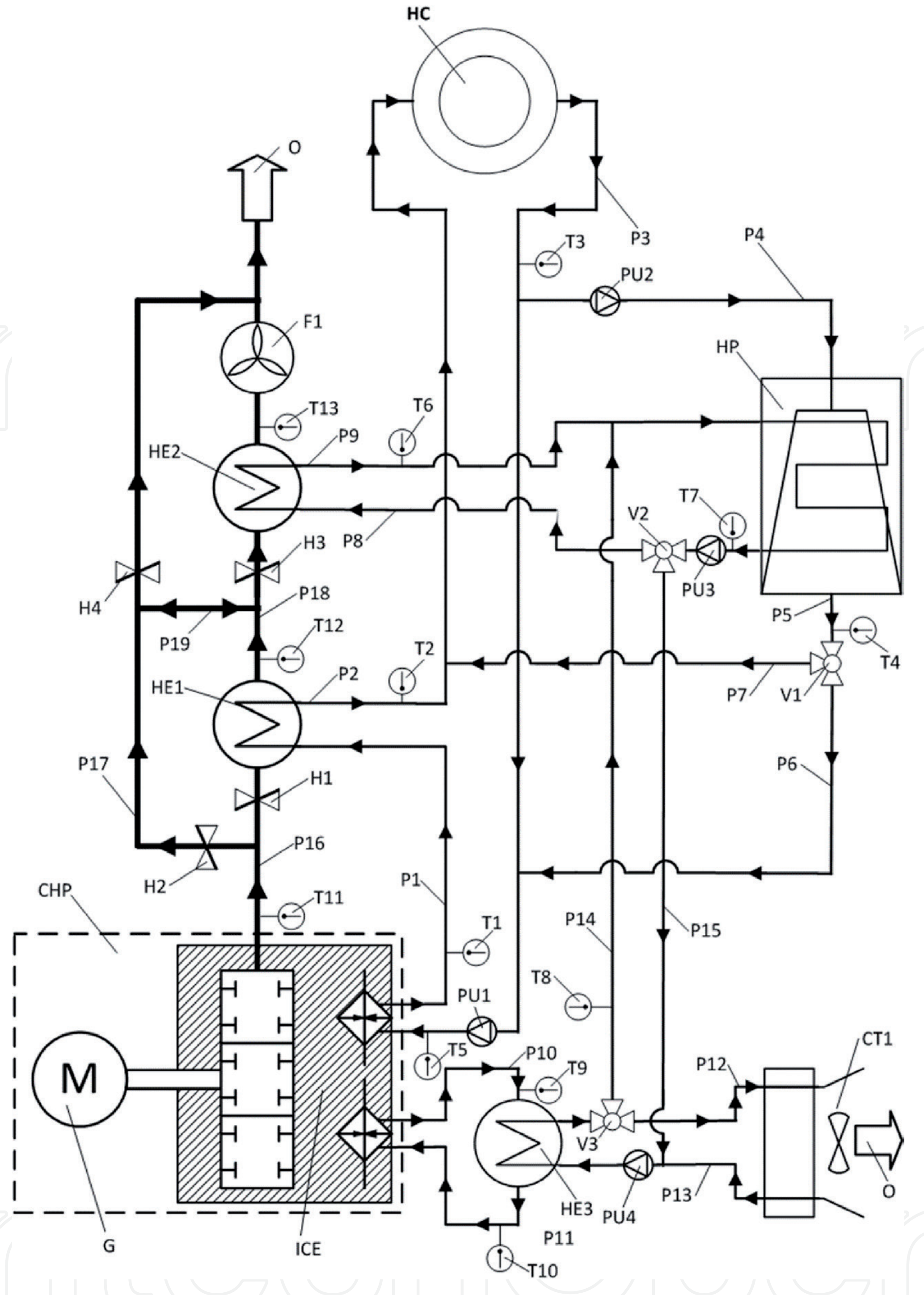

Figure 1.
The principle of exploiting the low-temperature sources of the CHP plant using the high-temperature heat pump [7].

(H1 - H4), fan (F1), pumps (PU1 - PU4), backup cooling system (CT1), external environment (O) and temperature sensors (T1 - T13) [7].

The drive unit of the combined heat and power plant (CHP) is directly connected to the high temperature district heating system of the end user (HC) with integrated cooling system or heat exchanger with piping (P1 and P3). The primary medium or heat transfer medium in a high-temperature district heating system is water, which transfers the thermal energy of the combustion engine cooling system to the end consumer (HC) of the high-temperature district heating system.

The operation of a combustion gas engine (ICE) produces hot exhaust gasses which are discharged through the pipe (P16) into two heat exchangers (HE1 and

HE2) connected in series. The first of the heat exchangers (HE1) on the exhaust system is designed to use the high-temperature heat of the exhaust gasses, which it transfers directly to the primary medium of the high-temperature heating system. After the high-temperature heat is dissipated in the heat exchanger (HE1), the exhaust gasses continue their path through the pipe (P18) to the heat exchanger (HE2). Due to the low temperature of the exhaust gasses in the pipe (P18) and the heating of the primary medium in the pipe (P8) (HE2), the heat of the primary medium is not suitable for further direct use in a high temperature heating system. To use this low-temperature source, a high-temperature heat pump (HP) is therefore used, into which the condenser directs the return flow of the district heating system. The heat exchanger (HE2) heats the secondary medium (water or a mixture of water and glycol) by further cooling the exhaust gasses and condensing the water contained in the exhaust gasses. This medium circulates in a closed circuit between the heat exchanger (HE2) and the evaporator of the high-temperature heat pump (HP). In the evaporator of the high-temperature heat pump (HP) the secondary medium evaporates the refrigerant of the heat pump (HP).

In a similar way, the low-temperature heat source intercooler 2nd stage and gas engine lubricating oil (ICE) is used via a pipe connection (P10 and P11) to the heat exchanger (HE3).

Due to the use of this low-temperature heat source, the evaporator of the high-temperature heat pump (HP) is connected to a secondary heat exchanger (HE3), which contributes part of the low-temperature heat to the evaporation of the working medium in the evaporator of the high-temperature heat pump (HP). One or more heat exchangers can be integrated in the series or parallel connection of CHP gas engines and high temperature heat pumps to use the excess low temperature heat sources which are now released into the environment.

To illustrate the process of using low-temperature heat sources from CHP gas engines, data on the operation of the commercially available CHP plant were obtained [8]. In **Table 3** nominal power of the 3.3 MW CHP plant given. The estimated operating time of the CHP plant depends on the heat consumer's demand. In the presented example are about 4000 h/year. The operation mode of the district heating pipe network or HC heat consumers is 90/60°C in winter and 90/55°C in summer.

3.1 Excess low-temperature heat from the CHP gas engine

The excess low temperature heat of the CHP gas engine is released unused to the environment in several ways. The most common are:

- heat from exhaust gases with a temperature of 120°C, which is released to the environment through the exhaust system of the CHP gas engine. During the operation of the CHP gas engine, hot exhaust gas with a temperature of approximately 365°C is fed into the heat exchanger HE1 (**Figure 1**), where it is cooled to a temperature of 120°C and then released to the environment. Exhaust gas at a temperature of 120°C that is discharged to the environment represents a significant low-temperature energy potential.

- heat of the external cooling system (CT) of the CHP gas engine. The cooling system is used to cool the compressed air during the 2nd stage intercooler. In this process, the 2nd stage intercooler transfers the compressed air heat to a water-glycol mixture, which is heated to 45°C and fed into an air cooling system (CT), where it is cooled to 40°C. The heat flow of the cooling system (CT), which is dissipated to the environment as low-temperature waste heat, is 197 kW.

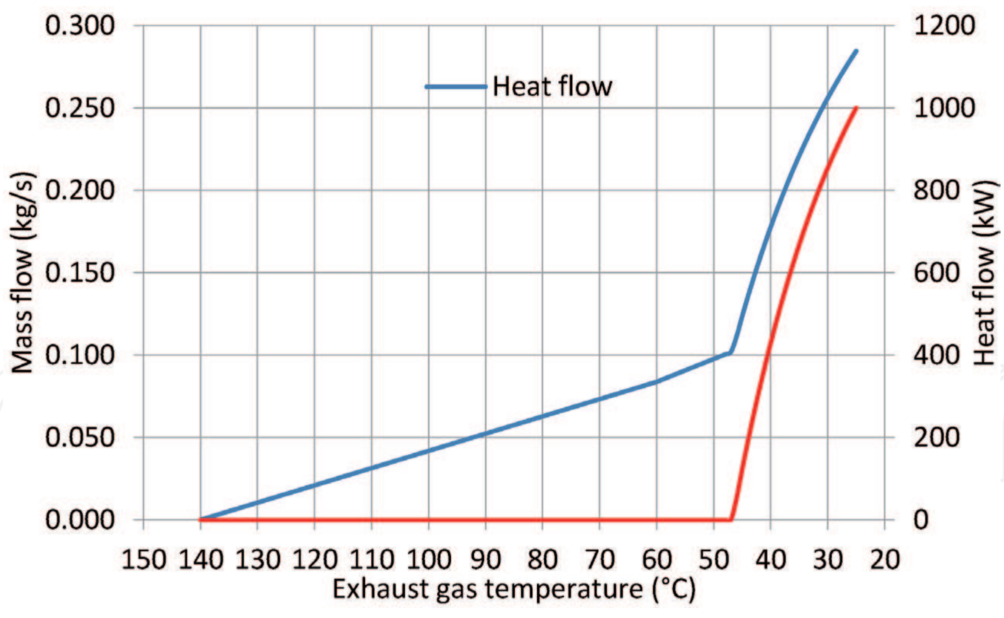

Figure 2.
The obtained low-temperature heat flow with an additional cooling of the flue gasses from the CHP gas engine [9].

In order to use the low temperature heat of the exhaust gas with a temperature of 120°C, it is necessary to install the condenser heat exchanger HE2 (**Figure 1**) in the exhaust system of the gas engine, where the exhaust gases should be cooled down to a temperature of 25°C. For this purpose, a computer simulation of the cooling of the exhaust gases was carried out using the Aspen plus software, the results of which are shown in **Figure 2** [9].

The heat flux obtained with additional cooling of the flue gasses from the CHP unit is presented on **Figure 2**. the specifications of which are shown in **Table 3**, where the flue gasses are first cooled from a temperature of 120°C to a temperature of 46°C, at which the water from the flue gasses starts to condense in the condenser heat exchanger HE2 (**Figure 1**). **Figure 2** shows the mass flow of condensed water from the flue gas as a function of the temperatures of the flue gasses.

The diagrams in **Figure 2** show that the CHP exhaust gas are first cooled from a temperature of 120°C to a temperature of 46°C, yielding approximately 400 kW of heat. However, further cooling of the exhaust gases causes condensation of water vapor, which is present in the exhaust gases. Most of the heat, about 700 kW, is obtained by cooling the exhaust gases from 46–25°C, producing about 0.250 kg/s of condensate.

By further cooling the exhaust gases of the CHP gas engine to about 5°C, an additional 600 kW of heat could be obtained. By exploiting the heat released from the surface of the CHP gas engine and heating the air in the room where the CHP device is installed, an additional 202 kW of heat could be obtained. This means that by further cooling the exhaust gases from 25–5°C and utilizing the heat released from the external surfaces of the CHP unit, approximately 800 kW of low-temperature heat could be extracted, which could be utilized by a high-temperature heat pump and thus further increase the primary fuel efficiency of the CHP gas engine to about 117% relative to the LHV of natural gas. The temperature to which the flue gases would be cooled depends on the economics of operation of high-temperature heat pumps, because as the temperature of the low-temperature source decreases, the average COP of the heat pumps decreases rapidly. By lowering the evaporation temperature of the refrigerant in the evaporator of the high-temperature heat pump, the pressure ratio of the compressor increases, so more power is required for the electric motor drive of the compressor, which results in a lower COP.

3.2 High-temperature heat pump

High-temperature heat pumps have a high added value and contribute a lot to energy dependence reduction. They can be used in all industries where waste heat flows of different fluids are generated. They allow an economically and ecologically efficient use of low-temperature resources to improve specific energy use in processes, increase efficiency and consequently reduce CO_2 emissions through the reduced consumption of fossil fuels for heat generation. The high-temperature heat pump has created the possibility of using heat from renewable or non-renewable low-temperature energy sources to meet the needs of technological processes or high-temperature heating systems.

Heat pumps have been around for many years, about as long as refrigeration units. The rapid development of heat pumps was triggered by the first oil crisis. People then began an intensive search for a replacement for fossil fuels and corresponding technological solutions. Laws related to pollution became stricter, people became aware of pollution and its effects, and energy prices increased. Heat pumps became popular due to their energy efficiency and environmental friendliness. In most of the cases, heat pumps were used for cooling purposes, while they were used for heating buildings only in case of low temperature heating up to 60°C. With the high temperature heat pump, low temperature heat sources up to 55°C can be used so that the heat potential is used to produce hot water up to 85°C [10]. This heat can be used for heating buildings or in industrial processes, and simultaneously cold water can be produced (down to 10°C), for air conditioning needs [11, 12].

The single-stage high temperature heat pump operation is based on the deprivation of heat from a low-temperature fluid (water) to get it to a higher temperature level.

For high-temperature heat pumps different low-temperature heat sources can be used:

- geothermal water with temperature around 55°C,
- the flue gasses heat,
- low-temperature energy sources from industry,
- waste heat of cooling systems, such as cold-storage chambers, meat processing industry,
- sea water heat, heat of lakes, groundwater, rivers, etc.

High-temperature heat pump efficiency is determined by a heating number, which is the ratio between the heat flow generated in the condenser for heating requirements and the electricity consumed to drive the compressor. The evaporator heat flow indicates how much heat was generated from the low temperature energy source and the condenser heat flow indicates how much heat was generated for heating purposes. The determination of the power required to drive the compressor allows the determination of the power consumption for the compression of the refrigerant, which is a substance with special physical properties [13]. The use of the high temperature heat pump allows:

- Use of low temperature heat sources in an area where the infrastructure for high temperature heating already exists,

- improve energy efficiency,
- replacement of the obsolete technology with the new one, which offers much higher efficiency and more environmentally friendly energy production,
- Reducing the emission factor (CO2/kWh), thereby reducing greenhouse gas emissions, and
- rease in heat production rates and a quick return on investment.

The operating characteristics of the 500-kW high-temperature heat pump as a function of the speed of a compressor, the required temperature of the output water, and the water temperature of a low-temperature source are given in **Figures 3** and **4** [10]. The results are given for different operating conditions using the working fluid R717 (NH3) and the commercial 50-bar piston compressor for the hot water temperatures from 65 to 85°C. Other refrigerants were found to be less suitable due to lower enthalpy difference between vapor and liquid

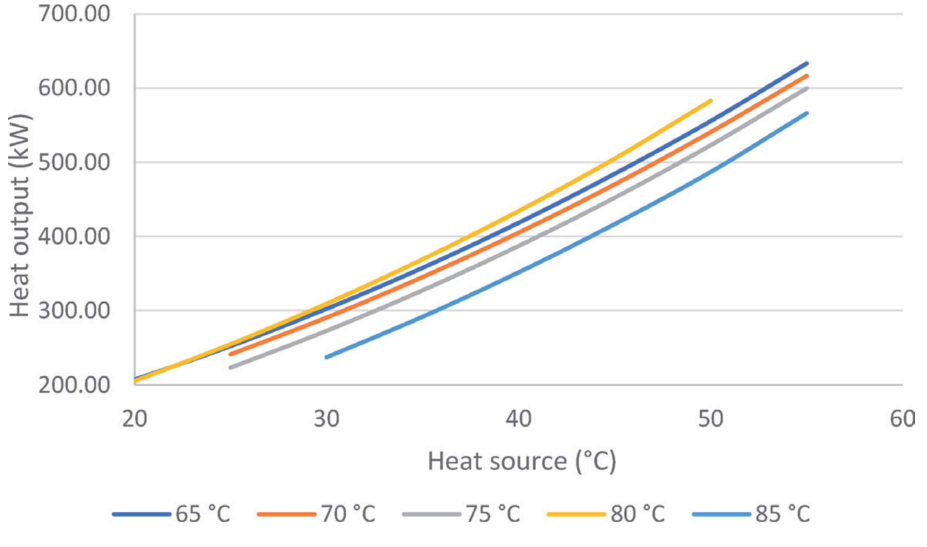

Figure 3.
The heat output in dependence of source inflow temperature for different temperatures of hot water.

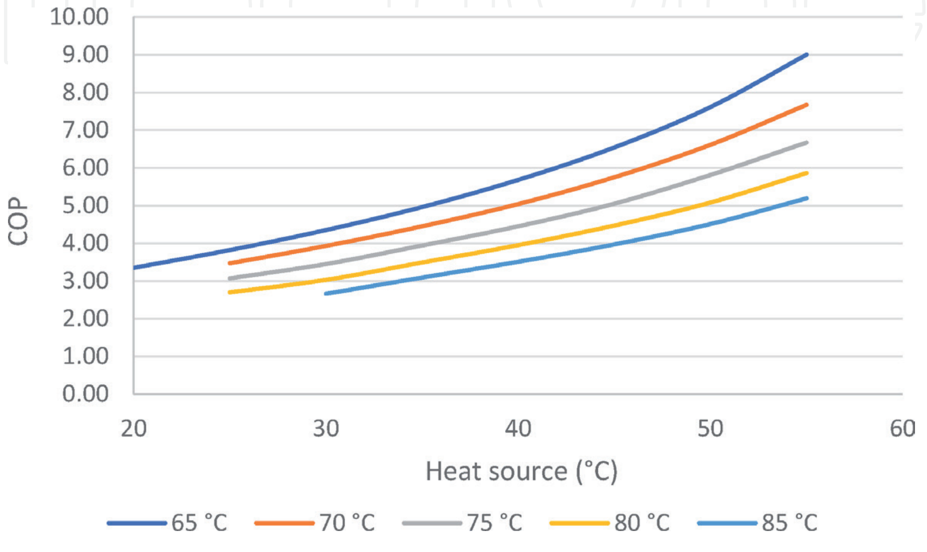

Figure 4.
The COP in dependence of source inflow temperature for different temperatures of hot water.

phases, lower heat flux, and lower COP. The capacity of the compressor in the HTHP can be controlled in steps (970; 1,450; and 1,600 rpm) or by a stepless control of the electric motor driving the compressor.

4. Process simulation with AspenPlus software package

In order to be able to use the energy of the exhaust gasses at a temperature of 120°C, a retrofit in the form of an additional heat exchanger (HE2) in the exhaust gas system is required, which would cool the exhaust gasses to 25°C. In this way, 1,100 kW of heat could be recovered. The second low temperature heat source is the cooling system 2nd stage intercooler (HE3) where 197 kW of heat could be recovered. The temperature of both low-temperature heat sources is too low to be used directly for high-temperature heating, but can still be used by using the HTHP, which raises the temperature level to a level suitable for high-temperature heating. A high temperature heat pump (or several of them) is integrated into the CHP system, as shown in **Figure 1**, to use the low temperature heat exchangers HE2 in HE3. The heat flow recovered from the high temperature heat pump is used to reheat the water return to a temperature of 70°C. In case the return water temperature is too high, the heated water is sent directly to the supply line through valve V1 - **Figure 1**. The total low-temperature heat flow obtained by the CHP unit with a nominal capacity of 3.3 MW with heat exchangers HE2 and HE3 is approximately 1,297 kW. To utilize the 1,297 kW from the low-temperature heat source by heating the return water from the high-temperature heating system from 60–70°C, which is the maximum water temperature allowed to enter the CHP unit, would require four high-temperature heat pumps with a rated capacity of 500 kW. The low-temperature energy source of HE2 and HE3 is utilized with the circulation of a glycol-water mixture, to which four high-temperature heat pumps are connected in sequence.

To utilize the excess low-temperature heat from the CHP gas engine, whose operating data are given in **Table 3**, a computer simulation of four series-connected high-temperature heat pumps with a rated capacity of 500 kW was performed using the Aspen Plus software package. The operating data of a 500 kW high temperature heat pump at a compressor speed of 1450 rpm are given in **Table 3**. Heat generation with a 500 kW high temperature heat pump can be modified with a frequency controlled electric motor drive of a reciprocating compressor with a maximum permissible speed of 1600 rpm.

Figure 5 schematically shows the serial connection of four high-temperature heat pumps with some results of computer simulation. Four series-connected high-temperature heat pumps consist of four compressors (COMP1, COMP2, COMP3, COMP4), four refrigerant evaporators (EVAP1, EVAP2, EVAP3, EVAP4), four condensers (COND1, COND2, COND3, EXP3) and four expansion valves (VALVE1, VALVE2, VALVE3, VALVE4). The low-temperature heat source of four series-connected high-temperature heat pumps is water or a mixture of water and glycol heated in a heat exchanger (HE2 and HE3), shown in **Figure 1**.

Water or a mixture of water and glycol, first heated slightly to 50°C in a heat exchanger HE2 and HE3 and fed through line P9 and P14 shown in **Figure 1** and **Figure 5** successively through all four evaporators (EVAP1, EVAP2, EVAP3, EVAP4). Chilled water or a mixture of water and glycol at about 23°C leaving the EVAP 4 evaporator is returned to the heat exchanger HE2 and HE3 via line P8 and P15. In each of the four evaporators of high-temperature heat pumps, the evaporation pressure of the refrigerant (ammonia) is different because it depends on the temperature and the available heat flow obtained in each individual evaporator. Refrigerant vapors leaving the evaporators are compressed by compressors

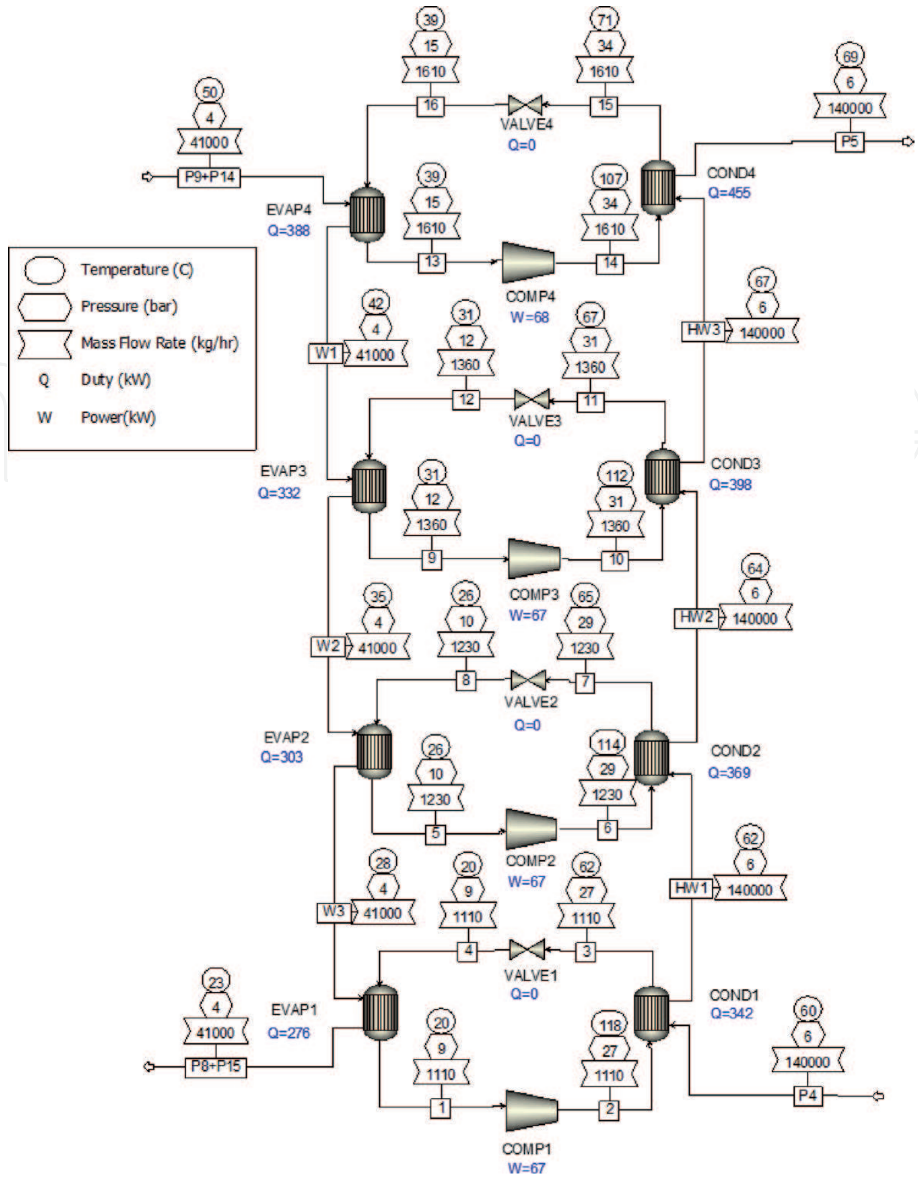

Figure 5.
The scene of four series-connected high-temperature heat pumps with the results of computer simulation using the Aspen plus software package.

(COMP1, COMP2, COMP3, COMP4) to the pressure required to condense the refrigerant in series-connected condensers (COND1, COND2, COND3, COND4) when heating the district heating return water.

The return water of the district heating system is fed to the first condenser via pipe P4, as shown in **Figures 1** and **5**, and leads sequentially to each individual condenser of the high-temperature heat pump. In each condenser, the heating water heats up a little until the desired temperature is reached in the last condenser. The water of the district heating system heated in this way is then fed to the CHP gas engine via pipe P5, in which it is heated to the final temperature of the district heating system.

To compare the operating characteristics of the system of four series-connected high-temperature heat pumps for the exploitation of low-temperature CHP gas engine heat sources, a computer simulation of one high-temperature heat pump with the same operating characteristics as four parallel-connected 500 kW high-temperature heat pumps is made.

Figure 6 shows a diagram of one high-temperature heat pump consisting of a single compressor (COMP), a refrigerant evaporator (EVAP), a condenser (COND) and an expansion valve (VALVE). The low temperature heat source of a high

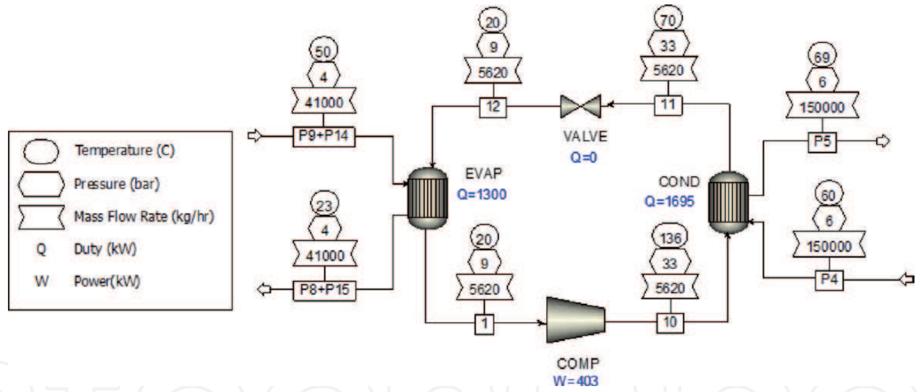

Figure 6.
Schematic diagram of a high-temperature heat pump with the results of a computer simulation using the Aspen plus software package.

temperature heat pump is water, or a mixture of water and glycol heated in the heat exchanger HE2 and HE3 shown in **Figure 1**. The water or mixture of water and glycol is heated to about 50°C and through line P9 and P14 shown in **Figures 1** and **6**, is fed to a high temperature heat pump evaporator (EVAP), where it is cooled to about 23°C and returned to the heat exchanger HE2 and HE3.

Refrigerant vapors leaving the evaporator (EVAP) are compressed in the compressor (COMP) to the pressure required to condense the refrigerant in the condenser (COND) when heating the return water of the district heating system. In the condenser, the return water of the district heating system is heated to the desired temperature and then returned to the CHP gas engine via pipe P5, where it is heated to the final temperature.

A summary of the results of the computer simulation of the four high-temperature heat pumps connected in series in **Figure 5** is shown in **Table 1**. The computer simulation results presented in **Table 1** show that the average COP of all four high temperature heat pumps is 5.81. To drive the frequency-controlled electric motor drives of the compressors in all four high-temperature heat pumps, 269 kW of electricity would be required. By lowering the temperature of a low-temperature heat source, the COP and the output of the series-connected high-temperature heat pumps also decrease. The COP of high-temperature heat pumps also decreases as the district heating return heating water increases. The calculation was made by heating the heating return water from a temperature of 60°C to a temperature of 70°C in series-connected condensers of four high-temperature heat pumps.

A summary of the results of the computer simulation of a high temperature heat pump in **Figure 6** is shown in **Table 2**. The results of the computer simulation in

HTHP sequence number	Required power compressor (kW)	Compressor pressure ratio (Pa)	Evaporator heat flux (kW)	Condenser heat flux (kW)	COP
1	67	3.00	276	342	5.10
2	67	2.90	303	369	5.51
3	67	2.58	332	398	5.94
4	68	2.27	388	455	6.69
In total	269		1,299	1,564	5.81

Table 1.
*Summary of the results of the computer simulation of the four series connection of high-temperature heat pumps from **Figure 5**.*

HTHP sequence number	Required power compressor (kW)	Compressor pressure ratio (Pa)	Evaporator heat flux (kW)	Condenser heat flux (kW)	COP
1	403	3.67	1,300	1,695	4.21

Table 2.
Summary of the results of the computer simulation of the single high-temperature heat pump from ***Figure 6****.*

Table 2 show that the average COP value of a high temperature heat pump is 4.21, which is much less than four serial connected high temperature heat pumps. The reason for this is that it is necessary to overcome the greater temperature difference between the outlet temperature of the low temperature heat source and the desired temperature of the heating water return of the heating system with a high temperature heat pump. To drive the frequency-controlled electric motor drive of a

	CHP	CHP + HTHP	
Natural gas LHV	9.5	9.5	kWh/Nm^3
Energy input (LHV)	7,351	7,351	kW
Mechanical output	3,428	3,428	kW
Electrical output	3,349	3,349	kW_e
Recoverable thermal output:			
• Intercooler 1st stage	883	883	kW_{th}
• Lube oil	290	290	kW_{th}
• Jacket water	463	463	kW_{th}
Exhaust gas cooled to 120°C	1,399	1,399	kW_{th}
Total directly recoverable thermal output (90°C)	3,035	3,035	kW_{th}
Heat to be dissipated:			
• Intercooler 2nd stage	197		kW_{th}
• Surface heat	202	202	kW_{th}
Exploited low temperature available heat:			
• Additional flue gas cooling to 25°C		1,100	kW_{th}
• Intercooler 2nd stage		197	kW_{th}
Total exploited low temperature thermal output		1,297	kW_{th}
Heat generated with HTHP (70°C)		1,564	kW_{th}
Absorbed power HTHP		269	kW_e
Total exploited thermal output		4,332	kW_{th}
Total thermal output CHP + HTHP		4,599	$kW_{th\ total}$
Total energy output generated	6,384	7,679	kW_{total}
Net electrical output	3,349	3,080	kW_e
Electrical efficiency	45.6	41.9	%
Thermal efficiency	41.3	62.5	%
Total efficiency CHP + HTHP	86.8	104.4	%

Table 3.
Technical data for CHP device [6] rated power 3.3 MW and technical data for CHP device rated power 3.3 MW with series-installed high-temperature heat pumps [7].

compressor of a high-temperature heat pump, a higher electrical power (403 kW) is therefore required, since a higher-pressure ratio between the evaporator pressure in the evaporator and the condensing pressure in the condenser must be created.

The energy consumption efficiency of natural gas and the utilization of excess low-temperature heat of a CHP gas engine with four series-connected high-temperature heat pumps are given in **Table 3**.

Electricity is needed to drive the frequency-controlled electric motors of the high-pressure compressors of high-temperature heat pumps. The electricity can be drawn from the grid or electricity from a gas engine with combined heat and power generation can be used. In **Table 3**, we have used 269 kW of electricity generated by a CHP unit to drive four high-temperature heat pumps connected in series, so that the electrical efficiency of the CHP fell from 45.6% to 41.9%. The total heat produced by the CHP and the four CHP units to use the excess low temperature heat from the CHP gas engine increased from 41.3% to 62.5%. The overall energy efficiency of the primary fuel of the CHP was increased by 17.6%, from 86.8% to 104.4%.

5. Economics of excess heat recovery of CHP gas engines

The economics of the exploitation of low-temperature heat sources from a selected CHP gas engine with the four HTHP, was calculated in MS Excel. For the HTHP drive, instead of the electricity produced by the CHP device, we can use electricity from the electricity grid.

The price of electricity, when we take it from the grid, is made up of production costs, transport costs, distribution costs, nominal power, various taxes, etc. and averages 95.2 €/MWh. The price of electricity produced in combined heat and power generation and sold on the electricity market averages 43.5 € /MWh. For the

Data on heat production		
Average COP four HTHP	5.81	
Average operation power four HTHP	78.2%	
Rated power of HTHP	4 x 500	kW_{th}
Average heat flow four HTHP	1,564	kW_{th}
Working hours per year	4,000	h/a
Yearly production of heat with four HTHP	6,256	MWh/a
Electricity consumption of four HTHP	269	kW_e
Specific electricity consumption of HTHP	0.172	kWh_e/kWh_{th}
Energy price		
Price of heat	0.0480	EUR/kWh
Price of electricity	0.0435 / 0.0952	EUR/kWh
Price of produced heat with HTHP	0.0075 / 0.0164	EUR/kWh
Economic data		
Investment into HTHP system	720,000	EUR
Discount rate	2.0	%

Table 4.
Basic operating data of the high-temperature heat pump (HTHP), energy prices and other economic data.

economic calculation of the surplus heat recovery of CHP gas engines with HTHP, electricity prices vary from country to country.

Two calculations have been made:

- with electricity to power the compressor in the high-temperature heat pump taken from the grid (95.2 €/MWh) and

- with electricity produced by the CHP unit (43.5 €/MWh).

Basic technical and economic data are given in **Table 4**. The average price of heat was defined as the production price of heat produced from natural gas with CHP device and gas boilers district heating system.

The economic calculation of the exploitation of low-temperature heat sources from a CHP plant with the HTHP using electricity from a CHP plant (43.5€/MWh) is shown as a diagram in **Figure 7**.

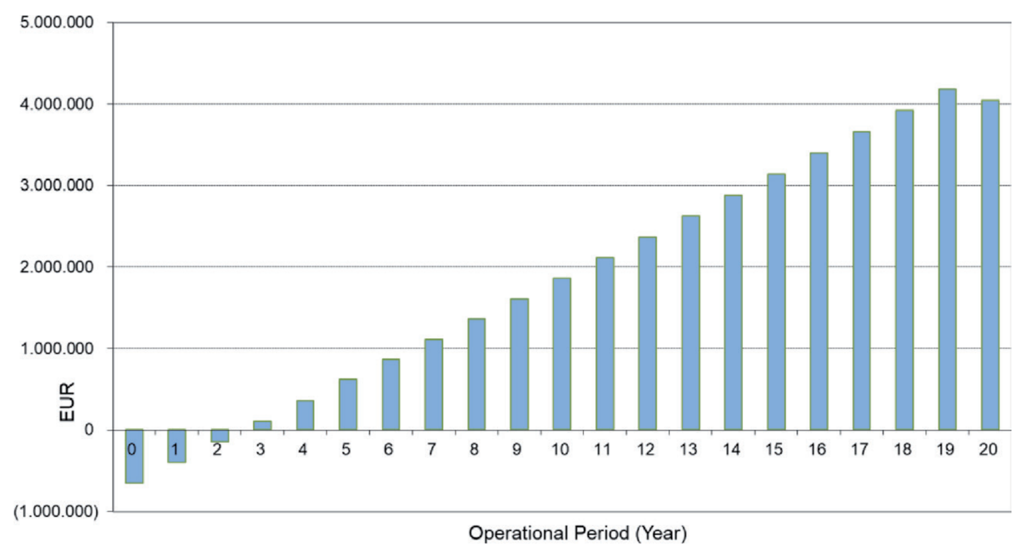

Figure 7.
Cumulated discounted cash flow at the price of the electricity at 43.5 €/MWh.

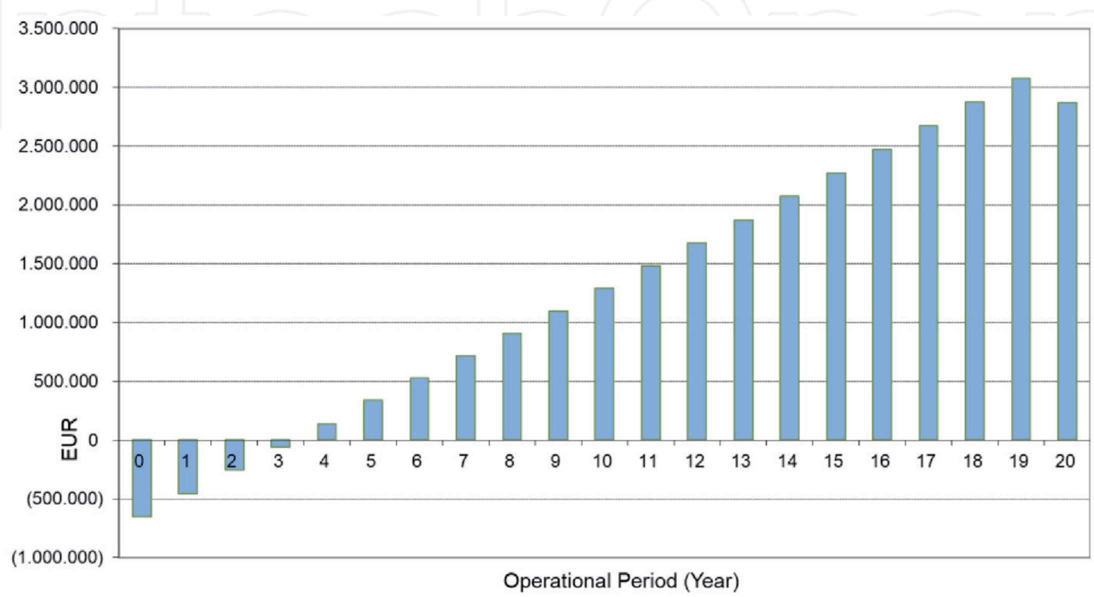

Figure 8.
Cumulated discounted cash flow at the price of the electricity at 95.2 €/MWh.

The diagram in **Figure 7** shows the internal rate of return IRR = 39.4% and payback of the investment exploiting excess heat from CHP device with four series-connected high-temperature heat pumps is approximately 2.5 years.

The economic calculation of the exploitation of low temperature heat sources from the CHP device with four series-connected high-temperature heat pumps with the electricity taken from the grid (95.2 €/MWh) is shown as a diagram in **Figure 8**.

The diagram in **Figure 8** shows the internal rate of return IRR = 30.5% and payback of the investment exploiting excess heat from CHP device with four series-connected high-temperature heat pumps is approximately 3.3 years.

6. Conclusions

An innovative technical solution for increasing the efficiency of the primary fuel and thus reducing CO_2 emissions by retrofitting existing or new CHP gas engines with high-temperature heat pumps is presented. High-temperature heat pumps use the excess heat of the exhaust gasses and the heat of the cooling system of the CHP gas engine and heat the return water of the district heating system.

The described principle of using the excess heat of CHP gas engines can also be used for the use of low-temperature heat sources, including hot water boilers and other types of CHP equipment.

In order to use the excess heat of the exhaust gasses and the cooling system of the CHP gas engine, it is necessary to install a heat exchanger in the exhaust system, where they are further cooled by cooling and condensation of the water contained in the exhaust gasses. The heat generated in this way is too low to be used directly for high-temperature heating, but it can also be used to heat the return water of the district heating system by using high-temperature heat pumps.

To illustrate how the innovative technology of using low-temperature sources of CHP gas engines works, a computer simulation of four series-connected high-temperature heat pumps was carried out using the Aspen plus software package. With a system of series-connected high-temperature heat pumps, the overall efficiency of natural gas can be increased by 17.6% (from 86.8% to 104.4% in terms of LHV of natural gas) by using low-temperature heat sources of CHP gas engine. An increase of 17.6% in the primary energy efficiency of the natural gas CHP gas engine is achieved when the exhaust gasses from the gas engine are cooled to a temperature of 25°C.

The energetic efficiency of the primary fuel of the CHP gas engine can be significantly increased to approx. 117% in relation to the LHV of natural gas by additional cooling of the exhaust gasses (up to approx. 5°C) and utilization of the heat emitted from the surface of the CHP gas engine to the environment. The temperature to which the exhaust gasses would be cooled depends on the economic efficiency of the operation of high-temperature heat pumps, because when the temperature of a low-temperature source drops, the average COP of heat pumps drops rapidly.

The presented technical solution for increasing the primary fuel efficiency of the CHP gas engine by using the excess heat of the exhaust gasses and the cooling system of the gas engine is also very economical with a very short return on investment.

During the computer simulation of the presented technical solutions for increasing the efficiency of the primary fuel of the CHP gas engine using high temperature heat pumps, the operating parameters of the manufacturer of the CHP gas engine and the high temperature heat pump were taken into account.

Author details

Darko Goričanec and Danijela Urbancl*
Faculty of Chemistry and Chemical Engineering, University of Maribor, Maribor, Slovenia

*Address all correspondence to: danijela.urbancl@um.si

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