Energy and economic analysis of flue gas heat recovery systems improving the energy efficiency of gas cogeneration units

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Abstract. This paper presents the results of energy and economic analyses of a gas-fired CHP plant. The analyses were carried out for three variants of technical solutions to improve the thermal efficiency of the CHP plant. The fuel combustion process involves the generation of a large amount of heat. In addition, the heat is dissipated to the surroundings through the exhaust gas with a high temperature of 300÷350 °C. Therefore, to limit heat loss, a heat recovery system is used, which removes heat from the engine body and from the hot exhaust gases through a heat exchanger, allowing the exhaust gases to be cooled to a temperature of 100÷120 °C. In addition, heat is recovered from the oil cooling process and intercoolers. The recovered heat is usually supplied to the heating water in the district heating network. For the calculations, the temperature distribution of the return water from the district heating network during the year was assumed. First, the benefits of adding an additional economizer to pre-heat district heating water were analysed, Next, a heat recovery system was simulated to cool the flue gases to lower temperatures using an absorption heat pump or a compressor heat pump.

1 Introduction

In recent years, interest in energy recovery systems has increased significantly due to the changes in the energy market caused by increased fuel prices and CO_2 emission allowances prices. Using heat recovery systems is one way to improve the energy efficiency of combined heat and power plants (CHP plants). Nowadays, cogeneration units with gas engines are the most popular way to reduce heat production from coal-fired CHP plants. Research carried out worldwide mainly concerns issues related to improving heat recovery systems.

The primary solution for heat recovery systems from exhaust gases is to use economizers to heat water. The amount of heat mainly recovered depends on the temperature of the cooling water at the inlet to the installation. The research in [1] presents the possibility of using heat from flue gases from coal-fired boilers as an alternative to standard regenerative heating using steam from the turbine vent. The work [2] describes the

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benefits of using scrubbers for heat recovery, and the optimization of the installation parameters and geometric dimensions was performed.

Due to the high temperatures of water returning from district heating networks, it is impossible to recover a significant amount of heat contained in the exhaust gases. Therefore, current research towards increasing heat generation efficiency focuses on using low-temperature heat networks equipped with absorption heat pumps. The articles [3], [4], [5], [6] present balance models of sample exhaust heat recovery systems using heat pumps. Another solution most commonly found in the literature [7], [8] is the preheating and humidification of the air supplied to the combustion process. This solution reduces fuel consumption by heat sources and increases the dew point temperature.

This article presents the results of technical, economic and ecological research on heat recovery systems for gas-fired cogeneration units. The proposed solutions allow for the reduction of energy demand by increasing the efficiency of the CHP plant, reducing CO_2 emissions, and increasing economic profits. The analyses were prepared based on cogeneration units often used in combined heat and power plants.

2 Technical description of the gas cogeneration units

The CHP unit mainly consists of a gas engine (GE), a power generator (G) and an engine heat recovery system. High-methane natural gas is fed into the spark-ignition reciprocating engine, which burns it in the cylinders. CHP engines can also be fuelled with lower calorific value fuels, such as biogas or gas from demethaning mines. The air required for the combustion process is supplied to the engine via a turbocharger. Table 1 shows the most essential nominal technical parameters for reciprocating engine CHP units.

Table 1. Nominal parameters of the analysed gas engine.

Parameter	Gas Engine	Unit
Gross electrical output	4.4	MWe
Heat output	4.2	MWt
Thermal power delivered in fuel	9.6	MWt
Electrical net efficiency	45.6	%
Thermal net efficiency	42.4	%
Total net efficiency	87.3	%
Hot flue gas temperature	340	°C
Cooled flue gas temperature	120	°C
Flue gas mass flow rate	6.9	kg/sec

The fuel combustion process involves the generation of a large amount of heat. Almost half of the energy generated is converted into mechanical energy. The heat generated causes the engine body to heat up and then disperse this heat to the environment through convection and radiation. In addition, the heat is dissipated to the surroundings through the exhaust gas with a high temperature of $300 \div 350^{\circ}C$. Therefore, to limit heat loss, a heat recovery system is used, which removes heat from the engine body and from the hot exhaust gases through a heat exchanger, allowing the exhaust gases to be cooled to a temperature of $100 \div 120\ ^{\circ}C$. In addition, heat is recovered from the oil cooling process and intercoolers. The recovered heat is usually supplied to the heating water in the district heating network.

Energy-economic analyses of the proposed additional heat recovery from CHP units were carried out for three options:

- installation of an additional flue gas heat exchanger;
- installation of an additional flue gas heat exchanger to preheat the electrical heat pump feed medium;

- installation of an additional flue gas heat exchanger to heat the absorption heat pump medium.

2.1 Proposed heat recovery system with additional exhaust gases heat exchanger

A primary solution to increase the efficiency of gas-fired CHP units is installing an additional heat recovery from flue gas. This makes it possible to reduce the temperature of the flue gas discharged into the chimney.

Figure 1 shows a process diagram of a CHP unit with additional flue gas heat recovery.

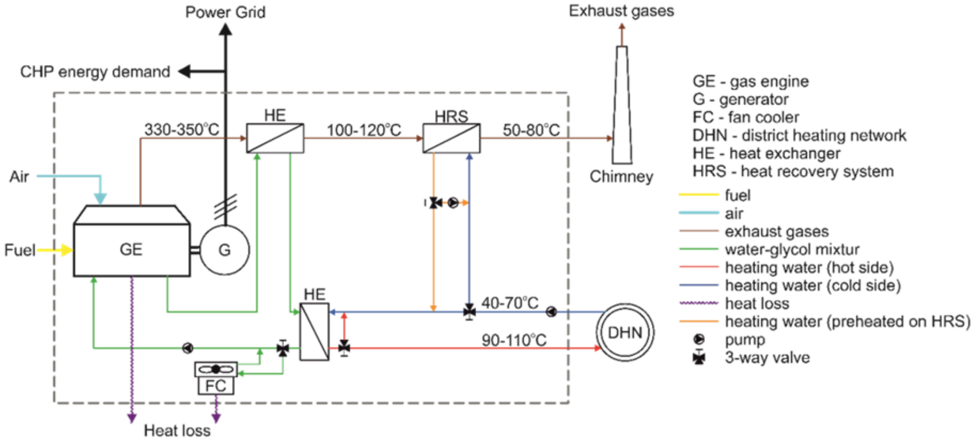

Fig. 1. Simplified process diagram of a gas-fired cogeneration unit with additional HRS.

2.2 Proposed heat recovery system with compressor heat pump

The compressor heat pump uses electrical energy to transform heat from lower parameters to higher parameters. Using an additional low-temperature circuit to cool the flue gas makes it possible to reduce the temperature of the flue gas at the inlet to the chimney even below the dew point. This solution improves the CHP unit's efficiency and the CHP network's performance. Figure 2 shows a simplified process diagram of a CHP unit with additional flue gas heat recovery and a compressor heat pump.

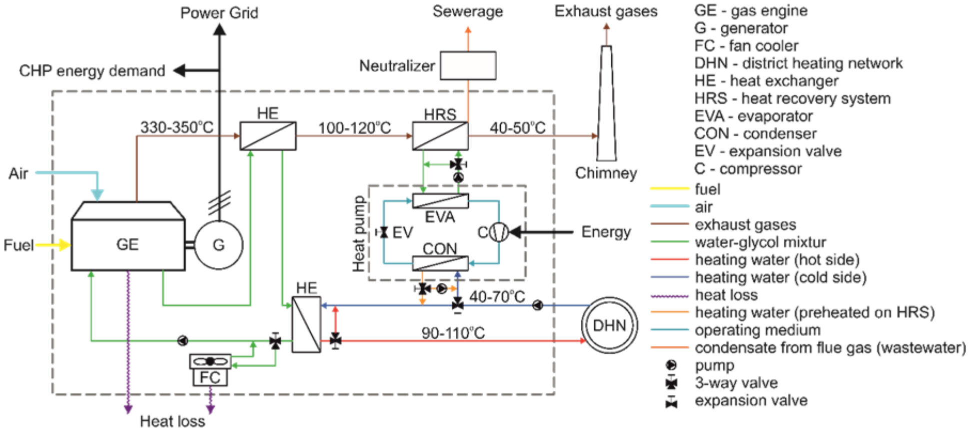

Fig. 2. Simplified process diagram of a gas-fired cogeneration unit with compressor heat pump.

2.3 Proposed heat recovery system with absorption heat pump

An absorption heat pump uses a thermal compressor to transform heat from lower parameters to higher parameters. An additional low-temperature circuit is also used to cool the flue gases below the dew point temperature. The proposed solution is based on burning more fuel to supply heat to the thermal compressor. Figure 3 shows a simplified process diagram of a cogeneration unit with additional flue gas heat recovery and an absorption heat pump.

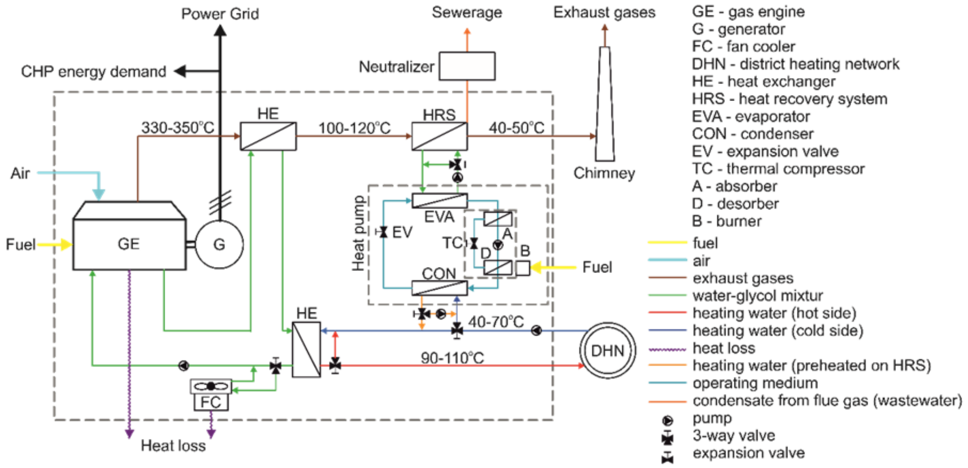

Fig. 3. Simplified process diagram of a gas-fired cogeneration unit with absorption heat pump.

3 Determination of the energy balance

The following relationship was used to determine the exhaust gas enthalpy at the inlet and outlet of the heat recovery system

$$Mh_{fg} = \sum[\mathrm{i}] \cdot Mh_{i\,T_n}^{\;T_{fg}}, \tag{1}$$

where Mh_{fg} – flue gas molar enthalpy at given temperature T_{fg}, kJ/kmol, $Mh_{i\,T_n}^{\;T_{fg}}$ – molar enthalpy of ith substance in the flue gas at a given temperature T_{fg}, kJ/kmol.

The thermal power recovered from the flue gases was determined as the sum of the sensible heat due to the reduction of the flue gas temperature and the latent heat from the condensation process:

$$\dot{Q} = \dot{n}_{wfg} \cdot (Mh_{inlet} - Mh_{outlet}) + \dot{n}_{cond} \cdot Mr, \tag{2}$$

where $\dot{Q}$ – thermal power and Mr - molar condensation heat.

In the case of the installation of an economiser cooled directly by water from the district heating system, the additional heat supplied to the district heating system can be determined from the formula

$$\Delta\dot{Q}_{eco} = \dot{Q}, \tag{3}$$

where $\Delta\dot{Q}_{eco}$– additional heat production for solution with economizer, W.

For heat pump solutions, the amount of additional heat released to the district heating network can be determined according to the following relationship

$$\Delta\dot{Q}_{HP} = \dot{Q}\cdot\frac{COP}{COP-1}, \tag{4}$$

where $\Delta\dot{Q}_{HP}$ – additional heat production for solution with heat pumps, W.

The following table summarises the heat output of the flue gas heat exchanger analysed and the nominal heat output of the heat pump.

Table 2. Thermal output of combustion heat exchanger and heat pump.

Variant	**Gas Engine**	**Unit**
Additional economizer $\Delta\dot{Q}_{eco}$	370	kW
Additional economizer for heat pump solutions $\dot{Q}$	837	kW
Compressor heat pump $\Delta\dot{Q}_{HP}$	1,046	kW
Gas-fired absorption heat pump $\Delta\dot{Q}_{HP}$	2,145	kW

Table 3 summarises the annual heat balance of the heat recovery system form flue gas with the amount of heat removed from the flue gas and the amount of additional heat produced.

Table 3. The additional heat recovered from flue gas and additional heat production.

Variant	**Gas Engine**	**Unit**
Additional economizer	3,035	MWh/a
Additional economizer for heat pump solutions	6,670	MWh/a
Compressor heat pump	8,337	MWh/a
Gas-fired absorption heat pump	17,091	MWh/a

Table 4 summarises the estimated increase in heat production and overall efficiency relative to a basic gas engine CHP unit.

Table 4. Heat production and total power generation net efficiency for the proposed gas engine CHP units.

Parameter	**Economizer**	**Compressor heat pump**	**Gas-fired absoprtion heat pump**	**Unit**
	33,878	33,878	33,878	MWh/a
The primary energy production	36,495	36,495	36,495	MWh/a
The primary fuel demand	79,959	79,959	79,959	MWh/a
The primary energy demand	581	581	581	MWh/a
The additional heat production	3,035	8,337	17,091	MWh/a
The additional energy demand	8	1,685	181	MWh/a
The additional fuel demand	0	0	10,688	MWh/a
The total operating net efficiency	91.8	96.3	96.3	%
The growth rate of heat production	9.0	24.6	50.4	%

4 Economic analysis of the heat recovery system

The economic analysis included estimated capital expenditures, operating profits and operating costs. The analysis was carried out for a period of 15 years of operation of the gas cogeneration unit. Cash flow expressed in the following equation

$$CF_t = OPRO - OPEX - CAPEX, \tag{5}$$

where: CF_t – cash flow, €; $OPRO$ – operating profits, €; $OPEX$ – operating expenditures, €; $CAPEX$ – capital expenditures, €.

The operating costs mainly include reduced profits from increased electricity consumption, wastewater disposal costs and the cost of heating water to make up for losses in the district heating network. Revenues are the sum of profits resulting from heat production and treated condensate. Table 5 summarises the data from the cash flow analysis, which was used for further cost-effectiveness analysis.

Table 5. Heat production and total generation net efficiency.

Parameter	Economizer	Compressor heat pump	Gas-fired absorption heat pump	Unit
Capital expenditures (CAPEX)	130,000.00	2,160,000.00	840,000.00	
Operating profits (OPRO)	196,640.74	540,230.34	1,079,795.77	/a
Operating expenditures (OPEX)	1,053.61	334,754.91	853,837.07	/a

The profitability of the investment was determined using 4 basic parameters used in economic analysis, i.e.: net present value, internal rate of return, simple and discounted payback time. The Net Present Value (NPV) is used to determine the total profit or loss over a given period. A negative value of this indicator indicates that the project is unprofitable. The net present value is expressed by the following equation:

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+k)^t}, \tag{6}$$

If the value of the internal rate of return (IRR) is greater than the discount rate, then the investment is considered to be financially reasonable. The higher the value of the internal rate of return, the less risky the investment becomes. The internal rate of return is described by the following relationship:

$$IRR = \sum_{t=0}^{N} \frac{CF_t}{(1+k)^t} = 0, \tag{7}$$

The Simple Payback Time (SPBT) is the period before the present value of an investment reaches zero, i.e.: the sum of annual profits equals the sum of investment outlays. The Simple Payback Time does not take into account the change in the nominal value over the lifetime of the investment. In contrast, the discounted payback time (DPBT) makes it possible to take into account the loss or increase in the value of the denomination. The Simple Payback Time and the Discounted Payback Time are described respectively by the following equations:

$$\sum_{\mathrm{t=0}}^{\mathrm{SPBT}} CF_t = 0 \tag{8}$$

$$\sum_{\mathrm{t=0}}^{\mathrm{DPBT}} \frac{CF_t}{(1+r)^t} = 0 \tag{9}$$

Table 6 summarises the parameters used to analyse the cost-effectiveness of the investment.

Table 6. Increase in heat production and total generation net efficiency.

Parameter	Economizer	Economizer + compressor heat pump	Economizer + absorption heat pump	Unit
NPV	2,803,806.91	922,131.31	2,549,380.48	
IRR	150.5%	4.8%	26.1%	-
SPBT	0.7	10.5	3.7	years

The payback period of the investment ranges from approximately 8 months to 10.5 years. The value of the internal rate of return is almost three times the value of the discount rate. The net present value after 20 years of operation is approximately EUR 12 million.

5 Conclusion

This paper presents the results of energy and economic analyses of a gas-fired CHP plant. The analyses were carried out for three variants of technical solutions to improve the thermal efficiency of the CHP plant. The analyses showed a significant increase in heat production and efficiency compared to a solution without energy recovery systems. The results of the analysis indicate that the investment is highly cost-effective. The simple payback period for the completed investment ranges from a few months to about 10 years, depending on the solution, while the discounted cash flow after 20 years of operation was about 12 million euros. The use of a heat recovery system in CHP enables increased plant efficiency. The available solutions presented in this paper have measurable economic, energy and environmental benefits. The gas-fired absorption heat pump is the most energy-efficient of the possible solutions presented in the article. However, the cost-effectiveness of this solution is strongly dependent on market gas prices.

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