Design of Renewable Energy Production in District Heating System.

Martina Mudrá [a], *Ján* Takács [b]

[a] Faculty of Civil Engineering, Department of Building Services, Slovak University of Technology in Bratislava, Bratislava, Slovak Republic, email address: martina.mudra@stuba.sk

[b] Faculty of Civil Engineering, Department of Building Services, Slovak University of Technology in Bratislava, Bratislava, Slovak Republic, email address: jan.takacs@stuba.sk

Abstract. One way to decarbonise the heat supply in buildings by using environmentally friendly and highly energy-efficient equipment and technologies that save primary energy is through existing district heating systems (DHS´s) that supply several buildings at once. Many heat sources and equipment on the heat production and distribution side of these DHS´s are beyond their service life or use fossil fuels as an energy source. It is therefore necessary to modernize such systems through highly efficient and renewable energy sources (RES´s). As the Slovak Republic has a number of DHS´s, we have designed streamlining the existing heat source operation for the DHS of the West housing estate in the town of Brezno through a cogeneration unit (CU) and water - to - water heat pumps (HP´s). The existing heat source consists of three hot water boilers burning natural gas. In addition to the existing equipment, we designed a CU and HP´s, which would be used to prepare hot water. The flow of the heating heat transfer medium passes first through the HP´s and then through the CU. If the temperature of the working medium is not sufficient, the flow of heat transfer medium will also pass through the boilers. The operation of the CU and HP´s is designed in island mode, i. e. without external connection to the electricity grid. The proposal is based on real operational data provided to us by heat supplier for the period 2016 - 2018. We have assessed the proposal from the point of view of energy and economics. From the point of view of energy, we focused on energy consumption before the design of new equipment and the expected energy consumption after the design of new equipment. From the point of view of economics, we examined the return on investment. The aim of the proposal is to point out the importance of modernizing DHS´s, as they are an ideal place for the application of high-efficiency technological equipment and equipment using renewable energy.

Keywords. District heating system, cogeneration unit, heat pump, hot water.
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1. Introduction

The depletion of fossil fuels, climate change, and the consequences of human activity that result in rising levels of atmospheric CO_2 concentration force society to consider using alternative or renewable energy sources (RES´s) [1]. In buildings, more than 80% of energy is used in the form of heat, cold or electricity to ensure the comfort of their users through energy systems such as heating, ventilation and air conditioning, domestic hot water, and electrical installations [2]. Therefore, the European Union (EU) is issuing strategy papers aimed at increasing the use of renewable energy sources and reducing the energy intensity of heating, ventilation, and air conditioning systems [2].

Point 35 of Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency states that high-efficiency cogeneration and district heating offer significant potential for primary energy savings [3].

2. Operation of the Existing Heat Source

2.1 Description of the Site

Combined heat and power through a cogeneration unit (CU) and heat pumps (HP´s) will be designed for the West housing estate located in the town of Brezno, Slovakia. The existing hot water boiler plant is situated near the Hron River in the residential area of the Ladislav Novomeský District. The proximity of a watercourse creates preconditions for an excess of groundwater in the surrounding subsoil – a source of low-temperature energy. This energy will be transformed to a higher temperature level by water-to-water HP´s [4].

2.2 Condition of the Boiler Plant

During heating season, there is uninterrupted 24-hour operation. In summer, the boiler plant is in operation from 4:00 am to 11:00 pm. The heat transfer medium is hot water with the original design temperature gradient of 90/70 °C. The heat source is represented by three hot water boilers with a total output of 6.76 MW. A flue gas heat exchanger is installed after each of these boilers. Hot water preparation is realized through plate heat exchangers connected in series as pre-heating and water heating with the circulation of these exchangers leading to better cooling of the return water to the boilers [4].

Fig. 1 shows the interior view of the existing boiler plant.

Fig. 1 – Interior view of the existing boiler plant [4].

3. Design Model for the Application of New Devices

3.1 Operation of the New Heat Source

A CU and HP´s shall be installed instead of the existing heat source - hot water boilers. The energy source for driving the CU will be natural gas. The energy source for driving the HP´s will be the electricity produced by the CU. The CU and HP´s will be used to prepare hot water in an accumulative way. The storage tank will be located behind the CU and HP´s and, at a time when the demand for hot water consumption is reduced, the heated hot water will accumulate in it. The accumulated heat will be supplied to the grid at the time of increased demand. The essence of the design is ensuring a continuous operation of the equipment so that it works as long as possible and with a minimum of starts [4].

3.2 Power of the Cogeneration Unit and Heat Pumps

The average hourly heat demand for domestic hot water preparation in 2016 was 275 kW, in 2017 it was 280 kW, and in 2018 it was 267 kW. By comparing the data for the period 2016 - 2018, the heat output of the CU and two HP´s was set to 270 kW [4].

The CU and HP´s will be located in front of the boilers in the direction of the return heating water flow. The heat transfer medium - heating water has a temperature of 45 °C. The aim is to produce a heat-transfer working substance - heating water with a temperature of 60 °C. The temperature drop in the hot water system is therefore 60/45 °C, which means that the temperature difference ($\Delta\theta$) is 15 K. A very important parameter in the design of thermal outputs of the equipment is also the volume flow that will flow through the system. The volume flow that enters the system must be equal to the volume flow that leaves it. The volume flow at a heat output of 270 kW and a temperature difference of 15 K is 15.48 m^3/h [4].

The HP´s operate with a primary gradient of 5/1 °C - this means that a low-temperature heat source enters the HP´s (groundwater from wells) and is transformed in the HP´s to a higher temperature, transferred to the secondary heating system circuit. The underground water flow is high enough to supply the energy that is used. Return heating water with a temperature of 45 °C enters the HP and is heated up by 10 K, which means that the water temperature at the outlet of the HP will be 55 °C. This time the temperature difference ($\Delta\theta$) is known to be 10 K and the volume flow (M) through both HP´s is 15.48 m^3/h. The output of both HP´s was calculated to be 180 kW. It follows from the above that the heat output of the CU will be 90 kW [4].

The CU works with a temperature gradient ($\Delta\theta$) of 20 K as standard. This means that if water with a temperature of 55 °C enters the CU, the CU will heat the water to 75 °C at the outlet of the CU. We know determine the volume flow rate that the CU must take to reach 60 °C at the outlet of the unit and before entering the hot water storage tank. The volume flow through the CU to reach 60 °C at the outlet of the unit and before entering the hot water storage tank is 3.87 m^3/h [4].

For better controllability of the system, two identical two-stage water-water HP´s are proposed. Through a detailed recalculation, the design of two identical HP´s was determined, while the heat output of one was 89.6 kW [4].

Fig. 2 shows a schematic diagram of the CU and HP´s.

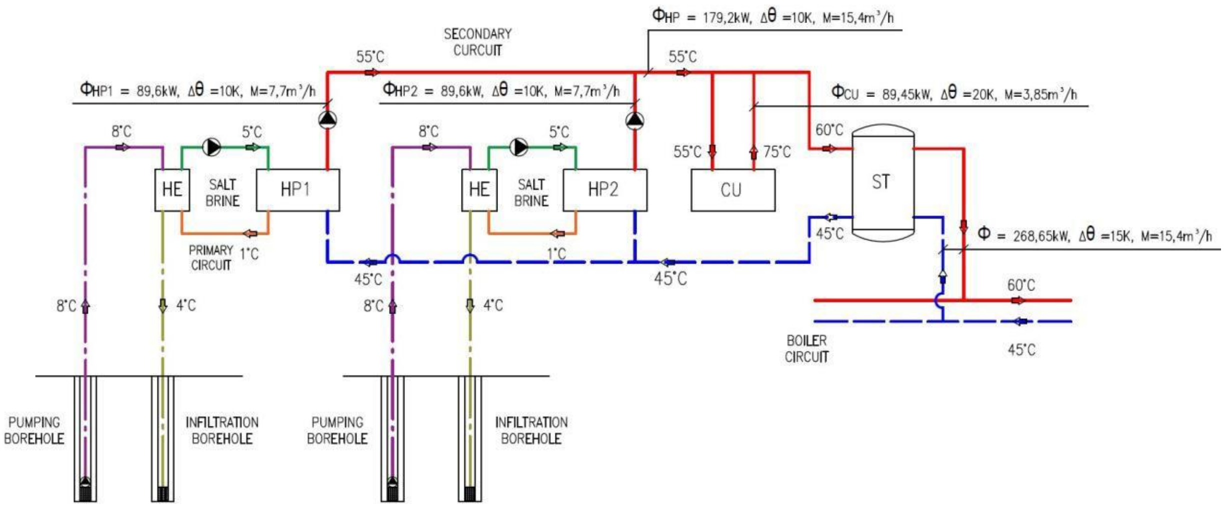

Fig. 2 - Schematic diagram of the cogeneration unit and heat pumps [4].
HE – heat exchanger, HP – heat pump, CU – cogeneration unit, ST – storage tank

4. Results – Energy Aspects

4.1 Natural Gas Consumption

To be able to assess the proposed design from an economic point of view, it is important to determine how much natural gas is saved by installing new technological equipment, a CU and HP´s, as compared to the original condition. The equipment was designed based on the operation and average energy consumption in 2016 - 2018. The average natural gas consumption was 598,740 m^3/year and the average heat produced by the heat source was 6,066,354 kWh/year for the period 2016 – 2018 [4].

The number of days in individual periods, the number of operating hours during the day, and the expected hourly outputs of the set are given in **Tab. 1**. Using these data, the amount of thermal energy produced per year can be determined. In real operation, however, there may be moments when the equipment breaks down or there is a planned shut down due to its maintenance, which is taken into account by reducing the produced thermal energy by 5% [4]. For clarity, the data are shown in **Tab. 1**.

The thermal energy produced by boilers is 3,817,305 MWh. A very important data is the consumption of natural gas by the CU. The producer of the CU declares that the maximum hourly consumption of natural gas is approximately 24 nm^3/h at a calorific value of natural gas of 35.5 MJ/m^3 [6].

The consumption of natural gas for the CU in individual periods and throughout the year is shown in **Tab. 2**. The total natural gas consumption by the CU throughout the year is 189,240 m^3. The value of the total heat in natural gas is obtained as the product of the total consumption of natural gas by the CU and the average calorific value of the fuel (9.701 kWh / m^3), which is 1,835,817 kWh [4].

Tab. 1 - Use of cogeneration unit and heat pumps throughout the year [4].

Season	Months	Days	Operating hours	Operating hours in the season (h)	Hourly power of equipment (kW)	Produced thermal energy reduced by 5% (kWh)
Winter	7	212	24	5,088	300	1,450,080
Transition	2	61	24	1,464	270	375,516
Summer	3	92	19	1,748	255	423,453
Σ CU +HP	12	365	-	8,300	-	2,249,049

Tab. 2 - Natural gas consumed by the cogeneration unit [4].

Season	Hourly natural gas consumption by cogeneration unit (nm^3/h)	Operating hours in the season (h)	Final consumption of natural gas by the cogeneration unit reduced by 5% (m^3)
Winter	24	5,088	116,006
Transition	24	1,464	33,379
Summer	24	1,748	39,854
Σ	-	8,300	189,240

These findings show that 1,835,817 kWh of energy consumed in natural gas is needed to produce 2,249,049 kWh of heat energy per year by the CU and HP´s [4].

To determine the total consumption of natural gas at a heat source, we need to know the consumption of natural gas by gas boilers. The consumption of natural gas by boilers was calculated to 401,527 m^3. It follows from the above that the estimated total consumption of natural gas at the heat source is 590,767 m^3 [4].

If we look at the average natural gas consumption before the installation of the unit, which is 598,740 m^3/year and the expected natural gas consumption after the installation of the unit, which is 590,767 m^3/year, it is seen that applying a CU and HP´s should save 7,973 m^3 of natural gas as compared to the existing operation of gas boilers [4].

At the time when the application was being addressed, the purchase price of natural gas per 1 kWh was 0.04234 euros [5]. By multiplying the saved amount of natural gas by the average value of combustion heat (10.754 kWh/m^3) and the purchase price of natural gas, an annual saving of 3,631 euros is determined [4].

4.2 Electricity Consumed

A CU is a device for the combined production of heat and electricity [7]. A part of the generated electricity is used for its consumption, the predominant part is used to drive the HP´s. It will also power submersible pumps in pumping wells and circulating pumps on the primary and secondary side [4].

The surcharge for electricity is 34.55 euros/MWh [4].

To find the prices of revenues for high-efficiency cogeneration, we must determine how much electricity is produced by the CU each month and throughout the year. The obtained data are shown in **Tab. 3**.

The electricity produced during the annual operation of the facility will be 567,302 kWh per year, which represents 567.302 MWh per year. This value is again reduced by 5% due to a fault or maintenance on the equipment [4].

As we know the surcharge for electricity and the amount of electricity produced, we can use the product of these items to find out what the revenues for high-efficiency cogeneration will be. Annual revenues for high-efficiency cogeneration amount to 19,600 euros [4].

Tab. 3 - Amount of electricity produced by the cogeneration unit [4].

Season	Months	Days	Operating hours	Operating hours in the season (h)	Hourly electricity production (kWe)	Electricity produced reduced by 5% (kWh)
Winter	7	212	24	5,088	73	352,853
Transition	2	61	24	1,464	73	101,528
Summer	3	92	19	1,748	68	112,921
Σ CU +HP	12	365	-	8,300	-	567,302

5. Results – Economic Aspects

The total investment costs for the implementation of the work amount to 502,820 euros [6].

5.1 Cogeneration Unit Maintenance Costs

For the CU, we consider the costs of maintenance service of the CU, including work and transport within Slovakia. The average cost per operating hour of a CU, including all the costs mentioned above, is 1.54 euros/Mth [6].

The number of year-round operating hours of the CU was estimated to 8,300. Due to possible failures or repairs on the equipment, we will reduce the operating hours by 5 %. The resulting number of operating hours is 7,885. If this figure is multiplied by the average cost per 1 operating hour, the resulting annual maintenance costs of the CU amounts to 12,143 euros [4].

5.2 Heat Pumps Maintenance Costs

The maintenance is considered to take place once a year. Maintenance costs include routine maintenance, refrigerant inspection, transport from Bratislava to Brezno and back [4].

The annual maintenance costs for both HP´s are 1,206 euros. The work of a service technician is already included in this final price [4].

5.3 Profitability Based on Cash Flow

Since the streamlining of the operation of the heat source is solved in the boiler plant, which is managed by the energy company, we can claim a legitimate claim from depreciation in the price of heat. We must divide the individual equipment and works into depreciation groups and write off the relevant amount each year. This written-off amount represents cash income through the price of heat (quasi-profit item without the need for taxation).

Subsequently, in the individual years, we apply the saved finances on natural gas and revenues for high-efficiency cogeneration. During these years, we also must think about the maintenance of the CU equipment and HP´s, which represent negative items. With the sum of profit and loss items in individual years, we work towards the overall benefit from the operation of the facility [4]. Results are visualized in the form of accumulated cash flow as shown in **Fig. 3**.

Fig. 3 shows that the revenue from depreciation, financial savings on natural gas and revenues for high-efficiency cogeneration will return the investment in 6 years from the installation of the equipment [4].

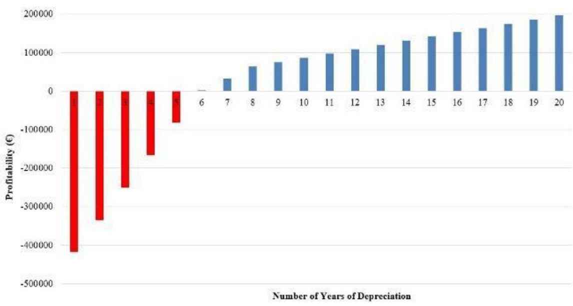

Fig. 3 - Cumulated cash flow [4].

6. Discussion

The reason to apply the CU and HP´s in the given operation was the fact that DHS´s have the potential for high efficiency combined heat and power generation and efficient use of environmental energy through HP´s. These devices can be installed separately, but as mentioned in the article, there is also a presumption of the interaction of both devices.

The CU could also supply electricity to the public electricity network, but at the time of this optimization study, there was a ban on connecting new larger sources of electricity to the public electricity network.

The application of a CU and HP´s to the existing operation of hot water gas boilers saves fossil fuel - natural gas, the reserves of which are gradually running out. The energy of the environment - groundwater - is used instead. From an energy point of view, the same or more heat energy is produced but less fuel is consumed.

7. Conclusion

To ensure energy efficiency, the original technologies are gradually being replaced by modern equipment. First, it is important to determine the area of operation of these facilities, which is also affected by the determination of performance. A CU and HP´s were used to produce the heat needed to prepare hot water in an accumulative way, especially in the summer. During the heating season, the additional heat produced will not accumulate but will be supplied to the heating network.

8. Acknowledgement

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Data Statement

The datasets analysed during the current study are not publicly available, because the heat source operator has not approved their publication but will be available on individual request.