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Heat Plant as a Heat Source of the Centralized Heat Supply with High Efficiency

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Abstract. Efficient district heating (DH) is defined in the Act. 100/2014 Coll. of 20th of March 2014 amending and supplementing Law no. 657/2004 Coll. Thermal Energy as amended. Art. I, § 2 of the letter z), provides: Efficient district heating is district heating system, which supply at least 50% of the heat produced from renewable energy sources or 50% of heat from industrial processes, 75% of the heat produced by high-efficiency cogeneration or 50% of the heat produced by a combination thereof. The role of the authors of the article was to propose a reconstruction of the heat plant with an annual supply of 30,000 MWh of heat so that the heat source meets the conditions of effective DH.

INTRODUCTION

Heating Plant (HP) supplied the city with heat was built in the late 80's. HP has been installed 8 hot water boilers with a total thermal output of 25 MW. The first heat source reconstruction took place between 2001 and 2008. Currently, the heating and power plant (HaPP) has installed four gas hot water boilers and two cogeneration units (CU) [3]. The total installed thermal capacity is \( P_q = 13.16 \) MW and electric power \( P_e = 2.52 \) MW (Fig. 1, variant V0). Moreover, the original backup consists of three boilers on natural gas (NG) installed in HaPP. The aim of the reconstruction is planned to ensure that HaPP become a source of heat of efficient district heating. In real terms of the localization of HaPP this objective can be achieved in two ways: at least 75% of the heat produced by high-efficiency combined heat and power production (CU) [2], or at least 50% of the heat produced by combining renewable energy sources (RES) [1] and high efficient CU.

OPTIMIZING THE RECONSTRUCTION OF HEATING AND POWER PLANT

Optimize the design of the reconstruction consists of three parts:
• design of the combined heat and power production unit (CU) and woodchips boiler (BW) heat rate
• optimization of loading selected combination boiler sequence and CU
• choosing the optimal boiler sequence and CU.

For replacing physically worn CU1 several alternatives were considered, CU with an electrical capacity of 0.6 MW, respectively 0.8 MW. Because of location, climate and economic conditions of the city, mainly forest biomass is usable for the production of heat from renewable energy sources. Variants of BW with a heat output of 0.6 MW, 0.8 MW and 1.0 MW were compared. By modeling the optimal operation of installed and the new boilers and CU in HaPP, woodchips boiler with a heat output of 0.8 MW and CU with an electrical capacity of 0.8 MW were selected.
In the paper they were compared three variants of reconstruction of the Tp. In all scenarios is accounted the operation of boilers B1, B2, B3, B4 on natural gas and CU2. Currently operated CU1 (Fig. 1, Fig. 2, a variant V0) will be replaced. As part of the reconstruction of the heating plant is expected to install:

- cogeneration units CU3, CU4, CU5  
- cogeneration unit CU3 and woodchip boiler BW  
- cogeneration units CU3, CU4 and BW

In the Fig. 1 are for variants V0, V1, V2a and V2b shown installed boiler thermal power, CU and total installed thermal and electrical power of the HaPP. The variant V1 expect permission of the operation of CU2 to maximal electrical capacity 1.19 MW.

<table>
<thead>
<tr>
<th>Variant V0 - current state</th>
<th>( P_q ) (MW)</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>1.08</th>
<th>1.68</th>
<th>( P_{q_{\text{Tp}}} = 13.16 ) MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>CU2</td>
<td>CU1</td>
<td>1.00</td>
<td>1.52</td>
<td>( P_{e_{\text{Tp}}} = 2.52 ) MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variant V1 - reconstruction (CU3 + CU4 + CU5)</th>
<th>( P_q ) (MW)</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>1.30</th>
<th>0.92</th>
<th>0.92</th>
<th>0.92</th>
<th>( P_{q_{\text{Tp}}} = 14.46 ) MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>CU2</td>
<td>CU3</td>
<td>CU4</td>
<td>CU5</td>
<td>1.19</td>
<td>0.80</td>
<td>0.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variant V2a - reconstruction (BW + CU3)</th>
<th>( P_q ) (MW)</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>0.80</th>
<th>1.08</th>
<th>0.92</th>
<th>( P_{q_{\text{Tp}}} = 13.20 ) MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>BW</td>
<td>CU2</td>
<td>CU3</td>
<td>1.00</td>
<td>0.80</td>
<td>( P_{e_{\text{Tp}}} = 1.80 ) MW</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Variant V2b - reconstruction (BW + CU3 + CU4)</th>
<th>( P_q ) (MW)</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>2.60</th>
<th>0.80</th>
<th>1.08</th>
<th>0.92</th>
<th>0.92</th>
<th>( P_{q_{\text{Tp}}} = 14.12 ) MW</th>
</tr>
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<tbody>
<tr>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>BW</td>
<td>CU2</td>
<td>CU3</td>
<td>CU4</td>
<td>1.00</td>
<td>0.80</td>
<td>0.80</td>
</tr>
</tbody>
</table>

FIGURE 1. Compared variants of the HaPP reconstruction

Boilers and CU were sequenced and loaded so that, depending on the optimization criterion - the maximum profit of production, distribution and supply of heat during the year - optimally cover the needs of heat for district heating system (DHS). To meet optimization criteria - DHS maximum profit - during the year should be sequenced and loaded boilers B on natural gas, BW and CU in HaPP so that the flow of fuel costs on heat \( n_{\text{fuel,q,\text{diff}}} \) defined by a differential method of dividing the cost of electricity and heat were at least \( [4] \)

\[
 n_{\text{fuel,q,\text{diff}}} = \min. \tag{1}\]

DHS heat demand during the year are set at intervals of 1 h. Annual load duration diagram of HaPP is characterized by an annual duration the maximum load of 2430 h, load factor value of 0.277 and refers to the number of degree-day \( D_{20} = 2580 \) K.day. To optimize the loading and sequencing of boilers and CU in reconstructed HaPP the method of characteristics was used.
EFFICIENT DISTRICT HEATING

Figure 2 shows the real operation of boilers B1, B2, B3 and B4 (BNG) working with natural gas and cogeneration units CU1 and CU2 during the year (variant V0). In the HaPP due to economic reasons were chosen installed thermal power of CU so the CU meet the needs of heat for hot water beside the heating season. Operation physically worn CU1 was due to a malfunction restricted. It is planned to replace it with the new CU. Of the total annual heat production in the HaPP, CU produced 46.2% and natural gas boilers 53.8%. The heat source in terms of share of heat production from high-efficiency cogeneration is operated so that at present does not meet the requirement of effective DH.

To meet the conditions of supply at least 75% of heat from high-efficiency cogeneration should be in HaPP installed three new cogeneration units CU3, CU4 and CU5 and if necessary operate the CU2 on its maximal electrical power 1.19 MW. According to variant V1 cogeneration units will cover 75.6% of the annual heat production in HaPP (Fig. 3, Fig. 6), the effective DH condition is met.

Fig. 4 and Fig. 5 shows the operation of the optimally sequenced and loaded boilers and CU during a year of variant V2a and V2b. According to variant V2a, cogeneration units CU2 and CU3 supply 45.2%, woodchips boiler BW 14.5% and natural gas boilers 40.3% of the annual heat production at HaPP. A combination of heat production from RES and CU is together produced 59.7% of total heat supplied to DHS (Fig. 6). The share of heat produced from RES and CU, according to a variant V2b increased to 71.7%. CU units CU2, CU3 and CU4 supply 61.1%, woodchips boiler BW 10.6% boiler and natural gas boilers 28.3% of the annual heat production in HaPP. Variant V2a and V2b meet the requirement of effective DH, because more than 50% of heat is produced by a combination of RES and CU.
As shown in Fig. 6, coefficient $k_{\text{e\_DH}}$ of efficient DH is defined as the ratio of annual heat supply to DHS by high efficiency cogeneration ($Q_{\text{CU}}$) and heat produced from renewable energy sources ($Q_{\text{BW}}$) to the total annual heat supply $Q_{\text{CU}}$ by cogeneration units, woodchips boiler $Q_{\text{BW}}$ and natural gas boilers $Q_{\text{BNG}}$.

$$
k_{\text{e\_DH}} = \frac{Q_{\text{CU}} + Q_{\text{BW}}}{Q_{\text{CU}} + Q_{\text{BW}} + Q_{\text{BNG}}}
$$

(Eq. 2)

**FIGURE 6.** Shares of CUs, woodchips and natural gas boilers on an annual heat production in HaPP, and district heating coefficient $k_{\text{e\_DH}}$ of effective DH

**ECONOMIC EVALUATION OF VARIANTS OF RECONSTRUCTION OF HEATING AND POWER PLANT**

Economic and financial analysis of heat production in the HaPP after its reconstruction according to variants V1, V2a and V2b was performed using the software EFINA. Calculated are the cost of production and distribution of heat during the reporting period 2015 to 2029.

The basic assumptions used in the calculations are as follows:

- capital construction in 2015,
- considering the constant production and supply of heat to DHS (as in 2015) during the reporting period of 15 years,
- prices of natural gas, woodchips and the redemption price of electricity produced by CU will not change, they are determined according to year 2015,
- investment and other fixed costs are set at the estimated price level of 2015,
- loans represent 30% of investment costs,
- model price of heat is determined by the price of heat in 2015, in subsequent years the fixed component of the heat price increases depreciation of new investment costs and at the same time is reduced variable component prices due to the heat production from the woodchips and the increased production of electricity from high efficiency cogeneration.

In the economic calculations of evaluated alternatives of heating and power plant reconstruction are considered economically justified costs defined as costs necessary for the production of heat from natural gas, woodchips and high efficiency cogeneration.

Investment costs (IC) of variant V2b are 90.3%, variant V2a 56.9% of the IC of variant V1 (Fig. 7).

The return on investment ranges from 6 years (variant V2a) to 9 years (variant V1). Variant V2a is most advantageous in terms of value and internal rate of return (IRR = 16.2%) as well, the lowest internal rate of return IRR = 11.6% belongs to variant V1. The sensitivity analysis shows that the economic evaluation of compared variants are mostly affected by the price of natural gas and heat.
Compared fixed $C_{FC}$ and variable $C_{VC}$ component of the cost of heat to the price of heat of variant V0 are shown in Fig. 8. The total price of heat in the period 2016-2029 variant V2a is reduced to 86.4% of the heat variant V0 and to 90.0% of the variant V1. In 2015 was fixed component $C_{FC}$ 33.7% of the total price of heat of variant V0. As a result of the investment cost of variant V1 is the fixed component of the heat price increased to 42.2%. In a variant V2b increased production of electricity from high efficiency cogeneration and heat production from woodchips forms the variable component of the heat price $C_{VC}$ 48.1% of the total price of heat, while the variable component of variant V0 is 66.3% of the total price of heat.

FIGURE 7. Specific investment costs of variants V0, V1, V2a, V2b

CONCLUSION

The paper analyzed the possibilities of achieving efficient district heating when the original heat source – the heating plant was built in the densely built-up urban area.

If the reconstruction of heating plant have to meet the condition for efficient district heating production at least 75% of heat from high-efficiency cogeneration (variant V1), nowadays the problem is to obtain the permission from the distribution company to connect the CU to the distribution network.
Proportional heat price components of variations V0, V1, V2a, V2b

Investment costs for reconstruction of the HaPP according to variant V1 are the highest, also economic evaluation of this option is the least favorably from compared variants. For these reasons, the desired proportion of at least 75% of heat production from high efficiency cogeneration in heat plants originally built for residential district according to the authors of the article is high. To meet the conditions of effective DH would be appropriate to reduce this share to at least 50% of the supply of heat produced by the CU. In the HaPP with steam and/or combustion turbines installed may reasonably be required at least 75% of the heat produced by high efficiency cogeneration.

In order to meet the conditions of effective DH, where the heat source supplies at least 50% of the heat produced by a combination of renewable energy sources and high efficiency cogeneration, it is necessary to focus on woodchips boilers with optimally tuned installed thermal power. Sufficient resources of woodchips are required in economically feasible distance from the heat source. Location of heat source is also a limiting factor for the operation of woodchips boilers in terms of environmental considerations and traffic load.

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