ABSTRACT

The district energy systems, especially combined heat and power production (CHP) technologies, play an increasingly important role in local energy supply. On 25 October 2012, the EU adopted the Directive 2012/27/EU on energy efficiency, which establishes a common framework of measures for the promotion of energy efficiency within the Union in order to ensure the achievement of the Union’s 2020 20 % headline target on energy efficiency and to pave the way for further energy efficiency improvements beyond that date.

The paper discusses the possibilities of using technically, economically and environmentally justified heat from the NPP Krško for the purpose of the district heating of Krško and Brežice area. Different steam extractions on secondary site of NPP Krško were analysed. The feasibility study showed that steam extraction just behind the high pressure turbine is the most optimal heat source from the technical, spatial and economic aspects. In addition, the possibility of using low temperature heat on tertiary side with 2-stages heat pumps was analysed.

The feasibility study also analysed alternatives in the Krško - Brežice region, such as heat production from biomass, biogas, natural gas plant (existing and new), geothermal energy, alternative without action, etc.

Among all analysed heat sources, the extraction on the secondary side of NPP Krško showed the most promising results. The solution would be cheaper for the majority of the end users in Krško and Brežice. A realisation of the CHP production from NPP Krško would achieve not only economic, but also great environmental benefits. The analyses have shown that more than a half of the produced heat for the heating purposes in that area is based on fossil fuels, which produces 20,000 tonnes of CO$_2$ emissions per year. The rest of the heat is mainly produced from wood, which does not contribute to the CO$_2$ emissions but it can be problematic from the “particulates larger than 10 µm” (PM$_{10}$) emission point of view.
1 INTRODUCTION

The paper introduces some of the important findings of a feasibility study of using heat from NPP Krško for district heating purposes performed by SIPRO engineering based on GEN energija order [1]. Similar study, however for a new planned unit in Krško (JEK2) was carried out by Imuthes in 2008 [2]. Both studies analysed a wide spectrum of technological, environmental and economic characteristics and can be a good basis for further studies and decisions.

In local energy supply, district energy systems play an increasingly important role, being based on sustainable sources and efficient combined heat and power (CHP). CHP is common for coal and gas fired power plants but not obvious for Nuclear Power Plants (NPP). However, there are several projects in the world that have implemented cogeneration in NPPs. Nowadays, about 60 reactors worldwide produce heat for district heating, industrial processes or desalination.

2 HEAT CONSUMPTION IN KRŠKO AND BREŽICE

Heat from the NPP Krško can be used for different purposes, i.e. district heating, district cooling, as a steam for industrial processes, in agriculture. Only district heating is analysed in this paper.

Figure 1 shows current structure of fuels used in Krško and Brežice. There are mainly three different kind of fuels used in this region. These figures are specific for the city of Krško and Brežice, and should not be generalized on to the whole county, since the town has multiple joint boilers which provide heat for residential apartment buildings and institutions. These joint boiler rooms produce an estimated 12.1 MW of heat in Krško and 11.3 MW in Brežice. Based on the current heat need, consideration of coincidence factor of 0.75, heat losses and need for sanitary water, the total required installed power for district heating in Krško and Brežice is approximately 80 MW. This number is also input design parameter for heat extraction in NPP Krško.

Figure 1: Share of used fuel in Krško and Brežice at the end of 2012.
3 COMBINED HEAT AND POWER IN NPP KRŠKO

The main purpose of the study [1] was to identify possible sources of heat in NPP Krško that could provide sufficient energy for the district heating. In principal two major sources were found as convenient. These are steam extraction on the secondary side of the NPP Krško and hot water on the tertiary side.

3.1 Heat Extraction on Secondary Side

Several alternatives were identified and studied as possible heat sources on secondary side [3]:

1. High-pressure turbine (HPT) replacement,
2. Between moisture separator – reheater (MSR) and low-pressure (LP) turbine,
3. Existing steam extraction on high-pressure (HP) turbine,
4. Steam cross pipe between reheaters 2A and 2B, and
5. Low-pressure turbine.

High-pressure turbine replacement

The steam generators produce 1962 t/h of saturated steam with a temperature of 281.2 °C, rate of moisture < 0.1 % and a pressure of 64.4 bar. Steam expands in the HP turbine to the pressure of 9.6 bar and a temperature of 178 °C. NPP Krško is planning to replace the HP turbine in the near future. In that case it might be reasonable to design the turbine with additional extraction pipes on the last stage of the turbine. A simplified diagram of the system is shown in Figure 2. Replacing of the HP turbine is the most expensive option. From a thermo-dynamical point of view this option is equal to alternative no. 5, yet the implementation is technically not possible due to space restrictions under the HP turbine.

![Figure 2: A simplified scheme of steam extraction on the last stage of high-pressure turbine.](image)

Extraction between MSR and LPT

The steam is dried and reheated in the MSR. The steam mass flow rate of 2 x 650 t/h, pressure 9.7 bar and temperature 269.8 °C, enters into the low-pressure turbine. Implementation is technically demanding [4]. A cross-connection between both MSRs would be made and a steam pipe connection to the heat exchanger. The steam is of high quality (no
droplets) which is needed for the low pressure turbine and would be wasted for district heating. DH steam would normally be routed directly into a heat exchanger where moisture is not a factor.

**Existing steam extractions on high-pressure turbine**

The first already existing steam extraction is on the 5th stage of high-pressure turbine. The purposes of this extraction are as follows:

- Steam for high-pressure preheaters for feedwater
- Steam for the 1st stage of reheating in MSR
- Auxiliary Steam System (SA) line

One of the possibilities, for the purpose of the district heating, is an added connection to the Auxiliary Steam System (SA) line. Figure 3 shows how the heat exchanger for district heating could be connected to the SA line.

![Diagram of steam extraction on high-pressure turbine](image)

**Figure 3: A simplified scheme of steam extraction on the existing 5th stage of the high-pressure turbine.**

80 MW of thermal power requires an extraction flow capacity of 120 t/h, which can be technically achieved from the SA line. Based on the turbine vendor, an additional steam extraction in the range of 120 t/h would mean 19.5 MWe drop in electricity production. For every 30 t/h of increased steam extraction a decrease of electrical power would be approximately 4.9 MWe (-0.67 %).

**Steam cross-pipe between reheaters 2A and 2B**

Another possible location of the steam extraction is just on the exit of the steam pipe from the high-pressure turbine on the so called cross-connection of the steam pipe before entering into the MSR.
Steam is extracted at 9.6 bar and a dryness of $x=0.87$. A regulating valve then dampens the steam to a pressure of 4.5 bar abs, $147.9\, ^\circ\text{C}$ and $x=0.89$. At these conditions 128 t/h of steam is needed to provide 80 MW of thermal power, estimating full condensation and an outlet temperature $63\, ^\circ\text{C}$. This modification would mean 17.1 MWe of electric power loss.

Low-pressure turbine

A possibility of the steam extraction on the low-pressure turbines was also studied. However, already on the highest existing steam extraction ($3^{rd}$ stage of low-pressure turbine) the steam parameters do not allow steam extraction from the low-pressure turbine for the purpose of district heating.

After detailed analysis of five different alternatives, it was decided that the most appropriate one is alternative no. 4, where heat is extracted from steam cross-pipe between reheaters 2A and 2B. This alternative was the first candidate for further analysis.

3.2 Heat Extraction on Tertiary Side

Plant tertiary water can also be used as a heat source for district heating. When cooling water from the Sava River passes through Plant main condenser it is heated for approx. $13\, ^\circ\text{C}$ in average. Irrespective of huge amount of thermal energy water at such low temperatures cannot be directly used for district heating. In order to increase the level of temperature to approximately $90\, ^\circ\text{C}$ heat pumps have to be used. The main advantage of using heat pumps instead of heat extraction on secondary side is that there is no impact on NPP Krško’s electricity production. The heat pumps would consume about 26 MW of electricity in case of maximal heat demand. The Coefficient of Performance (COP) of such large heat pumps is about 3. However, this cannot be directly compared to the heat pumps for low energy houses with COP > 4 where water is heated up to $50\, ^\circ\text{C}$ instead of $90\, ^\circ\text{C}$.

Figure 5: Heat pump on the tertiary system.
4 DISTRICT NETWORK

District network is comprised of three main elements, i.e. pipelines, distribution pump houses and heat pump station. In principal there are two types of district heating networks: direct and indirect. Heat can be transferred on the heating media directly from the distribution system or via heat exchangers. Majority of the district heating networks are based on indirect heat transfer due to the more simple operation and also higher safety [5]. Therefore, the indirect system was assumed for Krško and Brežice district heating.

Two different design temperature regimes were analysed. Low temperature regime (90/60 °C) was assumed for heat pumps and high temperature regime (120/60 °C) for heat extraction on secondary side of NPP Krško, respectively. Advantages of high temperature regime are lower flow, lower distribution pump costs [5], better regulation of inlet temperature and better adaptation of the existing situation in Krško and Brežice.

Hydraulic and thermo-dynamic analysis was performed for calculation of hydraulic and thermal conditions in district network. Planning of pipeline was carried out with Termis software [7], which is one of the leading program tools for planning, optimization and maintenance of the district systems.

When planning area of district heating a recommended values of annual concentration of consumption have to be considered [8]. These values are between 1 to 1.2 MWh/m for rural areas and 2 to 3 MWh/m in urban areas. However, an economic feasibility depends also on heat production costs which vary on type of heat source. 12 sections were taken into account, 6 in Krško (1 - Stara vas, 2 - Videm lower part, 3 - Videm upper part, 4 - Krško center, 5 - Narpel, Gric, 6 - Leskovec.) and 6 in Brežice (1 - Brezina, 2 - Sentlenart, 3 - Brežice north, 4 - Crnc, Zakot 5 - Trnje, 6 - Brežice center) as seen in Figure 6. The total length of the pipelines in planned district network is approximately 78 kilometers.

Figure 6: Regions where district heating is financially plausible in Krško (left) and Brežice.
5 ECONOMIC ANALYSIS

In addition to the heat sources in NPP Krško, the alternatives were also examined. These alternatives were chosen based on adequacy criteria of energy, environmental and spatial availability in Krško and Brežice region. The following solutions as a heat source were analysed: biomass (cogeneration plant, heating station), natural gas (new gas-fired power plant, modification in existing plant TEB, cogeneration in gas engines), combination of natural gas and biomass (combination of gas engines and biomass boilers), biogas, geothermal energy and alternative without action (keeping current situation).

Screening of all possible variants revealed that the steam extraction on secondary side of NPP Krško (Variant 1) and the heat pumps on tertiary side of NPP Krško in combination with biomass boilers (Variant 2) are the most convenient solutions. Therefore, only these two variants were compared in the economic analysis, which considered costs of the entire systems. Besides the main heat source and the district system also backup heat source and heat substation for each house or department were considered. Regardless of very high operational reliability of NPP Krško, a backup system is still needed to cover outages and the (un)planned shutdowns of the plant. Backup heat source must be the same installed thermal power as the main heat sources. It is comprised of 40 MW of existing heating boilers in Krško and Brežice, and an additional 40 MW of a new gas fired boiler. Table 1 shows the most important economic parameters for both variants.

Table 1: Comparison of two different variants for district heating.

<table>
<thead>
<tr>
<th></th>
<th>Variant 1: steam extraction on cross-pipe between reheaters 2A and 2B</th>
<th>Variant 2: heat pumps on tertiary side</th>
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<tbody>
<tr>
<td>Lifetime of investment</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Annual heat consumption (GWh)</td>
<td>172</td>
<td>172</td>
</tr>
<tr>
<td>Selling heat price (€/MWht)</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Investment costs (mio €)</td>
<td>57</td>
<td>87</td>
</tr>
<tr>
<td>Operational costs (mio €/year)</td>
<td>3</td>
<td>5.5</td>
</tr>
<tr>
<td>Production price (€/MWht)</td>
<td>29</td>
<td>43</td>
</tr>
<tr>
<td>Return of investment* (years)</td>
<td>18</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>Net positive value** (mio €)</td>
<td>7.7</td>
<td>-40</td>
</tr>
</tbody>
</table>

* with financial costs, ** at 7 % discount rate

From NPP Krško point of view using heat source on tertiary side is more acceptable since it does not impact on operation, however the economic results showed that only Variant 1 with steam extraction on cross-pipe between reheaters 2A and 2B is economically feasible. The results in Table 2 showed that selling price of 55 €/MWh in case of Variant 1 is lower than the planned future prices of different individual systems. Moreover, the prices of existing boilers with an exception of wood boiler are also higher than the selling price of the Variant 1. The price of existing systems do not involve depreciation costs, therefore the existing wood boilers would be cheaper.
Table 2: Comparison of district heating from NPP Krško and individual systems (variant with no action) [9].

<table>
<thead>
<tr>
<th>Existing boilers</th>
<th>Production price * (€/MWh)</th>
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<tbody>
<tr>
<td>Existing district heating**</td>
<td>78</td>
</tr>
<tr>
<td>Heating oil boiler</td>
<td>102</td>
</tr>
<tr>
<td>Natural gas boiler</td>
<td>95</td>
</tr>
<tr>
<td>Wood boiler</td>
<td>45</td>
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<table>
<thead>
<tr>
<th>Planned boilers:</th>
<th></th>
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<tbody>
<tr>
<td>Natural gas boiler</td>
<td>99</td>
</tr>
<tr>
<td>Wood boiler</td>
<td>59</td>
</tr>
<tr>
<td>Heat pump boiler</td>
<td>61</td>
</tr>
</tbody>
</table>

| District heating from NPP Krško (Variant 1) | 55 |

* operational and depreciation costs, ** small district boiler systems where available

6 CONCLUSIONS

An estimated 80 MW of heat is needed for district heating of Krško and Brežice. Two different variants have been proposed; steam extraction from the secondary loop, with the use of heat exchangers and from the tertiary loop via heat pumps. The second variant is combined with biomass boilers too. The comprehensive comparison analysis showed that the most convenient solution from technological, economic and environmental aspects is the steam extraction directly from the secondary loop in NPP Krško.

The results of economic analysis also showed that the current average costs for households and other buildings are significantly higher than the calculated selling price of proposed district heating. A decision for an implementation of the project can be also corroborated by environmental benefits which were not considered in economic analysis as external costs.

REFERENCES


