SOLAR WATER PREHEATING FOR OPEN DISTRICT HEATING NETS – SYSTEM INTEGRATION OF LARGE-SCALE FACILITIES

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Abstract

In combined heat and power (CHP) plants with so-called open district heating nets, large quantities of cold water (e.g. 12 °C) are heated to supply temperatures (e.g. 60 °C) using fossil fuels. Such water can be effectively preheated by solar thermal systems before conventional heating to supply temperature. Due to high basic load, low inlet temperature and good climatic conditions in most parts of the Commonwealth of Independent States (CIS), extraordinary solar gains and solar heat generation costs of less than 1 Euro-Cent/kWh_{th} can be achieved during the frost-free season.

The purpose of this investigation is to identify the most suitable solution to integrate large-scale solar thermal installations into the complex process of CHP plants in Central Asia and Russia. The influence of a solar thermal system on the CHP process and on the electricity generation has been investigated based on the actual process of the central CHP plant in Bishkek (Kyrgyzstan). The results indicate that the construction of a large solar thermal plant is possible under the present technical boundary conditions. Preheating of feed water does only have a small impact on power production of electricity, which will be overcompensated by the heat production of a solar thermal system.

Keywords: district heating, preheating of feed water, combined heat and power (CHP) process, effect on electricity generation

1. Introduction

District heating has its origin at the end of the 19th century. Currently approx. 210.000 km (5,3 times circumference of the earth) district heating pipes are installed in all countries of the European Union, covering around 10 % of the heat demand (cf. Dalenbäck, 2010; Euroheat, 2007). Over the past 100 years large capital investments in public district heating have been made in Scandinavia, the Commonwealth of Independent States (CIS) and the Baltic countries with the result of a high market penetration (e.g. in Russia by 63 %) (cf. Euroheat, 2007). Since the end of the 1970's all major countries of the European Union use large-scale solar thermal systems[1] for the integration into local and district heating networks. At present Europe has a total of 126 large-scale solar thermal systems with an installed capacity of 175 MW_{th}. Dalenbäck (2010) describes these systems and their typology of integration into district heating networks. Due to the return temperatures of 40..50 °C in the European heat nets only flat or vacuum tube collectors are operating with average solar heat costs of 4..8 Euro-Cent/kW_{th}.

District heating nets for heat supply are very common in cities of the CIS and are very often combined with large combined heat and power (CHP) plants. A situation valid for most regions of Central Asia and Russia has been found in Bishkek, the capital of Kyrgyzstan with similar latitude as Rome (Italy). Official statistics indicate that about 350.000 inhabitants in the city center of Bishkek receive domestic hot water and energy for space heating from the central CHP plant of Bishkek. The real number of consumers is difficult to estimate, local authorities assume the overall number to be around 700.000. The district heating net shows various differences to technologies used in Europe: It is constructed as an open-circuit system, where domestic hot water is used by the consumers directly out of the net without any heat exchanger coupling (see Figure 1). Thus, the district heating net of Bishkek has to be refilled with approx. 2600 m^3 cold water (12 °C)

[1] large-scale solar thermal system: installed capacity over 350 kW_{th}

per hour. This is accomplished by the CHP plants with the conventional heating of cold water to 60 °C, the temperature level required in the period from May to September (frost-free period) when no space heating is needed and ambient air temperature is usually above 20 °C, even at night.

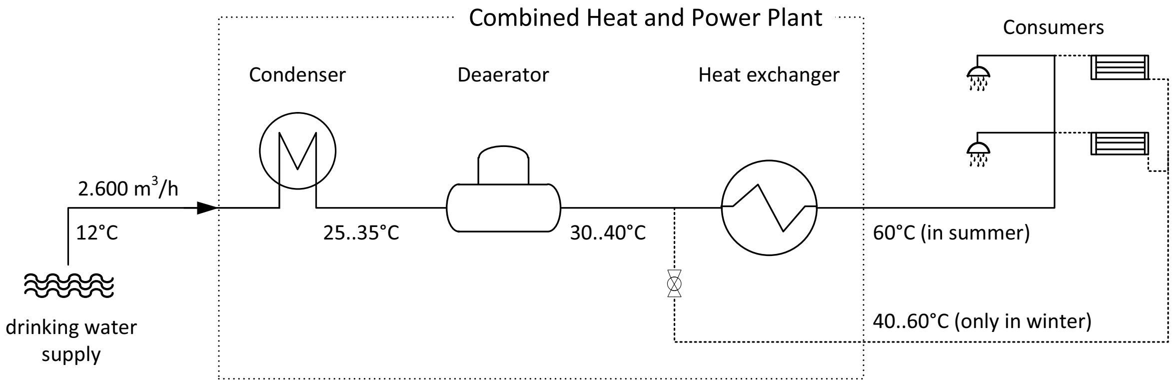

Fig. 1: Simplified hydraulic scheme of a typical open-circuit district heating net in CIS: Domestic hot water is used by the consumers directly out of the net without any heat exchanger coupling.

Alternatively this water can be preheated using uncovered collectors before the conventional heating to the supply temperature (cf. Vajen et al. 2008). For this application no solar buffer storage is necessary because of the high basic load. Due to the low inlet temperature and furthermore excellent climatic conditions (high irradiation, high ambient temperature) very high solar gains can be achieved. For Bishkek specific solar gains are estimated to be around 1000 kWh/m^2_{coll} during the frost-free period, which is about four times higher than the solar gains typically achieved in swimming pool heating in Central Europe. Solar heat cost of less than 1 Euro-Cent/kWh and an annual emission reduction of 0,31 t CO2 per m^2 collector area are expected (cf. Budig et al. 2008). The CHP plant of Bishkek has a total potential of approx. 45.000 m^2 of uncovered collectors and thus offers an emission reduction of annually 14.000 t CO2.

However, not all CHP plants in the CIS have similar boundary conditions so that not everywhere solar preheating is reasonable. The following technical characteristics of CHP plants are necessary in order to apply uncovered collectors for water preheating:

- high basic load (→ no storage is needed + large solar thermal installation)
- open-circuit or mix-circuit district heating net (→ low water inlet temperature)[2]
- CHP-operation mode based on the heat load in the frost-free period

The purpose of this investigation is to identify the efficient way to integrate large-scale solar thermal installations into the complex process of CHP plants in Central Asia and Russia. Hereby, the influence of a solar thermal system on the power plant process and on the electricity generation is of particular importance. The investigations are based on the actual process of the CHP plant in Bishkek (Kyrgyzstan). Possible negative effects caused by the integration of a large system into a CHP plant are discussed and concepts are presented to avoid or minimize these effects.

2. System integration of large scale facilities

In order to find solutions for optimal solar integration of large-scale solar heating systems, it is necessary to consider the basic operation process of a CHP plant in detail. Figure 2 shows the simplified hydraulic scheme of the Bishkek CHP plant with particular emphasis on the feed water within the entire CHP process: Cold

[2] Approx. 40 % of the CHP plants have a closed-circuit system with almost no need for water refilling and relatively high return temperatures like in Europe.

feed water at 12 °C supplied by the public utilities is treated[3] at the beginning and preheated afterwards in the condenser to approx. 27 °C. After the condenser the water passes the deaerator[4] and finally the heat exchanger, in which it is heated up to 60 °C. Figure 3 illustrates the temperature profile of the feed water during CHP process.

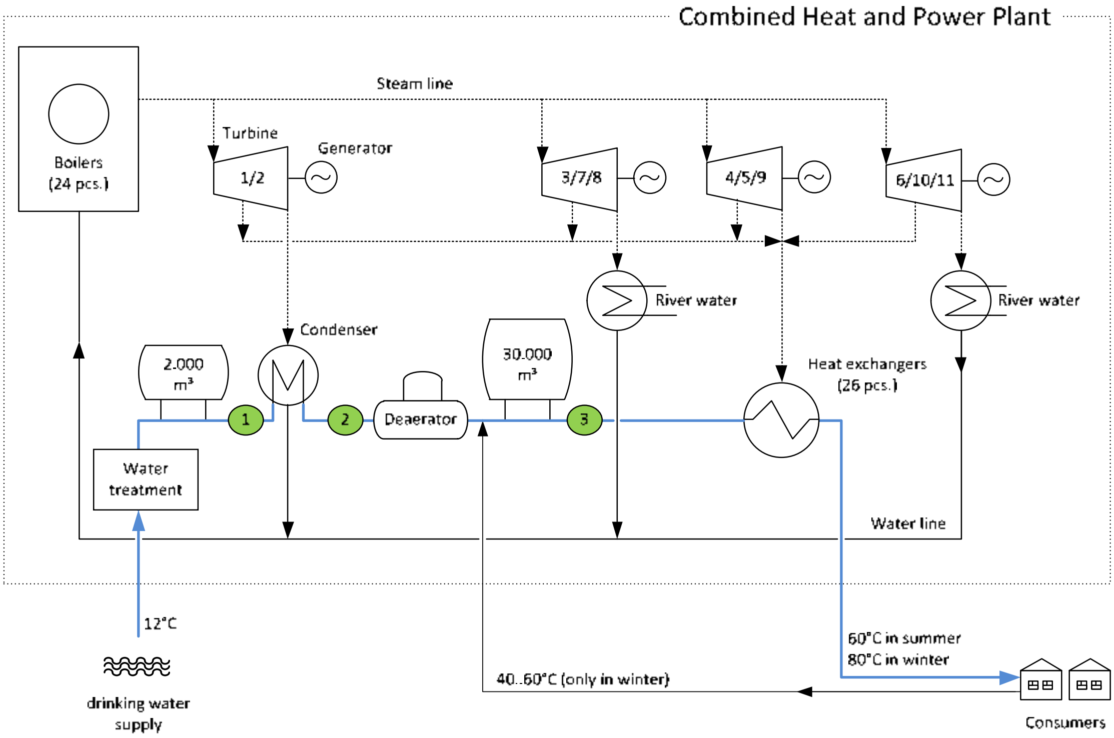

Fig. 2: Simplified hydraulic scheme of the CHP plant of Bishkek. The blue line illustrates the feed water stream through the CHP process. Points 1, 2 and 3 indicate possible integration points for a solar thermal system.

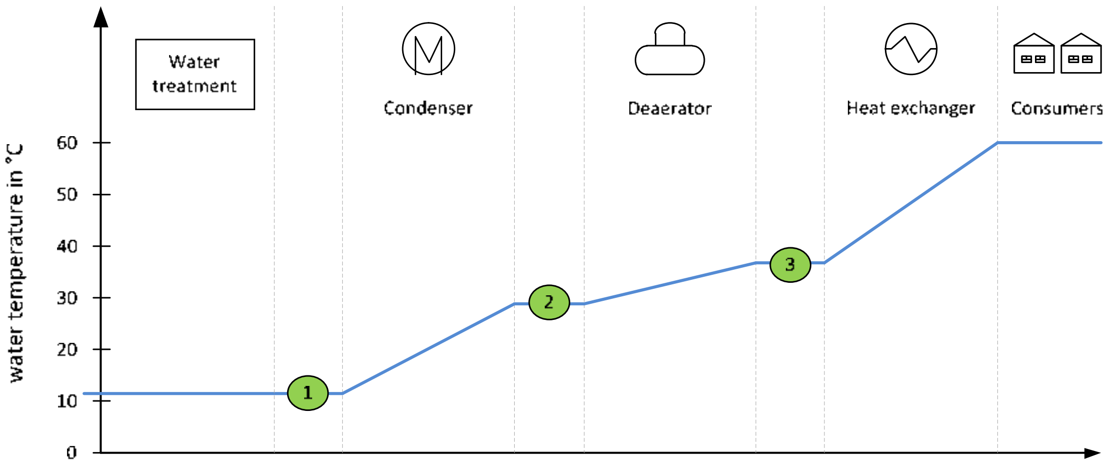

Fig. 3: Temperature profile of the feed water during the CHP process in summer. During winter the water is heated up in the heat exchangers to approx. 80 °C, while the forward-connected process is not subject to any changes.

[3] After mechanical cleaning there is a chemical treatment of the water. This process is required to reduce the water hardness (removal of cations (calcium, magnesium and sodium)). In order to protect the installations that are in contact with the feed water from corrosion and deposition of antisoluble salts, various additives are added to the water.

[4] The deaerator separates aggressive gases (such as oxygen and carbon dioxide) from the feed water, while the feed water is being heated up.

Due to the low feed water temperature, the energetic and economic optimal integration point for solar thermal system is before the condenser (point 1). The maximum feed water temperature is limited to $T_{W,in}$ = 30..33°C, because of the condenser material (see chapter 4). Uncovered collectors are the most effective solution for this temperature range. Furthermore, the solar thermal system can be integrated between condenser and deaerator (point 2). Due to the higher feed water temperatures flat plate collectors should be used instead of uncovered collectors. These, however, are not yet economically competitive with the still low, but rapidly increasing energy prices in the CIS. Between deaerator and heat exchanger (point 3) the integration of flat plate collectors are also technically feasible, but increasingly uneconomic.

According to the results of the detailed analysis of the CHP process, changes of the existing installations and mode of operation is not necessary while integrating a solar thermal system for feed water. However, an increase of feed water temperature before the condenser affects the electrical power generation and can lead to increasing corrosion of the condenser. These possible negative effects on the CHP process are discussed in detail within the next chapter.

3. Effect A: Decrease of electrical power generation

The operating mode of a CHP plant in the CIS does not differ from those in Europe and is based on the Clausius-Rankine cycle. In a steam turbine the enthalpy of steam is converted into mechanical energy. The expanded steam can be extracted from various stages of the turbine and used for district heating or supply of industrial process heat. After the last turbine stage, the steam is cooled down in a condenser before entering the steam generator. Figure 4 illustrates the part of the CHP process, in which the steam is condensed using the feed water. Increased feed water temperatures (e.g. caused by a solar preheating) are responsible for an increase of steam enthalpy h_{E3} of the last turbine stage. This process is responsible for both a reduction of the overall turbine efficiency as well as a decrease of electrical power generation P_{Gen}.

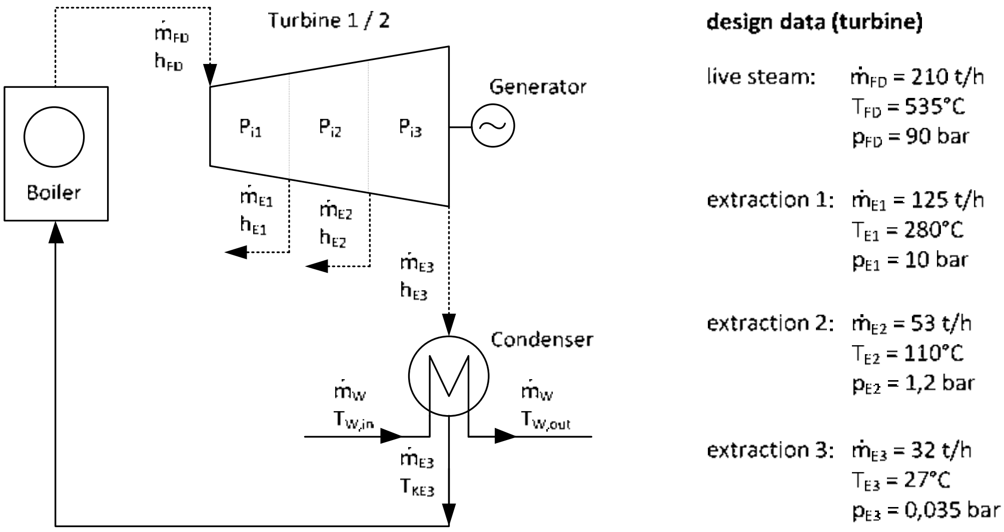

Fig. 4: Detail of the CHP process (Bishkek CHP plant). In the turbine, steam is released from three stages of the turbine.

The total turbine power P_{iGes} is the equivalent of the sum of the partial performance, which can be determined from the product of the respective mass flow and difference of enthalpy of the individual steam extractions (cf. Schaumann, 2005):

$$\begin{aligned} P_{iGes} = P_{i1} + P_{i2} + P_{i3} = \dot{m}_{FD} * (h_{FD} - h_{E1}) \\ +(\dot{m}_{FD} - \dot{m}_{E1}) * (h_{E1} - h_{E2}) \\ +(\dot{m}_{FD} - \dot{m}_{E1} - \dot{m}_{E2}) * (h_{E2} - h_{E3}) \end{aligned} \quad \text{(Eq. 1)}$$

The total turbine power P_{iGes} is therefore greater, the higher the live steam parameters values and the lower the waste steam parameters values. The relation between steam enthalpy h_{E3} and feed water temperature

$T_{W,in}$ results from the energy balance of the condenser, (see Figure 4):

$$\dot{m}_W * (h_{W,out} - h_{W,in}) = \dot{m}_{E3} * (h_{E3} - h_{KE3})$$

$$\Leftrightarrow \quad h_{E3} = \dot{m}_W * \frac{c_p * (T_{W,out} - T_{W,in})}{\dot{m}_{E3}} + c_p * T_{KE3} \qquad \text{(Eq. 2)}$$

The dependency of the total turbine power P_{iGes} on the feed water $T_{W,in}$ is obtained by inserting Eq. 2 in Eq. 1. The electrical generator power is determined by the product of the turbine power and the overall given efficiency of the CHP plant:

$$P_{Gen} = P_{iGes} * \eta \qquad \text{(Eq. 3)}$$

According to Eq. 2 the waste steam temperature depends on the feed water temperature: Higher feed water temperature leads to higher waste steam temperature. Figure 5 shows the correlation between waste steam temperature and the resulting maximum feed water temperature. For example, steam with 27 °C requires a feed water temperature of approx. $T_{W,in}$ = 10 °C to condense (this is valid for the design point of the turbine). During summer period at Bishkek CHP plant the feed water has an average temperature of $T_{W,in}$ = 12,8 °C. According to the dimensioning the waste steam temperature should be 30 °C. However, at present the measured waste steam temperature is T_{E3} = 40°C. Due to long operation time (more than 40 years) a possible explanation for this effect could be material wear of the condenser. This can have two consequences: It is likely that the vacuum at the exit of the turbine has been deteriorated (increase of pressure p_{E3}), as the steam could not cool down to T_{E3} = 30°C during the expansion. Furthermore, it is possible that the heat transfer of the condenser (e.g. caused by fouling) has been decreased. The kind of material wear is important for the effect on the electrical power generation: If the increased waste steam temperature is only caused by a poorer vacuum, an increase of feed water temperature up to $T_{W,in}$ = 23°C would not have an impact on the electrical power production. It is evident from Figure 5, if the feed water temperature is higher than $T_{W,in}$ = 23°C, a waste steam temperature higher than T_{E3} = 40°C will be archived. If the increased waste steam temperature would only be caused by decreased heat transfer of the condenser, an increase of feed water temperature will trigger an increase of waste steam temperature and so lead to a decrease of the electrical power production.

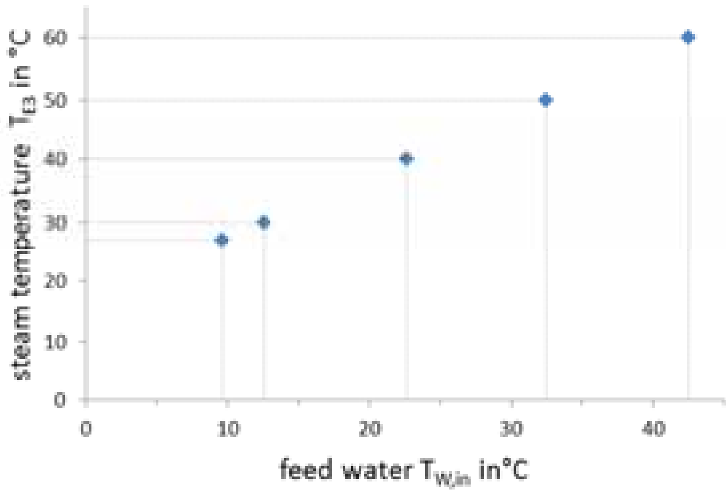

Fig. 5: Correlation between the waste steam temperature and the feed water temperature.

In reality, it is generally assumed that both kinds of material wear occur with unknown impacts. Figure 6 shows the correlation between the feed water temperature and the reduction in electricity generation. "Reference 40" describes the correlation for a poorer vacuum and "Reference 30" describes the correlation for a decreased heat transfer of the condenser. The real correlation lies in between these two extremes. Hence, the electrical power production will decrease by 1,4..2,9 %, if a solar preheating results in a feed water temperature of $T_{W,in}$ = 33°C. The turbine in Bishkek has a nominal power of around $P_{Gen} = 32\ MW_{el}$ and therefore the electrical power generation will decrease by 460..950 kW_{el}. In contrast, there is a thermal gain of approx. 60 MW_{th}[5].

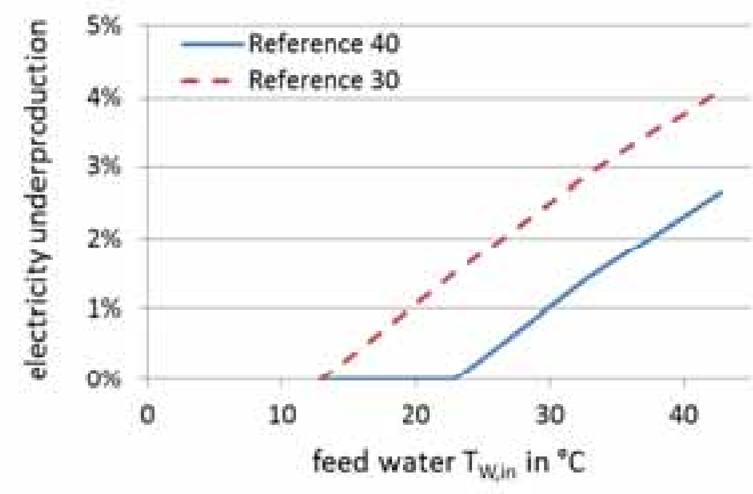

Fig. 6: Electricity underproduction as a function of feed water temperature according to kind of material wear (Reference 40: poorer vacuum at the exit of the turbine; Reference 30: decreased heat transfer of the condenser).

4. Effect B: Increase of corrosion

At the CHP plant in Bishkek the waste steam is cooled down in the condenser, after leaving the last turbine stage. During this process the feed water flows through the brass pipes of the condenser, whereby the feed water is heated up. An increase of feed water temperature before the condenser can lead to strengthened corrosion of these brass pipes.

Brass is an alloy of copper and zinc, which can be damaged by the so-called dezincification (a form of selective corrosion). Dezincification selectively removes zinc from the alloy, leaving a weakened copper-rich structure (cf. Piatti et al., 1963; Held and Schnell, 2000). Due to the complex interactions of the factors on dezincification, the extent of the dezincification only can be specified in terms of probabilities (cf. Köhler, 1996; EN 12505-2, 2004). Conditions favoring dezincification are (a) alloys with a higher content of zinc[6], (b) an operating medium with higher chloride / sulphate ion contends as well as low carbonate hardness and (c) higher temperatures as well as lower velocities of the operating medium. According to the Turner-Diagram[7] the condenser at Bishkek CHP plant is operating nearby critical chloride-carbonate ratios under the current material and water properties. Due to the catalytic effect of the feed water temperature, the rate of the dezincification increases with increasing feed water temperature. Operational experience of (Borodin, 2008) indicates that an operation of the condenser with feed water temperatures higher than $T_{W,in}$ = 30..33°C (ca. $T_{W,out}$ = 45°C) should be avoided.

5. Conclusions

Large solar thermal installations can be effectively applied to preheat water for open district heating nets in cities of CIS. Solar heat cost of less than 1 Euro-Cent/kWh are expected, which is about four to eight times lower than the solar heat costs typically achieved in large-scale solar thermal systems integrated into district

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[5] $(32{,}8°C - 12{,}7°C) * 4187 \frac{J}{kg\,K} * 2570 \frac{kg}{h} \approx 60\ MW_{th}$

[6] Brass containing more than 15% is susceptible to dezincification.

[7] The Turner diagram is an indicator of the water ability to support dezincification.

heating networks in Europe. According to the results of a detailed analysis of typically CHP processes, there are no changes of the present technological processes required while integrating a solar thermal system. However, an increase of feed water temperature affects the electrical power generation and can lead to corrosion of the condenser. The electrical power generation will decrease by 1,4..2,9 % (460..950 kW_{el}), if a solar preheating increases the feed water temperature from $T_{W,in}$ = 12 °C to $T_{W,out}$ = 33 °C. In contrast, there is a thermal gain of approx. 60 MW_{th}, whereby a coefficient of performance of 21..44 results.

Furthermore, solar thermal preheating of feed water can lead to strengthened corrosion of the condenser. Operational experience of Bishkek CHP plant stuff indicates that an operation of the condenser with feed water temperatures higher than $T_{W,in}$ = 30..33°C should be avoided. Preheated feed water with higher temperatures should be integrated into the CHP process after the condenser.

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Nomenclature

h_{E1}	steam enthalpy (turbine stage 1), kJ/kg	P_{i2}	partial turbine power (stage 2), kW
h_{E2}	steam enthalpy (turbine stage 2), kJ/kg	P_{i3}	partial turbine power (stage 3), kW
h_{E3}	steam enthalpy (turbine stage 3), kJ/kg	p_{E1}	pressure (turbine stage 1)
h_{FD}	steam enthalpy (turbine inlet), kJ/kg	p_{E2}	pressure (turbine stage 2)
h_{KE3}	condensate enthalpy, kJ/kg	p_{E3}	pressure (turbine stage 3)
$h_{W,in}$	water enthalpy (condenser inlet), kJ/kg	p_{FD}	pressure (turbine inlet)
$h_{W,out}$	water enthalpy (condenser outlet), kJ/kg	T_{E1}	steam temperature (turbine stage 1), °C
$\dot{m}_{E1}$	steam mass flow (turbine stage 1), kg/s	T_{E2}	steam temperature (turbine stage 2), °C
$\dot{m}_{E2}$	steam mass flow (turbine stage 2), kg/s	T_{E3}	steam temperature (turbine stage 3), °C
$\dot{m}_{E3}$	steam mass flow (turbine stage 3), kg/s	$T_{W,in}$	water temperature (condenser inlet), °C
$\dot{m}_{FD}$	steam mass flow (turbine inlet), kg/s	$T_{W,out}$	water temperature (condenser outlet), °C
$\dot{m}_{W}$	water mass flow (condenser), kg/s	T_{KE3}	condensate temperature, °C
P_{Gen}	electrical generator power, kW	η	overall efficiency
P_{iGes}	total turbine power, kW	CHP	Combined heat and power
P_{i1}	partial turbine power (stage 1), kW	CIS	Commonwealth of Independent States

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