EVALUATION OF THE EFFECTS OF WASTEWATER HEAT PUMP INTEGRATION INTO DISTRICT HEATING SYSTEMS BY SIMULATION

by

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The integration of wastewater heat pumps (using purified water) in district heating systems is analyzed in this paper. The simulation procedure is proposed to analyze the impacts of stochasticity of purified water temperature and flow to heat pump integration and operation. The analysis includes calculation of the daily and seasonal coefficient of performance, as well as fossil fuel savings and CO_2 emission reduction due to wastewater heat pump use. The proposed procedure is implemented for the case study in the city of Šabac (Serbia) and obtained results are discussed and evaluated. The historical data for two heating seasons was used for simulation. It was shown that the wastewater heat pump could provide 27-28% savings in fuel consumption, and 3.6-4.1% GHG emissions reduction, while the seasonal COP could be 4.2 - 4.3. Simulation based approach shows approximately 40% less savings of fuel consumption, compared to the approach based on the average values of heat pump input parameters.

Key words: *wastewater, heat pump, district heating, simulation*

Introduction

Energy systems are transforming towards more intensive utilization of renewable and sustainable energy sources with aim to replace fossil fuels and reduce negative impact on environment and climate change [1]. Most of the district heating (DH) systems in the Europe are currently in the transition process from 3rd to 4th and 5th generation [2]. On the supply side, this process is characterized by substitution of combined heat and power and heat plants fueled mostly by fossil fuels with heat sources based on low temperature waste heat and RES. In this transition process, introduction of heat pumps is recognized as a very efficient solution for utilization of different low temperature heat sources [3-6]. In addition, due to significant increase of RES utilization for electricity generation, implementation of electrically driven heat pumps in DH systems should be one of the main mechanisms for decarbonization of heating energy sector [7-9]. However, finding a proper low temperature heat source that can be utilized by heat pumps in densely populated urban areas is not easy. Heat source should have a proper range of temperature, stability over time and proximity to DH network [10, 11].

Wastewater was officially recognized by the EU as a renewable source of energy [12]. In this way, wastewater treatment plant (WWTP) appeared as a source of a significant amount of low temperature heat and wastewater heat recovery became a valuable option for GHG emis-

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sions reduction [1, 4, 13]. The WWTP are usually located near urban areas, which implies that wastewater heat meets requirement for proximity of heat source. In addition, waste heat from wastewater heat is more long-term resilient comparing to industrial or excess heat [14]. After treatment in WWTP, the temperature of treated (purified) water is usually significantly over outdoor temperature [15]. This water temperature is characterized by seasonal, predictable and relatively low variation [16]. However, the variations of threated water flow rate are unpredictable and significantly higher [15].

Various case studies have been published to present the state-of-the-art integration of wastewater heat pump (WWHP) into DH and cooling systems [17-20]. Each of the analyzed systems can be considered unique, with different energy savings, increasing the share of RES, and reduction in GHG emissions [1].

Heat pump operation in DH systems is strongly affected by the characteristics of treated water and by the DH systems operation regime [20]. Heat pump power is directly proportional to the flow rate and temperature of treated water, while the efficiency of a heat pump (indicated by COP) is strongly affected by the temperature of a heat source (treated water) and the temperature regime of water in a DH system. The temperature regime of water in a DH system is the function of outdoor temperature and other weather conditions. Therefore, the real efficiency of heat pump operation (expressed as seasonal COP) can be evaluated only after some period of operation [21]. The GHG reduction depends on fuel, previously used in the DH system, but also on an energy mix that is used in electricity production.

In the phase of the heat pump selection and design, it should be very useful to have information about the expected results of heat pump operation in the reality, considering all parameters that may influence its operation. Therefore, in this paper, the simulation procedure to analysis of the impacts of all previously mentioned parameters on the effect of heat pump integration in the existing DH systems is proposed. The operation of a selected heat pump is simulated. Available waste heat is calculated, the heat pump COP is selected and produced energy is calculated based on historical hourly data about treated water flow rate and temperature, as well as on historical data about the outdoor temperature and temperature regime in a DH system in the same period. Thereafter, obtained data about hourly, daily, and annual heat pump production and electricity consumption are used for calculation of daily and seasonal COP, as well as for evaluation of fossil fuel savings and CO_2 reduction due to WWHP integration in a DH system.This procedure was implemented in the city of Šabac, Serbia, as a case study. The operation is analyzed with and without daily heat storage, based on available historical data for two heating seasons.

Methodology for simulation of WWHP integration in DH system

System configuration

This research is focused on the problem of WWHP integration in the existing DH system (in operation) fueled by natural gas (or some other fossil fuel). To achieve maximal technical and economic feasibility, the WWHP is used for baseload cover, while the fossil-fueled heat plants will be used to cover the remained heat demand, including peak load. The typical scheme of the existing DH system with integrated WWHP is presented in fig. 1.

The optimal location of a WWHP is in the near vicinity of the existing DH plant. The reason is the minimizing costs of water transport and heat losses. The treated water is pumped to the heat pump evaporator by uninsulated pipes, while the transport of hot water, after the heat pump, required insulated supply and return pipe-lines. The desirable option is to discharge

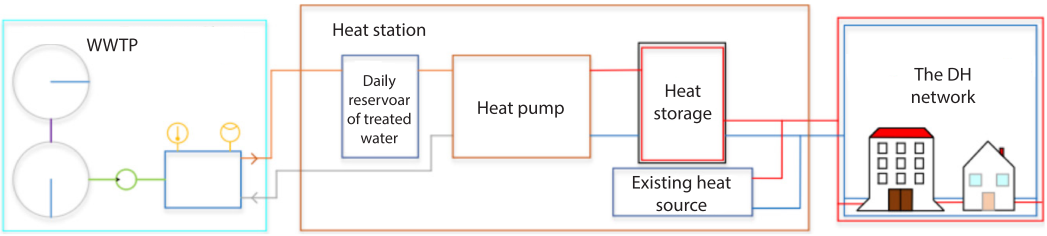

Figure 1. General scheme for WWTP integration in DH system

treated water at the heat pump location if it is possible. Otherwise, the treated water must be pumped in a loop, back to the WWTP, and be discharged at the regular location.

A daily reservoir of treated water is installed at the discharge of WWTP, before the heat pump. This reservoir operates as a *buffer* to optimize the amount of treated water introduced into a heat pump. It aims to reduce the variability of the wastewater flow into a heat pump during the day. When the flow from the WWTP is higher than the maximum acceptable for the operation of a heat pump, this reservoir would be supplied with excess water. The water from the reservoir later would be used as an additional input to the heat pump, in cases of insufficient flow from the WWTP.

The purpose of a heat storage installation is to ensure maximal economic and environmental effects of the heat pump operation. The produced heat substitutes energy that otherwise would be produced by the combustion of fossil fuel. Consequently, the reduction of fossil fuel use and the reduction of emissions are proportional to the duration of heat pump operation. The introduction of heat storage enables a longer period of heat pump operation during a heating season. In periods without heat supply to consumers, produced energy is stored and distributed when the demand exists.

Simulation of operation

The simulation of WWHP operation should provide information about amount of heat that could be produced from this RES and associated electricity consumption for a heat pump operation. Recoverable heat power of treated wastewater [kW] is determined:

$$\dot{Q}_w = \dot{m} c \Delta T \tag{1}$$

where $\dot{m}$ [kgs^{-1}] is the mass-flow, c [kJkg^{-1}K^{-1}] is the specific thermal capacity, and ΔT [K] is the temperature difference of treated water. The common range of temperature difference between the entrance and the exit of the heat exchanger-evaporator is 3-5 K [22].

The mass-flow and the temperature difference are major variables in calculating the recoverable heat potential of wastewater treatment plants. However, the mass-flow rate in eq. (1) cannot be over nominal value at the heat pump entrance. In the cases of higher flow, the reservoir of treated water is filled by overflow. Mass-flow of treated wastewater at the inlet of the heat pump evaporator will remain at maximal value, even if the real flow rate at discharge from WWTP is lower, as long as there is water in a buffer reservoir. In the case when the buffer is empty, the real flow rate at the discharge from WWTP is used in eq. (1).

Heat energy is produced in heat pumps by utilizing recoverable heat:

$$\dot{Q}_h = \dot{Q}_w \frac{COP}{COP-1} \tag{2}$$

and by using electricity for compressor operation:

$$\dot{Q}_E = \dot{Q}_h \frac{1}{COP} \tag{3}$$

where $\dot{Q}_h$ [kW] is the thermal power of heat pump, $\dot{Q}_E$ [kW] is the power of heat pump compressor, and COP is the coefficient of performance.

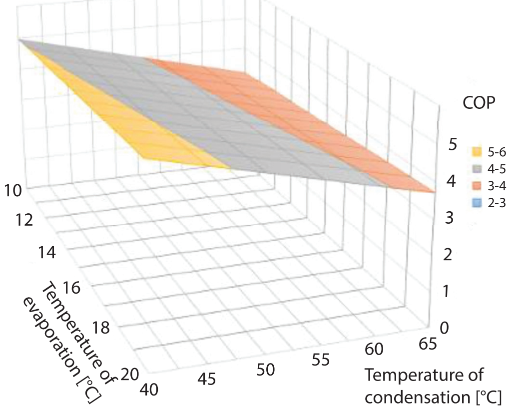

Figure 2. Calculated COP factor for ammonia heat pump

Heat power and engaged compressor power are calculated based on recoverable heat power of treated water and selected COP. The COP for a water-to-water heat pump is strongly dependent on the temperature of the heat source (the treated water) and the temperature of the heat sink (the supply water to the DH system). Evaluation of COP, for different source and sink temperatures for large-scale ammonia heat pumps, is shown in fig. 2. It is calculated based on [23-25]. The figure shows COP increase with an increasing evaporation temperature and COP decrease with increasing condensation temperature. In general, COP decreases with an increase in temperature difference between condensation and evaporation. The values of COP over 5 are possible for temperature of condensation less than 45 °C, with the evaporation temperature over 12 °C, while if the temperature of condensation is over 60 °C, COP is less than 4. To provide better characteristics of heat pump operation, temperature of condensation is limited to 65 °C, while the minimum temperature of evaporation is limited to 10 °C.

For the simulation of the whole system operation, the measured hourly data about the temperature and flow rate of treated water should be provided, as well as the corresponding data about the outdoor temperature, for a whole heating season(s). The outdoor temperature is used as a parameter for the determination of supply and return temperature in a DH system, in which a heat pump is aimed to be integrated. As an example, the supply and return water temperature profile, in a DH system with the constant flow, as a function of outdoor temperature for a selected DH system in Serbia is presented in fig. 3 [26]. The DH system operates in a closed cycle. Supply water is heated in a heat pump and/or heat plant, then transported by insulated pipes, and transfer heat to consumers at heat exchangers. Chilled water is returned to the heat pump and/or heat plant for new heating. It is noted that with the decrease of outdoor temperature, temperatures of supply and the return water increase, as well as the difference between them. Since the temperature of purified water, at the exit of the WWTP, has the same reverse dependence on outdoor temperature, the heat pump will obtain its maximum power and best performance during periods of relatively higher outdoor temperatures, while during periods of colder weather it will operate with lower power

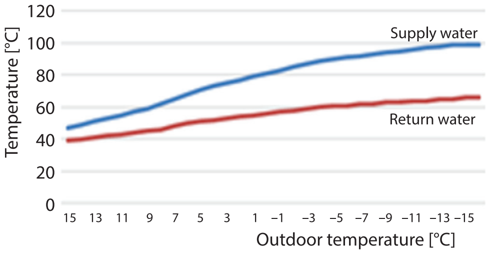

Figure 3. Supply and return water temperature profile in the constant flow DH system

and slightly lower efficiency (COP). Taking into consideration the accepted limit for the temperature of condensation (65 °C), it is evident that the heat pump itself can provide a desirable temperature regime for outdoor temperatures 7 °C and higher, while for outdoor temperatures corresponding to return temperature higher than 65 °C, the heat pump will not be in operation.

Calculating powers from eqs. (1)-(3) for every hour in the heating season provides information about consumed or produced energy in the selected hour, fig. 4. In that way, the analysis of WWHP operation can be done for an hour, day, selected period, or the whole heating season. For a more realistic picture of WWHP potential and efficiency, the historical data for more heating seasons should be used, and the proposed procedure should be conducted.

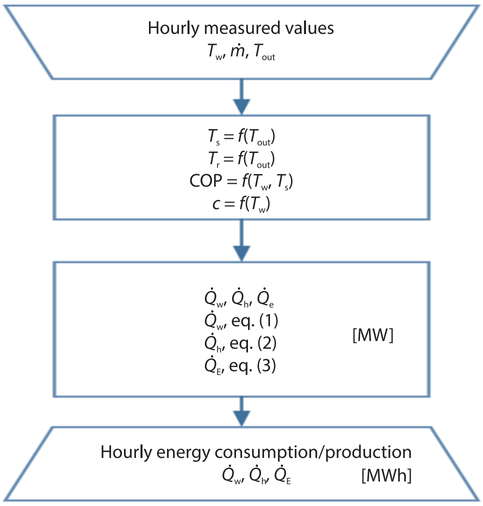

Figure 4. Simulation flow chart

In addition, GHG savings due to WWHP introduction can be calculated as a difference between the emissions from the DH system after the heat pump implementation, and the emissions that would be for the generation of the same amount of energy using the conventional (currently use) technology.

Case study: Simulation of WWHP integration in Šabac DH system

The DHS in Šabac

Approximately 7600 households and 540 customers from the commercial group (public and commercial buildings, industry*, etc.*) in Šabac are supplied with heat from the DH system. There is no domestic hot water production [26].

The heating season lasts from October 1st until April 30th. Heat is supplied on days when the average outdoor temperature is less than 12 °C. Usually, heat is supplied 16 hours per day, except during the *ice days* characterized by an average daily temperature lower than –3 °C, when the heat energy is delivered 24 hours per day.

Heat production is completely based on natural gas use. The total, nominal heat power of three heat plants is 67.2 MW. The base load is approximately 10 MW, while the maximal recorded power accounts about for 80% of the available nominal power of heat sources [26]. The average annual natural gas consumption is around 7 million m^3, with the average efficiency of heat sources of 92%. The heat network is built from pre-insulated pipes, and it is 23 km long. The average heat losses in distribution are 10.15% [27].

Energy potential of WWTP – temperature and flow of purified wastewater

Wastewater generated in Šabac is by origin mainly communal, and to a lesser extent treated industrial wastewater or infiltration water. The technology of wastewater treatment within the plant includes physical and biological treatments with incorporated nitrification and denitrification processes, as well as sludge treatment. Purified water is discharged into the Sava River. The facility is in operation since 2018.

The water temperatures at the discharge point to the Sava for the period January-April 2018, and for the 2018/2019 and 2019/2020 heating seasons are presented in fig. 5. The water temperature directly depends on the ambient temperature. Even in the case of the lowest recorded outdoor temperatures in the considered period, the treated water temperature was not lower than 10 °C. Therefore, a 5 °C temperature reduction in the heat pump evaporator is assumed eq. (1).

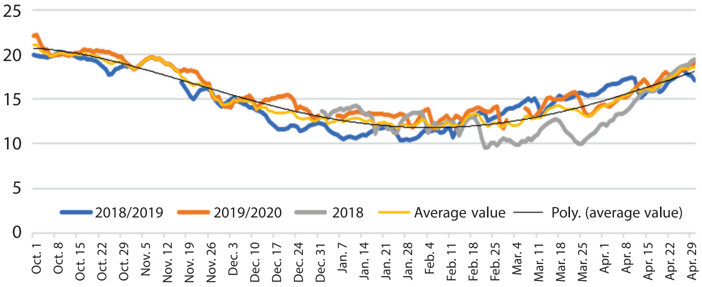

Figure 5. Daily water temperature at the discharge of WWTP

Unlike the water temperature at the discharge, which is dependent on the outdoor air temperature and is relatively predictable, the water flow is characterized by significantly greater variation and unpredictability. As an illustration, the variation of flow in the 2019/2020 heating season is presented in fig. 6. The average ratio of hourly maximum and minimum flow during the day is 3.1 for the considered period, but for some days this ratio was higher than 5 and in extreme cases even higher than 10.

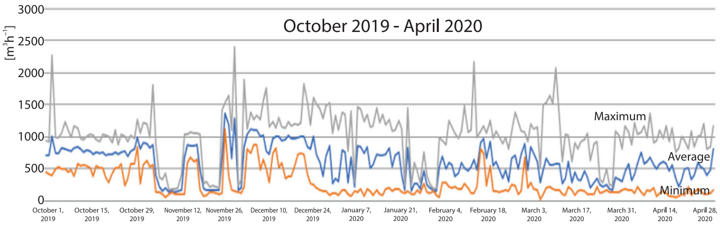

Figure 6. Average, minimal and maximal hourly water flow at the discharge point of WWTP

Stochasticity of a flow and temperature variability causes the variability of the recoverable heat potential of purified water, and consequently, the amount of energy that could be produced. The available heat power of WWTP as a heat source is presented in tab. 1. Values of heat power are calculated using eq. (1) for the monthly averages, mean minimums, and maximums of the flow. By months, the average power of the heat source ranges from 2836 kW in January to 4038 kW in March, *i.e.*, it is in the range of ±20% of the average value (3518 kW). The ratio between the maximum and minimum available power during the month is significant (from 2.5-3).

Table 1 Recoverable heat potential [kW]

Month	October	November	December	January	February	March	April
Average	3076	3409	3714	2836	3924	4038	3845
Minimum	1805	2002	2035	1452	2438	2359	2040
Maximum	4368	5085	5556	4506	6012	6324	6218

Selection of a heat pump, heat storage and reservoir of purified water

The selection of a heat pump is based on the characteristics of the heat source (WWTP) and the consumption pattern of the DH system. A single heat pump of 6 MW nominal power, with a two-stage compressor and with ammonia as a working fluid is selected. This heat pump corresponds to the average flow rate of purified water in the considered period (683 m^3 per hour).

To achieve optimal system operation (maximizing COP), the heat pump should be adjusted to operate in a limited temperature range. The maximum output temperature of the water was selected to be 65 °C. In this way, the COP was ensured to be at least 3, even in the least favorable case, fig. 2. If necessary, water from the heat pump output will be further heated in the existing heat plant.

The reservoir of purified water and heat storage, each of 2500 m^3 capacity, are selected to satisfy demands on a daily base.

Effects of heat pump utilization

Analysis of daily operation

For analyzing effects of daily operation, two days from the 2019/2020 heating season were selected. For these days hourly changes of outdoor temperatures, as well as mean hourly flow and an average temperature of purified water for these two selected days are presented in fig. 7. The days were chosen to represent low energy demand (November 1st, 2019 – the beginning of the heating season, relatively high outdoor temperature), and high energy demand (December 30th, 2019, temperature below 0 °C throughout the day).

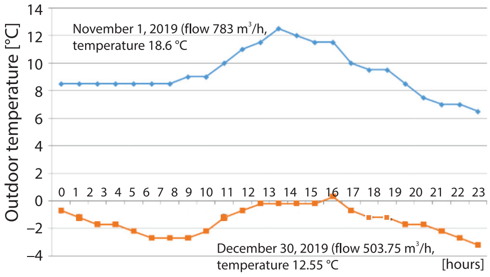

Figure 7. Outdoor temperatures for selected days

The results of the simulation of the DH system operation in these two days are presented in fig. 8. The hourly engagement of the heat power of gas boilers, heat pumps, and heat storage to meet the heat demands are presented, as well as shares of each heat source in providing the daily required amounts of heat. The simulation of the heat storage operation during these two days is given in fig. 9.

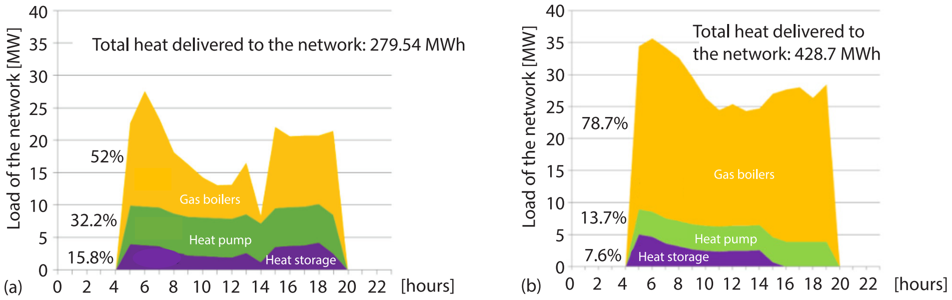

Figure 8. Simulation of the daily heat supply; (a) low energy emand and (b) high energy emand

The considered day of low energy demand for heating is characterized by a flow of purified water that is higher than the nominal as well as by the high temperature of purified water. In such a case, the heat pump would operate with maximal power. The share of heat energy produced by the heat pump (with the usage of heat storage) is 48%. The distribution of heat energy from the heat storage is determined by the maximum supply flow and temperatures in the

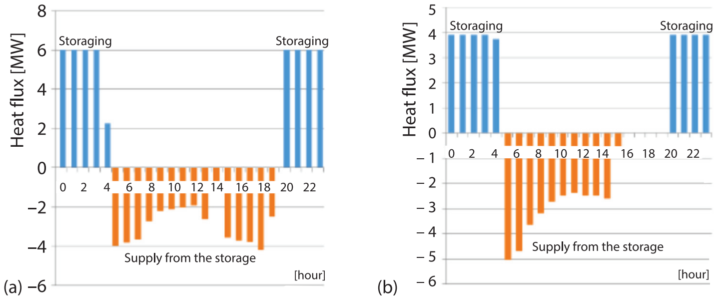

Figure 9. Simulation of the daily heat storage operation; (a) low energy emand and (b) high energy emand

supply and return lines, while the dynamic of the discharge follows the heat load curve, fig. 8. The average daily COP, in this case, would be 4.77.

In the case of high energy demand, the available flow of purified water was lower than the nominal one and the heat pump would not be able to reach the nominal power. The storage discharge dynamic follows the load curve, but as the actual heat pump power would be less than 2/3 of maximal, the heat storage would be discharged at 3 p. m., fig. 9. In this case, the average daily COP value would be 3.97.

Analysis of annual operation – energy efficiency and natural gas savings

The possible annual share of heat that could be produced by a heat pump in Šabac DH system was determined based on a simulation of a heat pump operation in two heating seasons: 2018/2019 and 2019/2020. The actual recorded values of supply and return water temperatures in the DH network were used for the simulation, for each hour during the analyzed period. The introduction of a daily reservoir of treated water mitigates daily variation of wastewater flow, while the temperature variations during the day are negligible. Therefore, the average daily values of flow and temperature were used for simulation of the heat pump production and operation of daily heat storage.

Daily average of engaged heat power of heat pumps in the 2018/2019 and 2019/2020 heating seasons are presented in fig. 10. Obtained results indicate that the average heat power provided by the heat pump would be 3.55 MW (59.1% of heat pump nominal power) and 3.66 MW (61% of heat pump nominal power) in the 2018/2019 and 2019/2020 heating seasons, respectively. This means that although heat pump power was selected in accordance with the average flow, power in operation is approximately 60%, mostly due to the stochasticity of treated wastewater flow. The wastewater temperature affects the heat pump power by variability of specific thermal capacity in eq. (1), but this influence is less significant. Results of heat pump operation simulation for these two seasons are summarized in tab. 2.

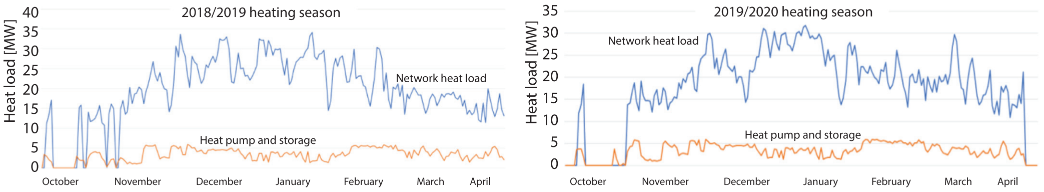

Figure 10. Daily engaged heat pump power and network heat load

Table 2. Annual parameters of the simulation of the DH system operation

Heating season	2018/2019		2019/2020	
Operation time	[hour]		[hour]	
Period of heat supply to consumers	2433		2543	
Period of heat pump operation	4226		4235	
Period of supply from heat storage	1134		1126	
Energy production	[MWh]	[%]	[MWh]	[%]
Heat energy in the DH network	55175.7	100	54495.4	100
Gas boilers	39868.9	72,3	38696.0	71.0
Heat pump	15306.8	27.8	15799.4	29.0
Directly	9535.7	17.3	9961.9	18.3
From the heat storage	5771.1	10.5	5837.5	10.7
Avoided natural gas consumption	16820.7	-	17362.0	–
Electricity for the heat pump operation	3629.4	6.6	3687.5	6.8
COP – seasonal	4.22		4.28	

The GHG Emissions

Emissions of GHG from the existing DHS in Šabac, as well as from the DHS with an integrated heat pump are presented in tab. 3. Table includes emissions due to natural gas combustion in boilers during the heat production, as well as emissions in the power sector during the production of electricity necessary for heat pump and circulating pumps operation [28].

For both heating seasons, the reduction in GHG emissions is achieved (466-522 tones per year). These reductions are proportional to achieved seasonal COP, that is the reduction is higher in the 2019/2020 heating season.

Table 3. The GHG emission in baseline case and with heat pump implementation (tones CO_{2eq})

Emission source	Baseline		With heat pump	
	2018/2019	2019/2020	2018/2019	2019/2020
Boilers	12118	11968	8719	8460
Electricity for existing equipment operation	878	878	838	838
Electricity for heat pump operation			2504	2544
Electricity for circulating pumps operation			469	482
Total	12996	12846	12530	12324
Difference to current state	–	–	–466	–522
Achieved reduction of CO_{2eq}	–	–	3.6%	4.1%

Discussion of results

Purified wastewater has significant energy potential, that only could be utilized through DH systems. The main challenge in its utilization is unpredictability and significant variability of purified wastewater flow. The reservoir of purified water of 2500 m^3 capacity was designed to ensure 10 hours of average flow to supply the heat pump in the case of average minimal flow at the discharge point of WWTP. However, the simulation of annual operation shows that this capacity should ensure the average availability of approximately 60% of nominal heat pump power during the heating season. The increasing of the capacity of reservoirs of purified water would increase this availability, but the problem could be the availability of space for additional reservoirs, as well as the additional costs.

The analysis of simulations of daily operation indicates that the maximal efficiency of a heat pump is obtained in periods of relatively low heat demand. That is the period with the highest temperature of the heat source and the lowest temperature of the heat sink. Such conditions are characteristic of the beginning and the end of the heating season. Under optimal conditions, COP in that period could be close to 5. The daily COP in the periods of high heat demand is less than 4 as the consequence of a bigger difference between temperatures of the heat source (treated wastewater) and heat sink (supply water).

The analysis of annual operation shows that period of heat pump operation are around 4230 hours. Energy production of this system would be around 15300-15800 MWh in regular heating season that is around 25-30% of total heat energy in DH network. This also means, that the avoided natural gas consumption is between 16820 MWh and 17362 MWh. In addition, the analysis of annual operation shows that in the case of the city of Šabac, 17.3-18.3% of DH system heat demand could be covered by a WWHP and an additional 10.5-10.7% by the utilization of heat storage. Obviously, using of a heat pump without heat storage is irrational, as the heat consumption has daily breaks (there is no domestic hot water supply). Without heat storage, the heat pump operation would be limited to 2400-2500 hours per year. The calculated share of WWHP with heat storage in heat production is significantly less than the calculated value obtained with nominal heat pump power (6 MW × 4000 h = 24000 MWh). The reduction (approximately 40%) is the consequence of the previously mentioned treated wastewater flow stochasticity.

The overall efficiency of heat pump operation, expressed by COP, for both seasons is very similar (4.22 and 4.28). In season 2019/2020 is slightly better due to slightly higher outside temperatures in that heating season.

For both heating seasons, the reduction in GHG emissions is achieved. The reduction of primary energy (natural gas) consumption is not followed by a proportional reduction in GHG emissions, due to mostly coal-based electricity production in the Serbian power sector. The CO_{2eq} emission reduction is between 3.6 and 4.1%. With the expected change in the Serbian power sector and a higher share of RES in electricity production, the GHG reduction will be more significant.

Conclusions

Treated wastewater heat presents viable RES potential. This RES is available in all cities, densely populated urban areas, with WWTP. The utilization of this, low temperature energy source is only possible by heat pumps, while due to significant capacity, the DH systems are ideal recipients of produced energy. As the transformation of DH systems leads to a lowering of supply water temperature, the significance of WWHP implementation will grow in the future.

The amount of produced energy and the efficiency of heat pump operation strongly depends on the characteristics of treated wastewater (temperature and flow) and DH system operation (temperature of return and supply water). These characteristics and associated values are variable – all temperatures are strongly dependent on outdoor temperature, while the wastewater flow is very unpredictable. Therefore, in the phase of preliminary designing and feasibility analysis, stochasticity of outdoor temperatures and wastewater flows should be taken into consideration, to avoid incorrect conclusions obtained by using average values of listed characteristics (an approach which is mostly correct in cases of constant flow and temperature of heat source). The procedure, proposed in this paper, takes into consideration historical data of WWTP operation and associated data about outdoor temperature for simulation of the operation of heat pump integrated into the existing DH system.

The proposed procedure was implemented for the analyses of the process of WWHP integration in the DH system in Šabac (Serbia). The historical data for two heating seasons was used for simulation. It was shown that the WWHP could provide 27-28% savings in fuel consumption, and 3.6-4.1% GHG emissions reduction, while the seasonal COP could be 4.2-4.3. Although this approach shows approximately 40% less savings of fuel consumption, compared to the approach based on the average value, it gives a more realistic picture of possible achievements with WWHP use and should be used in further economic analysis.

Nomenclature

c – specific thermal capacity, [kJkg^{-1}K]
$\dot{m}$ – mass-flow, [kgs^{-1}]
$\dot{Q}_h$ – heat pump power, [kW]
$\dot{Q}_E$ – power of heat pump compressor, [kW]
$\dot{Q}_w$ – heat power of treated wastewater, [kW]
ΔT – temperature drop in evaporator, [K]
T_w – temperature of purified water, [K]
T_{out} – outdoor temperature, [K]
T_r – temperature of return water, [K]
T_s – temperature of supply water, [K]

Acronyms

DH – district heating
WWHP – wastewater heat pump
WWTP – wastewater treatment plant

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