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High-Resolution Assessment of Wastewater Heat Recovery Potential for Urban Decarbonization

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Abstract

This study assesses the technical potential for wastewater heat recovery in Sofia and its contribution to domestic hot water supply and greenhouse gas reduction. Heat extraction locations were identified using temperature and flow data from the sewer network and the municipal wastewater treatment plant (WWTP) Kubratovo. Temperature thresholds were defined to ensure stable biological treatment ($\geq 10°C$ influent) and environmental protection ($\geq 5°C$ effluent). Four scenarios were analyzed, considering heat recovery at the WWTP inlet and outlet with $\Delta T = 2–4$ K. The heat recovery potential is evaluated using 15-minute temperature and flow data by applying scenario-specific temperature thresholds, enabling a dynamic assessment that captures real variations in both flow and temperature and explicitly accounts for system shutdown periods. Heat recovery at the WWTP effluent provides higher and more stable yields than at the influent. The potential ranges from 238,536–380,314 MWh/year at the inlet and 264,828–529,705 MWh/year at the outlet. Under the most favorable scenario (effluent, $\Delta T = 4$ K), the recovered heat can supply domestic hot water to over 76,000 households, reducing emissions by more than 200,000 t CO_2/year when replacing natural gas.

Keywords: Wastewater Heat Recovery; Sewer Network; Wastewater Treatment Plant; Thermal Energy Recovery; Urban Decarbonization.

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1. Introduction

Sustainable management of energy under increasing climate and resource availability pressures requires the exploration of alternative, low-carbon energy sources. The revised EU Renewable Energy Directive sets a binding target of at least a 42.5% share of renewable energy in the EU's gross final energy consumption by 2030, with an indicative target of 45% [1]. These ambitious goals require the integration of non-conventional renewable energy sources to reduce dependence on fossil fuels.

Bulgaria's Updated Integrated National Energy and Climate Plan (2024) is in line with the EU climate and energy framework and sets an ambitious target of at least a 34% share of renewable energy by 2030 in the electricity, heating and cooling, and transport sectors [2]. Since 2021, all new buildings in Bulgaria are required to comply with the definition of nearly zero-energy buildings (nZEB). This implies that 55% of the electricity and thermal energy consumed

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during buildings' life cycles must be generated from renewable energy sources (RES). Although no national legislation framework has yet been formally enforced to regulate these requirements in detail, the obligation is in force [3].

Municipal wastewater is increasingly recognized not only as a waste stream but also as a potential carrier of recoverable resources, including energy, within the framework of sustainable and circular urban systems [4-6]. The theoretically recoverable heat from the wastewater can be estimated through the specific heat capacity and flow rate. Thus, for water ($\rho \approx 1000$ kg/m^3, cp ≈ 4.18 kJ/kg·K), a temperature difference of 1 K corresponds to approximately 1.16 kWh energy per cubic meter. Usually, the wastewater temperature varies significantly depending on the season and wastewater sources. Hart & Halden [7] report that about 75% of the global wastewater temperatures are in the range of 6.9 to 34.3°C over a year. Thus, the heat of the municipal wastewater has the potential to be an efficient, alternative energy source. In recognition of this potential the EU Renewable Energy Directive 2018/2001 classifies wastewater heat as a renewable resource [8].

Recovered heat from wastewater can serve various end uses depending on the scale of recovery and proximity to consumers. Wastewater heat recovery can generally be implemented at three main levels within the urban water system.

- At the source: Individual in-building systems extract heat directly from domestic wastewater streams [9, 10], most commonly for domestic hot water preparation.
- Along the sewer network: Heat can be recovered from sewer collectors, serving individual buildings, neighborhoods, or larger urban areas [11].
- At the wastewater treatment plant (WWTP): Finally, heat recovery can be applied either at the influent or effluent of the WWTP, where large and more stable flows are available.

When applied at the network or at the WWTP level, the recovered heat is typically used for space heating and/or domestic hot water preparation, most often via heat pump systems that upgrade low-temperature sources to usable levels [12, 13]. In urban areas with centralized heating, this heat can be integrated into the network, replacing fossil-based heat generation [14]. Seasonal operation is also possible: in winter, heat pumps provide heating of the premises, while in summer they can be used for cooling, for example through reversible heat pumps or absorption chillers [4]. However, the extent of heat extraction is limited, as excessive cooling of wastewater is not recommended [15].

Wastewater heat recovery projects have been implemented in Europe for several decades, with early examples in Norway and Sweden demonstrating both technical feasibility and long-term operational stability. Oslo has integrated the wastewater heat into its district heating system since the 1980s, and Stockholm has developed a large-scale heat recovery project to support its extensive district heating network [14, 15]. Representative case studies, in a real operational environment, are summarized in Table 1, demonstrating the growing adoption of wastewater heat recovery as part of national and municipal strategies for energy neutrality and decarbonization.

Table 1. Some successfully implemented, ongoing and planned projects for wastewater heat recovery

Country	City	Heat source	Installed Heat Plant capacity (MW)	Source temp (°C)	Flow (l/s)	Status / Year	Reference
Sweden	Stockholm	WWTP effluent	225	7-22		Operational since 1986; ongoing	[16]
Norway	Sandvika (Oslo area)	WWTP influent	13		3000	Operational since 1989 + new power in 2013	[17]
UK	Kingston upon Thames (London)	WWTP effluent	1.5		744	Detailed Feasibility 2020; council updates 2024	[18]
Germany	Lemgo	WWTP effluent	2.4	13		Operational ~2019-2020	[19]
UK	Galashiels, Scotland	Sewer network	0.8	12-15		Operational 2015-2016	[20]
Austria	Vienna (Simmering)	WWTP effluent	55			Phase 1 in operation Dec 2023; expansion to 110 MW planned by 2027	[21]
Switzerland	Zuerich (Altstetten & Hoengg)	WWTP effluent		11-15	~2500	Phased build-out 2018-2026+ (172 GWh heat / 35 GWh cooling in end state)	[22]

The wastewater heat recovery has been predominantly implemented for WWTP effluent, thus not affecting the treatment processes. This approach simplifies the operational control and allows for a greater permissible temperature drop compared to the heat recovery for WWTP influent, thereby increasing system efficiency [14, 15]. Heat recovery can also be realized in the sewer collectors [11], closer to the potential consumers, thus increasing the efficiency.

The temperature decrease of wastewater due to heat recovery is a critical factor determining the overall efficiency of the process. In case of heat recovery either along the network or from the WWTP influent, the excessive cooling of the wastewater flow may have a consequent negative impact on the efficiency of the nitrification process [11, 15]. Additional challenges may occur in combined sewer systems, where rainfall and snowmelt can substantially reduce wastewater temperatures and increase hydraulic turbulence, leading to sediment resuspension and heat exchanger fouling [23]. In case of heat recovery from the WWTP effluent, the temperature reduction may affect the receiving river body ecosystem; thus, the allowable temperature decrease needs to be compliant with the specific climate and natural conditions. The distance to end users turns out to be also a critical factor influencing the overall heat recovery system's efficiency; the closer the consumers benefiting from the heat recovery are, the better [15, 24]. In many studies the threshold temperatures are defined by the water utilities, while the underlying criteria and methods are not always explicitly described [4, 25]. Furthermore, assessments often rely on modeling approaches or aggregated (e.g., daily) data [4, 25], which may not fully capture intra-day variability of the temperatures or the impact of rainfall events, particularly in combined sewer systems.

The need to clarify these site-specific and sewage system-specific factors limits the widespread use of heat recovery from wastewater, although the successful large-scale implementations demonstrate the technical feasibility of this green energy approach. In Bulgaria, the energy recovery technologies such as anaerobic digestion of the excessive sludge and consequent combined heat and power generation are applied only in the bigger WWTPs, and the energy utilization is within the WWTP's campus, whereas the direct recovery of heat from sewer systems or WWTP influent or effluent for use in neighboring areas or district heating networks has not yet been implemented [5].

This study presents a city-scale assessment of the wastewater heat recovery potential of the sewer system of Sofia, Bulgaria. High-resolution operational input data of the temperature and flow of the sewer network and of the influent and effluent of WWTP Kubratovo have been used. The analysis integrates multiple heat extraction points and evaluates seasonal and diurnal variability, as well as the influence of external factors such as rainfall events. Different temperature thresholds and permissible temperature drops are selected, analyzed, and compared considering the operational requirements of the wastewater treatment process and the seasonal temperatures of the receiving river body. By capturing the dynamic behavior of both flow and temperature, the study provides a more representative estimation of recoverable heat and its potential contribution to domestic hot water supply and urban decarbonization. The results support low-carbon heating strategies by providing a quantified basis for decision-making in the selection of optimal heat recovery locations and estimation of the potential energy yields.

2. Characteristics of the Case Study Area

Sofia Municipality has a population of over 1.2 million inhabitants, with the vast majority residing within the urban area [26]. The city is located at an average elevation of approximately 550 m above sea level in the Sofia Valley and represents the most densely populated region in Bulgaria (≈960 inhabitants/km²) [27, 28] (see Figure 1).

Figure 1. Study area and main sewer network collectors with temperature monitoring locations

The climate is moderate continental, with distinct seasonal variations in temperature (see Figure 2). The maximum temperatures exceed 30-35°C in June-August, while the winter temperatures may drop below -10 to -15°C in December-February [29]. Precipitation is unevenly distributed throughout the year. The long-term mean annual precipitation is about 676 mm (2012-2022), with a slightly lower value of 611 mm recorded in 2022 [29]. The rainfall in June typically accounts for about 13% of the annual total, but its share exceeds 25% in 2022 [29].

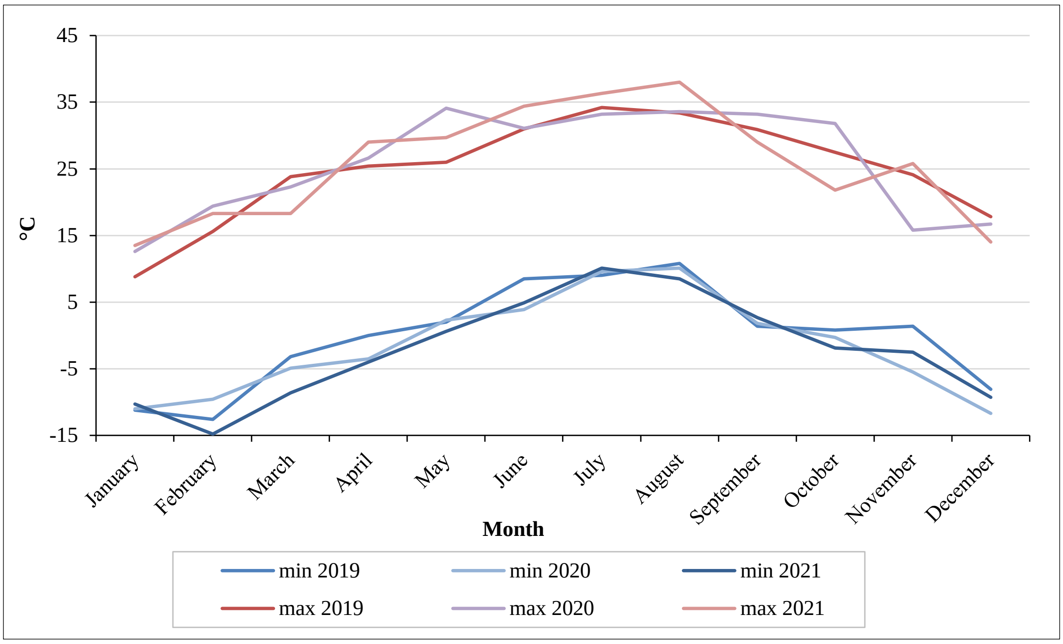


Figure 2. Max and min monthly temperatures in Sofia

2.1. Heating System

The heating season in Bulgaria is normatively set in the period October – April, as the exact start and end dates depend on the actual weather conditions and forecasts [30]. The heat supply companies should be ready to deliver heating within this period.

A part of Sofia city has centralized district heating system based on combined heat and power production. Due to the nature of district heating networks, they are developed in areas with higher population density. Heat production is ensured by two thermoelectric power plants (TPPs), two heating plants (HPs), and seven temporary heating plants (THPs). Natural gas is the primary fuel used, and at present these facilities provide reliable heat supply to connected consumers [3].

The heating company "Toplofikatsiya Sofia" is the largest natural gas consumer in Bulgaria. The company serves more than 410,000 residential and commercial customers and their number increases annually by 0.5–0.7%. Over the last decade, the connected design heat load has grown by 7.7%. At present, however, the electricity and heat produced by "Toplofikatsiya Sofia" do not meet the renewable energy share required for nZEB compliance [3]. A significant part of the key installations of "Toplofikatsiya Sofia" are outdated and at the end of their service life, in need of urgent replacement with modern, highly efficient technologies [3].

2.2. Water Supply and Sewerage Systems

100% of the population in Sofia City is connected to the centralized potable water supply system, and 96% are connected to the sewer network and the WWTP [31]. In 2022 the sewer network is predominantly combined (2,725 km), with only a small proportion (about 220 km) being separate. In the central urban areas, the network is predominantly combined, with 233 combined sewer overflows to relieve the hydraulic load of the collectors during rainfall events. In newer residential districts, separate systems are more common. The collectors are built mostly with concrete pipes conveying the wastewater predominantly by gravity to the WWTP. There are also a few low-lying satellite districts where the wastewater is pumped into the main sewer network via four pumping stations (PS): Novi Iskar, Gorublyane, Iliyantsi, and Benkovski (the last 3 are shown on Figure 1). The two main incoming sewer collectors to the treatment plant ("Vodyasht 1" and "Vodyasht 2") are above-ground channels covered with concrete slabs, while in the immediate vicinity of the WWTP they transition into open channels. WWTP Kubratovo is located northeast of Sofia, as shown in Figure 1.

3. Methodological Framework, Data Sets and Theoretical Background

3.1. Methodological Framework for Data Selection and Analysis

A stepwise methodological framework based on high-resolution temperature and flow data was applied to assess the wastewater heat recovery potential. The approach follows a structured sequence of analytical steps, illustrated in Figure 3.

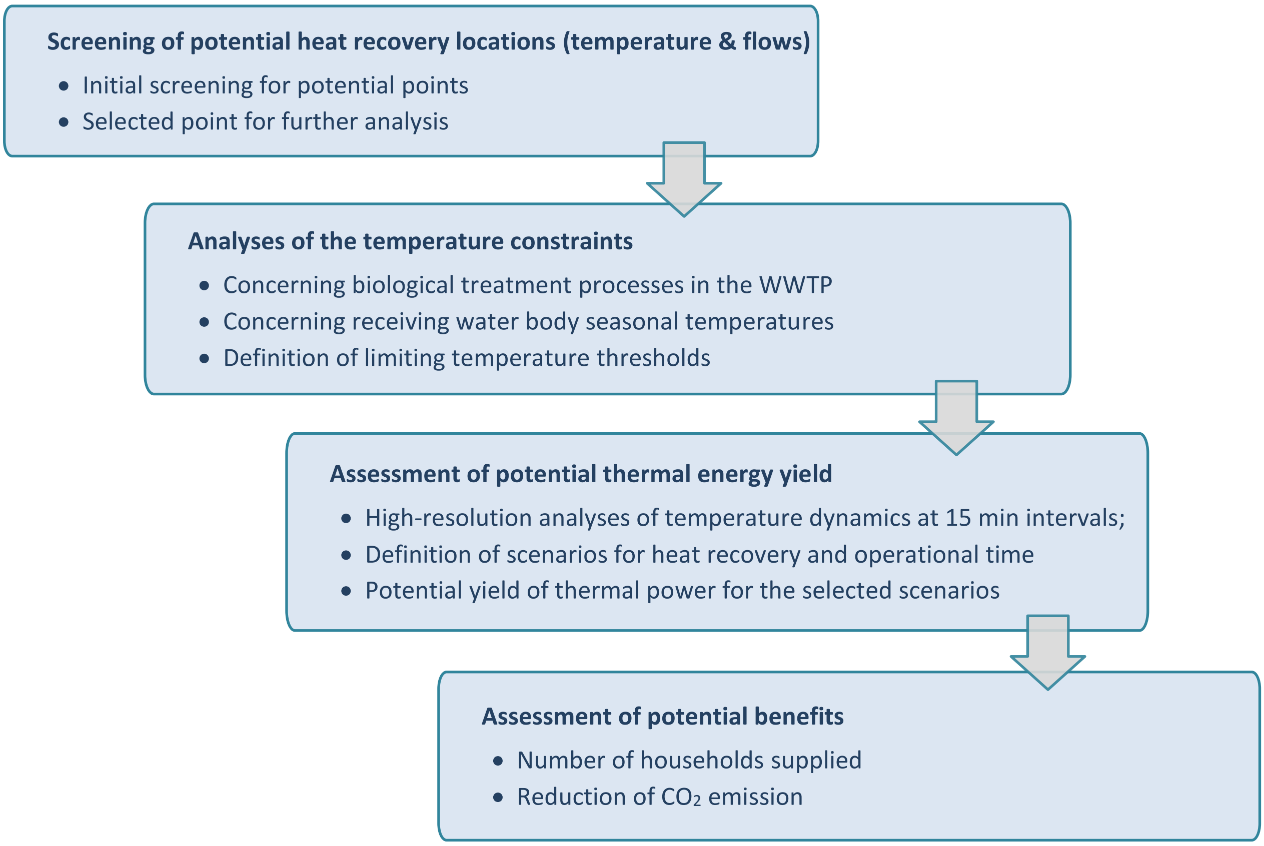


Figure 3. Flowchart of the methodological framework for wastewater heat recovery assessment

- **Selection of monitoring locations** within the sewer network and at the WWTP (influent, biological treatment stage, and effluent), based on the operational data availability and relevance for heat recovery assessment.
- **Data compilation and pre-processing**, including quality control, removal of incomplete records, and harmonization of temporal resolution to 15-minute intervals where applicable.
- **Analysis of temporal variability** of wastewater temperature and flow at daily, seasonal, and intra-day scales to identify characteristic patterns and short-term fluctuations.
- **Definition of operational temperature thresholds** to ensure safe, sustainable, and efficient operation of both the sewer network and wastewater treatment processes, taking into account the receiving river body's seasonal temperatures.
- **Estimation of recoverable heat**, based on two temperature-drop scenarios ($\Delta T = 2$ K and $\Delta T = 4$ K), accounting for operational constraints and shutdown periods.
- **Comparison of extraction points** to identify the most suitable locations for heat recovery from a technical perspective.

3.2. Databases

The study has analyzed various datasets concerning wastewater flows, temperatures, and the performance of the biological treatment stage of the WWTP in cold weather. All the data associated with the sewer system have been provided by the sewer system operator “Sofiyska Voda”. Data concerning seasonal temperatures in the receiving river water body before/after discharge from WWTP Kubratovo have also been collected and analyzed.

3.2.1. Wastewater Temperature Data

Within the EU project Digital Water City, funded under Horizon 2020 Program, low-cost temperature sensors were installed at the combined sewer overflows to record water temperature, detect and log the duration of overflow events, and issue alerts in cases of dry-weather overflows associated with blockages in the sewer network [32]. The monitoring locations were selected based on operational observations, focusing on sewer sections suspected of hydraulic overloading. Data were collected at 5-minute intervals. Some data series were incomplete due to sensor relocation, hydraulic disturbances, and occasional GPRS communication failure. The available data for year 2021 from these sensors have been processed and analyzed.

Temperature data were also collected from the inlet, outlet and aeration basin of WWTP Kubratovo within the operational monitoring of the technological process. Temperature and flow data for 2019 were available at daily resolution, while for 2020 and 2021 inlet and outlet temperature and flow data were recorded at 15-minute intervals. Temperature data for the aeration basin were available at daily resolution for all analyzed years. Although high-resolution (15-min) measurements were available only for 2020–2021, the comparison of the three years shows similar seasonal trends and temperature ranges, indicating that the analyzed high-resolution period can be considered representative for the studied system. Minor data gaps at the hourly scale are present in the high-resolution datasets; however, these are limited in duration and do not affect the overall trends and results of the analysis.

3.2.2. Wastewater Flow Data

The wastewater flows at the temperature monitoring sites along the sewer network have been assessed based on the hydraulic model developed and maintained by the operator “Sofiyska Voda”. The flows at the inlet of the WWTP were obtained from the plant’s monitoring system. Daily flow rates were available for 2019, while 15-minute flow data were available for 2020 and 2021.

3.2.3. Wastewater Quality Data

Data on BOD_5 and TN concentrations at the inlet and outlet of the WWTP for 2019, 2020 and 2021 were obtained from the operational monitoring of the technological processes. These data were analyzed to evaluate the sensitivity of the biological processes to wastewater temperature.

3.3. Theoretical Foundations for Heat Recovery

3.3.1. Theoretical Background

The objective of this study was to perform a comparative assessment of the heat recovery potential at different temperature regimes. Therefore, the effects of losses in the pipelines, real characteristics of the heat exchangers (e.g., pipe diameters, installation constraints, flow rates, velocities, pressure losses and other site-specific limitations) have not been considered. A similar approach has been applied in other publications [14, 33].

The potential for heat recovery in the system is determined through calculating the heat flow when transferring sensible heat in a flowing fluid (Equation 1). This relationship is based on the energy balance of the fluid and determines the amount of heat that can be transferred at a given mass flow rate and temperature difference:

$$\mathrm{Q} = \mathrm{V} \cdot \rho \cdot \mathrm{cp} \cdot \Delta\mathrm{T}\ [\mathrm{kW}] \tag{1}$$

where, V is fluid flow rate [m^3/s]; ρ is density [kg/m^3]; cp is specific heat capacity [kJ/kg·K]; ΔT is temperature difference [K].

The mass flow rate determines the amount of substance that passes through the system, the specific heat capacity characterizes the ability of the fluid to accumulate heat, and the temperature difference is the driving force of heat exchange.

Then, based on operating hours and volume flow rates at specific points, the Energy [kWh] is calculated:

$$\mathrm{E} = \mathrm{Q}.\mathrm{t} \tag{2}$$

where, t is the operating time in hours.

Due to its simplicity and versatility, this method is a basic tool in the analysis of energy systems, heat exchangers and heat recovery processes.

4. Results

4.1. Screening of Potential Heat Recovery Locations and Their Key Characteristics

4.1.1. Initial Screening of Potential Points

Figure 4 presents the average daily temperatures recorded at different points within the sewer network, together with the corresponding rainfall data for 2021.

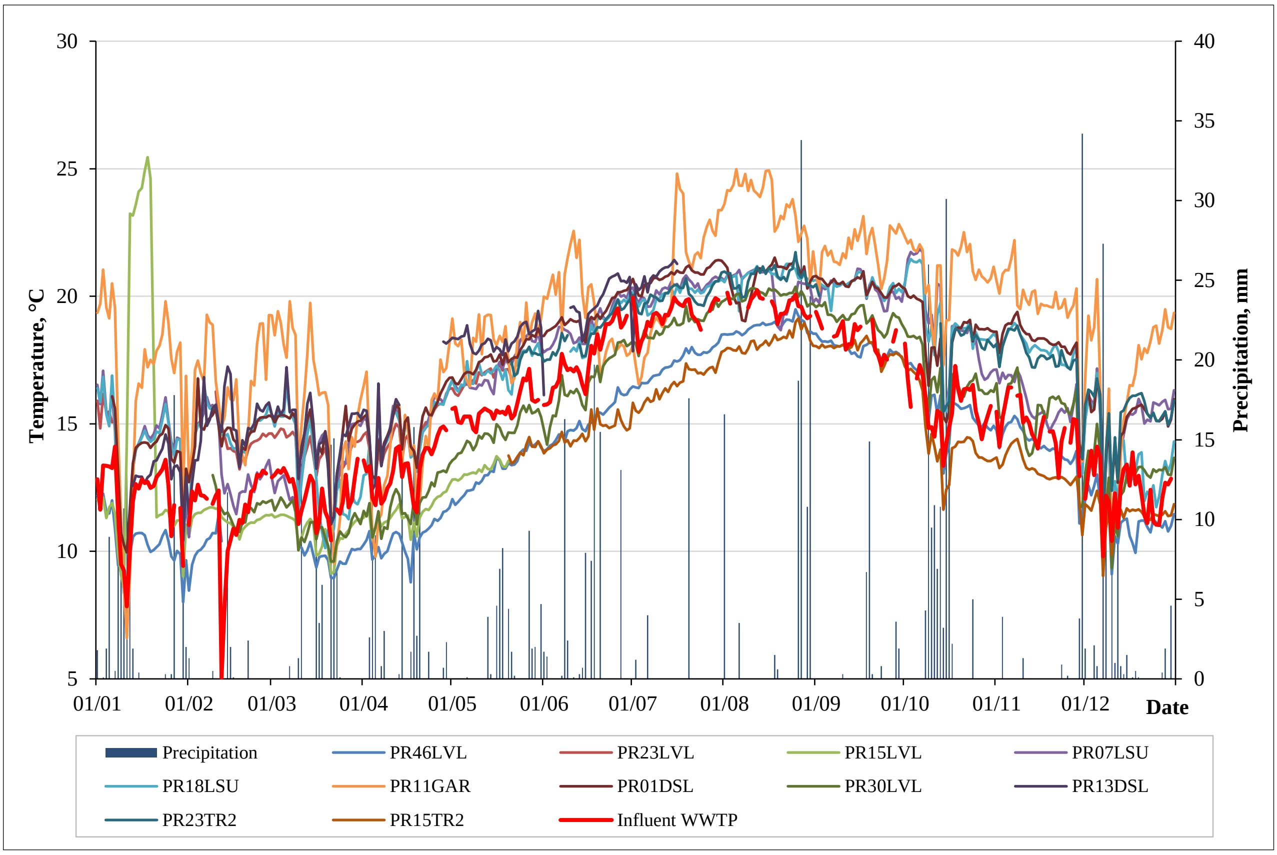


Figure 4. Daily temperatures and precipitation in 2021

As shown in Figure 4, temperatures at most locations are higher than those measured at the WWTP influent. The graph also clearly illustrates the temperature reduction in the sewer network during periods of consecutive rainy days.

Common statistical parameters concerning temperature (minimum, maximum, daily average, and 5th and 90th percentile values) and daily flow values (based on hydraulic modeling) in 2021 for several sensors along the sewer network are presented in Table 2.

Table 2. Characteristic daily values of the temperatures and flow in the sewer in 2021

Sensor	Tmin (°C)	Tmax (°C)	T daily average (°C)	T5% - T95% (°C)	Flow rate (m^3/day)	% of WWTP influent flow
PR07LSU	6.69	21.85	16.86	12.11-20.88	20823	6.0
PR18LSU	7.04	21.46	16.93	11.47-20.95	44640	12.9
PR11GAR	6.59	24.98	18.74	12.20-23.99	912	0.3
PR01DSL	9.96	21.52	17.40	13.28-21.13	27739	8.0
PR30LVL	9.34	20.37	15.46	10.65-20.08	19149	5.6
PR13DSL	9.07	21.42	16.46	12.03-20.85	19690	5.7
PR23TR2	10.98	21.73	18.37	15.11-20.97	9992	2.9

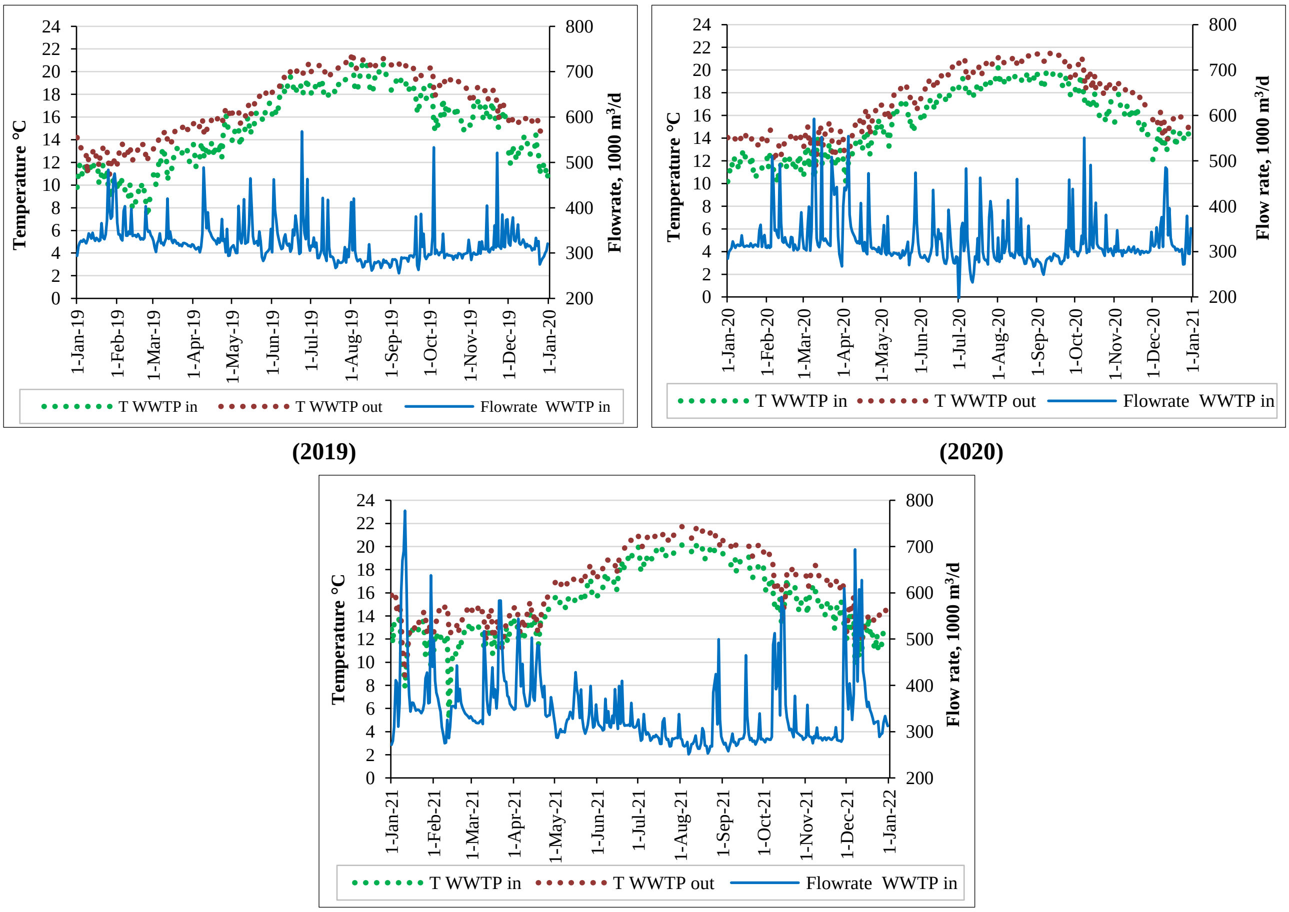
The wastewater temperatures within the sewer network are generally higher than those at the WWTP influent (Figure 4), but the corresponding flow rates (Table 2) represent only 0.3–12.9% of the total WWTP influent flow. Therefore, centralized heat recovery from sewer network locations is better suited for site-specific or local-scale applications. Due to the limited hydraulic capacity and resulting low recoverable thermal power, these locations were excluded from further analysis.

4.1.2. Selected Points for Further Analysis

Further analysis focused on locations at the wastewater treatment plant (WWTP). Consequently, two principal extraction points were selected for detailed evaluation: the WWTP influent and the WWTP effluent.

The influent was considered primarily due to its shorter distance to potential heat consumers, which may reduce distribution losses and associated infrastructure requirements in densely populated urban areas. The distance from the district heating plant to the influent extraction point is approximately 5 km, whereas the corresponding distance to the effluent point exceeds 6 km (Figure 1). In addition, the change of inlet wastewater temperature is closely related to the biological activity in the treatment stage, while the change of the effluent temperature is not related to the treatment process but may affect the water ecosystem in the receiving water body.

The seasonal pattern of temperature change for the analyzed period (2019-2021) is presented on Figure 5. During the coldest months (December, January, and February) the influent temperature at the WWTP falls below 12°C, which restricts the available temperature margin for heat recovery during winter conditions (Figure 5). The maximum daily temperatures recorded in January were 11.8°C, 12.98°C, and 14.1°C; and in February, 10.7°C, 13.19°C, and 13.16°C for the years 2019, 2020, and 2021, respectively.



(2019) **(2020)**

(2021)

Figure 5. Average daily temperatures and flow rates at WWTP

In February 2019, a substantial number of days had average daily temperatures below 12°C. During the rest of the year, such occurrences are rare, and mean daily temperatures below this threshold are almost absent. Nevertheless, during the winter months, nighttime temperatures frequently drop below 12°C for several hours. The temperature and flow data for the analyzed years exhibit similar seasonal and daily patterns. Short periods with wastewater temperatures (e.g., below 12°C) occur considerably less frequently in the WWTP effluent than in the influent.

4.2. Operational Temperature Constraints

4.2.1. Influence of the Temperature in the Aeration Basin on the Treatment Process

Table 3 summarizes the typical statistical parameters of the average daily temperature at the WWTP inlet, in the aeration basin, and at the WWTP outlet, and Figures 6 and 7 present a comparison among the characteristic values of temperatures and flows within the WWTP and throughout the investigated period.

Table 3. Characteristics of the daily inlet flow (Q inlet) and average temperatures at the inlet, aeration basin (AB) and outlet of the WWTP

	2019				2020				2021			
Parameter	**Q_{inlet} (m^3/day)**	**T_{inlet} (°C)**	**T_{AB} (°C)**	**T_{outlet} (°C)**	**Q_{inlet} (m^3/day)**	**T_{inlet} (°C)**	**T_{AB} (°C)**	**T_{outlet} (°C)**	**Q_{inlet} (m^3/day)**	**T_{inlet} (°C)**	**T_{AB} (°C)**	**T_{outlet} (°C)**
average	323 622	15.1	17.4	17.1	325 568	15.5	17.6	17.3	344 990	15.1	16.2	16.6
min	255 466	7.2	11.3	11.0	248 630	10.0	12.2	11.3	250 993	5.1	9.2	8.8
max	568 264	20.9	22.7	21.7	592 412	20.2	22.1	21.5	777 365	20.2	22.9	21.7
5th percentile	277 910	9.6	12.3	12.5	274 763	11.2	13.8	13.1	270 234	11.0	11.8	12.4
95th percentile	403 761	19.6	21.9	20.8	458 512	19.5	21.8	21.2	515 919	19.8	22.4	21.2

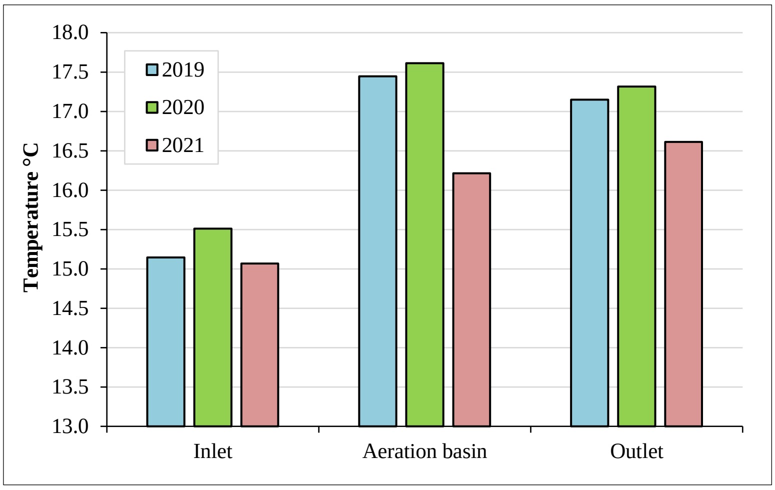


Figure 6. Comparison between the average annual temperatures at WWTP inlet/outlet and in the aeration basin

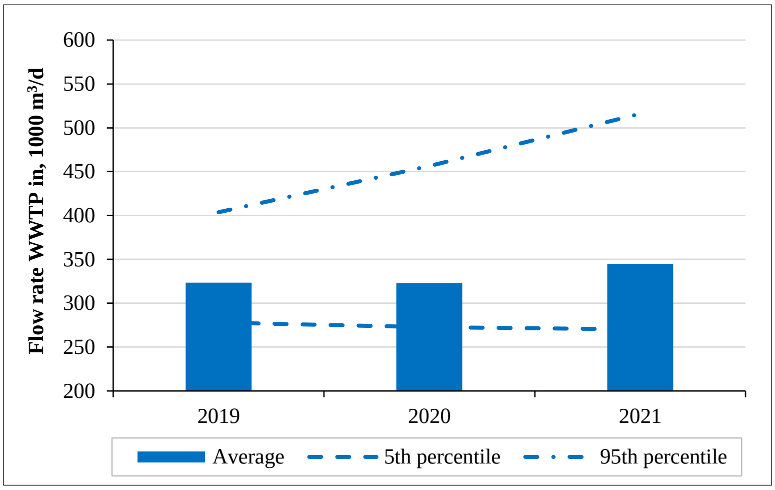


Figure 7. Characteristics of the wastewater inlet flow to WWTP

The annual change of the wastewater temperature follows a similar pattern for each of the monitored locations at the WWTP within the investigated period, with maximums in July-August and minimums in December-January (Figure 5). The values are slightly lower in 2021 due to more frequent rain events that increase the inlet flow but lower the inlet temperature (Figures 6 and 7). Nevertheless, the annual fluctuations show a substantial tendency of increased temperature in the aeration basin compared to the wastewater inlet temperature. This phenomenon is due to biological oxidation processes and aeration effects.

The wastewater temperature inevitably influences the biological treatment processes in the aeration basin. Temperatures below 12°C are considered critical for the efficiency of the nitrification process, and this was noted in the EU Directive 2024/3019 concerning urban wastewater treatment [34]. The directive requires the annual mean concentration of TN in the effluent to be up to 8 mg/l (or 80% reduction) for WWTPs above 150,000 population equivalents, as is the case for WWTP Kubratovo in Sofia. It is explicitly mentioned, however, that samples for TN taken at temperatures in the aeration basin below 12°C may be excluded from calculating the annual mean effluent concentration for TN.

Tables 4 and 5 present the average concentrations for BOD_5 and TN at the WWTP influent and effluent for the days with average temperature below and above 12°C in the aeration basin.

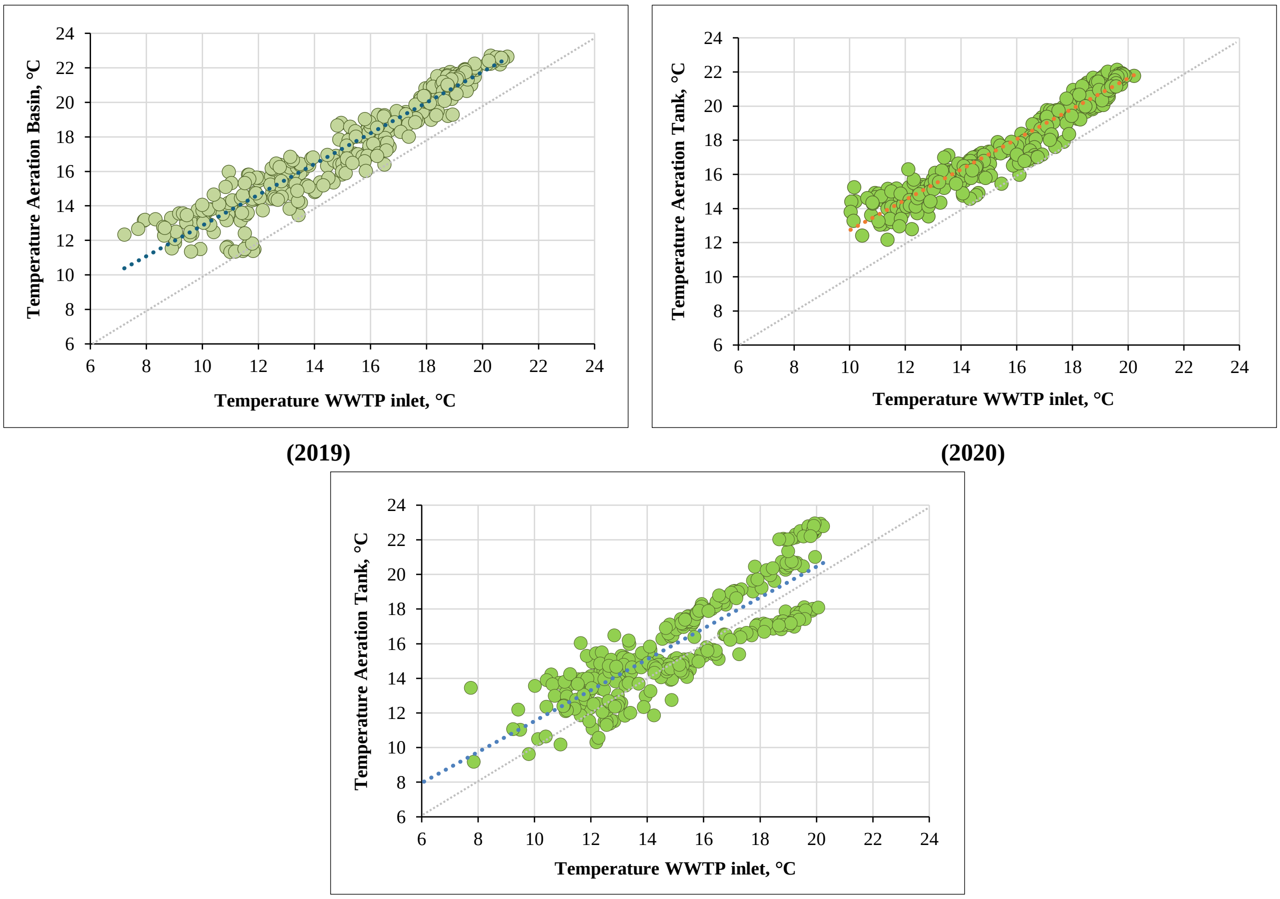
Table 4. Performance of WWTP Kubratovo concerning BOD_5 removal for average daily temperature below and above 12°C in the aeration basin

Year/Parameter		2019		2020		2021	
		T < 12° C	T ≥ 12° C	T < 12° C	T ≥ 12° C	T < 12° C	T ≥ 12° C
Total number of days	number	15	350	0	365	21	344
Number of samples	number	15	350	0	365	21	344
Average concentration WWTP inlet	mg/l	155.0	145.1	-	141.0	86.1	138.2
Average concentrations WWTP outlet	mg/l	10.0	8.8	-	7.9	12.8	10.0
Average rate of BOD5 removal	%	92.6	93.0	-	93.5	78.3	91.6

Table 5. Performance of WWTP Kubratovo concerning TN removal for temperatures below and above 12°C in aeration basin

Year/Parameter		2019		2020		2021	
		T < 12° C	T ≥ 12° C	T < 12° C	T ≥ 12° C	T < 12° C	T ≥ 12° C
Total number of days	number	15	350	0	365	21	344
Number of samples	number	3	48	0	48	17	78
Average concentration WWTP inlet	mg/l	26.73	34.33	-	32.38	23.99	30.53
Average concentrations WWTP outlet	mg/l	9.43	8.75	-	8.77	8.55	8.89
Average rate of TN removal	%	63.5	73.8	-	71.0	61.0	68.9

A clear relationship between the wastewater temperature at the WWTP influent and the temperature in the biological treatment stage is observed, as illustrated on Figure 8. The graphical comparison demonstrates that temperature variations at the influent are directly reflected in the aeration basin, with a consistent temperature offset of around 2 °C. In the predominant case the wastewater temperature in the aeration basin is higher than the temperature in the WWTP influent and there are only a few days in 2019 and 2021 with temperature below 12 °C in the aeration basin, shown also in Table 5.



(2019) **(2020)**

(2021)

Figure 8. Correlation between the wastewater temperature in the aeration basin and WWTP inlet

4.2.2. Temperatures in the Receiving Water Body

The closest monitoring points of the Iskar River from the national monitoring network are BG1IS00459MS1270 (before WWTP Kubratovo discharge) and BG1IS135R1426 (after WWTP Kubratovo discharge). Both points are at about a 3 km distance from the discharging point of WWTP Kubratovo, and in the upstream section there is a confluence of the tributary Lesnovska River into the Iskar River before the discharge of the WWTP.

The monitoring data about the temperature in the Iskar River are scarce: -1 to 2 single samples per month. That's why a longer period has been analyzed, 2016-2021, for calculation of the average monthly temperatures in the river. The average monthly temperatures of the WWTP effluent have been calculated for the period 2019-2021 based on average daily temperatures (Figure 9). Figure 10 shows the difference between the effluent and the river temperature in percent.

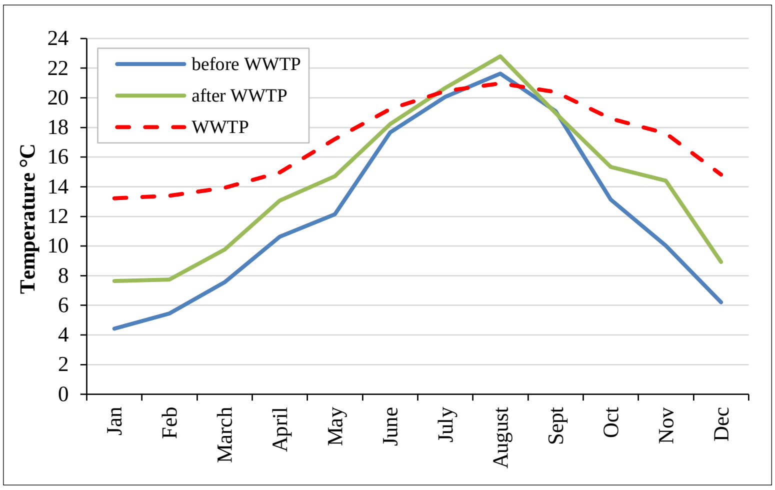


Figure 9. Average monthly temperatures in Iskar River and in WWTP effluent

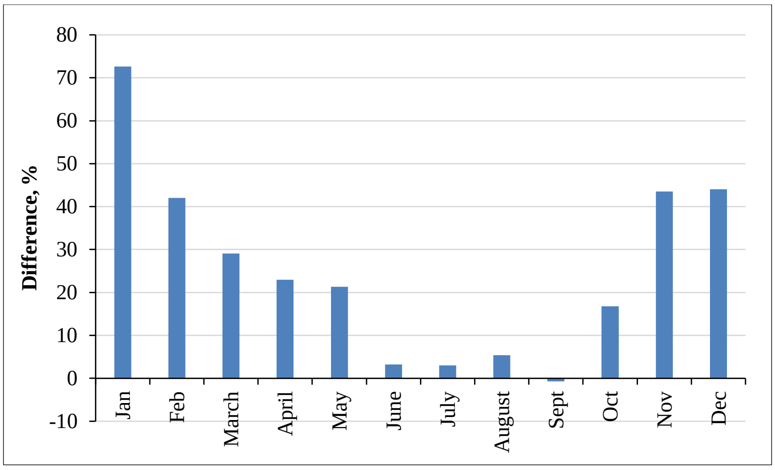


Figure 10. Percent difference of the river temperature after WWTP discharge compared to the river temperature before WWTP discharge

4.2.3. Definition of Temperature Thresholds

4.2.3.1. Influent Temperature Threshold

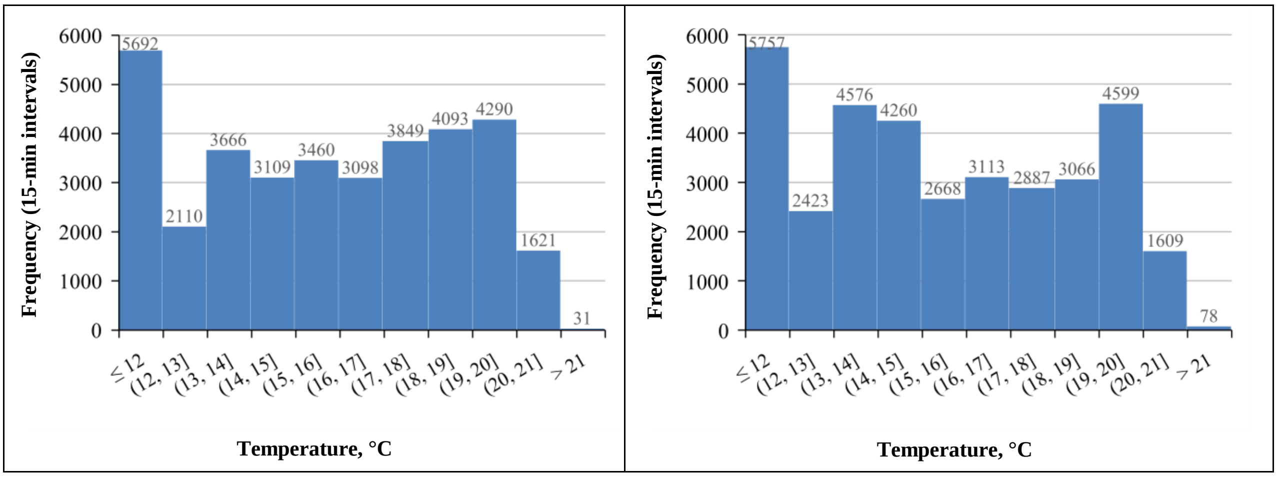
When assessing heat recovery at the influent, the primary constraint is the stable biological treatment processes, i.e. to ensure 12 ºC at the aeration basin the temperature of the WWTP influent should be kept above 10 ºC (Figure 8). This means that corresponding to the selected scenarios in the methodology (i.e., temperature drops of –2 and 4 K), the heat recovery system should cease operation when the wastewater influent temperature falls below 12 ºC and 14 ºC, respectively.

4.2.3.2. Effluent Temperature Threshold

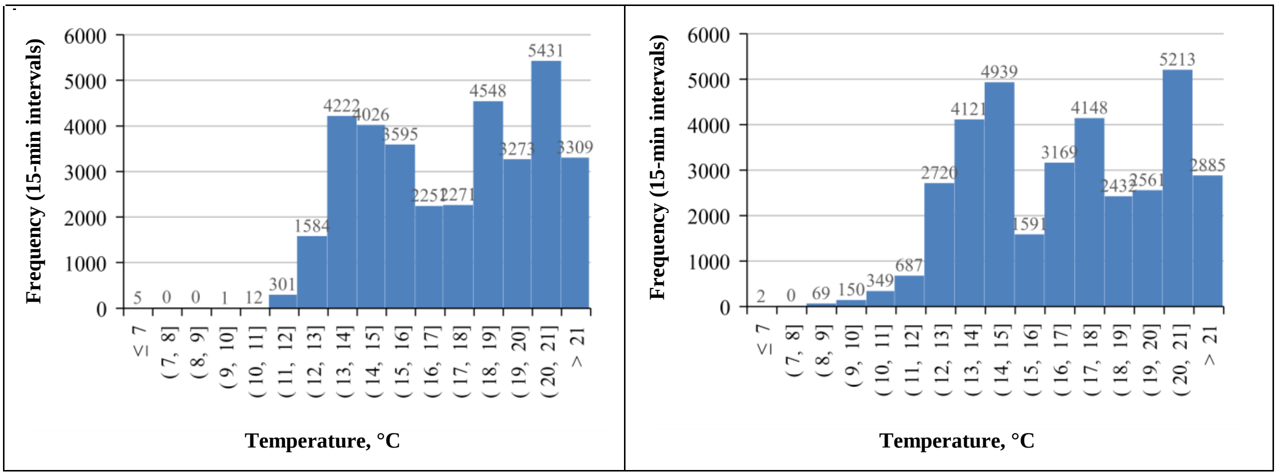
The temperature limitations at the effluent are mainly governed by ecological considerations, i.e., the need to comply with the natural temperature regime of the receiving water body—the Iskar River. On this basis, and adopting a conservative approach, a minimum effluent temperature threshold of 5°C was selected for further analysis. This value corresponds to the lower range of the observed winter river temperatures. Accordingly, under the selected scenarios in the methodology (i.e., temperature drops of –2 and 4 K), the heat recovery system should stop operating when the wastewater effluent temperature drops down below 7 ºC and 9 ºC, respectively.

4.3. Assessment of Heat Recovery Potential

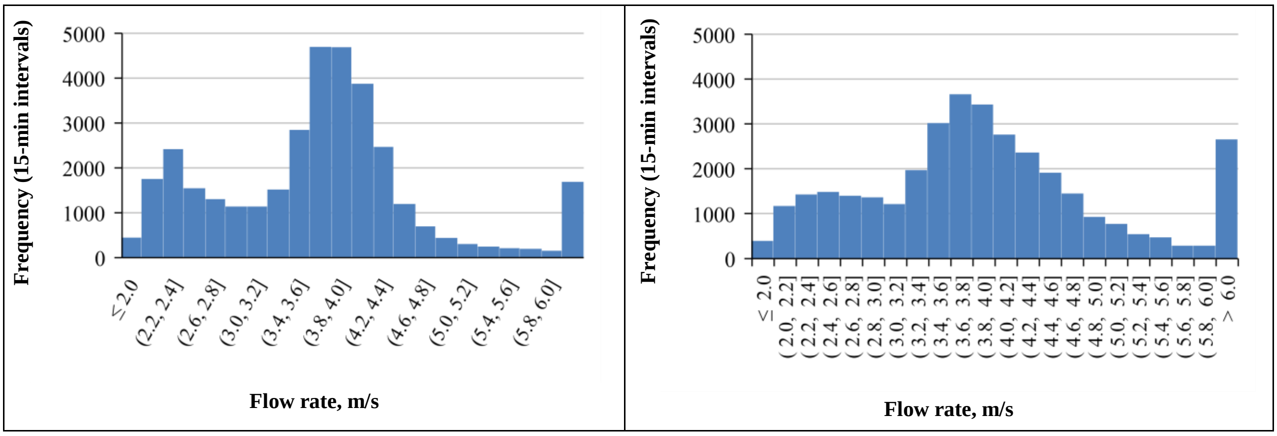
High-resolution analyses of the temperature dynamics. The analysis was performed at 15-minute time resolution in order to determine the effective operating intervals and the corresponding recoverable thermal energy under each configuration. The histograms on Figure 11 present the distribution of 15-minute temperature data of 15-minute intervals.



a) Influent temperature intervals in 2020 **b) Influent temperature intervals in 2021**



c) Effluent temperature intervals in 2020, **d) Effluent temperature intervals in 2021**



e) Flow rate intervals in 2020, [m^3/s] **f) Flow rate intervals in 2021, [m^3/s]**

Figure 11. Histograms of wastewater temperatures and flow rates at 15-minute intervals for 2020 and 2021

4.3.1. Scenarios for Assessment of Heat Recovery Potential

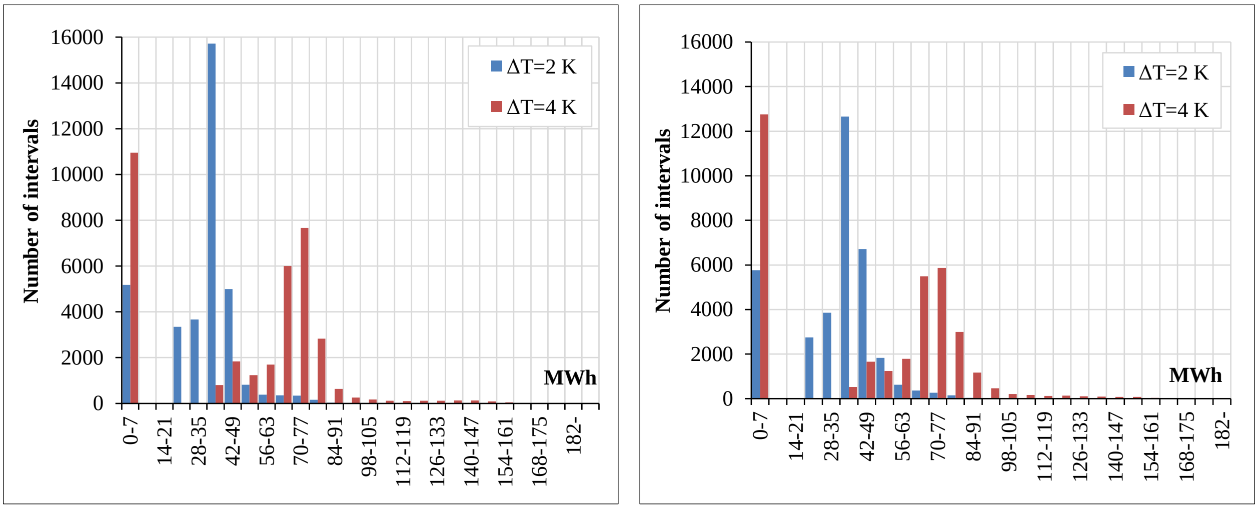
Using the temperature limits established in the previous section, the heat recovery potential was quantified under four operating scenarios combining two extraction locations and two assumed temperature drops:

- Scenario 1a – heat recovery at the WWTP influent, assuming a temperature drop of ΔT = 2 K and a minimum operational influent temperature of 12 °C;
- Scenario 1b – heat recovery at the WWTP influent, assuming a temperature drop of ΔT = 4 K and a minimum operational influent temperature of 14 °C;
- Scenario 2a – heat recovery at the WWTP effluent, assuming a temperature drop of ΔT = 2 K and a minimum operational effluent temperature of 7 °C;
- Scenario 2b – heat recovery at the WWTP effluent, assuming a temperature drop of ΔT = 4 K and a minimum operational effluent temperature of 9 °C.

The operational time of the heat recovery system was defined based on minimum allowable wastewater temperature thresholds. System operation was considered feasible only when wastewater temperatures remained above the predefined thresholds, to ensure safe operation of both wastewater treatment processes and environmental compliance at the discharge point.

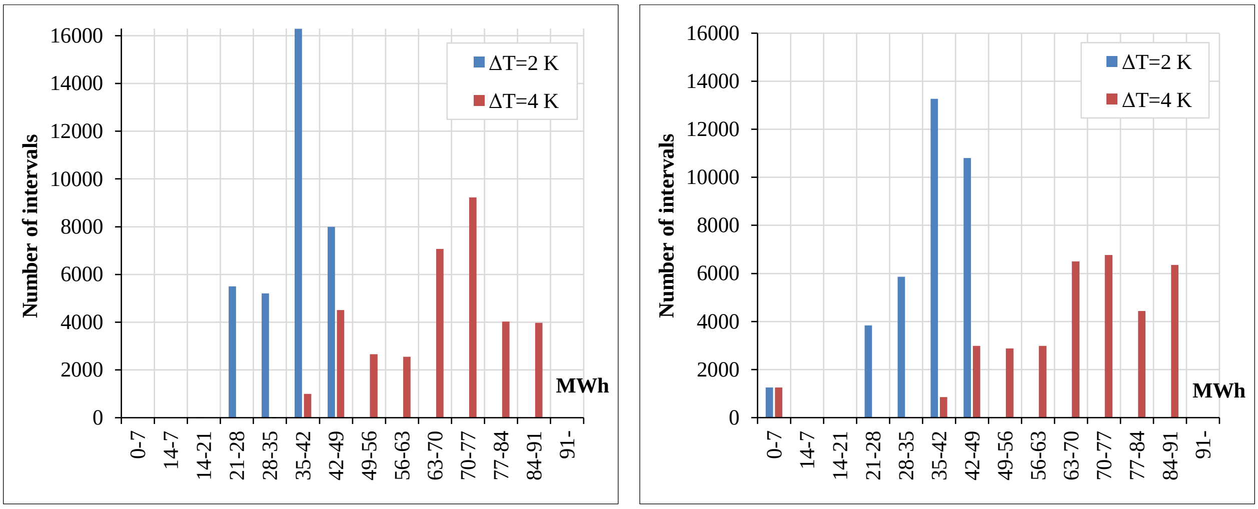
4.3.2. Potential Yield of Thermal Power

The potential yield of thermal power (in MWh), calculated at 15-minute intervals, from WWTP influent is presented as a histogram on Figure 12 and from WWTP effluent on Figure 13.



(a) 2020 **(b) 2021**

Figure 12. Histogram of the potential thermal energy in 15-minute intervals at the WWTP inlet

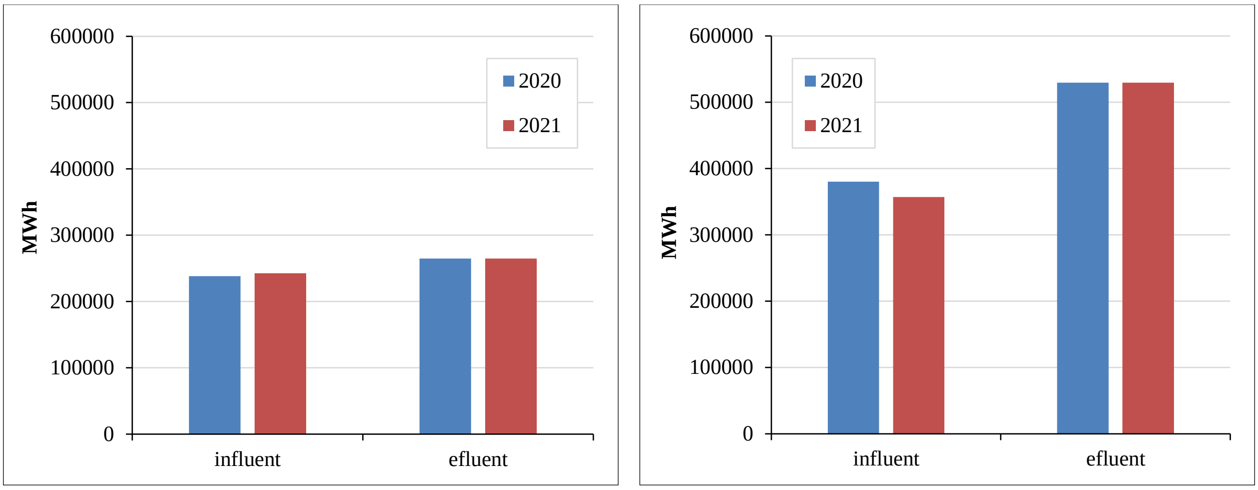


(a) 2020 **(b) 2021**

Figure 13. Histogram of thermal energy in 15-minute intervals at the WWTP outlet

Fifteen-minute intervals during which the wastewater temperature was below the defined operational threshold were excluded from the calculation of recoverable thermal energy. This conservative approach is intended to ensure compliance with the temperature constraints established in Section 4.2.

Based on the above histograms, Figure 14 presents the estimated total annual potential for thermal energy production (MWh) for 2020 and 2021.



(a) ΔT=2 K **(b) ΔT=4 K**

Figure 14. Total annual thermal energy potential

4.4. Assessment of Potential Benefits

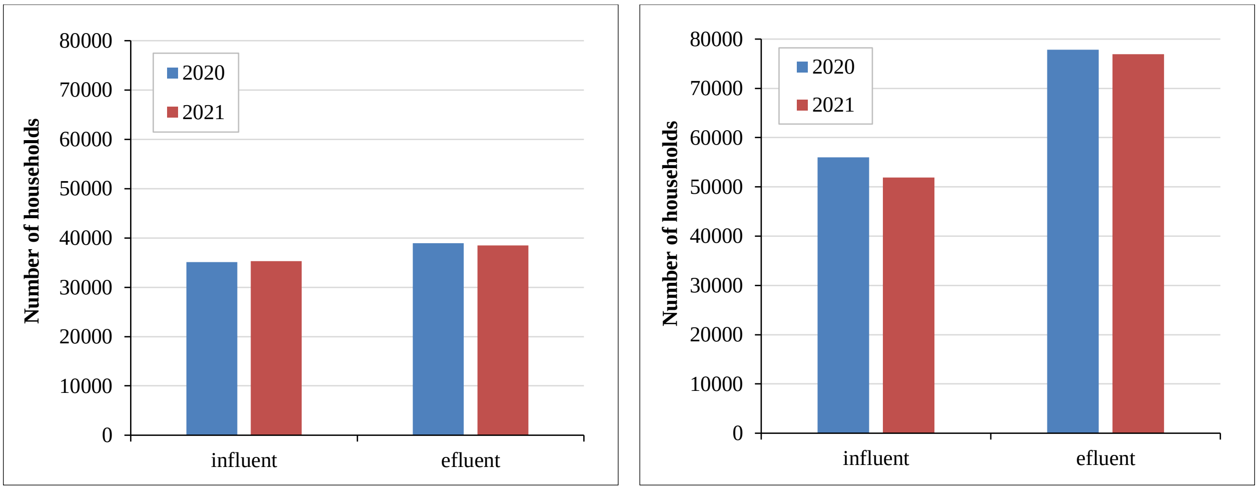
4.4.1. Potential Number of Households

According to the Bulgarian household design standards, the maximum consumption of hot water is 120 L/day per person, based on the total of 240 l/d/cap [35]. The design value represents a maximum normative consumption scenario and therefore provides a conservative upper-bound estimate of household heat demand. According to NSI data, an average Bulgarian household consists of approximately 2.7 people [36], which results in an annual consumption of 109500 L/year per household. Assuming a water density of 1000 kg/m³, this corresponds to approximately 109,500 kg per household annually. To provide this amount of hot water, thermal energy is required to increase the temperature from about 10°C to 60°C (ΔT = 50 K). The required thermal energy was calculated using Equation 3:

$$E = m \cdot cp \cdot \Delta T \,/\, 3.6 \cdot 10^{6} \text{ [MWh]} \tag{3}$$

where, *m* is the total mass of water consumed per household per year [kg/year per household].

Therefore, a household consumes approximately 6.9 MWh, which represents the theoretical energy required for water heating, without considering heat losses within the system. The number of households that can be supplied with recovered thermal energy from the sewer system, at different extraction points, is shown on Figure 15.



(a) ΔT=2 K **(b) ΔT=4 K**

Figure 15. Potential number of households supplied with recovered thermal energy

4.4.2. Expected CO_2 Reduction

If this thermal energy replaces electric water heating, emissions that would be generated when producing the corresponding amount of electricity from the national electricity mix would be avoided.

- Replacing electricity with recovered heat could reduce the carbon footprint.
- The average carbon intensity of electricity in Bulgaria for 2023 is approximately 0.38 kg CO_2 /kWh [37].
- Based on the annual heat consumption estimations, the saved CO_2 emissions per household are year ≈ 2.4 t CO_2 /year.
- For the best evaluated option with potential to supply 76 969 households ≈ 201 288 t CO_2 /year could be saved.

Assuming natural gas-based water heating the associated emissions are approximately **0**.202 kg CO_2/kWh [38]. Under equivalent energy demand would mean saving ≈ 1390.18 kg CO_2/year ≈ 1.39 t CO_2/year per household and total of ≈ 107 000 t CO_2/year could be saved for 76 969 households.

5. Discussion

Given the inherent complexity of large urban sewer systems, analyses often rely on limited datasets, either in terms of temporal coverage or spatial resolution. In many cases, dedicated monitoring campaigns are implemented to obtain representative data, with a one-to-two-year period generally sufficient to capture seasonal variability [6, 25]. In the present study, the use of high-resolution data from WWTP Kubratovo for two years, complemented by daily data for three years, shows consistent seasonal patterns. As illustrated in Table 3, key temperature indicators (the average values and the interval in which 90% of the samples fall, i.e., between the 5th and the 95th percentile) remain comparable across the analyzed 3-year period, indicating that extending the observation period would not introduce significant additional variability.

5.1. Dynamics of Wastewater Temperature and Flow

Wastewater temperature and flows are key parameters governing the efficiency of heat recovery from wastewater. The results show that the wastewater temperature is mostly influenced by the seasonal air temperatures. It shows a typical seasonal pattern along the sewer network and within the WWTP with maximum values in summer and minimum values during the winter months. Such seasonal variability was observed in other studies too [7, 25].

The population density, however, and the rainfall events can also have local (in terms of space and duration) effects on the wastewater temperature. Along the sewer network the registered temperatures are predominantly higher than at the WWTP influent, which may be attributed to the fact that the two main incoming collectors to the treatment plant are above ground, resulting in greater heat losses. Within the network, local fluctuations are evident. For instance, the temperature at sensor PR30LVL is higher than at PR46LVL, indicating that wastewater temperatures increase when entering more densely built-up areas (Figure 4). A similar behavior is observed for PR15TR2, where temperatures are also lower compared to sensors located in more densely urbanized areas. In wet periods, e.g., during the spring months of March and April, frequent rainfall events lead to substantial variability and sharp temperature drops in wastewater (see Figure 4).

The wastewater flows at the temperature monitoring points along the sewer network are taken from the hydraulic model of the sewer system of Sofiyska Voda. The relatively small flow rates of the monitored collectors (0.3 to 13% compared to the WWTP influent) limit the suitability of these locations for large-scale heat recovery, and therefore the potential energy yield at these locations was not further analyzed. A more detailed assessment of local temperature variations within the sewer network would require a denser monitoring system with additional temperature sensors alongside the main collectors. Due to the limited number of temperature sensors, the results should be interpreted with caution, as some sensors may be influenced by local effects such as heat network leakages. Additional sensors and optimized monitoring locations would improve the robustness of the analysis.

However, heat extraction at the sewer network level may still be feasible through decentralized or hybrid solutions. In such cases, although the available flow is lower, higher temperature drops could be applied compared to WWTP-based recovery, as only a portion of the total wastewater volume is affected, and partial reheating of the flow may occur along the sewer network due to heat exchange with the surrounding soil and ambient conditions [25]. To ensure that such approaches do not negatively impact downstream treatment processes, detailed temperature modeling of the sewer network is recommended to maintain the required influent temperature at the WWTP [25]. In this context, the threshold values identified in the present study may serve as a practical reference for defining acceptable temperature limits at the WWTP inlet.

5.2. Temperature and Flow Dynamics at the WWTP

Within the investigated period, the annual change of the wastewater temperature follows a similar pattern for each of the monitored locations at the WWTP (influent, aeration basin, and effluent) with maximums in July-August and minimums in December–January (Figure 5). The values are slightly lower in 2021 due to more frequent rain events that increase the inlet flow but sharply lower the inlet temperature (Figures 6 and 7). Minimum average daily values are reached in January–February, where the influent temperature falls below 12°C. During the rest of the year, such occurrences are rare, and mean daily temperatures below this threshold are almost absent. Regardless of the specific annual fluctuations, the 5th percentile of the WWTP influent temperatures is around 10.6°C, and the corresponding 95th percentile is around 19.6°C. The respective values for the WWTP effluent are higher, as the 5th percentile is around 12.7°C and the 95th percentile is around 21°C. The results clearly indicate that there is a substantial difference between the range of wastewater influent and effluent temperatures due to heat generation during biological oxidation and aeration processes. Thus, for example, 90% of the wastewater influent temperatures are in the range of 9.6 to 19.8°C, while the corresponding values for wastewater effluent are 12.4–21.2°C. The percentage of days with daily temperatures below 12°C of the wastewater influent is in the range of 10 to over 20%, while the corresponding percentage in the aeration basin is 0 (in 2020) to 6% and in the WWTP effluent, below 3% (see Tables 4 and 5).

The flow regime at the WWTP remains relatively stable throughout the year, with most frequent flows concentrated in the range of 3.4–4.2 m^3/s (Figure 11). During the drier periods, e.g., in August and September, the wastewater flow remains relatively uniform, accompanied by a smooth change in the average temperature. The peak flow values on Figure 5 align closely with rainfall events exceeding 10 mm, a pattern that is particularly evident during periods of consecutive rainy days, as shown on Figure 4. The increased flow during these events results in temperature drops of the wastewater, though these fluctuations are relatively short in time, around a few days, and have no significant impact on an annual basis.

Although night-time flows typically decrease to around 2 m^3/s and rainfall events cause temporary peaks, the overall variation is moderate compared to the temperature-driven operational constraints. These results indicate that hydraulic variability is not the primary limiting factor for heat recovery feasibility. This finding is consistent with previous studies that identify temperature constraints, rather than flow variability, as the dominant limiting factor for wastewater heat recovery potential [25].

The analysis indicates that wastewater temperature is primarily driven by seasonal variation (i.e., ambient air temperature), while rainfall events introduce short-term fluctuations, often resulting in temporary temperature drops. In contrast, wastewater flow is characterized mainly by diurnal variability, with additional peak values occurring during rainfall events. This distinction highlights that temperature governs the overall availability and stability of heat recovery, whereas flow variations play a secondary role under typical operating conditions.

5.3. Definition of Temperature Constraints

Temperature constraints for the WWTP influent were linked to the preservation of biological treatment performance. The average daily threshold temperature of 12°C in the aeration basin was selected to preserve a sustainable nitrification process. It is well known that the nitrification process is very sensitive to temperature. The reported values for activated sludge are in the range of 10 to 30°C [39], 12 to 30 [40], and 15 to 25 [41], as the bacteria growth decreases significantly with the decrease in the temperature. The effect of low temperatures (i.e., below 12°C) is more visible on the removal rate rather than on the outlet concentrations of WWTP Kubratovo, although it was expected to be more significant. It should be noted that the monitoring results for TN at temperatures below 12°C in the aeration basin were limited in number. More frequent monitoring, at low temperatures, would increase the robustness of the conclusions. The TN removal is compliant with the requirement of the former urban wastewater directive (Directive 91/271/EEC, in force until 2024), i.e., the TN in the treated effluent is to be below 10 mg/L.

The performance of the biological stage for BOD_5 is very good throughout the year, as the average annual concentrations of the effluent are well below the normative requirement of 25 mg/L O_2 [34]. Despite the good results, a certain negative effect of low temperatures (i.e., below 12°C) was observed in terms of both concentration and removal rate (Table 4).

The results confirm the sensitivity of biological treatment processes to temperature variations, particularly with respect to nitrification, and highlight the importance of maintaining minimum temperature thresholds when evaluating heat recovery potential, as also emphasized in recent city-scale analyses [42].

Concerning WWTP effluent, a minimum effluent temperature threshold of 5 °C was selected in the study, which is comparable with the temperatures in the river in the winter months at the monitoring point upstream of WWTP Kubratovo (Figure 9). The impact of WWTP effluent on the receiving water body temperature is different throughout the year. It is quite significant in the winter months (Jan., Feb., Nov., and December), where the river temperature after the WWTP discharge is above 40% higher than the one upstream, before the WWTP (Figures 9 and 10). In the spring and autumn months (March-May, October) this difference decreases down to about 20%-30%, while in summer months the effect of WWTP discharge is insignificant—below 5%. This suggests that controlled heat extraction at the WWTP effluent could contribute not only to energy recovery but also to mitigating thermal impacts on the receiving water body, particularly during cold periods. It has to be noted that in summer months the temperatures in the Iskar River reach quite high values—above 20 degrees—that could negatively influence the oxygen availability in water and may be detrimental for the river ecosystem. A potential decrease of the WWTP effluent temperature can have a positive effect on the river.

Temperature influent and effluent constraints were applied uniformly to the datasets analyzed to determine feasible operating periods prior to the quantification of recoverable thermal energy.

5.4. Potential for Heat Recovery

The detailed analysis of data at 15-minute intervals in this study shows that during the winter months, nighttime temperatures of the WWTP influent frequently drop below 12°C for several hours. This restricts the available temperature margin for heat recovery from the influent during winter conditions (Figure 11). Such short-term fluctuations are often not fully captured in studies based on aggregated (e.g., daily or only dry flow) data or modeling approaches [11, 25, 42], which may not fully represent the operational stability of heat recovery systems.

The potential for heat recovery has been analyzed in detail for both WWTP influent and WWTP effluent, taking into account the wastewater temperatures and the potential impact on the downstream processes—biological treatment in the aeration basin and the receiving river body. The analysis considers temperature-drop scenarios (ΔT = 2 K and 4 K), which are consistent with commonly applied values in previous studies [14], while also accounting for site-specific operational constraints, i.e., maintaining the threshold temperature of 12°C in the aeration basin in case of heat recovery from WWTP influent and the threshold temperature of 5°C in case of heat recovery from the WWTP effluent. This approach is consistent with commonly applied methodologies in the literature, where the recoverable heat is estimated based on the thermal content of wastewater using flow rate and temperature difference [11], and provides a consistent basis for comparison between different locations and operating conditions.

Based on these preconditions, a minimum WWTP influent temperature of 10°C is adopted as a critical parameter governing the heat recovery potential. This value is consistent with operational constraints reported by Abdel-Aal et al. [11], where a similar threshold temperature (e.g.٩ و °C defined by water utilities) is applied to ensure stable biological treatment performance.

Since the heat pump operation responds to instantaneous wastewater temperature rather than daily averages, the evaluation at 15-minute resolution is essential to determine effective operating time and system reliability. Figure 11 illustrates the substantial difference in operational availability between the two extraction points. At the WWTP influent, more than 5,000 fifteen-minute intervals fall below 12°C in 2020, corresponding to over 53 days of shutdown under Scenario 1a. For ΔT = 4 K, the required shutdown period exceeds 114 days, increasing further in 2021 to 59 and 132 days, respectively. In contrast, at the WWTP effluent, intervals below the defined thresholds are negligible, indicating near-continuous operational feasibility.

Despite the substantially longer shutdown periods observed at the influent under ΔT = 4 K, the annual thermal energy yield remains higher compared to ΔT = 2 K. In 2020, the estimated energy increases from 238,536 MWh (ΔT = 2 K) to 380,314 MWh (ΔT = 4 K), while in 2021 it rises from 242,726 MWh to 357,167 MWh. This demonstrates that higher temperature drops may be more advantageous from an annual energy perspective, despite reduced operational time.

The total annual energy production at the WWTP effluent exceeds that at the influent under both temperature-drop scenarios. For ΔT = 2 K, the effluent yields approximately 11% (264,853 MWh in 2020) and 9% (264,828 MWh in 2021) more energy, while for ΔT = 4 K the difference becomes significantly larger, reaching 39% (529,705 MWh) in 2020 and 48% (529,656 MWh) in 2021. This clearly shows that WWTP effluent is a more reliable and technically favorable source for heat recovery due to both higher temperatures and significantly reduced operational interruptions. When normalized per capita, the obtained heat recovery potential (approximately 0.4 MWh per capita per year) falls within the range of 0.3–0.6 MWh per capita per year reported by Somogyi et al. [14], demonstrating that the results are representative at the urban scale despite differences in system configuration and boundary conditions.

5.5. Potential Benefits

Among the four analyzed scenarios, Scenario 2b yields the highest thermal energy potential, corresponding to a theoretical domestic hot water demand of more than 76,000 households. The actual number of households that could benefit may differ from this value, depending on the final system configuration and hot water demand patterns. The distribution losses and the engineering constraints associated with the implementation of the heat recovery system are site specific and have to be considered too in case of project realization. According to the business plan of the water utilities operator, Sofiyska Voda, the average daily water consumption ranged between 123.6 and 130.3 L/cap/day in the period 2016–2022 [43], demonstrating that the actual domestic hot water consumption may be lower than the maximum design values. Consequently, the number of households that could benefit from the recovered heat may be higher. A more precise estimation would require detailed data on domestic hot water consumption from the district heating company (Toplofikatsiya Sofia), which was not available to the authors.

In addition, the estimated CO_2 emission reduction of approximately 201,000 t CO_2 /year corresponds to about 4% of the total annual greenhouse gas emissions of Sofia, highlighting the potential contribution of wastewater heat recovery at the urban scale [44].

6. Conclusion

The present study provides a high-resolution assessment of wastewater heat recovery potential in the sewer network and at the WWTP in Sofia. Using multi-year temperature and flow datasets with a temporal resolution of up to 15 minutes, the analysis captures seasonal and short-term variability, enabling a realistic evaluation of operational constraints and energy recovery potential.

The results demonstrate that wastewater is a substantial and reliable source of recoverable thermal energy within the urban system. Heat recovery at the WWTP effluent is more favorable than at the influent due to higher and more stable temperatures, fewer operational interruptions, and reduced constraints related to biological treatment processes. For both analyzed years, the recoverable energy potential at the outlet exceeds that at the inlet for temperature drops of 2 K and 4 K, while higher temperature drops may yield greater annual energy output despite increased non-operational periods. The defined temperature thresholds ensure the protection of treatment processes and can support further assessment of heat recovery potential within the sewer network.

The analysis shows that temperature variability, rather than flow fluctuations, is an important limiting factor for heat recovery feasibility, particularly in combined sewer systems influenced by rainfall. High-resolution data is therefore essential to accurately capture these effects and assess system performance.

Under the most favorable scenario, the estimated energy potential could supply domestic hot water demand for more than 76,000 households, with corresponding CO_2 emission reductions of approximately 201,288 t CO_2 /year, highlighting the potential contribution of wastewater heat recovery at the urban scale. Heat recovery at the WWTP effluent may also reduce thermal impacts on the receiving water body. Although the present study evaluates theoretical technical potential, the results provide a solid basis for further feasibility studies, system optimization, and the integration of wastewater heat into urban energy planning.

6.1. Limitations and Recommendations for Further Research

The use of fixed ΔT values represents a simplification of real system operation. In practice, variable temperature drops and modulating heat pump operation can be applied, allowing the system to adapt to changing thermal and hydraulic conditions [45]. Such an approach enables more flexible operation and may increase the total amount of recoverable energy. These considerations highlight the need for further optimization studies and more detailed field measurements before full-scale implementation.

The estimates of potential recoverable energy presented in this study are subject to refinement as boundary conditions become more accurately defined through additional data. The current calculations are based on a fixed ΔT and binary (on/off) heat-pump operation. In addition, heat losses, heat exchanger efficiency, and hydraulic constraints have not been explicitly considered. As a result, the presented estimates should be interpreted as a theoretical upper-bound technical potential, while the actual recoverable energy in real applications is expected to be lower.

The feasibility of wastewater heat recovery is strongly constrained by the distance between the point of heat extraction and the location of heat use. Because of the low temperature levels involved, transmission over long distances leads to significant losses and high investment costs for insulated pipelines. Several studies emphasize that economically viable projects are typically limited to a radius of a few hundred meters up to 1–2 km from the consumer [4, 14]. In most successful applications, heat exchangers are placed in close proximity to buildings or district heating substations to minimize losses [16]. In specific feasibility assessments for district heating, however, transmission distances of up to 3–5 km have been considered, though such cases remain exceptional [5].

The number of operational intervals indicates that year-round operation of the installation is feasible, making the recovered energy suitable for domestic hot water heating. The districts located between the WWTP and the CHP are predominantly low-density residential areas and are not served by a centralized heating network, indicating that the utilization of the recovered heat would likely require decentralized or low-temperature distribution systems.

While this study provides an assessment of the technical potential for wastewater heat recovery, it does not explicitly address the practical barriers to implementation. Factors such as hydraulic constraints, pipe dimensions, installation feasibility, and the operational reliability of heat exchangers can substantially influence project outcomes. Future research should therefore incorporate multi-criteria optimization frameworks that account for both the maximization of recoverable energy and the preservation of wastewater treatment efficiency, while also considering the locational and operational challenges inherent to sewer infrastructure, supporting the transition from theoretical assessments toward integrated techno-economic and operational analyses.

7. Declarations

7.1. Author Contributions

Conceptualization, E.T., G.D., and I.H.; methodology, E.T. and G.D.; software, E.T., V.R., and V.D.; validation, E.T., G.D., and I.H.; formal analysis, E.T. and G.D.; investigation, E.T., G.D., and V.D.; resources, E.T., G.D., and V.D.; data curation, E.T., G.D., and V.R.; writing—original draft preparation, E.T. and G.D.; writing—review and editing, E.T., G.D., I.H., V.R., and V.D.; visualization, E.T., G.D., and V.D. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

Data was obtained from Sofiyska voda AD and are not publicly available due to data ownership restrictions.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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