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Energy Recovery from Wastewater: A Study on Heating and Cooling of a Multipurpose Building with Sewage-Reclaimed Heat Energy

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Received: 27 November 2019; Accepted: 19 December 2019; Published: 22 December 2019

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Abstract: To achieve technically-feasible and socially-desirable sustainable management of urban areas, new paradigms have been developed to enhance the sustainability of water and its resources in modern cities. Wastewater is no longer seen as a wasted resource, but rather, as a mining ground from which to obtain valuable chemicals and energy; for example, heat energy, which is often neglected, can be recovered from wastewater for different purposes. In this work, we analyze the design and application of energy recovery from wastewater for heating and cooling a building in Brno (Czech Republic) by means of heat exchangers and pumps. The temperature and the flow rate of the wastewater flowing in a sewer located in the proximity of the building were monitored for a one-year period, and the energy requirement for the building was calculated as 957 MWh per year. Two options were evaluated: heating and cooling using a conventional system (connected to the local grid), and heat recovery from wastewater using heat exchangers and coupled heat pumps. The analysis of the scenarios suggested that the solution based on heat recovery from wastewater was more feasible, showing a 59% decrease in energy consumption compared to the conventional solution (respectively, 259,151 kWh and 620,475 kWh per year). The impact of heat recovery from wastewater on the kinetics of the wastewater resource recovery facility was evaluated, showing a negligible impact in both summer (increase of 0.045 °C) and winter conditions (decrease of 0.056 °C).

Keywords: heat recovery; urban wastewater; temperature; energy recovery; thermal energy; urban water cycle

1. Introduction

The nexus between water and energy is becoming ever more crucial in the development of innovative solutions to achieve technically-feasible and socially-desirable sustainable management for the growth and resilience of urban areas [1]. Novel strategies are being developed to enhance the sustainability of the water cycle and the recycling of its resources in modern cities [2]. Wastewater is no longer seen as a wasted resource, but rather, as a mining ground from which to obtain valuable chemicals [3], nutrients [4,5], and energy [6]. Therefore, urban wastewater systems should be viewed, planned, and built according to a new set of rules and performance expectations that deviate from current standard practices. These rules should be based on entirely new paradigms that, while maintaining current environmental protection practices, should address the now fundamental requirements of robustness, sustainability, and resource recovery through flexible and site-specific solutions, including decentralization and a wider array of possible applicable technologies [3]. Sewage can be considered a source of different types of energy: electrical energy from bioelectrochemical wastewater treatment processes [7,8], low-head hydroelectric energy [9], biogas from anaerobic digestion [10], renewable fuels from residual sludge processing [11,12], and heat energy [13]. The latter is particularly appealing in the framework of water–energy sustainable urban development; in particular, the heat energy recovery potential from wastewater could possibly be even higher than its recoverable chemical energy potential [14,15], and it does not require biological treatment to be converted into a directly usable form. Waste heat from wastewater is reportedly able to generate electrical energy via a thermoelectric generator [16], but the implementation of this is difficult within an urban context. A more accessible technology is the energy recovery from wastewater using heat exchangers installed directly in the sewage collection system [17]. A heat exchanger is installed in direct contact with the wastewater that serves as a heat source or sink, and is later connected to a heat pump and then to the heating and cooling system of a building situated in close proximity. Temperatures of civil wastewater may be more than 25–27 °C in domestic outflows [18], representing a significant thermal energy source [16]; at the inlet of water treatment plants or water resource recovery facilities (WRRFs), the temperature is far lower (15–25 °C or lower, depending on the climate) [16,19,20], and thus, its use for heat recovery may be less practical. Also, heat recovery at this stage should be carefully considered, as it might interfere with treatment processes: biological processes, including denitrification, are sensitive to wastewater temperature, as biological reaction rates depend on Arrhenius' law, and excessive heat extraction from sewage could harm their efficiency [21]. Recently, it has been proposed that heat recovery from wastewater be used to assist in conventional cooling systems in coping with heat waves [22].

This paper presents a case study concerning heat energy recovery from wastewater for heating and cooling a building in Brno (Czech Republic) by means of heat pumps and exchangers. The advantages of the planned solution over conventional heating or cooling systems are described. To the best of the authors' knowledge, this is the first example of planned heat energy recovery from sewage in this European country.

2. Case Study Premises

2.1. Target Building

The building selected for the case study is located in the Brno city center, Czech Republic, and is situated in the proximity of the main collector of the municipal sewer. The edifice consists of a multifunctional, 13-storey building, including four underground floors, with an area of 111.5 m by 50 m. The underground, ground, and first floors are reserved for parking, the second and third floors are dedicated to a shopping gallery, while the rest of the building is occupied by administration offices, with a total rented area of 20,000 m^2.

The annual heating energy consumption of the building was calculated to be just over 500 MWh, while the annual cooling consumption was just under 457 MWh. Therefore, the overall annual energy demand of the building for heat conditioning is around approximately 957 MWh. Peak power requirements were determined as 800 and 1000 kW, respectively, for heating and cooling. An analysis of the concurrent heating and cooling power demand is summarized in Figure 1.

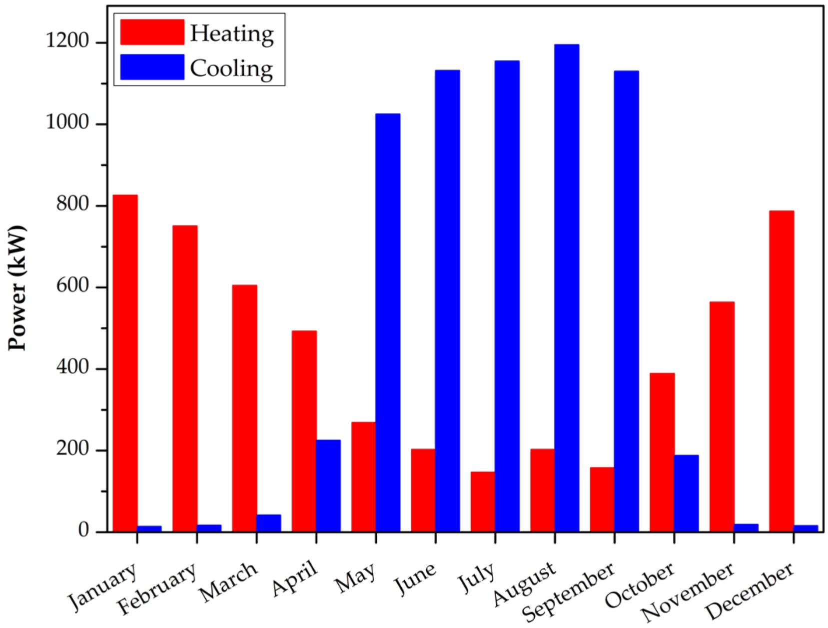

Figure 1. Monthly power demand for cooling and heating in the multipurpose building.

2.2. The Sewer System

The main sewer is located below the street in the proximity of the multipurpose building; the pipe size is 5.1 (width) by 3 (height) m, with a bottom gradient of 3.25‰. The wastewater flow rate and temperature were monitored for one year (from 16 June 2015 to 15 June 2016) before the beginning of the actual design process to preliminarily assess the feasibility and the extent of potential heat recovery from wastewater. The average dry weather flow was 291 L s^{-1}, with daily variability shown in Figure 2; high variations in hourly data may be ascribed to the extended time range of measurements, including winter and summer holidays. Several universities are located in Brno, and the city hosts around 70,000 students, with an additional 90,000 daily commuters. These facts are reflected in the aforementioned high hourly variability and low flow rate during university holidays (July and August). Monthly variability is shown in Table 1.

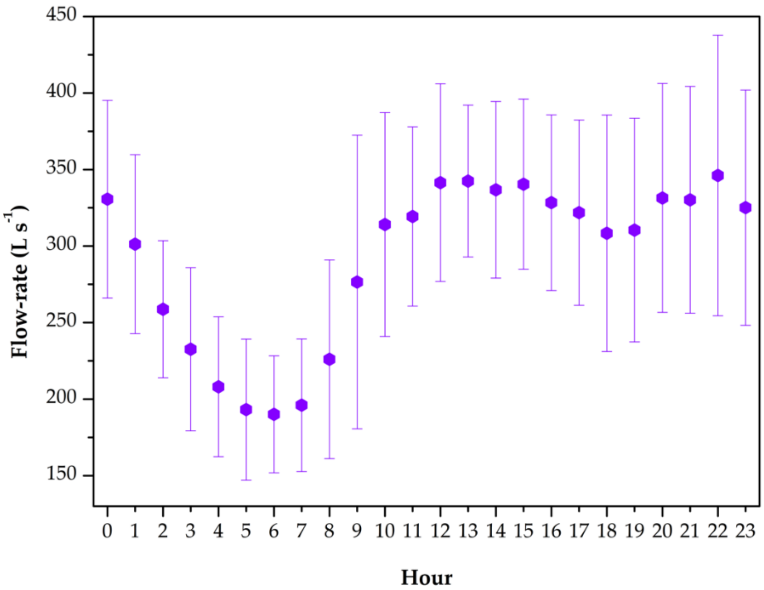

Figure 2. Mean hourly flow rate in the sewer during monitoring in the study year. Bars represent the standard deviations of the data during the observation period.

Table 1. Maximum, minimum, and average values for the sewer's flow rate during monitoring. SD: standard deviation.

Q	Month												Year
(L s^{-1})	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**-**
Max	427.9	454.8	338.0	389.7	344.7	425.6	299.8	313.3	389.7	470.6	405.4	427.9	470.6
Min	167.2	200.9	171.7	160.4	182.9	135.7	158.2	147.0	144.7	164.9	131.2	167.2	131.2
Mean	302.8	354.1	272.6	286.1	268.5	287.7	233.4	240.0	272.8	391.7	304.3	302.8	291.9
SD	72.5	76.8	57.3	66.1	52.3	84.1	40.1	53.2	67.4	95.1	91.6	72.5	83.4

The average temperature recorded during the monitoring period was 15.2 °C, with a minimum of 11.8 °C in February and a maximum of 18.7 °C in September, following the pattern shown in Figure 3.

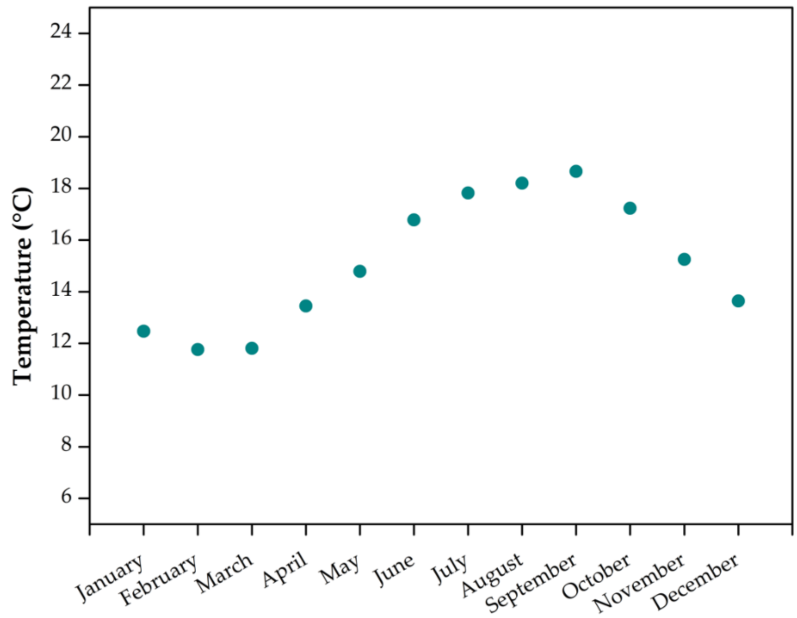

Figure 3. Monthly temperature of the wastewater in the sewer, recorded in the proximity of the building.

The temperature trend observed in the sewer was in accordance with the data reported by Cipolla and Maglionico [17], Wanner et al. [23], and Kretschmer et al. [19], respectively, in Bologna (Italy), Zurich (Switzerland), and in a 24,000-population town in Austria.

2.3. Heat Recovery: Influence on the Wastewater Temperature

Based on the aforementioned data, it is possible to use Equation (1) (modified from the original equation proposed by Kretschmer et al. [19]) to graphically depict the relationships between the wastewater flow rate diverted at the recovery site for heat exchange (Q_{RS}, L s^{-1}), available heat potential (P_{RS}, kW), and temperature difference or decrease due to heat recovery (ΔT_{RS}, K), as shown in Figure 4:

$$P_{RS} = Q_{RS} \cdot c \cdot \Delta T_{RS} \cdot \rho \quad (1)$$

where c is the specific heat capacity of wastewater (4.18 kJ kg^{-1} °C^{-1} [24]), and ρ represents the wastewater density (assumed to be 1000 kg m^{-3}).

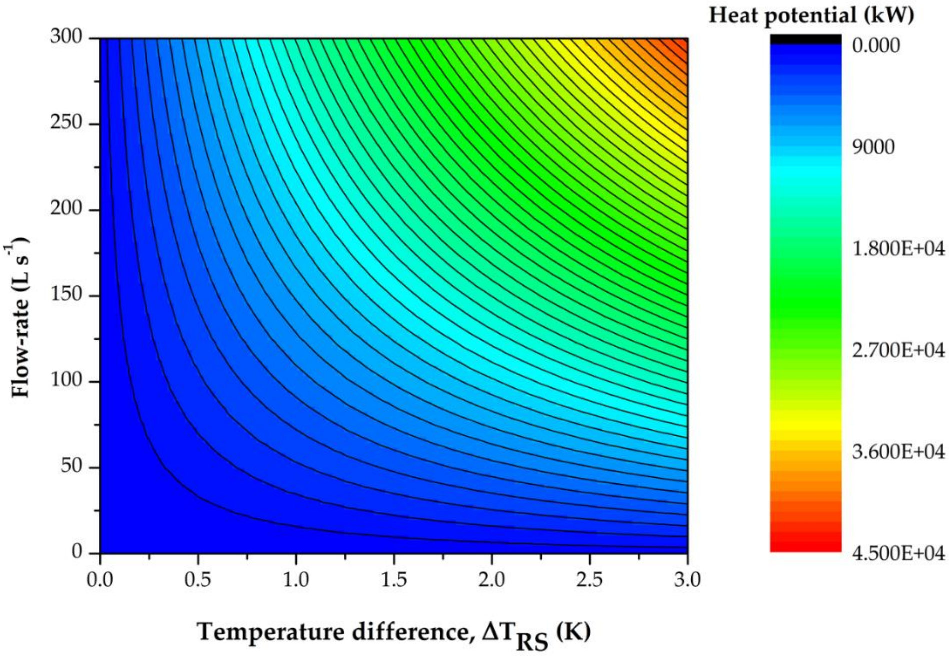

Figure 4. Relationship between the heat exchanger flow rate, temperature, and power recovered.

The change of temperature in the sewer immediately after the reintroduction of the heat-recovered wastewater (ΔT_{SEWER}, °C) can be calculated using Equation (2) [19]:

$$\Delta T_{SEWER} = (Q_{RS} \cdot \Delta T_{RS})/Q_{SEWER}, \quad (2)$$

where Q_{SEWER} is the flow rate in the sewer in the proximity of the building (L s^{-1}). Similarly, the change in the temperature of the wastewater at the inflow of the WRRF (ΔT_{WRRF}) due to the heat recovery process can be computed using Equation (3):

$$\Delta T_{WRRF} = (Q_{RS} \cdot \Delta T_{RS})/Q_{WRRF,} \quad (3)$$

where Q_{WRRF} is the flow rate at the inflow of the WRRF (L s^{-1}).

Considering an 800-kW heat power demand, coupled with a flow rate of 90 L s^{-1}, the decrease in the wastewater temperature would be 2.12 °C, calculated using Equation (1). Taking into consideration the winter months, when heat demand is higher (December, January, and February, as shown in Figure 1), the temperature drop calculated using Equation (2) would be in the range of 0.42–1.45 °C, in the case of the maximum and minimum flow rates recorded in that period.

In the case of a 1000-kW power demand for cooling, the temperature drop calculated using Equation (1) would be 2.65 °C at a flow of 90 L s^{-1}. Similar to the heating condition, the change in temperature after heat exchange may be computed using Equation (2). Considering the summer period flow rate, a temperature increase in the range of 0.52–1.76 °C could be expected.

Based on the heat exchanged from wastewater, it is possible to calculate the temperature drop or increase at the inflow of the local wastewater treatment plant, applying Equation (3). The flow rate at the Brno WRRF is reported as 4.222 m^3 s^{-1} [25]; therefore, the flow to the heat exchanger is 2.13% of the WWRF inflow, while during maximum sewer flow (470 L s^{-1}), the percentage increases to 11.1%. The temperature decrease due to heat exchange for heating is equal to 0.045 °C, while the increase due to cooling is 0.056 °C, both calculated at the inflow of the WWRF. Based on that, it is possible to state that the application of heat recovery from wastewater for the building conditioning would not affect the kinetics of the processes of WWRF. A different situation, which should be specifically evaluated, would consist of a diffuse application of heat exchange in a multitude of buildings within the city, a condition that may lead to significant changes in the influent wastewater temperature to the plant.

3. Indoor Heating and Cooling Options

3.1. Conventional Indoor Heating and Cooling

According to calculations based on a preliminary conventional indoor conditioning system scheme, the building would require an 824-kW thermal unit to be installed, including a 3% power margin on peak power for heating. The total heating energy consumption is considered equal to the annual building heat demand of 500,293 kWh. Under the same hypotheses, the cooling system would consist of three units with an overall power of 1030 kW, including the same margin on the peak. With a cooling system coefficient of performance (COP) of 3.9 (declared by the manufacturer), this would imply an energy consumption of 120,183 kWh per year. The sum of energy consumed by the heating and cooling system would thus imply an overall energy consumption of 620,475 kWh per year (option 1).

3.2. Heat Recovery from Wastewater

The second option considered is heat recovery from wastewater. In this case, a commercial HUBER™ ThermWin system (HUBER SE, Berching, Germany [26]) was installed, as shown in Figure 5. The system is composed of a connection with the bottom of the sewer pipe, a shaft equipped with a screen, an aboveground heat exchanger, and a heat pump. Different from other applications in which the heat pump is located directly in the sewer conduits [18,27], this solution foresees a shaft installed near the sewer bottom, connected purely by gravity. The shaft serves as a sump for the pump feeding the heat exchanger, and houses a coarse screen to avoid unwanted material carried by the wastewater from reaching the heat exchanger. Collected solids would then be sent back to the mains by a vertical screw equipped with brushes. A dedicated hydrodynamic study was carried out on the sewer–shaft intersection to evaluate the likelihood of any operational issues [28]. The hydrodynamics of the setup were computed using the FLOW-3D model software (Flow-Science Inc., Santa Fe, NM, USA) in order to ensure the availability of a flow rate of 90 L s^{-1}, which is necessary for the system's operation under any flow-rate conditions, as shown in Figure 6.

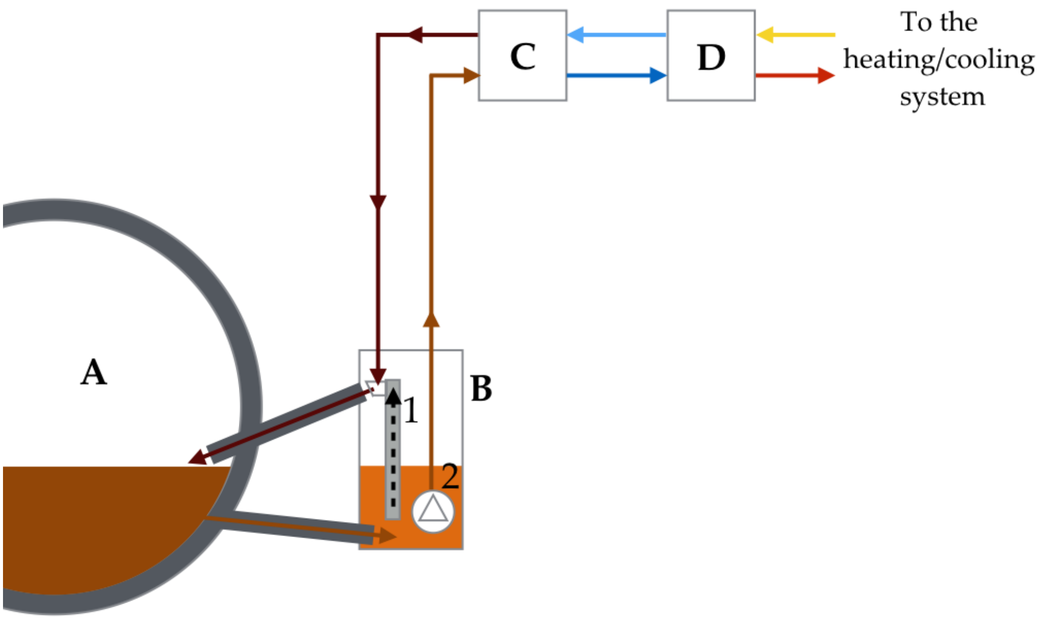

Figure 5. Scheme of the heat recovery system. A: Sewer collector; B: pump with pretreatment (2) and vertical screen (1); C: heat exchanger; D: heat pump. The sewer and pump shaft are underground, while the heat exchanger and heat pump are located aboveground.

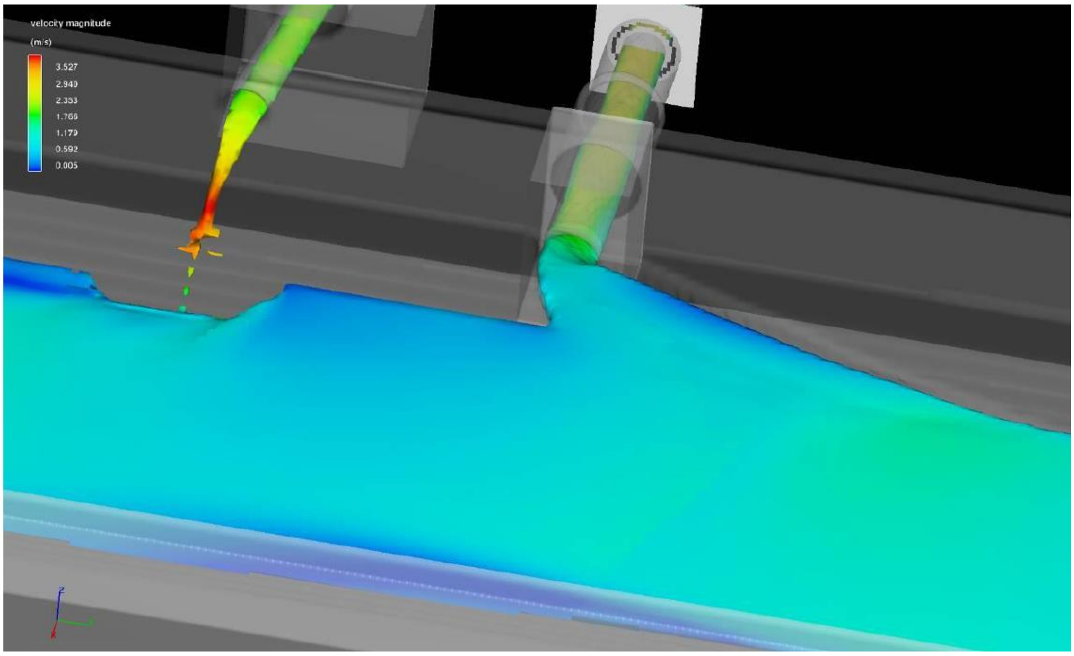

Figure 6. Scheme of the intersection between the inflow and outflow pipes and the main sewer, at a 323 L s^{-1} flow rate. Reproduced with permission from [28].

The system consists of two heat pumps connected to three heat exchangers. The installed power of heat pumps and exchangers is rated at 700 kW; in addition, a supplementary 180 kW of power is required to operate the system. A supplementary conventional heating system is provided, with an installed power of 800 kW. The system is designed to work in combined mode: 10% of the demand is provided by conventional heating and 90% by wastewater-recovered heat. This would result in an annual energy consumption for the conventional heating fraction of 50,029 kWh (10% of the yearly consumption), and 112,566 kWh for the heat pumps–exchangers assembly, based on a manufacturer-declared 3.9 COP. The annual energy requirement for the heating demand under option 2 is therefore estimated to be 162,595 kWh.

Considering cooling requirements, a similar pattern is replicated: 90% of the energy demand is covered by wastewater-recovered energy and 10% by conventional cooling. An additional 400 kW unit is planned to assist the 700-kW-rated wastewater energy recovery unit. The former unit works at specifications rated 4.2 COP, while the heat pump–exchanger system is rated 6.6 COP. The total energy required for heating or cooling is then determined as the sum of energy for the booster conventional cooling system (10,874 kWh) and for the heat pump–exchanger system (62,276 kWh), with a total of 73,150 kWh. Additional energy requirements derive from the operation of blowers, heat exchangers, pumps, and electric drive shears, and are calculated as 23,406 kWh y^{-1}.

Thus, the overall annual direct energy consumption for option 2, including cooling, heating, and related energy needs, is estimated to be 259,151 kWh, in addition to the fraction recovered from wastewater. This sums to more than 58% lower energy requirements than in an equivalent conventional system.

4. Comparison and Discussion

Based on the results shown in Sections 3.1 and 3.2, the energy requirements in the case of the use of heat pumps and exchangers for wastewater heat recovery are almost 59% lower than those required for a conventional solution. As shown in Figure 7, the option of energy recovery from wastewater could be considered advantageous for both heating and cooling, even though the advantage is more prominent in the former case.

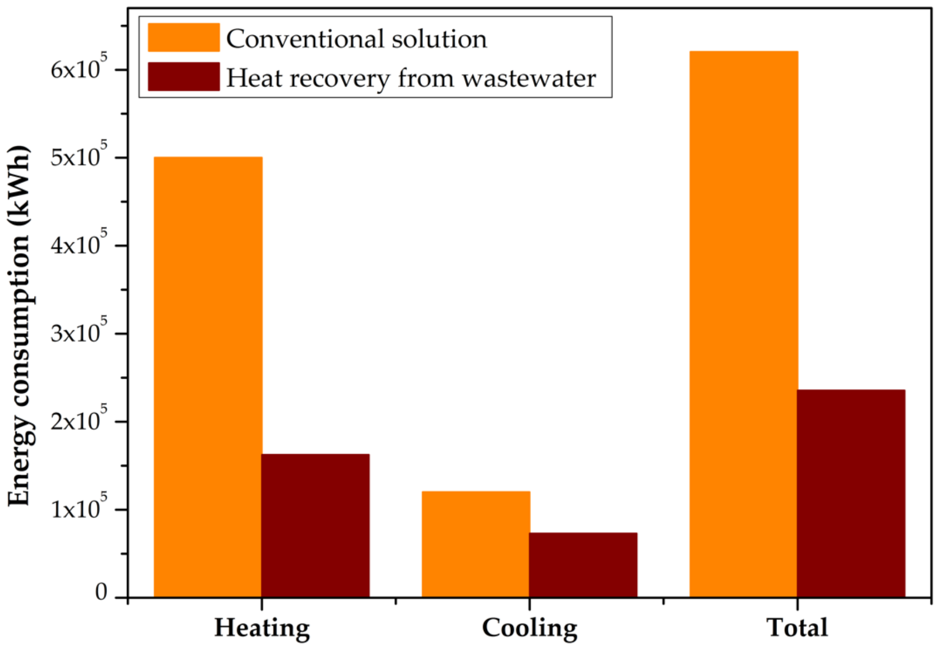

Figure 7. Energy consumption for heating, cooling, and overall energy consumption in the two options considered.

The results suggest the feasibility of energy recovery from wastewater to reduce the energy demands of the study building. However, from technical and operational points of view, it should be highlighted that such a new and locally-untested application may be more complex than a conventional heating system, and can only be feasible when the main sewer is located in close proximity to the building. In addition, it would be complicated to retrofit an existing building with such a solution, suggesting that this approach should be implemented in new urbanizations.

Additional issues should be considered in relation to similar applications. One is related to the "ownership" of the wastewater-embedded heat. As a "waste," wastewater is currently considered a liability, with costs associated with its treatment and disposal. Users normally pay a treatment fee, usually associated with their water consumption. If this pilot application becomes successful, wastewater would gain a sort of "redemption" value, and appropriate schemes would have to be developed to apportion this resource and collect revenue from its exploitation. The water utility should be able to charge an appropriate heat recovery fee to users, as they would be enjoying savings from lower heating and conditioning bills, to maintain sewerage system sustainability and fair conditions to all users. If too many users attempt to exploit a similar scheme in an uncontrolled, unregulated fashion, an excessive wastewater temperature reduction could occur, with a negative impact on WRRF performance, and thus, on all users and on the sewerage system itself. Therefore, a multidisciplinary approach should be followed with all the stakeholders involved when planning extensive heat recovery from wastewater, [29,30].

Even though it may seem like a free resource, embedded heat exploitation is, in fact, the cause of indirect costs, even to water utility companies. The kinetics of the biological sewage treatment processes follow Arrhenius' law, i.e., they are dependent on environmental (water) temperature, such that lower temperatures imply slower biodegradation rates [31]:

$$k = k_{20} \cdot \theta^{(T-20)}, \quad (4)$$

where k is the temperature-dependent reaction rate coefficient (d^{-1}), k_{20} is the reaction rate at the temperature of 20 °C (1.104 d^{-1}, as proposed by Sheridan et al. [32]), θ is the heat coefficient (1.047 for aerobic wastewater treatment [33], adimensional), and T is the temperature of the wastewater (°C). Temperature influences a large number of biochemical processes in wastewater treatment, including oxygen transfer [34], nitrification [35], aerobic and anaerobic organic matter removal [36], and biomass decay [37].

Based on Equation (4), considering increases or drops in wastewater temperature at the WRRF inflow, and comparing the kinetics of biological processes to those in original conditions, it is possible to estimate the effects of heat recovery; in the situation considered, the difference would be minimal in both winter and summer, i.e., equal to a decrease of $2.28 \cdot 10^{-3}$ d^{-1} and an increase of $2.84 \cdot 10^{-3}$ d^{-1}, respectively. The results of the simulation suggest that the influence of the heat recovery in a large single building would have negligible effects on the biochemical processes of the WRRF. Multiple heat recovery applications would have a different outcome. If recovery is too high, wastewater temperature drop may be significant, and may have adverse consequences on the efficiency of treatment processes, reducing carbon and especially nitrogen removal rates, and inducing the need to upgrade the possible treatment units. All these situations require a preliminary facility assessment to determine the limits to which wastewater heat energy recovery can be carried out without impairment [19]; recently, modeling has been proposed as a solution to evaluate the amount of heat that can be recovered from wastewater without harming the biological processes in WRRFs [38–40].

5. Conclusions

The planning of a wastewater-supplied heating and cooling system for a multipurpose building in Brno (Czech Republic) was carried out. The tested system required a far lower energy consumption (235,745 kWh), i.e., almost 59% less than a conventional solution. The impact analysis of wastewater heat recovery on the downstream WRRF biological processes proved such an impact to be negligible, i.e., an influent wastewater temperature decrease of 0.045 °C and an increase of 0.056 °C, respectively, in winter and summer. Therefore, the envisioned solution would enhance the overall sustainability of the building without impairing the wastewater treatment performance; however, performance and efficiency issues may develop, should the general application of this solution be attempted throughout the city.

In view of the possibility of a more generalized adoption of these systems, preliminary WRRF performance assessments should be carried out. In addition, sewer operators should consider introducing pricing schemes for the exploitation of wastewater-embedded heat energy, both to safeguard wastewater treatment facility performance and as a principle of fair treatment of all stakeholders.

Author Contributions: Conceptualization, J.R. and P.H.; software, J.R.; investigation, J.R. and P.H.; writing—original draft preparation, D.C.; writing—review and editing, D.C. and A.C.; supervision, A.C. and P.H.; funding acquisition, P.H. and A.C. All the authors contributed substantially to the work reported. All authors have read and agreed to the published version of the manuscript.

Funding: This paper has been worked out under project No. LO1408 "AdMaS UP-Advanced Materials, Structures and Technologies", supported by the Ministry of Education, Youth and Sports under the "National Sustainability Programme I".

Conflicts of Interest: The authors declare no conflict of interest.

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