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The Thermal Potential of Wastewater for Heating and Cooling Buildings: A Case Study of a Low Exergy Building in Madrid

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Abstract: The use of technologies that allow for the utilization of renewable energies wasted around buildings is one of the ways to ensure the decarbonization of the sector. Wastewater from buildings is a renewable source of thermal energy. Groundwater and rainwater are important components of wastewater that flow into sewerage systems. The main objective of this research is to estimate the thermal potential of wastewater for the heating and cooling of buildings. In this paper, an office building with a low-energy system (TABS) was studied for one year to assess the energy contribution of wastewater in a hybrid system that includes geothermal exchangers and a wastewater exchanger. This study shows that wastewater from sewerage systems that flows faster than 5 L/s can make enough heat to power an office building with a power demand of 45 kW (60 W/m^2). The energy contribution of wastewater from the sewerage system is more favorable in heating scenarios than in cooling ones, improving the system efficiency by over 22% compared to geothermal systems. Rainwater enhances cooling efficiency by over 14% compared to geothermal systems. This finding could help to establish a predictive method or guidelines for the design and sizing of heat exchangers in sewerage systems.

Keywords: WWHR; wastewater heat exchanger; sewerage system; TABS; building energy management; heat recovery; geothermal

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1. Introduction

Energy demand has resulted in the production of high percentages of polluting gases for the environment [1] and human beings, as well as the continuous depletion of fossil resources [2]. The residential sector represents 31% of total energy consumption worldwide [3]. To reduce these problems, it is appropriate to use site-specific renewable energy sources [4], including energy from the environment of the buildings [5]. It is possible to achieve this if buildings have low-energy technologies compatible with the use of low speed, pressure, and temperature energies [6,7].

A low-energy building allows the energy it receives to come from sources close to its environment [8], promoting energy-efficient heating and cooling systems [9], with technologies that allow for their proper operation [10,11].

In this regard, for three decades, heat has been recovered from wastewater for the heating and cooling of buildings. Switzerland has carried out several research projects for the advancement of knowledge and technology in this area, being the pioneer country with the largest number of research projects developed in this field [12]. In Asia, Japan and China have encouraged private sector investment in the use of wastewater by modifying and regularizing wastewater laws [13]. Similarly, several projects have been developed in Europe and North America, among which we can highlight [14,15].

As a result, the EU Directive 2018/2001 allows wastewater to be used as a renewable energy source [16]. According to the scientific literature, there are three levels of heat usage from this source: inside buildings (small scale), in the sewerage system (medium scale), or at a wastewater treatment plant (large-scale applications) [17,18].

A constant contribution of renewable energy to the sewerage system has been observed at all three levels of utilization. Indeed, in residential and tertiary buildings, different activities involve the demand and consumption of domestic hot water [19]. The average daily wastewater production per person is 130 L, with temperatures ranging from 20 °C to 25 °C [20]. Since this hot water is discharged into the sewerage system, the wastewater flowing into these networks is maintained throughout the year at temperatures between 12 °C and 24 °C [21].

Thermal wastewater recovery requires a heat exchanger (HE) and heat pumps (HP). The combination of this technology makes it an innovative system [22,23]. The efficiency of the system as well as the costs depend on the flow rate and temperature of the wastewater [16]. It is estimated that the production of 1 kWh of energy in wastewater heating installations would cost about $0.07 to $0.22 [24]. However, it is necessary that the water reaches a wastewater treatment plant (WWTP) with a minimum temperature of 10 °C after use in the building (cooling) to guarantee a limit value of pollutant concentration in the wastewater to be treated in the WWTP [12].

In some countries, rainwater complements conventional water sources for non-potable use [25]. The factors determining the incorporation of these systems are the amount and frequency of precipitation (weather conditions) and the demand for this non-potable water in the buildings [26,27].

This paper is part of a research work that takes as a reference and is developed in continuity with an R&D project entitled "Development of an innovative system for collecting waste energy from urban water for use in heating and cooling buildings, RESIDAQUA" (2019–2021). At the early stage of the research, it was determined that two of the most influential parameters in this thermal recovery potential are the temperature and the flow rate of the wastewater. It is noted that the urban sewerage system in Madrid can guarantee average flow rates of 50 L/s of wastewater at an average temperature of 15 °C [15]. The question of the contribution of the flow rate and temperature of the groundwater and rainwater was then raised. Under this approach, one of the case studies evaluated in the R&D project "RESIDAQUA" was used for this research: the Apolonio Morales 29 office building, located in Madrid (Spain). In this building, which has a Thermo-Active Building System (TABS), a heat exchanger was implemented to take advantage of the thermal energy of wastewater (groundwater and rainwater).

The wastewater In the building was used for the air conditioning system in two ways: to transfer temperature by means of two heat pumps (HPs) of 22 kW each to the fluid that passes into the hermos-active structure and to pre-treat the outside air entering the building through a water-air exchanger, in winter by increasing the air temperature with thermodynamic panels on the roof, and in summer by lowering the air temperature with water from the cistern.

In addition, information from a monitoring system of temperature and flow of wastewater in the sewerage system near the case study building was used in this research. The objective was to draw conclusions about the potential use of this wastewater, including the contribution of heat energy from the consumption of domestic hot water in buildings in an urban environment.

Therefore, the main objective of this research was to estimate the thermal potential of wastewater to cover its whole-year thermal demand for heating and cooling. The secondary objective was to determine the impact that groundwater and rainwater have on the thermal efficiency of a sewerage wastewater heat exchanger to ensure proper thermal comfort inside of the building. Within the focus of these objectives, the following issues were explored:

- The type of thermal energy that can be harnessed from wastewater, for heating or for cooling, and in which period of the year this energy is more effective.
- The impact of wastewater (groundwater and rainwater) on the flow and temperature in the sewerage system and, consequently, how the efficiency of the HPs (COP/EER) is affected according to source-side temperature, building demand, and location of the heat exchanger.

- The hypothetical efficiency of the thermal exchange of wastewater flowing through the sewerage systems on the actual temperature and flow rate measurements, and what is its contribution to the geothermal exchange system currently in place in the case study building.

2. Materials and Methods

The case study is the Apolonio Morales 29 office building, with a floor area of 803 m^2. Through its development and a series of cross-cutting design measures, the building's energy demand is low. The annual electricity consumption of Apolonio Morales 29 office building is currently less than 20 kWh/(m^2-year) for heating and 10 kWh/(m^2-year) for cooling, which implies that it is below the energy consumption range for an office building: 33.4–47.8 kWh/(m^2-year) for heating and 35.6–73.9 kWh/(m^2-year) for cooling, according to [28].

The HVAC system of the Apolonio Morales 29 office building is based on the thermal inertia of its structure and powered by a fluid that circulates inside the thermoactivated slabs (TABS).

The system for capturing thermal energy from the surrounding environment is a hybrid system with two renewable sources: very low enthalpy geothermal energy, through twenty-two 10-m-deep geothermal piles and six 100-m-deep vertical geothermal borehole exchangers, and a wastewater heat exchanger installed in the building's cistern, which collects water from the building's manholes. The first manhole is located at a lower level of the groundwater table, and the second manhole is located at a higher level of the groundwater drainage, which collects the water from the first manhole, thanks to a pumping system, and rainwater collected from the entire surface of the building, both from the roof and courtyard.

Figure 1 shows the wastewater heat exchanger, installed on the walls of the cistern, and connected in a closed circuit to the geothermal collector. It consists of a 100 m spiral pipe circuit of Pex Φ 20 mm with an EVAL-anti-oxygen barrier layer. The cistern is buried beneath the engine room of the building and has a maximum volume of 12 m^3. To comply with current sanitary regulations, the thermal saturation of the water is avoided by means of a pumping system that renews the water when it reaches a certain limit. The water is kept at temperatures below 20 °C to prevent the proliferation of legionella bacteria and bad odors in the water that is reused in sanitary units and for the irrigation system.

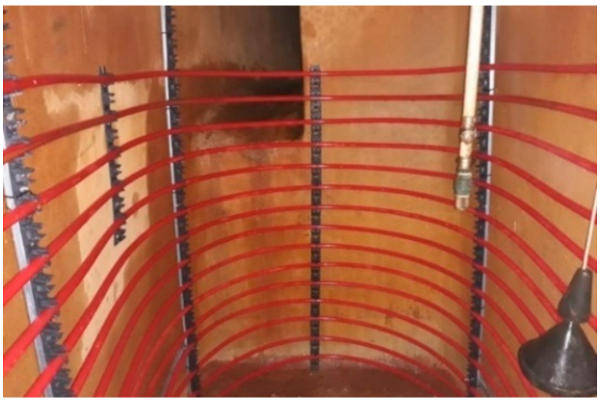


Figure 1. Heat exchange circuit installed in the cistern of the Apolonio Morales 29 office building.

The HVAC system is continuously monitored in real time by a set of sensors and devices that are part of a complex building management system (BMS). The visualization of historical or real-time data is achieved through a graphical interface, which allows the user to perform trend analysis with reference to temperature, flow, and energy parameters at various points of the system. The data is collected and recorded in a database for further evaluation by the user.

This research leverages part of the data from the existing monitoring system in the building and a monitoring system developed in the frame of the RESIDAQUA R&D project with the aim of monitoring temperature and flow in the wastewater at a point in the sewerage system near the building. The precision of the pipe sensor is ±2%/±3% RH, the calorie counter is Ef = ±(1 + 0.01 qp/q)%, and the temperature sensor in the sewerage system is ±1 cm. The systems are shown in Figure 2.

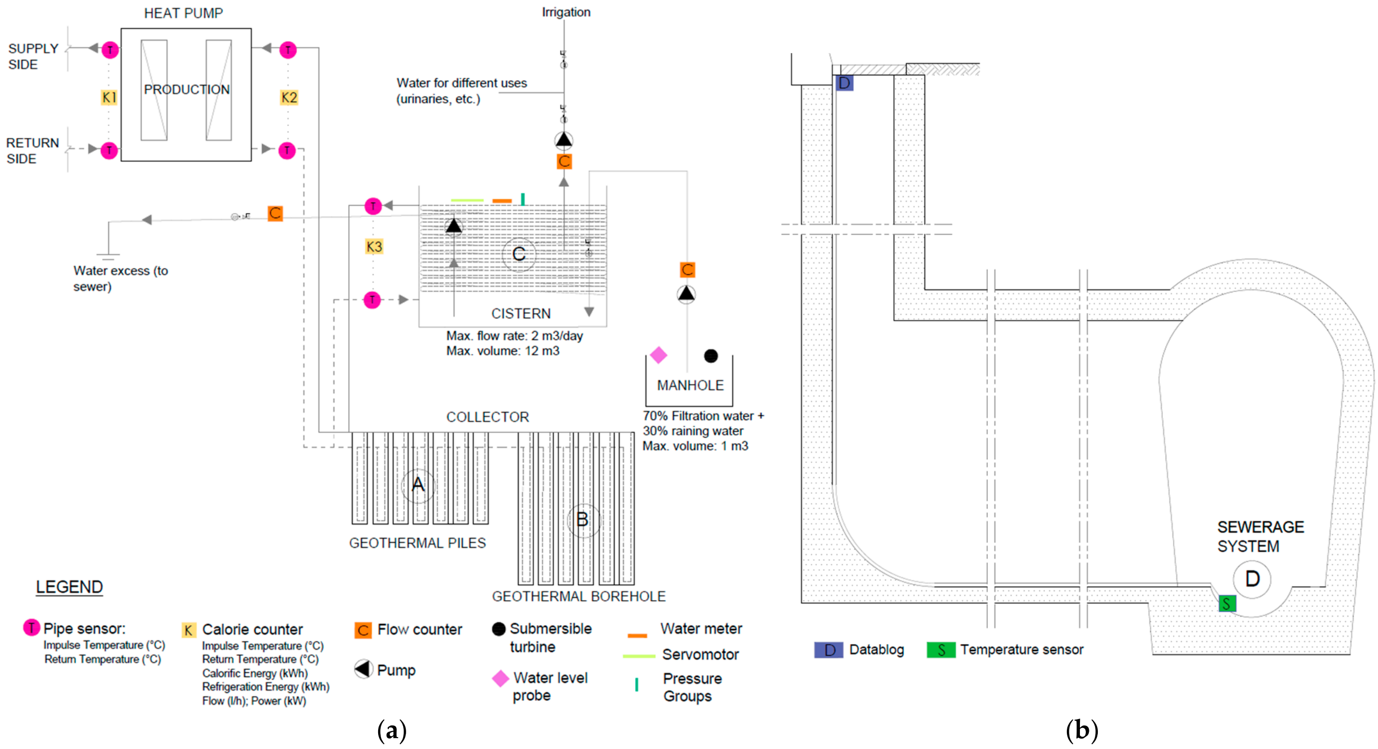


Figure 2. (**a**) HVAC system diagram (source-side) and the three types of heat exchangers (A), (B), (C). (**b**) Monitoring system in sewerage system and the hypothetical heat exchanger (D).

By processing the data recorded by the monitoring system, it has been possible to analyze the efficiency of the HPs (COP/EER) and the energy provided by the source, compared to the total energy required by the building for heating and cooling. The HPs receive the energy contribution of all different renewable sources in the building environment, thanks to the heat exchangers (HEs) that are part of the system, and the rest is due to electric energy.

Additionally, the efficiency of the HPs (COP/EER) operating with HEs A + B + C was compared with the efficiency of the same HPs operating with a hypothetical HE, which was installed in the sewerage system for the use of energy from domestic wastewater. The objective of both systems is to cover the energy required by the Apolonio Morales 29 office building for heating and cooling. Table 1 illustrates sources and consequently the different heat exchangers considered in this research.

The study begins with an analysis of the primary energy sources for the four HEs separately or in their actual configurations and combinations. In addition, some climatic parameters were added to evaluate any possible relationship between all the variables studied.

Table 2 shows the analysis of the coverage and efficiency of the HPs (COP/EER) with different renewable sources in the building environment and their water source temperature analysis. For this analysis, eight representative periods, with a minimum duration of one week, were taken as data samples: four for the heating mode (sunny days, cloudy days, rainy days, and rainy nights) and four for the cooling mode (sunny days, cloudy days, rainy days, and rainy nights).

Table 1. Heat exchangers considered for this research.

Heat Exchanger	Source	Situation	Name
Geothermal 10-m-deep pile	Geothermal	Real (existing)	A
Geothermal 100-m-deep borehole heat exchangers	Geothermal	Real (existing)	B
Wastewater heat spiral exchanger (cistern)	Ground and rainwater	Real (existing)	C
Wastewater exchanger (sewerage system)	Domestic wastewater and rainwater	Hypothetical	D

Table 2. Analysis of the coverage and efficiency of the different renewable sources of the building environment.

Level	Source Temperature Analysis (°C)	Water Flow Temperature Analysis (°C)	Power and Coverage Analysis (kW)	Coverage Analysis (%)	Efficiency Analysis
Building	-	-	Production power (building thermal loads) (kW)	-	-
Heat exchanger A (real)	Average ground temperature at the level of 10-m-deep geothermal piles (°C)	Supply and return water temperature in the 10-m-deep geothermal piles (°C)	Pile exchanger system power (kW)	Pile exchanger system coverage (%)	Real heat exchanger system
Heat exchanger B (real)	Average ground temperature at the level of 100-m-deep borehole exchangers (°C)	Supply and return water temperature in the 100-m-deep borehole exchangers (°C)	Borehole exchanger system power (kW)	Borehole exchanger system coverage (%)	
Heat exchanger C (real)	Water temperature at the manhole level (groundwater) (°C)	-	-	-	
	Water temperature at the cistern level (ground and rainwater) (°C)	Supply and return water temperature in the heat exchanger (°C)	Heat exchanger power (kW)	Heat exchanger coverage (%)	
Heat exchanger D (hypothetical)	Water temperature at the sewerage system level (domestic wastewater and rainwater) (°C)	-	Wastewater heat exchanger power (kW)	Wastewater heat exchanger coverage (%)	Heat exchanger ideal

Considering that the heat transfer fluid in the cooling and heating building system is a liquid (water), the thermal power variation at each point of the system is determined through a simplification of the equation of heat balance:

$$\text{Cooling or heating power (W)} = Q \times \rho \times c \times \Delta T \quad (1)$$

where Q is the water flow rate (L/h); ρ is the specific density of water that is the equal of 1 (kg/L); ce is the specific heat of water that is 1 kcal/(kg·°C); and ΔT is the thermal gap (T supply − T return) (°C).

Since the specific heat of water is 1 kcal/(kg·°C) and the density of water is 1 kg/L, the simplification of the formula above is:

$$\text{Coolingorheatingpower(W)} = \frac{Q \times \Delta T}{0.86} \quad (2)$$

where Q is the water flow rate (L/h) and ΔT the thermal gap (T supply $-$ T return) (°C).

W to kW conversion value has been applied.

The calculation of the maximum power available in the sewerage system (heating or cooling) is directly dependent on the flow rate and temperature monitored. In the calculation of the thermal gap, local regulations are considered, limiting the alteration of the temperature of the wastewater flowing in the sewerage system to a maximum of 2 °C.

Knowing the power obtained from each source at the different points of the system, the efficiency of the HPs (COP/EER) is calculated. The efficiency of the HPs of the actual heating and cooling system has been calculated together with HEs A, B, and C, where the energy from these sources is mixed in a single collector, as shown in Figure 2a. The sources are mixed in a single collector because a free outlet in the existing collector was used for the connection of a new HE to take advantage of the energy provided by the wastewater (groundwater and rainwater) collected in the cistern.

The efficiency of the HPs has been calculated on the one hand with the data monitored for the real system, denominated A + B + C (real), where C is a prototype, and on the other hand, in a hypothetical case where HE C is optimized, denominated A + B + C (optimized). Optimized means that HE C is improved in different ways (size, technology, conditions, etc.) to obtain the maximum utilization of the residual energy and the maximum efficiency.

The theoretical efficiency with which the HPs would operate to cover the actual energy demand of the building can be obtained from the table provided in the manufacturer's catalog, calculated according to the UNE-EN 14511-3:2023 standard [29]. In the manufacturer's table, the efficiency is calculated by crossing the monitored temperature (source side) with the monitored production temperature of the HPs (demand of the building) at each moment. Considering that HPs operate with variable flow, which is ideally sized and provides at any given moment the adequate flow to generate the required energy to meet the demand, efficiency, in this case, will only be affected by temperature.

The efficiency of the heat recovery from sewerage wastewater, denominated D (hypothetical), is obtained with the mentioned theoretical analysis, based on the hypothetical condition that the heat exchange between source and HE is obtained with a thermal jump of 5 °C, as used for another case study in Madrid by [15]. It has also been considered that the HE is suitably sized to obtain maximum efficiency.

In this hypothesis, the parameters of water flow velocity, exchange surface, water renewal effects, water contact time with the exchange surface, and economic factors linked to the cost of investment are not considered.

Knowing the efficiency of the HPs, the capacity of this residual source to cover the demand of the building is calculated based on Figure 3 and using the following equation:

$$\text{Heating Efficiency} = \frac{Q2}{(Q2 - Q1)} \quad (3)$$

$$\text{Cooling Performance} = \frac{Q1}{(Q1 - Q2)} \quad (4)$$

where $Q1$ is power obtained of each HE (each renewable source) and $Q2$ is demand of the building.

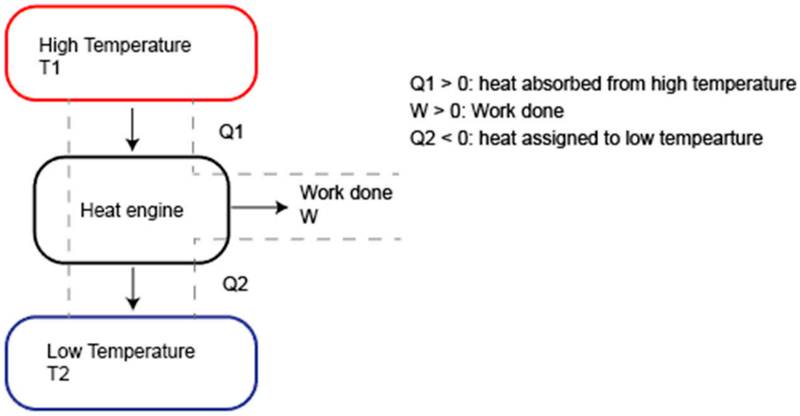


Figure 3. Diagram for the efficiency of the HPs (COP/EER) calculation.

3. Data Analysis

Figure 4 shows the temperature variation of the three energy sources on an annual basis. Wastewater at the sewerage system level has more favorable temperatures in the winter. In the intermediate seasons and the first weeks of summer, wastewater (groundwater and rainwater) and geothermal water have more favorable temperatures for cooling energy. However, from a temperature perspective, wastewater (groundwater and rainwater) is a more efficient source of energy than geothermal, even in winter, as ground temperature is altered and impaired via thermal exchange with the building.

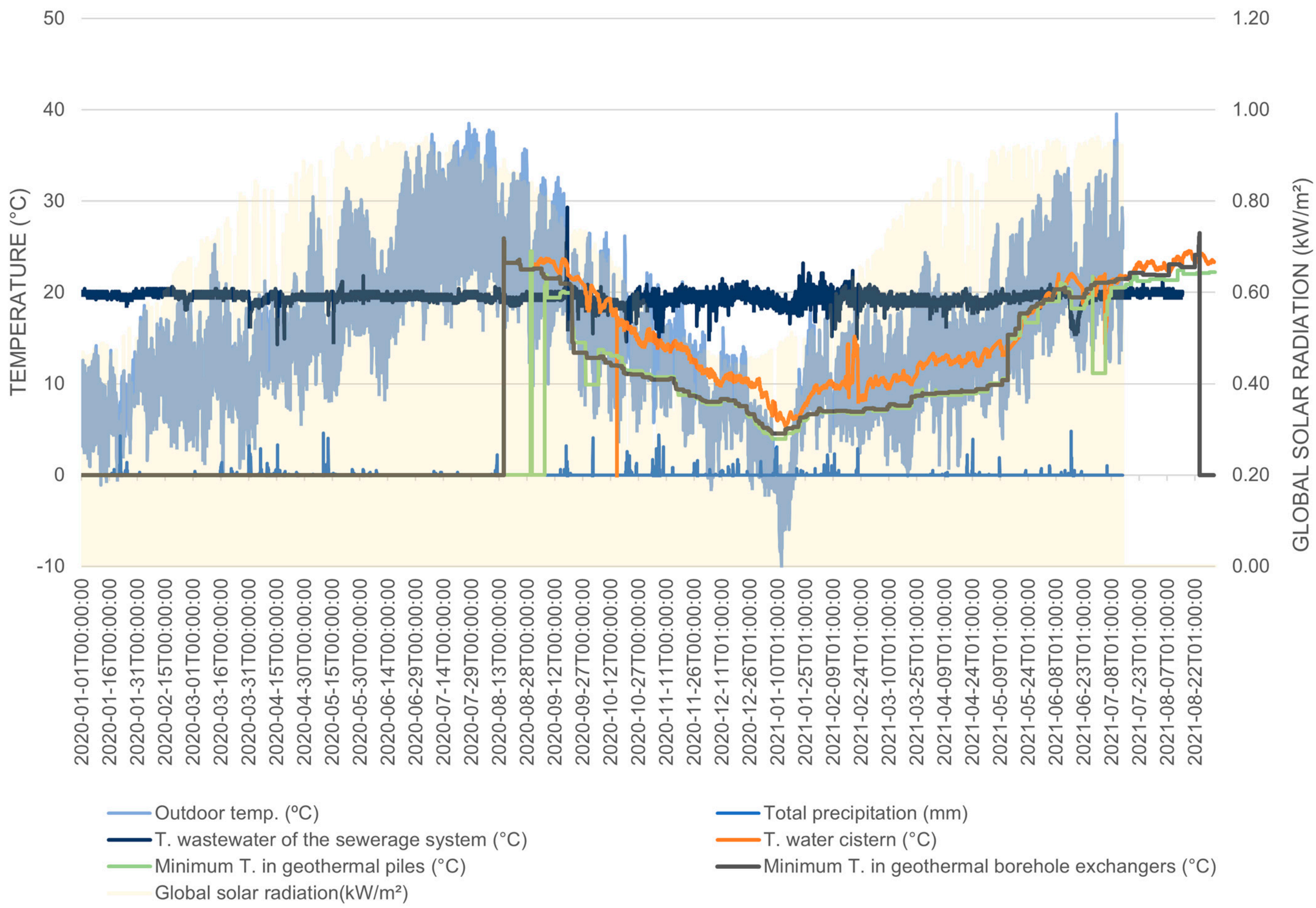
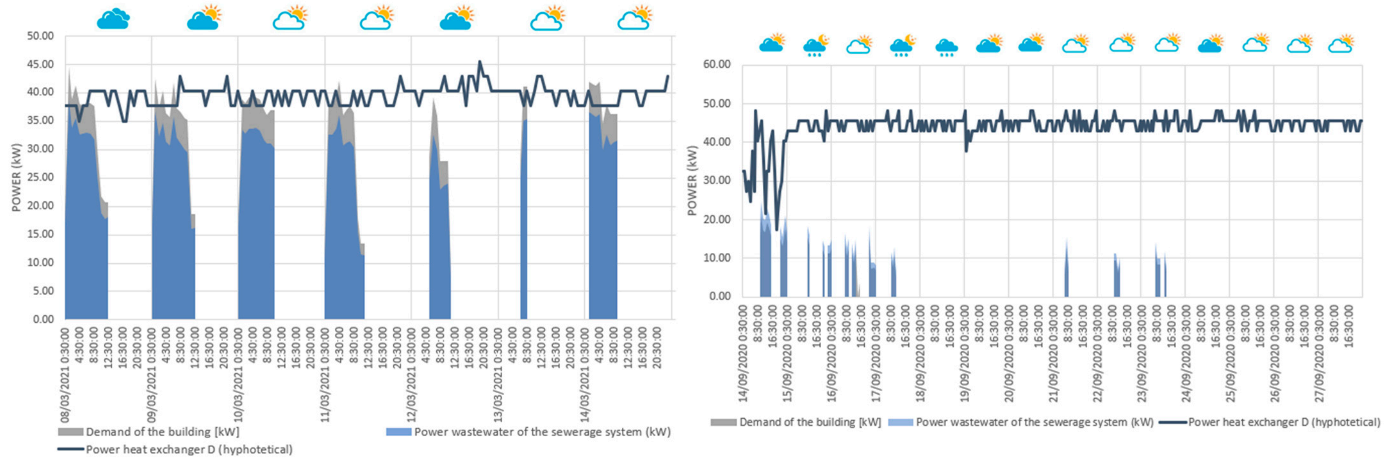


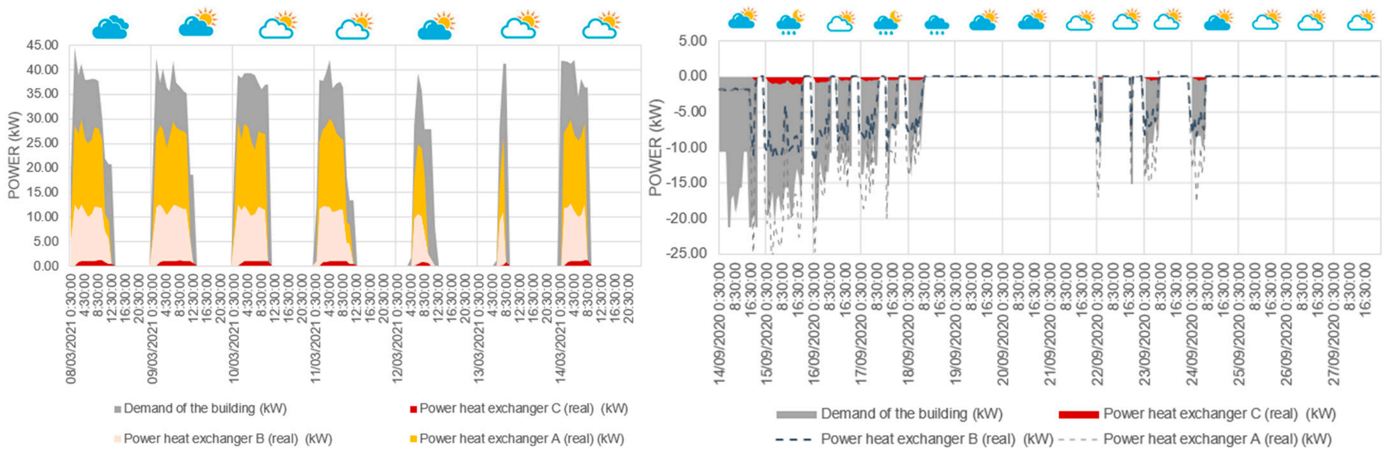
Figure 4. Analysis of the primary energy sources on an annual basis.

As an example, Figures 5 and 6 show the results of the analysis of the coverage on demand of different HEs considered for this research (A + B + C real, and D hypothetical) in one of the most representative scenarios for the heating mode in winter (Scenario 2. 8–14 March 2021) and for the cooling mode in summer (Scenario 8. 14–27 September 2020).



(a) (b)

Figure 5. (**a**) Heating mode in winter (Scenario 2. 8–14 March 2021). Analysis of the coverage on demand of hypothetical HE D. (**b**) Cooling mode in winter (Scenario 8. 14–27 September 2020). Analysis of the coverage on demand of hypothetical HE D.



(a) (b)

Figure 6. (**a**) Heating mode in winter (Scenario 2. 8–14 March 2021). Analysis of the coverage on demand of real HEs A, B, and C. (**b**) Cooling mode in winter (Scenario 8. 14–27 September 2020). Analysis of the coverage on demand of real HEs A, B, and C.

Figure 5 illustrates the results of the analysis of the coverage on demand of hypothetical HE D for the heating mode in winter (on the left) and cooling mode in summer (on the right). In both cases, the thermal demand of the building can be covered with this source, with an energy surplus in the summer. In both cases, the power available at the source level is about 45 kW, considering a thermal jump of 2 °C.

Figure 6 shows demand coverage values for HEs A + B + C (real) in a selected week. In both heating and cooling modes of the HPs, the maximum demand of the building is covered mainly by renewable sources, and a small part is covered by the electricity supplied by the HPs. In the heating mode, the maximum demand of the building (44.57 kW) is covered by renewable sources, mainly by HEs A + B (15.21 kW + 15.57 kW), and a small part is covered by HE C (1.22 kW). In the cooling mode, the maximum demand for the specific week under study (−21.25 kW) is also covered by renewable sources, mainly by HEs A + B (−13.66 kW + −14.82 kW), and a small part is covered by HE C (−1.10 kW).

Table 3 contains the efficiency of the HPs (COP/EER) in different scenarios.

Table 3. Efficiency of the HPs in different scenarios.

Heat Exchanger	COP/EER	Heating				Cooling			
		Sunny Days	Cloudy Days	Rainy Days	Rainy Nights	Sunny Days	Cloudy Days	Rainy Days	Rainy Nights
A + B + C (Real)	Min.	0.86	2.94	3.00	0.22	0.49	1.41	1.50	0.56
	Median	4.01	4.03	3.97	3.97	3.02	1.74	1.90	3.20
	Mean	3.93	3.93	3.89	3.83	3.44	2.51	2.02	3.59
	Sd	0.62	0.42	0.38	0.60	1.67	1.80	0.40	1.93
	Max.	9.09	5.77	5.53	4.47	10.40	9.14	2.81	9.45
A + B + C (C upgraded)	Min.	4.33	4.78	6.14	5.41	5.67	5.13	5.28	5.41
	Median	5.83	5.95	6.74	6.14	6.63	5.32	5.32	6.04
	Mean	5.93	6.09	6.74	6.26	6.53	5.80	5.37	5.98
	Sd	0.88	0.79	0.21	0.68	0.40	0.67	0.10	0.26
	Max.	8.19	8.19	6.96	7.16	7.30	7.01	5.63	6.42
D (Hypothetical)	Min.	5.53	5.55	6.09	5.98	5.98	6.09	6.05	5.24
	Median	7.21	7.22	6.31	6.12	6.92	6.29	6.09	6.14
	Mean	7.22	7.33	0.13	6.10	6.18	6.23	6.10	6.09
	Sd	0.77	0.73	0.13	0.08	0.15	0.09	0.04	0.20
	Max.	9.38	9.13	6.47	6.27	6.92	6.38	6.22	6.38

Sd: standard deviation. Efficiency = COP/EER.

4. Results and Discussion

The analysis of thermal and energy use in different climatological scenarios allows us to define scenarios and control the strategies of the exchanger.

Based on the data summarized in Figure 4 and Table 3, wastewater from the sewerage system (source D) has a constant range of temperatures between 15 °C and 25 °C throughout the year. In the intermediate seasons (spring and autumn) and the first weeks of summer, (ground and rainwater) (source C) and geothermal sources (A and B) have more favorable temperatures for cooling.

Despite the more favorable groundwater temperatures in winter (Figure 4), the greatest amount of energy used to cover the heating energy required by the building is provided by sources A and B, followed by source C. The same happens in cooling. This is mainly due to different sizes and flow rates of the HEs. HEs A and B have a larger exchange surface area than HE C. In addition, the sum of the circular sections of the pipes that flow to the collector is greater for geothermal heat exchangers (A + B). This affects the flow rates associated with each heat exchanger, since there is no flow regulation system, and the water flow is naturally distributed in the various pipes.

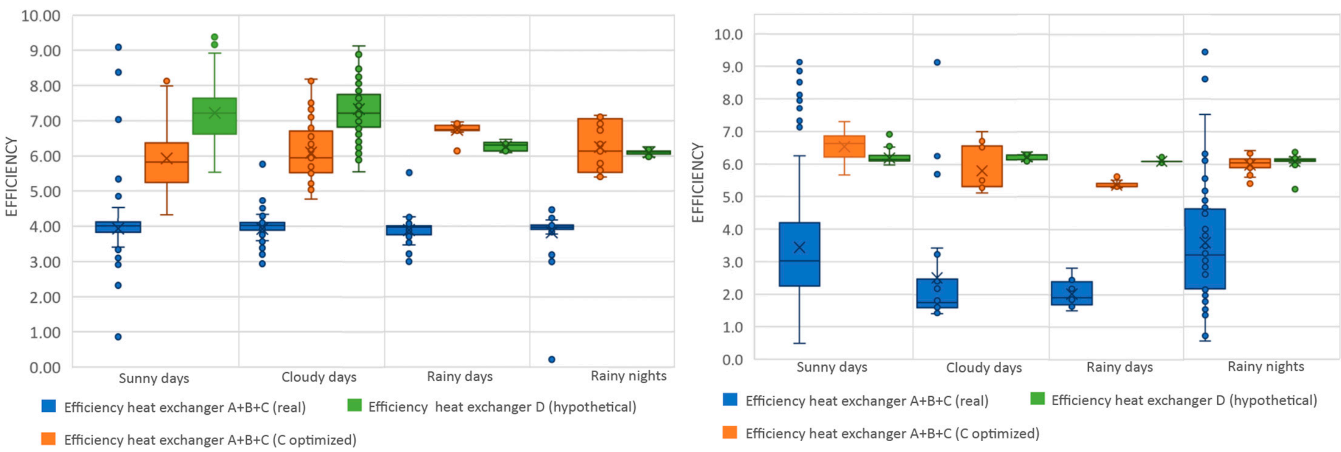
The current demand for the heating and cooling of the case study building can be ap-appropriately covered by HPs operating with HE using renewable energy from sewerage wastewater, as illustrated in Figure 5. The maximum demand of the building (45 kW) can be fully covered by this source, which, with average flow rates of 5 L/s measured at the measurement point considered, and a 2 °C thermal jump, can provide up to 45 kW, both in heating and cooling.

In Madrid, a flow rate of 5 L/s is a minimum value. As mentioned in the introduction, it is noticeable that wastewater can reach flows of 50 L/s in Madrid [15]. Therefore, the energy potential of wastewater in urban sewerage systems can reach much higher values (up to 10 times the calculated power from the monitoring data), which would cover not only the demand of a building but of an entire district.

The effective coverage capacity and the amount of additional electricity that could be provided by the HPs depends, secondly, on the characteristics of the HEs and the performance of the machine (COP/EER). This depends, in turn, on the temperature of the source.

These findings reveal that:

- As illustrated in Figure 7, the energy contribution of wastewater from the sewerage system (source D) resulting from the use of domestic hot water:
    - is beneficial for heating scenarios, since higher efficiency increases are observed for HE D compared to HE A + B + C (real) on sunny and cloudy days, with 83.60% and 86.73%, respectively, against 50.75% and 55.17% for HE A + B + C (optimized). In this case, replacing the set of A + B + C sources with source D could lead to efficiency improvements of more than 22%.
    - is not favorable for cooling scenarios, since lower efficiency increases are observed for HE D compared to HE A + B + C (real) on sunny days, with 79.72%, against 89.89% for HE A + B + C (optimized). In this case, the reduction in efficiency by replacing the set of A + B + C sources with source D could be up to 5%.
- As shows in Figure 7, the energy contribution of rainwater:
    - is more impactful on HE D due to the greater amount of rain collected in the sewerage system.
    - is not favorable for heating scenarios, since lower performance increases are observed for HE D compared to HE A + B + C (real) on rainy days and rainy nights, with 61.07% and 59.15%, respectively, against 73.19% and 63.21% for HE A + B + C (optimized). In this case, the reduction in efficiency by replacing the set of A + B + C sources with source D could be up to 7%.
    - is beneficial for cooling scenarios, since higher efficiency increases are observed for HE D compared to HE A + B + C (optimized) on rainy days and rainy nights with 201.97% and 69.92%, respectively, against 165.87% and 66.89% for HE A + B + C (optimized). In this case, replacing the set of A + B + C sources with source D could lead to efficiency improvements of more than 14%.



(**a**) (**b**)

Figure 7. (**a**) Box and whisker plot of efficiency in winter. (**b**) Box and whisker plot of efficiency in summer. In both box and whisker plots, in blue, efficiency HEs A + B + C (real), in orange, efficiency HEs A + B + C (optimized), and in green, efficiency HE D (hypothetical).

It is important to highlight that the source exploited by means of the HE C is the groundwater and rainwater collected from the surface of the office building under study. In contrast, the source used by the HE D depends on domestic hot water consumption and rainwater from all the surface urban areas upstream of the heat ex-changer in the sewerage system.

In the case of a mixed system, equipped with a set of heat exchangers, such as HE A + B + C, the installation of an automatic cut-off valve and servomotors in the exchanger circuits would allow for the control of the water temperature, depending on the outside weather and the presence or absence of rain, etc., preventing the efficiency of the thermal exchange from becoming impaired.

5. Conclusions

This research shows that wastewater from sewerage systems with a flow of higher than 5 L/s can provide sufficient thermal energy to meet the energy demand of a high-efficiency office building located in a high-standing residential area of Madrid with a power demand of 45 kW (60 W/m^2).

The flow rate is the parameter that directly affects the calculation of the maximum power available in the sewerage system, in the hypothesis that the thermal gap is constant (2 °C). The urban sewerage system guarantees sufficient flows and continuous water renewal throughout the year. This demonstrates the highest profitability of an exchanger in the sewerage system and is suitably sized since it ensures the coverage of the building's energy demand with maximum efficiency (COP/EER).

In turn, the effective efficiency (COP/EER) of the system is determined by the characteristics of the HEs and the temperature of the source. The constant and favorable temperature range of 15 °C to 25 °C recorded for sewage from the urban sewerage system throughout the year is provided by continuous heat input from domestic hot water.

The energy contribution of wastewater from the sewerage system (source D), resulting from the use of domestic hot water, is beneficial for heating scenarios. Wastewater from a sewerage system could lead to efficiency improvements of more than 22% compared to a geothermal system. On the other hand, it is not favorable for cooling scenarios: the reduction in efficiency by replacing a geothermal system with a system that exchanges energy with wastewater could be up to 5%.

The energy contribution of rainwater is more favorable in cooling scenarios than in heating ones, improving the system efficiency by more than 14% compared to a geothermal system. This result can be explained by the fact that the volume of water discharged into the sewerage system after a rainfall event is able to reduce the temperature of the wastewater in a very impactful way.

This finding might contribute to the development of a predictive method or guidelines for the design and sizing of heat exchangers in sewerage systems.

In the case of a heat exchanger in sewerage systems, this research provides sufficient data to decide whether rainwater is convenient to be discharged before or after the point where the heat exchanger is placed, depending on the energy demand of the building (whether it is prevalent in heating or cooling). In this decision, the urban characteristics (asphalted areas and natural green areas), climate conditions, and pluviometry must be considered.

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Nomenclature

WWHR	Wastewater Heat Recovery
TABS	Thermo-Active Building System
HE	Heat Exchanger
HEs	Heat Exchangers
HP	Heat Pump
HPs	Heat Pumps
WWTP	Wastewater Treatment Plant
HVAC	Heating, Ventilation and Air Conditioning
BMS	Building Management System
COP	Coefficient of performance
EER	Energy Efficiency Ratio
A, B	Geothermal sources
C	Groundwater + rainwater
D	Sewerage wastewater (domestic wastewater + rainwater)

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