energies

MDPI

Article

Experimental Development of the Horizontal Drain Water Heat Recovery Unit

Sabina Kordana-Obuch * and Mariusz Starzec

Department of Infrastructure and Water Management, Rzeszow University of Technology, al. Powstańców Warszawy 6, 35-959 Rzeszow, Poland; mstarzec1990@prz.edu.pl
* Correspondence: sk@prz.edu.pl

Abstract: The increase in energy demand, the scarcity of resources, as well as the adverse environmental impact of burning fossil fuels make it necessary to diversify the energy sources used. This also applies to the residential sector, which accounts for a significant proportion of global energy consumption. Particular attention should be paid to water heating, as the importance of this process in the energy balance of buildings is steadily increasing. One of the methods used to decrease energy consumption for heating water is to recover heat from greywater. However, commercially available horizontal drain water heat recovery (DWHR) units are characterized by low effectiveness, which creates a need for further research to improve it. The aim of the paper was to evaluate the possibility of improving the effectiveness of a circular horizontal DWHR unit through the use of baffles. Six different baffle models for installation in the greywater section of the heat exchanger were analyzed. The tests were conducted under the assumption of the installation of the DWHR unit on the horizontal shower waste pipe. They showed that the effectiveness of the unit equipped with baffles was higher by several to as much as 40% compared to the DWHR unit without baffles. This is tantamount to an increase in annual financial savings resulting from greywater heat recovery, as well as a reduction in CO_2 emissions into the atmosphere. However, it was not possible to clearly identify the optimum baffle model. In any case, the selection should consider the hydraulic conditions in the heat exchanger before installing the baffles. The results can provide guidance for companies interested in bringing new equipment and technologies to the market.

Keywords: domestic hot water; greywater; shower; energy consumption; CO_2 emission; energy efficiency; heat exchanger; waste heat

Citation: Kordana-Obuch, S.; Starzec, M. Experimental Development of the Horizontal Drain Water Heat Recovery Unit. *Energies* **2023**, *16*, 4634. https://doi.org/10.3390/en16124634

Academic Editor: Helena M. Ramos

Received: 22 May 2023
Revised: 7 June 2023
Accepted: 8 June 2023
Published: 10 June 2023

1. Introduction

The development of globalization processes has resulted in dynamic economic growth. In many cases, this has been followed by a change in consumption patterns, manifested, among other things, in a significant increase in energy demand [1,2]. Given the finite nature of fossil fuel resources and increasing production costs [3,4], as well as the adverse environmental impact of the mining sector [5], energy transformation appears to be an inevitable process. Igliński et al. [6] pointed out that, in the case of the European Union, this transformation is to be based mainly on the diversification of energy sources used, with a predominance of renewable sources. The need to introduce diversification in the energy sector as a means to guarantee the sustainability of the energy supply was also noted by Rabbi et al. [7]. Therefore, it is not surprising that the employment of renewable energy sources and low-carbon techniques is gaining growing attention [8], and the energy efficiency of various processes has become one of the key aspects of life [9,10].

Measures aimed at reducing resource consumption and greenhouse gas emissions are taken for both companies focused on environmentally sustainable production [11] and residential buildings [12]. However, in many parts of the world, the emphasis is on the sustainable development of housing [13]. This is because the residential sector is responsible for a substantial portion of global energy usage [14]. In the European Union, for example, this share is approximately 28%, which corresponds to almost 13% of greenhouse gas emissions [15]. At the same time, a change in the proportion of energy consumption for individual purposes is noticeable, which is the result of the energy transition in buildings. Domestic hot water (DHW) heating has become increasingly important in the energy consumption balance [16]. Alrwashdeh et al. [17] even pointed out that a reduction in energy consumption for water heating, achieved together with other building retrofits, can contribute to the transformation of buildings into the so-called surplus energy buildings.

A study by Ratajczak et al. [18] indicated that the consumption of DHW at 55 °C is in a fairly wide range from 40.2 to even 88.0 L per person per day. It depends mainly on the habits of the occupants, as well as the size of the system and the type of sanitary facilities installed [19]. The outside temperature is also important. Studies carried out in different regions have demonstrated that the demand for DHW is higher in the winter months than in the summer [20,21]. It should also be noted that the energy demand for heating a given volume of water is highest during the winter season due to the relatively low temperature of cold water [22]. Therefore, measures to reduce energy consumption in buildings should focus on opportunities to decrease the usage of fossil fuels for DHW heating. The greatest attention should be paid to those methods that guarantee an effective use of energy in the winter season.

Such methods include the recovery of waste energy from wastewater, which, in 2018, was recognized by the European Parliament and the Council as a third generation renewable energy source [23]. The recovery of energy carried by wastewater can be implemented at different levels of the system [24]. Nagpal et al. [25] indicated that this could be the component level, the building level, the sewer pipe network level, as well as the wastewater treatment plant level. However, Ravichandran et al. [26] suggested that small-scale wastewater heat recovery systems are the most sustainable option. The only exception is in cold regions with high population density. A general review of such systems by Wehbi et al. [27] showed that they are considered to be economically and environmentally efficient methods. On the other hand, Piotrowska and Słyś [28] found that the recovery of energy from wastewater holds special significance in the context of the circular economy.

In the instance of small-scale wastewater heat recovery systems, an energy source is usually greywater, which can also be used as an alternative water source [29]. Greywater usually includes wastewater produced during body washing and laundry and sometimes also wastewater generated in the kitchen. It can account for up to 75% of the total household wastewater production [30]. It is characterized by a higher temperature and a much lower pollutant load than blackwater. Depending on the appliances from which the greywater is discharged, the heat it carries can be recovered using single systems or hybrid systems [27]. Single systems are mainly based on the heat exchange process. The heat carried by greywater is transferred to cold water by means of drain water heat recovery (DWHR) units. These units are usually installed on the greywater outflow from the shower tray [31,32]. However, there are known cases of heat recovery from greywater discharged from other appliances, such as those in the kitchen [33,34]. Sometimes, the energy source is greywater from a group of sanitary appliances [35]. Heat recovery with DWHR units is already possible with low flow rates of greywater and cold water through the unit. As a result, these heat exchangers can be used successfully even in single-family houses [36]. In the case of hybrid systems, the heat exchanger is used together with another device. These can be, for example, solar panels or a heat pump [37,38]. In the latter case, traditional heat pumps are usually used. However, alternative solutions with greater environmental compatibility are increasingly being sought. For example, Zhang et al. [39] dedicated their research to the transcritical CO_2 heat pump. The use of heat pumps is justified when significant amounts of warm wastewater are produced in a building. In the case of single-family buildings or individual apartments, the use of heat pumps is neither technically nor financially justified.

The above information shows that greywater is an interesting and effective domestic hot water heating alternative. However, a study conducted on the example of Poland [40] showed that only a small proportion of the population would be willing to consider installing a DWHR unit in an existing house. This is probably due to the need for significant modifications to the internal building installations, which is associated with an increase in investment expenditure. Another problem may be the lack of room to install a vertical heat exchanger [25,27], characterized by the highest effectiveness among the solutions available on the market. Horizontal heat exchangers or those installed in the linear shower drain typically require less interference with the internal piping. However, they are characterized by a lower effectiveness of greywater heat recovery [27,31]. This is primarily due to the smaller heat exchange surface compared to vertical units. The thickness of the greywater layer is also important. In the case of horizontal DWHR units, it is much higher; as a result of which, the heat is transferred to the water less efficiently. Therefore, it is necessary to conduct research to improve the effectiveness of the horizontal DWHR units. This has already been noted by other authors [28,41].

The aim of the paper was to evaluate the possibility of improving the effectiveness of a horizontal circular DWHR unit by using baffles in the greywater section of the heat exchanger. Considering that the influence of the baffle geometry on the effectiveness of DWHR units has not been described in the literature so far, six different baffle models were analyzed in the study. Their geometry was designed by taking into account the cross-section of the heat exchanger and flow parameters. It was modified during the study to achieve optimal results. The baffles were not part of the heat exchanger casing; thus, it was possible to modify their layout in any way. The research concept was developed under the assumption of the need to improve quality of life through the use of energy efficient technology, where sustainable materials that do not harm the environment would be used. For this reason, the baffles were made of biodegradable material, polylactide. This ensures that the material used for the baffles will not be a burden on the environment at the end of their useful life. The analysis was carried out under established laboratory conditions, assuming that the flow rates of water and greywater through the DWHR unit are the same. The terms DWHR unit and heat exchanger are used interchangeably in the paper.

2. Materials and Methods

Research on the possibility of improving the effectiveness of the horizontal circular DWHR unit was carried out according to the procedure shown in Figure 1.

2.1. Characteristics of the Horizontal Drain Water Heat Recovery Unit

The potential for improving the effectiveness of a horizontal DWHR unit was analyzed using a circular heat exchanger as an example. This unit is characterized by a simple design and, thus, a relatively low price. It is designed to be installed on the shower waste pipe, mainly in residential buildings. Due to its horizontal layout, it is applicable in both newly constructed and pre-existing buildings, and its installation does not require significant interference with the internal installations in the building. However, studies on such a heat exchanger have shown that its effectiveness is low. This raises the need for further research into how to increase the amount of heat energy recovered from greywater.

The parameters of the horizontal DWHR unit are summarized in Table 1. On the other hand, Figure 2 presents the tested heat exchanger.

2.2. Geometry of Baffles

According to the procedure presented in Figure 1, the geometry of the baffles was determined in two stages. First, three preliminary baffle models were designed, and the validity of their installation in the horizontal DWHR unit with a circular cross-section was analyzed. After the results of laboratory tests were analyzed, these models were modified to improve the results. As a result, three other baffle models dedicated to use in circular horizontal DWHR units were developed. All baffle models were designed in such a way as to adhere closely to the outer wall of the heat exchanger from its inner side (Figure 2b).

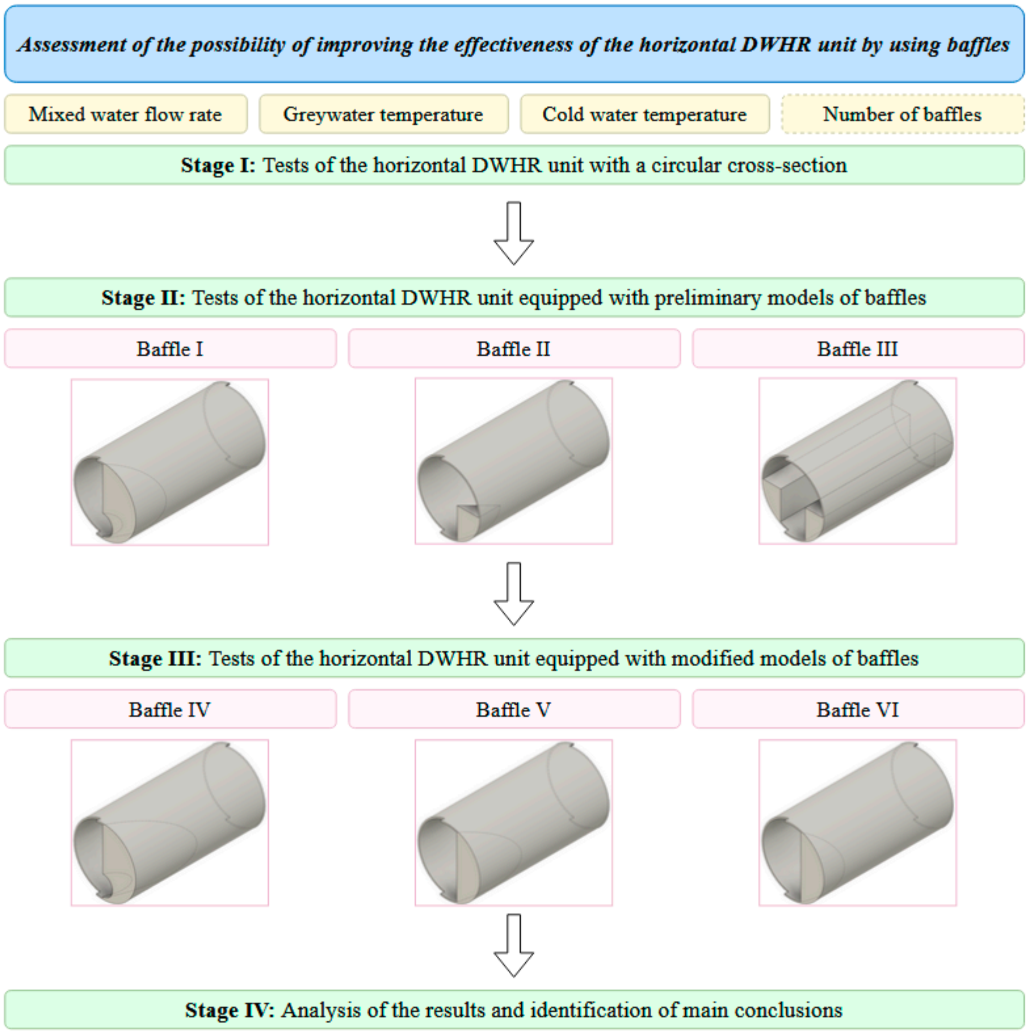


Figure 1. Research plan.

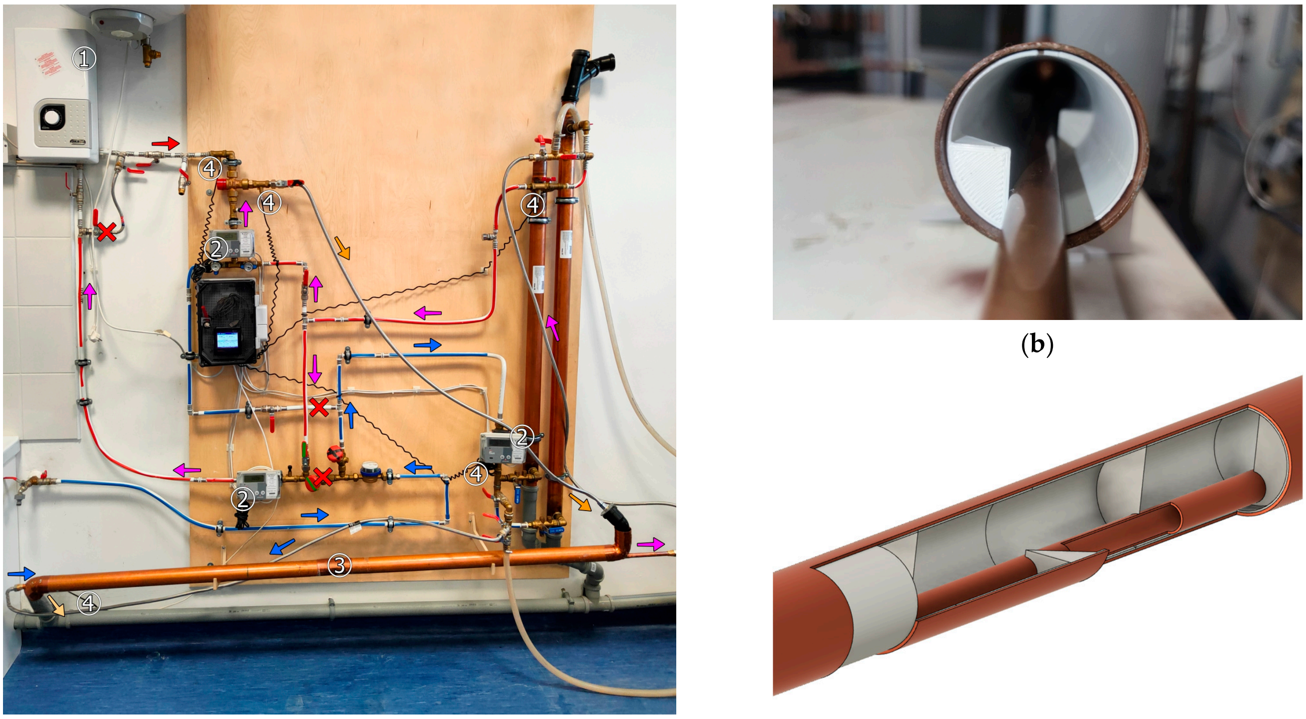
Table 1. Design parameters of the horizontal DWHR unit.

Design Parameters	Unit	Value
The length of the heat exchanger	m	2.0
The outer diameter of the copper drain pipe	mm	54
The wall thickness of the copper drain pipe	mm	1.5
The outer diameter of the copper water pipe	mm	15
The wall thickness of the copper water pipe	mm	1.0
The distance of the water pipe from the bottom of the drain pipe	mm	2.0

2.2.1. Preliminary Baffle Models

The first three geometries of the baffles were developed considering the internal diameter of the greywater pipe and the external diameter and location of the pipe transporting the heated water. An attempt was also made to adapt the geometry of type I–III baffles to the range of possible flow rates of water and greywater through the DWHR unit. The designed models are shown in Figure 3. The left side of Figure 3 presents 3D models of type I–III baffles, while its right side shows the longitudinal cross-sections of these baffles.

All baffle models were made with a 0.10 m long body and an internal part designed to disrupt the flow of greywater through the unit. In the case of models I and II, the internal part of the baffle was located on one side only. These baffles were mounted in the heat exchanger in such a way that the internal part was alternately on the left and right side of the unit. In both cases, the internal part of the baffle was located at an angle of 45 degrees to the direction of greywater flow. The maximum width of the internal part of the baffle, measured along the axis of the unit, reached 24.5 mm and 16.5 mm, for type I and II baffles, respectively. The structure of type III baffle was slightly different. Its internal part was located symmetrically on both sides, along the entire length of the baffle. The maximum width of the internal part of the type III baffle reached 13.5 mm on each side.

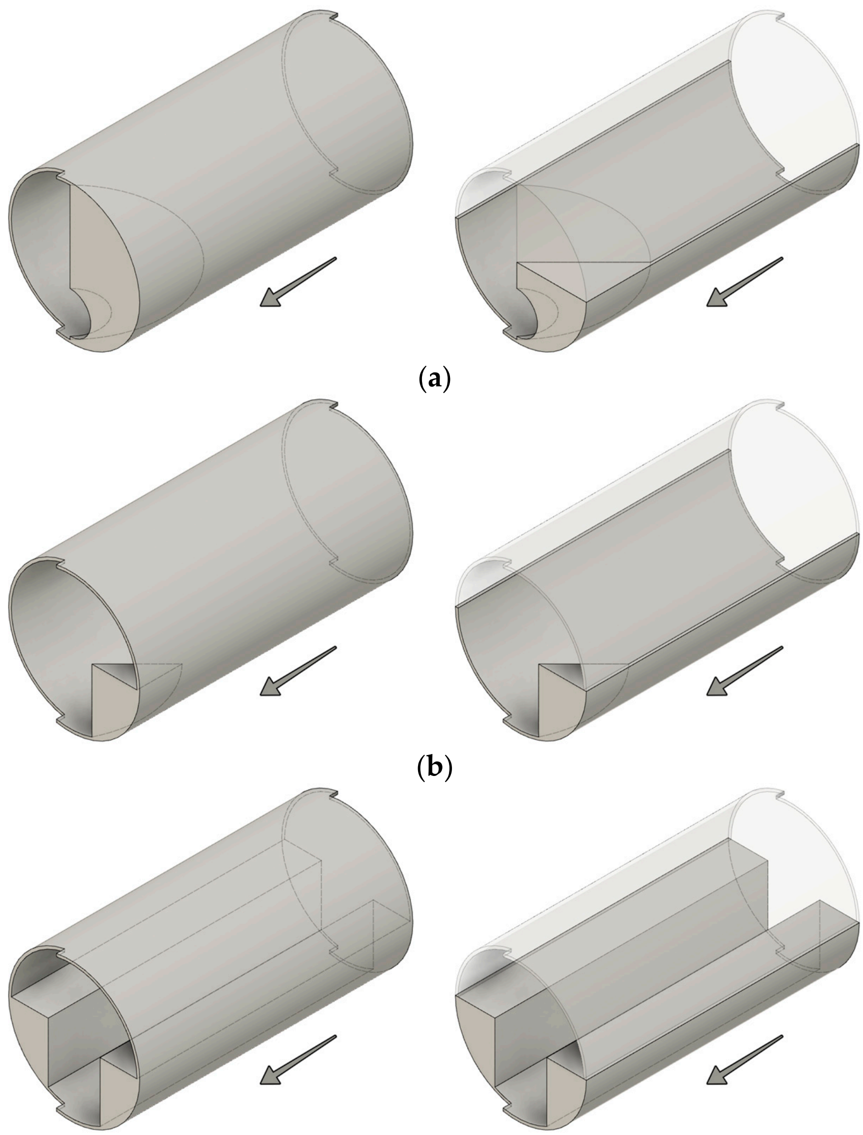


(**a**) (**b**) (**c**)

Figure 2. Tested horizontal DWHR unit: (**a**) test stand with the heat exchanger; (**b**) inside of the heat exchanger equipped with baffles; (**c**) cross-sections of a 3D model of the heat exchanger equipped with baffles: 1, hot water heater; 2, Sharky 473 ultrasonic flow meters; 3, tested DWHR unit; 4, Pt500 resistive temperature sensors; → cold water flow direction; → preheated water flow direction; → hot water flow direction; → mixed water flow direction; → greywater flow direction at the outlet of the heat exchanger; ✖ no flow in the section.

2.2.2. Modified Baffle Models

The study also analyzed three modified baffle models (IV–VI), which are shown in Figure 4. As with Figure 3, the left side of Figure 4 presents 3D models of type IV–VI baffles, while its right side shows longitudinal cross-sections of these baffles. Based on the findings garnered from the previous stage of the analysis, type I baffle was modified. As in the case of the preliminary baffle models, the modified models were made of a 0.1 m long body and an internal part. The internal part of type IV baffle was twice as long as the internal part of type I baffle. In the case of type V baffle, its internal part was narrowed to 16.5 mm and located at the same angle to the direction of greywater flow. as in the case of type IV baffle. On the other hand, the internal part of type VI baffle was located at the same angle to the direction of greywater flow, as in the case of type I baffle, but its width was narrowed in the same way as in type V baffle. The baffles were made of biodegradable material (polylactide).



(a)

(b)

(c)

Figure 3. Baffle geometries considered in the first stage of the study: (**a**) type I; (**b**) type II; (**c**) type III (the arrow shows the direction of greywater flow through the baffle).

2.3. Effectiveness Assessment of the DWHR Unit

When the flow rates of water and greywater through the DWHR unit are equal, the effectiveness of the unit can be determined using a commonly known relationship, which is described by Equation (1):

$$\varepsilon = \frac{T_{dw} - T_{cdw}}{T_{dw} - T_{cw}} \cdot 100, \quad (1)$$

where ε is the effectiveness of the DWHR unit,%; T_{dw} is the temperature of greywater at the inlet to the heat exchanger, °C; T_{cw} is the temperature of cold water, °C; T_{cdw} is the temperature of greywater at the outlet of the heat exchanger, °C.

Table 2 summarizes the values of the input variables. Three mixed water flow rates from the showerhead (q_{wm}) were analyzed, as well as two greywater temperatures at the inlet to the DWHR unit (T_{dw}) and two cold water temperatures (T_{cw}). A tolerance of ±0.1 °C was adopted. Furthermore, the installation of the heat exchanger with two different bottom slopes was considered, as well as the possibility of installing a different number of baffles. Considering six different baffle designs, the implementation of the study required the analysis of 312 cases of heat exchanger operation.

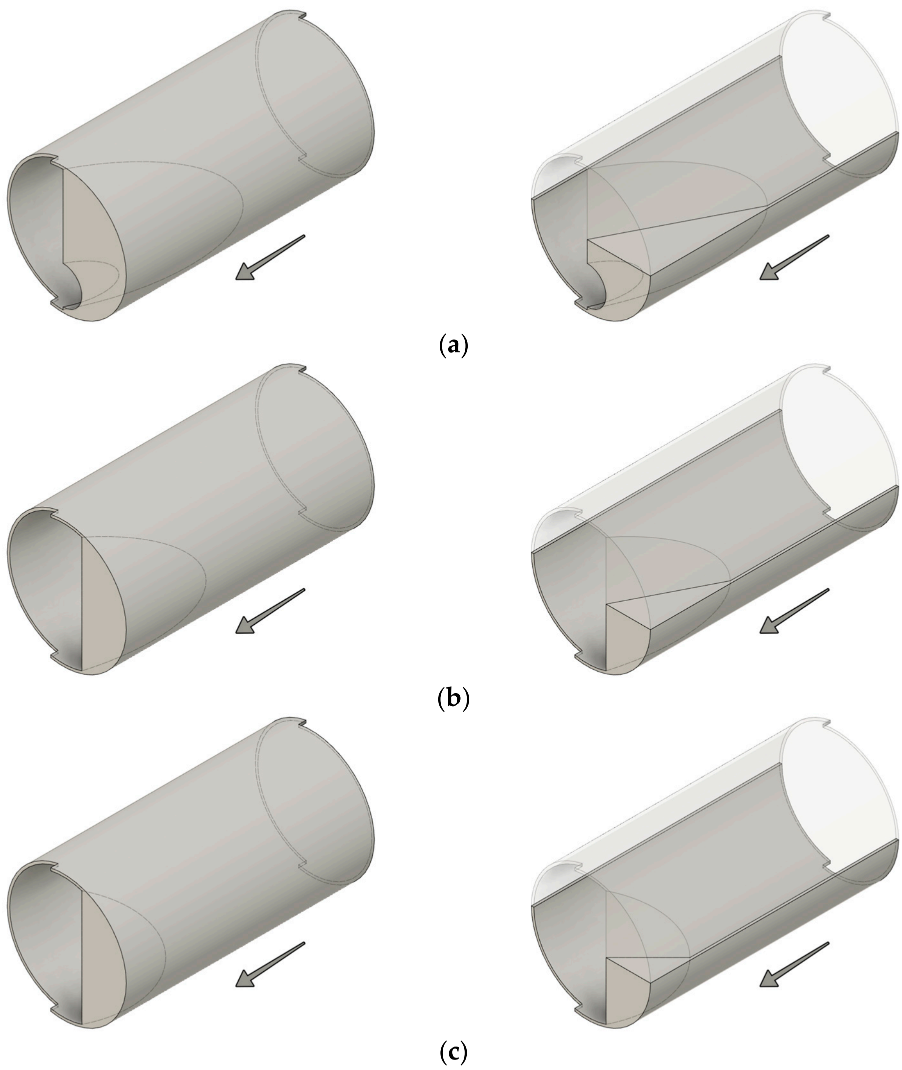


Figure 4. Baffle geometries considered in the second stage of the study: (**a**) type IV; (**b**) type V; (**c**) type VI (the arrow shows the direction of greywater flow through the baffle).

Table 2. Adopted values of the input parameters for the effectiveness evaluation of the DWHR unit.

Input Parameters	Unit	Value
Mixed water flow rate (q_{wm})	L/min	4, 7, 10
Greywater temperature at the inlet to the DWHR unit (T_{dw})	°C	35, 40
Cold water temperature (T_{cw})	°C	10, 15
DWHR unit bottom slope (i)	%	1, 2
Number of baffles	—	10, 20
Indoor air temperature (T_i)	°C	24
Water temperature drop in the shower [32]	°C	5
Domestic hot water temperature (T_{hw})	°C	60

The tests were carried out using the Simex MultiCon CMC-144 data recorder (Simex Sp. z o.o., Gdansk, Poland), Pt500 resistive temperature sensors, and Sharky 473 ultrasonic flow meters (Diehl Metering GmbH, Nuremberg, Germany). The accuracy of the measuring tools is presented in the manufacturers' data sheets.

2.4. Assessment of Potential Benefits of Equipping the DWHR Unit with Baffles

Based on the results of laboratory tests, it was possible to estimate the potential energy savings resulting from the installation of the DWHR unit. The paper presents the results of the analysis of the most favorable and least favorable operating conditions of a greywater heat recovery system. Considering that, depending on the type of primary energy carrier used to heat domestic hot water (natural gas, electricity), the water heater efficiency (η) can reach different values, the analysis was carried out for η = 0.8–1.0. The energy consumption to heat the water used during a shower (C_{hw}) was determined on the basis of Equation (2). The potential energy saving per shower (E_s) was calculated as the difference between the values of C_{hw} for a conventional plumbing system and a system equipped with a DWHR unit using the following equation:

$$C_{hw} = \frac{q_c \cdot l \cdot c_p \cdot \rho \cdot (T_{hw} - T_0)}{\eta \cdot 3.6 \cdot 10^6}, \tag{2}$$

where C_{hw} is the energy consumption to heat the water used during a shower, kWh; q_c is the flow rate of heated water, determined based on the heat balance equation of the shower mixing valve, m^3/s; l is the shower length, s; c_p is the specific heat capacity of water, J/(kg·K); ρ is the density of water, kg/m^3; T_{hw} is the hot water temperature, °C; T_0 is the water temperature at the inlet to the DHW heater, equal to the temperature of cold water (T_{cw}) in the case of installations without the heat exchanger or the temperature of preheated water (T_{pw}) in the case of using the DWHR unit, °C.

The determination of the value of C_{hw} formed the basis for estimating the potential financial savings resulting from the recovery of waste heat from greywater and comparing carbon dioxide emissions. This analysis was conducted using a three-member family as a representative sample. This is due to the fact that, according to Statistics Poland [42], the average number of people living in a household in Poland is less than three. It was assumed that each individual would use 35 L of water for showering daily [43]. Unit prices of electricity and natural gas (C_e) were assumed based on data for households in Rzeszow for 2023. Due to the significant dynamics of the prices of energy carriers, this analysis was additionally extended by assessing the impact of changes in these prices on the results. On the other hand, emission factors (F_e) were determined on the basis of [44,45] for electricity and natural gas, respectively. Annual water heating costs for showering (AC) were determined on the basis of Equation (3). Annual CO_2 emissions resulting from heating water for showering (AE) were calculated based on Equation (4):

$$AC = 365 \cdot D \cdot C_{hw} \cdot C_e \tag{3}$$

$$AE = 365 \cdot D \cdot C_{hw} \cdot F_e \tag{4}$$

where AC is the annual water heating costs, EUR/year; AE is the annual CO_2 emissions, kg/year; D is the number of residents; C_e is the unit price of electricity/natural gas, EUR/kWh; F_e is the emission factor, kg/kWh.

3. Results

3.1. Assessment of the Effectiveness of the Horizontal DWHR Unit without Baffles

Figure 5 shows how the effectiveness of the tested DWHR unit is shaped in various operating conditions. The columns in red correspond to the situation where the heat exchanger was laid with a slope of 1%. On the other hand, the columns in green represent the effectiveness of the unit laid with a slope of 2%. The results indicate that the effectiveness of the DWHR unit increased as the flow rates of water and greywater through the unit decreased. This confirms the results obtained for other types of horizontal shower heat exchangers [31,41]. This trend was maintained in all cases, regardless of the slope of the bottom of the heat exchanger and the temperatures of both media that flowed through the unit. The effectiveness of the heat exchanger at a flow rate of both media of 4 L/min exceeded 20% in each case and was in the range of 20.83% to 22.02%. Therefore, it was lower than the effectiveness of vertical DWHR units, which ranges from 30 to even 75% [28].

The results for q_{wm} = 10 L/min ranged from 3.21 to 4.18 percentage points lower than for q_{wm} = 4 L/min, with the highest effectiveness decreases seen when the temperature difference between water and greywater was the lowest. Considering that many shower heads have a flow rate of 9–10 L/min, and q_{wm} of 5–7 L/min is only characteristic of water-saving shower heads or those with a flow limiter installed, improving the effectiveness of this unit seems to be a necessity. Shower heads with a flow rate of q_{wm} = 4 L/min are not commercially available. However, it should be noted that, in some residential buildings, especially multistorey ones, the pressure in the system is not sufficient to provide an outflow corresponding to the features of the shower head. Considering the potential for energy recovery and the associated financial savings based solely on the technical data of the shower head would lead to unreliable results in such a situation.

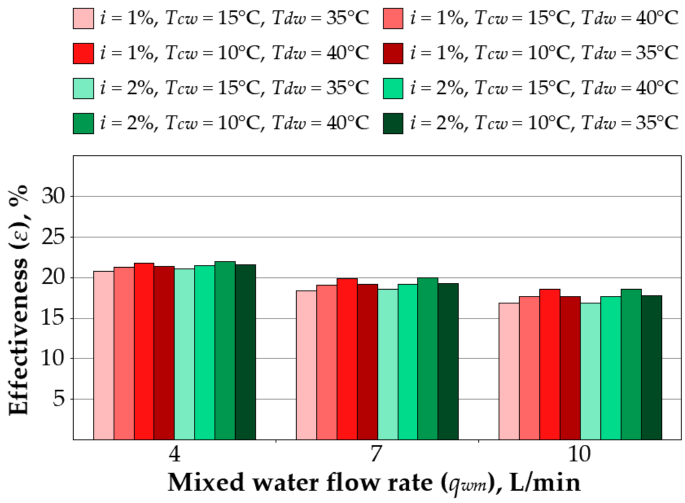


Figure 5. Effectiveness of the drain water heat recovery unit without baffles (designations as in Table 2).

From laboratory results, it can also be concluded that the effectiveness of the DWHR unit increased as the slope of its bottom increased. However, the results obtained for i = 2% were only slightly higher than those obtained for i = 1%. The differences reached a maximum of 0.22 percentage points and, in most cases, were even lower. Based on previous studies [31], it can be assumed that increasing the slope of the bottom of the heat exchanger above 2% would result in a further increase in effectiveness. In this case, the increase in the effectiveness of the heat exchanger results from lowering the greywater fill level in the unit. As a result, the thickness of the layer of greywater above the copper pipe transporting heated water, is also reduced. Under such conditions, the process of heat transfer from greywater to water is more effective. However, it should be borne in mind that reducing the fill level in the unit too much will result in the excessive reduction of the heat exchange surface, as a consequence of which the efficiency of the unit will start to decrease. It should also be noted that the consequence of a too high value of i is an increase in the total height that must be provided for the installation of the heat exchanger, and this is usually limited. Furthermore, assuming that the horizontal heat exchanger is to replace a section of the waste pipe, the slope of its bottom should be adapted to the slope with which the waste pipe is laid. Therefore, it cannot be indiscriminately increased.

The research also confirmed the trend described in [32,41], which was that the greater the temperature difference between water and greywater (ΔT), the higher the effectiveness of the DWHR unit. This makes the use of DWHR units especially beneficial in winter, when the energy demand for heating water is the highest due to the low temperature of cold water [22]. In the case of the circular heat exchanger, an increase in ΔT from 20 °C to 30 °C resulted in an increase in the effectiveness of 0.93–1.73 percentage points. The observed differences increased with increasing media flow through the heat exchanger. The effect of the bottom slope (i) on the unit susceptibility to changes in effectiveness was also observed depending on the value of ΔT. The increase in i resulted in a slight decrease in the observed differences in effectiveness of the DWHR unit.

Based on research, it can also be seen that the total amount of energy recovered from greywater (E_s) at a given shower length (l) increases with increasing q_{wm}, although the effectiveness of the DWHR unit (ε) decreases. This is due to the increase in the volume of the heat source medium and the volume of the heated water. In the most favorable situation, during a 10-min shower, the use of the DWHR unit will save between approximately 380 Wh and even more than 800 Wh, respectively, at q_{wm} = 4 L/min and at q_{wm} = 10 L/min. Figures 6 and 7 show the amount of energy that can be saved during one shower of a given length. Figure 6 is based on the assumption that i = 2% and ΔT = 30 °C. On the other hand, Figure 7 refers to the situation when i = 1% and ΔT = 20 °C. The results confirm that the operating parameters of the installation and the slope of the DWHR unit bottom have a significant impact on the amount of energy that can be saved. As a result, these parameters also determine how large of a reduction in greenhouse gas emissions can be achieved by the user of a particular type of heat exchanger.

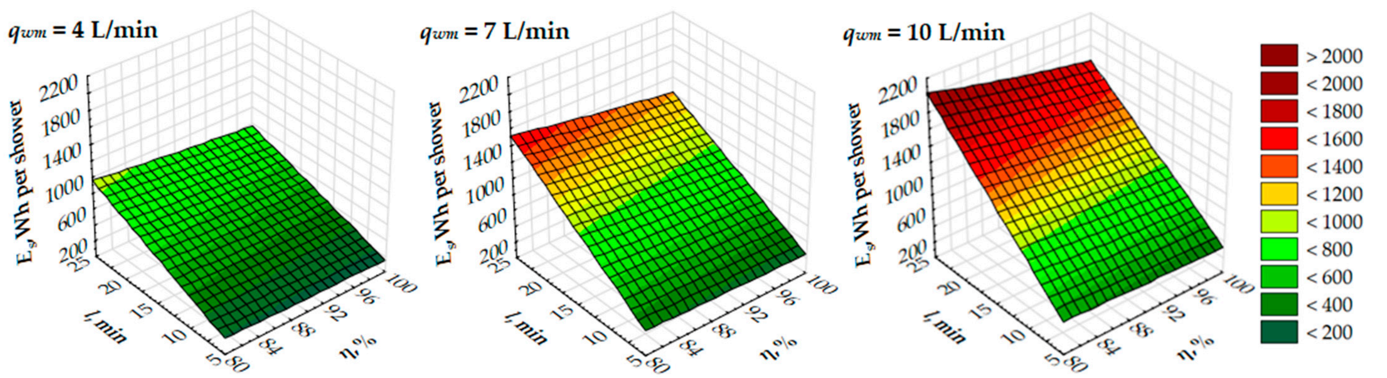


Figure 6. Energy saving per shower for ΔT = 30 °C and i = 2%: E_s, energy saving; l, shower length; η, domestic hot water heater efficiency; ΔT, temperature difference between greywater and water; i, heat exchanger bottom slope; q_{wm}, mixed water flow rate, L/min.

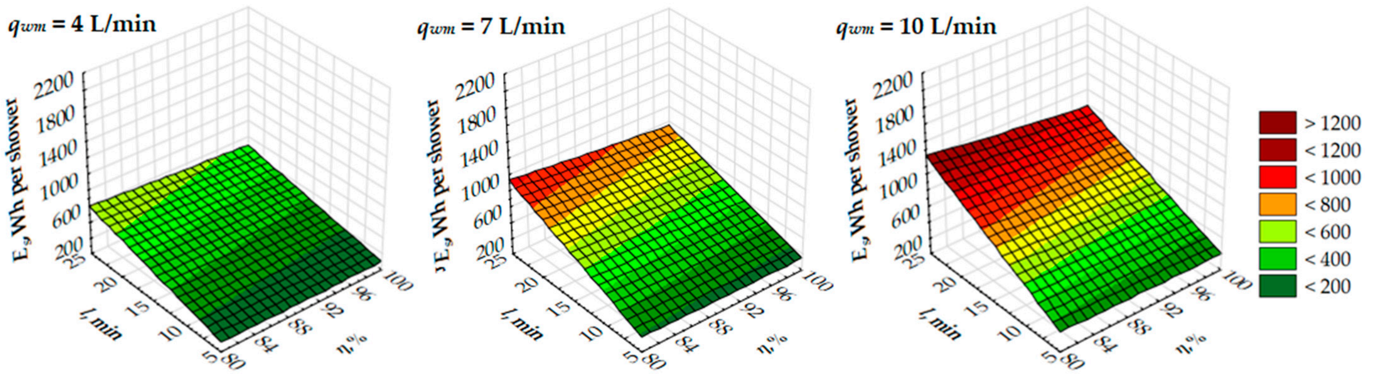


Figure 7. Energy saving per shower for ΔT = 20 °C and i = 1% (designations as in Figure 6).

3.2. Evaluation of the Effectiveness of the DWHR Unit Equipped with Baffles

3.2.1. Preliminary Baffle Models

The analysis of the effectiveness of the horizontal circular DWHR unit confirmed that the effectiveness of such units is low, which is one of the main reasons for the low interest in their use. In response to this problem, the paper analyzed the suitability of equipping the heat exchanger with baffles. Figure 8 shows the results of the effectiveness analysis of the DWHR unit equipped with the preliminary baffle models. For comparison, Figure 8 also shows the values of the heat exchanger without baffles. For lower flow rates

(q_{wm} = 4 L/min and q_{wm} = 7 L/min), the most favorable results were obtained using type I baffle, with a significant effect of the number of baffles on the results of the analysis. Equipping the heat exchanger with the maximum possible number of baffles (20) resulted in an increase in effectiveness from about 4.7 to more than 6 percentage points compared to the situation shown in Figure 5. This increase ranged from about 23.5% to about 30.5% of the initial effectiveness of the unit. It should also be noted that the use of type I baffle proved slightly more beneficial when the heat exchanger was laid with a slope (i) of 2%. Under the least favorable conditions, the effectiveness of the unit increased by 27.7%. It is also important that the increases in the effectiveness of the DWHR unit (resulting from its equipping with type I baffles) were relatively high at the lowest temperature difference ΔT, i.e., when the effectiveness of the shower heat exchangers was the lowest, as confirmed by numerous studies [31,32,41]. Under the operating conditions considered for the heat exchanger, they were approximately 26% for i = 1% and more than 29% for i = 2%.

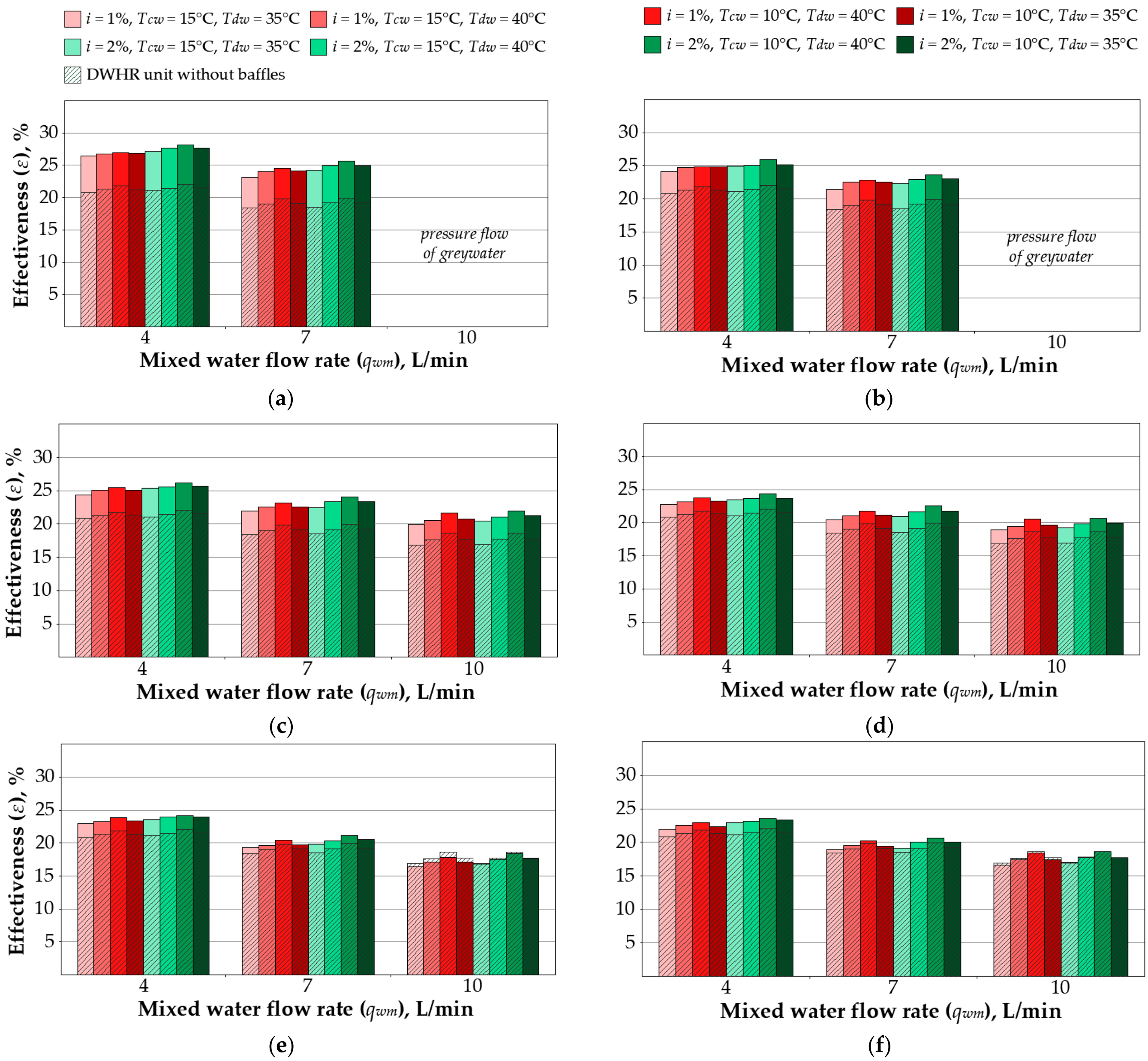


Figure 8. The effectiveness of the DWHR unit equipped with preliminary baffle models: (**a**) type I, 20 baffles; (**b**) type I, 10 baffles; (**c**) type II, 20 baffles; (**d**) type II, 10 baffles; (**e**) type III, 20 baffles; (**f**) type III, 10 baffles (designations as in Table 2).

Reducing the number of type I baffles that were installed in the DWHR unit to 10, while keeping the distances between the baffles equal, resulted in a reduction in the effectiveness of the heat exchanger. When the slope of the bottom of the heat exchanger (i) was 1%, its effectiveness was only 3–3.5 percentage points higher than that of the exchanger without baffles. This represents an increase from more than 14% to about 18%. Increasing the slope of the bottom of the heat exchanger to 2% improved the results by about 0.5 percentage points compared to when i = 1%. Therefore, the results prove that increasing the number of baffles installed in horizontal shower heat exchangers is beneficial. However, it should be noted that the installation of baffles reduces the cross-sectional area of the greywater section of the DWHR unit. The number of baffles should be adapted to the conditions of greywater flow through the unit in each case. In a situation where q_{wm} = 10 L/min, the use of type I baffles resulted in the pressurized operation of the unit. Overloading the heat exchanger is unacceptable. It should not be forgotten that the primary function of the internal sewage system is the effective drainage of wastewater generated in the building, and this function cannot be disturbed. Therefore, type I baffles can only be used when water-saving shower heads are used. It is also impossible to use them when the source of energy is greywater discharged from more than one sanitary appliance.

The best results for q_{wm} = 10 L/min were obtained in this stage of the study when type II baffles were used. Again, increasing the number of baffles allowed for better results. Doubling the number of baffles resulted in an increase in the unit effectiveness by at least 1.25 percentage points. However, it should be noted that the increases in the effectiveness of the DWHR unit in relation to the effectiveness of the unit without baffles were definitely lower than in the case of type I baffles. In the most favorable case (20 baffles, i = 2%, ΔT = 20 °C), they did not exceed 21%. The trend regarding the effect of the flow rate (q_{wm}) on the effectiveness of the DWHR unit was also confirmed. Although the use of type II baffles proved to be the best option for q_{wm} = 10 L/min, the effectiveness of the heat exchanger (ε) at flow rates of 4 L/min and 7 L/min was higher than for q_{wm} = 10 L/min.

In addition, research has shown that the use of baffles does not always guarantee an increase in the effectiveness of the DWHR unit. The use of type III baffles increased the effectiveness of the heat exchanger only at lower flows. When q_{wm} = 10 L/min, the results were comparable to those for the DWHR unit without baffles and, in some cases, even lower. This problem was particularly evident when the unit was laid with a slope of i = 1% and was equipped with a large number of baffles. The most likely reason for this is that the cross-sectional area of the greywater section of the heat exchanger is too limited in its lower part. As a consequence, most of the warm greywater, especially at high flow rates, flows above the pipe carrying the heated water. Therefore, baffles cannot be installed in heat exchangers indiscriminately, without prior analysis of the hydraulic conditions in the unit.

3.2.2. Modified Baffle Models

In the next stage of the research, the validity of equipping the heat exchanger with modified baffle models was analyzed. It can be seen from Figure 9 that its use allowed us to improve the results obtained in the previous stage of the research. As in the case of type I–III baffles, it was not possible to indicate one specific baffle model, the use of which would allow obtaining the most favorable results under all conditions. Equipping the DWHR unit with type IV baffles guaranteed an increase in effectiveness of up to 9.5 percentage points (more than 40%) at a flow rate of q_{wm} = 4 L/min. As with other baffle models, the highest increases were obtained for i = 2% and the maximum possible number of baffles. When using 10 baffles spaced at fixed distances, the highest recorded effectiveness increases in relation to the DWHR unit without baffles did not exceed 7 percentage points (above 30%). The effect of the number of baffles on the dependence of the heat exchanger effectiveness on the slope of its bottom (i) was also noticed. For a lower number of baffles, this influence was slightly less significant.

Type IV baffles turned out to be the most attractive option for water-saving shower heads with a flow rate of q_{wm} = 7 L/min. However, the reported increases in the effectiveness of the DWHR unit were not as high as for q_{wm} = 4 L/min. If 20 baffles are installed, they do not reach 7 percentage points, whereas with 10 baffles, they do not exceed 5 percentage points. It is worth noting that not only the absolute increases in effectiveness were lower than for q_{wm} = 4 L/min. When analyzing the percentage increases in relation to the DWHR unit without baffles, it can be seen that they ranged from about 30% to almost 37% when 20 baffles were installed and from about 22% to almost 27% for 10 baffles.

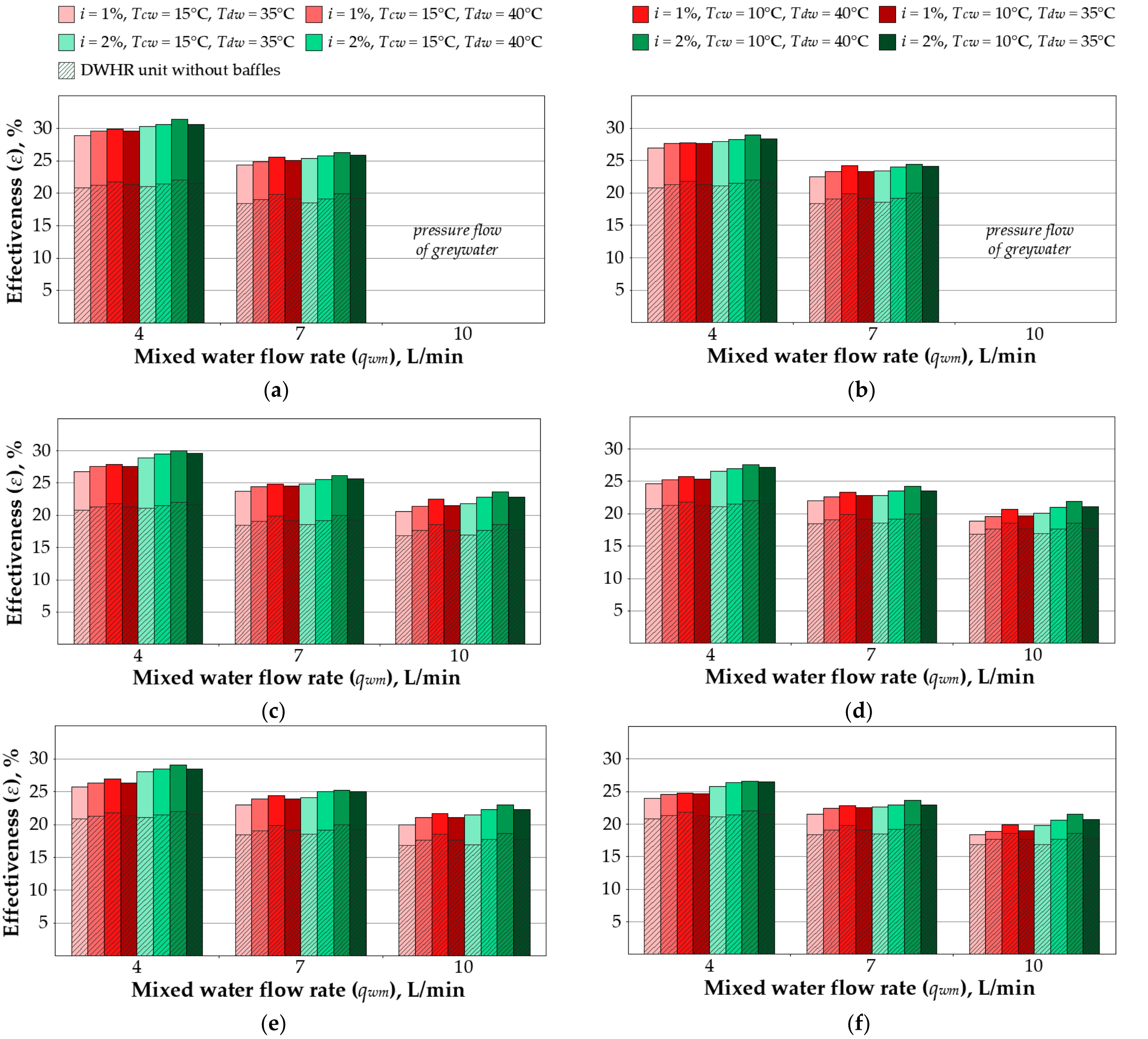


Figure 9. The effectiveness of the DWHR unit equipped with modified baffle models: (**a**) type IV, 20 baffles; (**b**) type IV, 10 baffles; (**c**) type V, 20 baffles; (**d**) type V, 10 baffles; (**e**) type VI, 20 baffles; (**f**) type VI, 10 baffles (designations as in Table 2).

Due to the significant reduction in the cross-sectional area, as in the case of type I baffles, increasing the flow rate of greywater through the heat exchanger resulted in its pressurized operation. Therefore, these baffles can also be used only for water-saving installations.

When type V baffles were used, less satisfactory results were obtained than for type IV baffles, but they were more favorable than for type I baffles. On the contrary, the effectiveness of the heat exchanger equipped with type VI baffles was comparable to that obtained in the first stage of the study for type I baffles. This indicates that the length of the internal part of the baffle can have a significant impact on the validity of its use. Furthermore, the study confirmed that regardless of the baffle geometry, there is a clear effect of the flow rate of water and greywater through the heat exchanger on its effectiveness. In each case, an increase in the value of q_{wm} resulted in a decrease in the temperature of the preheated water at the outlet of the heat exchanger.

In installations equipped with shower heads with a flow rate (q_{wm}) of 10 L/min, only those baffles could be considered, the installation of which did not result in the excessive reduction of the cross-section of the greywater section of the DWHR unit. For modified baffle models, the choice was limited to type V and VI baffles. Slightly better results were obtained for type V baffles. In such a situation, their use guarantees an increase in the effectiveness of the DWHR unit by even more than 5 percentage points (i = 2%, 20 baffles), which corresponds to an increase of more than 30%. Equipping the heat exchanger with 10 type V baffles allowed it to increase its effectiveness by approximately 2 to more than 3 percentage points, depending on the slope of its bottom (i) and the temperatures of the media flowing through the unit. The results obtained with the use of type VI baffles were somewhat less satisfactory.

As part of the research, the uncertainty of the measurements was also analyzed. Figures 10 and 11 present the results obtained with the use of the most favorable baffle models during three measurement series. The length of each series was 15 min. These results confirm the repeatability of experimental results and prove that the heat exchanger will work stably even during long-term water intake from the shower head.

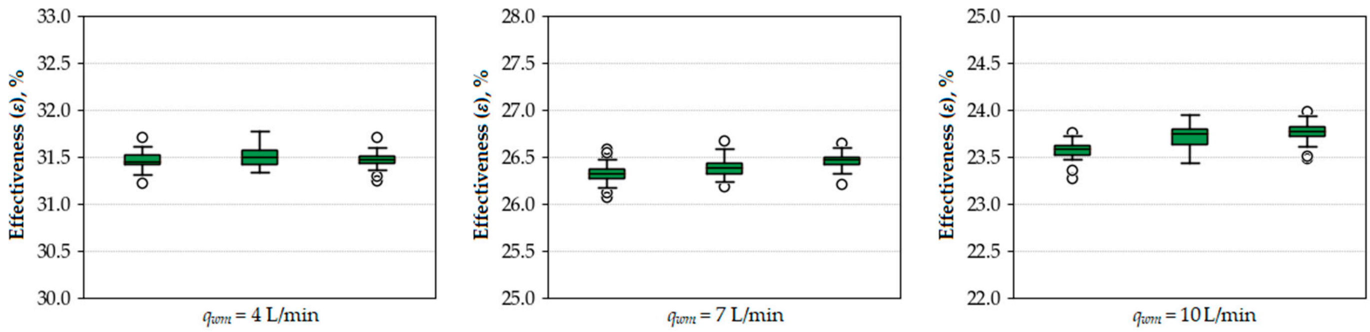


Figure 10. The effectiveness of the horizontal heat exchanger equipped with baffles for ΔT = 30 °C and i = 2% (∘, outliers; other designations as in Table 2).

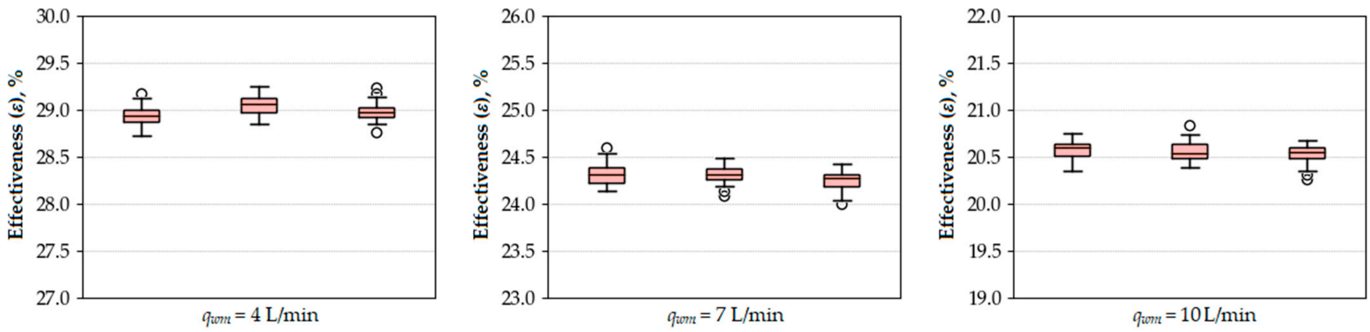


Figure 11. The effectiveness of the horizontal heat exchanger equipped with baffles for ΔT = 20 °C and i = 1% (∘, outliers; other designations as in Table 2).

3.3. Evaluation of the Potential Benefits of the DWHR Unit and Its Equipping with Baffles

3.3.1. Energy Savings

The research also determined the amount of energy that could be recovered (E_s) during a shower of a certain length (l). Figures 12 and 13 show the results determined under the assumption that the instantaneous DHW heater worked with the heat exchanger equipped with 20 baffles. The figures show the most advantageous solution under the given conditions. Therefore, the plots relating to the flow rates (q_{wm}) of 4 L/min and 7 L/min assumed that the DWHR unit was equipped with type IV baffles. For the flow rate of q_{wm} = 10 L/min, the results for type V baffles were based on. Similarly to the DWHR unit without baffles, the two most extreme cases were depicted. The results confirmed that the temperatures of the media flowing through the heat exchanger and the slope of its bottom have a significant impact on the energy savings resulting from the application of the greywater heat recovery system. The higher the water flow rate from the shower head, the greater the differences in the effects, which is related to both an increase in mixed water consumption and a decrease in the effectiveness of the DWHR unit.

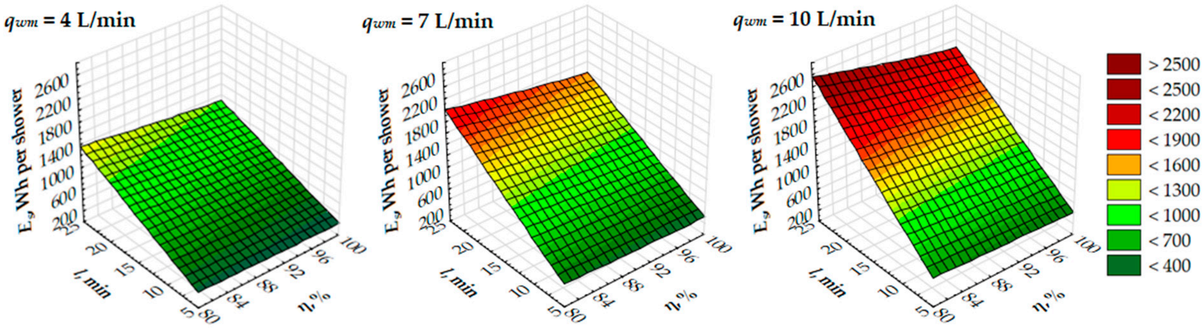


Figure 12. Potential energy saving per shower for ΔT = 30 °C and i = 2% (designations as in Figure 6).

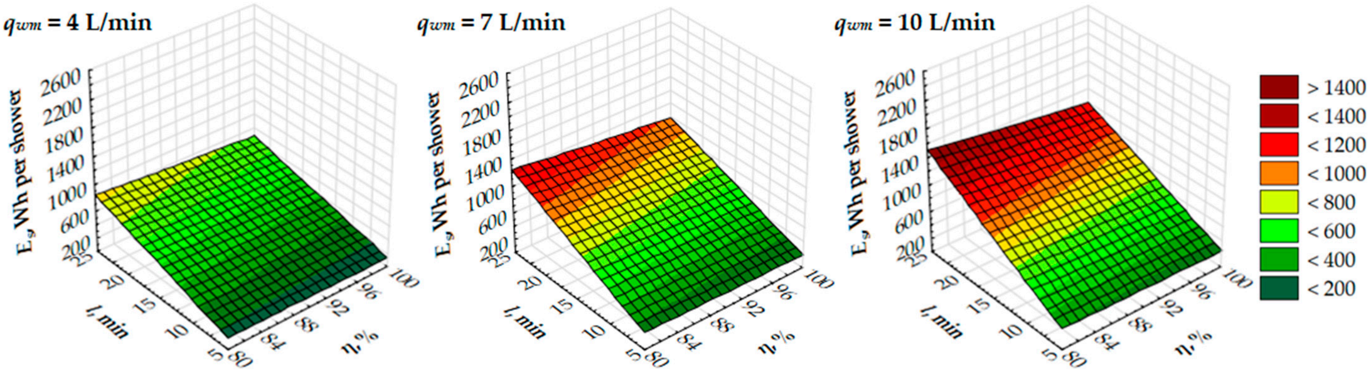


Figure 13. Potential energy saving per shower for ΔT = 20 °C and i = 1% (designations as in Figure 6).

3.3.2. Financial Savings

Based on the calculations, it was also possible to determine the possible financial and environmental benefits of using the DWHR unit on the shower waste pipe. Figures 14 and 15 show the theoretical annual water heating costs for a family of three. The plots considered the use of the DWHR unit with and without baffles, as well as the lack of a greywater heat recovery system. All results were estimated assuming the shower water consumption of 35 L per person per day. The findings presented in the surface plots indicate that the amount of fees incurred to heat water for showering is primarily determined by the type of domestic hot water heater (WH). If an electric hot water heater (EWH) is used, the annual cost of heating water is approximately EUR 240 to EUR 425 depending on the mixed and cold water temperatures and the effectiveness of the unit. An increase in the temperature difference (ΔT) by 10 °C results in an increase in the annual water heating costs (AC) by almost 40%. On the other hand, the use of a low-efficiency water heater (η = 80%) can increase these costs by 25%. The cold water temperature depends on the season and the climatic zone and cannot be influenced by the user. However, the user has influence on the temperature of the water delivered to the WH. Preheating water with the use of the DWHR unit without baffles can reduce the cost of heating water for showering by several percent. The use of the heat exchanger equipped with baffles saves approximately 17% (for q_{wm} = 10 L/min and ΔT = 20 °C) to more than 27% (for q_{wm} = 4 L/min and ΔT = 30 °C) of the expenses incurred for this purpose. If an electric water heater is used, a family of three can expect to save up to EUR 115 per year. Assuming constant water consumption per person, regardless of the characteristics of the shower head, the most significant financial savings can be made when the WH efficiency (η) and the mixed water flow rate (q_{wm}) are the lowest of those analyzed, while ΔT is the highest. This is because, in such conditions, both the energy usage for water heating and the effectiveness of the heat exchanger are the highest.

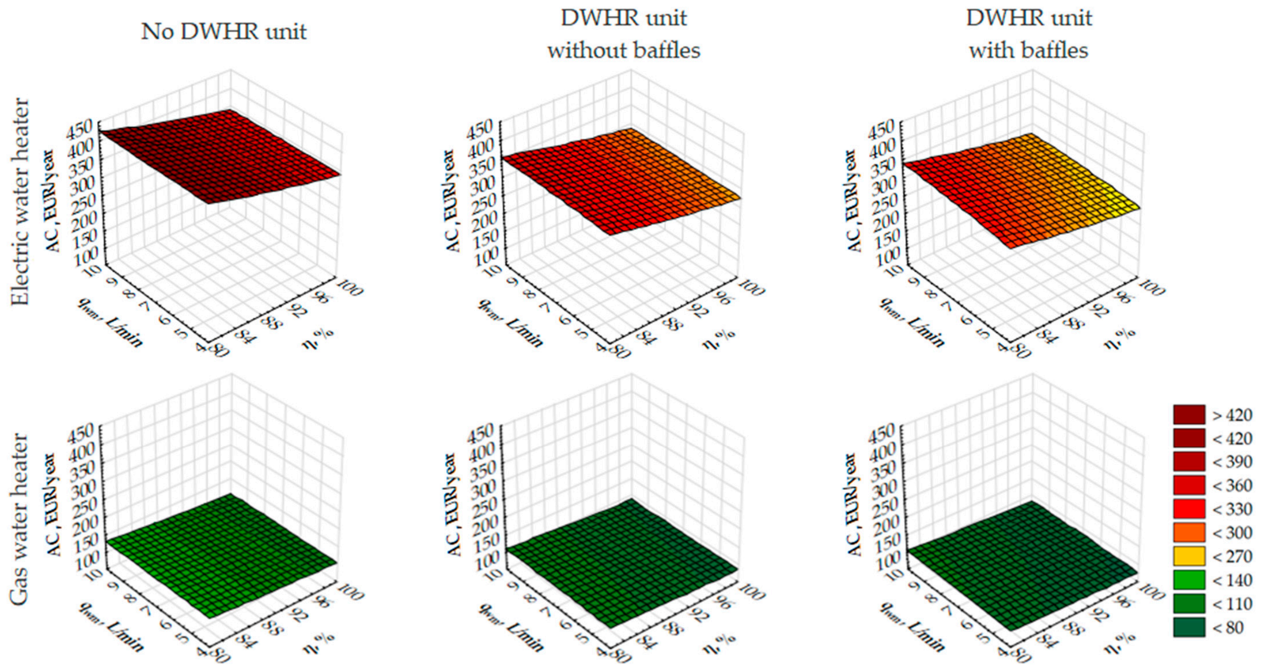


Figure 14. Annual water heating costs for showering for ΔT = 30 °C and i = 2%: AC, annual water heating costs; q_{wm}, mixed water flow rate; η, domestic hot water heater efficiency.

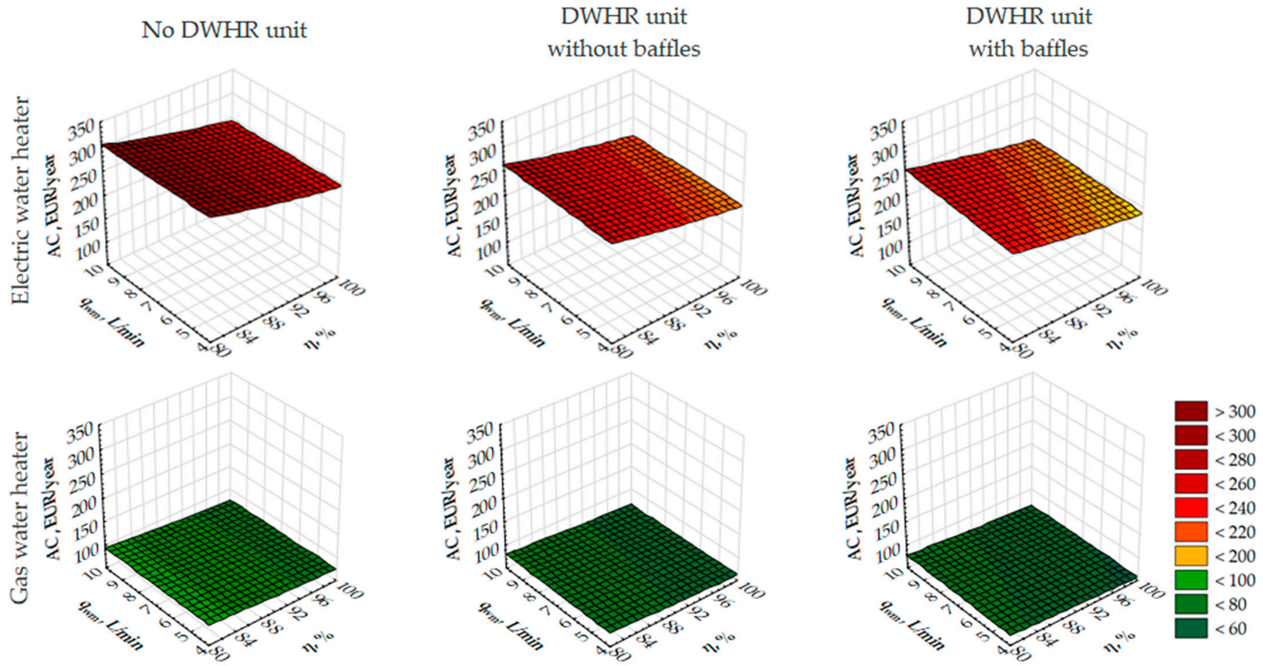


Figure 15. Annual water heating costs for showering for ΔT = 20 °C and i = 1% (designations as in Figure 14).

When using a gas water heater, the projected financial savings were not as satisfactory. An average family can expect to save a maximum of EUR 22 and EUR 36 per year, for ΔT = 20 °C and ΔT = 30 °C, respectively. If the DWHR unit without baffles is used, the projected savings are a few to several euros lower. When analyzing the calculation results, it can also be seen that, in the case of gas water heaters (GWHs), the impact of the heater efficiency on the projected financial savings expressed in euros is clearly lower than for EWHs. This is due to the fact that, in the current year, the unit price of natural gas for households in Poland is about three times lower than that of electricity. However, it should be noted that natural gas prices are currently frozen in Poland. Starting in 2024, a significant increase is expected as a result of the government's energy strategy [46]. Its amount will depend on the market situation. Therefore, it may turn out that the financial benefits resulting from the cooperation of the DWHR unit with GWH will be significantly higher.

To estimate the impact of changes in energy price on potential annual financial savings, it was further analyzed how these savings (ΔAC) would be affected by a change in the unit energy price between −50% and +50%. Figure 16 shows the results for the DWHR unit with baffles for both above cases, assuming a daily water usage for showering of 35 L per person. The analysis was carried out assuming that η = 0.98 and η = 0.82, for EWH and GWH, respectively.

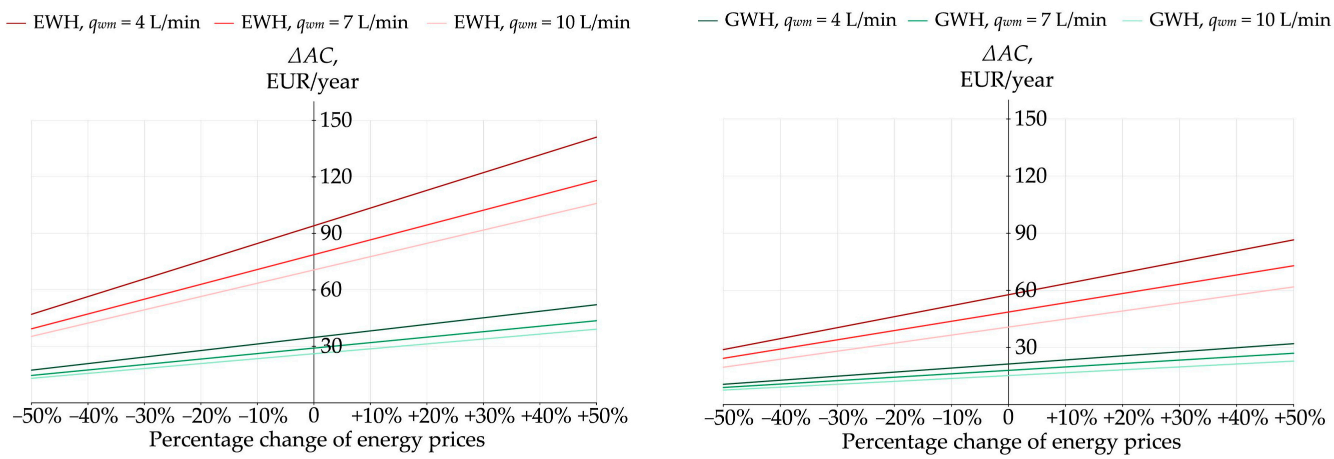


Figure 16. Evaluation of the impact of changes in unit energy prices on annual financial savings resulting from the use of the DWHR unit with baffles: (**a**) ΔT = 30 °C and i = 2%; (**b**) ΔT = 20 °C and i = 1% (EWH, electric water heater; GWH, gas water heater; ΔAC, annual financial savings, EUR/year; other designations as in Figure 6).

The results showed that the unit energy price has a significant impact on projected annual financial savings (ΔAC). Higher differences were observed for electricity, which is a consequence of the higher base price of this energy carrier. When analyzing different values of q_{wm}, it can be seen that the highest changes in ΔAC values were observed for q_{wm} = 4 L/min. This is due to the fact that, with a constant daily water consumption for showering, the lower the mixed water flow rate from the shower head, the higher the base value of this parameter (ΔAC). As mentioned earlier, this is related to the higher effectiveness of the heat exchanger at lower water and greywater flow rates through this unit. As q_{wm} increased, the impact of the change in energy unit price was reduced. However, it should be noted that, even for q_{wm} = 10 L/min, changes in annual financial savings of several tens of euros can be expected. In the case of GWH, the change in ΔAC should not exceed a dozen euros. It should also be noted that for both energy carriers, the greater the temperature difference between greywater and cold water, the greater the impact of their price changes on the potential annual financial savings. Again, this is due to the fact that the effectiveness of the heat exchanger increased with the increase of ΔT. It should be noted that the relationships presented in Figure 16 are linear. Therefore, the absolute change in ΔAC is the same for both an increase and a decrease in the energy price by a given percentage. However, considering that household energy prices have gradually increased in recent years, one can also expect a significant increase in the projected financial savings arising from the use of the DWHR unit. The higher these increases are, the higher the financial efficiency of the heat exchanger under the given operational circumstances.

3.3.3. Environmental Impact

The recovery of heat from greywater also has an influence on the environment. Reducing the energy usage for water heating not only diminishes the expenses for energy supply, but the utilization of fossil fuels and the release of their combustion products into the atmosphere are also reduced. Figures 17 and 18 show the annual CO_2 emissions determined for the above cases. The figures show that, in the case of using EWH, heating water for showering for an average Polish family can generate emissions of more than 1000 kg of CO_2 per year. On the scale of the entire estate, city, or province, these will be gigantic values. Such high CO_2 emissions result, in this case, from the fact that the decrease in emissions of fuel combustion products is very slow in Poland. Data presented in [47] indicate that Poland is the leader in CO_2 emitted per kilowatt-hour of electricity in the entire European Union. This is another factor that supports the need to take measures to reduce electricity consumption. The use of the DWHR unit without baffles guarantees, for an average Polish family, a reduction in CO_2 emissions of between approximately 105 kg (for i = 1% and ΔT = 20 °C) and 260 kg (for i = 2% and ΔT = 30 °C) per year. When the heat exchanger is equipped with baffles, this reduction can reach 130 kg to even 370 kg of CO_2 per year, which can be as much as 27% of the initial emission.

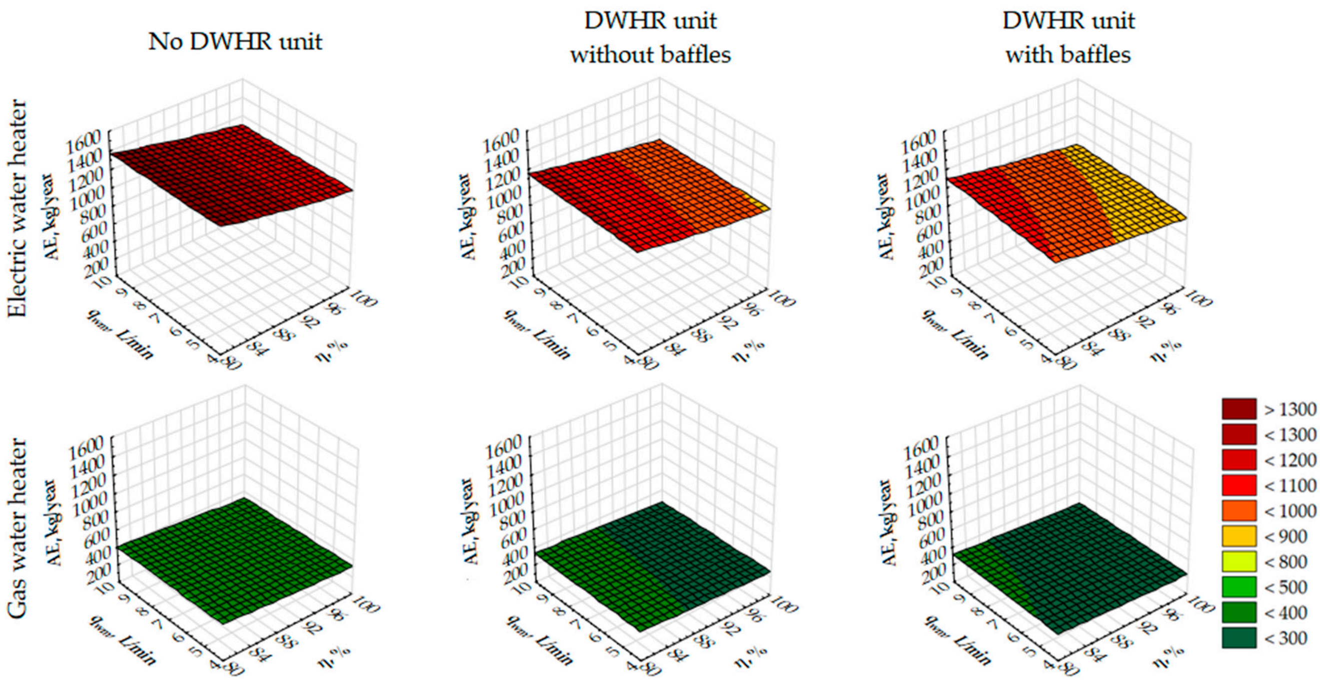


Figure 17. Annual CO_2 emissions resulting from heating water for showering for ΔT = 30 °C and i = 2%: AE, annual CO_2 emissions (other designations as in Figure 14).

When GWH is used, the emission is considerably lower and, for an average family, should not exceed 400 kg CO_2 per year. In such a situation, the use of the DWHR unit with baffles reduces CO_2 emissions by less than 40 kg to a maximum of 110 kg. These are definitely lower values than those in the case of heating water with electricity. However, it should be borne in mind that one of the objectives of the European Union is to reduce carbon dioxide emissions from fossil fuel sources installed in buildings, and natural gas is undoubtedly one of such sources.

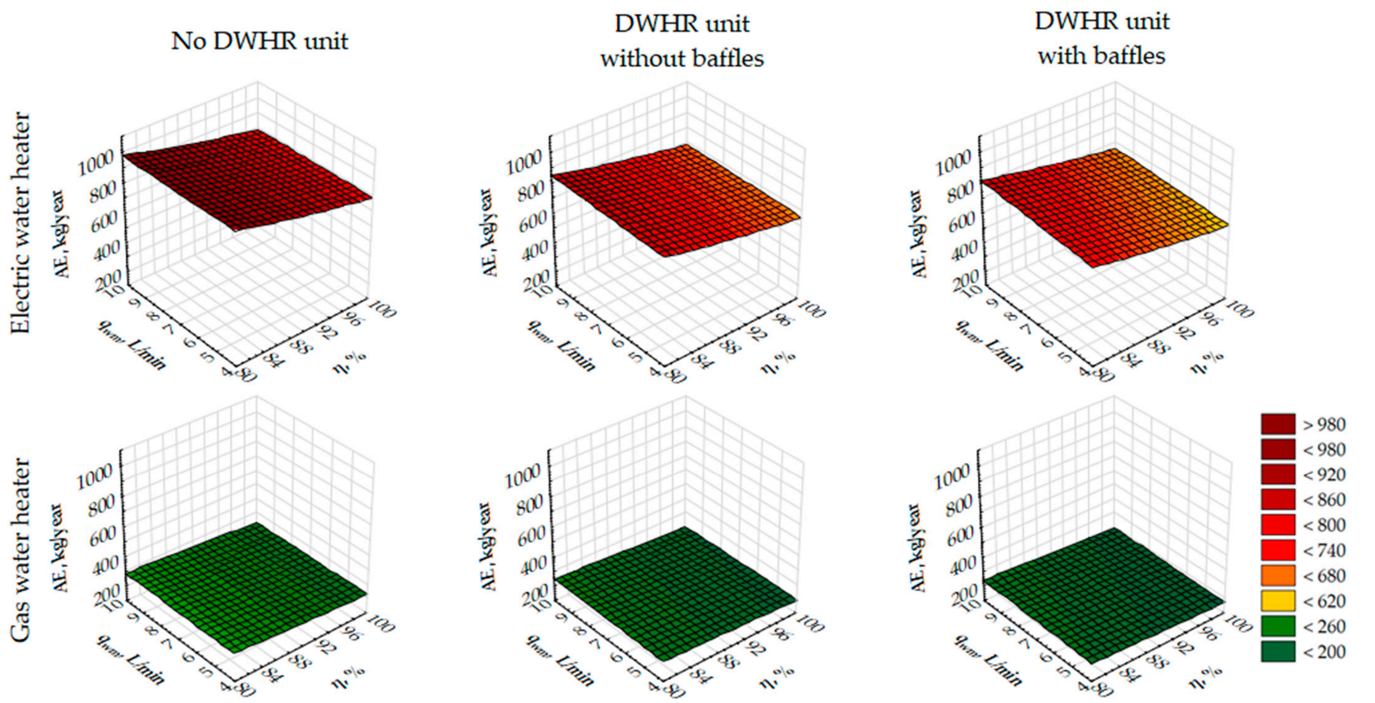


Figure 18. Annual CO_2 emissions resulting from heating water for showering for ΔT = 20 °C and i = 1% (designations as in Figures 14 and 17).

4. Discussion

This research resulted from the need to develop clean technologies using alternative energy sources, including waste energy from wastewater. They were also a response to rising energy prices [48], climate change caused by greenhouse gas emissions [49], and the need to increase the competitiveness of clean technologies [50]. It is worth noting that, in January 2023 alone, more than 18,000 new apartments were commissioned in Poland [51]. The housing stock in this country amounts to more than 15 million flats [42]. In some European countries, such as Germany, France, Spain, or the United Kingdom, the stock is even higher. In Germany, for example, they exceed 43 million [52]. To this should also be added other facilities where domestic hot water is used, such as hotels, sanatoriums, hospitals, and sports facilities. All of these facilities are potential application sites for DWHR units. Considering that the use of greywater energy is undoubtedly an environmentally friendly technology, DWHR systems should be used on a large scale in all these buildings. Such an approach would reduce the consumption of fossil fuels and, as a result, also significantly reduce the dust and gas emissions from their combustion. Its long-term result would be an improvement in the quality of atmospheric air. Therefore, greywater heat recovery is a future-proof solution that will certainly gain popularity in the coming years.

As mentioned in the Introduction, the most efficient type of shower heat exchangers are vertical DWHR units. However, in many cases, their application is not possible, especially in existing facilities [40]. In such a situation, the most rational solution seems to be the application of horizontal DWHR units, whose effectiveness, however, is not satisfactory. Research has shown that equipping the horizontal circular heat exchanger with elements that increase the turbulent flow of greywater allows for a significant increase in its effectiveness. In the analyzed case, the use of baffles resulted in an increase in the unit effectiveness from several to as much as 40% compared to the heat exchanger without baffles. The highest increases were observed at the lowest flow rates of water and greywater through the DWHR unit and the unit bottom slope of i = 2%. However, the amount of energy that can be saved, and consequently also the expected reduction in emissions of fossil fuel combustion products, depends not only on the effectiveness of the heat exchanger but also on the consumption of water for showering. Studies have shown that, with an increase in the mixed water flow rate from the shower head (q_{wm}), at a certain shower length (l), the amount of energy that can be saved increases, although the effectiveness of the heat exchanger decreases. This confirms the results obtained by Piotrowska and Słyś [41] for another type of shower heat exchanger. Therefore, the greatest benefits from the installation of the DWHR unit are to be expected in installations where shower heads with a high flow rate (q_{wm}) are used. However, considering that water resources in Poland are among the lowest in Europe [53], and the global water deficit can double between 2010 and 2050 [54], greywater energy recovery cannot be implemented without concern for water resources. Implementing selected sustainable development goals (SDGs) [55], such as SDG 7 ("Affordable and clean energy") or SDG 13 ("Climate action"), does not release responsibility for the other goals. This is especially true for SDG 6, which aims to ensure access to clean water for all people on Earth. It should also be noted that water is needed at all stages of energy production. Therefore, priority should be given to reducing water consumption for showering by installing flow limiters, replacing shower heads, or simply shortening the length of the shower. Reducing the consumption of DHW is the easiest way to reduce the energy used to heat water. As a result, not only will the costs of water heating be reduced but also the fees incurred for water supply and sewage disposal. It is only when water-saving fittings are used that energy recovery from greywater can be considered a priority.

The reduction in energy consumption for water heating, resulting from the recovery of heat carried by greywater, can contribute to the reduction in the costs incurred to supply the building with energy. The amount of expected savings is primarily dependent on the unit price of the energy carrier used to heat water. For this reason, particularly beneficial financial effects can be expected when EWH is used to heat water. Considering that further increases in the price of electricity are forecasted for the coming years [56], the installation of the DWHR unit and equipping it with appropriate baffle models will certainly contribute to improving the budgets of households. The cost effectiveness of the system in the coming years will also be influenced by the purchase price of the heat exchanger and baffles, as well as the costs of their installation. However, considering that polylactide is relatively inexpensive compared to copper, from which the DWHR unit is made, and that the installation of the baffles appears to be trouble-free and does not require specialized technical facilities, equipping the heat exchanger with baffles will certainly prove profitable. If DHW is prepared with the use of GWH, the expected financial savings are not so satisfactory. However, it should be considered that the relatively low price of natural gas for Polish households is the result of top-down regulations and price freezes. Next year, a significant increase in the prices of this energy carrier is expected, which will be a consequence of the energy strategy adopted by the government [46]. The European Commission also forecasts an increase in gas prices until 2050 [56]. Therefore, there is a good chance that the actual financial savings will be significantly higher than those indicated in the analysis.

An additional effect of the DWHR unit, especially the one equipped with baffles, will be to reduce the negative environmental impact of burning fossil fuels. The use of systems aimed at reducing energy consumption and protecting the state of the atmosphere is recommended for all countries. However, in the case of Poland, this issue is of particular importance, as this country is the leader in CO_2 emitted per kilowatt-hour of electricity in the entire European Union. It is also at the forefront of countries characterized by the highest total power sector emissions in the European Union. Approximately twice as many emissions are generated only by Germany [57]. Next in line are Italy, Spain, and the Czech Republic [57]. Despite the measures taken in recent years to reduce CO_2 emissions, there is still much to be conducted in most countries around the world. Therefore, it is important to develop and implement energy saving technologies that exert a positive influence on the climate of our planet.

The most likely recipients of the research results are companies interested in introducing new devices and technologies to the market. In the case of the horizontal circular DWHR unit, installation works involving the assembly of baffles can be carried out without specialist technical support. As a result, the effectiveness of the unit can be improved even by small companies in the construction and sanitary sectors. It should be noted that the cost of producing the baffles is relatively low compared to the price of the heat exchanger, which is mainly due to the materials used. Considering that equipping the DWHR unit with baffles can guarantee an increase in its effectiveness of up to 40%, it can be assumed that this is a solution for reducing the costs incurred to supply the building with energy. In addition, it can be applied to both new and existing units. When using the horizontal heat exchanger, interference with the existing building structure is limited to a minimum. Therefore, actions aimed at improving its effectiveness and, as a result, also the comfort and safety of using a domestic hot water installation [58] should be considered reasonable.

It should be noted that the research certainly does not exhaust the issue of improving the effectiveness of the horizontal heat exchangers and does not fully solve the problem. Baffle models I–VI were developed with the assumption of minimizing the risk of suspension deposition during the greywater flow. For this reason, elements that would cause a sharp change in the direction of the greywater flow were not considered in the baffle designs. However, thus far, no studies have been conducted to assess the impact of contaminants present in greywater [30,59] on the effectiveness of the horizontal DWHR units equipped with baffles, and such studies are undoubtedly needed. During long-term use, it may be necessary to periodically clean the unit. If systematic cleaning of the heat exchangers becomes a routine, it may be reasonable to introduce modifications to the described baffle models, as a result of which the effectiveness of the horizontal DWHR units equipped with baffles will increase.

The limitation of the research is also the lack of consideration of heat exchangers with a different geometry. Changing the cross-section of the unit would certainly affect both the effectiveness of the heat exchanger and the possibility of its improvement as a result of installing a particular type of baffle. The study focused on the unit whose external dimension corresponded to the standard diameter of the shower waste pipe. If the heat source was to be greywater from more sanitary appliances, it would certainly be necessary to use a DWHR unit with a greater capacity. Therefore, further research will focus on assessing the potential for improving the effectiveness of horizontal heat exchangers with other geometries. DWHR units with different designs will also be considered. Greater emphasis will also be placed on the use of different materials that are not a burden on the environment at the end of the system's lifetime.

5. Conclusions

An analysis of the possibility of improving the effectiveness of the horizontal circular DWHR unit by using baffles in the greywater section of the heat exchanger allowed the following findings to be drawn:

- The application of both the DWHR unit without baffles and the heat exchanger equipped with baffles allowed for the recovery of a significant amount of energy contained in greywater. However, the effectiveness of the DWHR unit with baffles was greater by several to even 40% compared to the basic unit.
- The choice of the baffle model should take into account the hydraulic conditions in the heat exchanger prior to baffle installation, to avoid the pressurized operation of the unit.
- In each case, the greater the temperature difference between the warm greywater and cold water, the higher the effectiveness of the heat exchanger.
- The effectiveness of the DWHR unit rises as the mixed water flow rate from the shower head drops. However, the amount of energy that can be saved is also conditioned by the volume of water used.

- The greatest financial savings resulting from equipping the DWHR unit with baffles were visible when the DHW was prepared with the use of EWH.
- The potential reduction in CO_2 emissions, resulting from the application of the greywater heat recovery system, is the greatest when water is heated in an electrically powered device.

Future research ought to concentrate on assessing the potential for enhancing the effectiveness of horizontal DWHR units with other designs. Particular attention should be paid to the systems that can be used when greywater is discharged from a group of sanitary appliances. Units suitable for installation with water-efficient taps should also be considered, as saving water is as important as reducing energy consumption for its heating. Regardless of the research that is being carried out to improve the effectiveness of DWHR units, measures should be taken to educate the public and improve their environmental awareness. Despite the fact that wastewater is no longer perceived as waste, many potential users still have concerns about the use of DWHR units. These fears result from both the lack of knowledge in the field of greywater heat recovery and the relatively high costs of purchasing DWHR units. For this reason, it is necessary to implement promotional campaigns and programs that subsidize the purchase of these units. Only such an approach will allow the full benefits of their implementation to be reaped.

6. Patents

The presented solution was applied to the Patent Office of the Republic of Poland on 30 November 2022 with the number P.443001.

Author Contributions: Conceptualization, S.K.-O. and M.S.; methodology, S.K.-O. and M.S.; validation, S.K.-O. and M.S.; formal analysis, S.K.-O. and M.S.; investigation, S.K.-O. and M.S.; writing—original draft preparation, S.K.-O. and M.S.; writing—review and editing, S.K.-O.; visualization, S.K.-O. and M.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research was partially financed by *Podkarpackie Centrum Innowacji Sp. z o. o.* as part of the Competition in the project "Podkarpackie Innovation Center", implemented under the Regional Operational Program of the Podkarpackie Voivodeship for 2014–2020, Priority Axis I: Competitive and Innovative Economy, Action: Competition for R&D projects, Call for proposals: III. Project No: N3_479, Contract No: 24/PRZ/1/DG/PCI/2021.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the reviewers for their feedback, which has helped improve the quality of the manuscript, and Energies' staff and editors for handling the paper.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Amanowicz, Ł.; Ratajczak, K.; Dudkiewicz, E. Recent Advancements in Ventilation Systems Used to Decrease Energy Consumption in Buildings—Literature Review. *Energies* **2023**, *16*, 1853. [CrossRef]
2. Igliński, B.; Pietrzak, M.B.; Kiełkowska, U.; Skrzatek, M.; Kumar, G.; Piechota, G. The assessment of renewable energy in Poland on the background of the world renewable energy sector. *Energy* **2022**, *261*, 125319. [CrossRef]
3. Kovalenko, Y.; Katkov, M.; Ponomarenko, I.; Malovanyy, M.; Tymchuk, I. Utilization of drainage water heat in flooded urban areas. *Ecol. Quest.* **2022**, *33*, 31–41. [CrossRef]
4. Watson, B.; Lange, I.; Linn, J. Coal demand, market forces, and U.S. coal mine closures. *Econ. Inq.* **2023**, *61*, 35–57. [CrossRef]
5. Pohrebennyk, V.; Koszelnik, P.; Mitryasova, O.; Dzhumelia, E.; Zdeb, M. Environmental Monitoring of Soils of Post-Industrial Mining Areas. *J. Ecol. Eng.* **2019**, *20*, 53–61. [CrossRef]
6. Igliński, B.; Pietrzak, M.B.; Kiełkowska, U.; Skrzatek, M.; Gajdos, A.; Zyadin, A.; Natarajan, K. How to Meet the Green Deal Objectives—Is It Possible to Obtain 100% RES at the Regional Level in the EU? *Energies* **2022**, *15*, 2296. [CrossRef]
7. Rabbi, M.F.; Popp, J.; Máté, D.; Kovács, S. Energy Security and Energy Transition to Achieve Carbon Neutrality. *Energies* **2022**, *15*, 8126. [CrossRef]

8. Voznyak, O.; Spodyniuk, N.; Antypov, I.; Dudkiewicz, E.; Kasynets, M.; Savchenko, O.; Tarasenko, S. Efficiency Improvement of Eco-Friendly Solar Heat Supply System as a Building Coating. *Sustainability* **2023**, *15*, 2831. [CrossRef]
9. Matetić, I.; Štajduhar, I.; Wolf, I.; Ljubic, S. A Review of Data-Driven Approaches and Techniques for Fault Detection and Diagnosis in HVAC Systems. *Sensors* **2023**, *23*, 1. [CrossRef]
10. Zeng, X.; Sun, X.; Zhao, F. Energy-saving intelligent manufacturing optimization scheme for new energy vehicles. *Int. J. Emerg. Electr. Power Syst.* **2022**, *23*, 913–926. [CrossRef]
11. Schestak, I.; Spriet, J.; Black, K.; Styles, D.; Faragò, M.; Rygaard, M.; Williams, A.P. Heat recovery and water reuse in micro-distilleries improves eco-efficiency of alcohol production. *J. Environ. Manag.* **2023**, *325*, 116468. [CrossRef] [PubMed]
12. Hadengue, B.; Morgenroth, E.; Larsen, T.A. Screening innovative technologies for energy-efficient domestic hot water systems. *J. Environ. Manag.* **2022**, *320*, 115713. [CrossRef] [PubMed]
13. Sierra, L.; Lizana, M.; Pino, C.; Ilaya-Ayza, A.; Neculman, B. Structural Model for Socially Sustainable Public Housing Decision-Making in Chile. *Int. J. Environ. Res. Public Health* **2023**, *20*, 2543. [CrossRef] [PubMed]
14. Ascione, F.; De Masi, R.F.; Mastellone, M.; Vanoli, G.P. Building rating systems: A novel review about capabilities, current limits and open issues. *Sustain. Cities Soc.* **2022**, *76*, 103498. [CrossRef]
15. European Commission. *EU Energy in Figures. Statistical Pocketbook 2022*; Publications Office of the European Union: Luxembourg, 2022. Available online: https://op.europa.eu/en/publication-detail/-/publication/7d9ae428-3ae8-11ed-9c68-01aa75ed71a1/language-en (accessed on 8 February 2023).
16. Amanowicz, Ł. Peak Power of Heat Source for Domestic Hot Water Preparation (DHW) for Residential Estate in Poland as a Representative Case Study for the Climate of Central Europe. *Energies* **2021**, *14*, 8047. [CrossRef]
17. Alrwashdeh, S.S.; Ammari, H.; Jweihan, Y.S.; Qadourah, J.A.; Al-Kheetan, M.J.; Al-Falahat, A.M. Refurbishment of Existing Building toward a Surplus Energy Building in Jordan. *Open Constr. Build. Technol. J.* **2022**, *16*, e187483682208150. [CrossRef]
18. Ratajczak, K.; Michalak, K.; Narojczyk, M.; Amanowicz, Ł. Real Domestic Hot Water Consumption in Residential Buildings and Its Impact on Buildings' Energy Performance—Case Study in Poland. *Energies* **2021**, *14*, 5010. [CrossRef]
19. Nejranowski, J.; Szaflik, W. Hot Water Consumption Time in Multi-Apartment Buildings. *J. Ecol. Eng.* **2020**, *21*, 199–202. [CrossRef]
20. George, D.; Pearre, N.S.; Swan, L.G. High resolution measured domestic hot water consumption of Canadian homes. *Energy Build.* **2015**, *109*, 304–315. [CrossRef]
21. Lomet, A.; Suard, F.; Chèze, D. Statistical Modeling for Real Domestic Hot Water Consumption Forecasting. *Energy Procedia* **2015**, *70*, 379–387. [CrossRef]
22. Giglio, T.; Santos, V.; Lamberts, R. Analyzing the impact of small solar water heating systems on peak demand and on emissions in the Brazilian context. *Renew. Energy* **2019**, *133*, 1404–1413. [CrossRef]
23. Neugebauer, G.; Lichtenwoehrer, P.; Huber, F.; Stoeglehner, G.; Kretschmer, F. Potentials and Integrated Suitability Pre-assessment of Wastewater Treatment Plants as Local Energy Cells. *Front. Environ. Sci.* **2022**, *9*, 785557. [CrossRef]
24. Hidalgo, D.; Martín-Marroquín, J.M.; Castro, J. Wastewater as a Source of Heat Energy. In *Heat Energy Recovery for Industrial Processes and Wastes. Green Energy and Technology*; Borge-Diez, D., Rosales-Asensio, E., Eds.; Springer: Cham, Switzerland, 2023; pp. 1–20. [CrossRef]
25. Nagpal, H.; Spriet, J.; Murali, M.K.; McNabola, A. Heat Recovery from Wastewater—A Review of Available Resource. *Water* **2021**, *13*, 1274. [CrossRef]
26. Ravichandran, A.; Diaz-Elsayed, N.; Thomas, S.; Zhang, Q. An assessment of the influence of local conditions on the economic and environmental sustainability of drain water heat recovery systems. *J. Clean. Prod.* **2021**, *279*, 123589. [CrossRef]
27. Wehbi, Z.; Taher, R.; Faraj, J.; Ramadan, M.; Castelain, C.; Khaled, M. A short review of recent studies on wastewater heat recovery systems: Types and applications. *Energy Rep.* **2022**, *8*, 896–907. [CrossRef]
28. Piotrowska, B.; Słyś, D. Comprehensive Analysis of the State of Technology in the Field of Waste Heat Recovery from Grey Water. *Energies* **2023**, *16*, 137. [CrossRef]
29. Kordana-Obuch, S.; Starzec, M.; Wojtoń, M.; Słyś, D. Greywater as a Future Sustainable Energy and Water Source: Bibliometric Mapping of Current Knowledge and Strategies. *Energies* **2023**, *16*, 934. [CrossRef]
30. Noutsopoulos, C.; Andreadakis, A.; Kouris, N.; Charchousi, D.; Mendrinou, P.; Galani, A.; Mantziaras, I.; Koumaki, E. Greywater characterization and loadings—Physicochemical treatment to promote onsite reuse. *J. Environ. Manag.* **2018**, *216*, 337–346. [CrossRef]
31. Kordana-Obuch, S.; Starzec, M. Horizontal Shower Heat Exchanger as an Effective Domestic Hot Water Heating Alternative. *Energies* **2022**, *15*, 4829. [CrossRef]
32. Vavřička, R.; Boháč, J.; Matuška, T. Experimental development of the plate shower heat exchanger to reduce the domestic hot water energy demand. *Energy Build.* **2022**, *254*, 111536. [CrossRef]
33. Schestak, I.; Spriet, J.; Styles, D.; Williams, A.P. Introducing a Calculator for the Environmental and Financial Potential of Drain Water Heat Recovery in Commercial Kitchens. *Water* **2021**, *13*, 3486. [CrossRef]
34. Singh, A.P.; Spriet, J.; McNabola, A. Experimental and numerical investigation of drain water heat recovery in a grease interceptor. *J. Clean. Prod.* **2023**, *403*, 136799. [CrossRef]
35. Sayegh, M.A.; Ludwińska, A.; Rajski, K.; Dudkiewicz, E. Environmental and energy saving potential from greywater in hotels. *Sci. Total Environ.* **2021**, *761*, 143220. [CrossRef] [PubMed]

36. Selimli, S.; Eljetlawi, I.A.M. The experimental study of thermal energy recovery from shower greywater. *Energy Sources Part A* **2021**, *43*, 3032–3044. [CrossRef]
37. Poredoš, P.; Vidrih, B.; Poredoš, A. Performance and Exergy Analyses of a Solar Assisted Heat Pump with Seasonal Heat Storage and Grey Water Heat Recovery Unit. *Entropy* **2020**, *23*, 47. [CrossRef]
38. Stec, A.; Mazur, A. An Analysis of Eco-Technology Allowing Water and Energy Saving in an Environmentally Friendly House—A Case Study from Poland. *Buildings* **2019**, *9*, 180. [CrossRef]
39. Zhang, D.; Fang, C.; Gao, Z.; Wang, X.; Shen, C.; Li, H. Energy, environmental and economic assessment of wastewater heat recovery systems in hotel buildings. *Appl. Therm. Eng.* **2023**, *222*, 119949. [CrossRef]
40. Kordana-Obuch, S.; Starzec, M.; Słyś, D. Assessment of the Feasibility of Implementing Shower Heat Exchangers in Residential Buildings Based on Users' Energy Saving Preferences. *Energies* **2021**, *14*, 5547. [CrossRef]
41. Piotrowska, B.; Słyś, D. Variant analysis of financial and energy efficiency of the heat recovery system and domestic hot water preparation for a single-family building: The case of Poland. *J. Build. Eng.* **2023**, *65*, 105769. [CrossRef]
42. Statistics Poland. Local Data Bank. Available online: https://bdl.stat.gov.pl/bdl/start (accessed on 19 April 2023).
43. Chudzicki, J.; Sosnowski, S. *Instalacje Wodociągowe—Projektowanie, Wykonanie, Eksploatacja*, 3rd ed.; Seidel-Przywecki: Warsaw, Poland, 2011.
44. The National Centre for Emissions Management (KOBiZE). *Wskaźniki Emisyjności CO_2, SO_2, NOx, CO i Pyłu Całkowitego dla Energii Elektrycznej*; IOŚ-PIB: Warszawa, Poland, 2022. Available online: https://www.kobize.pl/en/file/wskazniki-emisyjnosci/id/184/wskazniki-emisyjnosci-dla-energii-elektrycznej-za-rok-2021-opublikowane-w-grudniu-2022-r (accessed on 24 April 2023).
45. The National Centre for Emissions Management (KOBiZE). *Wskaźniki Emisji Zanieczyszczeń ze Spalania Paliw dla Źródeł o Nominalnej mocy Cieplnej do 5 MW, Zastosowane do Automatycznego Wyliczenia Emisji w Raporcie do Krajowej Bazy za rok 2022*; IOŚ-PIB: Warszawa, Poland, 2023. Available online: https://krajowabaza.kobize.pl/docs/Wska%C5%BAniki_ma%C5%82e_%C5%BAr%C3%B3dla_spalania_paliw_2022.pdf (accessed on 24 April 2023).
46. Ministry of Climate and Environment. Energy Policy of Poland Until 2040. Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski (accessed on 4 May 2023).
47. Our World in Data. Carbon Intensity of Electricity. 2022. Available online: https://ourworldindata.org/grapher/carbon-intensity-electricity?region=Europe (accessed on 5 May 2023).
48. European Council. Infographic—Energy Price Rise since 2021. Available online: https://www.consilium.europa.eu/en/infographics/energy-prices-2021/ (accessed on 19 April 2023).
49. Stec, A.; Mazur, A.; Słyś, D. Evaluating the financial efficiency of energy and water saving installations in passive house. *E3S Web Conf.* **2017**, *22*, 00168. [CrossRef]
50. Bilan, Y.; Samusevych, Y.; Lyeonov, S.; Strzelec, M.; Tenytska, I. The Keys to Clean Energy Technology: Impact of Environmental Taxes on Biofuel Production and Consumption. *Energies* **2022**, *15*, 9470. [CrossRef]
51. Statistics Poland. Residential Construction in the Period of January 2023. Available online: https://stat.gov.pl/en/topics/industry-construction-fixed-assets/construction/residential-construction-in-the-period-of-january-2023,3,128.html (accessed on 19 April 2023).
52. Statista. Total Housing Stock in Selected Countries in Europe in 2021, by Country. Available online: https://www.statista.com/statistics/898238/housing-stock-in-european-countries-in-total/ (accessed on 9 March 2023).
53. Kubiak-Wójcicka, K.; Machula, S. Influence of Climate Changes on the State of Water Resources in Poland and Their Usage. *Geosciences* **2020**, *10*, 312. [CrossRef]
54. Bijl, D.L.; Biemans, H.; Bogaart, P.W.; Dekker, S.C.; Doelman, J.C.; Stehfest, E.; van Vuuren, D.P. A Global Analysis of Future Water Deficit Based On Different Allocation Mechanisms. *Water Resour. Res.* **2018**, *54*, 5803–5824. [CrossRef]
55. United Nations (UN). *The Sustainable Development Goals Report 2021*; United Nations: New York, NY, USA, 2021.
56. European Commission. EU Reference Scenario 2020: Energy, Transport and GHG Emissions—Trends to 2050. Available online: https://op.europa.eu/en/publication-detail/-/publication/96c2ca82-e85e-11eb-93a8-01aa75ed71a1/language-en (accessed on 9 May 2023).
57. EMBER. European Electricity Review 2023. Available online: https://ember-climate.org/insights/research/european-electricity-review-2023/#supporting-material (accessed on 9 May 2023).
58. Tchórzewska-Cieślak, B.; Pietrucha-Urbanik, K. Water System Safety Analysis Model. *Energies* **2023**, *16*, 2809. [CrossRef]
59. Ziembowicz, S.; Kida, M.; Koszelnik, P. Elimination of a Mixture of Microplastics Using Conventional and Detergent-Assisted Coagulation. *Materials* **2023**, *16*, 4070. [CrossRef]