energies

Article

Horizontal Shower Heat Exchanger as an Effective Domestic Hot Water Heating Alternative

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: Wastewater has significant potential as a source of clean energy. This energy can be used both within external sewer networks and on the scale of individual residential buildings, and the use of shower heat exchangers appears to be the most reasonable solution. However, in the case of Poland, the problem is still the unwillingness of society to use this type of solution, caused mainly by the lack of space for the installation of vertical drain water heat recovery (DWHR) units and the low efficiency of horizontal units. In response to this issue, the efficiency of a new compact shower heat exchanger designed to be mounted below the shower tray, as well as its linear counterpart, was investigated under various operating conditions. In addition, the financial efficiency of using the compact DWHR unit with average water consumption for showering was evaluated. For this purpose, discount methods were used to estimate the financial efficiency of investments. The study showed that the compact shower heat exchanger has higher efficiency than its linear counterpart. Depending on the temperature of cold water and the flow rate of both media through the heat exchanger, it achieves efficiencies ranging from 22.43% to 31.82%, while the efficiency of the linear DWHR unit did not exceed 23.03% in the study. The financial analysis showed that its use is particularly beneficial when the building uses an electric hot water heater. The investment's sensitivity to changes in the independent variables is small in this case, even with low water consumption per shower. The only exceptions are investment outlays. Therefore, the compact DWHR unit is a clean energy device, which in many cases is financially viable.

Keywords: drain water heat recovery (DWHR) unit; heat exchanger efficiency; discounted payback period (DPP); internal rate of return (IRR); net present value (NPV); profitability index (PI)

check for updates

Citation: Kordana-Obuch, S.; Starzec, M. Horizontal Shower Heat Exchanger as an Effective Domestic Hot Water Heating Alternative. *Energies* **2022**, *15*, 4829. https://doi.org/10.3390/en15134829

Academic Editor: Fabrizio Ascione

Received: 10 June 2022
Accepted: 28 June 2022
Published: 1 July 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The need to manage wastewater raises many problems due to its significant pollution and the need to remove harmful substances [1,2]. However, wastewater should not be viewed solely as a problem because it is rich in valuable resources that can be recovered [3,4]. The recovery of resources from wastewater can offset freshwater abstraction and fertilizer production [5,6]. Nagpal et al. [7] and Sitzenfrei et al. [8] further point out the significant potential of this resource as a clean energy source usable at the scale of individual buildings as well as large communities and neighborhoods. Buildings mainly use heat exchangers mounted on the outlet of warm drain water [9]. This solution can be used in both residential and industrial facilities [10]. For larger amounts of wastewater, a heat pump application is necessary [11]. The lower source of energy for this device can be greywater [12], raw sewage transported by sewage collectors and flowing through the technological facilities of the sewage treatment plant [13,14], as well as treated sewage flowing towards the receiver [15]. Industrial wastewater can also be used as a heat source [16]. For example, Reiners et al. [17] analyzed the efficiency of a heat pump using wastewater from the coal mining industry in ultra-low-temperature district heating systems. On the other hand, Kannoh [18] used an adsorption heat pump to recover energy from the wastewater from dyeing processes.

Economically, the most rational solution is to implement small-scale drain water heat recovery systems [19]. Research shows that if the recovered energy is used to preheat water in a residential building, the return on investment can be achieved after only two years [20]. However, much depends on the type of building [21], the tap fittings used [22], the method for recovering the heat deposited in the drain water [23], and the price of the primary energy source [24]. The amount of drain water used as a heat source is also important. The simplest and most popular solution is the use of shower heat exchangers [25,26]. However, there are known cases where the source of waste energy is the drain water discharged from a larger number of sanitary facilities [27,28]. All this means that the expected payback period can vary over a wide range. Under unfavorable circumstances, it may even exceed the technical lifetime of the heat recovery system [29], which discourages potential users from implementing such solutions.

However, risk accompanies each investment and only a few of them contribute to environmental protection. The application of drain water heat exchangers, unlike other ways of using waste heat (e.g., by means of heat pumps [30,31]), leads to a reduction in fossil fuel consumption without the need for external energy. This is important, as the share of water heating in total energy consumption in buildings has increased significantly in recent years [32]. The use of drain water heat recovery units also contributes to a significant reduction in carbon dioxide emissions, as well as other harmful products of fuel combustion [33,34]. As a result, drain water heat recovery systems are increasingly being used as part of sustainable [35] and energy-efficient [36] construction. They are also used in smart homes [37], and their implementation can contribute to improving the safety of the domestic hot water supply to the shower system [38]. It is worth noting that systems dedicated to drain water heat recovery can be successfully applied together with other environmentally friendly water- and energy-saving solutions [39]. Therefore, considering that the water–energy–waste nexus approach has been gaining importance in recent years [40–42], the application potential of drain water heat recovery systems also increases. An additional incentive for their application may also be the need to switch to low-temperature district heating systems [43]. However, in the case of Poland, the problem remains the reluctance of society to apply this type of solution. An earlier study by the authors [44] showed that shower heat exchangers are not currently used in residential buildings in Poland, despite the fact that the availability of such products on the market is increasing. Additionally, only a few percent of Polish society expresses a definite wish to have such a device in the building where they currently live. It is caused by the lack of space to install highly efficient vertical heat exchanger and the low efficiency and often high price of horizontal units. Therefore, one should not expect a sudden increase in the implementation of shower heat exchangers in the near future, especially since studies on the attitudes of Europeans towards the use of greywater indicate a clear lack of acceptance for this medium [45]. Therefore, it is necessary to find an optimal design of horizontal shower heat exchangers and to promote them as devices to increase the comfort and safety of showering with limited space requirements. The possibilities to increase the use of alternative energy sources are determined by the scope of innovations [46], and reducing energy consumption in a building cannot be done without considering the comfort of its users [47].

The purpose of the paper is to present the results of research on the efficiency evaluation of a new compact shower heat exchanger solution under various operating conditions. The assumption in designing the device was to minimize manufacturing costs and limit interference in the existing plumbing system. As part of the research, prototypes of the above-mentioned device and a simple linear heat exchanger with identical cross section and length were made (Figure 1). Then, both devices were tested under established laboratory conditions and the efficiencies of both devices were compared. Potential financial savings resulting from the installation of the compact unit on the shower drain were also determined, as financial efficiency is one of the main determinants of the implementation of a given solution. The analysis was carried out with the assumption that all the water used for showering will be preheated in the heat exchanger. The investigated devices are interchangeably referred to in the paper as shower heat exchangers and drain water heat recovery (DWHR) units.

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

Figure 1. Tested shower heat exchangers: (**a**) compact DWHR unit; (**b**) linear DWHR unit.

2. Materials and Methods

2.1. Characteristics of the Tested Shower Heat Exchangers

The application of DWHR units allows the heat deposited in drain water to be recovered to preheat water used in the shower. There are currently many types of shower heat exchangers available on the world and European markets, differing in design, direction of water and drain water flow, as well as space requirements. Depending on the operating conditions of the shower system, the type of heat source and the distance between the various components of the plumbing system, the preheated water discharged from the DWHR unit can be fed to the domestic hot water heater, the shower mixing valve, or both. The option of supplying preheated water to both the domestic hot water heater and the shower mixing valve is considered to be the most beneficial [48]. This is due to the largest volume of heated water compared to other solutions. Therefore, the tests were carried out for this configuration of the heat recovery system. However, the DWHR units used should have a compact design, allowing them to be installed in virtually any condition. Also, they should be as efficient as possible at a relatively low price.

The research involved evaluating the efficiency of two prototypes of shower heat exchangers. The prototype of the compact horizontal DWHR unit with a rectangular cross section consists of six sections with a total length of 1.5 m, arranged in series with a constant slope of 2%. The geometry of the unit was adapted to the size of the space available below the shower tray (Figure 2a). For comparative purposes, a solution that was to be used as part of the waste pipe, having a linear form, was also analyzed (Figure 2b). Its length and cross section are analogous to the previous DWHR unit. However, due to the location, it is possible to install the device with different slopes adapted to the slope of the waste pipe. In the study, the efficiency of the linear DWHR unit was analyzed with slopes (i) ranging from 0 to 6%.

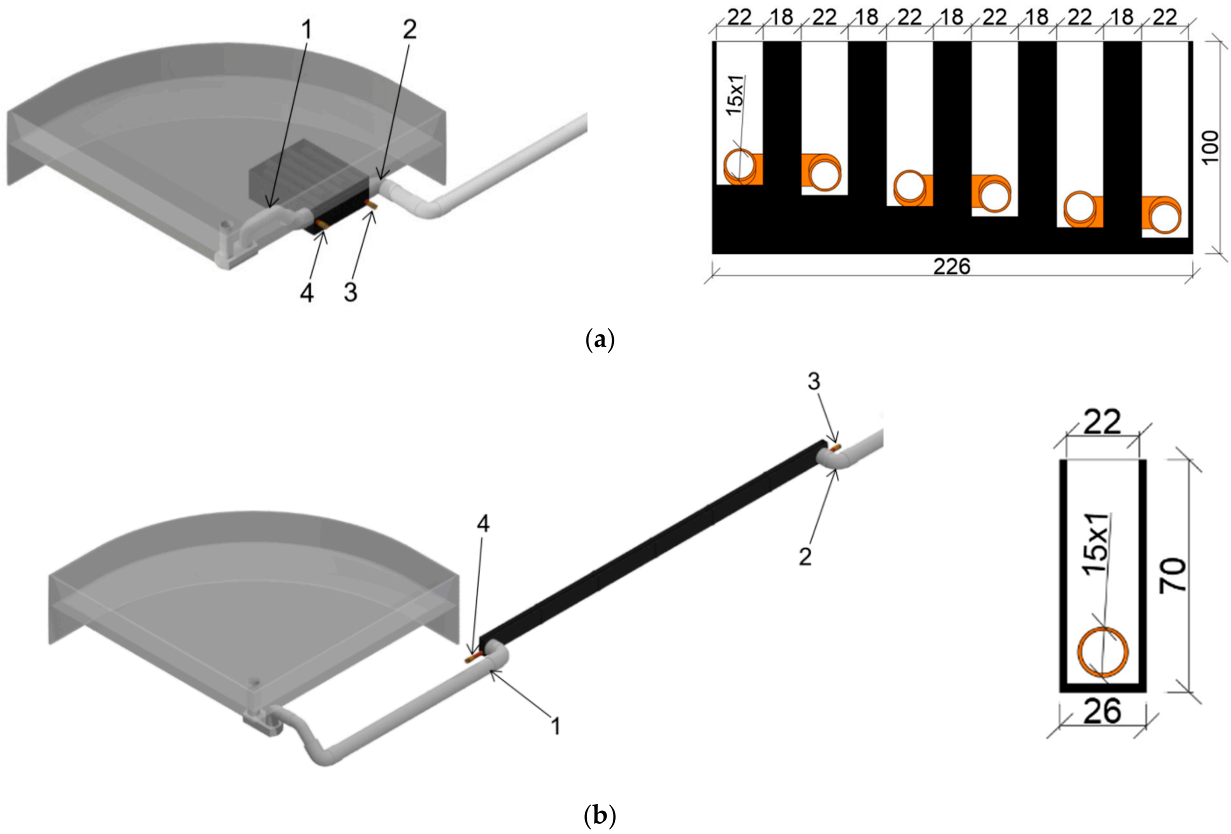


Figure 2. Location of the tested shower heat exchangers (1—drain water inlet; 2—drain water outlet; 3—cold water inlet; 4—preheated water outlet): (**a**) compact DWHR unit; (**b**) linear DWHR unit.

The tests were performed according to the procedure shown in Figure 3.

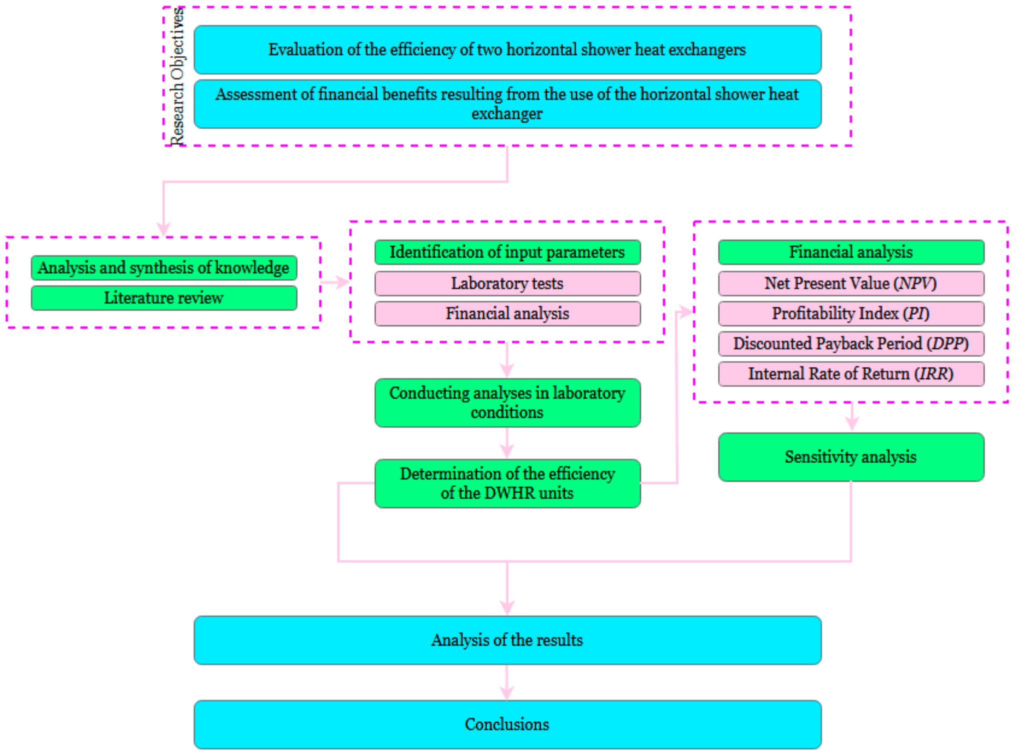


Figure 3. Research plan.

2.2. Assessment of the Efficiency of Shower Heat Exchangers

To determine the efficiency of the tested shower heat exchangers, the well-known Equation (1) was used, based on the results of the temperature measurements of the media at the input and output of the device.

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

where: ε—DWHR unit effectiveness; T_{dw}—drain water temperature at the inlet to the DWHR unit, °C; T_{cw}—cold water temperature, °C; T_{cdw}—drain water temperature at the outlet of the DWHR unit, °C.

The media temperatures at the input and output of the heat exchanger were measured at different flow rates of mixed water from the shower head. The influence of the temperature difference between the heat-transferring drain water and the heated water on the efficiency of the heat exchanger was also investigated. Table 1 shows the assumed values of the input parameters. A tolerance of ±0.1 °C was adopted.

Table 1. Assumed values of the input parameters for the efficiency analysis of shower heat exchangers.

Input Parameters	Unit	Value
Mixed water flow rate (q_{mw})	L/min	4, 5, 6, 7, 8, 9, 10
Mixed water temperature (T_{mw})	°C	40
Hot water temperature (T_{hw})	°C	55
Cold water temperature (T_{cw})	°C	10, 12, 14, 16, 18
Water temperature drop in the shower (ΔT_s) [26]	°C	5
Drain water temperature (T_{dw})	°C	35
Indoor air temperature (T_i)	°C	24
Linear DWHR unit bottom slope (i)	%	0, 0.5, 1, 2, 3, 4, 6

The Simex MultiCon CMC-144 data recorder was used to record and control the output parameters during the experimental tests. Temperatures of water and drain water were measured using Pt500 resistive temperature sensors. The measurement of the media flow rates was carried out with the use of Sharky 473 ultrasonic flow meters. The accuracy of individual devices is specified in their data sheets.

2.3. Financial Analysis of the Compact Shower Heat Exchanger Application

An analysis of the profitability of the compact shower heat exchanger was carried out under different operating conditions based on the results of net present value (NPV) and profitability index (PI) calculations. The discounted payback period (DPP) and the internal rate of return (IRR) were also determined. These indices are often used to evaluate projects in the broadly defined energy sector [49,50].

The net present value is an indicator that measures the difference between the discounted income of a project and the discounted expenses incurred for that project [51]. In the case of drain water heat recovery systems, revenues are the savings achieved by reducing energy consumption for domestic hot water heating. The expenses are the costs of purchasing and installing the shower heat exchanger. The investment can only be considered profitable if NPV > 0. The NPV can be determined from Equation (2).

$$\mathrm{NPV} = -\mathrm{INV} + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t}\,, \tag{2}$$

where: NPV—net present value, €; INV—initial investment, €; CF_t—financial savings forecast for a given year t, €; r—discount rate, -; n—number of years of system operation, years.

Another of the indicators used, the profitability index, can be defined as the ratio of the present value of future financial flows to initial investment outlays [51]. The project can be considered profitable when PI > 1. The higher the value of PI, which can be determined based on Equation (3), the higher the financial benefits achieved.

$$\mathrm{PI} = \frac{\sum_{t=1}^{n} \frac{CF_t}{(1+r)^t}}{\mathrm{INV}} = \frac{\mathrm{NPV} + \mathrm{INV}}{\mathrm{INV}}\,, \tag{3}$$

where: PI—profitability index, -.

Based on the calculated present value of future financial flows and the known amount of investment outlays, the discounted payback period was also determined. This is the number of years after which the projected discounted income from the project will exceed the investment outlays [52]. The length of the discounted payback period can be determined when the project turns out to be profitable. Equation (4) is used for this purpose.

$$\mathrm{DPP} = Y + \frac{|\mathrm{NPV}_Y| \cdot (1+r)^{Y+1}}{CF_{Y+1}}\,, \tag{4}$$

where: DPP—discounted payback period, years; Y—number of complete years before full payback; $|\mathrm{NPV}_Y|$—unrecovered expenditures at the end of year Y, €; CF_{Y+1}—financial savings forecast for a year (Y+1), €.

The internal rate of return is the value of the discount rate at which the present value of future net cash flows from the investment project compensates the initial investment outlays [51]. In other words, if r = IRR, NPV = 0. The approximate value of IRR can be determined from Equation (5).

$$\mathrm{IRR} = r_1 + \frac{\mathrm{NPV}_1 \cdot (r_2 - r_1)}{\mathrm{NPV}_1 + |\mathrm{NPV}_2|}\,, \tag{5}$$

where: IRR—internal rate of return, %; r_1—the discount rate for which NPV > 0 (close to zero), %; r_2—the discount rate for which NPV < 0 (close to zero), %; NPV_1—the net present value determined on the basis of r_1; NPV_2—the net present value determined on the basis of r_2.

The analysis was performed for a compact shower heat exchanger dedicated for use below the shower tray. This is due to the fact that the application of this solution allows for greater energy savings and its installation is cheaper and easier. To determine the trend of changes in investment profitability when changing the water flow rate from the shower head (q_{mw}), the analysis was carried out for three values of q_{mw}. The assumed values correspond to the minimum, average, and maximum flow rates among those for which laboratory tests were conducted. The assumed minimum value of the mixed water flow rate (q_{mw} = 4 L/min) is slightly lower than the flow rate characteristic of the water-saving shower heads and faucets with flow limiters, where $q_{mw} \geq 5$ L/min. However, measurements carried out in dwellings of multi-story buildings have shown that the water pressure in the system is sometimes insufficient to ensure the flow rate corresponding to the characteristics of the shower head. Conducting the analysis assuming a maximum mixed water flow rate would then overestimate the projected financial savings. This can lead to wrong investment decisions.

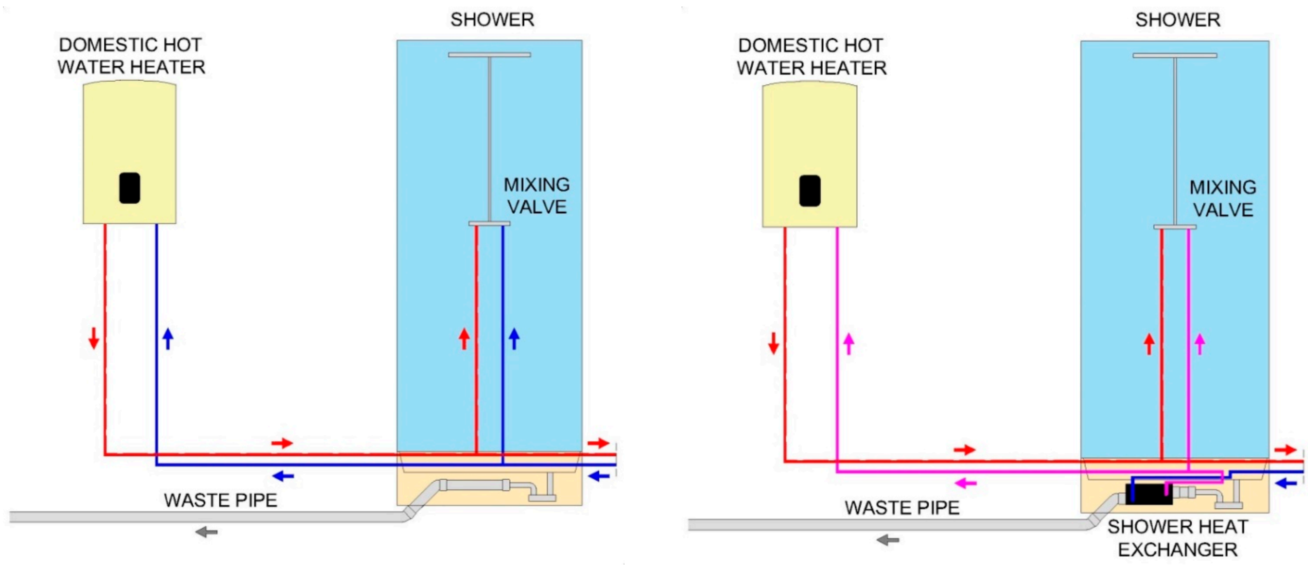
The value of future cash flows was determined on the basis of current electricity and natural gas prices in Poland. Calculations were carried out at the euro exchange rate of 1 EUR = 4.68 PLN. The energy consumption for showering was estimated based on the water temperatures assumed in Section 2.2 using the methodology described by the authors in [53]. Considering the results of previous studies [53], it was assumed that the average annual temperature of cold water supplied to the shower heat exchanger was 14 °C. The determination of the amount of hot water consumed was possible by using the heat balance equation. The analysis was carried out for a family of four under the assumption that each person takes a shower once a day. The length of the shower can vary over a wide range depending on individual user preferences. However, a survey conducted by Shan et al. [54]

showed that for more than 60% of Polish respondents, the shower length does not exceed 10 min. Approximately 90% of them, in turn, declared that they use a shower for no more than 15 min. Therefore, calculations were performed for different average shower lengths of 5, 10, and 15 min. The values of the other parameters used to calculate potential energy savings are summarized in Table 2. To determine the NPV, PI, IRR, and DPP, it was also necessary to assume the lifetime and the value of the discount rate. The number of years of operation of the system was assumed to be equal to 10 due to the fact that this is the average warranty period granted by manufacturers for shower heat exchangers. The value of the discount rate was assumed based on the data in the literature. The European Commission guidelines, in force until 2020, suggested the use of a 4% discount rate [55]. This approach is still reflected in the analyses conducted in the energy sector [56]. However, the current European Commission vademecum [57] states that the value of the discount rate should be adopted on the basis of national guidelines and/or adequately to the sector. No such guidelines are available in Poland. Consequently, the evaluation of the financial efficiency of the investment is often made with an a priori assumption of a discount rate of 5% [58]. However, Foltyn-Zarychta et al. [58] suggest that a discount rate of 4.72% or 4.39% should be used for the energy sector in Poland. On the other hand, an analysis conducted by the Organization for Economic Co-operation and Development (OECD) indicates that the average value of the discount rate adopted in projects in the energy sector is 4.78% [59]. Considering the slight differences between the above values, it was decided to perform the analysis assuming the average value given in [59].

Table 2. Assumed values of the input parameters for the profitability analysis of the compact shower heat exchanger application.

Input Parameters	Unit	Value
Shower length (l)	min	5, 10, 15
Mixed water flow rate (q_{mw})	L/min	4, 7, 10
Cold water temperature (T_{cw})	°C	14
Electric hot water heater efficiency (η_{el})	%	98
Gas hot water heater efficiency (η_{g})	%	80
Electricity price (EP)	€/kWh	0.160
Natural gas price (GP)	€/kWh	0.053
Water density (ρ) [60]	kg/m^3	989.14–996.51
Specific heat of water (c_p) [61]	J/(kg·K)	4181–4183
Discount rate [59]	%	4.78
The number of years of system operation (n)	years	10

The investment outlays related to the implementation of the shower heat exchanger result from the cost of purchasing the heat exchanger and the costs related to the reconstruction of the plumbing system. The costs of installation works are affected by the location of water and sewage piping, the location of the domestic hot water heater, and the method of installing the drain water heat recovery system. Particularly favorable conditions in terms of minimizing the costs of implementing a heat recovery system are found in multi-family buildings. In multi-family buildings, the distance between the hot water heater and the shower is small. In such conditions, installation works are limited to installing a shower heat exchanger between the shower tray siphon and the waste pipe and making a bypass to feed cold water into the DWHR unit. In favorable circumstances, the cold water supply lines to the hot water heater and the mixing valve do not need to be reconstructed and are used to transport the preheated water (Figure 4). This reduces costs connected with dismantling and reconstruction of the elements of the walls and floors in existing buildings. The profitability analysis of the heat exchanger application was carried out for such conditions.



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

Figure 4. Shower installation diagram: (**a**) without the compact DWHR unit; (**b**) with the compact DWHR unit.

The costs resulting from the implementation of the compact shower heat exchanger are summarized in Table 3.

Table 3. Investment outlays needed to implement the compact shower heat exchanger under Polish conditions.

Type of Expenditure	Expenditure €
Dismantling and reconstruction of wall elements	130
Modification of existing plumbing installation	20
Purchase of the shower heat exchanger	170
Total investment outlays (IO)	320

2.4. Sensitivity Analysis

The values of the variables determining the NPV may differ from those assumed in the project profitability assessment. To determine the impact of these changes on the obtained results of the calculation of the net present value, it is recommended to perform a sensitivity analysis [52].

Due to the wide scope of the analysis, the paper presents results for the case when the mixed water flow rate q_{mw} = 7 L/min and the shower length l = 5 min. This combination of parameters was chosen because it corresponds to the statistical water consumption for showering in Poland [62]. As part of the analysis, the impact of modifying the independent variables, i.e., the amount of investment outlays and energy prices, on the calculation results was assessed. For this purpose, a two-factor sensitivity analysis was used [49]. In addition, the risk of lowering projected savings in case of a change in the value of the discount rate (r) was also examined. The impact of changes in this parameter (r) was analyzed for its value ranging from 0% to 15%, assuming changes and no changes in energy prices. Negative values were not considered due to the negligible probability of their occurrence. Considering that in the case of cooperation of the compact DWHR unit with the gas hot water heater, the undertaking proved to be unprofitable at the assumed water consumption, the analysis was carried out for the variant of cooperation of the DWHR unit with the electric hot water heater, for which NPV = 98 EUR.

3. Results and Discussion

3.1. Evaluation of the Efficiency of the Compact and Linear Shower Heat Exchanger

The results of the tests on the evaluation of the efficiency (ε) of the linear and the compact heat exchangers at different values of cold water temperature are illustrated in Figures 5–9. In the case of the linear shower heat exchanger, the figures show the results for various slopes of its bottom. The presented values of the parameter ε are the median of three measuring series with a duration of 10 min each. To present the uncertainty of the measurements performed, Figure 10 additionally shows box–whisker charts for exemplary water and drain water flow rates through the compact DWHR unit and the average temperature of cold water (T_{cw} = 14 °C). The results obtained in each of the measurement series are presented separately.

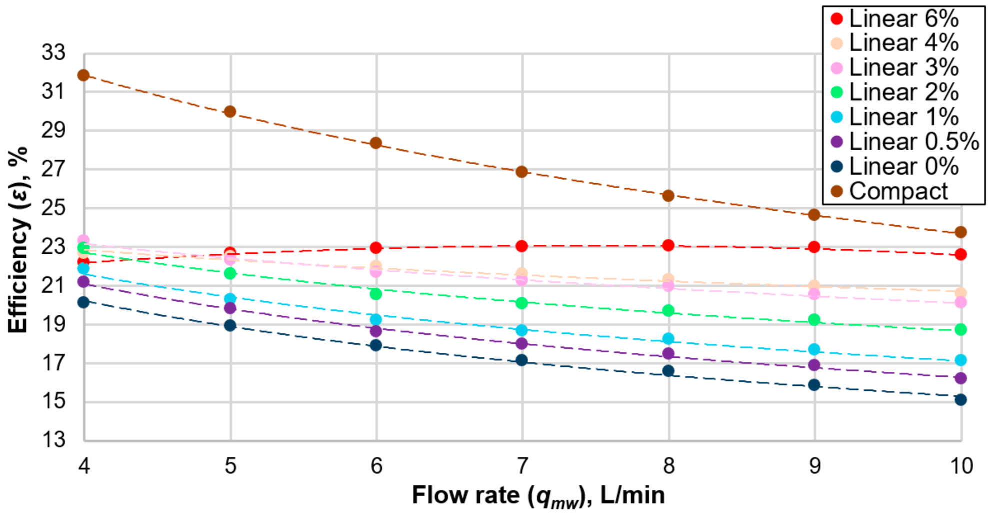


Figure 5. Efficiency of the shower heat exchangers determined for T_{cw} = 10 °C.

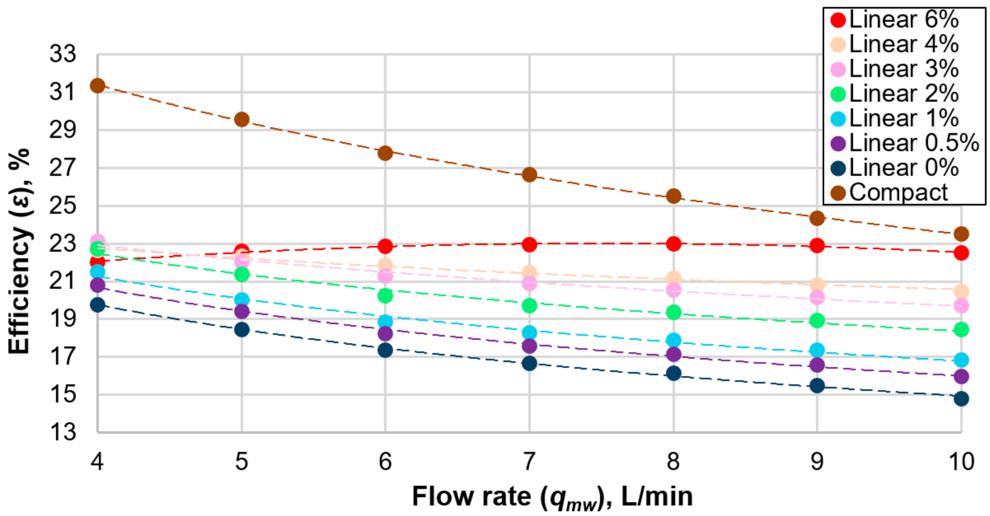


Figure 6. Efficiency of the shower heat exchangers determined for T_{cw} = 12 °C.

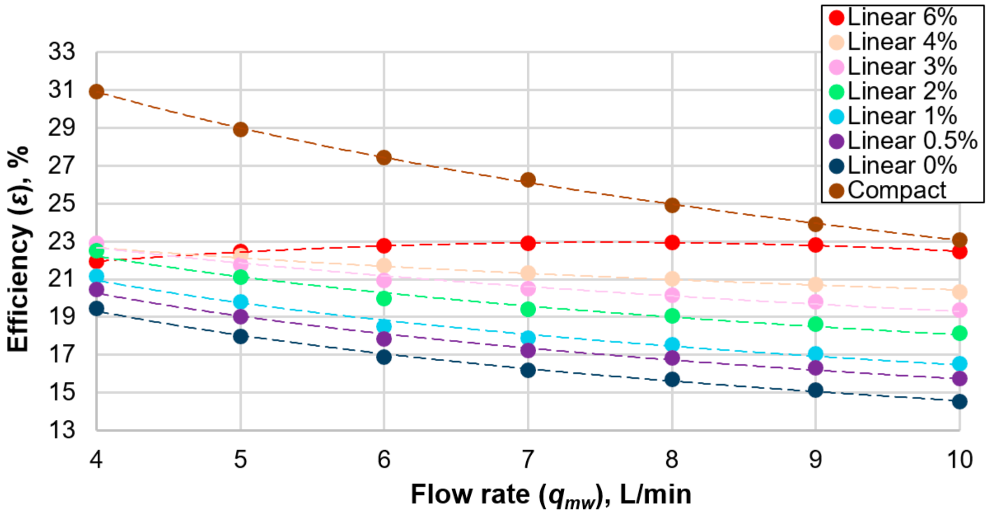


Figure 7. Efficiency of the shower heat exchangers determined for T_{cw} = 14 °C.

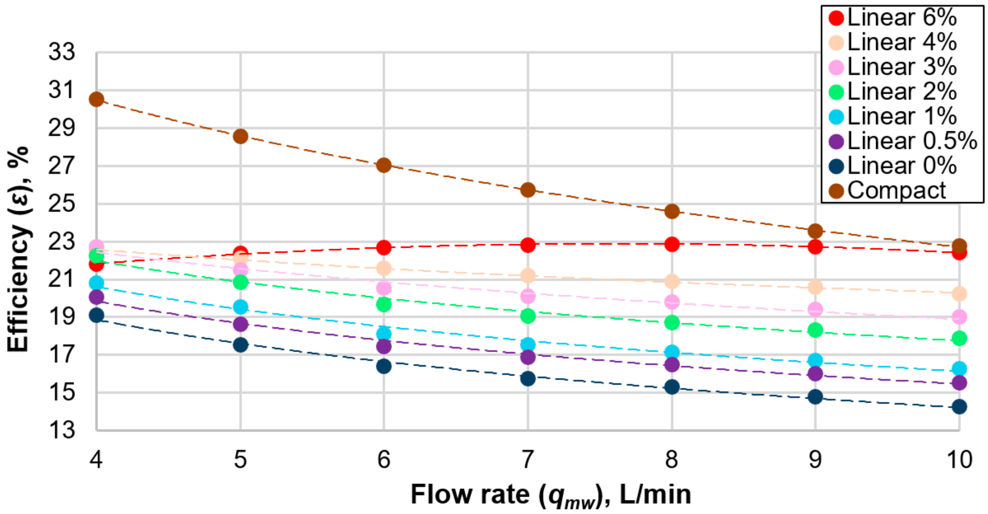


Figure 8. Efficiency of the shower heat exchangers determined for T_{cw} = 16 °C.

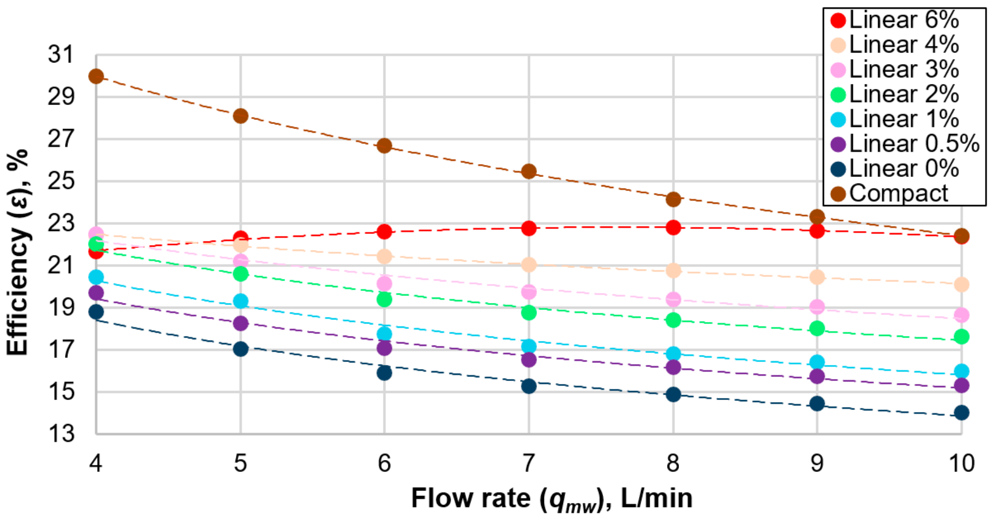


Figure 9. Efficiency of the shower heat exchangers determined for T_{cw} = 18 °C.

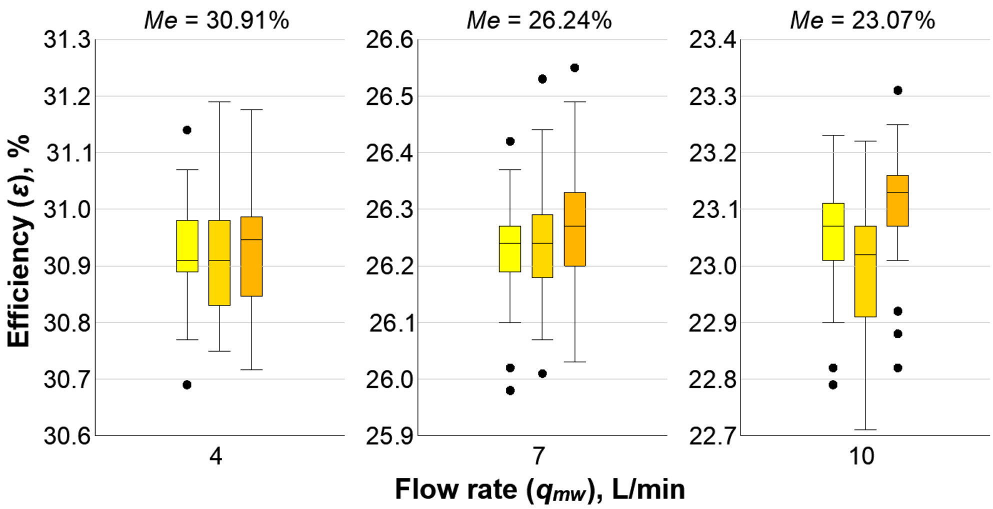


Figure 10. Efficiency of the compact shower heat exchanger determined for T_{cw} = 14 °C during three measurement series (*Me*—median of efficiency from three measurement series; •—outliers).

Research has shown that the temperature of cold water (T_{cw}), and therefore also the temperature difference between hot and cold water, has a strong influence on the efficiency (ε) of the linear DWHR unit. Each decrease in the temperature of the cold water (T_{cw}) resulted in an increase in the value of the parameter ε. For the lowest assumed cold water temperature (T_{cw} = 10 °C), the parameter ε varies in the range of 15.08% to 23.30%. On the other hand, at T_{cw} = 18 °C, the efficiency (ε) is in the range of 14.01% to 22.80%. This connection is the same as for other types of heat exchangers. Murr et al. [27] have shown that the highest energy recovery potential from drain water occurs at the lowest cold water temperatures using the example of a coiled heat exchanger. Vavřička et al. [26] confirmed that a decrease in the temperature difference between heated water and drain water results in a decrease in the efficiency of the plate shower heat exchanger. The study also showed that the influence of the temperature of the cold water on the efficiency of the DWHR unit tested is the smallest when the unit is installed with the maximum slope (i = 6%).

The impact of the bottom slope (i) of the linear DWHR unit and the water and drain water flow rate on the unit efficiency is variable and depends on the adopted combination of the other input parameters. In most cases, increasing the bottom slope (i) increases the efficiency (ε) of the linear shower heat exchanger. The lack of this dependence was observed only at the lowest flow rate (q_{mw} = 4 L/min). Under such conditions, the conduit transporting heated water is only partially immersed in warm drain water. As a consequence, the heat transfer surface is reduced. The highest efficiency (ε) at a flow rate of q_{mw} = 4 L/min was observed each time with a slope i = 3%, regardless of the temperature of the cold water (T_{cw}).

The research also showed that decreasing the flow rate of water and drain water through the DWHR unit (q_{mw}) increases the efficiency (ε) of the linear shower heat exchanger. This confirms the trend that has also been observed for falling-film drain water heat recovery systems [63]. This influence is the greater the smaller the bottom slope (i) of the device is. For example, with a bottom slope of i = 0%, the difference in the value of ε determined for q_{mw} = 4 L/min and q_{mw} = 10 L/min is approximately 4.90 percentage points. Installing a DWHR unit with a slope i = 4% generates, in this case, a difference in efficiency (ε) of 3.5 percentage points. The observed dependence does not occur when the linear DWHR unit is installed with the maximum slope (i = 6%). In this situation, the linear shower heat exchanger achieves the highest efficiency (ε) at the mixed water flow rate of q_{mw} = 8 L/min, regardless of the temperature of the cold water entering the DWHR unit.

Furthermore, as the flow rate of both media through the linear DWHR unit (q_{mw}) decreases, a decrease in the range of efficiency (ε) dependent on the bottom slope (i) is observed. At a flow rate of q_{mw} = 4 L/min, the parameter ε is in the range of 18.80% to

23.30% (Δε = 4.50 percentage points). When q_{mw} = 10 L/min, the parameter ε takes values from 14.01% to 22.56% (Δε = 8.55 percentage points).

Figures 5–9 also present the results for the compact DWHR unit. Their analysis showed that the efficiency (ε) of the compact shower heat exchanger increases with decreasing water and drain water flow through the unit (q_{mw}) and cold water temperature (T_{cw}). The difference in efficiency determined for flow rates q_{mw} = 4 L/min and q_{mw} = 10 L/min is in the range from 7.54 (for T_{cw} = 18 °C) to 8.08 percentage points (for T_{cw} = 10 °C). When comparing the ε values obtained for extreme temperatures of cold water (T_{cw} = 18 °C and T_{cw} = 10 °C) at defined flow rates of water and drain water through the DWHR unit (q_{mw}), differences were found from 1.29 to 1.85 percentage points.

The study also showed that the compact DWHR unit has a higher efficiency (ε) compared to its linear counterpart. It should be mentioned that the obtained increase in efficiency (ε) between the compact and linear shower heat exchanger is greater the smaller the media flow rate (q_{mw}). In the case of the highest flow rate value tested (q_{mw} = 10 L/min), this difference varies in the range from 5.04 (for T_{cw} = 10 °C) to 6.11 percentage points (for T_{cw} = 18 °C). On the other hand, at the flow rate q_{mw} = 4 L/min, the increase obtained in efficiency (ε) was in the range of 8.88 (for T_{cw} = 10 °C) to 9.78 percentage points (for T_{cw} = 18 °C). The research also shows that at a higher temperature of cold water (T_{cw}), the efficiency (ε) increase of the compact DWHR unit relative to its linear counterpart is slightly higher. Considering, in addition, that the spread of efficiency values is relatively small (Figure 10), it can be assumed that the compact shower heat exchanger provides stable operation during use.

In addition, the compact shower heat exchanger has several other advantages over the linear DWHR unit. The estimated price of both units on the Polish market is less than 200 EUR. The expenses for the reconstruction of the water supply installation are also similar for both shower heat exchangers. However, the costs related to the required reconstruction of the sewage installation in the existing facility differ significantly. In the case of the compact shower heat exchanger, no rebuilding of the sewage system is required; it is installed between the shower trap and the waste pipe. On the other hand, the installation of the linear heat exchanger requires interference with the waste pipe. In most cases, the necessary assembly works involve costly dismantling and reconstruction of wall and/or floor elements. The expenses to be incurred are influenced by the way in which the water and sewage pipes are routed and the standard of the bathroom. These costs can be in a wide range, and in many cases, exceed the estimated purchase cost of the shower heat exchanger. For this reason, a very important decision criterion when choosing the DWHR unit in existing buildings is the amount of investment required for the adaptation of the plumbing system.

3.2. Financial Analysis of the Application of the Compact Shower Heat Exchanger

Simulation calculations for different combinations of shower length (l) and mixed water flow rate (q_{mw}) from the shower head showed that both parameters have a significant influence on the profitability of the considered project. Table 4 presents results of NPV, PI, DPP, and IRR calculations, determined under the assumption of cooperation of the compact DWHR unit with the electric domestic hot water heater. The results clearly show that the project is already profitable with the water consumption for showering at the level of 35 L per person per day. For the combinations of input parameters considered, the net present value turned out to be negative (NPV = −39 EUR) only when q_{mw} = 4 L/min and the shower length l = 5 min. Doubling the shower length to 10 min while maintaining the same q_{mw} value resulted in an increase in NPV of more than 280 EUR. At l = 15 min, the NPV already exceeded 520 EUR and the discounted payback period was less than 40 months. It is also worth noting that at a water consumption for showering of 60 L per person per day, the profitability index exceeded 2.5, indicating that the projected savings clearly exceed the investment outlays. The internal rate of return, on the other hand, exceeds 30%. It is therefore more than six and a half times higher than the discount rate (r) used in the calculations. It also exceeds the minimum accepted rate of return assumed in analyses concerning energy investments. For example, Al-Sumaiti et al. [64] determined this value at 14%.

Table 4. Summary of the calculation results for an electric water heater.

Mixed Water Flow Rate (q_{mw})	Shower Length (l)	Net Present Value (NPV)	Profitability Index (PI)	Discounted Payback Period (DPP)	Internal Rate of Return (IRR)
L/min	min	€	-	years	%
4	5	−39	0.88	–	2.22
	10	243	1.76	5.11	18.34
	15	524	2.64	3.27	31.62
7	5	98	1.31	7.21	10.65
	10	516	2.61	3.31	31.25
	15	933	3.92	2.15	49.27
10	5	205	1.64	5.54	16.41
	10	729	3.28	2.59	40.62
	15	1254	4.92	1.69	62.52

When q_{mw} = 7 L/min, the project was found to be profitable even for short shower lengths, with NPVs ranging from 98 EUR (l = 5 min) to more than 330 EUR (l = 15 min). For conventional shower faucets (q_{mw} = 10 L/min), the NPV increases by approximately 110% and almost 35%, respectively. The profitability index increases by around 25%, and the discounted payback period is reduced by between 5.5 and 20 months depending on the shower length. As a result, with water consumption for showering at the level of 150 L per person per day, the investment should be returned after less than two years. This confirms the results of the analyses described in [20], according to which, under favorable conditions, the purchase of a shower heat exchanger can be returned after approximately two years. Also, the determined IRR values lead to the assumption that the application of the compact shower heat exchanger cooperating with the electric hot water heater will allow one to achieve significant financial savings. Only when q_{mw} = 7 L/min and l = 5 min is the calculated IRR value is quite low, which creates the need for additional analysis of this variant. In the case of other combinations of q_{mw} and l, the IRR values determined clearly indicate the profitability of the project.

For comparison, Table 5 presents the results of financial efficiency indicator calculations, determined assuming the cooperation of the compact DWHR unit with a gas hot water heater. The results of the analysis are no longer as favorable as when the energy source is supplied with electricity. This is due to the lower prices of natural gas compared to electricity. This is disadvantageous, as many more people in Poland heat water with devices powered by natural gas than electricity [44].

However, it should be noted that with a shower length of 10 min, the project has only proved financially unviable with a water flow rate of q_{mw} of 4 L/min. If the installation is functioning properly and the installation pressure is sufficient, it can be assumed that the project will be profitable. However, the NPV and PI values are relatively low. In the most favorable case, when one person consumes 150 L of water per day for showering, the NPV was less than 320 EUR. When the compact DWHR unit is combined with an electric water heater, higher values were obtained with a water consumption of 60 L per person per day. Only in the most favorable case IRR > 20%. With lower water consumption, results of a few or several percent were obtained. When NPV < 0 EUR, negative IRR values were obtained. Therefore, in the current situation on the Polish and global markets, these variants should be considered unprofitable. The results of the calculations indicate the need to improve the tested design of the compact shower heat exchanger to ensure the profitability of its use even with low water consumption for showering. However, it should be noted that the analyses conducted in Poland concerning the cooperation of the highly efficient vertical DWHR unit with a gas hot water heater showed that the application of this solution is financially profitable only when the total daily water consumption for showering significantly exceeds 200 L [29]. Therefore, considering the ease of installation of the compact DWHR unit and its relatively low price, it can be assumed that this solution has potential. Especially with similar water consumption for showering, the discounted payback period is shorter when using the tested compact DWHR unit. In addition, lower investment outlays compared to the vertical heat exchanger reduce the investment risk. Another study on the use of the vertical DWHR unit [65] showed, in turn, that by installing such a device, annual savings of 13 EUR per person can be expected, assuming a shower length of 10 min per day. For comparison, the use of the compact DWHR unit for the same shower length results in annual savings of 7.5–14 EUR per person depending on the mixed water flow rate from the shower head. The analysis by Stec et al. [34] also showed that the cooperation of the vertical DWHR unit with a gas combi boiler allows a family of four to reduce gas bills by more than 1000 EUR compared to a situation where the installation does not use a renewable energy source. However, this analysis was conducted assuming a 20-year system lifetime, which is far too long in relation to the lifetime of the domestic hot water system components. It should also be noted that the above-mentioned studies were carried out with the assumption of a cold water temperature of 10 °C. This significantly increases the projected financial savings in relation to the real values that can be expected from the use of the vertical shower heat exchanger cooperating with a natural gas device.

Table 5. Summary of the calculation results for a gas water heater.

Mixed Water Flow Rate (q_{mw})	Shower Length (l)	Net Present Value (NPV)	Profitability Index (PI)	Discounted Payback Period (DPP)	Internal Rate of Return (IRR)
L/min	min	€	-	years	%
4	5	−205	0.36	–	−12.10
	10	−90	0.72	–	−1.49
	15	25	1.08	9.11	6.32
7	5	−149	0.53	–	−6.39
	10	21	1.07	9.23	6.12
	15	192	1.60	5.69	15.74
10	5	−106	0.67	–	−2.70
	10	108	1.34	7.00	11.24
	15	323	2.01	4.41	22.29

The study also analyzed the impact of the system's lifetime on financial savings. This analysis was based on the NPV values determined for the system equipped with an electric water heater. Figure 11 shows the NPV ranges calculated assuming different shower lengths and different system lifetimes ranging from 1 to 10 years. From the figure, it is possible to identify the approximate payback period and net profit at other shower lengths (l) than those indicated in Tables 4 and 5. It is also possible to estimate how the projected profitability of the project will change if the lifetime of the shower heat exchanger is shortened.

The analysis confirmed that the amount of tap water used for showers has a significant impact on the financial benefits achieved and the discounted payback period of the investment. In each of the cases considered, the impact of the analysis period on the NPV is greater the longer the showers are. With low water consumption (q_{mw} = 4 L/min, l = 5 min), reducing the lifetime from 10 to, for example, 4 years results in a reduction in NPV of almost 200 EUR. Increasing the length of the shower by three times in this case results in a reduction in NPV of over 450 EUR to NPV = 65 EUR. When q_{mw} = 10 L/min, there is a reduction in financial savings of almost 300 EUR and approximately 850 EUR for l = 5 min and l = 15 min, respectively. Therefore, it can be seen that as the mixed water flow rate

(q_{mw}) increases, so does the potential gain from prolonging the shower, even though the efficiency (ε) of the compact shower heat exchanger is considerably lower in this situation.

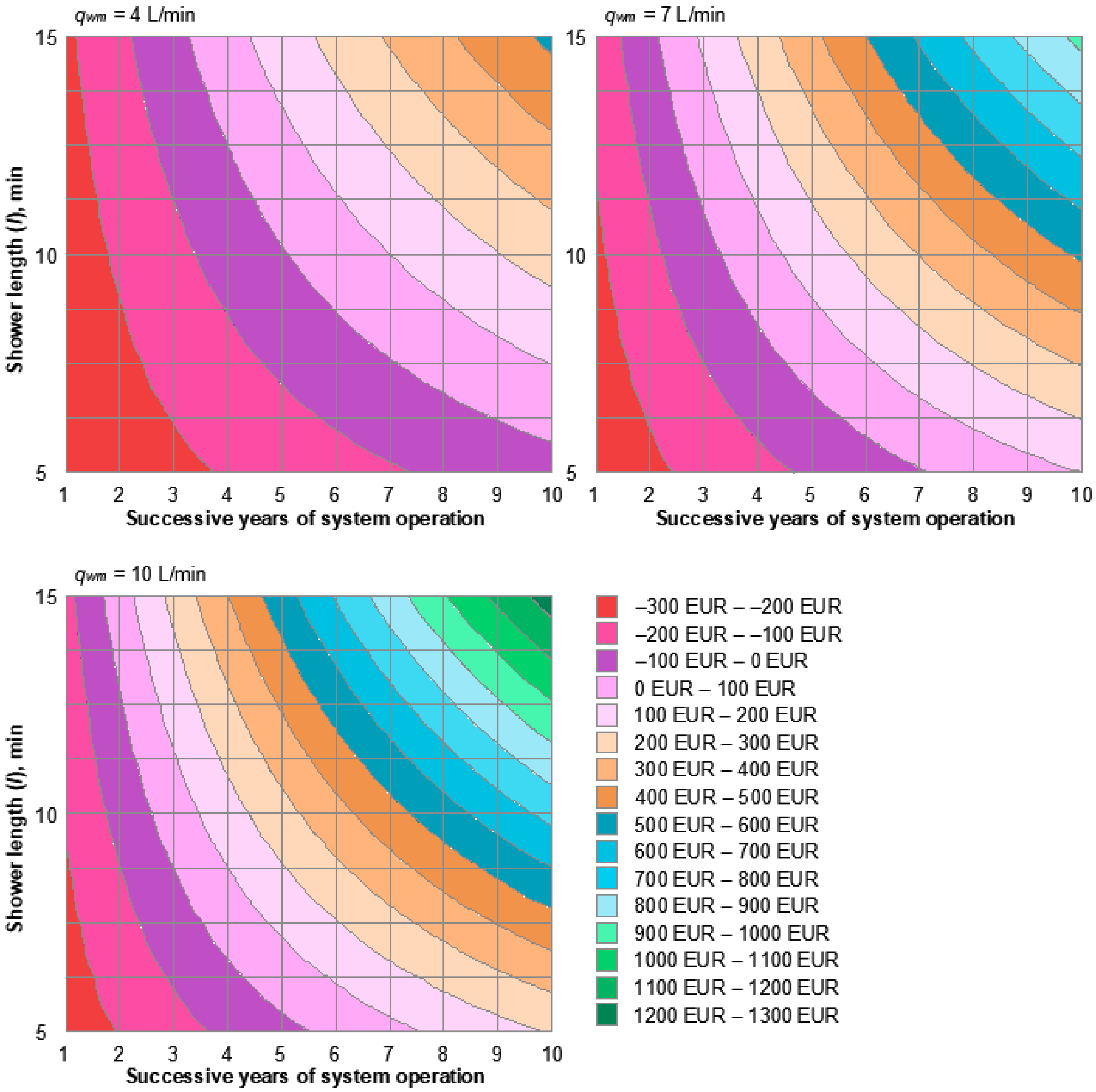


Figure 11. Net Present Value (NPV) calculation results depending on the shower length and system lifetime.

The presented results also prove that in the case of the longest showers, the differences in the determined DPP values are not significant. The influence of the shower length (l) is in this case is smaller the higher the mixed water flow (q_{mw}). For example, with q_{mw} = 10 L/min, shortening the 15 min showers by 2.5 min results in an increase in the discounted payback period of only 4 months. In turn, shortening 7.5 min showers by 2.5 min extends DPP by a full two years. If in the building a water-saving shower head is used with a flow rate of q_{mw} = 7 L/min, changing the shower length by 2.5 min would result in a slightly higher change in DPP. Shortening the shower length from l = 15 min to l = 12.5 min would extend the discounted payback period by 5.5 months. On the other hand, changing the shower length from l = 7.5 min to l = 5 min would extend the DPP by more than 2.5 years. Therefore, installing the compact shower heat exchanger is particularly beneficial in the case of conventional shower heads with high flow rates q_{mw}. Saving water by changing the length of the shower or even changing the number of users will not drastically extend the payback period in such a situation.

3.3. Sensitivity Analysis

According to the methodology described in Section 2.4, the evaluation of the financial efficiency of the compact shower heat exchanger was extended with a sensitivity analysis. This analysis was carried out assuming a water consumption for showering of 35 L per person per day and the cooperation of the compact shower heat exchanger with an electric hot water heater.

Figure 12 shows the results of a two-factor sensitivity analysis carried out to assess the sensitivity of the investment to changes in investment outlays (C_{IO}) and energy prices (C_{EP}). The pink line shows combinations of the above parameters for which NPV = 0 EUR, assuming a discount rate of r = 4.78%. The green area above the pink line represents the combinations of percentage changes in investment outlays and energy prices for which the NPV > 0 EUR. The blue color indicates the area where the occurrence of a given combination of C_{IO} and C_{EP} will reduce the NPV below zero and the project will become unprofitable. As mentioned in Section 2, the discount rate is generally assumed to be in the range of r = 4% to r = 5%. Therefore, for comparison purposes, the graph also shows lines depicting combinations of C_{IO} and C_{EP} at which NPV = 0 EUR, assuming the above values of r.

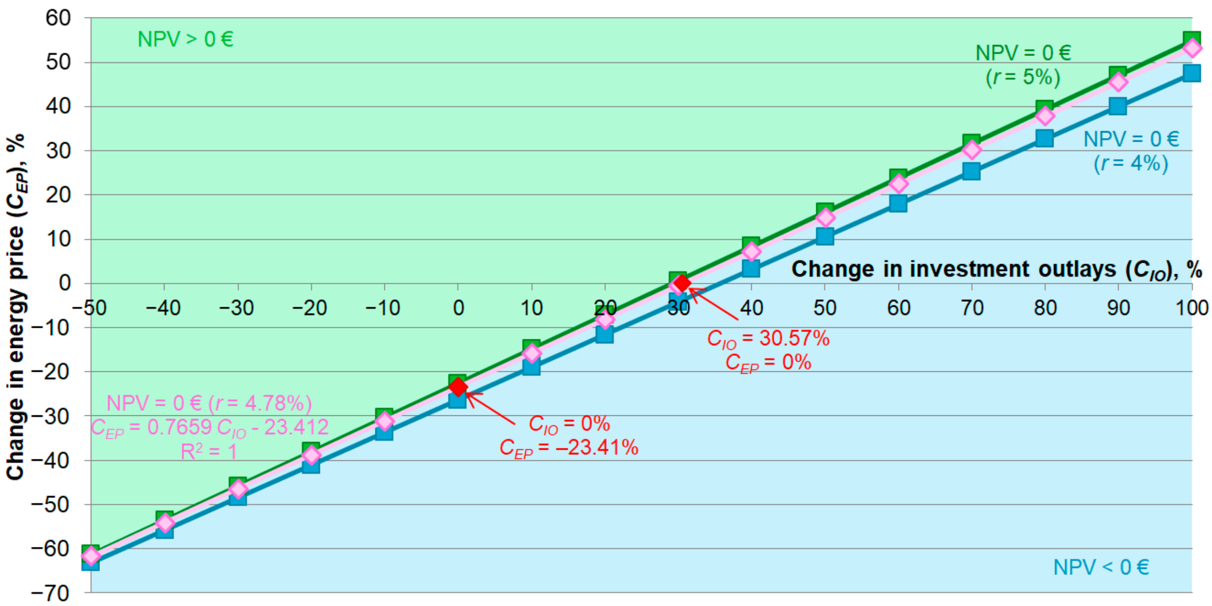


Figure 12. The results of the two-factor sensitivity analysis on the percentage changes in energy prices and investment outlays.

Figure 12 also shows the relative safety margins for energy prices and investment outlays. Under the given operating conditions of the DWHR unit, investment outlays can increase by up to 30.57% to around 418 EUR while maintaining constant electricity prices (EP). Electricity prices, in turn, can decrease by up to 23.41% to keep the project viable. This means that EP is reduced to approximately 12 cents per kWh. However, data on energy prices for household consumers [24] indicate a gradual increase in electricity prices. Forecasts for the following years also confirm this trend [66]. This also makes it possible to predict an increase in the estimated financial savings in the coming years compared to the baseline values. For example, in 2022, an increase in electricity prices for household consumers in Poland of almost 25% was reported compared to the previous year. In the event of an increase in energy prices, even an increase in the price of the shower heat exchanger compared to the assumed value would not necessarily result in a reduction of the NPV. For example, a 50% increase in IO would require a 14.88% increase in energy prices to keep the project viable. Considering that the baseline NPV is 98 EUR, an increase in energy prices of approximately 39% would ensure that the NPV remains unchanged in this case. Assuming the discount rate values of r = 4% and r = 5%, it would be 31% and 40%, respectively.

Figure 13 illustrates how projected financial savings (FS) will change if the value of the discount rate changes. The green color indicates the range of r values for which the project will remain profitable despite a change in the value of the discount factor over time. Pink indicates the value of r corresponding to the internal rate of return (IRR) at which NPV = 0 EUR. The blue color reflects the values of the discount rate at which the project becomes unprofitable. A decrease in the value of r in relation to the baseline value results in an increase in the projected savings (FS) and, consequently, also in the NPV. On the other hand, an increase in the discount rate results in a worsening of the profitability of the project. For example, an increase in r to 8% would result in a decrease in FS by more than 14%. As a consequence, the NPV would be reduced by approximately 60% and the profitability index would be only 1.12. The discounted payback period would then exceed 8 years. The project would remain viable, but the potential benefits of the project would be small. In the event of a further increase in the discount rate to the level of approximately 12%, the investment would become unprofitable and the DPP would exceed the technical life of the DWHR unit. However, it should be noted that such high values of r are very rarely considered in financial analyses. Therefore, it can be assumed that the probability of their occurrence is low.

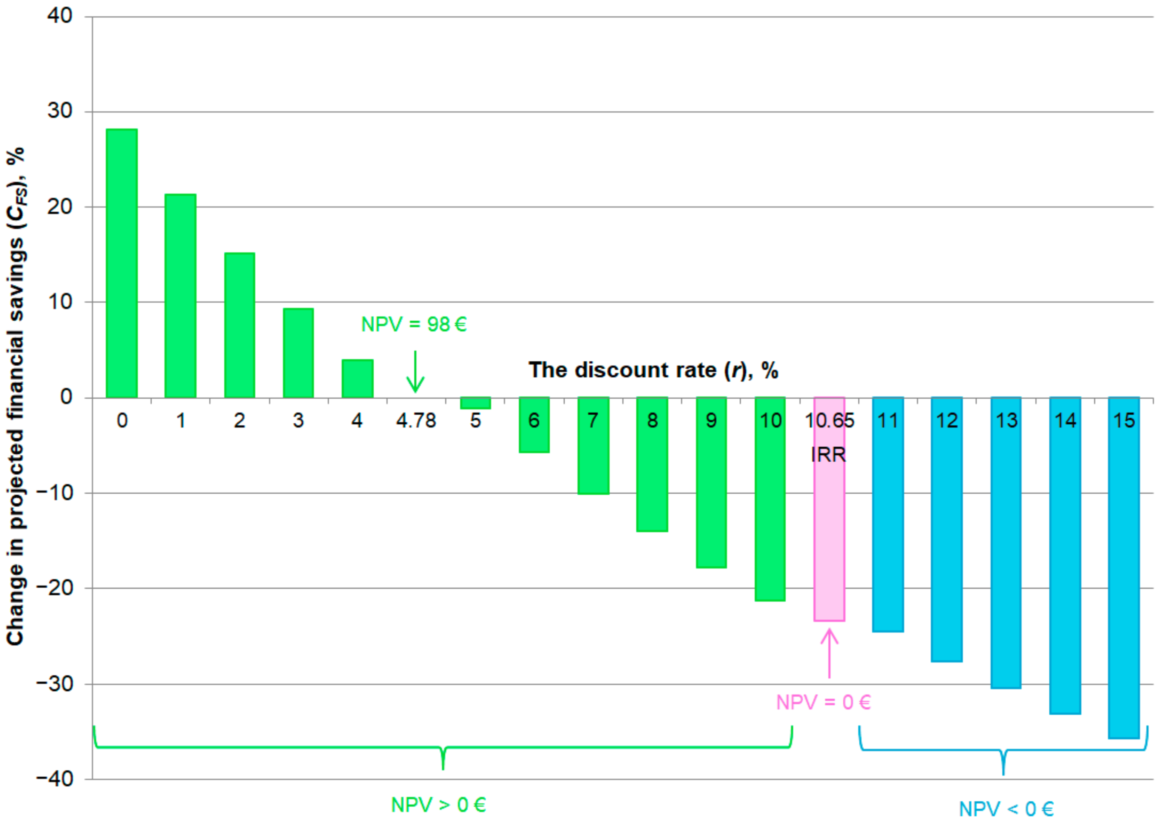


Figure 13. Impact of the discount rate on projected financial savings.

As part of the research, a two-factor sensitivity analysis was also performed with regard to the percentage changes in energy prices (C_{EP}) and the discount rate (r). Its results are presented in Figure 14. As in Figure 12, the pink color indicates combinations of C_{EP} and r for which NPV = 0 EUR. In the case of the analyzed variables, however, the determined relationship is no longer rectilinear, but takes the shape of a parabola. The green area above the pink line includes combinations of percentage changes in energy prices and the discount rate where NPV > 0 EUR. The blue color marks the area where the occurrence of a given combination of C_{EP} and r will result in a decrease in the NPV value below zero and the project will become unprofitable.

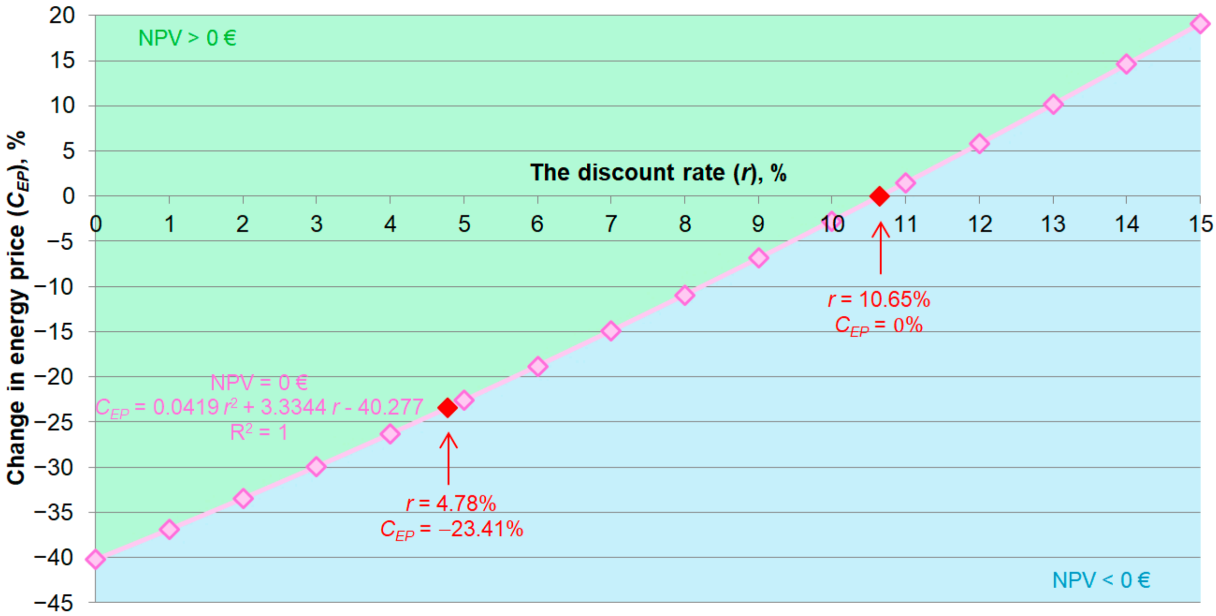


Figure 14. The results of the two-factor sensitivity analysis on the percentage changes in energy prices and the discount rate.

In Figure 14 it can be seen that as the discount rate increases, the energy price that guarantees the profitability of the project also increases. With the assumed value of r = 4.78%, the electricity price can decrease by a maximum of 23.41%, which confirms the results presented in Figure 12. If r = IRR = 10.65%, lowering the energy price would result in lowering the NPV value below zero. As mentioned above, energy prices are expected to increase in the following years, so the risk of failure is low in this case. With an increase in energy price of approximately 19%, the installation of the compact shower heat exchanger would remain profitable even at r = 15%. Therefore, it can be assumed that the risk of failure due to a change in r or EP is negligible. However, the value of these parameters has a significant influence on financial benefits.

The sensitivity analysis showed that among the variables examined, the amount of investment outlays has the greatest impact on the profitability of the project. It is mainly determined by the cost of reconstruction of the plumbing in the building, as well as the cost of disassembly and reconstruction of the wall and/or floor elements. The risk of an increase in IO is therefore considerable in the case of facilities where the shower is located in a different room than the domestic hot water heater. When the two appliances are in close proximity, this risk is negligible.

Before making a final decision about the purchase and installation of the shower heat exchanger, the water consumption of the building should also be considered. This analysis applies to a situation where an average of 140 L per day is used for showering. In the case of showers with a higher mixed water flow rate, longer showers, a higher number of users of the installation, or a longer lifetime, the financial savings are expected to increase compared to the projected values. The use of electric hot water heaters is not a common practice in Poland. However, considering the European Union's plans to ban the use of gas boilers, an increase in the use of such devices can be expected in the near future. The need to increase the security of the country through the diversification of energy sources is also important [67]. Therefore, shower heat exchangers have significant potential that is currently untapped.

3.4. Possibilities and Challenges

Considering the research results, the decision to install the compact shower heat exchanger should always be taken after analyzing the costs of modification of the plumbing in the building, as well as the costs of disassembly and reconstruction of wall and/or floor elements. Research has shown that the compact heat exchanger has potential, and its use is technically and financially justifiable under certain operating conditions. This applies primarily to existing multi-family buildings, where there is no need to make significant modifications to the existing plumbing system. A favorable situation also occurs in the case of newly built facilities, as well as during a general renovation of the bathroom. In such a situation, the installation of the compact DWHR unit will not involve high costs of rebuilding the walls and/or floors in the bathroom.

In the case of existing single-family homes, the problem may be the significant distance between the shower and the domestic hot water heater, which is often located in a separate room. Installing the shower heat exchanger in the manner described in the article would in such a situation require significant investment outlays. However, the solution to this could be to supply the preheated water only to the shower mixing valve. It is true that the amount of energy that can be recovered in such a situation is lower, but the installation costs of the DWHR unit would be significantly reduced. In addition, optimizing the geometry of the compact DWHR unit, which is the next stage of the research, will increase its efficiency. This will create favorable circumstances in which the use of this shower heat exchanger can be financially viable, as well as contribute to a significant reduction in emissions of carbon dioxide and other pollutants into the atmosphere.

Technical and financial issues are the main, but not the only, determinants of the implementation of a given solution. The impact of device operation on the environment and the comfort of using the shower installation should also be considered. In the case of Poland, the problem may be the lack of knowledge about the possibility of using the energy carried by drain water and the lack of experience in the operation of DWHR systems. Especially since data from the literature [68] indicate a large share of human factor among the causes of failure of technical systems. For this reason, the widespread application of shower heat exchangers will not be possible without the introduction of appropriate incentives and motivators. These incentives should include, first, the implementation of programs that provide for the financing of the purchase of DWHR units and sponsorship of research aimed at increasing the efficiency of these devices. It is also important to promote shower heat exchangers as devices that increase the safety and comfort of showering. An earlier study by the authors of [44] showed that demographic issues do not have a significant impact on the preferences of residents regarding the use of a shower heat exchanger. For this reason, the application of these devices should be promoted among all social groups. Children and adolescents should also be remembered, because these groups are potential operators of drain water heat recovery systems in the future.

4. Conclusions

An analysis of the efficiency of two prototype shower heat exchangers led to the following conclusions:

- The use of both shower heat exchangers allows for the recovery of part of the energy deposited in the drain water. However, the efficiency of the compact DWHR unit is higher;
- An increase in the temperature of cold water reduces the efficiency of shower heat exchangers;
- The impact of the linear DWHR unit bottom slope and water and drain water flow rate on the efficiency of the unit is variable and depends on the values of the other parameters. In most cases, increasing the bottom slope increases the efficiency of the unit;
- In the case of the compact DWHR unit, an increase in media flow results in a reduction in efficiency.

The financial analysis of the compact DWHR unit application also allowed for the formulation of the following conclusions:

- The use of the compact DWHR unit is particularly advantageous when the hot water source in the building is an electric domestic hot water heater;
- The investment is particularly vulnerable to changes in investment outlays;
- The sensitivity to changes in electricity prices and the discount rate is moderate. The net present value of the investment is unlikely to fall below zero. However, these parameters have a significant impact on the level of financial savings achieved.

Further research will focus on improving the geometry of the compact shower heat exchanger to optimize its efficiency under given operating conditions. The cross-sectional area of the water and drain water sections, the slope of the bottom, and the length of the device will be modified. In the research described in this paper, only one device's geometry was analyzed, which is a limitation of the research. It is expected that the planned research will allow a further increase in the efficiency of the device and profitability of its use, even in the case of its cooperation with a gas hot water heater.

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: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Núñez-López, J.M.; Rubio-Castro, E.; El-Halwagi, M.M.; Ponce-Ortega, J.M. Optimal design of total integrated residential complexes involving water-energy-waste nexus. *Clean Technol. Environ. Policy* **2018**, *20*, 1061–1085. [CrossRef]
2. Gubernat, S.; Masłoń, A.; Czarnota, J.; Koszelnik, P. Reactive Materials in the Removal of Phosphorus Compounds from Wastewater—A Review. *Materials* **2020**, *13*, 3377. [CrossRef] [PubMed]
3. Cecconet, D.; Raček, J.; Callegari, A.; Hlavinek, P. Energy Recovery from Wastewater: A Study on Heating and Cooling of a Multipurpose Building with Sewage-Reclaimed Heat Energy. *Sustainability* **2020**, *12*, 116. [CrossRef]
4. Preisner, M.; Smol, M.; Neverova-Dziopak, E.; Kowalewski, Z. Application of Activated Sludge Model for phosphorus recovery potential simulation. *Desalin. Water Treat.* **2021**, *232*, 199–207. [CrossRef]
5. Cabling, L.P.B.; Kobayashi, Y.; Davies, E.G.R.; Ashbolt, N.J.; Liu, Y. Life Cycle Assessment of Community-Based Sewer Mining: Integrated Heat Recovery and Fit-For-Purpose Water Reuse. *Environments* **2020**, *7*, 36. [CrossRef]
6. Diaz-Elsayed, N.; Rezaei, N.; Ndiaye, A.; Zhang, Q. Trends in the environmental and economic sustainability of wastewater-based resource recovery: A review. *J. Clean. Prod.* **2020**, *265*, 121598. [CrossRef]
7. Nagpal, H.; Spriet, J.; Murali, M.K.; McNabola, A. Heat Recovery from Wastewater—A Review of Available Resource. *Water* **2021**, *13*, 1274. [CrossRef]
8. Sitzenfrei, R.; Hillebrand, S.; Rauch, W. Investigating the interactions of decentralized and centralized wastewater heat recovery systems. *Water Sci. Technol.* **2017**, *75*, 1243–1250. [CrossRef]
9. Salama, M.; Sharqawy, M.H. Experimental investigation of the performance of a falling-film drain water heat recovery system. *Appl. Therm. Eng.* **2020**, *179*, 115712. [CrossRef]
10. 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]
11. 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]
12. Hadengue, B.; Morgenroth, E.; Larsen, T.A.; Baldini, L. Performance and dynamics of active greywater heat recovery in buildings. *Appl. Energ.* **2022**, *305*, 117677. [CrossRef]
13. Farman Ali, S.; Gillich, A. Opportunities to decarbonize heat in the UK using Urban Wastewater Heat Recovery. *Build. Serv. Eng. Res. Technol.* **2021**, *42*, 715–732. [CrossRef]

14. Živković, M.; Ivezić, D. Utilizing sewage wastewater heat in district heating systems in Serbia: Effects on sustainability. *Clean. Technol. Environ. Policy* **2022**, *24*, 579–593. [CrossRef]
15. Wilson, M.P.; Worrall, F. The heat recovery potential of 'wastewater': A national analysis of sewage effluent discharge temperatures. *Environ. Sci. Water Res. Technol.* **2021**, *7*, 1760. [CrossRef]
16. Christodoulides, P.; Agathokleous, R.; Aresti, L.; Aresti, S.A.; Tassou, S.A.; Florides, G.A. Waste Heat Recovery Technologies Revisited with Emphasis on New Solutions, including Heat Pipes, and Case Studies. *Energies* **2022**, *15*, 384. [CrossRef]
17. Reiners, T.; Gross, M.; Altieri, L.; Wagner, H.J.; Bertsch, V. Heat Pump Efficiency in fifth Generation Ultra-Low Temperature District Heating Networks using a Wastewater Heat Source. *Energy* **2021**, *236*, 121318. [CrossRef]
18. Kannoh, S. Heat recovery from warm waste water at dyeing process by absorption heat pump. *J. Heat Recov. Syst.* **1982**, *2*, 443–451. [CrossRef]
19. 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]
20. Selimli, S.; Eljetlawi, I.A.M. The experimental study of thermal energy recovery from shower greywater. *Energy Source Part A* **2021**, *43*, 3032–3044. [CrossRef]
21. Vranay, F.; Vranayova, Z.; Lis, A. Building´s heat potential on resources in respect to CO_2 emissions and primary energy reduction (Case study). *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1203*, 022139. [CrossRef]
22. Svintsov, A.P.; Kharun, M.I.; Mukarzel, S.A. Valve head for water fittings with high regulatory capacity. *Mag. Civ. Eng.* **2015**, *58*, 8–18. [CrossRef]
23. Piotrowska, B.; Słyś, D.; Kordana-Obuch, S.; Pochwat, K. Critical Analysis of the Current State of Knowledge in the Field of Waste Heat Recovery in Sewage Systems. *Resources* **2020**, *9*, 72. [CrossRef]
24. Eurostat Statistics Explained. Electricity Price Statistics. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_household_consumers (accessed on 16 May 2022).
25. Gabor, T.; Dan, V.; Tiuc, A.E.; Sur, I.M.; Badila, I.N. Experimental setup for analysis of drain water heat recovery system in civil buildings. *J. Environ. Prot. Ecol.* **2019**, *20*, 1960–1969.
26. 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]
27. Murr, R.; Khaled, M.; Faraj, J.; Harika, E.; Abdulhay, B. Multi drain heat recovery system—Thermal modeling, parametric analysis, and case study. *Energy Build.* **2020**, *228*, 110447. [CrossRef]
28. 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]
29. Kordana, S.; Słyś, D. Analysis of profitability of using a heat recovery system from grey water discharged from the shower (case study of Poland). *E3S Web Conf.* **2017**, *22*, 00085. [CrossRef]
30. Hyun, I.T.; Lee, J.H.; Yoon, Y.B.; Lee, K.H.; Nam, Y. The Potential and Utilization of Unused Energy Sources for Large-Scale Horticulture Facility Applications under Korean Climatic Conditions. *Energies* **2014**, *7*, 4781–4801. [CrossRef]
31. Kovalenko, Y.; Katkov, M.; Ponomarenko, I.; Malovanyy, M.; Tymchuk, I. Utilization of drainage water heat in flooded urban areas. *Ecol. Qustions* **2022**, *33*, 31–41. [CrossRef]
32. 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]
33. Deng, Z.; Mol, S.; Van Der Hoek, J.P. Shower heat exchanger: Reuse of energy from heated drinking water for CO_2 reduction. *Drink. Water Eng. Sci.* **2016**, *9*, 1–8. [CrossRef]
34. 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]
35. Zaloum, C.; Lafrance, M.; Gusdorf, J. *Drain Water Heat Recovery Characterization and Modeling*, 1st ed.; Sustainable Buildings and Communities, Natural Resources Canada: Ottawa, ON, Canada, 2007.
36. Zhao, L.; Zhang, W.; Wang, W. Recognition of Energy-Saving Influencing Factors of Construction Project Lifecycle Based on Knowledge Map. *Int. J. Pattern Recogn.* **2021**, *35*, 2159017. [CrossRef]
37. Lynggaard, P.; Skouby, K.E. Complex IoT Systems as Enablers for Smart Homes in a Smart City Vision. *Sensors* **2016**, *16*, 1840. [CrossRef] [PubMed]
38. Szpak, D. Method for Determining the Probability of a Lack of Water Supply to Consumers. *Energies* **2020**, *13*, 5361. [CrossRef]
39. 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]
40. del Carmen Munguía-López, A.; Núñez-López, J.M.; Ponce-Ortega, J.M. Identifying Fair Solutions in the Optimal Design of Integrated Residential Complexes. *Chem. Eng. Process.* **2020**, *157*, 108116. [CrossRef]
41. Raoufi, A.; Gorji, M. Water and energy management in a sustainable site: A case study of a living environment for street children in Tehran, Iran. *Sustain. Cities Soc.* **2021**, *68*, 102797. [CrossRef]
42. Sun, Y.; Deng, L.; Pan, S.Y.; Chiang, P.C.; Sable, S.S.; Shah, K.J. Integration of green and gray infrastructures for sponge city: Water and energy nexus. *Water-Energy Nexus* **2020**, *3*, 29–40. [CrossRef]
43. Østergaard, D.S.; Smith, K.M.; Tunzi, M.; Svendsen, S. Low-temperature operation of heating systems to enable 4th generation district heating: A review. *Energy* **2022**, *248*, 123529. [CrossRef]

44. 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]
45. Stec, A.; Słyś, D. Financial and Social Factors Influencing the Use of Unconventional Water Systems in Single-Family Houses in Eight European Countries. *Resources* **2022**, *11*, 16. [CrossRef]
46. Cholewa, M.; Mammadov, F.; Nowaczek, A. The obstacles and challenges of transition towards a renewable and sustainable energy system in Azerbaijan and Poland. *Miner. Econ.* **2022**, *35*, 155–169. [CrossRef]
47. Dudkiewicz, E.; Laska, M.; Fidorów-Kaprawy, N. Users' Sensations in the Context of Energy Efficiency Maintenance in Public Utility Buildings. *Energies* **2021**, *14*, 8159. [CrossRef]
48. Zaloum, C.; Gusdorf, J.; Parekh, A. *Performance Evaluation of Drain Water Heat Recovery Technology at the Canadian Centre for Housing Technology—Final Report*; Sustainable Buildings and Communities; Natural Resources Canada: Ottawa, ON, Canada, 2007.
49. Yang, H.; Kikuta, K.; Hayashi, M. Research on Carbon Reduction of Residential Buildings in Severe Cold Regions Based on Renovation of Envelopes. *Energies* **2022**, *15*, 1873. [CrossRef]
50. Zięty, J.J.; Olba-Zięty, E.; Stolarski, M.J.; Krzykowski, M.; Krzyżaniak, M. Legal Framework for the Sustainable Production of Short Rotation Coppice Biomass for Bioeconomy and Bioenergy. *Energies* **2022**, *15*, 1370. [CrossRef]
51. Van Horne, J.C.; Wachowicz, J.M., Jr. *Fundamentals of Financial Management*, 13th ed.; Prentice Hall/Pearson Education Limited: Harlow, UK, 2009.
52. Brigham, E.F.; Ehrhardt, M.C. *Financial Management: Theory and Practice*, 12th ed.; Thomson Higher Education: Mason, IA, USA, 2008.
53. Pochwat, K.; Kordana-Obuch, S.; Starzec, M.; Piotrowska, B. Financial Analysis of the Use of Two Horizontal Drain Water Heat Recovery Units. *Energies* **2020**, *13*, 4113. [CrossRef]
54. Shan, Y.; Yang, L.; Perren, K.; Zhang, Y. Household Water Consumption: Insight from a Survey in Greece and Poland. *Procedia Eng.* **2015**, *119*, 1409–1418. [CrossRef]
55. European Commission. *Guide to Cost-Benefit Analysis of Investment Projects: Economic Appraisal Tool for Cohesion Policy*; European Commission: Brussels, Belgium, 2015.
56. Ćetković, J.; Lakić, S.; Žarković, M.; Vujadinović, R.; Knežević, M.; Živković, A.; Cvijović, J. Environmental Benefits of Air Emission Reduction in the Waste Tire Management Practice. *Processes* **2022**, *10*, 787. [CrossRef]
57. European Commission. *Economic Appraisal Vademecum 2021–2027: General Principles and Sector Applications*; European Commission: Brussels, Belgium, 2021.
58. Foltyn-Zarychta, M.; Buła, R.; Pera, K. Discounting for Energy Transition Policies—Estimation of the Social Discount Rate for Poland. *Energies* **2021**, *14*, 741. [CrossRef]
59. OECD. *Cost-Benefit Analysis and the Environment: Further Developments and Policy Use*; OECD Publishing: Paris, France, 2018; pp. 399–422. [CrossRef]
60. Kell, G.S. Density, Thermal Expansivity, and Compressibility of Liquid Water from 0° to 150 °C: Correlations and Tables for Atmospheric Pressure and Saturation Reviewed and Expressed on 1968 Temperature Scale. *J. Chem. Eng. Data* **1975**, *20*, 97–105. [CrossRef]
61. Dinçer, İ.; Zamfirescu, C. *Drying Phenomena: Theory and Applications*, 1st ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2016; pp. 457–459.
62. Chudzicki, J.; Sosnowski, S. *Instalacje Wodociągowe—Projektowanie, Wykonanie, Eksploatacja*, 3rd ed.; Seidel-Przywecki: Warsaw, Poland, 2011.
63. Manouchehri, R.; Collins, M.R. Investigating the Impact of Plumbing Configuration on Energy Savings for Falling-Film Drain Water Heat Recovery Systems. *Energies* **2022**, *15*, 1141. [CrossRef]
64. Al-Sumaiti, A.S.; Kavousi-Fard, A.; Salama, M.; Pourbehzadi, M.; Reddy, S.; Rasheed, M.B. Economic Assessment of Distributed Generation Technologies: A Feasibility Study and Comparison with the Literature. *Energies* **2020**, *13*, 2764. [CrossRef]
65. Mazur, A. The impact of using of a DWHR heat exchanger on operating costs for a hot water preparation system and the amount of carbon dioxide emissions entering the atmosphere. *E3S Web Conf.* **2018**, *45*, 00052. [CrossRef]
66. Gabrielli, P.; Wüthrich, M.; Blume, S.; Sansavini, G. Data-driven modeling for long-term electricity price forecasting. *Energy* **2022**, *244*, 123107. [CrossRef]
67. Ruszel, M.; Masłoń, A.; Ogarek, P. Analysis of biogas from sewage sludge digestion in terms of diversification in the natural gas production structure in Poland. *Desalin. Water Treat.* **2021**, *232*, 298–307. [CrossRef]
68. Boryczko, K.; Szpak, D.; Żywiec, J.; Tchórzewska-Cieślak, B. The Use of a Fault Tree Analysis (FTA) in the Operator Reliability Assessment of the Critical Infrastructure on the Example of Water Supply System. *Energies* **2022**, *15*, 4416. [CrossRef]