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Analysis of the Life Cycle Cost of a Heat Recovery System from Greywater Using a Vertical “Tube-in-Tube” Heat Exchanger: Case Study of Poland

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Abstract: Significant amounts of waste heat are deposited in greywater, which can be utilized, among other things, for heating domestic hot water in residential buildings. The manuscript presents an economic analysis of a greywater heat recovery system using a vertical heat exchanger of the “tube-in-tube” type in a single-family building. The analysis is based on the results of experimental research on the energy efficiency of three domestic hot water preparation systems equipped with a vertical heat exchange unit. The analyzed systems had different concepts for the flow of preheated water and cold water. The research showed that the implementation of a vertical “tube-in-tube” heat exchanger can reduce the energy consumption for domestic hot water preparation by approximately 45.7% to 60.8%, depending on the system variant. Furthermore, it was determined that the energy savings associated with reducing domestic hot water consumption can cover the investment costs related to the purchase and system of the heat exchanger within a period of 2 to 5 years of system operation, depending on the design variant and the unit price of electricity.

Keywords: greywater heat recovery; vertical “tube-in-tube” heat exchanger; Life Cycle Cost analysis; domestic hot water preparation

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1. Introduction

Observed climate anomalies necessitate the need for thoughtful, systemic, and consistent actions aimed at mitigating the negative impact of human activities [1–4]. These actions should particularly focus on reducing greenhouse gas emissions from fossil fuel combustion [5–8].

According to data published by Eurostat, water heating for domestic purposes accounted for 14.8% of the total energy consumption in the residential sector in Europe in 2019 [9,10]. In terms of average household energy consumption, this share can reach up to 30% [11], and in passive buildings, it can even reach 50% [12].

Approximately 80–90% of the primary energy present in hot water flowing out of a shower drain is deposited in greywater [13–15]. This fact should emphasize the importance of implementing heat recovery systems in residential buildings [13,16]. By utilizing devices designed for heat recovery in wastewater systems and wastewater facilities, it is possible to recover up to 80% of the thermal energy deposited in wastewater [13,17–20].

As emphasized by Huber et al. [21], wastewater is a source of locally available and renewable heat and can therefore make a valuable contribution to the ongoing decarbonization of energy systems, which is essential for reducing greenhouse gas emissions. With increasing pressure on district heating efficiency, Thorse et al. [22] developed and tested the concept of a booster for DHW circulation in apartment buildings. The main result of these studies was the reduction in the district heating return temperature from 47.2 °C to 21.5 °C, which proves the significant efficiency of the presented concept. Counteracting the effects of global warming also requires actions aimed at improving the energy efficiency of buildings, which can be effectively implemented by reducing energy consumption for the preparation of domestic hot water, and as is known, the preparation of hot water in buildings generates significant energy consumption, and thus affects the costs of building maintenance [23].

Reducing the demand for energy needed to prepare domestic hot water in residential buildings is a topic undertaken by scientists from various research centers around the world [24,25].

The primary method for recovering waste energy from greywater is the use of Drain-Water Heat Recovery (DWHR) units [26,27]. Research published in recent years is mainly based on analyses of horizontal heat exchange units [28–31], with vertical counter-flow devices [32,33] being the most efficient and commonly used. Analyses conducted on vertical Drain Water Heat Recovery (DWHR) units focus on devices constructed with a vertical greywater drainpipe and a smaller-diameter pipe for cold water supply, spirally wound around the vertical greywater drainpipe [20,34–37].

Manouchehri and Collins [35] conducted research aimed at presenting a model for predicting the performance of a DWHR system equipped with a vertical spiral heat exchanger under steady-state conditions with variable temperatures and flow rates.

Ovadia and Sharqawi [20] evaluated the thermal and economic performance of a vertical spiral heat exchanger by experimentally and analytically studying its transient properties.

As reported by Wehbi et al. [38], another variant of a system that can be implemented in a water and wastewater system, based on vertical systems, involves the use of an accumulation tank for wastewater discharged from sanitary devices. According to studies published by Torras et al. [36], such heat exchangers are capable of recovering between 34% and 60% of the energy deposited in wastewater.

De Paepe et al. [37] presented a vertical heat recovery system from greywater generated by dishwashers, based on an accumulation tank. The system relies on the concept of storing the discharged water in a tank and introducing a spiral tube into it. Based on the conducted research, the authors concluded that wastewater heat recovery is economically viable.

The results of research conducted in the field of horizontal heat exchangers include modifications to their construction by increasing the heat exchange surface in order to increase the efficiency of heat recovery from wastewater. Such research was conducted by Kordana-Obuch and Starzec [39], analyzing the efficiency of a new compact shower heat exchanger designed for installation under a shower tray. It was determined that, depending on the temperature of the cold water and the flow rate of both media through the heat exchanger, it was possible to achieve efficiency in the range of 22.43% to 31.82%, while the efficiency of the exchanger in the form of linear drainage did not exceed 23.03%. There are also known studies [29] in the field of improving the efficiency of horizontal exchangers by using baffles to be installed in the part of the heat exchanger where greywater flows. Studies have shown that after installing baffles in the DWHR unit, the efficiency of energy recovery was higher from several to even 40% compared to the DWHR unit without this type of baffle.

Based on the analysis of the current state of knowledge, a significant research gap has been identified in the area of vertical “tube-in-tube” heat exchangers. While there are scientific publications on vertical spiral heat exchangers, no experimental research results have been presented for “tube-in-tube” exchangers. The aim of this manuscript is to fill the existing scientific literature gap in the field of vertical heat exchangers by presenting experimental research results for this specific type of heat exchanger.

The novelty of the presented manuscript involves experimental studies of the efficiency of recovery of waste energy deposited in greywater, carried out on a real model of a vertical “tube-in-tube” heat exchanger, which has not been tested so far. In addition, the experimental research was extended with an economic analysis of the application of the vertical “tube-in-tube” heat exchanger in a residential building.

2. Materials and Methods

2.1. Research Model

The basis for the analysis of the energy efficiency of the heat recovery system in the greywater system and domestic hot water preparation system was laboratory research. The physical research model (Figure 1) allowed for the replication of conditions similar to real-life scenarios in domestic hot water preparation and heat recovery from greywater in residential buildings.

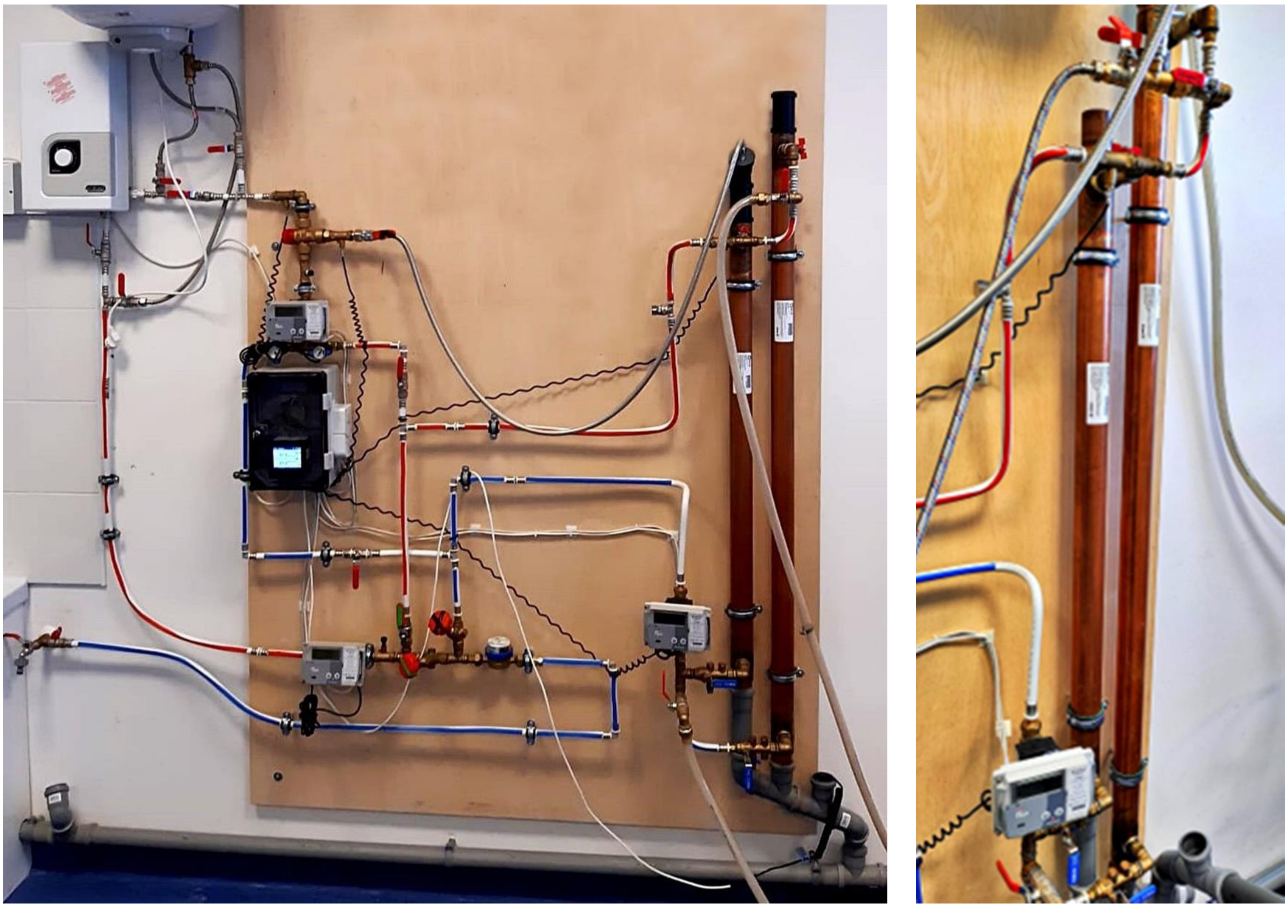


Figure 1. Laboratory station of the heat recovery system from greywater.

The waste heat recovery system from greywater and the domestic hot water preparation system were integrated with a flow-through electric water heater with a maximum heating power of 27 kW (by Kospel, Koszalin, Poland). Polyethylene pipes with enhanced thermal resistance were used for the system. An important component of the system was the selected measuring equipment. To monitor the measurement of parameter values, three ultrasonic flow meters of the Sharky 473 type, three electronic converters (by Apator, Toruń, Poland), and the MultiCon CMC-144 data logger were used (by Simex, Loreto, Italy). The measurement of tap water and greywater was carried out using resistance temperature sensors Pt500 class AA.

The experimental research focused on a vertical tube-in-tube heat exchanger unit, measuring 1680 mm in length, constructed using three copper pipes: (a) an internal wastewater pipe, (b) a middle pipe and an external pipe serving as the heat exchanger housing [40]. The main components of the analyzed heat exchanger are presented in Figure 2.

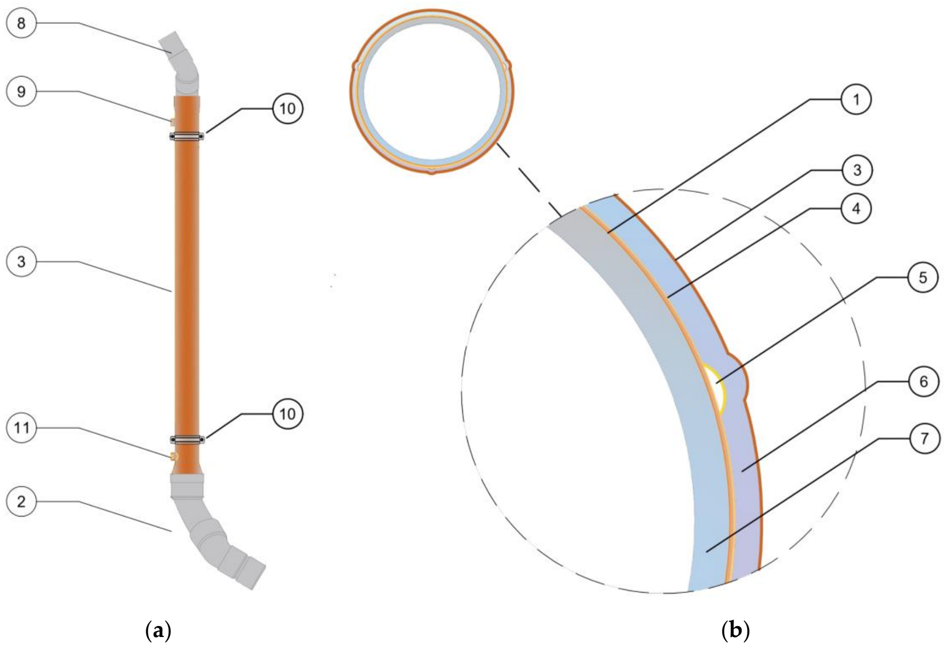


Figure 2. Construction of a vertical "tube-in-tube" heat exchanger type Showersave QB1-12,16 [40]. (**a**) General diagram of the device; (**b**) cross-sectional view of the device: 1—inner pipe; 2—greywater drainage to the wastewater system; 3—outer pipe; 4—middle pipe; 5—air; 6—cold tap water; 7—greywater; 8—inlet of greywater to the heat exchanger; 9—outlet fitting for preheated water; 10—mounting clamp; 11—inlet fitting for cold tap water.

2.2. Heat Recovery Efficiency Analysis

Based on literature data on water consumption in households for bathing purposes and considering the standards [41–45] related to the design and operation of sanitary devices, the values of dependent variables characterizing the research object were determined.

The values of the mixed water volume flow at the outlet of the mixing valve were adopted within the range of achievable values and taking into account the practice of limiting water consumption through the use of flow regulators in tap faucets [42,43,46].

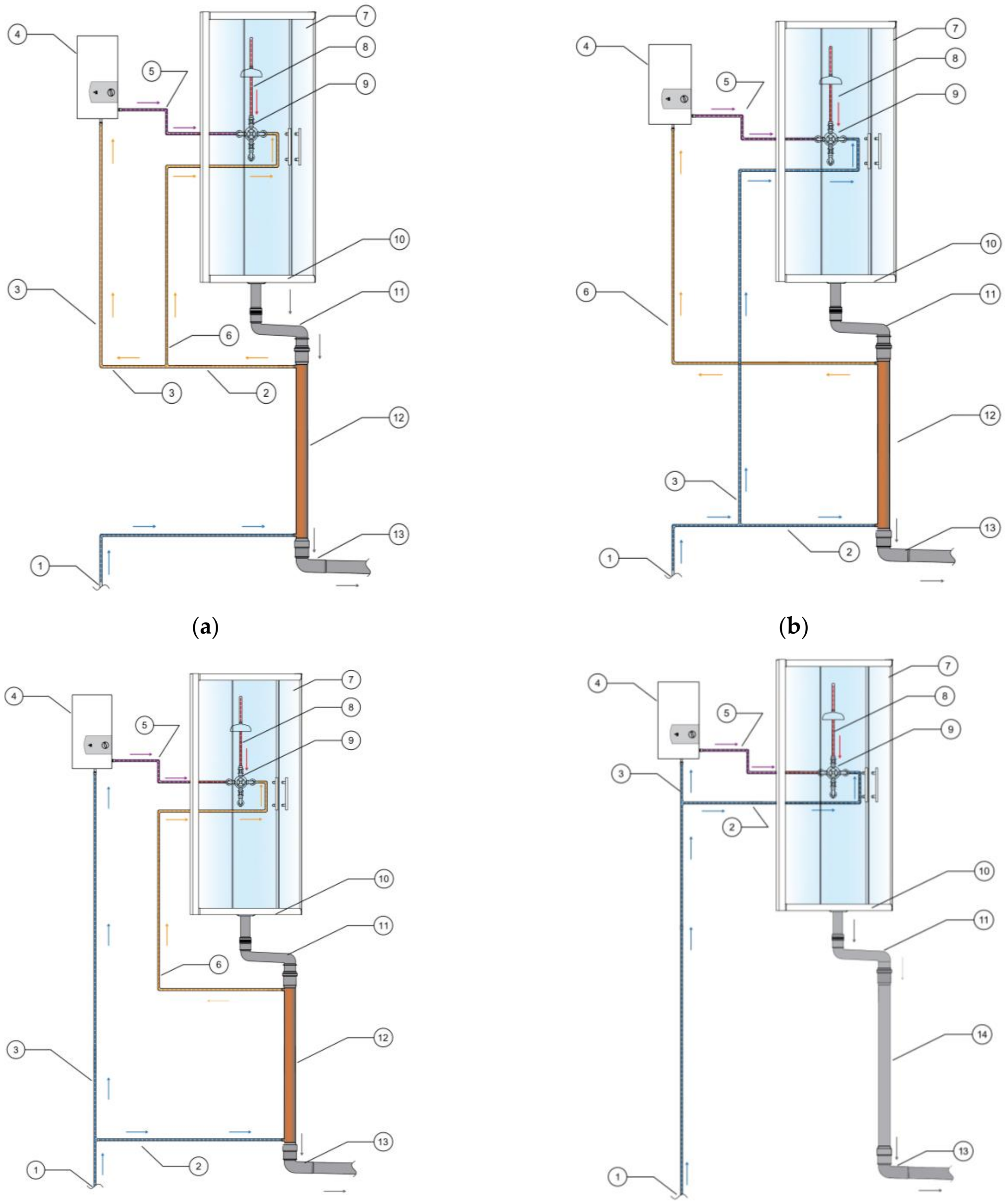
Shower faucets with a wide range of water flow rates are available on the market. However, it should be noted that the actual volume flow rate of water from sanitary points in the facility is also dependent on the water pressure in the plumbing system [46,47]. Therefore, determining a representative value of the water volume flow rate at the showerhead outlet is not obvious. For the analysis, two showerheads with typical water flow rates of Q = 7.5 dm^3/min and Q = 10 dm^3/min were selected.

The usage time of the sanitary device (t_u) was assumed to be 8 min, which is consistent with the data on the average length of a shower contained in the Residential End Uses of Water, Version 2: Executive Report [42].

During the analysis, the temperature of tap water Tc = 12 °C was assumed, which is within the range of the average annual temperature of tap water in Poland. For the experimental analysis, the hot water temperature was set at T_h = 55 °C, and two values of mixed water temperature, T_m = 38 °C and T_m = 40 °C, were chosen. These values fall within the commonly accepted range for sizing internal sanitary systems in Polish conditions [29].

For all experimentally analyzed cases of the vertical "tube-in-tube" heat exchanger, it was assumed that the temperature of greywater at the outlet of the shower tray would be equal to the temperature of the mixed water at the showerhead outlet. Heat losses resulting from the use of the sanitary device were omitted because, under the prevailing conditions similar to real-life conditions during the study, it was not possible to achieve losses that are observed in practice when using sanitary devices.

Energy and financial efficiency analyses of the heat recovery system were conducted for four different design options of the domestic hot water (DHW) preparation system (Figure 3): (a) Variant I—the DHW system is equipped with a vertical heat exchanger, where preheated water flows to both the electric water heater and the mixing valve; (b) Variant II—the DHW system is equipped with a vertical heat exchanger, where preheated water flows to the electric water heater; (c) Variant III—the DHW system is equipped with a vertical heat exchanger, where preheated water flows to the mixing valve; (d) Variant IV—the DHW system is not equipped with a heat exchanger [35,48].



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

(**c**) (**d**)

Figure 3. Variants of the domestic hot water preparation system for the shower cooperating with the instantaneous electric water heater [35,48]: (**a**) Variant I; (**b**) Variant II; (**c**) Variant III; (**d**) Variant IV; 1—cold tap water supply to the system; 2—cold tap water supply to the heat exchanger; 3—preheated or cold water supply to the water heater; 4—electric water heater; 5—hot water supply to the mixing valve; 6—preheated or cold water supply to the mixing valve; 7—shower cabin; 8—mixed water supply to the shower head; 9—mixing valve; 10—shower tray; 11—greywater inlet; 12—vertical heat exchanger; 13—greywater outlet; 14—vertical sewer pipe.

The energy efficiency of the heat recovery system, which is implemented according to Variant I, Variant II, and Variant III, can be determined using Equation (1). The energy recovery efficiency (ε) is calculated as the difference between the energy required to heat water for domestic purposes in a system without a heat exchanger and the energy demand in the DHW system [29,49].

$$\varepsilon = \frac{(\rho \cdot c_p \cdot t_s \cdot Q \cdot \triangle T_1) - (\rho_w \cdot c_p \cdot t_s \cdot Q \cdot \triangle T_2)}{(\rho_w \cdot c_p \cdot t_s \cdot Q \cdot \triangle T_1)} \cdot 100\% \quad (1)$$

where ρ—water density, kg/m^3; c_p—specific heat of water, J/(kg·K); t_s—shower length, s; Q—volume of heated water consumed, m^3/s; $\triangle T_1$—the difference between the inlet and outlet water temperatures of the electric heater in a conventional system, °C; $\triangle T_2$—the difference between the inlet and outlet water temperatures of the electric heater in the DWHR system, °C.

2.3. Economic Analysis

2.3.1. Case of Study

The object analyzed for the financial efficiency LCC is a single-family house with an inhabited attic. Due to the room layout, an electric water heater is located in the bathroom on the ground floor, which is directly adjacent to the kitchen. This device heats the water used in the kitchen, as well as in the bathrooms on the ground floor and the upper floor.

As part of the analysis, the Life Cycle Costs (LCCs) of four configurations of domestic hot water preparation systems in a single-family house were evaluated, with three design concepts assuming the system of a vertical "tube-in-tube" heat exchanger with a length of 1680 mm, which was tested under conditions similar to real-life scenarios.

The temperature of cold water (T_c), the temperature of mixed water at the shower outlet (T_m), the volume flow rate of mixed water (Q), and the length of a single shower (t_u) usage determine the water and energy consumption required for heating. Therefore, the adoption of representative values for these indicated input variables was significant due to the conducted economic analysis for the single-family house.

2.3.2. Life Cycle Cost Analysis

The financial efficiency analysis was conducted for a newly constructed residential building to assess the Life Cycle Costs (LCCs) of different design solutions for heat recovery system from greywater generated during shower usage. The design concept of the system with the highest investment value over the long-term operation period of 15 years was identified.

In the first stage of the financial efficiency analysis, a deterministic approach was adopted to estimate the LCCs, taking into account variations in input parameters provided as discrete values. The second stage of the analysis (sensitivity analysis) involved evaluating the profitability of the investment based on changes in the input parameter values, such as electricity prices [50].

The operational costs of the investment in each of the analyzed design scenarios were determined based on the demand for electricity and the amount of water used for showering. The charges resulting from the electricity consumption for water heating were calculated using the unit price of electricity and estimated energy requirements for water heating. The electricity supply prices were based on the tariff for household electricity distribution services by PGE in Poland for the year 2023. The unit charges for the aforementioned utilities were specified as follows:

- EUR 0.22/kWh—gross price for electricity services in households [51];
- EUR 2.22/m^3—price for collective water supply and wastewater disposal services [52].

The investment costs in the conventional variant (without heat exchanger) included the purchase costs of materials and fittings, as well as the system of the wastewater system and domestic hot water preparation system.

The investment costs in configurations that involved the system of a heat exchanger were increased by the catalog price of the Domestic Water Heat Recovery (DWHR) unit. Additionally, the configurations considering the system of a heat exchanger required the design of a dual wastewater system, separate for greywater and blackwater.

The total cost of the domestic hot water preparation system in the life cycle of the LCC investment can be determined using Formula (2) [53–55].

$$LCC = K_I + \left[\sum_{t=1}^{t_a} (1+r)^{-t} \right] \cdot K_O \tag{2}$$

where K_I—investment costs, EUR; t_a—operation time, years; t—another year of system operation, year; r—discount rate; K_O—operating costs, EUR.

In cases where the lifespan of the analyzed system extends beyond the foreseeable period of its use, there is no need to consider its residual value after the expected operating period. Therefore, the costs of disposing of the heat recovery system were not included in the calculations, in accordance with the guidelines for estimating the Life Cycle Costs of the investment [53].

It should be emphasized that due to the fact that DWHR units operate practically maintenance-free and do not require external energy supply [56], the maintenance costs have been omitted when estimating operating costs.

In the research, the operational lifespan of the domestic hot water preparation system was estimated without considering interruptions in usage due to residents' vacations and trips. All variables included in the Life Cycle Cost (LCC) investment cost analysis are compiled in Table 1.

Table 1. The values adopted in the LCC (Life Cycle Cost) analysis of the domestic hot water preparation and wastewater system in a residential building.

Parameter	Unit	Variant I	Variant II	Variant III	Variant IV
Capital expenditures in the base year	EUR	5149	5125	5140	3985
Price of water and wastewater in the base year	EUR/m^3	2.22	2.22	2.22	2.22
Electricity price in the base year	EUR/kWh	0.22	0.22	0.22	0.22
Number of system users	-	4	4	4	4
Lifetime	years	15	15	15	15
Discount rate	-	0.05	0.05	0.05	0.05
Single shower length	s	480	480	480	480

2.4. Sensitivity Analysis

In order to assess the profitability of the investment, an analysis was conducted to evaluate the impact of changes in electricity prices on the financial efficiency of installing a vertical "tube-in-tube" heat exchanger in a single-family home in Poland, considering a 15-year operational period of the system.

The sensitivity analysis of the investment, taking into account the risk associated with potential changes in the annual average cost of electricity generation, can be significant in the decision-making process regarding the application of a heat exchanger in the domestic hot water preparation system and wastewater system, especially in the face of the global energy crisis.

The sensitivity analysis was conducted as a scenario analysis, considering three possible scenarios of electricity price development in the Polish power system based on expert forecasts. The projected changes in electricity prices were determined based on data provided according to ENERGY INSTRAT estimates [57].

By 2038, analysts predict an increase in electricity costs for households. This trend is influenced by factors such as the specifics of the Polish energy sector, dependence on fossil fuels, a limited share of renewable and waste energy sources, as well as rising prices of CO_2 emission allowances [57–60].

In the conducted sensitivity analysis, three scenarios of electricity price changes for the years 2023–2038 were considered, corresponding to the 15-year operational period of the system. All scenarios in the analysis involve an increase in the unit price of electricity relative to the year 2023, but each scenario was developed by a different team of experts and describes a different forecast for the changes in this parameter (Figure 4).

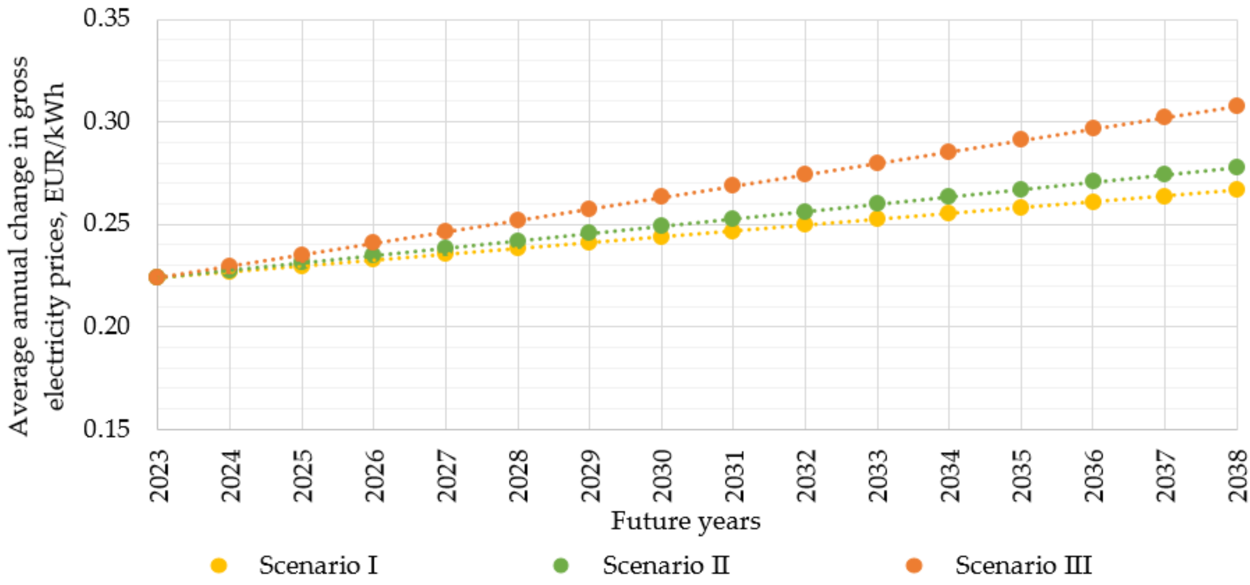


Figure 4. The average annual change in gross electricity prices from 2023 to 2038, considering three scenarios of variations in this parameter.

The research adopted the following scenarios:

- Scenario I—an increase in electricity prices by 21.50% according to the Institute of Renewable Energy;
- Scenario II—an increase in electricity prices by 27.20% according to PEP2040;
- Scenario III—an increase in electricity prices by 42.40% according to the NABE BASE [57].

3. Results and Discussion

3.1. Heat Recovery Efficiency Analysis

Based on the results of experimental studies, the energy efficiency of the DWHR system incorporating a "tube-in-tube" heat exchanger with a length of 1680 mm was determined. The obtained results of the experimental analysis are presented in Table 2, compared to the assumed values of input variables.

In the case of Variant I, the highest values of energy efficiency were achieved for the smallest assumed mixed water volume flow rate in the analysis, Q = 7.5 dm^3/min. As this parameter increased, the energy efficiency decreased. Furthermore, a relationship between energy efficiency and the temperature of the mixed water (T_m) supplied to the heat exchanger was demonstrated. Energy efficiency of the DWHR system increased with the rise in the T_m parameter.

Similar observations were made for Variant II. As the mixed water volume flow rate (Q) at the outlet of the mixing valve decreased and the temperature of the mixed water (T_m) increased, the energy efficiency of the heat recovery system increased.

The analysis of the results for Variant III also showed a decrease in energy efficiency with an increase in the mixed water volume flow rate (Q), while an increase in the bathwater temperature resulted in a reduction in energy efficiency. A smaller difference between the temperature of the mixed water (T_m) and the temperature of cold water (T_c) and a lower volume flow rate of water supplied to the electric water heater were directly related to the achieved energy efficiency of the DWHR system.

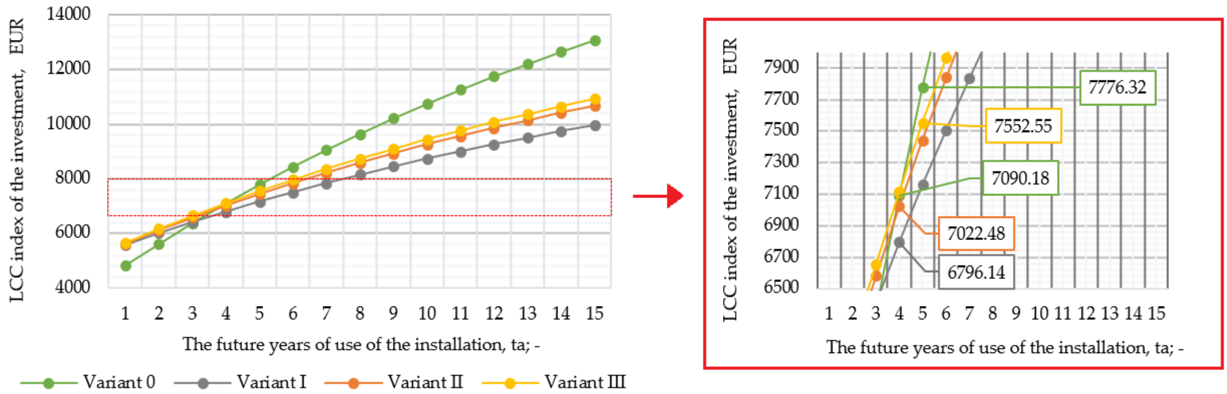
Table 2. Efficiency of heat recovery in the tested variants.

Temperature of the Water Mixed at the ShowerHead Outlet, T_m	Volume Flow of Water Mixed at the ShowerHead Outlet, Q	Variant I				Variant II				Variant III			
		Cold Water, T_c	Preheated Water, T_{ph}	Q_{ph}/Q	Energy Efficiency, ε	Cold Water, T_c	Preheated Water, T_{ph}	Q_{ph}/Q	Energy Efficiency, ε	Cold Water, T_c	Preheated Water, T_{ph}	Q_{ph}/Q	Energy Efficiency, ε
°C	dm^3/min	°C	°C	-	%	°C	°C	-	%	°C	°C	-	%
38	7.5	12.00	27.71	1.00	60.12	12.00	31.66	0.61	45.47	12.00	30.83	0.70	49.96
42		12.00	30.43	1.00	60.81	12.00	33.87	0.70	50.53	12.00	34.55	0.63	46.81
38	10	12.00	27.43	1.00	58.74	12.00	31.46	0.61	44.90	12.00	30.62	0.69	48.93
42		12.00	29.92	1.00	59.28	12.00	33.53	0.70	49.68	12.00	34.31	0.62	45.74

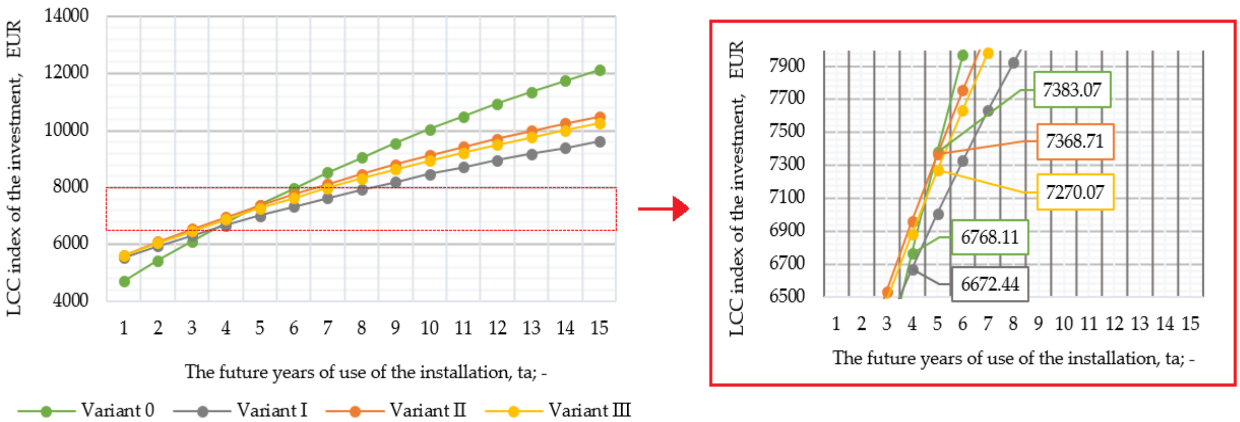
3.2. Life Cycle Cost Analysis

When analyzing the financial feasibility of investments related to the system of a vertical "tube-in-tube" heat exchanger, the Life Cycle Cost (LCC) indicators of individual DWHR system configurations were compared to the LCC indicators determined for the conventional system. The profitability of the investment was determined by achieving financial benefits through positive cash flows during the system's operational period, i.e., obtaining lower LCC values for the alternative projects (Variant I, Variant II, Variant III) compared to the base project (Variant IV).

Based on the obtained analysis results, it was assessed that the implementation of a heat exchanger is financially justified. The cost of purchasing the heat exchanger (approximately EUR 1100), which determined the difference in investment costs, is recovered within a 15-year operational period in each variant of the DWHR system. The financial benefits obtained (reduction in Life Cycle Costs in Variants I, II, and III compared to Variant IV) differ depending on the selected project variant. Figures 5 and 6 illustrate the LCC values for all four variants of the domestic hot water preparation system over a 15-year operational period, taking into account different values of mixed water temperature (T_m) and different volume flow rates of water at the showerhead outlet (Q).



(**a**)



(**b**)

Figure 5. Life Cycle Cost indicators of the system for different design variants and for a mixed water volume flow rate of $Q = 7.5$ dm^3/min: (**a**) T_m = 42 °C; (**b**) T_m = 38 °C; → - chart to detail view.

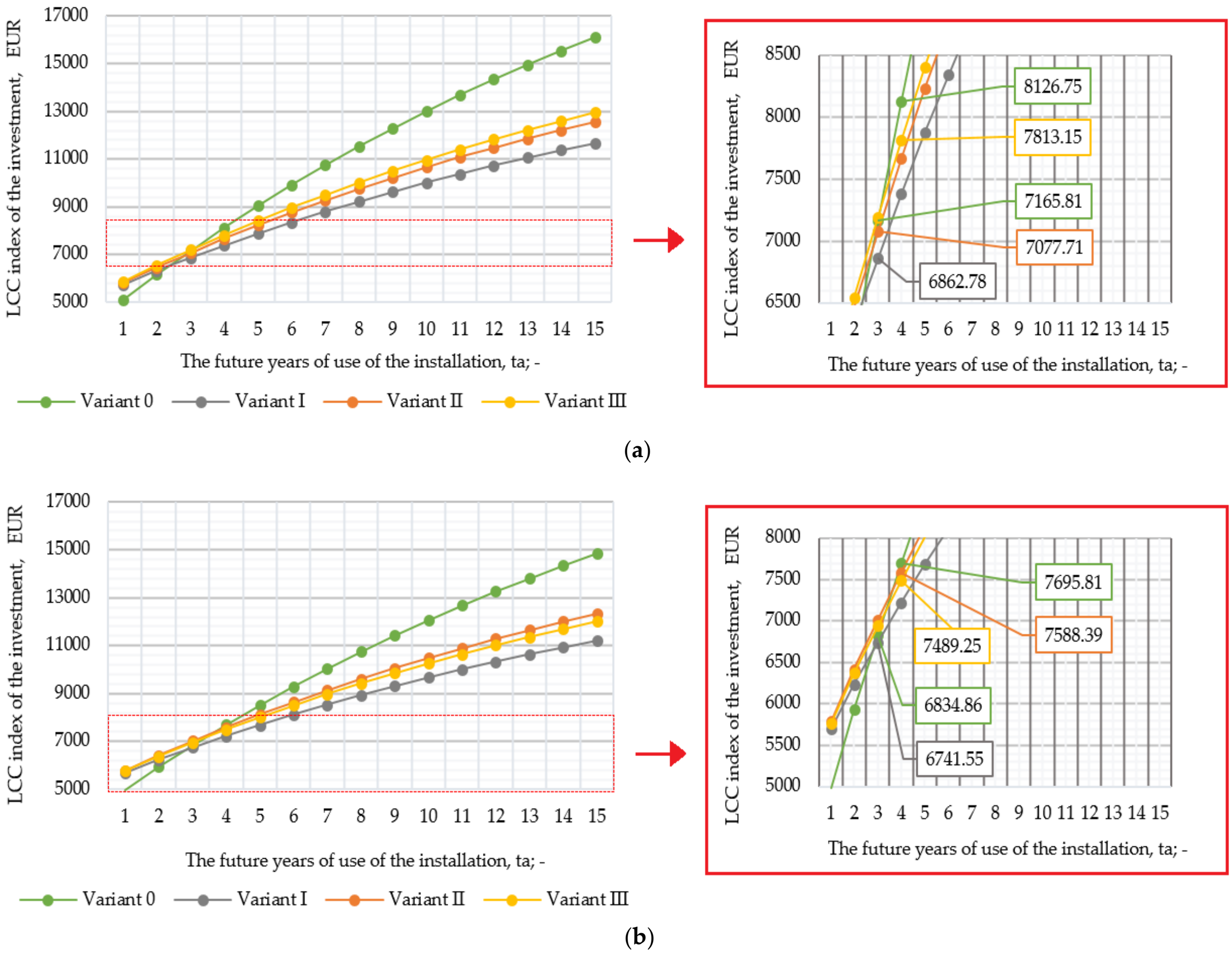


Figure 6. Life Cycle Cost indicators of the system for different design variants and for a mixed water volume flow rate of $Q = 10$ dm^3/min: (**a**) $T_m = 42$ °C; (**b**) $T_m = 38$ °C; → - chart to detail view.

The highest Life Cycle Cost (LCC) values were obtained during the analysis assuming that the mixed water temperature (T_m) was 42 °C and the volume flow rate of water at the showerhead outlet (Q) was 10 dm^3/min. In this case, the highest energy demand for domestic hot water preparation was observed. The lowest LCC values were achieved when the energy required for domestic hot water preparation was the lowest among the analyzed cases, i.e., for parameter values of $T_m = 38$ °C and $Q = 7.5$ dm^3/min.

Depending on the selected calculation parameters of T_m and Q, it was determined that in the case of Variant I, positive cash flows can be achieved within 2 to 4 years. For Variant II, this period ranges from 2 to 5 years, while for Variant III, positive cash flows can be obtained within 3 to 5 years.

In each of the analyzed research cases, Variant I of the DWHR system (preheated water supplied to the electric water heater and mixing valve) proved to be the most financially viable solution. If Variant I is not feasible and assuming that the mixed water temperature (T_m) is 42 °C, Variant II of the DWHR system may be beneficial, as it has a lower LCC value compared to Variant III.

When the temperature of the mixed water (T_m) is 38 °C and it is not possible to implement Variant I of the DWHR system, financially, it may be more feasible to consider Variant III of the DWHR system, as it has a lower value of the Life Cycle Cost (LCC) indicator compared to Variant II.

Furthermore, based on the conducted economic analysis, it was determined that in the 15th year of operation of the DWHR system, the reduction in the LCC indicator compared to the conventional system will be as follows:

- EUR 3104 for Variant I, EUR 2395 for Variant II, and EUR 2151 for Variant III when the temperature of the mixed water (T_m) is 42 °C and the volume flow rate of water at the showerhead (Q) is 7.5 dm^3/min.
- EUR 4428 for Variant I, EUR 3541 for Variant II, and EUR 3144 for Variant III when the temperature of the mixed water (T_m) is 42 °C and the volume flow rate of water at the showerhead (Q) is 10 dm^3/min.
- EUR 2523 for Variant I, EUR 1628 for Variant II, and EUR 1885 for Variant III when the temperature of the mixed water (T_m) is 38 °C and the volume flow rate of water at the showerhead (Q) is 7.5 dm^3/min.
- EUR 3628 for Variant I, EUR 2511 for Variant II, and EUR 2831 for Variant III when the temperature of the mixed water (T_m) is 38 °C and the volume flow rate of water at the showerhead (Q) is 10 dm^3/min.

3.3. Sensitivity Analysis

The results of the investment sensitivity analysis to changes in the unit price of energy in Poland over the years 2023–2028 are presented in Tables 3 and 4. The analysis includes the reduction in the Life Cycle Costs (LCCs) of the individual DWHR system variants compared to the conventional variant.

Table 3. Reduction in the LCC indicator in different design variants of the DWHR system, for a mixed water temperature of T_m = 42 °C, and for various scenarios of changes in electricity prices in the power system in Poland from 2023 to 2038.

The Life Cycle Cost Reduction Index of the Investment, EUR												
The future years, ta	Scenario 0			Scenario I			Scenario II			Scenario III		
	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III
Volume flow rate of the mixed water Q = 7.5 dm^3/min												
1	−772	−816	−852	−683	−742	−783	−666	−727	−769	−612	−683	−728
2	−399	−507	−563	−226	−363	−428	−191	−334	−401	−87	−248	−321
3	−44	−212	−288	210	−2	−91	261	40	−51	414	167	67
4	294	68	−26	625	342	231	692	397	282	891	562	436
5	616	335	224	1021	670	537	1102	737	600	1344	938	788
6	923	589	461	1397	982	829	1492	1060	902	1777	1296	1123
7	1215	831	688	1756	1279	1107	1864	1368	1190	2189	1637	1442
8	1494	1061	903	2098	1562	1371	2218	1662	1465	2581	1962	1745
9	1759	1281	1109	2423	1831	1623	2556	1941	1726	2954	2271	2035
10	2011	1490	1304	2733	2088	1863	2877	2207	1975	3310	2566	2310
11	2251	1689	1490	3028	2332	2091	3183	2461	2212	3649	2846	2572
12	2480	1879	1668	3309	2565	2309	3474	2702	2437	3971	3114	2822
13	2699	2059	1836	3576	2786	2516	3752	2932	2652	4279	3368	3060
14	2906	2231	1997	3831	2998	2714	4016	3151	2857	4571	3611	3287
15	3104	2395	2151	4074	3199	2902	4268	3359	3052	4850	3841	3503
Volume flow rate of the mixed water Q = 10 dm^3/min												
1	−651	−711	−761	−534	−613	−671	−511	−593	−653	−441	−535	−599
2	−162	−301	−385	65	−111	−210	111	−73	−175	247	42	−70
3	303	88	−27	636	367	229	703	423	280	903	591	434
4	746	459	314	1180	823	647	1267	895	714	1528	1113	914
5	1168	812	638	1698	1256	1046	1804	1345	1127	2122	1611	1372
6	1570	1149	947	2192	1669	1425	2316	1773	1520	2689	2085	1807
7	1953	1469	1242	2662	2063	1786	2803	2181	1895	3228	2537	2222
8	2318	1775	1522	3109	2437	2130	3267	2570	2252	3742	2967	2617
9	2665	2065	1789	3535	2794	2458	3709	2940	2592	4231	3377	2993
10	2996	2342	2043	3941	3134	2770	4130	3292	2915	4697	3767	3351

Table 3. *Cont.*

	The Life Cycle Cost Reduction Index of the Investment, EUR											
	Scenario 0			Scenario I			Scenario II			Scenario III		
The future years, ta	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III
11	3311	2606	2285	4328	3457	3067	4531	3628	3223	5141	4138	3693
12	3611	2857	2516	4696	3765	3350	4913	3947	3517	5564	4492	4018
13	3896	3096	2735	5046	4059	3620	5277	4252	3797	5967	4829	4327
14	4168	3324	2945	5380	4339	3876	5623	4541	4063	6350	5150	4622
15	4428	3541	3144	5698	4605	4121	5953	4818	4316	6715	5456	4902

Table 4. Reduction in the LCC indicator in different design variants of the DWHR system, for a mixed water temperature of T_m = 38 °C, and for various scenarios of changes in electricity prices in the power system in Poland from 2023 to 2038.

	The Life Cycle Cost Reduction Index of the Investment, EUR											
	Scenario 0			Scenario I			Scenario II			Scenario III		
The future years, ta	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III	Variant I	Variant II	Variant III
	Volume Flow Rate of the Mixed Water Q = 7.5 dm^3/min											
1	−826	−886	−876	−749	−828	−813	−733	−817	−800	−687	−782	−762
2	−503	−644	−610	−353	−532	−487	−323	−509	−462	−233	−441	−388
3	−197	−414	−357	23	−249	−176	67	−216	−140	199	−117	−31
4	96	−195	−116	382	20	120	439	63	167	611	192	308
5	374	14	113	724	277	401	793	329	459	1003	487	632
6	639	213	332	1049	521	669	1131	582	737	1377	767	940
7	892	403	540	1359	753	925	1452	824	1002	1732	1034	1233
8	1132	583	738	1654	975	1168	1758	1053	1254	2071	1288	1512
9	1361	755	927	1935	1186	1400	2050	1272	1494	2394	1530	1778
10	1579	919	1107	2202	1387	1620	2327	1480	1723	2701	1761	2032
11	1787	1075	1278	2457	1578	1831	2592	1679	1941	2994	1981	2273
12	1985	1223	1441	2700	1760	2031	2843	1868	2149	3273	2190	2503
13	2173	1365	1596	2931	1934	2221	3083	2048	2346	3538	2389	2722
14	2352	1499	1744	3152	2099	2403	3311	2219	2535	3791	2579	2930
15	2523	1628	1885	3361	2256	2576	3529	2382	2714	4032	2760	3129
	Volume flow rate of the mixed water Q = 10 dm^3/min											
1	−724	−805	−789	−624	−729	−706	−604	−714	−690	−544	−668	−640
2	−306	−486	−441	−110	−337	−279	−71	−307	−246	46	−218	−149
3	93	−182	−109	379	36	128	436	79	176	608	210	318
4	473	107	207	845	391	516	920	448	578	1143	618	764
5	835	383	507	1289	729	885	1380	798	961	1653	1006	1187
6	1179	646	794	1712	1051	1237	1819	1133	1325	2138	1376	1591
7	1508	896	1067	2115	1358	1572	2236	1451	1673	2600	1728	1976
8	1820	1134	1327	2498	1650	1891	2634	1754	2004	3041	2064	2342
9	2118	1360	1574	2863	1929	2195	3013	2042	2319	3460	2383	2691
10	2401	1576	1810	3211	2194	2484	3373	2317	2619	3860	2688	3023
11	2671	1782	2034	3543	2446	2759	3717	2579	2904	4240	2977	3339
12	2928	1978	2248	3858	2687	3022	4044	2828	3176	4602	3254	3641
13	3173	2165	2452	4159	2916	3272	4356	3066	3436	4947	3516	3927
14	3406	2342	2646	4445	3134	3510	4653	3292	3682	5276	3767	4201
15	3628	2511	2831	4717	3341	3736	4935	3507	3918	5589	4005	4461

Taking into account the increase in electricity prices and, consequently, the increase in operating costs, it affects the reduction of the payback period for the investment related to the system of the heat exchanger for all described variants of hot water preparation system.

It is estimated that for the analyzed scenarios of electricity price changes, the design solution described as Variant I allows for savings ranging from EUR 3361 to 6715 in the 15th year of system operation compared to the conventional system (Variant IV).

In the case of using Variant II, for the study case in the 15th year of DWHR system operation, financial savings related to the application of the heat exchanger can range from EUR 2256 to 5456 compared to the conventional system, depending on the increase in energy prices.

Variant III of the waste heat recovery system from greywater enables achieving financial savings ranging from EUR 2576 to 4902 compared to the investment costs and operating costs incurred after the assumed system operation period (in the 15th year of system operation), depending on the increase in energy prices in the Polish power system.

4. Conclusions

The results of the conducted experimental and economic analysis (LCC) confirm the viability of heat recovery from greywater in residential buildings. The obtained data demonstrate that the collaboration of a vertical heat exchanger of the "tube-in-tube" type in each of the described configurations allows for a significant reduction in energy consumption for the preparation of domestic hot water.

However, it should be noted that the system of a heat exchanger does not always represent a financially viable alternative to a conventional system without a DWHR unit, as the reduction in costs associated with the preparation of domestic hot water does not solely determine the financial viability of installing a heat exchanger.

The heat recovery system designed according to Variant I proved to yield financial benefits in the shortest period of time among the analyzed options.

The least favorable outcome was observed for Variant II. The Life Cycle Cost (LCC) analysis conducted for the single-family building showed that over a 15-year operational period, the DWHR system in which preheated water only flowed to the electric water heater resulted in the lowest financial benefits. This is due to the high investment costs that exceed the achieved savings resulting from the reduction in electricity consumption for the preparation of domestic hot water.

It is worth noting that in the analyzed case study, the difference between the investment costs of the DWHR systems and the estimated costs for the conventional system was mainly dependent on the heat exchanger price. Therefore, it is assessed that the costs associated with purchasing the DWHR unit can significantly impact the investment's profitability.

The sensitivity analysis of the Life Cycle Cost (LCC) indicator demonstrated that an increase in operating costs for the domestic hot water (DHW) preparation system resulting from higher electricity charges shortens the projected operational period required to achieve financial profits. This relationship was observed across all configurations of the DWHR system. Based on the above conclusions, it can be stated that in the case of the analyzed single-family building, the profitability of the DWHR system was primarily dependent on the heat exchanger price and the unit cost of energy. It is important to emphasize that the decision to adopt a specific heat recovery system configuration should consider the technical conditions of the heat exchanger system, as well as the average annual temperature of cold tap water and the temperature of water intended for bathing or showering.

Based on the conducted economic analysis for the case study utilizing the results of experimental research on the energy efficiency of waste heat recovery system, the following conclusions have been formulated:

1. The configuration of the heat recovery system significantly impacts the level of financial savings achieved and the payback period.

2. As demonstrated by the scenario analysis, projected increases in electricity prices can have a significant impact on the economic efficiency of the investment, leading to a shorter period for the investor to reap the financial benefits resulting from reduced energy consumption for the preparation of domestic hot water.
3. The Life Cycle Cost (LCC) indicators of individual configurations of domestic hot water preparation system are not equally susceptible to changes in electricity prices.
4. It can be inferred that the payback period for the initial investment will further decrease with the adoption of a scenario assuming a more negative forecast of electricity price increases.

Based on the analysis of the research results published so far, it was found that a major limitation in the use of DWHR units in residential buildings may be the lack of available space for development, which can be problematic, especially in the case of vertical heat exchangers. In addition, the price of heat exchangers available on the market is a limitation for potential users, which is why financial support programs may be important to eliminate this problem. Moreover, the introduction of appropriate legal regulations requiring the use of greywater as an alternative source of energy would certainly contribute to the popularization of this type of solution.

In addition, by analyzing possible strategies for further development of research on the recovery of waste heat from greywater, directions for further research were formulated, the results of which may prove important in the context of increasing economic benefits and popularization of DWHR systems.

1. Energy and economic analysis of collective wastewater heat recovery systems in the residential sector in the context of the purposefulness of combining wastewater streams, e.g., from single-family housing estates.
2. Development of high-efficiency and compact heat exchanger solutions, the construction of which would allow us to reduce the production costs and selling prices of devices, and their use would not require a large available space for development.
3. Development of tools supporting the decision-making process in the context of selecting the optimal type of heat exchanger and configuration of the DWHR system depending on the operating parameters.

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