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Family Dwelling House Localization in Poland as a Factor Influencing the Economic Effect of Rainwater Harvesting System with Underground Tank

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Abstract: Considering water resources, Poland ranks among the last in Europe. By using rainwater for sanitary purposes, drinking water is saved. This article presents the results of the economic analysis of rainwater utilization systems, based on a novel view that takes into account factors related to the location of the family detached house in the country, such as average annual rainfall and water and electricity prices. Two cases of rainwater management systems (domestic-garden and garden) were analyzed in six locations, while considering the diversity of precipitation in Poland in two variants, depending on the material of the tank, with two options of traditional electrical installation or photovoltaic panels. The evaluation of the profitability of the investment was carried out on the basis of indicators: NPV, LCC, and SPBT. The results of the analyses of all variants give the conclusion that, to achieve the greatest financial benefits, it is crucial that the building's rainwater demand is fully met by rainfall, the unit price of water is significantly higher than the unit price of electricity, operating costs are as low as possible through the use of renewable energy sources, and subsidies are a significant percentage of the investment.

Keywords: rainwater harvesting systems; price of water; water consumption; detached house; PV panels; storage tank; simple payback time SPBT; net present value NPV; life cycle cost LCC

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1. Introduction

Our planet's water resources are an extremely valuable and indispensable natural resource. Unfortunately, in recent decades, there has been a trend of declining water resources worldwide. This problem has several causes, among which are cited [1–4]:

- Climate change: global warming and climate change are contributing to rising temperatures, resulting in the accelerated evaporation of surface water. In addition, some regions are experiencing extreme weather events, such as prolonged droughts, which further reduce the availability of water.
- Degradation of aquatic ecosystems: water pollution, deforestation, overuse of water resources, and destruction of wetlands are leading to the degradation of aquatic ecosystems. These changes negatively affect water retention and natural purification processes, leading to a decrease in the availability of clean water.
- Increasing demand for water: population growth, economic development, urbanization, and agriculture require increasing amounts of water. The increasing demand for water associated with various economic sectors is resulting in the overuse of water resources.

The consequences of declining water resources are threats in the areas of: (1) food security and rising food prices, (2) public health and the risk of developing various diseases, and (3) water ecosystems, in which many water-dependent fish, bird, and plant species live.

The unsustainable balance of water resources is causing rising costs for its treatment and supply. This prompts measures to reduce water consumption. The need to save water has both an ecological and economic aspect. The implementation of a system that reduces the consumption of potable water in buildings can bring numerous tangible benefits from environmentally friendly solutions. This problem not only affects specific regions, but is global in scope.

Poland, like many other countries, is facing the challenges of dwindling water resources. In recent years, the country has experienced severe droughts and water shortages. Low groundwater levels, visibly declining lake water levels, and declining river levels are having a negative impact on agriculture, aquatic ecosystems, and the economy. According to the Central Statistical Office report titled "Poland on the path of sustainable development" [5], the situation is very worrying. Poland's water resources are small, characterized by significant seasonal variability and spatial diversity. On a per capita basis, Poland's water resources amount to less than 1.6 thousand cubic meters, which puts the country in one of the last places in Europe in this regard (ahead only of Malta, Cyprus, and the Czech Republic). This indicates a real threat of water scarcity, as, according to the United Nations, the limit of water scarcity has been set at 1.7 thousand m^3 per capita.

Water consumption in buildings is an important aspect of water resource management and environmental efficiency. The amount of water consumed in buildings is influenced by determinants that can be divided into three groups:

(1) Water supply infrastructure and plumbing systems: Properly designed, operated, and maintained water supply systems affect the efficiency of water delivery to users. The use of water-efficient appliances and tapware directly affects water consumption and can significantly reduce water use.
(2) User behavior and habits: The level of awareness of users about water resources and the efficient use of water, as well as education on water efficiency, such as information campaigns, can influence users to change their habits and reduce consumption.
(3) Water regulation and pricing policies: Water tariffs, fees, and subscription fees can influence user behavior and motivate water efficiency. Introducing and enforcing appropriate standards, including building certification, can promote technological innovation and encourage less water consumption in the use of appliances and systems.

In the context of the search for alternative water sources, the concept of using rainwater in buildings is interesting. In Poland, rainwater, previously recognized as wastewater, was defined in the Water Law [6] as the water resulting from precipitation. This has changed the approach to dealing with it. According to the ordinance [7], if rainwater collected in retention tanks is used to flush toilets, irrigate greenery, or for other cleaning activities, a separate system must be designed for it. This provision significantly facilitates the implementation of rainwater recovery systems in buildings. Therefore, rainwater, subject to treatment processes, can be used for specific purposes. An important issue from the point of view of implementing a system to reduce water consumption in a building is the division of consumption points into:

- those requiring a supply of drinking water (tap), which provides water for food, personal hygiene, and dishwashing purposes, with the quality specified in the decree of the Minister of Health [8], or;
- others, which can be supplied with water of lesser quality than drinking water, e.g., gray water generated during bathing and hand washing, after it has been treated in an adapted system, or rainwater, after it has been treated and stored. It is necessary to clearly label the rainwater collection points as water not suitable for human consumption.

The average standards for water consumption in Poland for different water consumers are given in the regulation [9]. The average daily water demand per capita in residential buildings is 80–160 $dm^3/(day \cdot resident)$, depending on the installation equipment in the apartment. The lower water demands values: 80–100 $dm^3/(day \cdot resident)$ apply to buildings with a local hot water preparation system. Currently, there is a reduction in water demand in residential buildings. Measurements for single-family buildings show that the average water demand in Poland is 120 $dm^3/(day \cdot resident)$ [10]. Table 1 shows the structure of water consumption for domestic purposes in residential buildings in Poland [10–13], Portugal [14,15], and Slovakia [16]. In Poland, according to various references [10–13], the distribution of water consumption for different purposes differs only slightly. However, the structure of water consumption varies in different countries. This is determined by their geographical location and the associated habits of the population. For example, in Portugal, the demand for water for personal hygiene and for irrigation of green areas around buildings is higher than in Poland. The structure of water consumption makes it possible to note that the use of rainwater for toilet flushing, cleaning purposes, laundry, or irrigation of green areas makes it possible to reduce the consumption of potable water in residential buildings by about 50% in Polish conditions.

Table 1. Percentage distribution of water consumption in residential buildings.

Structure of Water Consumption	Literature References					
	Poland [10]	**Poland [11]**	**Poland [12,13]**	**Portugal [14]**	**Portugal [15]**	**Slovakia [16]**
Consumption and dishwashing	7.4	3 + 10 = 13	4 + 6 = 10	8 + 1 = 9	5 + 2 = 7	6 + 5 = 11
Hand washing and bathing	36.5	10 + 26 = 36	35	14 + 39 = 53	10 + 32 = 42	36
Toilet flushing	29.8	30	32	29	28	29
Laundry washing	15.5	15	15	8	8	15
Gardening, car washing	10.8	6	8	1	15	9
Total consumption	100%	100%	100%	100%	100%	100%
Daily water demand per capita, dm^3	avg. 119	100–150 avg. 125	no data	avg. 154	avg. 165	avg. 120

In public buildings, on the other hand, where water is mainly used to flush toilets and for cleaning purposes, replacing it with rainwater will reduce tap water by up to 90% for office buildings (Table 2). This translates into savings from lower charges for mains water, as well as reducing water service charges.

Table 2. Percentage distribution of water consumption in public buildings [17].

Structure of Water Consumption	Public Building (Generally)	Office Building	Rooms in Hotels
Gastronomic	9	-	-
Hand washing	27	10	44.7
Body washing	-	-	32.6
Toilet flushing	43	49.9	22.4
Urinal flushing	20	-	-
Cleaning and other needs	1	40.1	-
Water leaks	-	-	0.3
Total consumption	100%	100%	100%

In the aspect of implementing an installation to reduce drinking water consumption, a key element is the achievement of economic effects. The aforementioned determinants indicate the need to consider many aspects when evaluating potential financial benefits. Analyses that take into account the different areas, design of the roof, volumes of rainwater storage tanks, and number of occupants are known. However, the location can also affect the economic aspect of the investment [18]. Different regions have not only fluctuating precipitation, but also different water fee structures that can affect the cost-effectiveness of rainwater use. Some jurisdictions may offer financial incentives or preferential prices for buildings that use rainwater recovery. It is necessary to understand the applicable regulations and policies on water prices. In addition, due to the significant investment costs, it is necessary to analyze and compare potential savings to assess the viability of the project. This article presents the results of an analysis to determine the financial efficiency of a rainwater harvesting system for a single-family house, depending on its location in the country. The regions' differences, in terms of tariffs, subsidies, precipitation, and types of storage tank and electric installation, are considered and assessed by the dynamic and static indicators. The method of analysis presented seems to be novel and significant for the accuracy of results, as indicated by the analyzed data.

2. Materials and Methods

2.1. Installation of Rainwater Recovery and Use in a Single-Family Building

Use of rainwater requires the design of dual systems in a building. Rainwater, which is generated by precipitation, is collected in dual systems, from roofs, balconies, terraces, or other surfaces with a low degree of pollution, with roofs being the preferred surface for rainwater collection. Its purity depends on the surface it comes into contact with, as well as the purity of the air. No additional treatment system is required, as the water is purified in a special filter [19,20].

In recent years, rainwater systems have become increasingly popular among investors. Companies offering rainwater recovery systems have a variety of solutions to offer their customers, ranging from offering specific components, such as retention tanks, filters, pumps, and distribution systems that can be customized to meet individual customer needs and requirements, to comprehensive solutions that include the design, installation, and maintenance of rainwater recovery systems. The companies offer dedicated solutions for specific types of buildings, such as single-family houses and commercial or public large-scale buildings with different uses.

In the case of a single-family house, depending on how rainwater is used, there are three systems:

- garden—allowing the use of rainwater for the irrigation of green areas during the growing season of plants, and for cleaning purposes or washing cars;
- domestic (indoor)—allowing the use of rainwater for flushing toilets and/or urinals, and for laundry and cleaning purposes; and
- domestic-garden, which is a combination of the above systems. An example diagram of a domestic-garden with an underground tank is shown in Figure 1.

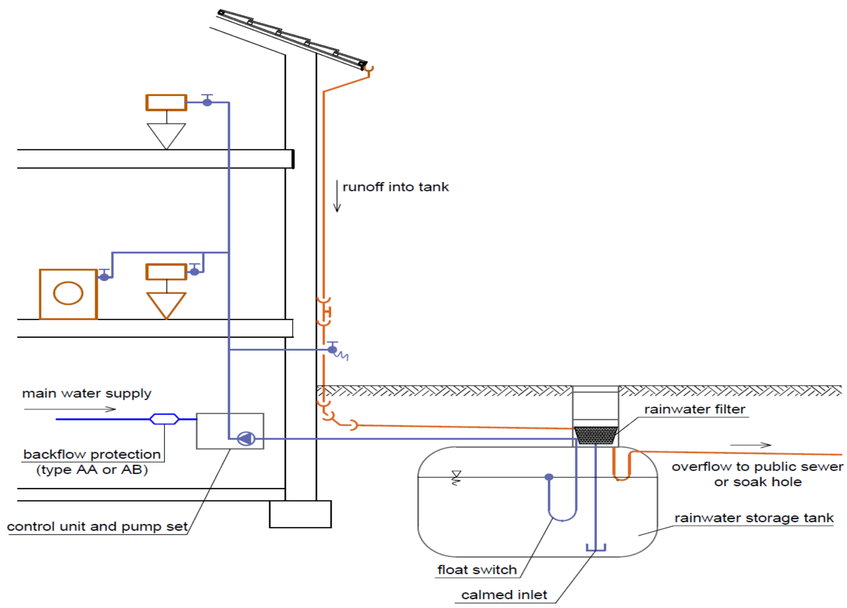

Figure 1. Scheme of domestic-garden rainwater management system with an underground tank.

In the rainwater management system shown in Figure 1, a filter system cleans rainwater of solid and biological contaminants, so that the water collected in the tank is clear and odor-free. Filters can be mounted on drainpipes, or there can be a so-called central filter mounted in front of the tank or in the tank at the rainwater inlet. The rainwater tank simultaneously serves as another cleaning stage. The oxygen-enriched rainwater is fed through a feed line with a calmed inlet to the bottom of a storage tank. Pollutants smaller than the mesh size of the filter settle to the bottom of the tank when they are heavier than the water, or float to the surface of the water when they are lighter, usually containing elements of organic matter. The sediment layer carries out a clarification function, thanks to the constant oxygen entry, even with low amounts of rain. Because of the low temperature of the water and the lack of sunlight, biological processes are inhibited, and the quality of the stored water does not deteriorate. In the event of heavy rainfall, suspended solids are discharged outside the tank when it overflows. A periodical storage tank overflow is desired because it supports the self-cleaning of the stored rainwater.

The most important, and also most expensive, component of a rainwater recovery system is the rainwater storage tank. The storage tanks available on the market are of different sizes, adapted for installation outside the building and inside the building, e.g., on the lowest floor (usually in the basement), and are made of different materials, i.e., plastic—polyethylene and polypropylene, concrete, corrosion-resistant steel, reinforced concrete, and fiberglass-reinforced polyester resins, with different shapes in decorative form for above-ground installation, typically in the shape of cylinders or cuboids. The most important aspect for the effective operation of the entire system is the correct determination of the volume of the tank. A tank with too large a volume generates higher investment costs and may also contribute to the deterioration of the quality of stored rainwater. On the other hand, a tank volume that is too small will contribute to the inefficient operation of the rainwater recovery system and prevent the storage of an adequate supply of water, which will require the system to be supported by water from the water supply system during non-rainy periods, while, in the case of longer or heavy rainfall, it will cause the tank to overflow and, thus, lose rainwater [21,22]. The location of the tank depends on the chosen rainwater management system. In the case of the use of rainwater for irrigation of greenery, above-ground tanks are mounted outside the building, usually at rainwater drainage pipes, and their operation in Polish conditions is limited from spring to autumn. In the case of domestic-garden systems, which are operated year-round, underground tanks or tanks located inside buildings are used. When deciding on the choice of an underground tank, the prevailing ground conditions should be taken into account, i.e., the maximum level of groundwater and the type of soil, the ground frost depth, and the potential load on the area due to pedestrian and vehicular traffic. It is absolutely necessary to follow the manufacturer's installation guidelines for maximum coverage and distance from other objects, such as buildings, roads, and embankments.

The pumps, together with the control system, ensure the flow of rainwater at the appropriate pressure. A distinction is made between systems equipped with submersible pumps mounted in the tank, which are used primarily in garden systems, and systems with normally aspirating or self-priming pumps operating at constant speed, or with a variable speed control located outside the tank in the so-called rainwater control panels. When using aspirating pumps, the suction side pipelines should be run with an elevation in the pump direction. The diameter of the pipe should be determined so that the flow velocity in it is 0.8–1.5 m/s [23], and the difference in pipe length and height between the bottom of the tank and the pump/rainwater control panel should be maintained, as much as possible, according to the pump manufacturer's guidelines. For multi-pump systems, separate pipes are used for each pump in the suction operation.

In the event of a long period without rain, it is necessary to switch the rainwater system to the main water supply. For this purpose, a connection to the mains water is made in rainwater management systems. The switchover occurs automatically when the minimum water level is reached in the storage tank. On the supply of the rainwater recovery system with mains water, backflow protection must be provided according to PN EN 1717 [24]. In each case, the connection to the potable water supply system must be verified with an air-break solenoid valve. If this solution is not included by the manufacturer, it is absolutely necessary to make one, using AA or AB air gap protection.

2.2. Methodology for Designing Rainwater Systems

Several different methods for designing a rainwater management system exist which are tailored to the complexity of the rainwater system and the purposes for which the collected rainwater can be used. A key element is the design of the correct tank volume and hydraulic sizing of the rainwater system. The determination of the design flow, the principles of the diameter selection, and the determination of pressure losses in the system are carried out according to the applicable national standard for the design of water supply systems; in Poland, this is PN-B-01706 [25]. Selecting diameters should be guided by the criterion of allowed velocity. The determination of the volume of the tank can be carried out according to the following methods: simplified, intermediate approach, and detailed given in the standards [26,27], according to the manufacturers' guidelines or simulation methods [28]. Based on the guidelines of standards, manufacturers, and distributors of rainwater management systems, it is necessary, in each case, to analyze the values of rainwater requirements adopted for particular applications. When determining the size of the tank, it is necessary, according to the chosen methodology, to assume a rainwater storage period of 14 to 21 days, or even 30 days for residential buildings, which, according to the manufacturer [29], is more in line with the actual demand for rainwater in the warm months.

To achieve the desired economic benefits and ensure proper operation of the rainwater management system, it is necessary to:

- adopt annual rainfall totals from a 30-year period for the location;
- determine the area from which rainwater will be collected and adopt the runoff coefficient depending on the coverage;
- for other surfaces, take into account only those whose contact with rainwater will not result in it containing major contaminants;
- determine the annual yield of rainwater and, based on the result, adopt the method of application of rainwater so that the demand is approximately equal to the yield;
- provide an emergency supply of water from the water mains and an appropriate backflow-prevention assembly on the pipe supplying tap water to the rainwater system;
- unambiguously mark rainwater collection points as water unfit for human consumption; and
- use plastic materials for rainwater systems, due to their high corrosivity.

In engineering practice, it is common to use the intermediate approach according to the standards [26,27], on the basis of which, taking into account the relevant guidelines, assumptions are made, such as:

- Average annual precipitation h_N over a 30-year period is expressed in dm^3/m^2 or mm, depending on the location of the building, read from a map available on the website [30]. For Poland, information can also be obtained from the IMGW website [31], where averaged precipitation totals for the 30-year normal period 1991–2020, based on data from 58 synoptic stations, are tabulated;
- The size of the drainage area A_A, which, in the case of a roof, is calculated as the area in the horizontal projection, regardless of the shape and slope of the roof. For other types of surfaces, only the area where it rains is taken for calculation;
- The value of the runoff coefficient e is adopted according to the type of drainage surface and the material with which it is covered; and
- Hydraulic efficiency of the filter η is usually assumed to be 0.9, or is based on the filter manufacturer's guidelines, as appropriate.

In the following steps of the methodology, the annual rainwater yield E_R was determined according to the relationship (1):

$$E_R = A_A \times e \cdot h_N \times \eta \quad (1)$$

where:

A_A—drainage area, m^2
e—runoff coefficient, -
h_N—average annual precipitation, dm^3/m^2, mm
η—hydraulic efficiency of the filter, -

and annual rainwater demand BW_A, according to relation (2):

$$BW_A = Pd \times n \cdot 365 + ABew \times BS_A \quad (2)$$

where:
Pd—daily rainwater demand per person, dm^3/(person-day)
n—number of people in the building, -
ABew—irrigated area, m^2
BS_A—specific annual rainwater demand for irrigated area, dm^3/m^2.

Based on the smaller of the calculated annual yield (1) and rainwater demand (2), the usable volume of the tank Vn is determined according to the relationship (3):

$$Vn = \text{minimum from } (BW_A \text{ or } E_R) \times W \quad (3)$$

The W factor in Formula (3), according to [26], is 0.06, and ensures that rainwater storage space is included in the calculation and is available for a period of 21 days without rainfall. On the contrary, the British Standard [27] gives a factor of W = 0.05, assuming an 18-day period.

The amount of rainwater used in a building and the annual water yield should be as equal as possible to ensure the best use of collected rainwater. The allowable deviation between the values should not be more than 20%, according to the Rainwater Recovery System Design Guide [29].

2.3. Characteristics of Precipitation in Poland

Precipitation in Poland fluctuates widely from year to year. According to the classification of pluvial conditions in Poland in the 1952–2022 period, there were both dry years, in which precipitation values were between 50 and 74% of normal values, and extremely wet years, in which precipitation values reached 126 and 150% of typical values [32].

The amount of precipitation in Poland depends largely on the terrain and distance from the sea. In the Polish lowlands, the annual precipitation is 500–600 mm. The lowest precipitation heights are recorded in eastern Greater Poland, Kujawy, and northwestern Mazovia. These areas are located in the shadow of precipitation of the Pomeranian Lake District and, at the same time, are far from the sea. Annual precipitation in these regions does not exceed 500 mm. The Mazurian and Pomeranian Lake Districts are characterized by an annual precipitation of 600–700 mm. Higher values are observed in the uplands—up to 800 mm. The northern and western parts of the Sandomierz Valley, due to its location in the rain shadow of the Swietokrzyskie Mountains, have an annual precipitation of 500–600 mm. The highest annual precipitation totals are recorded in the mountains, where they exceed 1200–1500 mm. The highest recorded precipitation in Poland occurs in Kasprowy Wierch, with an annual sum exceeding 1900 mm. Figure 2 shows a map of precipitation totals for Poland in the 30-year period 1991–2020 [30].

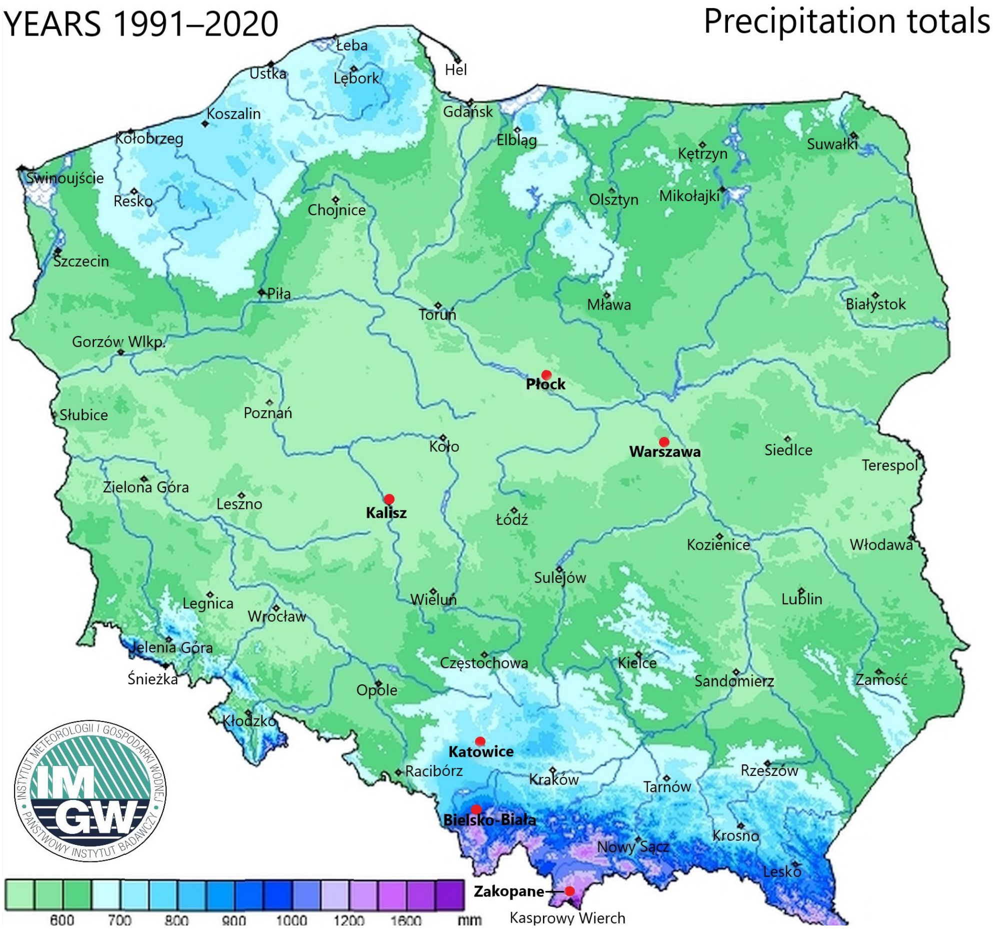

Figure 2. Average annual total precipitation in Poland for the years 1991–2020 [30].

Considering the annual distribution of precipitation in Poland, summer precipitation predominates. Climatic changes caused by rising air temperatures contribute to an increase in annual precipitation totals, but the projected increase in the 2030-going 20-year period compared to the reference period 1971–1990 is 1–4 percent and statistically insignificant. There is a projected trend of a few-percent increase in precipitation in the autumn and spring seasons and a decreasing share of summer precipitation in the annual precipitation total. However, despite the decrease in summer precipitation, it is worth noting that precipitation is currently characterized by greater intensity and contributes to a higher incidence of flash floods, waterlogging, and flooding [33].

2.4. Water Tariffs in Poland

Water prices in Poland are shaped by a number of factors, including the costs of production, distribution, transportation, access to water resources, and legislation. Water production costs include raw materials, electricity, chemicals, and infrastructure maintenance costs, among others. Water distribution costs are related to the maintenance of the water supply network and the cost of managing infrastructure, such as pipes, pumps, and water treatment plants. Additionally, water transportation costs depend on the distance between the water source and the place of consumption. Water prices are determined on the basis of the Law on Determination of Tariffs, Model Application for Approval of Tariffs, and Terms of Settlement for Collective Water Supply and Collective Sewage Disposal, based on the adjustment of the development and modernization plan for water supplies and sewerage facilities scheduled for implementation in the year of the tariff. One of the bases for differentiating prices and fee rates is the division of service recipients into two basic tariff groups: households and industrial customers. The possibility of differentiating prices and rates of charges for groups of customers is aimed at best adapting the tariff to the group, in order to provide the company with the necessary revenues, on the one hand, and to motivate rational use of water on the other. Appropriate tariff prices and fee rates should therefore ensure that the charges of service recipients generate revenues that ensure the self-financing of the enterprise's operations and its profit. Water and sewer system companies develop tariffs for collective water supply and sewage disposal in municipal areas. Thus, water prices in Poland vary depending on the region, the type of customer, and the billing method. In some places, particularly in rural areas, water prices may be higher, due to lower population density and higher water distribution costs.

2.5. National and Local Financial Support Programs

Rainwater management is a growing challenge, especially in cities and densely built-up areas, which is why more and more emphasis is being placed on designing sustainable rainwater management systems that allow on-site rainwater management. The implementation of rainwater management systems is currently being promoted in Poland through financial support programs at the national level, such as the My Water program (in Polish "Moja Woda"), funded by the National Fund for Environmental Protection and Water Management, and at the local level, through programs funded by cities and municipalities. The My Water program has been announced for the years 2020–2024. Owners of single-family houses can obtain a grant in the amount of up to 5000 PLN for installing domestic rainwater management systems, but no more than 80% of the investment costs incurred for implementing the system. The condition to receive the subsidy is a system with a rainwater tank with a minimum capacity of 2000 dm^3. In 2023, the call for applications for the program is expected to be announced in the fourth quarter. Subsidies from the My Water program can be combined with local government programs, as long as the total amount of subsidies does not exceed 100% of the investment cost.

Many local governments offer support for the implementation of sustainable rainwater management systems in their areas. In Kalisz, it is possible to obtain a subsidy of up to 100% of the cost of purchasing a rainwater tank, with the amount of the subsidy depending on the size of the tank and amounting to a maximum of 2000 PLN for tanks larger than 1000 dm^3. In Bielsko-Biala, as part of the "Bielsko-Biala Catches Rain" program, subsidies can be obtained in the amount of up to 50% of the expenses incurred for the purchase of the tank, its installation, and connection to the rainwater drainage system, but not more than 3000 PLN for underground tanks with a capacity of no less than 1000 dm^3. Warszawa, as part of the "Warszawa Collects Rainwater" program, offers a subsidy of up to 4000 PLN for the purchase and installation of tanks and infiltration systems, but no more than 80% of the costs incurred. In Wroclaw, as part of the "Catch the Rain" program, 80% of the cost of purchasing tanks and infiltration systems can be reimbursed, but no more than 5000 PLN for individuals. On the other hand, in Poznan, the subsidy for small retention is a maximum of 6000 PLN, provided that 80% of investment costs are not exceeded. The city that has a local subsidy program "ZbieraMY deszczówka" with the highest subsidy is Łódź. Individuals can apply for reimbursement of 80% of the cost, with a maximum of 10000 PLN. A grant of 10000 PLN can also be obtained for the construction and installation of rainwater management systems in Gdynia. For more detailed information on local government programs to subsidize rainwater management systems and the rules for receiving subsidies, please visit the websites of city offices.

3. Results and Discussion

3.1. Building and Installation Characteristic

An analysis of the feasibility and profitability of rainwater management was carried out using the example of a large single-family house inhabited by 6 people. Due to the variation of annual rainfall totals in Poland, it was decided to choose six locations for the single-family house localities with different values of rainfall. The selected locations are those marked with red dots in Figure 2. These are the cities of Kalisz, Plock, Warszawa, Katowice, Bielsko-Biala, and Zakopane. The building has a basement and two floors above ground. The area of the garden for irrigation is 500 m^2. The installation of water and rainwater was assumed to be made of polypropylene material.

The comparison case for the analyzed cases of rainwater management was named as Case 0, which means that there is no rainwater management on the property; instead, rainwater flows onto the ground surface next to the house.

For the analysis, two solutions for rainwater management systems were adopted, in which two options were considered: a plastic tank of the TRY HDPE type, from the manufacturer EuroPlast [34], and a concrete tank from the IRPOL company [35]. The analyzed options were called:

- Case 1: domestic-garden:

  W1—system with plastic rainwater tank by EuroPlast;
  W2—system with concrete rainwater tank by IRPOL.

- Case 2: garden:

  W3—system with plastic rainwater tank by EuroPlast;
  W4—system with concrete rainwater tank by IRPOL.

In Case 1, presented in Figure 3, water is supplied by a pipe, 50 × 4.6 mm from the water supply network, and delivered to 5 installation wells (WI–WV). Cold water is supplied to 8 rooms: in the basement, to a bathroom for a sink and shower; on the first floor, to two bathrooms for a bathtub, two sinks, and a shower; to the kitchen for a dishwasher and sink; in the attic, to three bathrooms for a sink and shower. The system supplies the rainwater control panel, RWC, and hot water preparation system, WH. Rainwater is delivered from the rainwater tank (RWT) to supply the toilet in the basement in the bathroom, two washing machines in the laundry room, the toilets on the first floor in two bathrooms, the toilets in the three bathrooms in the attic, the tap valve to purposes garden-watering. Thus, it was assumed that rainwater will be used for toilet flushing, laundry, and garden-watering. According to the standard [26], the annual rainwater demand for a household toilet is 24 dm^3/per day, and the connection of a washing machine requires an increase of 10 dm^3 per day. The specific annual rainwater demand for irrigating the BSA area is 200 dm^3/m^2; hence the annual rainwater demand of the BW_A, calculated according to relation (2), is:

$$BW_A = (24 + 10) \times 6 \times 365 + 500 \times 200 = 174460\ dm^3/year$$

Hydraulic calculations that included the selection of pipe diameters were carried out according to the assumptions of the standard [25]. Table 3 shows the values of normative outflows for individual draw-off points and the sum of normative outflows. Furthermore, it is considered that the demand for hot water for the entire building is equal to 5.59 dm^3/s.

Table 3. Normative outflow in a single-family house.

Draw-Off Point	Quantity	Normative Outflow Water dm^3/s	
		q_n Cold Water	q_n Rainwater
Toilet	6	0	0.13
Washing machine	2	0	0.25
Tap valve	1	0	0.5
Washbasin	8	0.07	0
Bathtub	2	0.15	0
Shower	6	0.15	0
Sink	1	0.07	0
Dishwasher	1	0.15	0
Total of outflow water		1.98	1.78

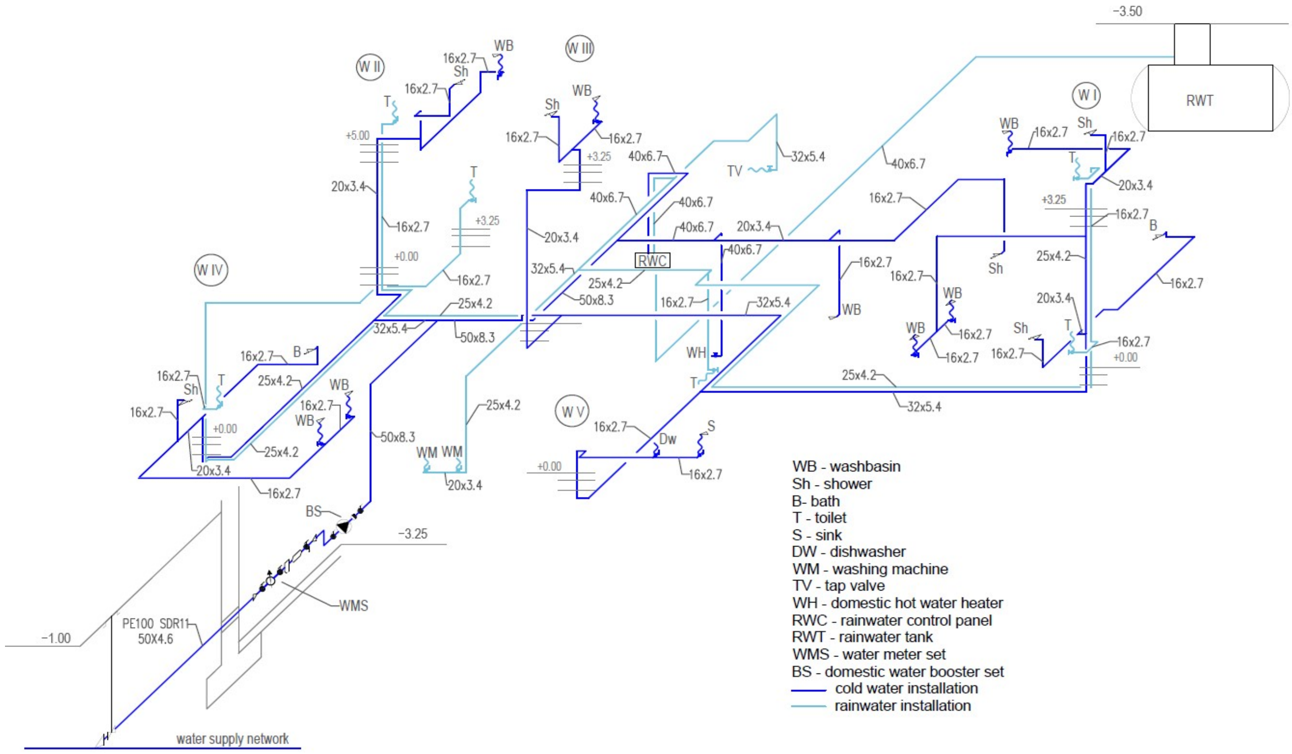

Figure 3. Scheme of cold and rainwater installation for domestic and garden purposes.

In case 2, rainwater collected through gutters is directed to a tank (two variants, W3 and W4) and used to garden-watering. In the case of a rainwater shortage, the tank is replenished with potable water. The specific annual rainwater demand for irrigation of the BSA area is 200 dm^3/m^2; hence, the annual rainwater demand of the BW_A according to relation (2) is:

$$BW_A = 500 \times 200 = 100{,}000\ dm^3/year$$

3.2. Size of Rainwater Tank

Both the high cost of purchasing a tank and the importance of its volume in the operation of a rainwater recovery system require meticulous analysis during its selection. In view of these factors, to perform the analysis, an intermediate approach was used to select the tank volume according to the standard [26], based on the assumptions made:

- Average values of annual precipitation totals h_N, expressed in mm, for the normal 30-year period 1991–2020 for selected locations were read from the IMGW website of [31] and are summarized in Table 4;
- The size of the drainage area A_A will be the sum of the roof area calculated in the horizontal projection: 253.98 m^2 for a sloping roof and 39.52 m^2 for a flat roof;
- The value of the runoff coefficient e was assumed, that is, according to the type and material of the drainage area: sloped roof, glazed tile equal to e = 0.9, flat roof e = 0.8;
- The hydraulic efficiency of the filter η was assumed to be 0.9.

Table 4. Average annual total precipitation and rain yield in selected locations.

Location/City	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
Annual total precipitation h_N; mm	493.8	511.5	549.7	723.2	998.3	1145.0
The annual rainwater yield E_R $dm^3/year$	116,340	119,782	129,510	169,357	233,780	269,763

The annual rainwater yield E_R calculated in each city is shown in Table 4.

Using relation (3), the smaller value of the calculated annual yield (Table 4) and rainwater demand (BW_A) was indicated and the usable tank volume Vn was determined. In case 1 for both variants, the proposed tank capacities and their prices according to [34,35] are shown in Table 5. Selected volumes of tanks in variants W1 and W2 in some cases differ due to the limited offer of concrete tank volumes by the manufacturer.

Table 5. Rainwater tank choice in case 1.

Location/City	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
Min. BW_A or E_R dm^3/year	116,340	119,782	129,510	169,357	174,460	174,460
Vn dm^3	6980	7187	7771	10,161	10,468	10,468
Tank size W1, dm^3	7000	8000	8000	11,000	11,000	11,000
Price W1, PLN	8399	9035	9035	12,147	12,147	12,147
Tank size W2, dm^3	8000	8000	8000	12,000	12,000	12,000
Price W2, PLN	2600	2600	2600	3700	3700	3700

The annual rainwater demand of BW_A for irrigation purposes is less than the water yield ($BW_A < E_R$); therefore, for all locations, Vn is 6000 dm^3; so, a 6000 dm^3 tank is proposed. In such a solution, the location does not matter in the tank selection, as the annual rainwater yield is greater than the demand. The selected device is summarized in Table 6.

Table 6. Rainwater tank choice in Case 2.

Location/City	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
Min. BW_A or E_R dm^3/year	100,000	100,000	100,000	100,000	100,000	100,000
Vn, dm^3	6000	6000	6000	6000	6000	6000
Tank size W3, dm^3	6000	6000	6000	6000	6000	6000
Price W3, PLN	6678	6678	6678	6678	6678	6678
Tank size W4, dm^3	6000	6000	6000	6000	6000	6000
Price W4, PLN	2100	2100	2100	2100	2100	2100

3.3. Economic Analysis

Economic analyses can be described by a number of indicators known from the literature [36–38]. Those most commonly used are the investment cost and the operating cost associated with the utility consumption. The evaluation of the profitability of the investment was carried out based on dynamic methods, which used the calculated indicators, net present value NPV and life cycle cost LCC, and, based on the static indicator, SPBT simple payback time. These indicators are mathematically expressed as [36,39]:

$$SPBT_i = \frac{IO_i}{AS_i} \tag{4}$$

$$NPV_i = \sum_{t=0}^{n} \frac{CF_{it}}{(1+R)^t} - IO_i \tag{5}$$

$$LCC_i = INV_i + \sum_{t=1}^{T} (1+R)^{-t} \cdot OC_i \tag{6}$$

where:

$SPBT_i$—simple payback time for i-variant of installation;
IO_i—initial outlay for i-variant of installation, PLN;
AS_i—the annual savings for i-variant of installation, PLN;
NPV_i—net present value for i-variant of installation, PLN;
CF_{it}—cash flows in the year t for i-variant of installation, PLN;

R—required rate of return (discount rate), -;
t—year of system operation;
n—system life span, years;
LCC_i—life cycle cost for i-variant of installation, PLN;
INV_i—investment costs for i-variant of installation, PLN;
OC_i—operating costs in a year t for i-variant of installation, PLN;
T—duration of the LCC analysis, years.

SPBT is the time after which the aggregate savings from reduced utility consumption equals the invested capital and begins to generate a profit for the investor in the form of lower charges for the water used, in this case, assuming constant energy prices and ignoring the impact of inflation. However, the SPBT index is not authoritative for a full evaluation of investments. Therefore, it is appropriate to determine a dynamic NPV indicator. The NPV should have the value NPV > 0, meaning discounted proceeds of the project are greater than the investment outlays, so the project is profitable [40]. On the other hand, a tool based on life cycle costing (LCC) assumptions can be used to compare the economic efficiency of investment alternatives and the profitability of a product over its life cycle. Depending on the details and purpose of the analysis, there are three types of life cycle costing: conventional LCC (also called traditional or business LCC), environmental LCC, and social LCC [41]. This tool requires quite a lot of data and is complementary to NPV analysis. According to IEC 60300-3-3 [42], LCC is the total cost incurred over the life cycle of a product. The LCC analysis allows combining of the economic and technical aspects of the evaluated project over its projected life [43].

To indicate the initial outlay, the costs of traditional cold-water installations (Case 0) and dual cold-water installations were included in the calculations for each variant. The difference in the cost of these installations was the value of IO in Formulas (4) and (6), according to the relationship:

$$IO_i = INV_{Wi} - INV_{W0} \quad (7)$$

The cost of traditional installation (Case 0) includes: pipes and fittings of the cold-water system and the cost of installation of the water system. The total cost of the traditional installation INV_{W0} is 14901 PLN.

The costs of dual installation in variants W1 and W2 include:

- pipes and fittings for the installation of cold water, rainwater, drainpipes that bring rainwater from the drainpipes to the tank;
- installation of cold water, rainwater, and drainage pipes;
- tank and its installation, including excavation;
- rainwater control unit;
- rainwater filter;
- float valve installed in the tank.

Since the sizes of water tanks vary from city to city, the investment costs for each location vary. Table 7 shows the costs of the dual installation in variants W1 and W2 and the difference in the cost of IO_i', which does not take into account the subsidy offered under the support program for rainwater management investments presented in Section 2.5. Next, the maximum amount of subsidy is given, which is possible under the national support program My Water and under local programs, in the case of localities such as Kalisz, Warszawa, and Bielsko-Biala. Since the subsidy received cannot exceed certain maximums throughout the budget, the subsidy values may be different for the two options. Table 7 shows the initial outlay of IO_i, after taking into account the subsidies in each city.

Table 7. Initial outlay in Case 1 in variants W1 and W2.

Location	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
Investment cost INV_{W1}	43,516	44,286	44,286	47,802	47,802	47,802
Cost difference IO′ (W1-W0)	28,615	29,385	29,385	32,901	32,901	32,901
Subsidy	7000	5000	9000	5000	8000	5000
IO_{W1} PLN	21,615	24,385	20,385	27,901	24,901	27,901
Investment cost INV_{W2}	37,923	27,923	37,923	39,023	39,023	39,023
Cost difference IO′ (W2-W0)	23,022	23,022	23,022	24,122	24,122	24,122
Subsidy	7000	5000	7080	5000	7531	5000
IO_{W2} PLN	16,022	18,022	15,942	19,122	16,591	19,122

An analysis of the calculation results in Table 7 shows that the cost of installing rainwater management in a domestic-garden system with a plastic tank is about 3-times the cost of a traditional system and 2.5-times the cost of a concrete tank. The subsidies offered in the W1 variant range from 15% of the value of the additional investment costs (W1-W0), in the case of Plock, to as much as 31% in the nation's capital. In the W2 variant, the subsidy is 21–31% of the additional costs.

The costs of dual installation in variants W3 and W4 include:

- pipes and fittings for the installation of cold water, rainwater, and drainpipes that bring rainwater from the drainpipes to the tank;
- installation of cold water, rainwater, and drainage pipes;
- tank and its installation, including excavation (the work of the excavator to lay sewer pipes and the work of excavation and installation of the tank are included);
- a set including the replenishment of drinking water in the tank, a pump in the tank, a float valve installed in the tank, and protection against backflow;
- rainwater filter.

Since the sizes of the water tanks in variants W3 and W4 in each city are the same, the investment costs for each location are the same. Table 8 shows the costs of dual installation in variants W3 and W4, as well as the difference in IO_i' costs, the amount of subsidies in each city, and the initial outlay of IO_i, after taking subsidies into account.

Table 8. Initial outlay in Case 2 in variants W3 and W4.

Location	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
Investment cost INV_{W3}	35,455	35,455	35,455	35,455	35,455	35,455
Cost difference IO′ (W3-W0)	20,554	20,554	20,554	20,554	20,554	20,554
Subsidy	7000	5000	9000	5000	8000	5000
IO_{W3} PLN	13,554	15,554	11,554	15,554	12,554	15,554
Investment cost INV_{w4}	30,859	30,859	30,859	30,859	30,859	30,859
Cost difference IO′ (W4-W0)	15,997	15,997	15,997	15,997	15,997	15,997
Subsidy	7000	5000	6680	5000	6551	5000
IO_{W4} PLN	8957	10,957	9277	10,957	9405	10,957

Installation costs for the garden system, shown in Table 8, indicate that the cost of installing rainwater management with a plastic tank is 2.4-times that of a traditional installation and 2-times that of a concrete tank. The subsidy offered in the W3 variant ranges from 24 to 44% of the investment value, while, in the W4 variant, it is from 31 to 47%.

Annual savings (AS) take into account the profit from the savings in drinking water and operating costs resulting from the operation of electrical equipment requiring electricity. As outlined in Section 2.4, water and sewerage companies develop tariffs for collective water supplies in municipal areas, and these prices vary by up to 80%. There are several known electricity suppliers in Poland, and the prices of 1 kWh also vary from supplier to supplier and from region to region. The water and electricity price rates in effect in each city in May 2023 are given in Table 9.

Table 9. Water and electric energy prices in different cities in Poland.

City	Water Price, PLN/m^3	Electric Energy PLN/kWh
Kalisz	4.19	0.83
Plock	6.36	0.83
Warszawa	4.29	0.81
Katowice	6.37	0.74
Bielsko-Biala	6.75	0.76
Zakopane	3.75	0.76

According to the regulation [9], the water demand for a resident is 140 dm^3/day. For watering purposes under Polish conditions, 2.5 d m^3/m^2·day and watering for 75 days a year are assumed. Thus, the annual demand for water from the water supply network (ZR) in the analyzed building is:

- in the case of traditional installation—Case 0:

$$ZR_{W0} = (140 \times 6 \times 365 + 500 \times 2.5 \times 75)/1000 = 400.4\ m^3/year \quad (8)$$

- in Case 1 (Variant W1 and W2), the annual demand for mains water will be reduced by the lesser of E_R or BWa, depending on the location of the building:

$$ZR_{W1/W2} = ZR_{W0} - \min\ (E_R/BW_A),\ m^3/year \quad (9)$$

The value of annual water demand in Case 1 for each location is summarized in Table 10.

Table 10. The annual water demand from a water supply network in Case 1 for selected building locations.

Location	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
			Variant W1/W2			
ZR, m^3/year	284.0	279.8	270.8	230.0	225.9	225.9

In Case 2 (variant W3 and W4), the annual demand for water from the water supply network will decrease by a value of 100 m^3/year, regardless of the location of the building, and will amount to:

$$ZR_{W3/W4} = ZR_{W0} - 100.0 = 400.4 - 100.0 = 300.4\ m^3/year \quad (10)$$

Operating costs (OC) related to power consumption were determined by assuming the rated power of the rainwater control panel of 880 W, according to the manufacturer's data sheet, and the operating time per year for watering for one hour in 75 days, and, additionally, in variant W1 and W2 for sanitation, 193 h per year. Taking into account the price of water (Table 9) and the water yield E_R, due to the use of development systems, the annual savings S_W in the water fee were calculated for each variant. This made it possible to determine the simple payback time of all variants. The results are shown in Table 11. Payback, in all variants, requires many years, even almost 85 years, in the case of Kalisz. A similarly long payback time for a single-family house in Poland is presented in publications [20,28].

Table 11. SPBT for cases 1 and 2.

Location	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
			Variant W1/W2			
S_W PLN/year	487	766	556	1085	1178	654
OC PLN/year	233	233	227	207	213	213
AS, PLN	255	534	329	878	965	441
$SPBT_{W1}$	84.8	45.7	62.0	31.8	25.8	63.2
$SPBT_{W2}$	62.8	33.8	48.5	21.8	17.2	43.3
			Variant W3/W4			
S_W PLN/year	419	636	429	637	675	375
OC PLN/year	137	137	134	122	125	125
AS, PLN	282	499	295	515	550	250
$SPBT_{W3}$	48.1	31.2	39.1	30.2	22.8	62.3
$SPBT_{W4}$	31.8	22.0	31.4	21.3	17.2	43.9

Figure 4 shows the dependence of SPBT on the price of water for the different variants. In the city of Bielsko-Biala, where the price of water is the highest, the payback time for all variants is the smallest, and the total savings will be returned in equal time in both systems with a concrete tank. Similar results were obtained by the authors of the publication [14], in which different water prices in cities in Portugal influenced the shorter payback period in the city with the higher water price. In Kalisz, there is a coincidence of many factors that cause investment in rainwater management to have the longest payback period, and the SPBT rate is more than double that of other areas of Poland. The lowest values of annual rainfall totals, the low price of water (4.19 PLN), and the highest price of electricity, make it economically obvious that a rainwater management system with underground tanks turns out to have a long payback period, even with a cheaper concrete tank and with a subsidy representing 24% of the additional investment cost. The garden system has the most unfavorable SPBT in Zakopane, due to the low price of water, i.e., 3.75 PLN.

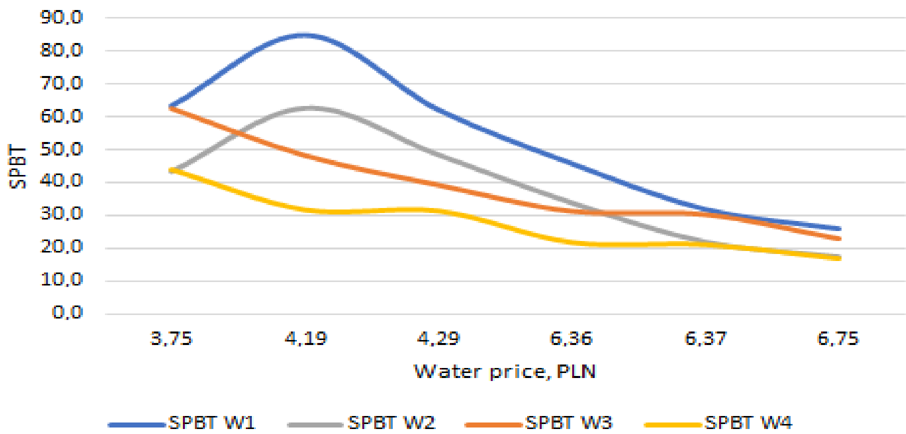

Figure 4. SPBT in particular variants.

In line with the trend of increasing water prices year after year, it was checked what the price of water would have to be in the current situation for the most expensive W1 and cheapest W4 investment to pay off after 10 years. The results shown in Table 12 suggest an increase in the price of water in the variant W1 from 130% to 391%, and in the variant W4 from 60% to 229%. This is certainly not a desirable solution for customers, but a price increase of 60% for Bielsko-Biala is not impossible. The authors checked which option would be the most favorable solution, from the perspective of customers, by checking which increase in the amount of subsidy would guarantee the profitability of additional investment in each city in 10 years. The results in Table 12 show that, in the case of variant W1, this value is up to 71–97% of the additional costs incurred for the installation of rainwater management. In the case of the cheapest variant, W4, the increase in the amount of subsidy would have to be greater by 60–119%.

Table 12. New prices of water and amount of subsidies, in case of SPBT = 10 years.

Location	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
			Variant W1			
New water price PLN/m^3	20.60	22.20	17.50	17.60	15.50	17.20
Growth	391%	248%	308%	176%	130%	359%
New subsidy, PLN	26,065	24,046	26,098	24,120	23,254	28,487
Growth	272%	381%	190%	382%	190%	470%
			Variant W4			
New water price PLN/m^3	10.3	12.3	10.6	12.30	10.80	12.3
Growth	146%	94%	148%	94%	60%	94%
New subsidy, PLN	13,137	10,967	13,004	10,808	10,461	10,967
Growth	88%	119%	64%	116%	60%	119%

Of great importance on the value of SPBT, in addition to the price of water, is the price of electricity, which, in the case of the most unfavorable variant, i.e., Kalisz, makes the operating costs of the system 50% of the costs achieved from water savings. Omitting this value is, therefore, unacceptable, but is, unfortunately, practiced in some analyses. Reducing the operating costs associated with the consumption of electricity for the operation of the rainwater panel is possible through the use of photovoltaic (PV) panel installations. Following this, the SPBT will decrease significantly, which will be especially noticeable in Kalisz. A review of the literature [37] shows that, if PV installations are used, the costs associated with the purchase of energy decrease in the range of 60–94%. Therefore, assuming that the cost of purchasing electricity reduces to 20% with the use of PV panels, the SPBT will also be lower. Detailed calculations, with the use of PV panel energy, are shown in Table 13. In the case of Kalisz, the SPBT halved, in the case of Bielsko-Biala, with the highest water price, the SPBT dropped by about 3 years, and, as before (Table 11), the variants W2 and W4, with a concrete tank, have similar SPBT ratios. The implementation of a domestic installation using rainwater, according to the assessment of this indicator, does not significantly change the scale of the payback time.

Table 13. SPBT, in the case of PV panel usage.

Location	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
			Variant W1/W2			
S_W PLN/year	487	766	556	1085	1178	654
OC PLN/year	47	47	45	41	43	43
AS, PLN	441	720	510	1044	1135	612
$SPBT_{W1}$	53.6	33.9	39.0	26.7	21.9	39.9
$SPBT_{W2}$	40.9	25.0	31.3	18.3	14.6	31.3
			Variant W3/W4			
S_W PLN/year	419	636	429	637	675	375
OC PLN/year	27	27	27	24	25	25
AS, PLN	392	609	402	613	650	350
$SPBT_{W3}$	34.6	25.6	28.7	25.4	19.3	44.4
$SPBT_{W4}$	22.9	18.0	23.1	17.9	14.5	31.3

The subsequent analyzed financial indicator is the ratio of the net present value. To determine the NPV for each of the four variants of the rainwater harvesting systems adopted for the study, the value of cash flows CF_{it} included in the Formula (5) for particular years was defined as the sum of initial outlays IO_i (from Formula (7)), additional operating costs incurred in a given year O_{it}, and savings S_{it}, resulting from the implementation of the system in i—variant. The value of cash flows was determined from the following formula:

$$CF_{it} = -IO_i - O_{it} + S_{it} \quad (11)$$

The S_{it} calculations take into account savings resulting from the reduced annual water demand from a water supply network after the i—variant of the implementation of the rainwater harvesting system, and were determined from the formula:

$$S_{it} = (ZR0 - ZRW_i) \cdot CW_t \quad (12)$$

where:

ZR_{W0} is the annual water demand from a water supply network in Case 0, m^3/year;

ZR_{Wi} is the annual water demand from a water supply network in i—variant of rainwater harvesting system, m^3/year;

CW_t is the water price in the year t, PLN/m^3.

The additional annual operating costs O_{it} take into account the electric energy consumption of the pump in the rainwater harvesting system. The O_{it} for a year t were determined from formula:

$$O_{it} = E_c \times CE_t \quad (13)$$

where:

E_c is the annual electric energy demand of the pump in i—variant of rainwater harvesting system, kWh/year;

CE_t is the electric energy price in the year t, PLN/kWh.

In order to determine annual savings S_{it}, water prices at each building location were adopted according to Table 9. After analyzing the increase in water prices in Poland over the past few years, an annual increase of 8.5% was assumed. In determining the additional annual operating costs O_{it} due to the pump operation in the system, the price of electricity was adopted from Table 9, with an assumed annual increase of 12%. The discount rate R for NPV was set at the level of 5%, as was assumed in calculations by other authors [37,39,44].

NPVs were determined for the analyzed options over the 30-year life of the installation, assuming the following options:

- A: when subsidizing the system from the nationwide program, local programs, and traditional electrical installation;
- B: when subsidizing the system from the nationwide program, local programs, and electrical installation with PV panels.

The results of the analysis, summarized in Table 14, showed that, in Option A, regardless of the variant of the system, under current conditions, the implementation of the water management system is financially viable only for the location of the buildings in Katowice and Bielsko-Biala. These are the localities with the highest water prices among the considered locations. In the case of using an electrical system with PV panels in the building (Option B), the implementation of a rainwater management system is financially viable in all localities, when cheaper concrete tanks are purchased (variants W2, W4), and in a garden system with plastic tanks (variant W3). The analysis also showed that, in Plock, in the case of a garden rainwater recovery system (variants W3 and W4), the investment will also be profitable, regardless of the electrical installation adopted in the building. This has to do with the high price of water (6.36 PLN) in this locality.

Figure 5 shows the net present values of all system variants for the most favorable option (Option B) for individual building locations. In Kalisz, investing in a domestic-garden system with a plastic underground tank is questionable. The NPVs obtained clearly show that the financial viability of implementing a rainwater system is influenced by: the cost of the tank, the price of water in the location, and annual precipitation, in an amount that covers rainwater needs. This relationship is perfectly reflected in Figure 5, where the NPVs obtained for Zakopane, with the highest annual precipitation, due to the lowest water price from the locations selected for the analysis, are significantly lower than for other cities with much lower annual precipitation. This is related to water prices, which are much higher in these localities than in Zakopane. The impact of the price of water on the financial viability of the installation can also be seen in the case of Warszawa and Plock. The price of water in Plock is much higher than in Warszawa, and, despite the lower annual precipitation in Plock, the NPVs obtained from the analysis are higher.

Table 14. NPV for 30 years of rainwater harvesting systems operation.

Option	Kalisz	Plock	Warszawa	Katowice	Bielsko-Biala	Zakopane
			Variant W1			
A	−17,999	−7424	−13,035	6453	13,391	−14,646
B	−2236	8338	2347	20,507	27,824	−212
			Variant W2			
A	−12,406	−1060	−8592	15,232	21,701	−5867
B	3356	14,702	6790	29,286	36,134	8566
			Variant W3			
A	−5115	3265	−2357	4571	9110	−8241
B	4169	12,550	6703	12,849	17,611	260
			Variant W4			
A	−518	7862	−80	9168	12,258	−3644
B	8765	17,146	8980	17,446	20,759	4856

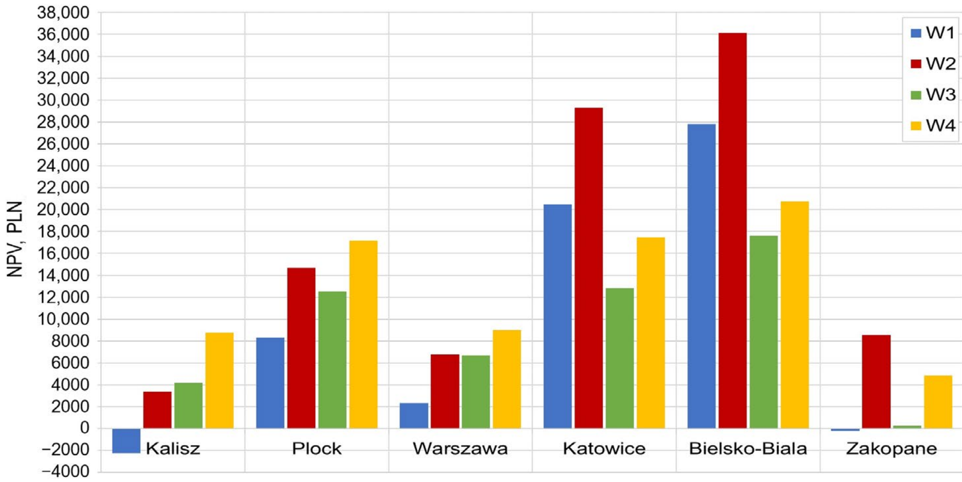

Figure 5. NPVs over the period of 30 years, depending on the analyzed system variants and the building location in Option B.

In order to complement the NPV analysis, the LCC analysis was additionally carried out for the adopted variants of the rainwater management system. LCC analysis was performed according to Formula (6). This analysis allows for balanced decisions during the selection of investment projects [37,43]. Residual costs were omitted from the quantitative analysis; therefore, they are not included in Formula (6). This is in line with the guidelines [45] and was similar to that adopted in studies by other authors [37,43].

The initial investment costs INV_i for the i-variant of the rainwater management system are costs incurred for the purchase and installation of a particular system. The purchase costs of individual system components for the i—variant installation were determined on the basis of manufacturers' and distributors' price lists. The investment costs also include the costs of installing and excavating the rainwater tank. At the same time, INV costs were reduced after taking into account national and local subsidies for the implementation of the rainwater management system. The discount rate R for the LCC analysis was set to 5%, as in the NPV analysis.

The LCC analysis was carried out for two operating periods: T = 15 years and T = 30 years. The assumption of the analysis of the period of 15 years results from the use of concrete tanks in variants W2 and W4, which are less durable. Therefore, in the LCC analysis for the period T = 30 years, the need to replace the tank after 15 years was assumed as an additional investment expense. As in the case of determining the value of the NPV indicator, two variants of the electrical installation in the building were adopted: traditional electrical installation in Option A and electrical installation with PV panels in Option B.

Detailed results of the LCC analysis for Option A for 15 years from Table 15 show that none of the variants analyzed for the rainwater recovery system are financially more profitable than variant W0, independent of the location of the building and the associated water price. However, the profitability of each variant of the rainwater recovery system, in relation to variant W0, increases with the extension of the analysis period. A similar relationship has occurred in other rainwater-use systems for single-family buildings shown in other publications [46]. In reference to Table 15, for example, the most financially unfavorable variant of the rainwater management system is W1 in Zakopane for T = 15 years. The LCC indicator is 50% higher than in variant W0. Extending the LCC analysis period to 30 years caused the difference for this case to be only 17%. Similarly, in Bielsko-Biala and Katowice, the 30-year LCC analysis period shows lower values than for the variant W0 LCC indicator value for all analyzed variants of the rainwater recovery system, whereby, the most financially profitable solution for these locations is variant W2. For the 30-year LCC analysis period, also for the location of the building in Plock, a lower LCC indicator value was obtained for variants W3 and W4 compared to variant W0, with the most favorable solution, in this case, being variant W4. For the remaining locations considered, the most financially viable variant was still the conventional installation (variant W0). Table 15 shows that the ratio of investment costs to life cycle costs for the period of 15 years, depending on the variant of the system and the location of the building, is 23–35% for variant W0, 51–68% for variant W1, 47–63% for variant W2, 41–57% for variant W3, and 38–53% for variant W4. Extending the LCC analysis period to 30 years reduces this ratio to the value of 10–17% for variant W0, 27–42% for variant W1, 25–39% for variant W2, 20–32% for variant W3, and 20–30% for variant W4, depending on the location of the building. The highest values of the INV/LCC ratio refer to the building in Zakopane, where, due to Zakopane having the highest annual precipitation, the selection of the largest rainwater tank was necessary. Zakopane also has the lowest water price, so the lowest profits from the implementation of a rainwater management system occur for this location.

Table 15. The LCC for analyzed rainwater management system variants in Option A.

Location	Variant	Analysis Period					
		T = 15 Years			T = 30 Years		
		OC PLN	LCC PLN	INV/LCC %	OC PLN	LCC PLN	INV/LCC %
Kalisz	W0	30,450	45,352	33	80,246	95,148	16
	W1	27,025	63,542	57	76,631	113,147	32
	W2	27,025	57,949	53	76,631	111,516	31
	W3	26,039	54,494	52	71,808	100,263	28
	W4	26,039	49,897	48	71,808	98,770	27
Plock	W0	46,220	61,122	24	121,806	136,707	11
	W1	37,731	77,018	51	104,844	144,131	27
	W2	37,731	70,654	47	104,844	141,730	26
	W3	37,870	68,325	45	102,986	133,442	23
	W4	37,870	63,728	41	102,986	131,949	22

Table 15. *Cont.*

Location	Variant	Analysis Period					
		T = 15 Years			T = 30 Years		
		OC PLN	LCC PLN	INV/LCC %	OC PLN	LCC PLN	INV/LCC %
Warszawa	W0	31,177	46,078	32	82,161	97,063	15
	W1	26,384	61,671	57	74,812	110,098	32
	W2	26,384	57,228	54	74,812	109,617	32
	W3	26,507	52,962	50	72,965	99,420	27
	W4	26,507	50,686	48	72,965	100,247	27
Katowice	W0	46,293	61,194	24	121,997	136,899	11
	W1	31,426	74,229	58	87,643	130,445	33
	W2	31,426	65,450	52	87,643	126,728	31
	W3	37,578	68,033	45	101,872	132,327	23
	W4	37,578	63,437	41	101,872	130,834	22
Bielsko-Biala	W0	49,054	63,956	23	129,275	144,176	10
	W1	32,644	72,446	55	90,983	130,785	30
	W2	32,644	64,137	49	90,983	127,537	29
	W3	39,727	67,182	41	107,611	135,066	20
	W4	39,727	64,034	38	107,611	135,022	20
Zakopane	W0	27,252	42,154	35	71,819	86,721	17
	W1	20,343	63,145	68	58,565	101,367	42
	W2	20,343	54,366	63	58,565	97,650	40
	W3	23,370	53,826	57	64,507	94,962	32
	W4	23,370	49,229	53	64,507	93,469	31

In the case of using PV panels (Option B), the LCC indicators are more profitable than for a traditional electrical installation (Option A). According to the literature [37], each solution with alternative energy sources improves the LCC index. For the analysis period T = 15 years, the LCC indicators values are lower compared to the traditional installation (variant W0) for variant W4 in Katowice and variants W2 and W4 in Bielsko-Biala (Figure 6a). For the analysis period T = 30 years, the implementation of the rainwater management system is more cost-effective compared to the conventional installation for the location of the building in Plock, Warszawa, Katowice, and Bielsko-Biala for each of the analyzed variants (W1–W4). Furthermore, in the case of Zakopane, the value of the LCC indicator is lower for variants W2, W3, and W4 compared to variant W0, and, for the location in Kalisz, it will be financially viable to implement a rainwater recovery system in variants W3 and W4 (Figure 6b). The implementation of rainwater management systems is the most financially viable for the location of the building in Katowice and Bielsko-Biala. In both locations, variant W2 turned out to be the most optimal. These are locations with similar annual precipitation values and the highest water prices. The investment is also beneficial in Plock, due to the high price of water, despite the much lower value of annual precipitation. The LCC ratio for the considered variants W1–W4 of the rainwater recovery system, compared to variant W0, is lower than in the case of Warszawa or Zakopane, where there is a much higher amount of annual precipitation, but low water prices. The values of this ratio (LCC_{Wi}/LCC_{W0}) for the analyzed locations are summarized for the LCC analysis period T = 30 years in Table 16.

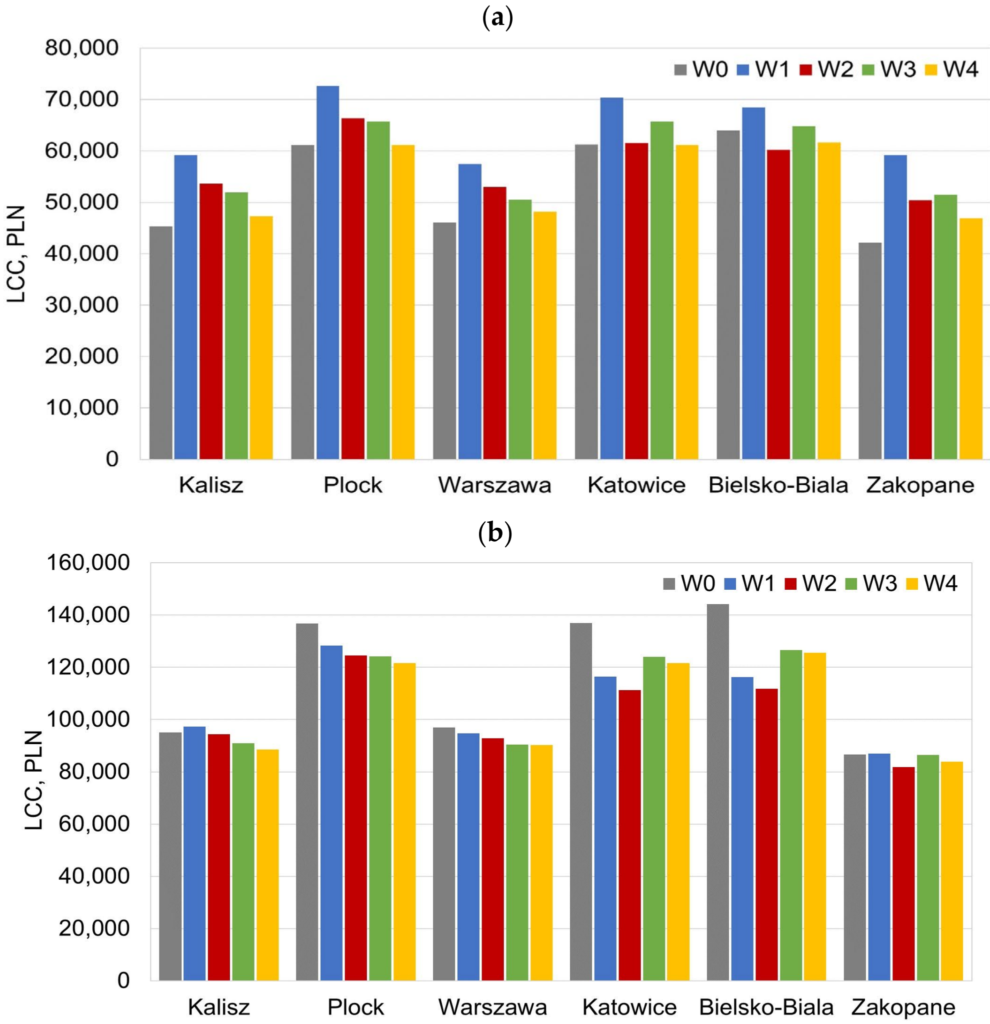

Figure 6. Life cycle costs for implemented variants of rainwater management system in Option B for: (**a**) 15 years of analysis, (**b**) 30 years of analysis.

Table 16. The ratio of the LCC indicator values for the analyzed rainwater management systems, compared to the installation in variant W0, for Option B and LCC analysis period T = 30 years.

Location	**LCC_{W1}/LCC_{W0} %**	**LCC_{W2}/LCC_{W0} %**	**LCC_{W3}/LCC_{W0} %**	**LCC_{W4}/LCC_{W0} %**
Kalisz	102	101	96	94
Plock	94	92	91	90
Warszawa	98	97	93	94
Katowice	85	82	91	90
Bielsko-Biala	81	78	88	88
Zakopane	100	96	100	98

4. Conclusions

Two cases of domestic-garden and garden rainwater management systems were analyzed in six locations, taking into account the diversity of rainfall in Poland; in two variants, depending on the material of the tank; and in two options: traditional or PV panel electrical installation. Summarizing the particular results of the analysis, it is shown that:

(1) The rainwater collection tank is a key investment cost; hence, the lower price of concrete tanks may encourage investors, although its key disadvantage is its short lifespan and the need for replacement after 15 years.

(2) Local financial support programs are offered in various regions of Poland, which, in addition to the national subsidy, further support the investment budget and account for between 15 and 47% of investment costs in the cases analyzed.
(3) The prices of water and electricity vary in different regions of Poland, with the price of water being particularly noticeable and significant, differing by up to 80%, in the cities under discussion.
(4) In the case of the domestic-garden and garden installations analyzed, taking into account current tap water prices, rainfall volumes, and investment subsidies, the annual water cost savings ranged from 480 to 1080 PLN, which is not an impressive figure.
(5) Almost double the investment outlay of a traditional installation makes the return on investment, according to the SPBT indicator, look very unfavorable, i.e., from 17 to 84 years, depending on the variant. Similar negative conclusions were presented by the authors in a publication that appeared 15 years ago, and, in the case of a single-family house, the return on investment costs ranged from 46 to 74 years [19].
(6) Despite the significant increase in water prices in recent years, as well as the spread of the rainwater management system, its popularization, and investment support programs, investors must still expect a long payback period for a single-family house.
(7) Investment in a less-extensive garden system does not clearly mean a shorter payback period, due to a lower subsidy amount representing a certain percentage of the investment.
(8) Even in simple economic analyses, the operating costs associated with the consumption of electricity for the operation of the rainwater panel cannot be ignored, as they can account for up to 50% of the costs saved from reduced water consumption on an annual basis.
(9) Under Polish conditions, the most advantageous option, at present, is the use of a water management system in Bielsko-Biala and Katowice, where the price of water is the highest and the amount of rainfall is adequate to provide the amount of rainwater.
(10) The bottom line is that, under Polish conditions, to achieve the greatest financial benefits from investing in a rainwater management system for a single-family house, it is crucial that the building's rainwater demand is fully met by rainfall, the unit price of water is at least 8-times the unit price of electricity, with the aim of keeping operating costs as low as possible through the use of renewable energy sources, and subsidies are a significant percentage of the investment.

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