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Technical and Financial Feasibility Analysis of Rainwater Harvesting Using Conventional or Green Roofs in an Industrial Building

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Abstract: Given the high annual water consumption for non-potable uses (1112.08 m^3, 65%) of an industrial building with a large roof area (4638 m^2) located in the Northeast of Portugal, this study aims to evaluate the technical and financial feasibility of a rainwater harvesting system for these uses, considering the existing conventional roof (scenario 1) and adapting a green roof to the existing roof (scenario 2). This evaluation was based on the impact of the two scenarios on the building's water savings. Under scenarios 1 and 2, the expected water savings were 64.47% and 59.43%, respectively. Therefore, the expected reduction in the annual water bill was €3867.07 + VAT (scenario 1) and €3564.63 + VAT (scenario 2). For scenario 1, considering a reservoir with 70 m^3 for non-potable purposes, such as washing the building's floor and use in industrial machines, and an initial investment of €41,109.13 + VAT, the single payback will be 11.29 years. The single payback for scenario 2 largely exceeded the lifetime of the green roof. However, as they are considered interesting solutions to reduce the negative externalities of industrial settlements, financial incentives could be proposed for the implementation of the green roof in this typology of buildings.

Keywords: water efficiency; rainwater harvesting; green roofs; technical and financial feasibility; industrial building

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1. Introduction

Urban population density growth, new lifestyles, and increasing water pollution lead to a continuous rise in the water demand, threatening freshwater ecosystems and the available water resources [1–3]. In addition, climate change is enhancing this threat to water quality and availability. Consequently, water scarcity and shortage are a worldwide reality [4]. During at least one season in 2019, water scarcity affected 29% of the EU Territory. Despite the decline of water abstraction by 15%, the area affected by water scarcity did not show any reduction. Moreover, since 2010 the water scarcity has been worsening [5]. In southern Europe (the region where Portugal is included), water abstraction by sector in 2015 was agriculture (49,637 million m^3), electricity cooling (16,469 million m^3), public water supply (11,370 million m^3), manufacturing and construction (6385 million m^3), and mining and quarrying (77 million m^3) [6]. Metalworking is an important manufacturing industry worldwide, integrating a wide range of industrial activities and an enormous diversity of products. Metalworking processes frequently require significant amounts of water for cooling, lubrication, and cleaning processes [7]. Therefore, searching for alternative water sources is paramount.

Rainwater Harvesting Systems (RWHS) are regarded as one of the more promising alternative or supplementary water resources when compared with other alternative water sources (e.g., water from WTP, grey water) owing to their minimal environmental impact and the low treatment needs [8–14]. In addition, RWHS reduces the volume of stormwater drained into the drainage system, the flooding risks, and the pressure on natural water resources minimizing the ecological footprint through potable water [15]. Despite the existing research worldwide focusing predominantly on RWHS installation in residential [12–14,16–20] and commercial buildings [4,10,21–30], implementing RWHS in metalworking industries facilities for cleaning or non-critical cooling processes and for activities when drinking water quality is not required (e.g., recharging flushing cisterns and irrigation of green spaces) can be an important tool, helping to reduce the pressure of this industry on traditional water sources [7].

Nature-based solutions such as green roofs (GR) can also be implemented in industrial buildings to promote the circular water management as well as water quantity and quality [31–34]. GR are engineered systems with vegetation installed on a constructed structure where several materials are arranged in layers, ensuring the vegetation's good establishment and development and preserving the built structure's physical integrity [35]. GR are classified as extensive if the substrate depth is below 15 cm, semi-extensive if the depth is between 15 and 25 cm, or intensive if the depth is above 25 cm [35,36]. The extensive GR typology can be an adequate option for existing buildings, where minimum intervention is desirable on the roof, because this typology is lighter, cheaper, and requires less maintenance [35,37]. From a hydrological perspective, GR retains, delays, and promotes the evapotranspiration of the rainfall, behaving as landscape sponges, decreasing the volume of rainwater discharged, and reducing overflows' peak [15,31,36]. Additionally, when compared with conventional roofs, GR can improve runoff water quality, which has the potential for non-potable uses [33,38–40]. From a building perspective, GR can potentially mitigate energy consumption and improve acoustic performance [15,41]. Other ecological services GR provides are their aesthetic value contributing to improving human health and well-being [42] and promoting biodiversity [43,44]. Therefore, combining RWHS with GR can have synergistic environmental benefits, balancing the ratio between water savings and stormwater capture [15,45,46]. This combination can be particularly important for industrial buildings as these facilities have large roof surfaces, maximizing the environmental benefits of both tools. Nevertheless, despite the potential benefits of this combination, very few studies have been addressed to evaluate the effectiveness and the interaction between RWHS and GR [15,45,46]. In Portugal, both RWHS with conventional roofs [30] and RWHS combined with GR [15,45,46] have not yet been deeply exploited.

Furthermore, to the best of the authors' knowledge, no research has been carried out on the technical and economic reliability of a RWHS with conventional or GR in industrial buildings. Therefore, the aim of this study is to evaluate the technical and financial feasibility of a RWHS: (1) Considering the existing conventional roof, and (2) Adapting a GR to the existing roof, in an industrial building. This assessment is based on the impact of the two scenarios on the water savings of the building. Given the lack of information in this area and the issues associated with water scarcity, this research is expected to be highly relevant to industrial building managers and could be a starting point for novel research.

2. Materials and Methods

2.1. The Case Study

The metalworking industry building is located nearby Bragança city (NE Portugal: 41°48′26″ N; 6°45′33″ W). The municipality of Bragança has 34,582 inhabitants [47]. As the climate is continental with Mediterranean influences, the precipitation (around 700 mm/year) occurs mainly in autumn and winter, but in a very irregular pattern [48]. Bragança has an high water demand: about 260 L/(inhabitant. day) [49]. This industrial activity started activity in 2015 and currently has 65 workers. The roof of the building is made of sheet metal, covering an area of 4638 m^2. The building consists of two floors: the ground floor with offices, sanitary facilities, production, and storage area, and the first floor with the changing room, sanitary facilities, and cafeteria.

2.2. Water Consumption Pattern and Measures to Improve Water Management

The company's management team provided an estimate of the water consumption pattern (Table 1) and, considering that the "other uses" account for 65% of potable water consumption and the large roof area of the building, the technical and financial feasibility of a RHWS for two scenarios was analyzed:

- Scenario 1: Considering the existing conventional roof;
- Scenario 2: Adapting a GR to the existing roof.

Table 1. Average annual and monthly water consumption by use category in the metalworking industry building under study.

Devices/Activity	Consumption (m^3/Year)	Consumption (m^3/Month)	Percentage (%)
Flushing cisterns	262.08	21.84	15
Urinals	33.84	2.82	2
Bathroom Faucets	104.00	8.67	6
Kitchen Faucets	115.20	9.60	7
Showers	76.80	6.40	5
Other uses (floor washing and industrial machinery)	1112.08	92.67	65
Total	1704.00	142.00	100

2.3. Technical and Financial Feasibility Analysis of the Proposed Scenarios

The scenarios proposed in Section 2.2 were then analyzed technically and financially.

2.3.1. Sizing of Rainwater Harvesting Systems and Selection of Green Roof Type

The simulation of RWHS sizing was carried out according to the simplified method proposed by [50], and adopted in Portugal, where the volume of rainwater to be harvested in a given period was determined by Equation (1):

$$V_a = C \times P \times A \times \eta_f \quad (1)$$

where:

- V_a: volume of rainwater in the reference period that can be used (L);
- C: runoff coefficient (dimensionless);
- P: average precipitation accumulated at the site (mm);
- A: roof area (m^2);
- η_f: hydraulic filtering efficiency (dimensionless).

When the simulation is performed for the metal roof, 0.9, can be assumed for C. Considering the extensive GR, the value for C is 0.5. A maximum hydraulic filtration efficiency (η_f) of 0.9 was considered. The average monthly rainfall was taken from [48], considering the rainfall series from 2012 to 2022.

In the present approach, an extensive GR with a saturated weight of 1 kN/m^2 was proposed. For existing buildings, where a minimum intervention on the roof is desirable, the extensive GR typology can be an adequate option to consider, since it is characterized by a substrate layer that varies between 8 and 15 cm in thickness, with a corresponding expected weight of the system that can go up to 1.77 kN/m^2 and is usually not accessible to the public. The vegetation for this type of GR is typically succulent and herbaceous (e.g., *Sedum* sp.), generally up to 50 cm high.

2.3.2. Criteria for Estimating the Initial Investment of the Implementation of the Proposed Scenarios

The estimate of the initial investment of implementing scenario 1 included the assessment of the cost of the following works and material necessary for its implementation: Remodeling of the rainwater drainage network, according to [51]; Supply and installation of the RWHS (to be located in the area surrounding the building), and all necessary accessories; Adaptation of the water supply network [51]; Supply and installation of the pumping group, and all necessary accessories. The initial investment for scenario 2 includes the costs of scenario 1 and the installation of the extensive GR, which consists of a sedum cover, a 10 cm thick technical substrate, a filter, drainage, protection, and anti-root layers. This system implies an initial investment of around €100/m^2 + VAT, including installation costs (based on market/manufacturer estimates).

The prices for the above works were those prevailing in the region in June 2023, and manufacturers provided prices for materials and equipment. Regarding the operation and maintenance costs for scenarios 1 and 2, the following should be noted: (i) The frequency of maintenance of the components of the RWHS was carried out according to the guidelines of [50] and the manufacturer's specifications. Although the maintenance of these systems is low, the filters need regular maintenance and cleaning during the lifetime of the RWHS, which is at least 20 years according to the manufacturer's specifications; (ii) Energy costs related to the pumping group have not been considered. Although RWHS may require a pressurization system, the associated energy consumption is equal to or less than if the supply comes from the public network [9]. According to the manufacturer, the pump does not require any maintenance, but the condensation plugs and built-in check valves are recommended to be checked and cleaned annually or as required during the lifetime of the pumping group, which is at least 10 years; (iii) The maintenance requirements for extensive GR are low compared to other GR typologies, and also the watering input is low, so that irrigation is kept to a minimum, used only for initial plant establishment and during high temperature weather [35]. GR is expected to have the same lifetime as the waterproofing of the building (30 to 40 years). In addition, GR can be expected to have an increased life expectancy of up to 40 years compared to conventional roofs (20 years), resulting in less frequent roof replacements and less intensive operational activities and costs over the life of the building [36]. Therefore, maintenance costs are not considered for the same reasons as (i), (ii), and (iii).

The reduction in water bills (as a result of implementing water-saving measures) was also analyzed. The prices charged by the municipality of Bragança were used to estimate the reduction in the annual value of the water bill [52].

2.3.3. Methods of Financial Evaluation and Discount Rate Selection

The measurement of the economic performance of a building/building element investment is usually based on the concept of net present value (NPV) [53]. NPV is the discounted value of the benefits less the costs that occur over the period under consideration. Either the net savings (NS) method, a variant of the net benefit method, or the internal rate of return (*IRR*) method could be used to assess the financial viability of proposed water-saving measures. Some authors have argued that the *IRR* method is more informative from a private investor's perspective [54,55]. The *IRR* measures the percentage return on an investment and is then compared to the investor's minimum acceptable rate of return to determine the financial attractiveness of the investment. An *IRR* greater than the discount rate indicates that the investment is economically efficient. The *IRR* formula is given in Equation (2).

$$PVNS_{A_1:A_2} = \sum_{t=0}^{N} \frac{S_t - (I_t + M_t + Rp_t) + RV_N}{(1 + IRR)^t} = 0 \tag{2}$$

where:

- $PVNS_{A_1:A_2}$: present value of net savings of alternative A_1 when compared with a mutually exclusive alternative, A_2;
- S_t : savings in year t of A_1 less those of A_2;
- I_t: investment costs in year t of A_1 less those of A_2;
- M_t: operation and maintenance costs in year t of A_1 less those of A_2;
- Rp_t: replacement costs in year t of A_1 less those of A_2;
- RV_N: residual value in year N of the study period of A_1 less that of A_2;
- N: number of years in the study period;
- IRR: internal rate of return, i.e., a discount rate for which $PVNS$ = 0.

The use of the *IRR* method (as well as other economic evaluation methods) is usually coupled with the use of the single payback (SPB) method, which is used as a pre-test of the economic efficiency of an investment (see Section 3.2. The SPB method measures how long it takes to recoup the cost of the investment. An investment with an SPB that is shorter than both the economic life of the building and the useful life of the building system generally indicates an economic investment, setting aside the time value of money [56]. Otherwise, it should be rejected. The SPB formula is presented in Equation (3).

$$I_0 = \sum_{t=0}^{Y} B_t - C_t \tag{3}$$

where:

- Y: the minimum length of time (usually number of years) over which future net cash flows must be accumulated in order to offset initial investment costs, where the minimum solution value of Y = SPB;
- B_t: relevant benefits (savings in this case) of A_1, less those of A_2, at the end of period t;
- C_t: relevant costs (excluding initial investment costs) of A_1, less those of A_2, at the end of period t;
- I_0: initial investment costs of a given alternative, A_1, less those of a mutually exclusive alternative, A_2, which may be the alternative of doing nothing.

Previous studies have shown that discount rates are a key economic parameter in long-term investment analysis [57]. Individual discount rates are estimated to model investment decisions that reflect an investor's expected return. Steinbach and Staniaszek [58] recommended a real discount rate of between 3% and 6% for private investors. A recent study [59], also dealing with the renovation of the Portuguese building stock, used a nominal discount rate of 2.52% for the financial analysis. It is worth noting that the low discount rate used in [59] may have reflected the low cost of long-term borrowing at the time (2021). The interest rate on long-term loans in Portugal fell from 4.98% in September 2014 to 1.55% in December 2021 [60]. However, since the beginning of 2022, this rate has shown a marked upward trend, reaching 4.54% in April 2023, reversing the downward trend of the previous period. A real discount rate of 5% has therefore been used in this study. The study period was set at 20 years for scenario 1 and 40 years for scenario 2.

3. Results and Discussion

3.1. Proposed Measures and Its Impacts on Water Saving

Considering that the item "other uses" accounts for 65% of the water consumption in this building and includes activities that do not require potable water (Table 1), the proposed water-saving measures include the evaluation of the implementation of the two scenarios mentioned in Section 2.2. Therefore, Tables 2 and 3 show the simulated storage volumes for the reservoir, considering scenarios 1 (using the existing conventional roof) and 2 (adapting GR to the existing roof), respectively.

Table 2. Reservoir sizing simulation using conventional roof (scenario 1) in the metalworking industry building.

Month	Monthly Precipitation (mm)	C	η_f	Roof Area (m^2)	Available Rainwater Volume (m^3)	Monthly Consumption (m^3)	Availability—Consumption (m^3)	Reservoir Volume (m^3)	Water at the End of the Month (m^3)	Public Network Supply (m^3)
October	90.62				340.43	92.67	247.76		70.00	0.00
November	88.84				333.74	92.67	241.07		70.00	0.00
December	102.60				385.45	92.67	292.77		70.00	0.00
January	84.15				316.12	92.67	223.44		70.00	0.00
February	73.50				276.12	92.67	183.45		70.00	0.00
March	67.14				252.22	92.67	159.54		70.00	0.00
April	78.94	0.90	0.90	4638	296.55	92.67	203.87	70.00	70.00	0.00
May	44.53				167.28	92.67	74.61		70.00	0.00
June	27.68				103.99	92.67	11.32		70.00	0.00
July	12.45				46.75	92.67	−45.92		24.08	0.00
August	14.67				55.11	92.67	−37.56		0.00	13.48
September	41.65				156.47	92.67	63.80		63.80	0.00
Total	726.75				2730.23	1112.08				13.48

Table 3. Reservoir sizing simulation using GR (scenario 2) in the metalworking industry building.

Month	Monthly Precipitation (mm)	C	η_f	Roof Area (m^2)	Available Rainwater Volume (m^3)	Monthly Consumption (m^3)	Availability—Consumption (m^3)	Reservoir Volume (m^3)	Water at the End of the Month (m^3)	Public Network Supply (m^3)
October	90.62				189.13	92.67	96.46		70.00	0.00
November	88.84				185.41	92.67	92.74		70.00	0.00
December	102.60				214.14	92.67	121.46		70.00	0.00
January	84.15				175.62	92.67	82.95		70.00	0.00
February	73.50				153.40	92.67	60.73		70.00	0.00
March	67.14				140.12	92.67	47.45		70.00	0.00
April	78.94	0.50	0.90	4638	164.75	92.67	72.07	70.00	70.00	0.00
May	44.53				92.93	92.67	0.26		70.00	0.00
June	27.68				57.77	92.67	−34.90		35.10	0.00
July	12.45				25.97	92.67	−66.70		0.00	31.60
August	14.67				30.62	92.67	−62.06		0.00	62.06
September	41.65				86.93	92.67	−5.75		0.00	5.77
Total	726.75				1516.79	1112.08				99.40

As the cistern is the most expensive RWHS component, sizing these systems prior to implementation is critical to their performance and economic reliability. Despite a wide range of RWHS sizing methods, experts have no unanimity on which is the best methodology [12,16,61,62]. Simplified sizing methods are approximate approaches that are useful for the first phase of RWHS design [63]. As the present study is an exploratory analysis, the implementation of each scenario is still hypothetical, and the "other uses" of water consumption are constant over time, the choice of a simplified method for sizing the reservoir was considered appropriate [62]. The projected 70 m^3 volume cistern (above this size the model showed that the efficiency increase was insignificant, whereas the costs increase) will allow for a total rainwater harvesting of 1098.60 m^3 (98.79%), requiring the use of public supply water only in August (scenario 1; Table 2). In scenario 2 (Table 3), the 70 m^3 allows a total rainwater harvesting of 1012.68 m^3 (91.06%), requiring water from the public supply from July to September. Therefore, taking into consideration the monthly consumption and the amount of rainwater available (which is very low in this location during the summer months), the water harvesting is sufficient to meet most of the demand in both scenarios.

The GR (scenario 2) retained about 1213.44 m^3 of rainwater (44.44%) by applying a runoff coefficient of 0.50 when compared to the conventional roof in which a runoff coefficient of 0.90 was considered. Even so, the available rainwater volume is enough to supply the building's consumption for "other uses", excepting July to September. These results align with data obtained by [64,65] concerning the hydrological performance of GRs under the Mediterranean climate that showed water retention from 37 to 100% and from 12 to 100%, respectively. The reduction in RWHS performance associated with the installation of GR was also reported by [15,45], who claimed that combined systems may reduce RWHS efficiency in low rainfall climates, whereas in higher rainfall climates they may have a positive effect on RWHS efficiency as GR reduces excessive rainwater runoff. Considering the climate of the studied region, scenario 1 showed a slightly better performance contributing to higher water savings (Table 4).

Table 4. Annual water consumption with water-saving measures in the metalworking industry building.

	Scenario 1 [(1)]	Scenario 2 [(2)]
Total Consumption without Measures (m^3/year)	1704.00	1704.00
Predicted Consumption with Measures (m^3/year)	605.40	691.32
Predicted Water Savings (m^3/year) and (%)	1098.60 (64.47)	1012.68 (59.43)

[(1)] RWHS considering the existing conventional roof; [(2)] RWHS adapting a GR to the existing roof.

3.2. Initial Investment and Financial Return of the Water-Saving Measures

The initial investment costs of scenarios 1 and 2 are presented in Table 5.

Table 5. Investment costs of scenario 1 and scenario 2.

Work Description	Scenario 1	Scenario 2
	Partial Cost (€)	
Remodeling of the rainwater drainage network	7636.04	7636.04
Supply and installation of the RWHS and all necessary accessories	27,820.64	27,820.64
Adaptation of the water supply network	3087.45	3087.45
Supply and installation of the pumping group, and all necessary accessories	2565.00	2565.00
Installation of a GR	-	463,800.00
Total cost (€ + VAT)	41,109.13	504,909.13

Before proceeding with the financial analysis, a pre-test was carried out to assess the economic efficiency of the two scenarios. Table 6 is based on the data from Tables 4 and 5 and shows the initial investment, annual water bill reduction, and SPB for both scenarios. Regarding the relationship between the choice of discount rates and the evolution of water costs, it is worth noting that, according to the economic/financial assessment rationale, the present value of the water cost savings decreases over time in the study period if the discount rate is higher than the growth rate of water prices, both measured in real terms. As the building owner is a private investor, this study assumed constant (real) water prices throughout the analysis. It should be noted that without water efficiency measures, the annual water bill is €6178.44 + VAT. The benefits (savings) and costs associated with these scenarios were measured against the no action alternative. Table 6 shows that the SPB for scenario 1 is 11.29 years, which is lower than both the useful life of the efficiency measure and the study period. On the other hand, it also shows that the SPB for scenario 2 is 154.62 years, which is much higher than the lifetime of the corresponding efficiency measure—40 years. Therefore, the investment associated with this scenario was considered economically inefficient at the micro level point of view.

Table 6. Initial investment, annual water bill reduction, and SPB for scenarios 1 and 2 applied to the metalworking industry building.

	Scenario 1	**Scenario 2**
Initial investment (€ + VAT)	41,109.13	504,909.13
Annual water bill with measures (€ + VAT)	2311.37	2613.81
Annual water bill reduction (€ + VAT)	3867.07	3564.63
SPB (years)	11.29	154.62

The financial valuation of the investment for scenario 1 required further refinement. Applying Equation (2), the *IRR* is 6.54%, which is higher than the discount rate used in the study—5%. As a robustness check, the *IRR* value was compared with the interest rate for long-term loans in Portugal (4.54%, in April 2023). According to figures provided by Statistics Portugal [66], the average annual inflation rate, as measured by the Consumer Price Index, is 1.21% for the period 2010–2022. Thus, the *IRR* value, expressed in nominal prices, was approximately 6.54 + 1.21 = 7.75%. As the choice of water price evolution was on the conservative side, an investment return of 7.75% appeared to be a fairly attractive financial return.

It should be emphasized that the present study has assessed the financial viability of the two scenarios, taking into account only the benefits that the implementation of water-saving measures would bring to the building owner. Thus, considering the similar benefits for both scenarios, the only financially feasible scenario is 1. The SPB value for scenario 2 largely exceeded the lifetime of the GR. In fact, the economic evaluation of the GR installation is not straightforward due to the limited information available and the small number of existing studies that have attempted to quantify its true economic impact. As a result, there are conflicting interpretations in the existing literature, with some authors arguing that the installation of GR leads to significant financial losses. In contrast, others conclude that GR are attractive investments [67].

Therefore, refs. [34,67,68] suggested that a GR feasibility study should include both financial analyses (to examine the financial return to the project owner) and economic and socio-environmental analyses (to assess whether a project effectively contributes to the national/local economy, society and environment). The results obtained by [34,67,68] showed that, at a financial level, the gains are less than the high initial costs borne by the building owners, resulting in variable capital losses even for extensive GR, and therefore replacing the existing roofs with GR is an expensive and unprofitable investment from a private sector perspective. However, GR could be profitable from an economic, societal, and environmental perspective when considering the benefits such as flood risk reduction, stormwater management, runoff quality, air quality improvement, CO_2 sequestration, and increased biodiversity habitats provided by this infrastructure. The financial results obtained here are in line with those obtained in the literature mentioned above, which also proposed the introduction of financial incentives for the implementation of GR installation in urban and industrial areas. Indeed, ref. [34] highlighted that GR are a good solution to reduce the negative impacts of industrial settlements.

4. Conclusions

In a climate change scenario, improving water use efficiency is of critical importance. Therefore, the strength of this research is to provide a simple and replicable methodology that allows industrial building managers to make decisions on which the best option is to improve water efficiency: a RWHS combined with a conventional roof or with a GR?

Nevertheless, further research is needed to provide RWHS sizing methodology to better deal with the more frequent climatic uncertainties that influence the amount and timing of rainfall, ultimately affecting RWHS efficiency. Although the high SPB for scenario 2 is explained by the fact that the present approach only assessed the benefits of implementing measures in reducing water consumption, it is necessary for further research to include other relevant benefits in the models that the installation of the GR could bring to the project. Another limitation is that under climate change, the price of water will increase significantly and unpredictably over time. However, as it is currently impossible to predict what water prices will be in future decades, it is not possible to take this into account in the SPB calculation methodology. In fact, the mentioned research limitations may have led to an overestimation of the SPB for this scenario. Therefore, scenario 2 should not be discarded in this building typology and in this climatic region without considering the other benefits that GR can bring to buildings, society, and the environment, which can overcome the initial high investment.

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