Assessment of the environmental impact and investment feasibility analysis of rainwater use in houses

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Abstract

The main objective of this work is to assess the environmental impact and investment feasibility analysis of rainwater harvesting systems for a low-cost house located in Florianópolis, southern Brazil, by using the concepts of Life Cycle Analysis (LCA). The environmental and investment feasibility analysis was performed for two scenarios, i.e., a scenario in which there is only a potable water system supplied by the water utility, and another scenario in which the potable water system is complemented by rainwater. Three types of rainwater storage tanks were analysed: plastic reinforced with glass fibre, high density polyethylene and reinforced concrete. Results indicate that plastic tanks reinforced with glass fibre are environmentally more feasible, while concrete tanks are economically more feasible. This study showed the importance of analysing environmental and economic aspects before implementing a system with rainwater utilization; thus better choices regarding the materials used in the systems, aiming at sustainability in buildings, can be made.

Keywords: rainwater harvesting, life cycle analysis, environmental and investment feasibility, houses.

1 Introduction

Amongst other natural resources, water is the most threatened due to its shortage and lack of potability all around the world. Thus, it is necessary to promote water conservation and alternative techniques that may contribute to potable water savings. Amongst some of such techniques, rainwater harvesting has been regarded as an easy way to promote potable water savings in buildings.

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However, the installation of a rainwater harvesting system in a building implies in a greater quantity of components and equipment (rainwater tanks, connections, pipes and pumps), and, consequently, greater consumption of raw materials and energy. Moreover, the general procedures to produce components and equipment used in rainwater harvesting systems involve complex processes that generate different environmental impacts.

The main environmental impacts due to rainwater harvesting systems are related to the emissions generated during their life cycle. According to [1], emissions of carbon dioxide (CO_2) during the life cycle of a domestic rainwater harvesting system are between 800–2000 kg of CO_2.

Some studies have evaluated the sustainability of rainwater harvesting systems and found that such systems tend to have higher environmental impacts than the networks of traditional water supplies [1–4].

Besides the environmental aspects, economic aspects such as costs and financial benefits, and the investment payback period, are factors that influence most decision makers in adopting or not a rainwater harvesting system.

However, few studies have been conducted to assess both the environmental and investment feasibility of rainwater harvesting systems considering embodied energy and emissions of carbon dioxide during their life cycle.

2 Objective

The objective of this paper is to analyse the environmental and investment feasibility of rainwater harvesting systems considering embodied energy and emissions of carbon dioxide for the life cycle of components of such systems for a house.

3 Methodology

To analyse the environmental and economic feasibility of different options of rainwater harvesting systems for a project of a residential building, a method was developed based on concepts of Life Cycle Analysis.

The project refers to a low-cost single-family house with a floor plan area of 61.3 m^2, located in Florianópolis, southern Brazil.

Two scenarios were evaluated, i.e., one in which there is only a potable water system supplied by the water utility, and another in which the potable water system is complemented by rainwater.

3.1 Definition of objectives and scope

The function of the systems is the water supply in residential buildings.

The life span adopted for the potable water system was 20 years, considering the replacement of components that have a different life span [5]. The functional unit adopted was the volume of water consumed in the house during the life span of the potable water system, for both scenarios.

3.2 Characterization and data collection

As for the characterization and data surveying, quantitative surveys and environmental data of materials used in both scenarios were carried out.

3.2.1 Potable water system

As for the characterization of the potable water systems, all components and materials were indicated as shown in the Table 1.

Table 1: Components and materials used in the potable water systems.

Components	System A	System 1	System 2	System 3
	Materials			
Upper rainwater tank	GFRP	GFRP	GFRP	GFRP
Pipes	PVC	PVC	PVC	PVC
Connections	PVC	PVC	PVC	PVC
Connections made with other materials	Metal and brass	Metal and brass	Metal and brass	Metal and brass
Devices and fittings	–	HDPE	HDPE	HDPE
Pumps	–	Cast iron	Cast iron	Cast iron
Lower rainwater storage tanks	–	GFRP	HDPE	Reinforced concrete

The potable water system supplied by the water utility (without use of rainwater) was called System A.

Three options for potable water system complemented by rainwater were analysed (System 1, System 2 and System 3). Each system had the rainwater storage tank composed of a different material, i.e.: plastic reinforced with glass fibre (GFRP), high density polyethylene (HDPE) and reinforced concrete.

3.2.2 Sizing of rainwater storage tanks

To evaluate the potential for potable water savings by using rainwater, the computer programme Netuno, version 3.0 was used [6]. The programme simulates a rainwater harvesting system equipped with an upper and a lower rainwater tank, taking into account the catchment surface area, the potable and non-potable water demands, the number of occupants of the building and the runoff coefficient.

The optimum tank capacity was taken as the one in which the potential for potable water savings increased 0.5% or less when increasing the tank capacity by 1000 litres. The input data used to perform the simulations are presented in Table 2.

3.3 Environmental assessment

The environmental assessment included the steps of extracting raw materials, processing, production and use of building components of all systems analysed.

Table 2: Input data used for simulations in the Netuno computer programme.

Daily rainfall data	Florianópolis/SC Years: 2000 to 2006
Catchment surface area (m²)	79.6
Demand for potable water fixed (litres per capita/day)	125
Number of occupants (peoples)	4
Rainwater demand (% of potable water demand)	30, 40 and 50
Runoff coefficient	0.80
Upper rainwater tank (litres)	250; 250 e 300
Lower rainwater storage tanks (litres)	Calculation for different capacities
Maximum tank capacity (litres)	30,000
Interval between tank capacities (litres)	1000
Difference between potential savings (%)	0.50

3.3.1 Embodied energy

The embodied energy in the systems was calculated based on the types and quantities of materials and embodied energy indices for each material. Eq. (1) was used to estimate the embodied energy in each system component.

$$\mathrm{EE}_{\mathrm{comp}} = \mathrm{M} \times \mathrm{EE} \tag{1}$$

where EE_{comp} is the embodied energy in a system component (MJ); M is the mass of the system component (kg/unit); EE is the embodied energy in the predominant material in the component (MJ/kg).

The embodied energy indices were obtained from references compiled by Tavares [7]. The mass of each component was obtained by contacting the manufacturers.

The total embodied energy for maintenance and replacement of components during the life span of the systems was verified by using Eq. (2).

$$\mathrm{EE}_{\mathrm{maint}} = \sum_{i=1}^{n} \left(\mathrm{n}_{\mathrm{r}} \times \mathrm{EE}_{\mathrm{comp}}\right)_{i} \tag{2}$$

where EE_{maint} is the total embodied energy for maintenance and replacement of components during the life span of the system (MJ); n_r is the number of times that components should be replaced over the life span of the system (times/life span of the system); EE_{comp} is the embodied energy in a system component (MJ); n is the number of system components that require replacements.

The estimate of the total embodied energy over the life span of each system was calculated using Eq. (3).

$$EE_{sist} = \left(\sum_{i=1}^{n} EE_{comp\ i} \right) + EE_{maint} \tag{3}$$

where EE_{sist} is the total embodied energy during the life span of the system (MJ); EE_{comp} is the embodied energy in a system component (MJ); EE_{maint} is the total embodied energy for maintenance and replacement of components during the life span of the system (MJ); n is the number of system components that require replacements.

3.3.2 Emissions of CO_2

The emissions of carbon dioxide (CO_2) generated in manufacturing processes of each component were verified by using Eq. (4).

$$R_{comp} = M \times R \tag{4}$$

where R_{comp} is the amount of carbon dioxide emissions generated in manufacturing processes of a system component (kg); M is the mass of the system component (t); R is the amount of carbon dioxide emissions generated in manufacturing processes of the material of the component (kg/t).

Data on the amount of emissions of carbon dioxide generated in the manufacture of materials of the components evaluated in this study were obtained from literature review.

To estimate the total amount of CO_2 generated in the system, Eq. (5) was used.

$$R_{total} = \sum_{i=1}^{n} R_{comp\ i} \tag{5}$$

where R_{total} is the total amount of carbon dioxide emissions generated in manufacturing processes of the system components (kg); R_{comp} is the amount of carbon dioxide emissions generated in manufacturing processes of a system component (kg); n is the number of components used during the life span of the system.

3.4 Investment feasibility analysis

As for the investment feasibility analysis, the costs of implementation and operation of systems were verified. The financial benefits and payback periods for the scenarios with rainwater harvesting were also assessed.

To calculate the financial benefit generated with the implementation of rainwater harvesting systems, the water rate practiced by the local utility was verified, according to the typology of the building studied. To estimate the cost of potable water considering the potential for potable water savings achieved by using rainwater, Eq. (6) was used.

$$c_{rain} = C_{potable} \times \left(1 - \frac{P}{100} \right) \times c_c \tag{6}$$

where C_{rain} is the monthly cost of potable water considering the use of rainwater (R\$/month); $C_{potable}$ is the monthly consumption of potable water without the use of rainwater (m^3/month); P is the potential for potable water savings (%); c_c is the amount charged by the water utility and wastewater generated according to the typology of the building (R\$/m^3).

The corrected payback was estimated by using Eq. (7).

$$I_{initial} \leq \sum_{i=1}^{m} \frac{B_m}{(1+r)^m} \tag{7}$$

where $I_{initial}$ is the initial investment for installation of equipment and components necessary for rainwater usage (R\$); m is the payback period (months); B_m is the monthly monetary benefit generated by the use of rainwater (R\$/ month); r is the minimum rate of attractiveness (dimensionless).

The payback period is numerically equal to *'m'* that equals or is immediately below the condition expressed by Eq. (7) for initial investment.

3.5 Indicator of environmental feasibility

The indicator of environmental feasibility is a quantitative index proposed in order to allow for comparative analysis of potable water systems by observing the relationship between the embodied energy into the system and potable water consumption in the building, considering or not the use of rainwater.

Eq. (8) was used to estimate the indicator of embodied energy per unit of water consumption for each system. The indicator of environmental feasibility is related to the functional unit (consumption of potable water during the life span of the systems). The higher the indicator, the greater the environmental impact of the system.

$$I_{EE} = \frac{EE_{sist} + \left(C_{water} \times EE_{water\_utility}\right)}{C_{water}} \tag{8}$$

where I_{EE} is the embodied energy indicator for potable water consumption (MJ/m^3); EE_{sist} is the embodied energy in the life span of the potable water systems (MJ); C_{water} is the consumption of potable water in the house during the life span of the system (m^3); $EE_{water\_utility}$ is the energy consumption per m^3 of water produced at the water utility (MJ/m^3).

3.6 Comparisons amongst systems

Comparisons between the building hydraulic systems for the two scenarios (with or without rainwater) were performed by comparing the indicators of environmental feasibility. The system that had the lowest score was considered the least environmentally impactful.

Comparisons regarding economic feasibility were based on payback periods obtained in the economic analysis. The system with the lowest payback period was considered more economically viable.

4 Results

4.1 Sizing of rainwater storage tanks

By performing the simulations in Netuno computer programme, potential for potable water savings and rainwater tank capacities were obtained as shown in Table 3.

Table 3: Main results of the sizing of rainwater storage tanks for the systems 1, 2 and 3.

Rainwater demand (% of potable water demand)	Optimum lower rainwater tank capacity (litres)	Potential for potable water savings (%)	Potable water savings (litres/month)	Upper rainwater tank capacity (litres)
30	4000	27.71	4156.5	250
40	7000	35.86	5379	250
50	11000	45.57	6835.5	300

4.2 Functional unit

Considering the potential for potable water savings obtained through simulations in Netuno (27.71%, 35.86% and 45.57%), the functional unit, i.e., the volume of potable water consumed in the house during the life span of the systems (20 years), was estimated as shown in Table 4.

Table 4: Functional unit used in the comparisons amongst the systems.

Systems	Rainwater demand (% of potable water demand)	Functional unit (m^3)
System A	0	3650.0
Systems 1, 2 and 3	30	2638.6
	40	2341.1
	50	1986.7

4.3 Environmental assessment

4.3.1 Embodied energy

The estimate of embodied energy for all systems is presented in Table 5. These values also include the energy embodied in equipment and components for the necessary maintenances during the life span of the systems.

Amongst the rainwater systems, system 1 has the lowest embodied energy.

Table 5: Embodied energy in all systems.

Rainwater demand (% of potable water demand)	Total embodied energy (MJ)			
	System A	System 1	System 2	System 3
0	13014.9	–	–	–
30	–	20331.6	29136.6	40734.2
40	–	37194.6	42436.6	66270.2
50	–	39858.6	51081.6	85426.0

4.3.2 Emissions of CO_2

Emissions of carbon dioxide (CO_2) generated during the manufacture of the materials constituting the main components of the systems were estimated based on references [7–9].

The amount of CO_2 emissions generated in manufacturing processes of the FRP, HDPE and concrete was estimated using Eqs. (4) and (5).

Figure 1 shows the estimated emissions of carbon dioxide generated in the manufacturing processes of the components of System A and Systems 1, 2 and 3.

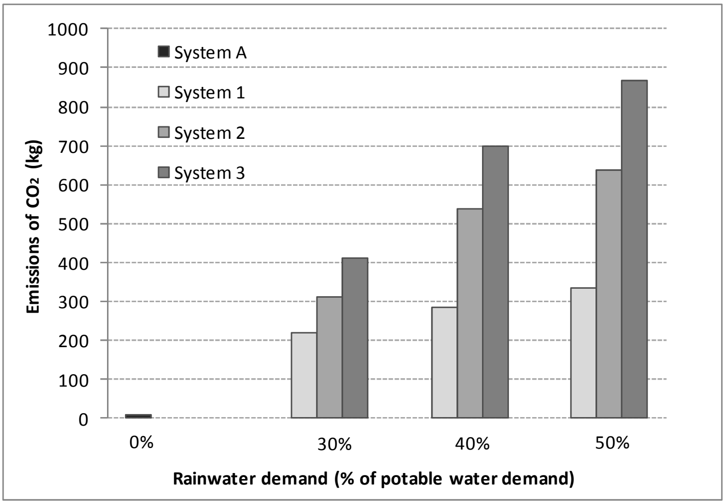

Figure 1: Emissions of carbon dioxide for system A and systems 1, 2 and 3.

The component that most influenced the generation of CO_2 emissions was the lower rainwater storage tanks. It was also noted that the amount of emissions generated increases as increases the capacity of the lower rainwater storage tanks.

Amongst the three rainwater systems, system 3 generated the largest amount of emissions, as the mass of concrete tanks is much greater than the mass of the other tanks.

4.4 Investment feasibility assessment

First, costs of all components for the four systems were obtained from stores in Florianópolis. Then, operation costs for the rainwater systems were also estimated (Table 6).

Table 6: Operation costs for the rainwater systems.

Item	Costs (R$/month)		
	Rainwater demand (% of potable water demand)		
	30%	40%	50%
Cost of electricity for pumping	0.08	0.11	0.14
Cost of potable water and wastewater without the use of rainwater	93.78	93.78	93.78
Cost of potable water and wastewater with the use of rainwater	56.51	48.94	48.94
Water rate practiced by the utility [10] for residential category "B"	24.47 (up to 10m ^{3}) and R$ 4.4844/m^3 excess	24.47 (up to 10m^3)	24.47 (up to 10m^3)
Wastewater rate charged by the utility	100% on the water costs		

Note: R$ stands for Brazilian Real (on 29 August 2011 R$ 1 = 0.6261US$ = £0.3816)

The costs of potable water and sewage obtained for rainwater demand of 40% and 50% of potable water demand were the same, as the consumption of potable water was less than 10 m^3 and thus the cost of potable water is framed within the range that is charged by the water utility, i.e., a fixed amount (minimum tariff).

The payback periods obtained for the rainwater harvesting systems are presented in Table 7. Payback periods longer than 20 years were considered inadequate.

Table 7: Payback periods for the rainwater harvesting systems.

Rainwater demand (% of potable water demand)	Payback periods (years)		
	System 1	System 2	System 3
30	25.3	32.7	14.5
40	42.7	>100	13.8
50	>100	>100	23.3

4.5 Indicator of environmental feasibility

To estimate the indicator of embodied energy per potable water consumption (I_{EE}), electricity consumption of 1.19 MJ/m^3 of potable water was obtained for Florianópolis [11].

Table 8 shows the environmental feasibility indicators obtained for the four systems. It can be observed that the higher the indicator, the higher the environmental impact of the system.

Table 8: Indicators of environmental feasibility.

Rainwater demand (% of potable water demand)	Indicator of embodied energy per potable water consumption (MJ/m³)			
	System A	System 1	System 2	System 3
0	4.76	–	–	–
30	–	8.97	12.3	16.7
40	–	15.36	17.35	26.38
50	–	16.37	20,62	33.64
Average	–	*13.6*	*16.8*	*25.6*

4.6 Comparisons amongst systems

Comparisons amongst the systems were performed using the environmental indicator proposed in this study. Since different rainwater demands were analysed, average figures were estimated.

Thus, based on indicators of embodied energy (I_{EE}), it was found that the embodied energy in each cubic meter of potable water supplied by potable water system complemented by rainwater was higher than in the system with no rainwater.

Considering the rainwater systems, it was found that system 1 has the lowest embodied energy indicator, so it is environmentally more viable than the other two systems with rainwater.

As for the financial analysis, system 3, which is composed of rainwater tanks made of reinforced concrete, was considered the most feasible, as it has the lowest payback periods.

5 Conclusions

This paper assessed the environmental and economic feasibility of rainwater harvesting systems in a case study for a low-cost house located in Florianópolis, southern Brazil.

Three types of rainwater storage tanks were analysed: plastic reinforced with glass fibre, high density polyethylene and reinforced concrete.

The results obtained in the environmental assessment indicated that systems that have high levels of embodied energy have a higher amount of emissions of carbon dioxide (CO_2) in the manufacturing processes of their components, and thus cause higher environmental impacts.

As for the financial assessment, it was found that the majority of the investment payback periods obtained for the systems analysed were considered inadequate because they are larger than 20 years, except for System 3, with rainwater demand of 30% and 40% of potable water demand.

Finally, the assessment of environmental indicators has shown that although the rainwater systems reduce potable water consumption, the embodied energy in each cubic meter of potable water supplied by these systems was greater than in the system with no rainwater.

In addition, the indicators of environmental feasibility of the three rainwater systems showed that system 1 is the most environmentally viable amongst them.

The study has shown the importance of assessing environmental and economic aspects before implementing a rainwater harvesting system, so that better choices related to sustainability in buildings can be made.

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