Does rainwater harvesting pay? Water–energy nexus assessment as a tool to achieve sustainability in water management

Rita Marteleira and Samuel Niza

ABSTRACT

Demographic growth that will take place on urban centers for the next decades may constitute a new challenge for water providers, which may then have to rely on more distant and/or poorer quality sources, or opt for energy-intensive technological solutions. In this context, the water–energy nexus will assume great relevance in near future water management policies and rainwater harvesting systems (RHS) may arise as an appealing alternative. The goal of this paper was to describe RaINvesT, a holistic tool developed to assess the viability of RHS, helping to adequately size the system, while allowing estimating its embodied energy per cubic meter (kWh/m^3). Additionally, considering the independence towards the public water supply network, an investment analysis is performed for both the water provider and the final user perspectives. RaINvesT was tested for a university campus: evidencing, in terms of embodied energy, a positive ratio of 0.013 kWh/m^3. The investment analysis has proven the RHS to be economically viable, revealing an investment return of about 12 years. The promotion of RHS can therefore represent a viable business model for water utilities, and can be a step forward in water systems decentralization, contributing to this sector sustainability for future cities.

Key words | climate change, embodied energy, greenhouse gas (GHG) emissions, rainwater harvesting, sustainability, water–energy nexus

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INTRODUCTION

Nowadays, modern cities rely on centralized and low-flexibility water supply systems (Perrone *et al.* 2011) which depend on extractions from distant rivers or profound aquifers, imposing water services with significant costs related to treatment and/or transport. Thus, opting for more sustainable (and less costly) solutions becomes more relevant, as demand is likely to keep increasing (Khastagir & Jayasuriya 2010). Hence the most significant demographic development will take place in urban centers for the next decades, new challenges will rise for water supply utilities, particularly regarding climate change impacts: likely to influence water resources availability, through droughts or floods, and to degrade water quality.

Rainwater harvesting systems (RHS) can help in diminishing the excessive urban runoff, while partially meeting the cities water demand – hence the water collected can be seen as a direct water source, using local available water and therefore increasing sustainability (Sharma *et al.* 2007). However, similarly to grey water recycling solutions, the use of harvested rainwater for human consumption is not well accepted by communities in general, due mostly to health concerns. Therefore, in urban contexts harvested rainwater is still mostly used for non-potable uses such as toilet flushing, watering of gardens, laundry and other washing purposes. The economic burdens of a RHS may also present an obstacle to their greater acceptance, such as the installation

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and maintenance costs of a secondary network (separated from the potable water (PW)) and the space requirements for the installation of reservoirs on the urban mesh.

The connection between water and energy has widely been a subject in literature, and is commonly referred to as the water–energy nexus. This nexus can be divided in two major branches: 'water for energy' and 'energy for water', the first comprehending the water volumes spent on energy production (hydroelectric plants, for example), and the second regarding power consumptions associated with water catchment, treatment and distribution (Perrone *et al.* 2011). Altogether, the amount of embodied energy per cubic meter of supplied water depends on a combination of variables, as the geographic location of its catchment, the raw water quality, and different calculation methods (Mo *et al.* 2011). Hoff (2011) has proven the importance of a water–energy balance by claiming that sometimes the horizontal transport of a cubic meter of water can require approximately the same energy as desalinating a cubic meter of salted water (depending on the distance), despite desalination being a very energy intensive technology (Hoff 2011).

It is, however, relevant to notice the absence of a holistic approach on the analysis of RHS. Moreover, when RHS are evaluated (commonly on households and rarely on larger buildings), it is either to meet a sizing optimization goal (Lash *et al.* 2014), to perform an embodied energy analysis, or analyzed from an economic viability perspective (the latter often considering only the customer's perspective, not seldom the utility's and rarely both). Moreover, these studies cross more than one of these analyses, as evidenced by Table 1.

Therefore, in order to fulfill this research gap, a major goal of the research presented in this paper was the development of RaINvesT (Rainwater harvesting INvestment analysis Tool), an instrument conceived to analyze the viability of an RHS, targeted for non-potable uses. RaINvesT was tested on the campus of Instituto Superior Técnico (IST), in Taguspark, Oeiras, Portugal.

METHODS

Conceptually, RaINvesT is divided into six operational modules, although interrelated, as shown in Figure 1, with all these modules operating on a single worksheet.

Water necessities module

On the first module, the volumes of water needed to satisfy the building water uses are estimated. According to what is permitted by the Portuguese legislation (Regulatory Decree no. 23/95, from August 23rd, Article no. 86), harvested rainwater is only permitted for non-potable uses. Thus, only toilet flushing (D_t) and garden watering (D_w) are considered here as potential uses for the harvested water – with the total water demand (D_{total}), in m^3/day, corresponding to the sum of these two water needs. However, this module can comprise any other water uses, as needed. Daily water necessities for toilet flushing are determined by the product of the capacity of each equipment (of 6 L per discharge, most commonly) per its daily average utilization, whilst for

Table 1 | Literature review on RHS – summary of scope

Author(s), year	Hydrological analysis	RHS sizing	Emb. energy	GHG emissions	Financial analysis
Anand & Apul (2011)			X	X	X
Angrill *et al.* (2012)	X	X		X	
Chiu *et al.* (2009)	X	X	X		X
Devkota *et al.* (2013)	X	X	X	X	X
Ghimire *et al.* (2014)	X		X	X	
Ghisi *et al.* (2009)	X	X			X
Racoviceanu *et al.* (2007)			X	X	
Rahman *et al.* (2012)	X	X			X
Walsh *et al.* (2014)	X	X			X
Zhang *et al.* (2009)	X	X			X

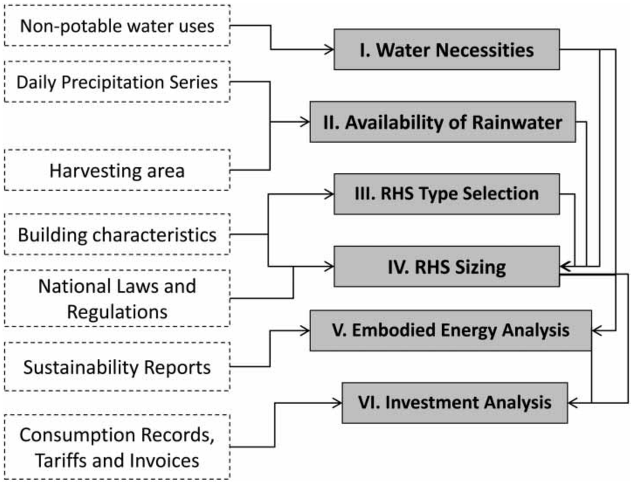

Figure 1 | RaINvesT modules and inputs.

watering purposes the water demand is obtained by affecting each area by its specific water intake (in $m^3/m^2 \cdot day$).

Availability of rainwater module

Daily rainfall series are required to operate RaINvesT, preferably for no less than 30 years to assure statistical representation. The initial rain in millimeters (first-flush) is subtracted from the total rainfall, which is usually discarded by being often contaminated by deposits on the collection area, as tree leaves or birds excreta, and the useful rainfall (mm) is obtained. Thus, the corresponding volume of useful rainwater to enter the RHS, on a daily basis, is subsequently calculated applying Equation (1). This volume depends not only on the extension of the collection area but also on the runoff coefficient. Finally, the volume of useful water is affected by the efficiency of the filters installed on the RHS, which is approximately 90% for most commercial equipment.

$$V = P_u \times C \times A \times \eta_f \quad (1)$$

where V = volume of useful rainfall (m^3), P_u = useful rainfall (mm), C = runoff coefficient (adimensional), A = collection area (m^2), and η_f = filters efficiency (%).

RHS type selection module

Two types of RHS solutions are commonly considered: a direct or an indirect system. For the most common option (the direct system), the collected rainwater is pumped directly from the reservoir (usually installed at the ground level or subterranean) to its final destination, exempting the installation of elevated tanks. Although the pumping requirements of these systems increase their operating costs, direct systems can be suitable solutions for buildings where the space on the roof or attic is a constraint, and have the advantage of assuring the water pressure necessary for some domestic equipment.

The alternative solution, the indirect system, includes pumping the water from the subterranean reservoir to elevated tanks, generally smaller, installed on the roof or attic. Through these secondary tanks, water can flow gravitically to its final uses. Indirect solutions are often considered more reliable, and also less energy intensive, thus with lower operational costs (Rodrigues 2010).

RHS sizing module

The optimal sizing of the RHS tank is generally a compromise between the use of harvested rainwater, the reliability of the system to satisfy water needs, and the available space for installation (Khastagir & Jayasuriya 2010). A daily balance is performed for the reservoir, in order to assess the system capacity to suppress water demands on a daily basis. This balance considers the water already in the tank (from the previous day) and the entrance of harvested rainwater (useful rainfall), as inputs, and as outputs the volume used for water needs, the overflow (in case of a surplus) and the remaining stored volume (which passed on to the following day). It should be noted that water demand should be maximized by the real volume of available water, given by the sum of the volume of useful rainfall and the volume already in the tank.

$$V_f = min((V_i + V - D_x), max) \quad (2)$$

where V_f = final volume of water (m^3), V_i = initial volume of water (m^3), V = volume of useful rainfall (m^3), and D_{Total} = daily water demand (m^3).

To test the system capability to meet the daily water demand, its reliability is expressed as the percentage of days in which the supply is: (a) independent from the potable water supply system (PWSS), with the RHS meeting all demands; (b) partially dependent (with water from the RHS and PWSS being used to meet demands); (c) or totally dependent on the PWSS (with no contribution from the RHS).

Embodied energy analysis module

The embodied energy of the RHS is here defined as the ratio between the pumping requirements (product of the pump power per average usage time period) and the volume of rainwater pumped, obtaining an indicator expressed in kWh/m^3 (Equation (3)).

$$E_{emb} = \frac{E}{D_{Total}} \tag{3}$$

where E_{emb} = embodied energy (kWh/m^3), E = daily energy demand (kWh/day), and D_{Total} = daily water demand (m)^3.

A comparison with the PWSS is then possible, considering for the latter its energy consumptions from catchment, treatment, transport and distribution phases. Similarly, the greenhouse gas (GHG) emissions associated with these energetic burdens can be determined for both systems: these energy consumptions are affected by the specific CO_2 equivalent emissions ratio considering a weighted average of the specific emissions.

Investment analysis

Finally, on the investment analysis module of RaINvesT, the economic viability of the RHS is estimated, either from the water utility perspective, or from the end consumer's. Two hypotheses can be considered, as a suggestion: on the first (I), the water provider utility bears the installation, operation and maintenance of the RHS and on the second hypothesis (II) the same costs are a responsibility of the end user. The several possible hypotheses can thus be analyzed under both perspectives.

The RHS installation costs include the elevated tanks, the diverse pipes, filters and accessories, as well as the submersible pump (and its operation costs). As for the system annual maintenance, it can be estimated considering the number of necessary hours per year and the average hourly salary of a technician. Finally, considering the interactions between the RHS end user and the PWSS, the reduction of PW inputs from the supply network is perceived in EBITDA calculations as a loss or an earning, under both perspectives. Thus, the utility 'PW output reduction (to the user)' loss equals the user's 'PW input reduction (from the utility)'. However, for the distribution utility, these lower PW inputs from the catchment utility (if different) can also appear as an earning. Moreover, for the utility, these volumes' associated reduction in energy requirements is accounted as an earning as well. It is relevant to mention that the revenues from taxing the harvested rainwater should be applied (RH taxation), although usually at a significantly lower tariff than the one applied to PW.

Table 2 summarizes these parameters. Finally, the economic viability of the project is assessed through the determination of the Net Present Value (NPV), considering for the RHS a usual lifetime of 15 years.

Table 2 | EBITDA calculation parameters for the two hypotheses

Hyp.	Entity	Losses (−)	Earnings (+)
I	SMAS	RHS installation RHS energy requirements RHS maintenance PW output reduction (to IST)	PW input reduction (from EPAL) PW energy requirements reduction RW taxation
	IST	RW taxation	PW input reduction (from SMAS)
II	SMAS	PW output reduction (to IST)	PW input (from EPAL) PW energy requirements reduction RW taxation
	IST	RHS installation RHS energy requirements RHS maintenance RW taxation	PW input reduction (from SMAS)

RESULTS AND DISCUSSION

The IST campus building was chosen as a case study, among other reasons due to the isolated location of this business park and its elevation compared to the remaining network, which represents a pumping effort for the water utility. Moreover, it is a recent public building (dating from 2009), with a considerable glass skylight (4,362 m^2), which makes it a potentially good candidate for rainwater collection.

Water necessities module

To determine water demand, an estimated number of 1,000 users was considered, including students, teachers, researchers and staff; assuming one flush per person per day. For watering purposes, only the interior gardens of the building were considered, adding up to seven flowerbeds and 11 trees (Figure 2), the green areas were measured adding up to a total of 723.6 m^2.

Water demand obtained was 8.53 m^3/day. Despite being apparently low, daily water consumption for toilet flushing of 6 m^3/day corresponds, in fact, to circa 26% of the building's daily average water demand from the consumed volumes declared in the building water invoices for 2010 and 2011.

Availability of rainwater module

In order to assess the available rainwater volumes in this region for Module II, daily rainfall data series from SNIRH (the Portuguese National Water Resources Information System) were consulted (SNIRH 2013) for the closest measuring station to Taguspark, Cacém Station, corresponding to a total of 28 hydrological years. A standard first-flush (ANQIP 2013) of 2 mm was then subtracted in order to obtain the useful rainfall, and for the glass skylight, a runoff coefficient of 0.9 was considered. On the RaINvesT data sheet, for each day of the 28 hydrological years considered, on 81.7% of the days there was no useful rainfall volume generated (either because no rainfall occurred or because it was lower than the first-flush requirements), a significantly high percentage which may diminish the RHS attractiveness for this location. However, on the remaining 19% of the days, over 64.5×10^3 m^3 (or approximately 2.3×10^3 m^3/year) could be harvested for the whole period of analysis.

Figure 2 | Interior gardens location on ground zero of IST plant.

RHS type selection module

The alternative of a direct system would not be viable for this case study, hence the installation of an RHS was not evaluated in the initial project of this building and the roof was not designed to support the significant weight of a reservoir. An indirect scheme was then considered, as there was no lack of space for installing the smaller elevated reservoirs and the predicted water uses had no pressure requirements. Moreover, as mentioned, the building was already equipped with two subterranean firefighting reservoirs of 25 m^3 each – as this capacity was overestimated comparatively to legal requirements (25 m^3 would be enough for emergency purposes), it was assumed that one of these reservoirs could be used as a rainwater harvesting tank. From this tank, treated and harvested rainwater would be pumped towards the elevated smaller tanks, distributed on the building roof, above the toilet facilities. Finally, water would flow by gravity towards toilet flushes on the three floors of the building, and similarly to the green areas for watering.

RHS sizing module

For the case study of the IST campus, there was no need to estimate the underground reservoir dimensions, since one of the two existing firefighting underground reservoirs were used (without compromising the minimum volume required for firefighting purposes). For the fixed harvesting volume of 25 m^3, the daily balance performed on the reservoir returned the following results, summarized in Table 3. It should be noted that, considering that the maximum capacity of the reservoir was dictated by the existing firefighting tanks, this final volume was then maximized by 25, in order not to surpass it.

Table 3 | Daily balance of the subterranean reservoir and RHS reliability results

	Results
Total potential use of harvested rainwater (28 years) (m^3)	27,227
Daily potential use of harvested rainwater (m^3/day)	2.66
% of daily demand met by the RHS	31.2%
(a) % of days of supply by the RHS only	26%
(b) % of days of supply by RHS+ PWSS	8%
(c) % of days of supply by the PWSS only	66%

Results evidenced that the RHS alone could meet water needs for 31.2% of days, which should be positively highlighted. By opposition, the days where there was no rainfall (or where it was lower than the stipulated first-flush height), in which water supply relied solely on the PWSS (meaning that no rainwater was used), corresponded to 66%.

Moreover, the fact that the percentage of days in which both rainwater and PW were used was so relatively low (8%) may be indicative of the seasonality affecting rainfall on this region as for the wet semester, when rainwater is abundant, the harvested rainwater is sufficient, but for the dry semester recurring to PWSS is still necessary. In other words, for most days, either there is rainwater available (stored from previous rainy days) and the supply relies on the RHS, or there is no rainwater and supply has to be assured by the PW network. This may indicate that the 25 m^3 of the subterranean reservoir is not a sufficient storage volume to confer a good reliability to the RHS. Another interesting outcome relates to the tank overflow, as significant percentages of the total volume of useful rainwater (V) are discarded (58%). This again constitutes evidence that the limited storage volume of 25 m^3 may not be sufficient to confer the RHS a good efficiency, given the amounts of harvested rainwater that are then wasted, assuming that a larger storage volume could enhance the RHS performance. For further applications of RaINvesT, where there is not a fixed volume for the subterranean reservoir, its volume must be optimized in order to diminish the waste of harvested water by a system overflow.

Figure 3 shows a scheme of the RHS conceived, with the connection between the subterranean reservoir and the elevated tanks, and the gravitical distribution of rainwater for the three floors toilet facilities, for flushing purposes.

The total daily energy estimated for this RHS was 0.11 kWh, assuming periods of 180 seconds for each pumping period (12 minutes/day) as sufficient to feed the elevated tanks.

Embodied energy analysis module

Regarding the embodied energy analysis performed for the PW network, the water catchment, treatment, transport

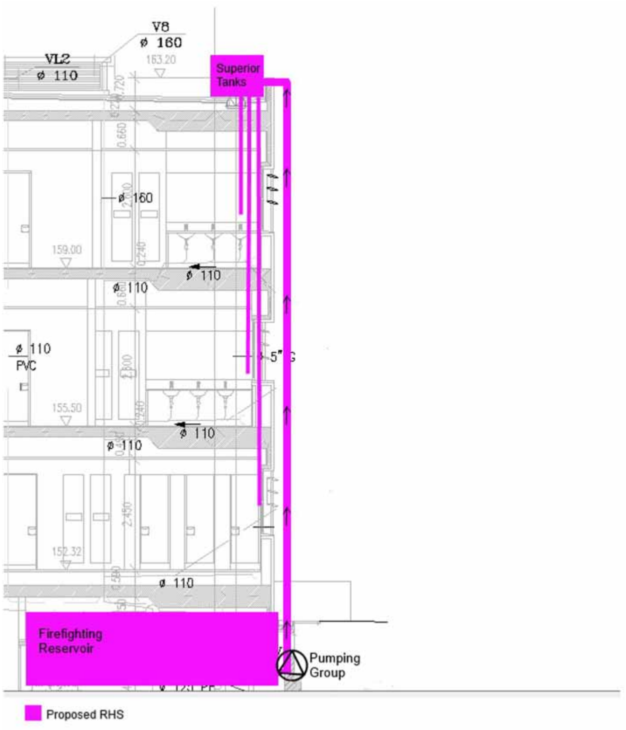

Figure 3 | Scheme of the RHS conceived for the IST building.

and distribution phases were considered, performed by EPAL and SMAS, adding up to 0.719 kWh/m^3. Table 4 summarizes these results (EPAL Empresa Portuguesa das Águas Livres 2010; ERSAR 2013; SMAS, Oeiras e Amadora 2013). Hence, the water itinerary was tracked from its catchment and treatment plants to obtain partial volumes which serve the Taguspark area, whilst energy consumptions were extracted from the utilities' sustainability assessment reports (SMAS 2013).

These embodied energy results are coherent with the examples found in the literature, since only the system operation was considered, excluding the construction of the infrastructure, as well as indirect energy contributions. However, for the RHS the embodied energy index obtained has proven to be significantly lower, which allowed an energy advantage compared to the existing supply network, which has a higher embodied energy index. Similarly, results indicate that the RHS solution has lower GHG emissions comparatively to the PWSS.

Results evidenced that the PWSS utilities are responsible for, in the Taguspark area, an emission equivalent of

Table 4 | Embodied energy results for the PW network

Utility	**EPAL**									**SMAS**
PWSS Phase	**Catchment**			**Treatment**				**Transport**		**Distribution**
Name of the facility	**EE. Castelo de Bode**	**E. Valada do Tejo**	**Other(s)**	**ETA Asseiceira**	**ETA Vale da Pedra**	**ETA Olhos de Água**	**Other(s)**	**EE Telheiras**	**EE Campo de Ourique**	**Sobrepressora Alto do Leceia**
Type of the facility	**Superficial catchment**	**Superficial catchment**	**Subterranean catchment**	**Treatment plant**	**Treatment plant**	**Treatment plant**	**Chlorination point**	**Pumping station**	**Pumping station**	**Pumping station**
% Supply of Oeiras	68.6	23.2	8.2	54.5	20.7	0.5	24.3	50.0	50.0	100.0
Emb. Energy (kwh/m^3)	0.067	0.146	0.135	0.049	0.106	0.078	0.053	0.154	0.154	0.484
Weighted Emb. Energy (kWh/m^3)	0.091			0.062				0.154		0.484
Total embodied energy (kWh/m^3)	0.791									

629.7 kg CO_2 eq, considering an average of specific emissions of 367 g CO_2 eq/kWh. This amount of GHG emitted is still significantly higher than GHG emissions obtained for the RHS: to the annual energy consumption of 40.15 kWh corresponded only 14.7 kg CO_2 eq – which can constitute another relevant advantage of RHS systems considering the impacts of climate change and the indisputable need to reduce GHG emissions. Once again, however, one should bear in mind that these calculations only take into consideration direct energy consumptions, discarding indirect consumptions such as the fuel of utilities vehicles, for example, which may correspond to considerable energy requirements (and increasing GHG emissions).

Investment analysis

The estimated cost for this RHS installation was only €6046, as the existent rainwater drainage system was used and so was the existing firefighting reservoir, exempting the need for new infrastructure and significantly diminishing these initial costs. Regarding the operational costs of the RHS, only the electricity for the pump was considered (0.11 kW/day and a tariff of 0.15 €/kW), adding up to solely €6.02 per year to the building electricity burden. Considering a semiannual maintenance for the filters, pumping system and other accessories (RHS_m), an annual cost of €192 was estimated.

Regarding the reduction of PW consumption from SMAS, it corresponded to a loss of €2464 (considering the SMAS tariff of 2.54 €/m^3 and an annual volume of rainwater used of circa 970 m^3 – from Module IV results. The same value was assumed as a gain for IST, in the form of savings of PW. This corresponded to circa €70 in energy savings for SMAS (PW_e), avoiding the distribution of such volumes of PW to IST. However, the reduction of PW from EPAL resulted in only a saving of €445 for SMAS (since EPAL tariff was lower, €0.46 €/m^3). Moreover, rainwater taxation of the 970 m^3 of rainwater potentially used by the RHS contributed only to €1232 of revenues for SMAS (0.3 €/m).

During the 15 years of the considered period, EBITDA was always negative from the SMAS perspective for the two hypotheses. From these results one can infer that RW taxation and the reduction of PW bought from EPAL were not sufficient to compensate the loss of revenues from PW sales to IST, as the latter involved a significantly higher tariff than the one paid to EPAL and/or the raw water tariff. However, from the IST point of view EBITDA was positive for the two hypotheses – it was negative only on year zero of hypotheses II due to the RHS installation costs borne by IST. Similarly, NPV was always negative for SMAS (−13 409€ and −5524€ for hypotheses I and II, respectively) and always positive for the IST (8266€ and 832€, respectively).

Regardless of assuming or not the installation/operation/maintenance costs, the RHS proved not to be a viable business model for this water distribution utility. However, from the client's perspective it is an advantageous investment for both hypotheses, with an obtained return period of nine years (for hypothesis II) and an IRR of 9% (higher than the discount rate used of 7%, and thus proving this RHS economic viability).

CONCLUSIONS

The projections for water supply in urban areas, assuring good quality and enough quantity, point to more energetically demanding systems. Rainwater harvesting can establish a viable alternative, improving those systems sustainability and reducing their dependence within the water–energy nexus. However, there is often a lack of an integrated vision that incorporates all the aspects of the viability of RHS, which encompasses not only their optimal sizing but also their embodied energy analysis and investment return.

RaINvesT has allowed assessing the investment associated with the installation of an indirect RHS on IST Campus on Taguspark, in terms of its independence towards the PW supply network and embodied energy analysis but also assessing its economic return.

Considering the fixed volume of the underground reservoir of 25 m^3, there was still a low percentage of operation days without PW inputs to meet water necessities. However, the system was proven to be a relevant contribution to reduce consumptions for non-potable uses. Moreover, the significant overflow was indicative of an underestimation of the underground reservoir – as for this case study, the use of the firefighting reservoirs limited the reservoir sizing. Despite this solution having significantly reduced the installation investment, it may have prejudiced the system reliability.

Further work is needed to assess the impact of different sizing solutions on the system reliability and its investment analysis. In terms of the embodied energy indexes, the RHS evidenced significantly lower embodied energy comparatively to the existing network, essentially due to its negligible pumping requirements, and, consequently, the GHG emissions for the RHS were also significantly lower.

Finally, the investment analysis module of RaINvesT has evidenced that the RHS is not a viable business model for this water distribution utility. Nevertheless, on the client perspective, it proved to be an advantageous investment, with an obtained return period of nine years. This is a very positive return period, considering that an RHS lifetime largely surpasses it.

Thus, one could assume that the installation of similar systems on neighboring buildings of the IST campus could provide a viable business model for the water utility as well, promoting its current system decentralization and long-term sustainability. Indeed, as a future development of this work, the study of the impacts of the installation of RHSs on more buildings is recommended, either in terms of supplied water volumes but also in terms of their energetic burden and return period for these investments. Other possible applications of this methodology could be on large isolated buildings, or groups of buildings, with significant non-PW uses and for which PW supply represents a challenge to the utility. Specifically, these situations on developing countries where resources as water and energy are scarce should be prominently addressed.

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