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Modeling for sustainability: Life cycle assessment application to evaluate environmental performance of water recycling solutions at the dwelling level

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Abstract

The reduction in drinking water consumption, also through the reuse and recycling of unconventional sources of water, has been identified as one of the goals of the sustainable development. This study focuses on evaluating and comparing the environmental impacts attributable to the use of source of water supply, such as rainwater harvesting and greywater recycling, alternative to the traditional one. The environmental impacts of both positive (reduction of the potable water consumption, stormwater runoff mitigation, wastewater reduction, etc.) and negative factors (system complexity, double network, tank, pump system, etc.) have been evaluated through the combined use of two models. The first is a Life Cycle Assessment (LCA) model, developed by means of Simapro software and based on Recipe 2008 method. The second is a hydrological model, realized with the EPA SWMM software. Models have been used to estimate the environmental impact of the following scenarios: (i) Business-As-Usual; (ii) rainwater harvesting system; (iii) greywater recycling system. Those scenarios have been applied to several configuration of single dwellings and apartment buildings. The Life Cycle stages evaluation showed how energy consumption for distribution system plays a critical role in the overall environmental performance of the solutions proposed, as well as use intensity of the technology. For greywater recycling system, the application of 1 m3 storage and treatment system serving thirty population equivalent results in a net positive impact, while for rainwater harvesting system, the high use intensity should be combined with an alternative reuse for recycled water, i.e. washing machine supply, to obtain an overall environmental benefit.

Keywords: Greywater; LCA; Rainwater harvesting; Sustainability

1. Introduction

Water scarcity is widely recognized as one of the most challenging consequence of the climate change, already afflicts 40% of the world population and is destined to grow in the coming years (WWAP, 2015). Its correlation with environmental degradation, biodiversity loss and human rights threat made it a strategic element in the Sustainable Development Agenda for United Nations (United Nations, 2015), where "ensuring availability and sustainable management of water and sanitation for all" has been listed as sixth sustainable development goal (WWAP, 2015). The full commitment to this issue is a milestone of 2030 agenda and a "universal and equitable" access to drinking water, increased efficiency in water use and supply, improving capacity-building support of local communities in order to decrease water scarcity through the application of sustainable techniques (e.g. water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies), are the main objectives.

The concept of sustainable solutions can be defined, in accordance with the definition of sustainable development, as technologies and techniques meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). Therefore, assessing the global impact of a local solution for water saving and recycling must be regarded, in this sense, as a crucial decision support step for designer and decision-makers.

Although Italy may not be considered a water-poor country, there are many regional differences in the water supply and consumption, with local water stresses and stormwater management issues. For this reason, the evaluation of rainwater harvesting, and greywater recycling solutions may be strategic to improve the sustainability of urban areas, as suggested by several studies Stephan and Stephan, 2017, Angrill et al., 2011, Angrill et al., 2017. Within this framework, the GST4Water project (Green-Smart Technology for Water) has been developed, with the main objective of creating hardware and software solutions for the sustainable use of water and promote rain and grey water reuse. The new instruments and technologies are, then, disclosed to encourage social change and improve awareness into water consumers. Moreover, smart and green solutions would be available for building and construction industry, supporting the establishment of smart, sustainable and resilient environments at building and urban scale.

1.1. GST4 W project presentation

The GST4Water project consists of four work-packages (WPs); the first two pertain to the development of: (a) a real time monitoring system of the mains water supply consumption at household; (b) a software cloud platform to manage and process information from the monitoring system; and (c) a user-friendly software interface to transfer information to users and water companies. WP1, in particular, analyzes the information from outdoor flow meters, while WP2 analyzes the indoor devices (showers, toilet flushing, washing machine, etc.). The third work package (WP3) is aimed to develop models and strategies for the optimal reuse of the grey and rainfall water at building level, while WP4 is focused on the elaboration of methods and tools to assess the economic and environmental sustainability of urban water systems at different scales, in particular household and urban. On one hand, a water sustainability tool is provided at household level along with environmental and economic performance indexes; on the other hand, the urban metabolism model is focused on the definition of different scenarios and strategies to limit the emissions and energy fluxes associated with the water consumption. Life Cycle Assessment (LCA) has been selected, as comprehensive impact assessment tool, to support water saving solution proposed, especially at household level.

This study, developed within the WP3 and WP4, fits this framework with a research activity devoted to assessing the sustainability of solutions proposed at a building scale, with the application of a Life Cycle Assessment tool.

Within the framework of GST4Water project, the main reuse option for recovered and recycled water has been identified in toilet flushing and garden irrigation (for rainwater only).

1.2. Decentralized system for water recycling and reuse

Two classes of technological solutions for water recovery in urban systems have been evaluated: Greywater Recovery Systems (GRS) and Rainwater Harvesting Systems (RHS).

1.2.1. Greywater recovery systems

A Greywater System (GRS) collects the gently used water from bathtubs, showers, handwashing basins and sometimes washing machines, and reuse it for non-potable uses. The volume of greywater produced by a households Dwumfour-Asare et al., 2017, Yu et al., 2013 typically range between 43.6 and 117 (liters per person per day) due to living habits and to plumbing fixtures (standard vs low consumption). These value are 70%–75% of the total household sewage water production in terms of volumes, despite corresponding to a rather limited portion of the pollution load (Noutsopoulos et al., 2017) A greywater system includes three major components (Fig. 1): a collection system with a coarse filter (1), which conveys greywater to the storage tank (2), where volumes are equalized, and (3) the treatment train who guarantees the quality requirements mandatory by law. The tank is usually equipped with an overflow and a mains water top-up system regulated by level controllers (Leong et al., 2017). A pump system delivers treated non-potable water to the users (7). Greywater systems have had a limited uptake in Italy compare to other European countries, due to significant plant costs, low prices of freshwater, and the perceived long-term risk of contamination.

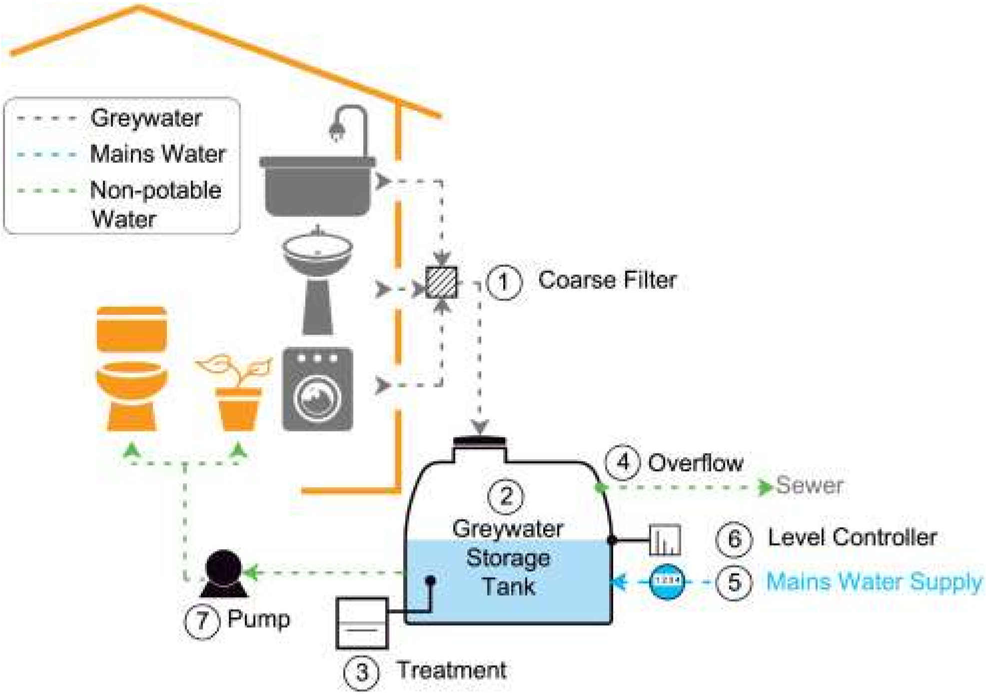

Fig. 1. Greywater recycling system. Adapted from Leong et al. (2017).

1.2.2. Rainwater harvesting systems

Systems aimed to capture and store rainwater have been generally used since 3rd millennium BC in the Near East and the Mediterranean regions (Mays, 2014). Ever since, rainwater-harvesting systems have evolved, and nowadays may still represents a valid technology to reduce the increasing demand for mains water supply.

A Rainwater Harvesting System (RHS), as illustrated in Fig. 2, includes four main elements: a catchment surface (1); a convey systems (2), which comprises gutters and some coarse filters to remove large solids (e.g. leaves and twigs); a storage tank (3), and a pump system (4) from which water is sent into the building or elsewhere (gardens, green roofs, etc.). Any excess of water, respect to the storage capacity of the tank, is delivered into the sewer system with a tank overflow (5), while a mains water top-up (6) system with level controller (7) ensures that the level of rainwater inside the tank does not go below a certain threshold level during periods without rainfall. Frequently, rainwater undergoes further treatment (additional filtration and disinfection) immediately before reuse (4) in order to lower health risks (Leong et al., 2017).

The non-potable water demand supplied by rainwater harvesting systems depends on the precipitation patterns, the volume of the tanks, and the demand for non-drinking water (Campisano et al., 2017). In California, due to the arid climate, the water saving efficiency does not exceed 10% (Loux et al., 2012), in Brazil due to tank size limitation it ranges from 14.7–17.7% (Ghisi and Mengotti de Oliveira, 2007). In Europe there is a marked improvement (Palla et al., 2011), and in Italy several studies show that water saving efficiencies of 70%–80% can be achieved with modest tank volumes Liuzzo et al., 2016, Palla et al., 2011.

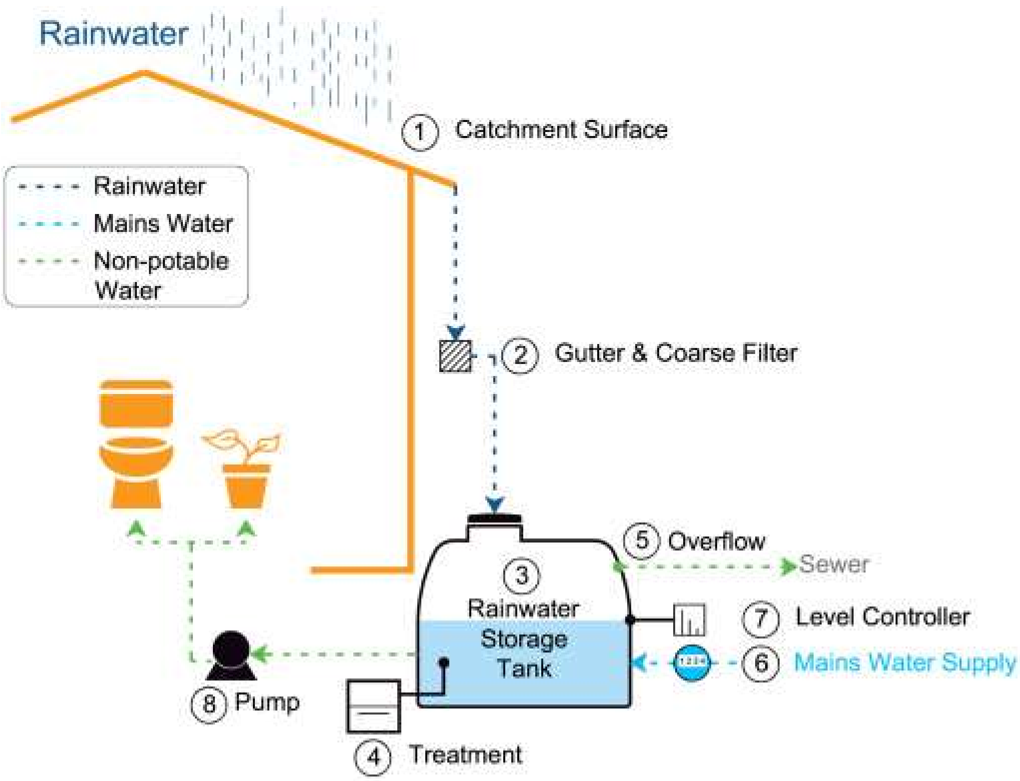

Fig. 2. Rainwater harvesting system. Adapted from Leong et al. (2017).

1.3. Life cycle assessment applied to water treatment

LCA, as defined with UNI EN ISO 14040 (2006), is generally applied for the assessment of eco-efficiency of product and processes. This analytical tool supports the quantification of environmental impacts generated throughout the whole life cycle, with each phase (production, use and end-of-life) carefully modeled and investigated (JRC, 2010). Thus including: extraction and transportation of raw materials, manufacturing process, distribution, use and maintenance, reuse (where possible) and waste treatment.

LCA applied to water recycling solutions offers an innovative perspective for most appropriated technique selection, considering technologies required to obtain the same level of environmental matrices quality, environmental benefit offered and possible criticality.

Several studies have been performed to evaluate the overall environmental impact of GRS, performed with different technologies (Dominguez et al., 2018), implemented into different residential zones (Jeong et al., 2018) and with different outline, i.e. with centralized treatment plant and re-distribution toward households or with small-scale treatment plant at building level (Opher and Friedler, 2016). Conclusions suggests that the decentralized approach offers the major environmental benefits. Moreover, the sizing of the system appears to play a significant role in the environmental performance of the solution.

As shown by Ghimire et al. (2017), literature available on LCA application on RHSs present quite different perspective and results on the issue, strongly depending on methodological approach toward the case studies proposed Crettaz et al., 1999, Angrill et al., 2011, Ghimire et al., 2014, Devkota et al., 2015, Morales-Pinzón et al., 2015, Petit-Boix et al., 2018, Yan et al., 2018.

1.4. Objectives

Based on the above, the first objective of this study is to evaluate the environmental impacts related to water recovery solutions proposed within the framework of GST4 W project, with the implementation of an LCA model of GRS and RHS. Environmental benefits deriving from water recovery solutions proposed are, then, accounted to obtain an evaluation of the overall environmental performance in comparison with Business-As- Usual (BAU) scenario.

2. Methodology

2.1. LCA methodology

Environmental impacts of the solution proposed have been calculated by the application of LCA (ISO, 2006). In particular, 1 m3 of reclaimed water has been chosen as functional unit (FU), in accordance with the major literature (Byrne et al., 2017), and a cradle-to-grave approach has driven the assessment.

In LCI compilation, a bottom-up approach has been applied. The product system constituted by the water reclamation solutions proposed has been built over a network of sub-processes representing the life cycle stages (i.e. production, use and End-of-Life) and the different components involved. As process analysis-based study, environmental impacts associated with inputs and outputs located outside of the system boundaries are excluded. Crawford et al. (2018) presented two alternative approaches: input–output analysis (EEIOA) and hybrid analysis. The former is regarded as "top-down" approach, based on macroeconomics, while the latter offers a combination of process based and EEIOA, considering both details on the processes and a broader perspective, with complexity related to the integration of different types of data and lack of software support. EEIOA intends to cover the entire economy including the product system, while hybrid analysis, following Crawford definition (2018), describes "the entire effort required from the economy to create a very specific output". In both cases, outputs are typically aggregated at a higher level than the one required by the goal of the present study. For these reasons, given the incompleteness related to the process-based approach, generating upstream, downstream and sideways truncation Lenzen, 2000, Majeau-Bettez et al., 2011, Crawford, 2011, it has been applied for LCI compilation, in order to comply with the GST4Water project requirements.

System boundaries include production phase for both water recovery and recycling solutions, as well as use phase and end-of-life (EoL). The expected life-span of the technologies is set in 50 years, in accordance with literature (e.g. Angrill et al., 2011, Stephan and Stephan, 2017) and commercial information available. Both models, for GRS and RHS has been developed with the support of Simapro 7.3.3. software (PRé, 2015) and standard processes used in absence of primary data are included into Ecoinvent 2.0 database (Frischknecht et al., 2007).

Recipe2008, in its hierarchical version, has been selected as impact calculation method (Goedkoop et al., 2009) and midpoint impact categories have been investigated, following the baseline method for characterization in the Handbook on LCA (Guinee et al., 2002), i.e. climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation

(PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionizing radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), mineral resource depletion (MRD) and fossil fuel depletion (FD). Considering the intrinsic uncertainties related to some impact categories, a limited set of impact indicators has been reported, including CC, OD, NLT, WD and FD.

The model set-up has been defined in accordance with GST4 W project findings. In particular, hydraulic modelinghas been identified as the driving design element for case studies definition. For both GRS and RHS, in fact, a total water consumption of 140 l/p/d, of which the 28% (39.22 l/p/d) for toilet flushing, has been assumed. This value is slightly higher than the 23% found experimentally in Bologna (ENEA, 2002), but totally in line with the recommendations of the Italian standard (UNI/TS 11445, 2012).

Water reuse options have been limited to toilet flushing for GRS and toilet flushing and irrigation for RHS. Nevertheless, some examples of possible alternatives for rainwater recycling are reported in literature Angrill et al., 2011, Vargas Parra, 2015, such as supply water for washing machine: this option has not been explored within GST4 W project framework, due to regulatory issue at local scale (DM 185/2003), but it has been used in the present study to complete the RHS assessment. In particular, the assumption is that the amount of water recovered from the RHS could be used for washing machine supply. The different hardness in tap and rainwater, lower in the proposed RHS solution, allows a lower consumption of detergent for clothes washing, with consequent environmental benefit Angrill et al., 2011, Vargas Parra, 2015.

While a general 28% of daily water saving per person on standard withdrawal can be attributed to the use of GRSs for toilet flushing, since they are produced regardless of climate conditions, RHSs, due to a more complex supply that depends on rainfall patterns at the site, required a detailed hydraulic/hydrological modeling that will be presented in the following.

2.2. Hydraulic/hydrologic model for RHS

A numerical model, that simulate the performance of rainwater systems under real precipitation patterns, is an important tool to forecast the suitability of RHSs to not only meet potable and non-potable water demands, but also to reduce discharge of stormwater or combined water, as in the case of Bologna sewer systems, and the associated pollutants to the environment. In this study, the hydraulic/hydrological model has been undertaken by means of EPA SWMM software version 5.1.012 (Rossman, 2015). The outcomes of the model are two indexes. The first one is the water saving efficiency index (E), which indicates the percentage of non-potable water demand that can be fulfilled by the tank, and therefore should not be bought from water public utility at a price (Cipolla et al., 2018). The other is the rainwater overflow ratio (O) which indicates the volume of stormwater exceeding the tank capacity compared with the system inflow. The model represents an important tool in supporting decisions on the suitability of rainwater systems (Cipolla et al., 2016). A detailed description of the model and of the performance's indexes can be found in Appendix A.

2.3. Case study analysis

The hydraulic/hydrological model has been applied to eight case studies, located in the city of Bologna, differing for roof dimensions, inhabitants, garden size, and tank volume as illustrated in Table 1. The city of Bologna is located in northern Italy and has a temperate subcontinental climate; the average precipitation is of 700–800 mm/year, mostly concentrated in late autumn and spring.

According to data collected within the monitoring activities done by the WP2 of the GST4water project, a total water consumption of 140 l/p/d, of which the 28% (39.22 l/p/d) for toilet flushing, has been assumed. Buildings falling in the "type A" category correspond to single-family detached home, while those falling into "type B" are real estates divided into several units, that are each separately owned, surrounded by common areas jointly owned. Buildings with garden are considered irrigated from April 1 to the end of September (154 days) with a constant daily volume of 1 l/m2. The selected scenarios, which correspond to the most common housing configurations in Bologna, and they have been simulated from to .

Table 1. Building's code, number of inhabitants (Person Equivalent—PE), roof area, garden area, irrigation volume, tank volume.

Building's code	PE [–]	Roof area [m2]	Garden area [m2]	Irrigation volume [l/m2/d]	Tank volume [m3]
A0	3	150	–	–	–
A1	3	150	–	–	2
A2	3	150	100	1	3.5
A3	3	150	150	1	4.5
B1	27	400	–	–	18
B2	27	400	200	1	24
B3	27	400	400	1	42

2.4. Life cycle inventory

The Inventory has been built following the life cycle stages typically identified, i.e. Production, Use and EoL.

2.4.1. Production phase

Inventory for the production phase includes the storage tank material (High Density Polyethylene, HDPE) and production, PVC distribution pipes, water treatment apparatus (i.e. filtration membranes and UV lamp) and electronic equipment (i.e. wiring board, flow control sensors, valves and cables) for both GRS and RHS. Distribution pipes have been modeled as 50 mm diameters PVC pipes, considering about 40 m per each application. Following manufacturers' specifications on water treatment, in particular, different apparatus has been modeled for GRS and RHS, i.e. double filtration (coarse and fine) for both, trickling filter of filling beads (modeled as natural stones) for GRS and UV light disinfection for RHS.

The storage tank sizing is clearly a key element of the system and it is expected to affect its overall environmental impact (Campisano et al., 2017). For this reason, a typical households' choice has been made for GRS, corresponding to a commercial version of a multi-stage treatment system, with 1 m3 capacity, fitting 10 to 30 population equivalent (PE). For RHS, storage tank sizing has been defined accordingly with the hydrological model's findings, therefore six different scenarios have been created (, , , , ,).

In both cases, HDPE has been selected as construction material, processed though thermoforming to commercial sizes and 0.001 m thickness. Where no primary data were available, assumptions have been made and the Ecoinvent processes have been selected on the basis of similarities and estimations (marked with * in the following tables).

Inventory for production phase of GRS is synthetically reported in the following Table 2, while Table 3 is referred to RHS, scenario , both in terms of total amount per each item and referred to the FU (i.e. 1 m3 of reclaimed water).

The production phase inventory is completed with a transport process, on average European distance and installation procedure, which is supposed to take place into an outdoor space, with ground excavation. Extracted material is assumed to be used locally for landscaping and construction site adjustment.

Table 2. Production phase inventory, GRS (10 PE).

Inventory item	Ecoinvent process	Total amount	Attribution to FU	Unit
Storage tank_raw material and processing	–	147.03	0.019	kg
Filtration membranes (UF)	Filter, decentralized unit, 250 m3/h, at plant/RER U*	0.002	2.61E−07	p
Recirculation system (n.3 pumps)	Pump 4kW /CH/I U	0.45	5.87E−05	p
Flow control sensors, valves	Potentiometer, unspecified, at plant/GLO U	2	2.61E−04	kg
Cables	Cable, without plugs, at plant/GLO U	10	1.3E−03	m
Aeration system (compressor)	Air compressor, screw-type compressor, 4 kW, at plant/RER/I U	0.15	1.96E−05	p
Recirculation and aeration system (pipes)_raw material and processing	Polyvinylchloride, emulsion polymerized,at plant/RER U Extrusion, plastic pipes/RER U	10	1.3E−03	kg
Wiring board	Printed wiring board, mixed mounted, unspec., solder mix, at plant/GLO U*	0.5	6.52E−05	kg
Beads	Quarry tile, at plant/CH U	50	6.52E−03	kg

Table 3. Production phase inventory for LCA, RHS, scenario A3.

Inventory item	Process[a]	Amount	Attribution to FU	Units
Storage tank raw material and processing	Polyethylene, HDPE, granulate, at plant/RER U Thermoforming, with calendering/RER U	160.64	6.18E−02	kg
Filtration membranes (UF)	Filter, decentralized unit, 250 m3/h, at plant/RER U*	0.002	7.69E−07	p
Recirculation system (pump)	Pump 4kW /CH/I U	0.15	5.77E−05	p
Flow control sensors, valves	Potentiometer, unspecified, at plant/GLO U	2	7.69E−04	kg
Cables	Cable, without plugs, at plant/GLO U	10	3.85E−03	m
Recirculation and aeration system (pipes)_raw material and processing	Polyvinylchloride, emulsion polymerized,at plant/RER U Extrusion, plastic pipes/RER U	10	3.85E−03	kg
Wiring board	Printed wiring board, mixed mounted, unspec., solder mix, at plant/GLO U*	0.5	1.92E−04	kg
UV lamp	Backlight, LCD screen, at plant/GLO U*	0.25	9.62E−05	kg

a

Names of materials and processes used according to Ecoinvent 2.2 database (Frischknecht et al., 2007).

2.4.2. Use phase

The use phase inventory has been defined considering:

1. Energy consumption for water pumping and electronic equipment supply. In particular, an average 1 h of functioning time per day is considered for each pump, thus leading to an energy consumption over the whole expected life span of the technologies of 32.850 kWh for GRS and 10.950 kWh for RHS. Italian energy country mix was selected, due to local relevance of case studies implemented. In order to evaluate the relative impact generated by the specific energy source, an alternative scenario has been built, both for GRS (10, 20 and 30 PE scenarios) and RHS (and scenarios) with the implementation of photovoltaic energy supply.

2. Maintenance rate for replaceable parts. In the following Table 4, spare parts supply is accounted; for each replaced part, EoL process has been implemented.

Filling beads for GRS are supposed to be maintained with periodical counter-current washing, thus no replacement is required nor accounted. In RHS application, additional disinfection is required during use phase. Therefore, 1 kg of sodium hypochlorite solution (15%) is accounted per year.

Table 4. Use phase inventory for LCA, GRS and RHS, scenario .

Inventory item	Replacement rate	System Type	Replacements required over life-span
Filtration membranes (UF)	6 months	GRS	200
		RHS	200
Recirculation system (pump)	10 years	GRS	4
		RHS	12
Recirculation system (pipes)	30 years (partial)	GRS	0.5
		RHS	0.5
Flow control sensors, valves	10 years	GRS	4
		RHS	4
Cables	30 years (partial)	GRS	0.5
		RHS	0.5
Wiring board	10 years	GRS	4
		RHS	4
Air compressor	10 years	GRS	4
		RHS	–
UV lamp	5 years	GRS	10
		RHS	–

2.4.3. End of Life

EoL processes have been modeled with final disposal of each component for both systems. Waste scenarios available into Ecoinvent databases have been implemented, as for replacement parts in Use phase. In particular, different process has been selected for the different inventory items:

(a) Treatment (i.e. dismantling and sorting) and disposal (i.e. incineration) have been accounted for electric equipment,
(b) Final disposal (i.e. incineration) for membrane filters,
(c) Treatment (i.e. shredding), recycling and final disposal (i.e. incineration) for plastic material. In the perspective of the UN Agenda for Sustainable Development (WWAP, 2015) and European Strategy for Plastics in a Circular Economy (COM/2018/028), recycling rate of 85% has been set. This choice has been made considering the time-span of the technology (i.e. 50 years) with expected technological progress and the application of selective de-construction of the site. The consequent environmental benefit (i.e. avoided impact) deriving from equivalent material recovery has been accounted.

2.5. Assessment set-up

The model implemented on Simapro was completed with impact assessment of each process for both the systems proposed. Processes have, then, been grouped by Life Cycle stage, in order to verify which phase generated the major environmental impact and, therefore, where to direct optimization efforts for real-scale applications. In addition to this, comparative assessments have been performed on different use scenarios and in reference to Business-As-Usual (BAU), as presented in the following.

2.5.1. Greywater system scenario

For GRS, since the modeled system is designed for a number of population equivalent ranging from 10 to 30, three scenarios have been set, for the use of the same GRS serving 10, 20 and 30 population equivalents. Therefore, different use intensities of the same solution have been tested.

BAU has been set as typical water consumption profile of equivalent number of users, i.e. 10, 20 and 30, over the expected time-span, i.e. 50 years. The average consumption per person is identified in 140 l of water from the distribution network (As for regional average data, and related discharge of wastewater into public sewerage). The same data for water consumption has been attributed to the GRS cases.

The sensitivity analysis has been set over the different use intensity for the solution (i.e. same tank and recirculation system for different PE—10, 20 and 30) and for different consumption profiles. In particular, five additional consumption profiles have been tested:

- 105 l/p/d, i.e. consumption profile in presence of water saving devices (e.g. aerated flow taps). This consumption profile is set accordingly to AQUASAVE project results (AQUASAVE - demonstrative implementation on an innovative system of rational use and re-use of water in a residential building in Bologna. LIFE97 ENV/IT/000106, Failla et al., 2001);
- 112 l/p/d, i.e. 20% of water saving compared to the standard consumption profile;
- 126 l/p/d, i.e. 10% of water saving compared to the standard consumption profile;
- 154 l/p/d, i.e. 10% of additional water consumption, compared to the standard consumption profile;
- 168 l/p/d, i.e. 20% of additional water consumption, compared to the standard consumption profile;

2.5.2. Rainwater harvesting system

Based on the hydraulic model for RHS, six scenarios have been compared, with reference with two BAU scenarios, i.e. standard consumption profile for households hosting n.3 (i.e. scenario) or n.27 (i.e. scenario) population equivalent, calculated over the expected life-span of the technology. The same water consumption profile as in GRS has been set.

In order to complete the assessment and trying to optimize the environmental benefit of the solution proposed, an alternative use for rainwater recycled through RHS has been modeled. Following Angrill et al. (2011) and Vargas Parra (2015), the environmental benefit derived from soft water supply has been accounted, in terms of amount of detergent saved. In fact, rainwater presents hardness value remarkably lower than tap water, thus improving the effectiveness of detergent's action and limiting its demand. In accordance with Vargas Parra (2015), detergent's dose difference per cubic meter between soft and hard water is 0.59. Detergent's inventory is modeled following Saouter and Hoof (2002).

3. Results

3.1. The hydraulic/hydrologic simulation results

The system performance is assessed at the entire simulation period for each scenario. Fig. 3 reports the results of the simulations in terms of water saving efficiency and overflow ratio under the city of Bologna weather conditions (808.8 mm of rainfall). The water saving efficiency, which indicates the percentage of non-potable water demand that can be fulfilled by the tank, and therefore should not be bought from water public utility at a price, ranges from 78.1 () and 79.4% () in a building with 3 inhabitants and from 59.5% () and 69.8% () in a building with 27 inhabitants. From one side this means that the presence of RHS equipped with a properly sized tank, determines a substantial reduction in the volumes of drinking water consumed for non-potable purposes. On the other, in order to guarantee this level of efficiency, it is necessary to increase the volume of the tank and this causes a significant increase in the cost of the plant and therefore of the payback period.

Reducing the consumption of non-drinking water is not the only benefit of an RHS. In some Italian cities such as Bologna, equipped with combined sewer systems, the widespread presence of the RHSs will lead to a sensible reduction in stormwater volumes discharged into the sewers. This, as demonstrated by other authors (Palla et al., 2017), determines a reduction in the number of combined sewer overflow spills and thus a reduction of pollutants discharged into the waterbodies. Through the O index the model allows to quantify this phenomenon. In a building with no RHS (scenario A0 and B0) 100% of the rainfall is discharged into the sewer system, while the presence of tanks reduces these volumes (Fig. 3 right) significantly. In conclusion, it can be said that during the feasibility checks of an RHS plant, not only the reductions in drinking water consumption but also the volumes of rainwater spilled into the sewer system should be taken into consideration.

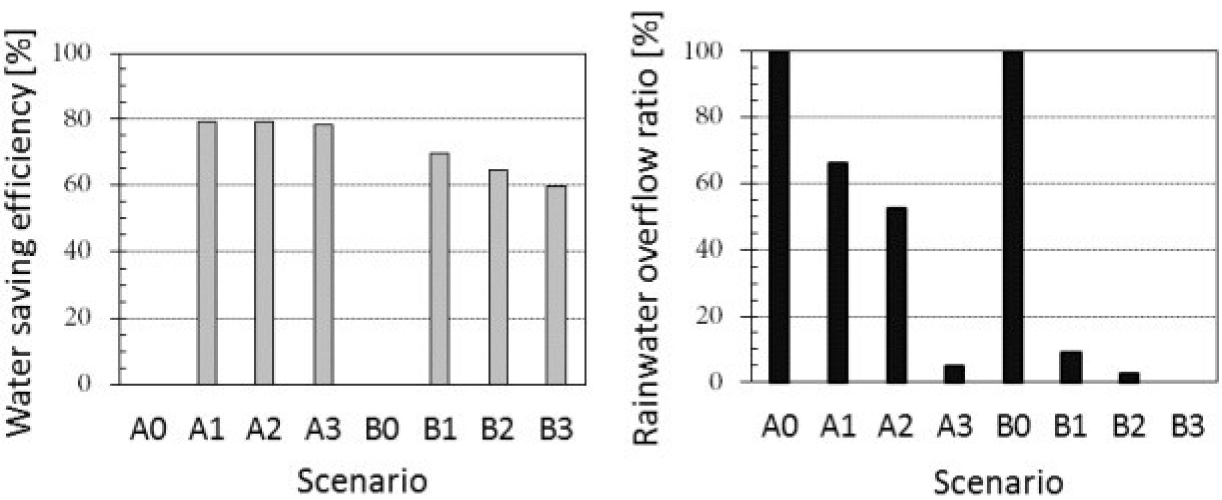

Fig. 3. Water saving efficiency (left) and rainwater overflow ratio (right) for each simulated scenario.

3.2. Life cycle stages evaluation

Based on Simapro model and impact calculation performed with Recipe2008 method, the following Table 5, Table 6 report results obtained for GRS and RHS, respectively, in relative characterization terms, as well as Fig. 4, Fig. 5

As evident from Fig. 6 above, the implementation of different energy supply would mainly affect the Climate Change indicator (as Global Warming Potential, kg CO), giving rise to a better performance ranging from about 89%–99%, in case of low use intensity applications (i.e. 10 PE scenario for GRS and scenario for RHS), to ten times, in case of high use intensity of GRS (i.e. 30 PE scenario). OD impact indicator shows improved performance as well, with value ranging from 69% (related to GRS, 10 PE) to 317% (for RHS, scenario); FD appears to follow the same pattern, but with lower intensity (1% variation over GRS, 10 PE scenario; 210% variation for RHS, scenario). WD results not affected by the different energy supply, as expected, while LO shows a negative performance in all cases, except for scenario for RHS.

Table 5. Life cycle evaluation for the Production, Use and EoL phases of the GRS, considering the following impacts: Climate Change (CC), Ozone depletion (OD), Land occupation (LO), Water depletion (WD), Fossil depletion (FD). Negative impact values indicate actual environmental benefits. The production phase considers the Storage Tank (ST), the Distribution System (DS): e.g. pipes and pumps, Water Treatment (WT): e.g.filters, beads and aeration, Electronic Equipment (EE):e.g. wiring board, valves, sensors, cables, Transport and Installation (TI). The use phase includes the Electricity consumption (EC), the

Replacements (R) production and disposal. The EoL phase considers the storage tank and pipes (ST&P), the Water Treatment Equipment, and the Electronic Equipment (EE).

	Climate change kg CO2 eq	Ozone depletion kg CFC-11 eq	Land occupation m2a	Water depletion m3	Fossil depletion kg oil eq
Production	**1,47E−01**	**8,48E−09**	**1,06E−02**	**1,08E−03**	**6,51E−02**
Storage tank	4,73E−02	7,47E−10	6,42E−03	1,79E−04	3,41E−02
Distribution system (pipes and pump)	6,74E−02	4,95E−09	2,70E−03	5,59E−04	2,17E−02
Water treatment (filters, beads and aeration)	1,22E−02	8,38E−10	3,98E−04	1,21E−04	3,35E−03
Electronic equipment (wiring board, valves, sensors, cables)	1,78E−02	1,90E−09	1,05E−03	2,17E−04	4,99E−03
Transport and installation	5,64E−04	8,02E−11	6,05E−06	1,62E−06	2,04E−04
Use	**1,85E+00**	**1,60E−07**	**2,85E−02**	**8,62E−03**	**5,92E−01**
Electricity consumption	1,50E+00	1,31E−07	1,37E−02	5,45E−03	4,85E−01
Replacements (production and disposal)	3,53E−01	2,85E−08	1,48E−02	3,17E−03	1,07E−01
EoL	**−2,74E−02**	**1,37E−10**	**6,94E−05**	**−4,25E−05**	**−2,69E−02**
Storage tank and pipes	−2,81E−02	8,12E−11	6,07E−05	−4,45E−05	−2,70E−02
Water treatment equipment	1,46E−08	2,57E−17	5,07E−12	1,36E−11	7,64E−11
Electronic equipment	3,93E−04	5,98E−12	3,61E−06	7,50E−07	2,28E−05
Transport	3,12E−04	4,93E−11	5,05E−06	1,17E−06	1,15E−04

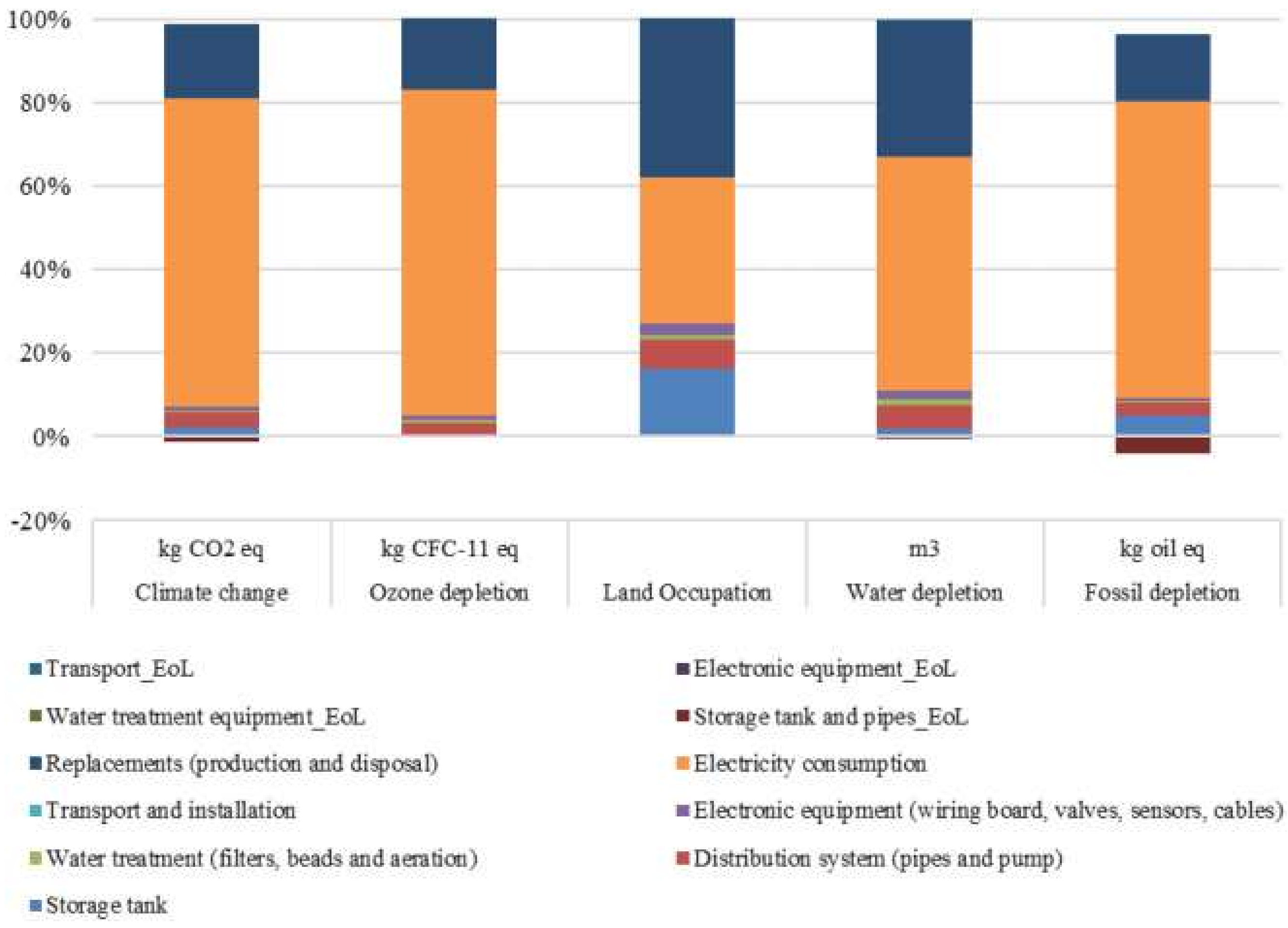

Fig. 4. Impact characterization, GRS.

Table 6. Life cycle evaluation for the Production, Use and EoL phases of the RHS scenario , considering the following impacts: Climate Change (CC), Ozone depletion (OD), Land occupation (LO), Water depletion (WD), Fossil depletion (FD). Negative impact values indicate actual environmental benefits. The production phase considers the Storage Tank (ST), the Distribution System (DS): e.g. pipes and pumps, Water Treatment (WT), Electronic Equipment (EE): e.g. wiring board, valves, sensors, cables, Transport and Installation (TI). The use phase includes the Electricity consumption (EC), Disinfectant consumption (DC), the Replacements (R): e.g production and disposal. The EoL phase considers the storage tank and pipes (ST&P), the Water Treatment Equipment, and the Electronic Equipment (EE), and the transport (T).

CC	OD	LO	WD	FD	
	kg CO2 eq	kg CFC-11 eq	m2a	m3	kg oil eq
Production	**3,08E−01**	**1,46E−08**	**2,94E−02**	**2,00E−03**	**1,65E−01**
Storage tank	1,67E−01	2,65E−09	2,27E−02	6,34E−04	1,21E−01
Distribution system (pipes and pump)	7,96E−02	5,41E−09	3,15E−03	6,36E−04	2,67E−02
Water treatment (filters, UV lamp)	1,03E−03	4,71E−11	9,52E−05	2,22E−05	3,37E−04
Electronic equipment (wiring board, valves, sensors, cables)	5,76E−02	6,17E−09	3,39E−03	7,04E−04	1,62E−02
Transport and installation	2,14E−03	2,99E−10	2,10E−05	5,83E−06	7,71E−04
Use	**3,19E+00**	**2,78E−07**	**4,75E−02**	**1,44E−02**	**1,02E+00**
Electricity consumption	2,70E+00	2,37E−07	2,47E−02	9,81E−03	8,74E−01
Disinfectant consumption	1,71E−02	1,24E−09	7,03E−04	1,80E−04	5,16E−03
Replacements (production and disposal)	4,71E−01	4,00E−08	2,21E−02	4,40E−03	1,38E−01
EoL	**−6,33E−02**	**4,50E−10**	**2,15E−04**	**−1,17E−04**	**−8,77E−02**
Storage tank and pipes	−6,65E−02	2,38E−10	1,81E−04	−1,27E−04	−8,83E−02
Water treatment equipment	8,02E−06	1,11E−12	1,46E−07	3,88E−08	2,87E−06
Electronic equipment	2,14E−03	4,45E−11	1,74E−05	6,02E−06	1,74E−04
Transport	1,05E−03	1,66E−10	1,70E−05	3,95E−06	3,88E−04

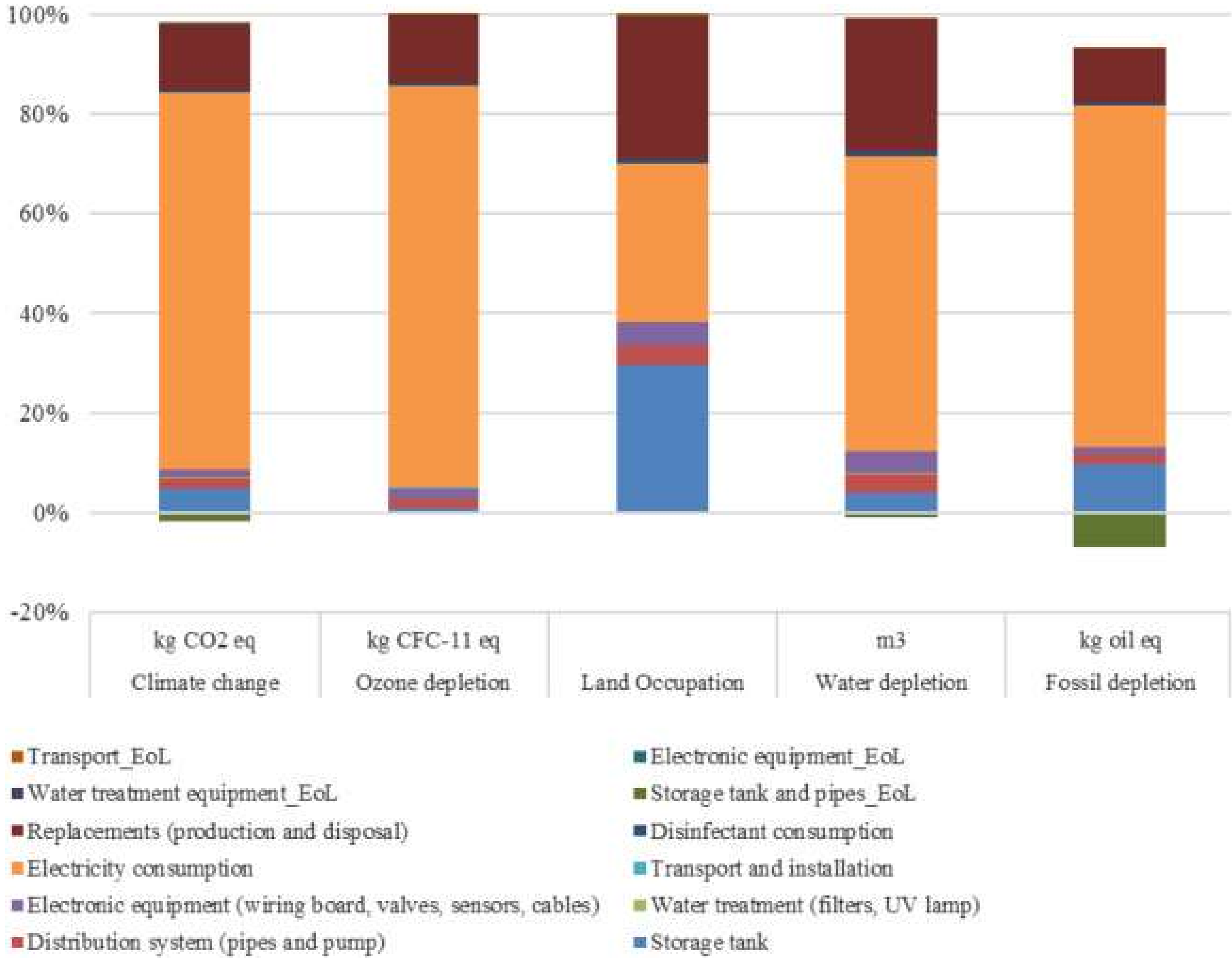

Fig. 5. Impact characterization, RHSAs shown by Table 5, Table 6, the impact generated by both solutions is largely dependent on Use phase, ranging from 80.83% to 94.88% of the total impact for both solutions, and, in particular, on energy demand. As in conventional water treatment systems, the energy consumption is mainly related to distribution system (i.e. pumping) (Crittenden et al., 2012). For this reason and following Jeong et al. (2018) an integrated system supplying energy and water from a local source, i.e. with the implementation of renewable energy system (e.g. photovoltaic panels), would sensibly improve the overall environmental performance of the solution proposed, as demonstrated by the following Fig. 6.

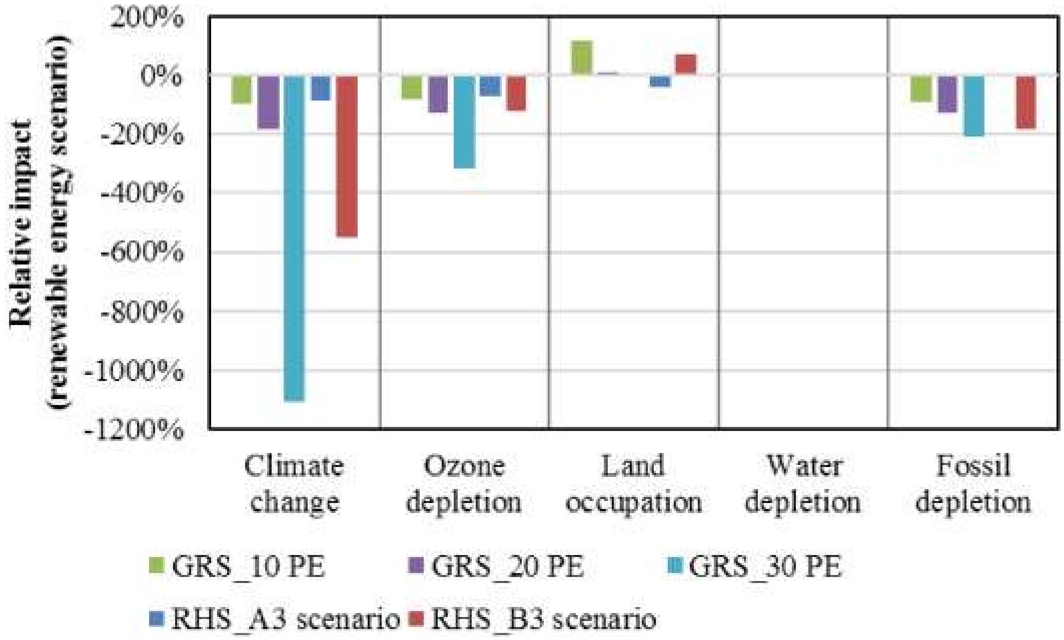

Fig. 6. Alternative energy supply evaluation, comparison between impact generated by the application of standard Electricity Country mix (IT) and Photovoltaic electricity supply (IT), in percentage, for GRS (10 PE, 20 PE and 30 PE) and RHS (and scenarios).

Nevertheless, for both GRS and RHS, spare parts supply and disposal account for the major part of metal depletion, as expected, and more than 40% for toxicity related impact categories (i.e. human toxicity, terrestrial and freshwater ecotoxicity), in accordance with typical Waste Electrical and Electronics Equipment (WEEE) profile (Oguchi et al., 2013).

Since six different scenarios have been modeled, the relative impact generated by life cycle stages have been evaluated for each of them. Production phase displays the higher variability, i.e. from 13.17% of to 32.46% of , while Use phase ranges between 73.51% of to 87.51% of and EoL between −5.97% of to −0.68% of (Fig. 7). Negative impact values, such as for EoL phase, indicate actual environmental benefits generated by the processes implemented, e.g. by the material recovery of storage tank plastic.

The same data have been plotted in comparison with storage tank volume (Fig. 8), showing how the increase in cubic meters of water storage leads to a decrease in Use phase impact, in relative terms, and in EoL, even if with lower variability. On the other hand, Production phase relative impact results grows together with storage volume, due to higher amount of HDPE required for the production of larger tanks.

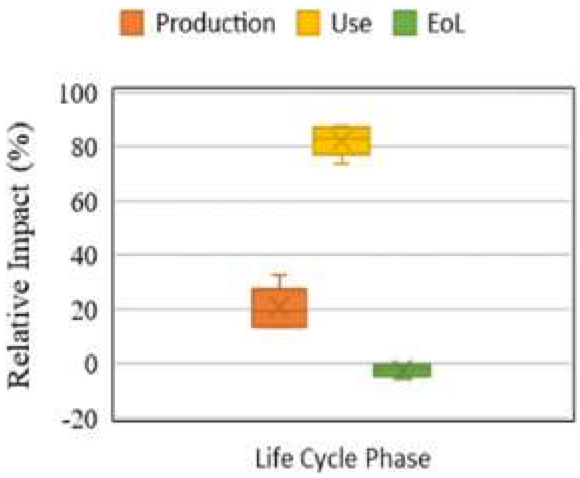

Fig. 7. RHS Life Cycle Stages evaluation in terms of relative impact.

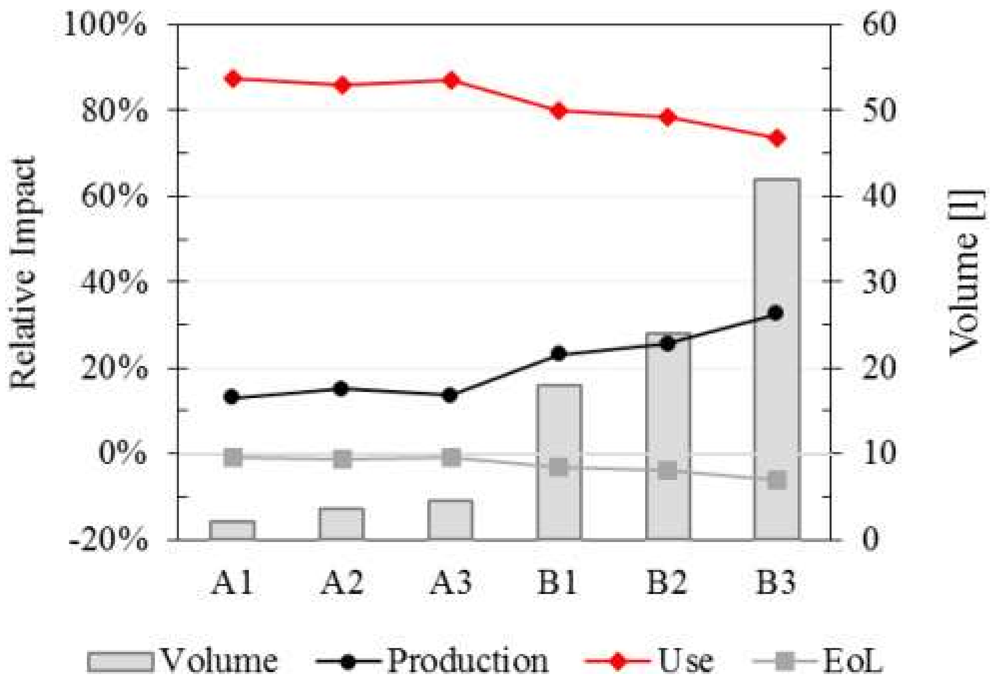

Fig. 8. RHS, Life Cycle Stage relative impact trend, related to storage tank volume.

3.3. Use intensity evaluation

Results obtained on Impact assessment of the different scenarios modeled are reported in the following.

3.3.1. GRS

Since a single typology of GRS has been modeled, with three possible use intensity scenarios, i.e. 10, 20 and 30 population equivalents, they have been assessed in comparison with the corresponding BAU. In accordance with Jeong et al. (2018), results suggest that higher use intensity, i.e. a larger number of population equivalent served by the same GRS, drastically reduces the relative impact of the solution. In particular, with n.30 population equivalent on the same technology, relative impact results neutral or positive for about 70% of impact categories, such as: TA, FE, ME, HT, POF, PMF, TET, FET, MET, IR, ALO, ULO, WD (Fig. 9).

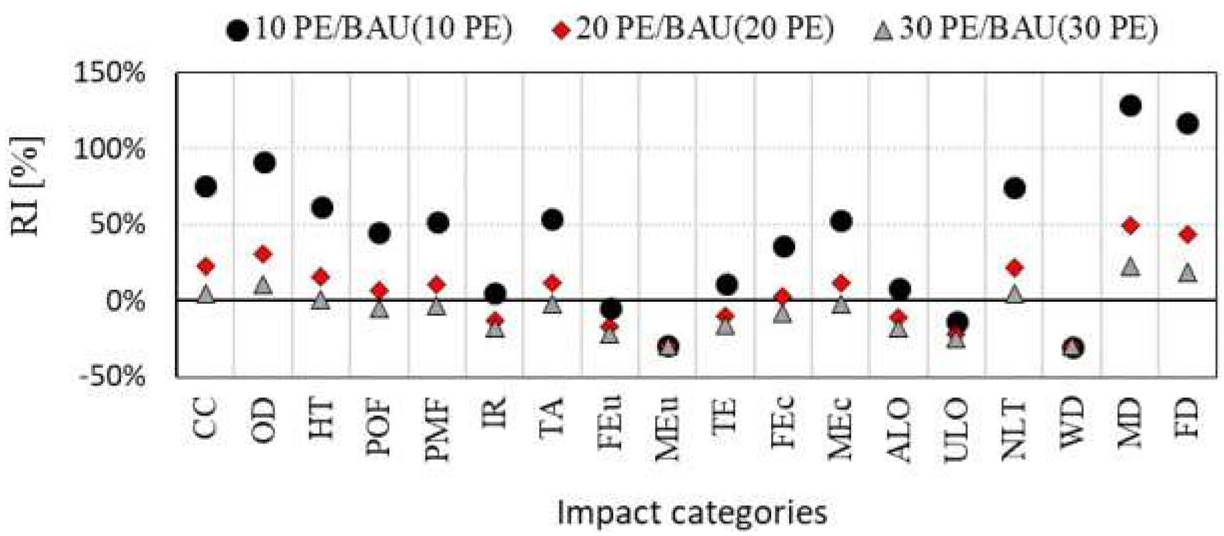

Fig. 9. GRS, impacts generated by scenarios of application (10, 20 and 30 PE) compared to corresponding BAU.

3.3.2. RHS

RHS scenarios have been compared with the BAU corresponding in terms of population equivalent and setting, i.e. for , and , for , and (Fig. 10).

As evident from Fig. 10, almost all impact categories display a higher impact, compared to corresponding BAU case, proving a poor overall environmental performance, in general terms. Nevertheless, following highlights from GRS evaluation and conclusions from Angrill et al. (2011), the different use intensity of the solution leads to different environmental impacts, with improvements for ULO, WD and results close to neutrality for MD. These quite negative results may be related to the model set-up and scale, in particular, to environmental benefits not properly accounted by LCA implemented i.e. decrease in local water scarcity or stress conditions, provided that only the building level has been investigated.

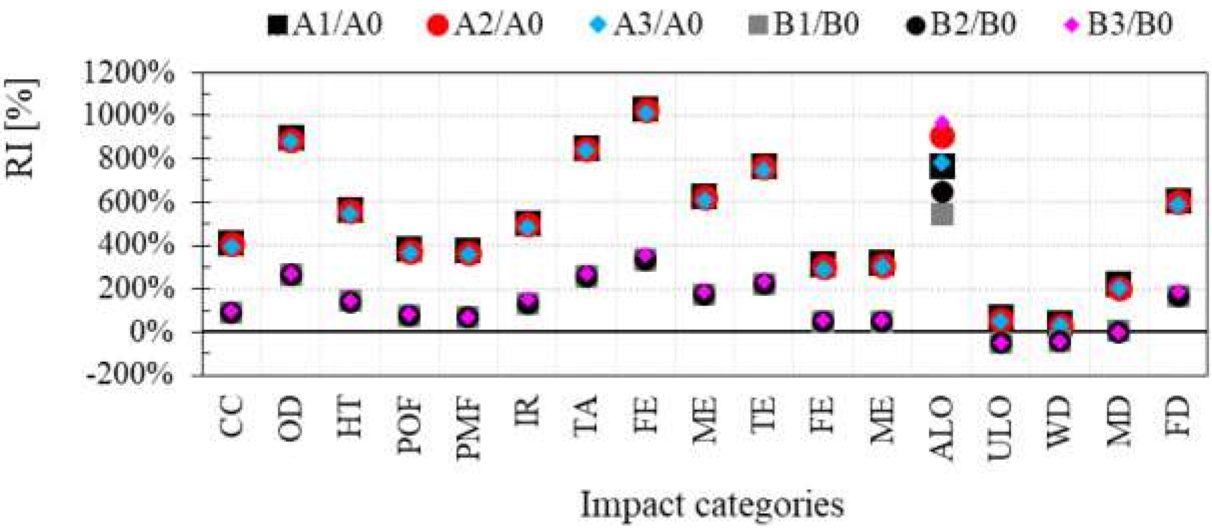

Fig. 10. RHS, impacts generated by scenarios of application (A1, , , , and) compared to corresponding BAU (i.e. and).

The alternative use for RHS has been modeled over two scenarios (and), i.e. washing machine supply (WM and WM) and results show a remarkable environmental improvement, with values ranging from one to ten times lower in toxicity related impact indicators for scenario and all impact indicators showing negative values (i.e. environmental benefit), except ALO, for scenario (Table 7).

Table 7. Evaluation of environmental benefit deriving from alternative use of recycled rainwater.

Impact categories	Unit	A3 impact	A3 WM impact	B3 impact	B3 WM impact	Variation A3	Variation B3
CC	kg CO2 eq	3.794	2.455	0.803	−0.537	−35%	−167%
OD	kg CFC-11 eq	0	0	0	0	−42%	−210%
HT	kg 1.4-DB eq	2.046	−0.075	0.41	−1.711	−104%	−518%
POF	kg NMVOC	0.01	0.007	0.002	−0.002	−37%	−178%
PMF	kg PM10 eq	0.006	0.004	0.001	−0.001	−39%	−198%
IR	kg U235 eq	0.801	0.424	0.183	−0.194	−47%	−206%
TA	kg SO2 eq	0.017	0.012	0.004	−0.002	−30%	−144%
FEu	kg P eq	0.002	0.001	0	0	−40%	−185%
MEu	kg N eq	0.001	0	0	0	−86%	−405%
TE	kg 1.4-DB eq	0	−0.004	0	−0.004	−1023%	−4891%
FEc	kg 1.4-DB eq	0.038	−0.146	0.008	−0.176	−486%	−2372%
MEc	kg 1.4-DB eq	0.039	−0.003	0.008	−0.034	−107%	−522%
ALO	m2a	0.065	0.029	0.042	0.006	−55%	−85%
ULO	m2a	0.023	0.014	0.004	−0.005	−38%	−220%
NLT	m2	0.001	0	0	0	−41%	−191%
WD	m3	0.028	0.012	0.009	−0.007	−58%	−180%
MD	kg Fe eq	0.671	0.553	0.112	−0.006	−18%	−105%
FD	kg oil eq	1.175	0.643	0.258	−0.273	−45%	−206%

3.4. Interpretation of results: sensitivity and uncertainty analysis

With the aim of verifying the impact of some crucial parameters on the overall assessment, a sensitivity analysis has been carried out, with particular regard to the variation of consumption profile and an uncertainty analysis, related to the application of process based on literature and database.

The variation of water consumption profile into the model implemented would necessarily introduce modifications into calculated impacts. Following impact categories panel previously presented, n.5 different consumption profiles have been tested, giving evidence of different response based on the impact category examined.

3.4.1. Sensitivity analysis

In particular, for GRS and 10 PE scenario (Fig. 11) and in relative terms over the standard consumption profile (i.e. 140), results obtained suggest that lower water consumption routines, e.g. 105 as indicated by AQUASAVE project (i.e. 25% savings over standard), lead to higher environmental impacts on CC, OD and FD, with an average increase of 46%. On the other hand, higher water consumption profiles, up to 20% above the standard, appear to trigger lower environmental impacts (up to 23% benefit). WD does not show any difference, while LO, on the contrary, express remarkable sensitivity on the specific parameter, with differences spanning from −250% to +125%, following the trend of the water consumption.

For RHS, scenarios proposed already outlined the sensitivity of the system to specific consumption profiles, i.e. different uses for water, number of people equivalent involved and rainwater storages, suggesting how use intensive applications generally improve the environmental performance of the system.

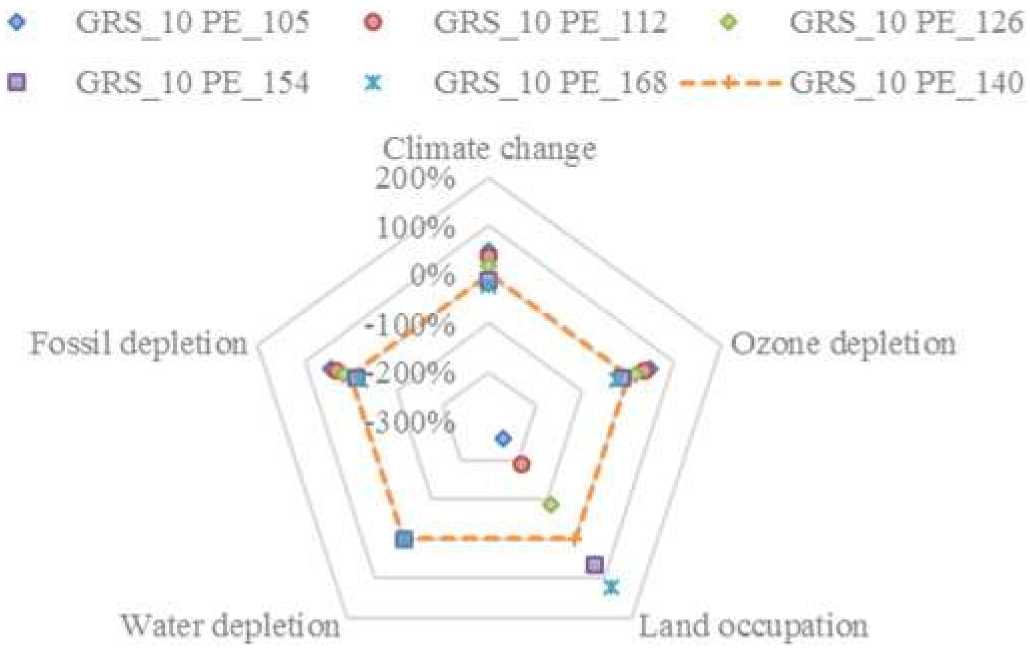

Fig. 11. Sensitivity analysis on water consumption profiles, GRS.

3.4.2. Uncertainty analysis

Considering the uncertainty typically related to database processes implementation (i.e. 20%), model's response for GRS appears completely in line with solicitation for WD impact category and quite similar for CC, OD and FD (with 29%, 27% and 26% variation, respectively). LO, in analogy with sensitivity analysis results, shows a dramatically high range of variation (i.e. 153%) (Fig. 12).

For RHS, considering the same uncertainty related to database process, impacts are calculated for and scenarios (i.e. n. 3 PE and n. 27 PE, same water use profile). Comparing results obtained with the homologous impact profile, the uncertainty applied introduces a comparable variation for CC, OD and FD in scenario (25%, 23% and 24%, respectively), while WD shows an almost undetectable variation and, on the contrary, impact on LO span in a range of 54%.

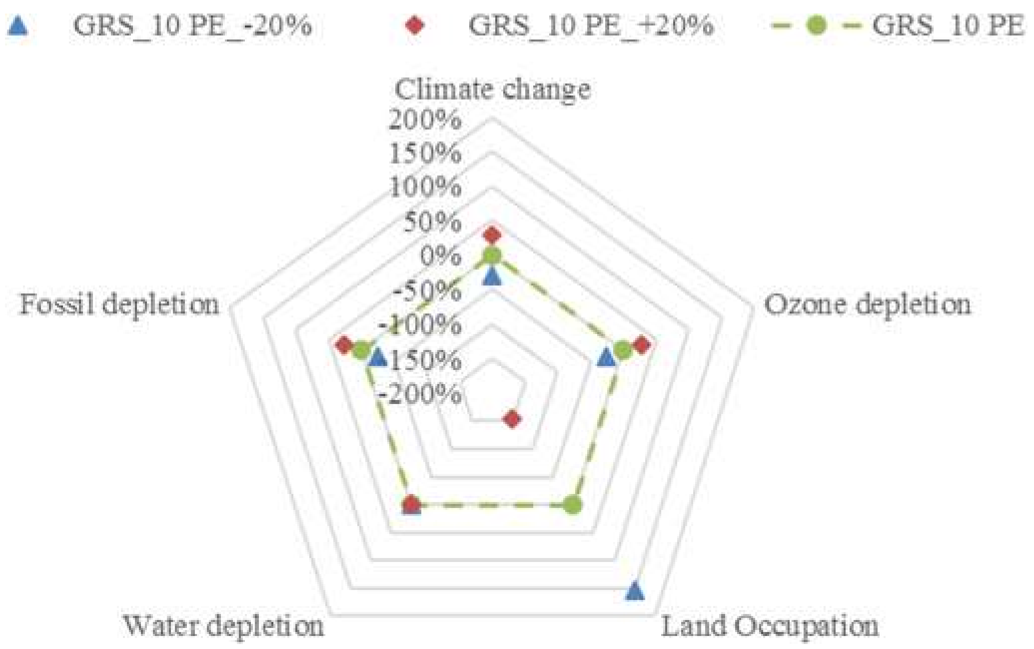

Fig. 12. Uncertainty analysis, GRS.

For scenario, uncertainty analysis returns quite a varied impact profile, with higher ranges of variation for CC, OD and FD (189%, 43% and 61%, respectively), almost the same variation for WD and higher range (295%), but of opposite sign, for LO (Table 8).

Table 8. Uncertainty analysis, RHS.

mpact categories	A3−20%	A3+20%	B3−20%	B3+20%
CC	−25%	25%	−189%	189%
OD	−23%	23%	−43%	43%
LO	−54%	54%	295%	−295%
WD	0%	0%	0%	0%
FD	−24%	24%	−61%	61%

4. Discussion

Environmental benefits deriving from water recovery solutions proposed for the urban framework at household level, i.e. GRS and RHS, are accounted, together with impacts generated, to evaluate the environmental performance in comparison with Business-As-Usual scenarios. The model considers water savings deriving from water recycling as toilet flushing water, for GRS, and flushing and irrigation for RHS.

The study was outlined in accordance with Angrill et al. (2011) for RHS, but with the implementation of an innovative hydrological modeling of catchment surfaces, under real historical rainfall precipitation patterns, as support for scenarios definition and major contribution to literature. The rainfall pattern selected followed 2009 records, as representative of 28 years of data reported by Regional Agency for Prevention, Environment and Energy of Emilia-Romagna, Italy (www.Arpae.it). This choice was made within the framework and the scope of GST4Water project and it clearly represents a limitation for the generalization of the present study's results in areas characterized by different climate.

The model outlined included, necessarily, several assumptions and simplifications, which could be summarized by the following, worth to be mentioned, among others:

Water storage tank are modeled in accordance with technical information of commercial items, available in the geographical framework of the project. Considering that about 20% of the overall impact is generated during the production phase and the use phase performance is affected by the maintenance parts required, a broader benchmark analysis would ensure a wider applicability of results. In addition to this, process data are included to account for embodied impacts.

Distribution piping within the modeled households is outlined in general terms as a more detailed approach would require specific information and it would, consequently, generate a set of further scenarios, with limited impact on the overall results. With the present approach, in fact, the distribution system accounts for about 18,6% of CO2 equivalent (i.e. less than typical process uncertainty) over GRS, thus proving how limited variation would be introduced with a more detailed modeling of the item.

Pump working time has been approximated to 1 hour/day, considering both water treatment and recirculation to the distribution system, as in worst case scenario, since, depending on the scenario outlined, the working time expected may be lower. Nevertheless, in absence of primary data, the worst case scenario is considered as a precautionary assumption, even where energy consumption for distribution system evidently plays a critical role over the general performance.

No financial analysis nor Life Cycle costing (LCC) were performed as not covered by the scope of GST4 W project, but they would clearly complete the evaluation with feasibility assessment;

Results obtained show how use intensity of the solution proposed appears as one of the key design element for the sustainable application of the solutions proposed. For GRS, the application of 1 m3 storage and treatment system serving thirty population equivalent results in a net positive impact, while for RHS, the high use intensity should be combined with an alternative reuse for recycled water, i.e. washing machine supply, to obtain an overall environmental benefit.

The poor environmental performance displayed by RHS appears to be connected with model limitation in accounting environmental benefits generated by the system at local scale. The avoided rainwater discharge into drainage system, for example, was modeled as avoided discharge of slightly contaminated water from residential building, thus generating a low positive impact on the system. In addition to this, advantages triggered at a local scale, such as runoff limitation during extreme rain events, could not be addressed with a standard LCA.

Sensitivity analysis performed on GRS showed how variation in water consumption profile may affect the impact at different levels. In particular, limitations introduced by the model, i.e. environmental benefit accounted in terms of water savings calculated in percentage on consumption, lead to higher environmental benefits in presence of higher water consumption. Thus, generating a paradox, in terms of recommendations to be derived and a major issue to be solved in future iteration of the LCA and research steps.

5. Conclusion

Within the framework of GST4Water project, the environmental sustainability of water recovery and recycling systems at building and urban scale, i.e. GRS and RHS, has been assessed by application of LCA methodology.

LCA model has been developed both for GRS and RHS, in a cradle-to-grave perspective, in order to evaluate environmental impacts of the solutions proposed.

For GRS, a single system has been outlined, with different use intensity scenarios (i.e. n.10, 20 and 30 PE), while for RHS a specific hydraulic/hydrologic numerical model, by means of SWMM software, and has been developed to take into account rainfall variability along the year. The model, which uses real rainfall time series as input data, makes it possible to estimate the efficiency of the system in terms of saved drinking water and the reduction of stormwater volumes discharged into the sewage system. The results of the simulations show that the presence of the gardens leads to an increase in the demand for recycled water in the summer. To guarantee system efficiency levels of at least 60%, it is therefore necessary to increase the tank volumes. On the one hand this causes an increase in the complexity and cost of the plant, on the other hand it determines a considerable environmental benefit deriving from the considerable reduction in the volumes of rainwater spilled into the sewers.

LCA results show how use phase determines the major impact both for GRS and RHS, suggesting, in an eco-design perspective, a possible combination of presented solutions with renewable and local energy supply system.

Comparing each solution and scenario with the corresponding BAU, it was possible to show how the use intensity affects the overall environmental performance. Solutions serving the higher number of PE, in fact, give rise to lower impacts and, compared to BAU, may even generate net environmental benefit, as for GRS applied to n.30 PE. RHS, on the other hand, display a poor environmental performance in general, due to model limitation in accounting environmental benefits at local scale, e.g. limitation of runoff during extreme rain events. For this reason, an alternative application for recycled rainwater has been considered, even though excluded from Italian regulation and, therefore, from the framework of GST4Water project, and washing machine supply scenarios have been modeled. In this case, the avoided impact related to lower amount of detergent necessary for washing, due to lower hardness of rainwater compared to tap water, ensures a remarkable improvement in environmental performance of the solutions. The combination of high use intensity of RHS (as in scenario) and alternative use for rainwater achieve a net environmental benefit.

Sensitivity analysis performed suggest that a variation in consumption profiles accounted may sensibly affect the final results, therefore a parametric LCA could represent the next iteration step for the study.

The results of the present study suggest that solutions proposed should be carefully chosen, considering the specific application. In general, higher use intensity should be pursued, as well as combination with energy supply from renewable sources, while small scale applications appear reasonable to address local issues, i.e. water scarcity.

Acknowledgment

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Appendix A. Supplementary data

The following is the Supplementary material related to this article.

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MMC S1. Supplementary information contains details on the hydrologic/hydraulic model.

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