Reuse of resources in the use phase of buildings. Solutions for water

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Abstract. Circular economy can be considered not only in relation to building construction materials, but also in relation to resources that are used in the use phase of buildings, such as water, energy or even nutrients. On the other hand, some constructive solutions are becoming increasingly important in the current scenario of climate change, taking into account the need to increase the resilience of the urban environment and the mitigation of emissions. This is the case, for example, of green roofs and living façades, which are an alternative to traditional grey infrastructure, offering many benefits to both citizens and cities. Beyond the ability to improve environmental conditions and quality of life, they can augment the energy efficiency of buildings, reduce flood risks in urban areas and be combined with rainwater harvesting systems. So, taking into account these trends for constructive solutions in the future, this paper analyses the possibilities of a circular use of water in buildings, aiming to create in the future "zero water" buildings. Particular attention is given to the compatibility between new green roofing solutions and rainwater harvesting systems in buildings, but the reuse of grey water and the possibility of nutrient recovery in buildings, such as urine (phosphorus) - which can be used in the building itself on green roofs - living facades or urban agriculture, are also referred to.

Keywords: Circular economy, zero-buildings, water, energy, nutrients

1. Introduction

Circular economy can be considered not only in relation to building construction materials, but also in relation to resources that are used in the use phase of buildings, such as water, energy or even nutrients. The relationship between these resources is inseparable and the nexus energy-water-food (or energy-water-nutrients) is currently recognized as the essential connexion for the sustainable development of mankind.

The importance of the interdependence between water and energy, also known as the water-energy nexus, is well recognized even in urban environments. Water is crucial in the production of most forms
of energy and energy is needed for the urban water cycle and domestic hot water heating [1]. Water and energy are also closely linked with food. In a world with a rising global population, agriculture accounts for 70% of global water withdrawal [2], while food production and the supply chain accounts for about 30% of total global energy consumption [3].

Zero-energy buildings have begun to enter the reality of cities in many parts of the world and the next steps should be the design and dissemination of zero-water and zero-nutrients buildings. On the other hand, some constructive solutions are becoming increasingly important in the current scenario of climate change, taking into account the need to increase the resilience of the urban environment and the mitigation of emissions, such as green roofs and living façades, which are an alternative to the traditional grey infrastructure, offering many benefits to both citizens and cities. Therefore, zero-buildings must integrate and enhance these constructive solutions that climate change will impose in the near future and must take into account the intrinsic relationship between water, energy and nutrients in urban environments, favouring an integrated approach.

Taking into account these trends for constructive solutions in the future, this paper analyses in particular the possibilities of a circular use of water in buildings, aiming to create in the future "zero water" buildings. Particular attention is given to the compatibility between green roofing solutions and rainwater harvesting systems in buildings, but also to the reuse of grey water in buildings and the possibility of nutrient recovery in buildings, such as urine (phosphorus), which can be used in the building itself on green roofs - living façades or urban agriculture, are also referred to.

2. Zero-water and zero-nutrients buildings
In the case of energy, the concept of zero-energy buildings does not mean a circular use of the resource, but rather that the total amount of resource used by the building is approximately equal to the amount of renewable resource produced or available on the site. In the case of water, part of the resource can be used in a circular way (water recycling), but alternative renewable sources such as rainwater can also be considered. In the case of zero-nutrient buildings, the resource shall be considered to be circular.

2.1. Basic principles for design of zero-water buildings
The design of zero-water buildings should be based on the 5Rs principle of efficient use of water [4], which can be summarized as follows:

- Reduce consumption
- Reduce losses and wastes
- Reuse water
- Recycle water
- Resort to alternative sources

The first R – Reduce consumption, includes the adoption of efficient products and devices, without being prejudicial to other measures of an economic, fiscal or sociological nature. The second R – Reduce losses and wastes, may involve interventions such as monitoring losses in buildings (flushing cisterns, garden irrigation systems, etc.) or the installation of circulation and return circuits of sanitary hot water.

The third and fourth Rs - reuse and recycling of waste water - are important measures for the design of zero-water buildings, which are distinguished by the fact that reuse is a serial use and recycling is a re-introduction of water at the beginning of the circuit (after treatment). Reuse has undergone some development in recent years in relation to greywater, in particular the reuse of effluents from baths and washbasins for discharges in toilets. The last R - Resort to alternative sources, may involve rainwater harvesting or the use of salt water, for example.

2.2. The importance of the recovery and reuse of nutrients in buildings
The recovery of minerals from wastewater is ever more important. Phosphorus recovery (P), for example, is at the top of global political priorities, as shown by the European Parliament statement of May 24, 2012 (§52), for example, which aims at 100% of P reuse in 2020.
Phosphorous is a unique non-renewable chemical element that is required for food production. About 90% of the world's P reserves are in China, USA, Russia and Morocco, where it has been estimated that today's recoverable reserves will be depleted within the next 30-40 to 300-400 years. These estimations diverge due to uncertainty regarding the volume and quality of global reserves, and to the accuracy of estimates for future demand [5-7].

However, even if the reserves do last a long time, they will have increasingly negative environmental impacts. Its uniqueness therefore makes it urgent to develop new technological solutions to enable its recovery and reuse in the value chain. Population increase and the intensification of global agriculture will place increasing pressure on the finite supply of this resource.

Security in the supply of agricultural fertilizers would provide a competitive advantage, and a new way to recover P from water bodies would contribute to efficient resource management. In the last half century, P concentrations in freshwater and terrestrial systems have increased by at least 75% and the world's annual consumption of P fertilizer is estimated at 18 Mtons per year in 2007 [6][8,9].

On the other hand, this rejection of domestic and industrial effluents rich in P and fertilizers leaching into water bodies is the major cause of eutrophication, which is probably the most significant unsolved problem in terms of water resources protection. Recent unofficial reports confirm that diffuse pollution is the main problem in European freshwaters [10,11].

Although the recovery of phosphorus constitutes an emergency in view of the security of food supply in Europe and pollution problems, its elimination through urine is one of the principal causes for the loss of the value chain. An average adult excretes about 1 g of phosphorus per day through urine and there are still no systems in regular operation for its recovery from aquatic systems or in urban wastewater treatment plants. The recovery of phosphorus in wastewater treatment plants is theoretically possible, but recovery at the source, i.e., in buildings, would have numerous advantages by reducing the load on the treatment plant, avoiding dilution and minimizing the costs and energy consumption in the process.

In fact, most of the nutrients evacuated by man are found in urine. Hence, using urine directly for agricultural purposes has already been the subject of pilot projects in South Africa, China, Germany and Sweden. China has installed more than 700 000 urine diverting toilets since 1998 and Germany already has some buildings with this technology. In Sweden, the separation of urine is increasingly regarded as a solution for rural villages to reduce the nutrient enrichment of natural water lines, and there are now over 135 000 urine diverting toilets, as well as specific recommendations for the use of urine collected in buildings [12].

In the Netherlands, Waternet, (Amsterdam’s water authority), has developed a pilot program for gathering and storing urine in public toilets since it is used for fertilizing public gardens and green roofs. It is estimated that a urine processing plant under construction in Amsterdam may eventually produce 1000 tonnes of fertilizer per year. At present, efforts are focused mainly on the recovery and subsequent direct use of urine as a fertilizer, but recovery of phosphorus at its source (buildings) seems to be the most appropriate way to avoid the loss of this essential chemical element and innovative technologies are nowadays under development, which may make this feasible in the future [13,14].

The separation of urine in buildings, with or without recovery of phosphorus, requires a revolution in our traditional bathrooms: urine separation toilets, urinals for residential buildings and their generalization to females, etc. Some of these products are already available on the market and there is potential for the use of urine or nutrients in the building itself, on green roofs or in urban agriculture, contributing to a circular economy and boosting these two constructive trends, which are now recognized as being of great importance in terms of sustainability policies.

3. Built environment and climate change
An important impact of climate change that is expected to intensify in the next decades is the increased intensity and frequency of heavy rainfall and other extreme weather events, such as heat waves [15]. It
is expected that precipitation changes differ from region to region with some areas becoming wetter and others drier.

In addition to the problem of the rising mean sea level, more frequent and intense rains lead to flooding in riverine areas and the overloading of public drainage systems. The increase in rainfall intensity is expected to lead to enhanced transport of pollutants and will also more often overload the capacity of sewer systems and wastewater treatment plants. Urban water supply systems can be disturbed by the deterioration of quality, as climate change has the potential to affect water quality in several ways. For example, lower summer flows in water reservoirs will reduce the volume available for diluting the treated effluents or uncontrollable discharges of sewage [16].

3.1. The contribution of buildings to climate change mitigation

The impacts of climate change affect urban ventilation and cooling, urban drainage and flood risk, and water resources, increasing the risk of disruptions in water supply. Primary mitigation strategies comprise carbon efficiency, energy efficiency of technology, system and infrastructure efficiency and service demand reduction through behavioral changes.

Around the world, it is estimated that the building sector contributes as much as a fifth of total global annual greenhouse gas emissions, making buildings the largest contributor to global greenhouse gas emissions and also consuming more than 32% of global final energy [17]. The major causes of this contribution are the extensive use of fossil fuel-based energy for thermal comfort, lighting, water heating, water supply and drainage, electrical equipment and appliances, as well as in the production of construction materials [18].

Given the massive growth in new construction, if nothing is done, greenhouse gas emissions from buildings will more than double in the next 20 years [19]. However, considering their whole life cycle (construction, operation or use and demolition), to obtain a significant reduction of CO2 emissions, effective measures must be taken during its use or operation phase, because the latter represents 80-90% of the total energy consumed throughout its entire life cycle.

The use of green roofs and living facades on buildings can bring great advantages, not only in terms of mitigation but also in terms of increased resilience and adaptation, since it reduces the flow of surface water and increases the number of green infrastructures, in addition to all its associated benefits. Green roofs can provide multiple benefits for air quality, mitigating excessive heat and enhancing biodiversity.

Taking into account the urban water-energy nexus, reduction of water consumption in the building cycle is also reflected in significant energy efficiency, considering the reduction of energy consumption needed to heat sanitary hot water and to pressurize water in buildings. This is also reflected in public systems (in the abstraction) pumping, and in the treatment of water and wastewater. Therefore, the nexus between water efficiency and energy efficiency should be one of the most important aspects that must be noted when considering the contribution of buildings to mitigation strategies.

A study carried out in Portugal by the ANQIP (Associação Nacional para a Qualidade nas Instalações Prediais) in a medium-sized city (Aveiro) found that energy savings due to the use of efficient products (classified in category “A” of ANQIP’s labeling scheme for water efficiency of products) allow a reduction in emissions higher than 100 kg of CO2 per capita and per year, in relation to the present scenario, taking into account only the heating of domestic hot water in buildings and energy consumption in public networks [20]. It should be noted that in Portugal, energy consumption for heating domestic hot water represents over 30% of total housing energy consumption.

The reuse of greywater and rainwater harvesting can also contribute to reducing energy consumptions. Compact installations for direct reuse of greywater (toilet and washbasin combined, for example), and reducing water consumption in the building, also lead to the saving of water and energy in the urban water cycle. As rainwater harvesting systems also reduce water consumption in houses, they additionally entail reductions in water flows and energy consumptions in public networks. Although rainwater harvesting systems demand a pressurization system in the building, the corresponding energy consumption is equal to or less than those that occur when the supply comes from the public network.
With regard to large installations for greywater reuse, with the "conventional" treatment for this type of water, we find that the energy consumed in the treatment makes the system "neutral" from an energy standpoint, i.e. the energy expended in the treatment of greywater, about 1.8 kWh/m³, is close to the energy saved in the urban water cycle. However, since the temperature of greywater from showers, for example, is generally above 30 °C, the utilization of this thermal energy for pre-heating hot water will allow a saving of about 3 kWh/m³, making these installations advantageous not only from the point of view of saving water, but also from an energy standpoint [21].

3.2. The role of the building water cycle within processes of adaptation and increased resilience

Buildings face great risks of damage from the projected impacts of climate change, having already experienced a substantial increase in extreme weather damage in recent decades. More than half the urban areas projected for developing countries by 2030 have yet to be built, offering great potential for integrated adaptation planning, but special attention should be paid also to existing buildings.

There are two impacts of climate change that bind directly with building networks of water supply and drainage: the increased intensity of heavy rainfall and extreme heat waves. In the case of increased intensity of heavy rainfall, the use of green roofs, for example, can bring numerous advantages because it reduces the flow of surface water by the effect of retention. Rainwater harvesting in buildings has the same benefits, also reducing flood peaks. Taking into account this type of impact, it will be also necessary to adjust design standards for new buildings and review the design of rainwater drainage in existing buildings.

Regarding extreme heat waves and the inherent risk of water scarcity, the adjustment of standards is again necessary, with regard to reviewing the sizing of water tanks and increasing efficiency in the use of water in buildings. Rainwater harvesting and the reuse of greywater shall be promoted. The first solution is particularly suited to answer the many impacts of climate change because it simultaneously reduces the flood peaks in urban areas and promotes additional water storage in buildings. The construction of green roofs combined with rainwater harvesting systems in buildings can boost the advantages of each of these technologies [23,24], whereby their integration should be considered a very promising solution to face climate change and increase sustainability in cities [25,26].

4. Discussion and results

Green roofs, living facades and rainwater harvesting systems in buildings are particularly important constructive systems to address the problems and needs that climate change currently provokes in urban environments. They can make important contributions in terms of mitigating the phenomenon and increasing the resilience of buildings, as well as encouraging a circular use of resources in buildings.

As previously mentioned, the combination of green roofs with rainwater harvesting systems is possible and can enhance the advantages of these systems. However, when designing a rainwater harvesting system combined with a green roof structure, several factors should be taken into account, especially roof runoff coefficients [27].

The runoff coefficient is a dimensionless parameter that represents the relationship between the total runoff volume from the roof and the total amount of precipitation in a certain time period and, in impervious roofs, it has a value near one. In the case of green roofs, average annual values of 0.5 for extensive green roofs (with a maximum depth of about 150 mm) and 0.3 for intensive green roofs is generally adopted. In fact, these values depend on the characteristics of the roof, such as the type of plants used and the characteristics of the substrate and are very dependent on the climatic conditions in the region, especially temperature and precipitation diagrams.

In a study carried out in Portugal by ANQIP as part of a research project to increase the sustainability of green roofs and living façades (through the use of cork) [28], it was concluded that in Mediterranean climates, monthly runoff coefficients are particularly important for sizing the storage tanks of rainwater harvesting systems, in view of the existence of long dry periods, extending in general throughout the summer period. In other climates, such as in central and northern Europe, where precipitation periods
occur in almost all months, the sizing of the storage tanks is often done on the basis of annual average runoff coefficients.

From the perspective of integrating green roofs with rainwater harvesting systems, some studies have been developed on a conventional extensive green roof system in the city of Oporto (Portugal) [29]. These studies have revealed low values of runoff coefficient but allowed the development of an expression to predict the monthly runoff coefficients for this type of conventional green roof [29]:

\[
C_M = \frac{0.016(P_M - R_M)}{(2T_M - T_{M-1})^{1.2}}
\]  

where:

- \(C_M\) = Runoff coefficient of month \(M\)
- \(P_M\) = Precipitation of month \(M\) (mm)
- \(R_M\) = Watering of month \(M\) (mm)
- \(T_M\) = Mean air temperature of month \(M\) (°C)
- \(T_{M-1}\) = Mean air temperature of month \(M-1\) (°C)

The application of this formula to several regions of Portugal, with different climatic characteristics (Mediterranean or Atlantic) led to the results presented in Table 1.

**Table 1.** Results of the application of the expression 1 to different stations in Portugal (monthly runoff coefficients)
In terms of annual averages, the values obtained were a minimum of 0.04 and a maximum of 0.14. It should be noted that these values are clearly lower than the average annual runoff coefficients proposed in the literature for green roofs in central/northern European countries, which sometimes are close to 0.3 for intensive green roofs and 0.5 for extensive green roofs. This shows that the integration of green roofs with rainwater harvesting systems still requires significant research, so as to characterize, in each specific region, the design parameters to be adopted.

5. Conclusions
Circular economy can be considered not only in relation to building construction materials, but also in relation to resources that are used in the use phase of buildings, such as water, energy or even nutrients, like phosphorus. In fact, the relationship between these resources is inseparable, constituting the so-called urban water-energy-nutrients nexus.

Some of the constructive solutions that should be generalized in the near future to mitigate climate change or adapt buildings to their impacts allow a circular use of some resources such as water or nutrients. This is the case, for example, of green roofs or rainwater harvesting systems.

The combination of these two systems is possible and may enhance the benefits of each. But it is necessary to develop further research in this field, as the studies shows that the results depend significantly on the constructive solutions adopted for these systems, and can be different from one region to another depending on local climate conditions.

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