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Applying exergy analysis to rainwater harvesting systems to assess resource efficiency

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A B S T R A C T

In our continued effort in reducing resource consumption, greener technologies such as rainwater harvesting could be very useful in diminishing our dependence on desalinated or treated water and the associated energy requirements. This paper applies exergy analysis and exergetic efficiency to evaluate the performance of eight different scenarios of urban rainwater harvesting systems in the Mediterranean-climate Metropolitan Area of Barcelona where water is a scarce resource. A life cycle approach is taken, where the production, use, and end-of-life stages of these rainwater harvesting systems are quantified in terms of energy and material requirements in order to produce 1 m^3 of rainwater per year for laundry purposes. The results show that the highest exergy input is associated with the energy uses, namely the transport of the materials to construct the rainwater harvesting systems. The scenario with the highest exergetic efficiency considers a 24 household building with a 21 m^3 rainwater storage tank installed below roof. Exergy requirements could be minimized by material substitution, minimizing weight or distance traveled.

1. Introduction

Water is a renewable resource, but the availability of this resource for society is limited. According to UNEP, less than 1 percent of all fresh water resources is usable for ecosystems and humans (UNEP, 2007; WWAP, 2006, based on data from Shiklomanov and Rodda, 2003). In addition, water consumption has been growing at more than twice the rate of population increase in the last century (Food and Agriculture Organization of the United Nations). Considering a growing population we can expect an increasing pressure on the available water resources.

Moreover, the available freshwater resources are being polluted affecting human and ecosystem health (UNEP, 2007). Limited water supply has been causing severe nutrition and health problems, limiting economic and social development in many arid and semi-arid regions of the world such as North Africa and the Middle East (Furumai, 2008). At the same time, climate model simulations for the 21st century are consistent in projecting precipitation increases in high latitudes and parts of the tropics, and decreases in some subtropical and lower mid-latitude regions (Gitay et al., 2002). Catalonia, located at the northeast of Spain, has recently suffered from water shortages affecting the Metropolitan Area of Barcelona (MAB) and surrounding suburbs (Otero et al., 2011).

The MAB (where this research is based) is the sixth most populated area of the European Union with more than 5 million inhabitants according to the Statistics Institute of Catalonia, where 81% of the water supplied to the city comes from superficial sources (from the rivers Ter and LLobregat), 14% from subterranean water and 5% is desalinated from the Mediterranean sea (IDESCAT, 2005).

The MAB climate is characterized as a semi-wet Mediterranean climate and is expected to have a diminishing precipitation of 10% annually over the next years (GENCAT, 2010).

Mediterranean climate is characterized as moderate wet with dry summer according to the Köppen classification (type C) and it is found in the five continents in the Western zone in a range of latitudes between 30° and 45°, in Africa it is found in Morocco, the North of Algeria, the North of Tunisia and the Cape area in South Africa (Elizabeth Port); in America it is found in two points: the South and center of California (U.S.A.) and Santiago of Chile (Chile); in Asia, in the Middle East; in Europe in the shores of the Mediterranean sea and in Oceania it is found in South-west Australia around Perth. In the Mediterranean Spanish plateau, summers are

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significantly hot and dry and the winters are cool and moist, bringing lots of rain and spring and fall are usually a mix between both summer and winter, with a moderate amount of rain and heat.

In recent times, environmental studies have been concerned with the failure to adopt greener technologies even though some water conservation techniques have been used for centuries in other activities, like agriculture. These concerns are also latent in water research (Kallis and Richard, 2010; Unruh, 2000; Cowan and Gunby, 1996) looking for alternatives to reduce tap water consumption and also reduce resource consumption in order to decrease pressure on the available water resources. A first step toward a more sustainable consumption of water would be to include current and future climate variability into water-related management to assist adaptation to longer-term climate change impacts (Bates et al., 2008). Secondly, it is important to evaluate new technologies and solutions for water conservation from an environmental, economic, and social perspective.

Currently, alternative water resources are being researched and evaluated to reduce dependence on desalinated water and other energy-intensive technologies, especially for cities (Farreny et al., 2011a,b; Domènech and Saurí, 2011) where in 2006, 24.5 million m^3 of desalinated water were consumed (for drinking water, industry and agriculture) and is expected to duplicate by 2015 (UNEP, 2008). Some examples of alternative water sources are: water reuse (from waste water or drainage water), stormwater, saltwater and brackish water, aquifer storage and recovery (mostly from stormwater), rainwater harvesting (RWH) and any other source designated as nontraditional in a regional water supply plan. RWH techniques are used to collect, store and distribute rainwater from different surfaces, such as land, roads, rooftop and rock catchments (Appan, 1999; Prinz, 1995; Zhu et al., 2004). Within the different options of alternative water resources, RWH systems are especially attractive due to:

- *Small cost of implementation*: There are several options to install these systems and most of them take benefit of the existing infrastructure, in urban cases, this infrastructure is the house or building that holds the storage facility and is itself the catchment area and depending on the size of the system it can be installed by the user.
- *Low energy consumption during use stage*: Only when the storage facility is installed underground or far from the target, to pump the water.
- *Simple construction*: Two basic components (Catchment area and a storage facility).
- *Non-scarce materials*: Building and construction materials are common and ordinary.
- *A variety of use of harvested water*: In urban areas common uses are: Gardening, laundry washing, car washing and toilet flushing.
- *Low treatment*: A filter or membrane is usually enough treatment for non potable uses depending on the catchment area.

With these characteristics RWH can diminish and in some cases solve problems such as water and groundwater scarcity and contamination. Also, it can help the economy of the population especially in cases of rising water prices.

In the case of urban areas, RWH is a multi beneficial strategy that may serve to cope with current water shortages, urban natural waterway degradation and flooding (Fletcher et al., 2008; Van Roon, 2007; Zhu et al., 2004) that are given by urban runoff (rainwater runoff from urban environments) and combined sewer (sanitary and stormwater runoffs) outflows. Even though roof water harvested onsite from buildings is usually the cleanest alternative water source available, requiring little treatment before being suitable for a wide variety of uses (Apostolidis and Hutton, 2006), other alternatives such as desalination have been preferred to support water supply in urban developments (Tsiourtis, 2001). It is only recently, that the use of decentralized, alternative water sources such as rainwater is being promoted (Domènech and Saurí, 2011; Farreny et al., 2011b; Morales-Pinzón et al., 2012).

Water recovery alternatives such as RWH systems undoubtedly promote energy conservation and lessen environmental load. However, it is important to quantify these environmental impacts for several reasons:

1. To compare with traditional water recovery methods such as desalination.
2. To compare amongst other non-traditional alternatives.
3. To establish an adequate scale and allocation (size of the system for different urban scenarios).
4. To identify potential for improvements.
5. To help decision makers obtain more sustainable strategies.

This study aims to evaluate several Domestic RWH strategies to collect water from roof runoffs in the MAB as a viable option for urban households to replace the consumption of tap water for laundry. The basic components considered are:

- *Storage facility*: A water tank installed underground, below roof or distributed on the roof (Fig. 1).
- *Catchment area*: Rooftop (250 m^2 and 700 m^2 for different scenarios).
- *Delivery system*: Set of pipes that transport water from the catchment area to the storage facility and from the storage facility to the building.

Exergy analysis has been applied extensively in the engineering sector and not so recently has demonstrated to be an excellent tool assessing environmental performance of different systems, processes or products, such as this RWH system. In this study exergy analysis is used to evaluate different RWH strategies using a life cycle approach. This research aims to adapt and integrate exergy analysis as an environmental tool in alternative water resources analysis, evaluating different strategies to install RWH systems based in exergy (materials and energy) consumption and also, evaluating exergetic efficiency of different strategies (scenarios). The utilization of exergy as an index of resource consumption (materials and energy) attempts to simplify the decision process.

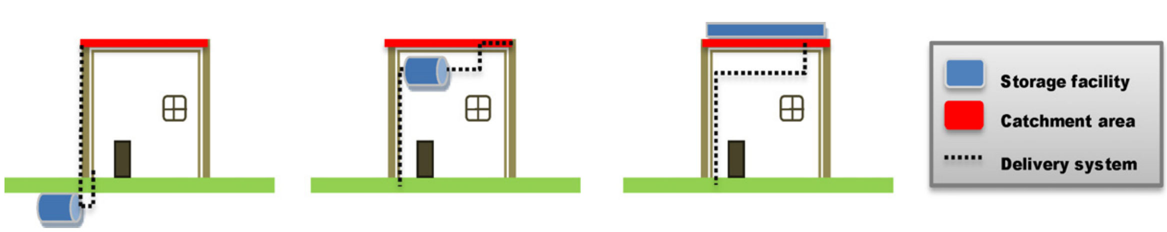

Fig. 1. Storage facility.