RAINWATER HARVESTING SYSTEM IN URBAN AREAS. A NOVEL ENVIRONMENTAL IMPACT INDICATOR.

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ABSTRACT

Rainwater harvesting (RWH) is the effective collection of rainwater during yielding rain periods and storage for a later use, making an important contribution to the availability of this resource. During the last years, an overall net negative impact of the climate change has been shown on water resources all around the world. Cities, as great consumers of water resource are causing an increment in cost and uncertainty in water supply. In the absence of run-off sewers systems in some urban areas, rainfall harvesting from parking lots and rooftops for various domestic uses that do not require potable water, such as irrigation, vehicle and cloth washing, and toilet flushing, can increase water supply and help combat the chronic water shortages. Recent work has been aimed to the methods to retrieve and store rain water and the different use depending on its quality, disregarding the environmental impact of the material and energy inputs related to the construction of the system. In order to obtain an environmental impact indicator, exergy analysis offers a rational basis to evaluate: fuels and resources, process, device, and system efficiencies, dissipations and their costs, and the value and cost of systems output.

INTRODUCTION

Water is a renewable resource, but the availability of this resource for society is limited. If in addition to this limited availability, there is an increase in density of population and growing water consumption, an increasing pressure on the available water resources is developed.

Moreover, the available freshwater resources are being polluted affecting human and ecosystem health, jeopardizing sustainable development. Water stress 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 et al., 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 sub-tropical and lower mid-latitude regions (Gitay, et al., 2002).

Nowadays, water management practices may not be as strengthened as it should be to contend with the impacts of climate change. As a first step, improved incorporation of information about current climate variability into water-related management would assist adaptation to longer-term climate change impacts. (Bates, et al., 2008). Secondly, new technologies and methodologies must be evaluated and incorporated.

Under actual conditions of water management and consumption, traditional and alternative forms of water resources are being considered as options to reduce potable treated water consumption. Rainwater harvesting systems are specially attractive due to:

- Small cost of implementation.
- Low or zero energy consumption.
- Simple construction.
- Low quantity of materials.
- Abundance of needed materials.
- A variety of use of harvested water.
- Low treatment.

In the case of urban areas, Rainwater harvesting (RWH) is a multi beneficial strategy that may serve to cope with current water shortages, urban stream degradation and flooding (Fletcher et al., 2008; van Roon, 2007; Zhu et al., 2004). 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).

By the use of rainwater, significant amounts of potable water are saved. Ghisi et al. (2009) evaluated the potential for potable water savings using rainwater for washing vehicles in petrol stations located in Brasilia in Brazil. They found that the average potential for potable water savings using rainwater is 32%. This is an encouraging number to continue improving RWH actual systems, methods and technologies.

Also, in order to obtain better results towards sustainability, the environmental effect of this systems must be considered, comparing RWH systems against other methodologies (e.g. desalination) and also studying different scales, allocation, materials and construction methods.

In the process of identification, prediction, and evaluation of relevant effects of development, Environmental Impact Analysis is considered a very helpful tool in the decision process, and is possible thru different methods, such as Life Cycle Analysis (LCA) that quantifies material requirements, energy consumption and gaseous and waste emissions. LCA has innumerable applications, and is of particular interest for this research, the environmental impact associated to the infrastructure of an urban system such as it has been applied to cities by Oliver-Solà (Oliver-Solà, et al., 2009a; Oliver-Solà, et al., 2009b; Oliver-Solà, et al., 2009c; Oliver-Solà, et al., 2011).

Also, applying a life cycle approach to define the exergy concept, helps obtain more reliable data and better results assessing efficiency of resource use (Talens, et al., 2009) to evaluate the exergetic efficiency of the system.

RAINWATER HARVESTING TECHNIQUES

Rainwater harvesting techniques are used to collect, store and distribute rainwater from different surfaces, such as land, roads, rooftop and rock catchments (Appan et al., 1999; Prinz et al., 1995; and Zhu et al., 2004)

There are three major forms of RWH:
• In situ RWH, collecting the rainfall on the surface where it falls and storing in the soil.
• External water harvesting, collecting runoff originating from rainfall over a surface elsewhere and stored offside, both are used for agricultural RWH.
• Domestic RWH (DRWH), where water is collected from roofs and street and courtyard runoffs. (Helmreich, 2009).

Since this research is focused on urban areas, this last option will be described with more detail.

Domestic Rainwater Harvesting (DRWH)

Harvested rainwater is a renewable source of water that can be ideal in domestic and landscape uses given the flexibility of solutions that this systems provide.

DRWH is a viable option for urban households to replace the consumption of tap water for gardening, toilet flushing and laundry washing i.e. service water. Different techniques to employ rainwater can range from simple and ancient to sophisticated and technological solutions.

DRWH systems have the following basic components: a storage facility (aboveground or underground tank), a catchment area (rooftop or courtyards and similar compacted or treated surfaces), and target area (domestic use, garden watering and small-scale productive activities). The catchment area divides DRWH into two groups, rooftop RWH (water is stored in either aboveground or underground tanks) and ground RWH (water is stored in underground tanks). (Mwenge Kahinda,J., 2010)

By nature, rainwater is soft water with fewer minerals than surface and groundwater. In

general it can be said that it has better quality. In the case of rooftop runoff, quality is dependent on both the roof type and the environmental conditions (not only the local climate but also the atmosphere pollution) (Farreny, et al. 2011).

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

ENVIRONMENTAL IMPACT ANALYSIS
It was developed primarily as a tool for predicting, assessing, estimating and communicating the environmental effects of proposed projects, plans and policies.

The Environmental Impact Assessment (EIA) definition adopted by the International Association of Impact Assessment (IAIA) is "the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made." (IAIA, 1999).

This tool was meant to provide the decision makers with information that is as comprehensive as possible about the different environmental effects the proposed activity would entail, including alternative courses of action and the zero-alternative (i.e., the no action alternative) (Viikari, 2004)

There are several methods available to accomplish Environmental Impact Assessment, some are specific for industry and others are more general, some examples of these methods are:

Life Cycle Analysis (LCA). Mostly used to identify and measure the impact of a product in the environment, considering different technologies for a diversity of industrial activities used to obtain a certain product. It is used in all countries for research, development and design (Frankl and Rubik, 1999)

GMP-RAM. A Specific method for Genetically Modified Plants, that combines two tools in this risk assessment method: (1) worksheets to compile Evidence of Risks, and (2) a Matrix of Assessment. (Katia Regina Evaristo, et al., 2009).

Fuzzy logic approach is applicable for the environmental impact properties that cannot be measured on a scale and instead are measured with a subjective indicator.

Life Cycle Assessment
The SETAC defined LCA as "an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements" (Society of Environmental Toxicology and Chemistry 1991). There are three steps to follow in order to obtain this evaluation, first is necessary to collect an inventory of inputs and outputs of the system, secondly, evaluate the potential environmental effects related to those inputs and outputs and finally the interpretation of the results.

To facilitate these tasks it is important to follow the four stages proposed by the ISO 14040 and 1 standards (ISO 14040. 2006; ISO 14044. 2006). goal and scope definition, inventory analysis, impact analysis and interpretation.

LCA has a wide variety of applications, e.g. can be applied to analyze a Rainwater Harvesting System, as it has been done recently by Angrill (Angrill et al., 2010). Where a RWH system is studied from the LCA approach to relate an environmental impact to the materials and processes used to construct, use and dispose this system. Comparing different designs of neighborhoods in the Mediterranean area, helping decision makers by providing helpful information on the environmental effect implied in the execution of this system.

Several variants of LCA have been developed in an attempt to make the resultant information more comprehensive to a wider audience, one of this is specially interesting for the matter of this paper, this is the LCEA (Life Cycle Energy Assessment) that attempts to replace monetary currency with energy currency.

LCEA deals with a perplexity: that different energy forms (heat, electricity, chemical energy etc.) have different quality and value as a consequence of the two main laws of thermodynamics. A thermodynamic measure of the quality of energy is exergy.
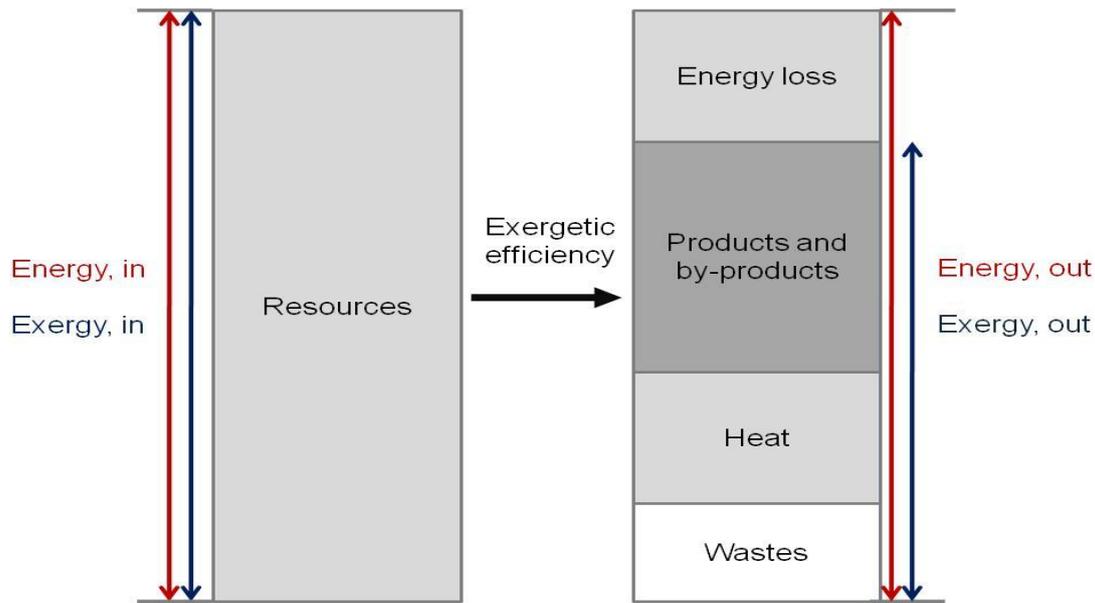
Figure 1. First and second law analysis of real process. (Dewulf et al. 2008). Modified by Talens, L. 2009.

EXERGY ANALYSIS

Exergy is defined as the maximum amount of useful work that can be extracted from a system by reversible processes as the system equilibrates with its surroundings. It is the 'useful' part of energy and there are four components of exergy: kinetic, potential, physical and chemical exergy (Szargut et al. 1988; Sciubba and Wall 2007). Figure 1 represents how energy is conserved in the system but its quality (exergy) is degraded.

In considering mass flows into and out of economic (i.e. industrial) processes the first three components of exergy can be safely neglected. Only the chemical composition is important (Ayres, 1998)

Exergy is not only a natural measure of the resource inputs to an economic system. It is also a measure of the material outputs.

Opposed to energy, exergy can be gained, lost, accumulated or even stored. The exergy of a substance is the work that can be extracted in changing a substance to another state different from its natural. (Ayres and Ayres 1999). The more efficient the process, the less exergy is embodied in the discarded materials.

Exergy Balance

The exergy content of waste materials can be calculated by two different approaches, one of these approaches requires a detailed knowledge of the chemical composition of the waste stream and the Gibbs free energies of formation of the components but for many chemical and metallurgical processes it is difficult to obtain reliable data on the chemical composition of the wastes. And the second approach uses an exergy balance equation (2) calculating process losses precisely, and this is not an easy task, but in most cases possible. (Ayres, 1998)

$$B_{waste} = B_{in} - \Delta B_{process} - B_{product} \qquad (2)$$

Exergy flow analysis

Exergy Flow Analysis (ExFA) accounts for all energy and material requirements in the same units.

This methodology consists of four steps. The first step is to establish the system boundaries by drawing a flow diagram of the process under study, determining which inputs/outputs stages and by-products are part of the system. Secondly, the process is broken down into operation units to study each one independently. Based on the material balance principle, the in and out flows are balanced for each process unit and finally the exergy of pure substances, mixtures and utilities is calculated. The total exergy of the system is equal to the chemical exergy of material and the exergy of utilities (Szargut et al., 1988).
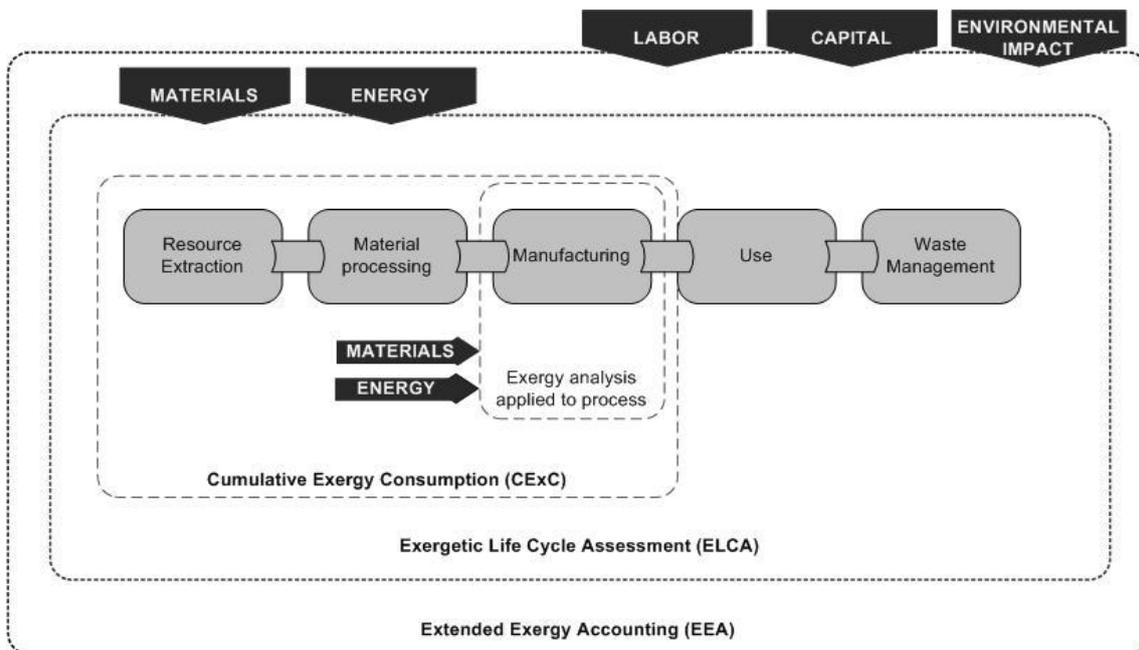
Figure 2. Exergy methodologies applied to industrial system and the life cycle of a good. Modified. (Talens, L. 2009).

Exergy analysis and LCA

Researchers found that its application could have considerably implications for environmental assessment to measure wastes and emissions and resource use (Ayres 1986; Szargut and Morris 1987). Also Ayres pointed that including exergy in LCA helps obtain more reliable data and better results (Ayres 1995).

Using exergy analysis, bring some advantages for LCA that are obtained over the standard approaches using energy and mass, separately. By using exergy as a common measure of inputs and outputs, we can immediately estimate exergetic efficiency, namely the ratio of exergy outputs to total exergy inputs (including utilities). And it also facilitates the comparison of impacts in different environmental domains that until this day has required a monetary measure, or necessarily remained unresolved.

There are two possible methods to combine LCA with exergy analysis, these are: Exergetic Life Cycle Analysis (ELCA) and Cumulative Exergy Consumption (CExC).

Exergetic Life Cycle Analysis

R. Cornelissen included exergy in LCA and defined the methodology known as Exergetic Life Cycle Assessment (ELCA). ELCA uses the same framework and inventory analysis of LCA and then based on the conditions and composition calculates the exergy of the flows. The impact assessment of resource used is limited to the calculation of the exergy of the energy and fuels inputs whereas emissions are evaluated based on the results obtained for each impact category.

The goal definition and scoping of the LCA and ELCA are completely identical. The inventory analysis of the ELCA is more extensive. A complete flowsheet of the mass and energy streams of the different production steps is required. The material and energy balances have to be closed. The accumulation of all exergy destruction in the life cycle gives the life cycle irreversibility of the product. The improvement analysis is the minimization of the life cycle irreversibility.

The exergy analysis pinpoints the places where the exergy destruction takes place and in the improvement analysis different possibilities can be presented to minimize the life cycle irreversibility, i.e. the irreversibility during the life cycle of the product or product system. (Cornelissen, 1997)

Cumulative Exergy Consumption

It is considered the first step of analyzing the life cycle on the basis of exergy, and accounts for the cumulative exergy use, from the extraction of natural resources to the final product.

Only takes into account the production and use of the product or material disregarding the disposal of the product and the influence of recycling.

Based on exergy there have been developed four methodologies: Exergy Analysis, Cumulative Exergy Consumption (CExC), Exergetic Life Cycle Analysis (ELCA) and Extended Exergy Analysis (EEA), figure 2 shows system boundaries, represented as discontinues lines, defined depending on the scope and inputs accounted by each tool.

Exergy analysis accounts for material and energy inputs in the manufacturing stage. On the other hand CExC and ELCA study the life cycle of products, including material and energy in each process (Talens, 2009). And EEA allows for the inclusion of exergetic equivalents of such non-energetic quantities as labor, capital and the costs of environmental remediation (Bligh, 2011).

A NOVEL APPLICATION

Rainwater harvesting has been left aside, while other alternatives such as desalination have been promoted to support water supply in urban developments (Tsiourtis, 2001), until recently, the use of decentralized, alternative water sources such as rainwater is being promoted (Domènech and Saurí, 2010; and Farreny, et al., 2011).

This new interest makes indispensable, the provision of environmental impact indicators, that help decision makers to a better identification of the most effective solution with the less environmental impact in order to obtain sustainable strategies for urban water management.

In order to improve the sustainability of our cities, it is necessary to establish the most adequate scale and allocation for RWH systems (Farreny et al., 2011).

Using exergy analysis as an environmental impact indicator, different strategies can be evaluated and compared, obtaining a helpful tool towards sustainable development.

CONCLUDING REMARKS

Rainwater qualities and rainwater harvesting systems characteristics makes it more than a viable option, a profitable and advantageous source of water, replacing tap water consumption, providing a solution or diminish to water scarcity problems.

LCA as an environmental impact analysis gets completed with exergy analysis, giving an overall image of the environmental effect that materials, processes, products or any activity produces by simply measuring the quality of the materials and energy inputs in the system with one indicator in exergy units, making the decision process easier and faster, estimating the exergetic efficiency of the system, facilitating impact comparison.

Exergy analysis shows the places where the exergy is destroyed and CExC and ELCA study the complete life cycle of the product (as a result of a process, could be a single material, product or product system).

With the purpose of achieving sustainable development, rainwater harvesting systems should be analyzed not only from a water management angle, but from the entire life cycle point of view.

**A practical case will be presented at conference.

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