Optimizing rainwater harvesting systems in urban areas.

By

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“I keep turning over new leaves, and spoiling them, as I used to spoil my copybooks; and I make so many beginnings there never will be an end.

(Jo March)”

- Louisa May Alcott, *Little Woman*

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Summary

Rainwater harvesting, though is an ancient technique to collect run-off rainwater for domestic water supply, agriculture and environmental management, it is not widely applied. Rainwater harvesting (RWH) systems could potentially play a key role in helping cities meet their water demand, as an alternative to conventional water treatment technologies such as desalination and other costly technologies.

This doctoral thesis aims to find the most efficient configuration of RWH, first by quantifying the resource consumption and environmental impacts associated to RWH in urban areas and then studying different configurations for domestic water supply considering Mediterranean and desert climate conditions.

The query is motivated by the increasing necessity to find preventive and corrective measures that help cope with water supply problems, especially considering climate change effects in the Mediterranean area and water supply problems in arid areas. Along with this, the hypothesis is based on the fact that rainwater is soft water, thus, requires less detergent and softener additives. Therefore, it represents an advantageous substitute for water used for laundry, especially where tap water presents high levels of water hardness and also whenever water availability is limited.

To analyze the different RWH configurations, the following methodologies were applied: exergy analysis and exergetic efficiency analysis to find resource consumption and efficiency; life cycle assessment (LCA) to identify environmental impacts; life cycle costing (LCC) to find economic feasibility and; data envelopment analysis (DEA) to identify best-practice frontier towards sustainability.

The results evidence that generally cluster configurations are more resource efficient than those in individual configurations, in exergetic and economic aspects. Environmental impacts were found to be inversely proportional to the increase in rainwater supply. Best-practice scenarios were found mostly dependent on the area of rainwater collection. Furthermore, savings from laundry additive consumption result in much improved economic and environmental performances in areas with hard tap water.

Resumen

El aprovechamiento de agua de lluvia, a pesar de ser una antigua técnica para recoger escorrentía para uso doméstico, agricultura y gestión ambiental, no tiene una amplia aplicación. Potencialmente, los sistemas de aprovechamiento de agua de lluvia (RWH) pueden jugar un papel clave en el abastecimiento de la demanda de agua urbana como una alternativa a las tecnologías convencionales de tratamiento de agua como son la desalinización y otras tecnologías costosas

Esta tesis doctoral tiene por objetivo encontrar las configuraciones de RWH más eficientes, primero cuantificando el consumo de recursos e impactos ambientales asociados con RWH en áreas urbanas, y, después, estudiando las diferentes configuraciones para abastecimiento doméstico considerando condiciones climáticas mediterráneas y áridas.

La investigación está motivada por el incremento en la necesidad de encontrar medidas correctoras y preventivas que ayuden a gestionar los problemas de abastecimiento de agua, especialmente considerando los efectos del cambio climático en el área mediterránea y los del abastecimiento de agua en las zonas áridas.

En línea con este planteamiento, la hipótesis se basa en el hecho que el agua pluvial es agua blanda y, por lo tanto, requiere menos detergente y aditivos suavizantes. Así pues, representa un sustituto ventajoso para el agua utilizada en lavandería, especialmente en lugares donde el agua de grifo presenta altos niveles de dureza, así como en cualquier punto donde la disponibilidad de agua es limitada.

Para analizar las diferentes configuraciones de RWH, se aplicaron las siguientes metodologías: análisis de exergía y análisis de eficiencia exergética para determinar el consumo de recursos y eficiencia; análisis de ciclo de vida (LCA) para identificar los impactos ambientales; análisis de ciclo de costes (LCC) para encontrar la viabilidad económica, y análisis envolvente de datos (DEA) para identificar la mejor práctica hacia la sostenibilidad.

En general, los resultados evidencian que configuraciones en clúster son más eficientes en recursos que las individuales, en términos exergéticos y económicos. Se encontró que los impactos ambientales son inversamente proporcionales al incremento en el abastecimiento de agua pluvial. Los escenarios de mejores prácticas son mayoritariamente dependientes del área de captación de agua. Además, los ahorros en el consumo de aditivos en lavandería resultan en una mejor conducta ambiental y económica en áreas con agua dura de grifo.

List of Acronyms and abbreviations

ALO	Agricultural Land Occupation
b_{ch}	Standard chemical exergy
CC	Climate change
CED	Cumulative Energy Demand
CExD	Cumulative Exergy Demand
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
EOL	End-of-life
ExA	Exergy Analysis
FD	Fossil Resource Depletion
FE	Freshwater Eutrophication
FET	Freshwater Ecotoxicity
FU	Functional Unit
g	Grams
HD	High Density
HDPE	High Density Polyethylene
HT	Human Toxicity
II	Initial Investment
IR	Ionizing Radiation
IRR	Internal Rate of Return
ISO	International Organization for Standardization
J	Joules
l	Liters
inh	Inhabitants
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory

LD	Low Density
m	Meters
MAB	Metropolitan Area of Barcelona
ME	Marine Eutrophication
MET	Marine Ecotoxicity
MRD	Mineral Resource Depletion
NLT	Natural Land Transformation
NPV	Net Present Value
OD	Ozone Depletion
PB	Payback Time
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
PP	Polypropylene
ppm	Parts per million
PV	Present Value
PVC	Polyvinyl chloride
RWH	Rainwater Harvesting
TA	Terrestrial Acidification
TET	Terrestrial Ecotoxicity
ULO	Urban Land Occupation
VRS	Variable Returns to Scale
WD	Water Depletion
WS	Rainwater supply

€	Euros
MXN	Mexican pesos

K	Kilo
M	Mega

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Preface

This thesis has been developed within the "Environmental Science and Technology" PhD program offered by the Institut de Ciencia I Tecnología Ambientals (ICTA) within the Sostenipra SGR 1412 research group at the Universitat Autònoma de Barcelona (UAB) from October 2010 to September 2015. This period includes one semester of the Master's program as an introduction to Industrial Ecology and a maternity leave of 4 months.

This thesis is divided in five parts and ten chapters.

Part I includes the introduction and theoretical framework and is divided in two chapters. **Chapter 1** presents an introduction to rainwater harvesting (RWH) systems in urban areas within a sustainable approach and defines the objectives of the thesis. **Chapter 2** describes the methodology used and presents the case studies considered in this thesis.

Part II is divided in two chapters that present the application of exergy tools to assess resource consumption in RWH systems in urban areas. **Chapter 3** applies exergy analysis and exergy efficiency tools to evaluate the resource consumption and the efficiency in the use of resources in Mediterranean areas in a single building utilization. **Chapter 4** increases the scope by studying the exergetic resource consumption in densely populated neighborhoods with Mediterranean climate conditions.

Part III is composed of four chapters that study the environmental and economic aspects of installing RWH systems. **Chapter 5** studies the cost-efficiency of eight different scenarios of RWH systems installed in single buildings. **Chapter 6** is based on previous chapter and explores further results on economic and financial analysis through a life cycle cost (LCC) analysis and also studies the environmental performance of eight scenarios of single buildings through a life cycle assessment (LCA). **Chapter 7** broadens previous chapter by studying seven scenarios of densely populated neighborhoods by the application of LCA and LCC. **Chapter 8** uses LCA and LCC to evaluate RWH systems in arid areas with low annual precipitation.

Part IV consists of **Chapter 9** that uses the results from chapters 3, 4, 6 and 7 to find the best-practice frontier by the application of an input-oriented variable returns to scale data envelopment analysis model to 15 scenarios or DMUs.

Part V concludes the dissertation and consists of **Chapter 10** that provides general conclusions, discussion and recommendations for future work.

Chapters 3 to 9 follow the format of an article and include: abstract, introduction, methodology, results, discussion and conclusion.

This thesis is mainly based on the following published papers:

> M. Violeta Vargas-Parra, Gara Villalba, and Xavier Gabarrell, "Applying Exergy Analysis to Rainwater Harvesting Systems to Assess Resource Efficiency," Resources, Conservation and Recycling 72, (March 2013): 50–59, doi:10.1016/j.resconrec.2012.12.008.
>
> M. Violeta Vargas-Parra M. Rosa Rovira-Val, Xavier Gabarrell and Gara Villalba, "Cost-Effective Rainwater Harvesting System in the Metropolitan Area of Barcelona," Journal of Water Supply: Research and Technology—AQUA 63, no. 7 (April 9, 2014): 586–595, doi:10.2166/aqua.2014.108.

This thesis is also based on the manuscripts that either have been submitted and are under review or that will be submitted in peer-review indexed journals.

Also, the following oral and poster communications include part of the thesis work:

> M. Violeta Vargas-Parra, Xavier Gabarrell and Gara Villalba (2011) "Rainwater harvesting system in urban areas. A novel environmental impacts indicator. *ISINI 2011, 11th International Conference of the International Society for Intercommunication of New Ideas*. Hermosillo, México. Oral communication.
>
> M. Violeta Vargas-Parra, M. Rosa Rovira-Val, Xavier Gabarrell and Gara Villalba (2013) "Cost Effective Rainwater Harvesting System in the Metropolitan Area of Barcelona". IWA 2013, 3rd International Conference on Water Economics, Statistics, and Finance. Marbella, Spain. Oral communication.
>
> M. Violeta Vargas-Parra, M. Rosa Rovira-Val, Gara Villalba and Xavier Gabarrell (2013) "Coste Del Ciclo de Vida Del Aprovechamiento de Aguas Pluviales En Barcelona. META 2014, XI Reunión de La Mesa Española de Tratamiento de Aguas. Alicante, España. Oral communication.
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> M. Violeta Vargas-Parra, M. Rosa Rovira-Val, Xavier Gabarrell and Gara Villalba. (2015) "Life Cycle Cost Implications of Urban Rainwater Harvesting in Hot-Arid Areas". ISIE 2015. 8th International Conference of the International Society for Industrial Ecology Surrey, United Kingdom. Oral communication.
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> M. Violeta Vargas-Parra, M. Rosa Rovira-Val, Xavier Gabarrell, Gara Villalba and Joan Rieradevall. (2015) "The Cost of Urban Rainwater Harvesting in the Sonoran

Desert". CILCA 2015. 6th International Conference on Life Cycle Assessment in Latin America Lima, Peru. Poster.

M. Violeta Vargas-Parra, M. Rosa Rovira-Val, Xavier Gabarrell, Gara Villalba and Joan Rieradevall. (2015) "Optimization of urban rainwater harvesting in northwestern Mexico from a life cycle costing perspective". LCM 2015. 7th International Conference on Life Cycle Management. Bordeaux, France. Poster.

Part I.

Introduction and framework

1

Introduction

Raindrop
Photography by Violeta Vargas

Chapter 1 Introduction

1.1 Sustainability.

Sustainability is defined as the endurance of systems and processes preserving biodiversity and productivity.

Towards a sustainable development, we must meet our current needs (environmental, economic and social well-being) without compromising the ability of future generations to meet their own needs (WCED 1987). Figure 1.1 represents the interrelationships between the three elements of sustainability.

FIG 1.1 THREE PILLARS OF SUSTAINABLE DEVELOPMENT.

A sustainable practice must meet economic feasibility, social responsibility and environmental protection and this may not be the same for every case or location.

Urban areas have become the center of attention from every point of view, and with all the reasons since this is where resource consumption has been intensified and not only that, but also residues and emissions are concentrated in this areas.

Urban water must be supplied for all sorts of uses: domestic, industrial or agricultural and at the same time, environment, society and economy must be maintained or enhanced to maintain or achieve sustainability.

1.2 Sustainability and industrial ecology

In the pursue of a solution, industrial ecology focuses on avoiding environmental impacts before these exist. Based on nature as a model, analyzes ongoing and/or new models towards a more efficient and resilient approach (Frosch 1992) by means of transforming the linear model to a closed-loop model.

Furthermore, the primary goal of industrial ecology is to promote sustainable development at the global, regional and local levels(Garner and Keoleian 1995), particularly avoiding partial analysis that can neglect important aspects affecting the system (Ayres and Ayres 2002).

In essence, industrial ecology studies material and energy flows in any activity and the impact of this activity on the environment. In addition to this, it also studies the socio-economic factors that are influencing the flows, the use and the transformation of resources (White 1994). The new Industrial ecology vision defines it as the chemical engineering outside the pipe (TCE 2007).

1.3 Water and urban areas.

Water is a basic need for life and health and is fundamental key to economic progress and even though water is a renewable resource, its availability is limited. Particularly in urban areas, population tends to accentuate water stress as population density intensifies.

Urban areas represent merely a 3% of land areas (Liu et al. 2014), however, water consumption has doubled the rate of population growth. Currently, 54% of the global population lives in urban areas and is expected to reach 70% in 2050 (FAO Statistics Division 2015). Considering a growing population we can expect also an increased water consumption.

Moreover, urban population not only consumes its own resources, it affects other ambits to satisfy its needs since this area is usually intense resource consumer.

Urban use of water in warm countries of the European Union is around 100 cubic meters per capita every year and 20% of the domestic water consumption is used in laundry (EEA 2010).

Different alternative water sources/technologies can be applied to suffice water demand in urban areas. These go from ancient techniques like rainwater harvesting to the ultimate Janicki Omniprocessor that processes feces to obtain water. A great variety in cost and on environmental impacts is also available on the market.

1.4 Water-Energy-Food Nexus

Most of current human threats rely on the production, use, distribution and disposal of water, energy and food. These three sectors are interconnected and interdependent of each other and hold a clear interdependence with the environment. The balance between the three is necessary to achieve an efficient use of resources. Water is needed to produce food and energy. Energy is needed to produce food and for water supply and sanitation, and food (biomass in energy crops) is needed to produce energy.

By 2050, agriculture will need to produce 60% more food globally (FAO 2009), total primary energy supply will be increased in a 27%-61% (World Energy Council 2013) and a 55% overall increase in global water consumption (OECD 2011). All this high demands on resources could end up causing social and geopolitical tensions, hampering economic development and risking people's water, energy and food security (German Government 2011).

Urban water supply must be taken as part of an integrated strategy, considering that resources are interrelated and that humans depend on them to achieve social, economic and environmental development.

1.5 RWH systems history

Traditionally, different types and forms of harvesting water have been used for centuries. The oldest techniques are still in use for agricultural purposes. One of the oldest dates back 4000 years or more in the Negev Desert of Israel (Evenari et al. 1971). Other irrigation techniques, such as floodwater farming have been in use for at least 1000 years in the desert areas of Arizona and New Mexico (Zaunderer, J. & Hutchinson 1988) and also in southern Tunisia a similar technique was discovered in the 19th century (Pacey and Cullis 1988).

However, agriculture is only one of the several uses that can be given to harvested water. Other uses include water for livestock, indoor heating of houses and a variety of domestic uses (with the appropriate treatment).

Roof catchments for domestic purposes date back to the Roman times at least 2000 B.C. And at the small-scale, in Africa and Asia, rainwater has been collected in jars and pots for thousands of years and some are still in use today. Mostly, water harvesting has been motivated by the tension caused after a prolonged dry period.

1.6 RWH in urban areas

Cities, as they grow in population and water needs must get water from greater distances or energy-intensive water treatments to obtain the quantity and quality of water for society. The problem is that this is really unsustainable.

Rainwater harvesting in urban areas is a multi-beneficial strategy that may serve to cope with current water shortages, urban natural waterway degradation and flooding (Zhu et al. 2004; Mitchell et al. 2005) that are given by urban runoff (rainwater runoff from urban environments) and combined sewer (sanitary and stormwater runoffs) outflows.

Moreover, these systems could help lower environmental and economic burdens, especially in urban areas where meeting water demand will be more energy intensive as well as costly as urban population increases.

Even though roof water harvested onsite from buildings is usually the cleanest alternative water source available, with no dissolved minerals aside from any dissolved carbon dioxide or dust, and hence, it is normally softer than surface or groundwater (WHO 2008) and even tap water (Farreny et al. 2011c; Rygaard et al. 2011a, 2011b), 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 2011a; Farreny et al. 2011c; Morales-Pinzón et al. 2012c).

Feasibility of rainwater harvesting techniques depends on the amount of precipitation and the distribution along the year, it also relies on quantity and quality of other available water sources, the specific quantity and quality required for use or consumption and the budget destined for this technology.

1.7 Objectives

The main objective of this thesis is to assess rainwater harvesting systems in urban areas for domestic purposes in two different urban compositions and also different climatic conditions from a sustainable perspective.

To achieve this main target, several goals have to be accomplished, and they are described below.

Objective I – To assess the environmental performance of rainwater harvesting systems. (Chapters 6, 7 and 8)

Objective II – To assess the economic performance of rainwater harvesting systems. (Chapters 5, 6, 7 and 8)

Objective III. To assess the resource use efficiency in rainwater harvesting systems. (Chapters 3 and 4)

Objective IV – To study the productive efficiency and estimate the production frontiers of rainwater harvesting systems. (Chapter 9)

2

Methodology


Barcelona rainy days
Photography by Violeta Vargas

Chapter 2 Methodology

This section presents the main methodologies applied to assess Rainwater Harvesting (RWH) systems. Within the Industrial Ecology multidisciplinary field, different tools were used, following a Life cycle approach: Exergy Analysis (ExA), Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Data Envelopment Analysis (DEA). Also, a small summary of case study systems is provided in info-sheets. Further details can be found in the following chapters. Table 2.1 shows the methodology applied in each chapter of the dissertation.

TABLE 2.1 METHODOLOGY APPLIED IN EACH CHAPTER.

	Methodology			
	ExA	LCA	LCC	DEA
Chapter 3	•			
Chapter 4	•			
Chapter 5			•	
Chapter 6		•	•	
Chapter 7		•	•	
Chapter 8		•	•	
Chapter 9				•

2.1 Exergy Analysis

The term Exergy refers to the Greek words ex (external) and ergos (work) and it was first used by Rant (1953). From the first law of thermodynamics, energy is never destroyed during a process, contrastingly, the second law of thermodynamics, accounts for the irreversibility of a process or the loss of energy quality. That being said, exergy can be defined as: "The exergy of a system, at a certain thermodynamic state, is the maximum amount of work that can be obtained when the system moves from that particular state to a state of equilibrium with the surroundings" (Gundersen 2011). So, the exergy contained in a material or subsystem is a measure of potential work and therefore, measurable in the same units as energy and work, i.e. Joules, kWh, BTU, etc.

In Industrial Ecology, exergy is used for resource and waste accounting, Exergy Analysis (ExA) can be used to assess resource consumption, measuring materials and energy in the same units for a holistic evaluation of the system and also facilitate evaluations by comparison of different options or solutions. Figure 2.1 represents how exergy inputs from resources produce exergy outputs as products and byproducts of a process, and how energy is preserved (first law of thermodynamics) but energy quality (exergy) is lost during the process (second law of thermodynamics).

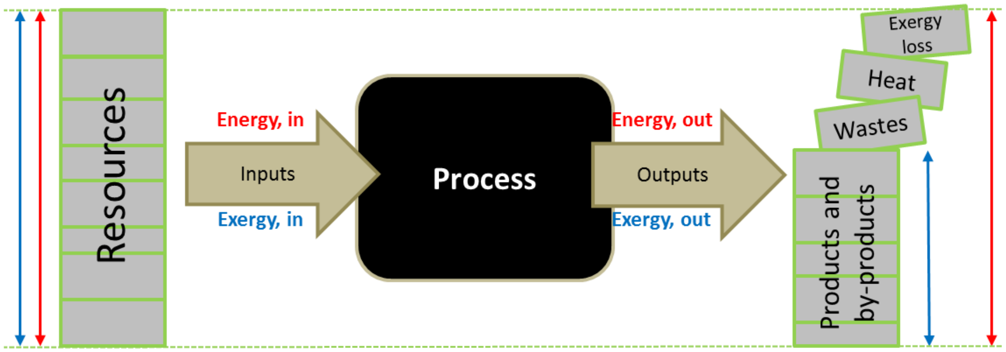


Fig 2.1 First and second law analysis of a process. Modified from (Talens 2009).

ExA consists of four steps, according to Talens (2009):

1) Establish system boundaries. Detect input/output stages.

2) Allocate inputs and outputs in operation units to study them independently.

3) Obtain a balance of in and out flows for each process unit.

4) Account for chemical exergy and exergy of utilities.

The standard exergy of several compounds can be found in Szargut et al. (1988) and also in the Appendix B and Appendix C in Accounting for Resources 2 (Ayres and Ayres 2000). When compounds or pure substances are not found in published sources, chemical exergy can be calculated from Szargut's equations in Exergy analysis of thermal, chemical, and metallurgical processes (Szargut et al. 1988), described in Table 2.2.

Table 2.2 Exergy equations description.

Definition	For complex substances	For chemical exergy content of any pure substance	For chemical exergy of mixtures
Formula	$B_{ch} = \sum_i g_i b^0_{g,i}$	$B_{ch} = \Delta G^0_f + \sum_i N_i b_i$	$B_{ch} = \sum_i N_i b_i + RT_0 y_i \ln y_i$
Variable definition	B_{ch} = Standard chemical exergy (MJ/kg). g_i = Szargut coefficient for *i*-th pure substance (MJ/kg). $b^0_{g,i}$ = Mass fraction of *i*-th pure substance in the complex substance. ΔG^0_f = Standard Gibbs free energy of formation of the compound (MJ/kg).		

N_i = Molar fraction of i-th pure element or substance.

b_i = Chemical exergy of i-th pure element or substance (MJ/kg).

R = Gas law constant (MJ/kgK).

T_0 = Temperature (K).

y_i = Mole fraction of i-th substance.

Moreover, Exergetic efficiency is defined as the ratio between the exergy obtained as a useful output and the exergy input. Exergy efficiency is always smaller than unity (Szargut et al. 1988)

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is an analytical tool that aims to evaluate the potential environmental aspects related to a product, process or activity's life. The life cycle is usually sectioned in stages that help the analytical process to obtain a detailed study and quantification of all inputs and outputs as they interact through processes into products and wastes.

The idea of an environmental LCA started in the late 60's, and the first formal analytical scheme was conceived by Harry E. Teasly in the United States for a Coca-Cola packaging study, although the term LCA was coined in 1990 at an international workshop sponsored by the Society of Environmental Toxicology and Chemistry (SETAC).

In 1993 the International Organization for Standardization (ISO) assigned a small group of SETAC LCA experts for a standard procedure and by 1997 the ISO14040 standard for Life cycle assessment – Principles and framework was complete. And after that, the ISO 14044 Life cycle assessment – Requirements and guidelines was published by 2006.

ISO 14040 (ISO 2006) identifies four interrelated phases for conducting an LCA (Figure 2.2)

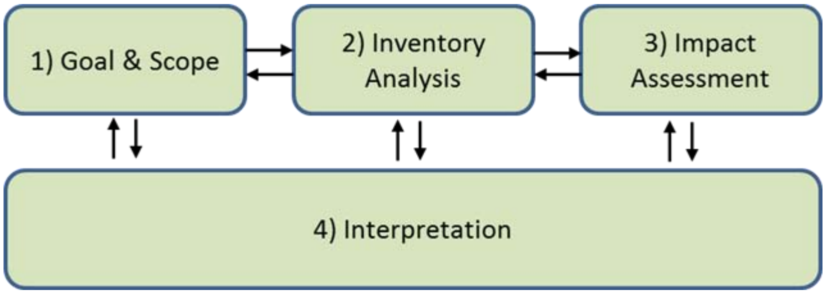


FIG 2.2 LCA FRAMEWORK.

The first phase is to define the product or service that is going to be study, for this thesis is a rainwater harvesting system installed in urban areas for non-potable domestic uses. Also, a basis for comparison must be chosen as functional unit, in this case is 1 m^3 of potential rainwater supply. Secondly, all resources are accounted as inputs and any generated pollutant is accounted as outputs developing the Life Cycle Inventory (LCI). Thirdly, the effects of resource use and the emissions generated are grouped and quantified into impact categories. Impact categories results can be chosen either at midpoint or endpoint level. Midpoint impact categories have a problem-oriented approach and on the other hand, endpoint impact categories are damage-oriented with higher level of uncertainty compared to midpoint results. Lastly, the fourth phase is the interpretation, where the results are reported and environmental impacts are studied systematically to present potential reductions.

For this thesis, ReCiPe (Goedkoop et al. 2013)impact assessment method was applied. This method has eighteen midpoint indicators and three endpoint indicators, although for this thesis only midpoint categories were used considering a hierarchist perspective which is based on the most common policy principles. Also, the single methods Cumulative Energy Demand (CED) and Cumulative Exergy Demand (CExD) were applied. Environmental impact categories are described in Table 2.3.

TABLE 2.3 ENVIRONMENTAL IMPACT CATEGORIES.

Abbreviation	Impact category	Unit	Definition/Impact indicator
CC	Climate change	kg CO_2 eq.	Alteration of global temperature caused by greenhouse gases. / Disturbances in global temperature and climatic phenomenon.
OD	Ozone Depletion	kg CFC-11 5 eq.	Diminution of the stratospheric ozone layer due to anthropogenic emissions of ozone depleting substances. / Increase of ultraviolet UV-B radiation and number of cases of skin illnesses.
TA	Terrestrial Acidification	kg SO_2 eq.	Reduction of the pH due to the acidifying effects of anthropogenic emissions. / Increase of the acidity in water and soil systems.
FE	Freshwater Eutrophication	kg P eq.	Accumulation of nutrients in freshwater systems. / Increase of nitrogen and phosphorus concentrations and formation of biomass
ME	Marine Eutrophication	kg N eq.	Accumulation of nutrients in marine systems. / Increase of nitrogen and phosphorus concentrations and formation of biomass.
HT	Human Toxicity	kg 14DCB eq.	Toxic effects of chemicals on humans. / Cancer, respiratory diseases, other non-carcinogenic effects and effects to ionising radiation.

POF	Photochemical Oxidant Formation	kg NMVOC6 eq.	Type of smog created from the effect of sunlight, heat and NMVOC and Nox. / Increase in the summer smog.
PMF	Particulate Matter Formation	kg PM10 eq.	Suspended extremely small particles originated from anthropogenic processes such as combustion, resource extraction, etc. / Increase in PM10 particles suspended on air.
TET	Terrestrial Ecotoxicity	kg 14DCB eq.	Toxic effects of chemicals on terrestrial ecosystem. / Biodiversity loss and/or extinction of species.
FET	Freshwater Ecotoxicity	kg 14DCB eq.	Toxic effects of chemicals on freshwater ecosystem. / Biodiversity loss and/or extinction of species.
MET	Marine Ecotoxicity	kg 14-DCB7 eq.	Toxic effects of chemicals on marine ecosystem. / Biodiversity loss and/or extinction of species.
IR	Ionising Radiation	kg U 235 eq.	Type of radiation composed of particles with enough energy to liberate an electron from an atom or molecule. / Effects of the radiation (health decline, cancer, illnesses, etc).
ALO	Agricultural Land Occupation	m^2 x yr	Impact on the land due to agriculture. / Species loss, soil loss, amount of organic dry matter content, etc.
ULO	Urban Land Occupation	m^2 x yr	Impact on the land due to anthropogenic settlement. / Species loss, soil loss, amount of organic dry matter content, etc.
NLT	Natural Land Transformation	m^2	Impact on the land due to agriculture, anthropogenic settlement and resource extractions. / Species loss, soil loss, amount of organic dry matter content, etc.
WD	Water Depletion	m^3	Decrease of the availability of non-biological resources (non- and renewable) as a result of their anthropogenic use. / Decrease of water resource based on the total amount of water used.
MRD	Mineral Resource Depletion	kg Fe eq.	Decrease of the availability of non-biological resources (non- and renewable) as a result of their anthropogenic use. / Decrease of mineral resources.
FD	Fossil Resource Depletion	kg oil eq.	Decrease of the availability of non-biological resources (non- and renewable) as a result of their anthropogenic use. / Decrease of fossil resources.
CED	Cumulative Energy Demand	MJ	Direct and indirect energy use. / Energy intensity of processes.

CExD	Cumulative Exergy Demand	MJ	Decrease in quality of resources that are removed from nature. / Quality of energy demand

Table adapted from: (Acero et al. 2014)

2.3 Life Cycle Costing

Towards sustainability, one of the pillars is economic development. In Industrial ecology, several options are available to assess the economic performance. One of the options is Life Cycle Cost analysis (LCC) since it follows the same life cycle approach as LCA. LCC can be analyzed through different economic evaluations like: cost-benefit analysis, cost-effective analysis, risk-benefit analysis, and others. For this thesis, cost-effective approach was applied for all studies within the LCC assessment.

The term “Life Cycle Cost” was first used in mid-60's in a military related document and soon the concept became popular in the 70's in the United States, mainly in the military industry field (Kawauchi and Rausand 1999). After that, the use was spread rapidly to other industries and other countries.

LCC is a systematic approach that evaluates the long-term cost effectiveness of an activity or project considering all relevant costs and benefits over its life and it is primarily used to evaluate and compare different alternatives (Ruegg et al. 1978).

ISO 15686-5 (2008) gives guidelines to perform LCC analyses of buildings and constructed assets and their parts. Based on ISO 15686-5:2008, three financial tools were selected for this thesis: Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Time (PB) described in Table 2.4.

TABLE 2.4 FINANCIAL TOOLS DESCRIPTION.

Tool	NPV	IRR	PB
Definition	The difference between the present value of cash inflows and cash outflows. Is used to analyze the profitability of each scenario as a project/investment.	Indicates the rate at which NPV becomes zero.	Gives an estimate of the time required to recover the cost of investment.
Formula	$NPV = -I + \sum_{i=0}^{T} \frac{C_i}{(1+r)^i}$	$NPV = \sum_{i=0}^{I} \frac{C_i}{(1+r)^i} = 0$	$PB = \frac{(p-n)}{p} + y_i$
Variable definition	I = Initial cost or initial investment. C_i =Cash flow at year i. (cash inflows minus cash outflows at year i)		

r = Discount rate.

p =The value of discounted cash flow at which the first positive value of discounted cumulative cash flow occurs.

n =The value of discounted cash flow at which the last negative value of discounted cumulative cash flow occurs.

y_i =The number of years after the initial investment at which last negative value of discounted cumulative cash flow occurs.

Cumulative cash flow= $\sum_i^T C_i$

For this thesis, data on cost of materials, labor, tools and equipment were obtained from databases and internet catalogues. Furthermore, we validated the costs by consulting a senior professional of water installations.

2.4 Data Envelopment Analysis

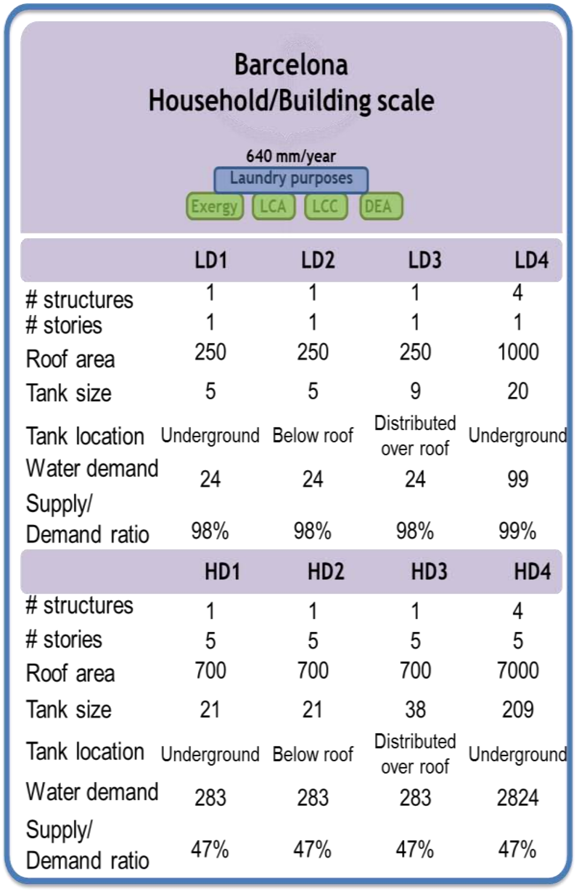
Searching for a sustainability index, two different approaches can be taken: the value approach or the modeling approach. Within the modeling approach, Data Envelopment Analysis (DEA) methodology has been getting attention from all fields in science.

DEA was developed by Charnes, Cooper and Rhodes (1978), as a linear programming-based technique designed to evaluate and compare the performance of a set of decision making units (DMU's) with common inputs and outputs. DEA identifies how efficiently a DMU uses the available resources to generate a set of outputs (Charnes et al. 1978). The best performing unit is assigned an efficiency score of unity or 100 per cent relative to this best performance and then calculates the remaining DMU's assigning values between 0 and 1 (Gerdessen and Pascucci 2013).

One of the main advantages of DEA is that it does not need any prior assumptions and therefore, is a nonparametric approach.

2.5 Case studies

Case studies are based in two different cities: Barcelona, Spain and Hermosillo, Mexico. 15 different scenarios are proposed to study Barcelona's rainwater harvesting systems configuration and 6 for Hermosillo. This is summarized in the next info-sheets from Figures 2.3 to 2.5 and further details can be found in each chapter.



Barcelona
Household/Building scale

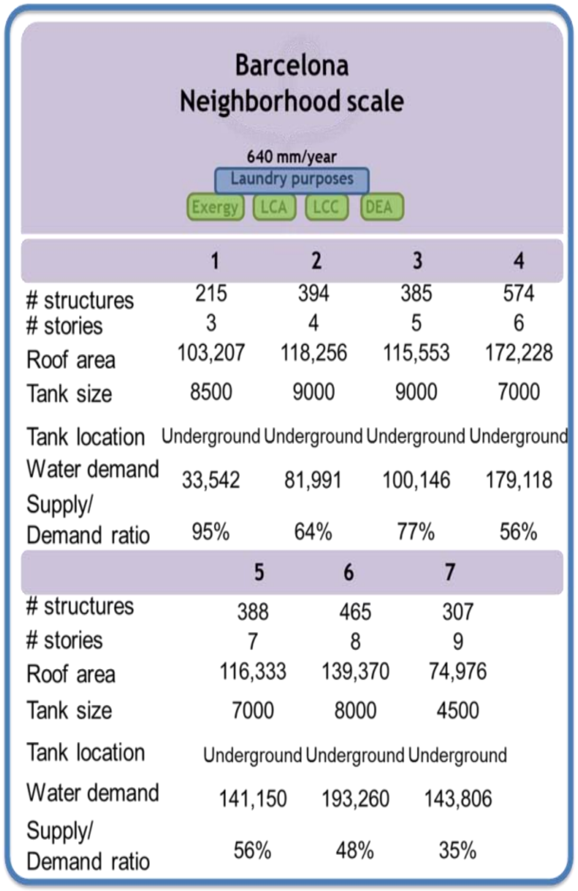
640 mm/year
Laundry purposes
Exergy LCA LCC DEA

	LD1	LD2	LD3	LD4
# structures	1	1	1	4
# stories	1	1	1	1
Roof area	250	250	250	1000
Tank size	5	5	9	20
Tank location	Underground	Below roof	Distributed over roof	Underground
Water demand	24	24	24	99
Supply/ Demand ratio	98%	98%	98%	99%

	HD1	HD2	HD3	HD4
# structures	1	1	1	4
# stories	5	5	5	5
Roof area	700	700	700	7000
Tank size	21	21	38	209
Tank location	Underground	Below roof	Distributed over roof	Underground
Water demand	283	283	283	2824
Supply/ Demand ratio	47%	47%	47%	47%

*Roof area in m^2; tank size and water demand in m^3.

FIG 2.5 BARCELONA HOUSEHOLD/BUILDING SCENARIOS SUMMARY.



Barcelona
Neighborhood scale

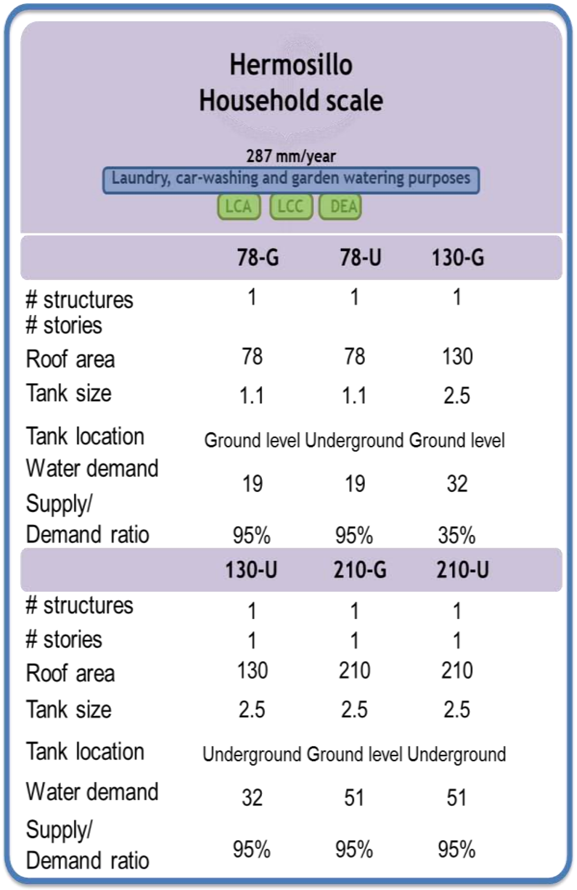
640 mm/year
Laundry purposes
Exergy LCA LCC DEA

	1	2	3	4
# structures	215	394	385	574
# stories	3	4	5	6
Roof area	103,207	118,256	115,553	172,228
Tank size	8500	9000	9000	7000
Tank location	Underground	Underground	Underground	Underground
Water demand	33,542	81,991	100,146	179,118
Supply/ Demand ratio	95%	64%	77%	56%

	5	6	7
# structures	388	465	307
# stories	7	8	9
Roof area	116,333	139,370	74,976
Tank size	7000	8000	4500
Tank location	Underground	Underground	Underground
Water demand	141,150	193,260	143,806
Supply/ Demand ratio	56%	48%	35%

*Roof area in m^2; tank size and water demand in m^3.

FIG 2.3 BARCELONA NEIGHBORHOOD SCENARIOS SUMMARY.



Hermosillo
Household scale

287 mm/year
Laundry, car-washing and garden watering purposes
LCA LCC DEA

	78-G	78-U	130-G
# structures	1	1	1
# stories			
Roof area	78	78	130
Tank size	1.1	1.1	2.5
Tank location	Ground level	Underground	Ground level
Water demand	19	19	32
Supply/ Demand ratio	95%	95%	35%

	130-U	210-G	210-U
# structures	1	1	1
# stories	1	1	1
Roof area	130	210	210
Tank size	2.5	2.5	2.5
Tank location	Underground	Ground level	Underground
Water demand	32	51	51
Supply/ Demand ratio	95%	95%	95%

*Roof area in m^2; tank size and water demand in m^3.

FIG 2.4 HERMOSILLO SCENARIOS SUMMARY.

Part II.

Resource efficiency

3

Exergy in buildings

Frosting
Photography by Violeta Vargas

Chapter 3 Exergy in buildings

based on the following paper: M. Violeta Vargas-Parra, Gara Villalba, and Xavier Gabarrell, “Applying Exergy Analysis to Rainwater Harvesting Systems to Assess Resource Efficiency,” Resources, Conservation and Recycling 72 (March 2013): 50–59, doi:10.1016/j.resconrec.2012.12.008.

Abstract

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 m3 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 m3 rainwater storage tank installed below roof. Exergy requirements could be minimized by material substitution, minimizing weight or distance traveled.

4

Exergy in neighborhoods

UAB rain
Photography by Violeta Vargas

Chapter 4 Exergy in neighborhoods.

based on a manuscript by: M. Violeta Vargas-Parra, Gara Villalba, Xavier Gabarrell and M. Rosa Rovira-Val.

Abstract

World population is not evenly distributed; urban population is already more than half of the total population and is expected to grow on a faster rate. Moreover, consequences of climate change are more intense in urban areas, especially water supply reliability. This study applies exergy analysis to evaluate and compare the performance of seven neighborhood scenarios based on Barcelona neighborhoods population density and Mediterranean climate conditions. Following a life cycle approach, three life stages are considered and all energy and materials required are quantified in exergy terms with the aim of producing 1 m^3 of rainwater for domestic laundry purposes.

Results show that the highest exergy input is associated with the production of pipe materials like Polyvinylchloride and energy needed to install an underground tank. Scenario with the lowest exergy consumption considers 307 buildings, 11,062 households and a 5,000 m^3 storage tank. Noteworthy, exergy consumption can be reduced, substituting pipe materials and installing the tank at ground level.

4.1 Introduction

World's population is concentrating in urban areas, more than half of the world's population lives in urban areas and is expected to grow on a faster rate the next decades (United Nations 2014). Moreover, population growth increases the struggle to meet cities water demand.

Being the sixth most populated area of Europe, Catalonia's water supply has been increased in the last decade. In the Metropolitan Area of Barcelona, 85% of water supply comes from the rivers Ter and Llobregat and the remaining 15 % from groundwater (EMA-AMB 2013). Furthermore, water depends on energy for treatment and distribution, also called the water-energy nexus. In 2012 269 hm^3 of water were treated, consuming 129.5 GWh of electricity.

Alternative water sources like rainwater harvesting (RWH) could reduce tap water consumption and decrease pressure on the available resources. RWH is especially attractive due to its low cost of implementation and its flexibility of installation. RWH systems can collect, store and distribute from different surfaces: land, roads, rooftop and rock catchments (Appan 2000; Zhu et al. 2004). Furthermore, rainwater contains no dissolved minerals, and therefore, it is normally softer than surface or groundwater (WHO, 2008) and even tap water (Farreny et al., 2011b; Rygaard et al., 2011a, 2011b, 2010). Towards urban water self-sufficiency, RWH is becoming a fundamental contributor (Rygaard et al. 2011b; Fragkou et al. 2015).

Previously, an exergy analysis was performed by Vargas-Parra et al. (2013) on eight different scenarios of urban configurations in Barcelona, however, those scenarios were designed on a more private action, with the bigger extent being 10 buildings and including 240 households with a 209 m^3 storage tank. Considering the population density of Barcelona neighborhoods, from 100 to 59,300 inh/km^2, more configurations should be available for neighborhoods.

Exergy analysis has been proved a useful tool to identify and quantify resource (energy and materials) consumption. In this study, exergy analysis is used as a resource accounting tool and to quantify and compare RWH systems for seven neighborhood scenarios based on actual data from Barcelona neighborhoods, collecting rainwater from the rooftop, then storing it in a centralized tank and finally distributing the rainwater directly to the laundry machine in each household.

4.2Method

4.2.1 Exergy Analysis

Exergy is the quality of resources or potential work that can be done, measured in the same units as energy and work (joules, kWh, btu, etc.). Exergy analysis makes it easier to compare between different options as it measures energy and materials in the same units.

Like energy, exergy can be classified in physical and chemical, where physical exergy can be decomposed in kinetic and potential based on the velocity and position of a body in reference to earth and gravity respectively (Gundersen 2011). Chemical exergy corresponds to the chemical composition of a substance in relation to the common components of the environment and is calculated using the Szargut et al. (1988) method.

For this study, exergy of materials was obtained from literature sources, primarily from Hoque et al. (2012) for construction materials and from Szargut (2005); and Dewulf et al. (2007) others were calculated using the inventory from Ecoinvent database for processes and Szargut's formula (Szargut et al. 1988).

$$\boldsymbol{B_{ch}} = \sum_i \boldsymbol{g_i} \boldsymbol{b^0_{g,i}} \qquad \text{EQUATION 4.1}$$

Where:

B_{ch} = Standard chemical exergy (MJ/kg).

$\mathrm{b}^0_{\mathrm{g,i}}$ = Mass fraction of i-th pure substance in the complex substance.

$\mathrm{g_i}$ = Szargut coefficient for i-th pure substance (MJ/kg).

4.2.2 Case study

System boundaries were set from a cradle-to-grave life cycle approach. Including the construction of the RWH system, its use during 50 years and the dismantling of the system and transport of construction waste to a waste management plant.

A list of all materials and energy required to install, use and dismantle a RWH system is presented in exergy units and is presented by life cycle stage in Table 4.1.

Construction stage considers all materials and energy needed to construct and install a RWH system.

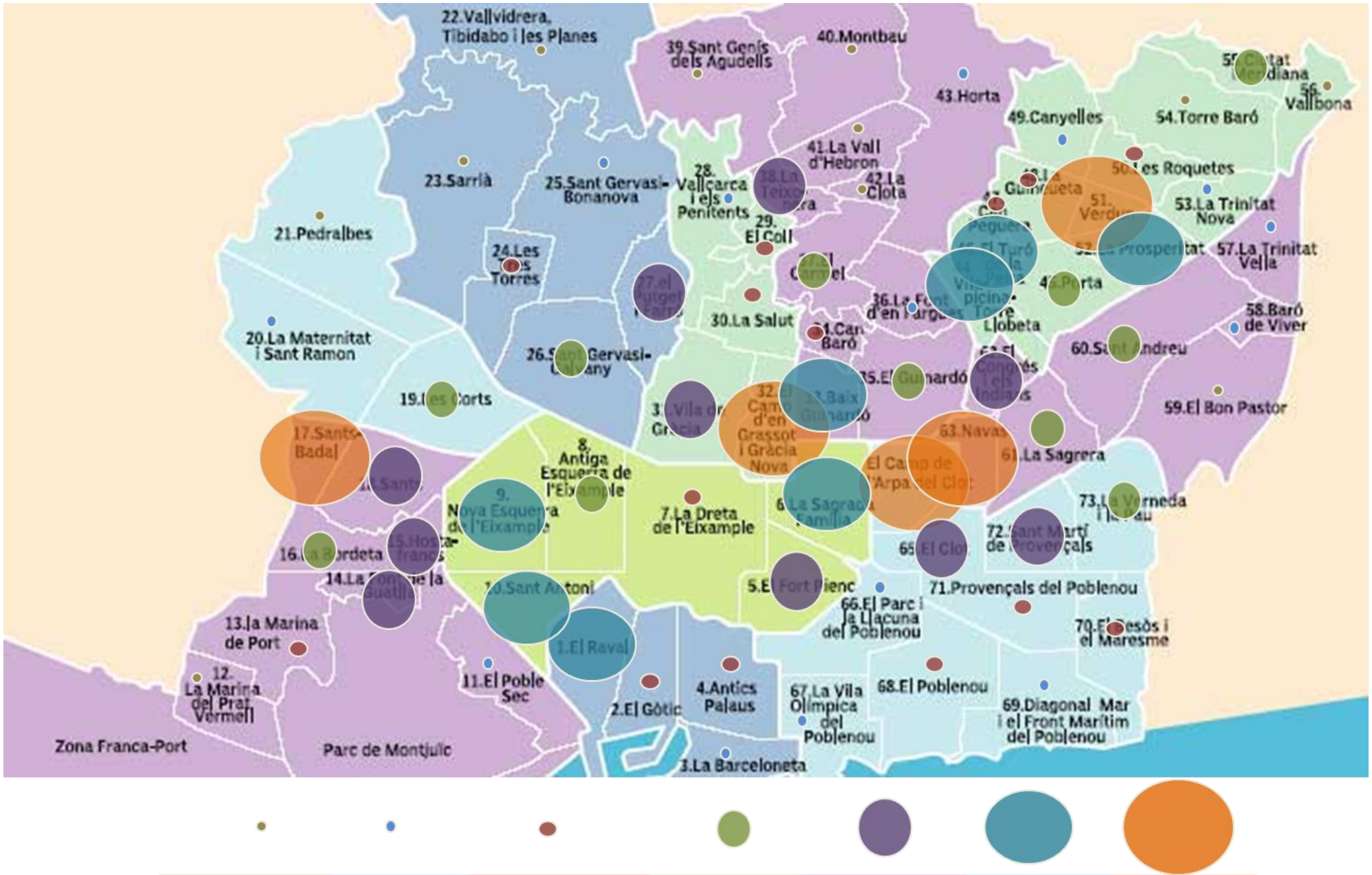
Replacement of materials with shorter lives are calculated and considered during the use stage, based on durability of the materials. Lifetime of the system is considered as 50 years for this study.

The end-of-life (EOL) stage includes the required energy to dismantle and transport the construction waste materials to a waste management plant.

TABLE 4.1 INPUTS IN EXERGY UNITS.

LIFE STAGE	INPUT	DESCRIPTION	EXERGY INPUT	CHEMICAL EXERGY (MJ)
Construction	Pipes and accesories	Polyvinylchloride, at regional storage	Polyvinylchloride	19.32
		Extrusion, plastic pipes	Extrusion plastic pipes	13.80
	Storage tank	Concrete, normal	Concrete	0.16
		Cast iron, at plant	Cast iron	8.20
		Steel product manufacturing, average metal working	Steel refining	8.65
		Plywood, outdoor use	Plywood	19.97
		Bitumen, at refinery	Bitumen	10.12
		Polyethylene terephthalate, granulate, amorphous, at plant	Polyethylene terephthalate	23.80
	Pumps	Steel, low-alloyed, at plant	Steel	8.91
		Steel product manufacturing, average metal working	Steel refining	8.65
	Filters	Polyethylene, HDPE, granulate	Polyethylene, HDPE	41.87
		Extrusion, plastic pipes	Extrusion plastic pipes	13.80
	Construction services	Diesel, burned in building machine	Diesel	45.80
Use	Electricity	Electricity, low voltage, production ES, at grid	Electricity	1.00
	Pumps	Steel, low-alloyed, at plant	Steel	8.91
		Steel product manufacturing, average metal working	Steel refining	8.65
	Filters	Polyethylene, HDPE, granulate	Polyethylene, HDPE	41.87
		Extrusion, plastic pipes	Extrusion plastic pipes	13.80
End-of-life	Transport	Diesel, burned in building machine	Diesel	45.80
	Demolition services	Diesel, burned in building machine	Diesel	45.80

Scenarios were designed on statistical data from Barcelona neighborhoods (Ajuntament de Barcelona, 2014) and are represented in Figure 4.1.



Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
< 8557	8558 -17015	17016 -25473	25474 - 33931	33932 - 42389	42390 - 50847	50847 - 59305

4.1 BARCELONA'S POPULATION DENSITY (2013)

Scenario description is given in Table 4.2 which is based on water demand and available rainfall. Storage tank size and potential rainwater supply were calculated using Plugrisost®, a free simulation model developed by Gabarrell et al. (2014). The model estimated the potential rainwater supply based on a daily time series of rainfall (from 1991 to 2010), a roof-runoff coefficient estimated at 0.9 (Singh 1992) and the roof area for collection. Water demand was calculated based on a laundry demand of 5 wash loads per week and household and a water consumption of 50 liters per load.

TABLE 4.2 SCENARIO DESCRIPTION FOR BARCELONA NEIGHBORHOODS

Scenario	N1	N2	N3	N4	N5	N6	N7
Building height in layers	3	4	5	6	7	8	9
Average neighborhood area (km^2)	3.68	1.48	0.91	1.12	0.7096	0.80	0.4926
Average neighborhood housing area (m^2)	134905	78065	53454	69830	46293	51673	34374
Average household area (m^2)	120	75	75	75	75	75	61
Households per layer	4	4	4	4	4	4	4
Households per building	12	16	20	24	28	32	36
Average households per neighborhood (2013)	2580	6307	7704	13778	10858	14866	11062
Buildings per neighborhood	215	394	385	574	387	464	307
Building collection area (m^2)	480	300	300	300	300	300	244
Average Inhabitants per household	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Average Inhabitants per building	31.8	42.4	53	63.6	74.2	84.8	95.4
water demand household (l/household/day)	35.7	35.7	35.7	35.7	35.7	35.7	35.7
water demand building (l/building/day)	428.6	571.4	714.3	857.1	1000.0	1142.9	1285.7
water demand neighborhood daily (l/neighborhood/day)	92149.4	225250.0	275125.0	492081.2	387775.0	530933.0	395071.4
collection area (m^2)	103207.3	118256.3	115552.5	172228.4	116332.5	139369.9	74975.8
Tank capacity (m^3)	4000.0	7500.0	9000.0	7000.0	7000.0	8000.0	4500.0
% demanda cubierta	82%	60%	54%	39%	38%	33%	25%
rw supply (m^3/year)	27427.6	49268.4	54108.6	70232.0	53453.5	64722.6	36411.7

4.3 Results

Calculations and estimations were applied to obtain an inventory of all materials and energy required for each scenario. Results are compiled in Table 4.3.

Through ExA, resource consumption of each scenario is identified. Each scenario has different rainwater supply according to their attributes, described earlier in this section. In order to obtain a comparable dataset, all inputs were calculated for a reference unit of $1m^3$ of rainwater. As a result, scenario with the lower resource consumption is identified. Scenario N7 has the lowest resource consumption per m^3 of rainwater supplied to the neighborhood.

Figure 4.2 shows exergetic resource consumption for each scenario by life cycle stage, from which is recognized that construction stage requires the most resources and use stage is the least resource consuming stage.

Table 4.3 Exergy analysis for Barcelona neighborhoods

LIFE STAGE	INPUT	EXERGY INPUT	CHEMICAL EXERGY (MJ/kg)	N1	N2	N3	N4	N5	N6	N7
Construction	Pipes and accessories	Polyvinylchloride	19.32	48.3	24.8	23.7	21.6	22.2	23.6	28.5
		Extrusion plastic pipes	13.80	34.5	17.7	16.9	15.4	15.8	16.9	20.4
	Storage tank	Concrete	0.16	3.9	4.5	4.3	4.1	4.1	3.1	2.2
		Cast iron	8.20	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		Steel refining	8.65	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		Plywood	19.97	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Bitumen	10.12	0.8	1.0	1.0	0.9	0.9	0.7	0.5
		Polyethylene terephthalate	23.80	1.0	1.2	1.2	1.1	1.1	0.8	0.6
	Pumps	Steel	8.91	0.5	0.3	0.3	0.2	0.2	0.2	0.3
		Steel refining	8.65	0.4	0.3	0.3	0.2	0.2	0.2	0.3
	Filters	Polyethylene, HDPE	41.87	0.6	0.4	0.3	0.3	0.3	0.3	0.4
		Extrusion plastic pipes	13.80	0.2	0.1	0.1	0.1	0.1	0.1	0.1
	Construction services	Diesel	45.80	54.2	58.7	54.5	52.0	51.3	41.5	32.7
Use	Electricity	Electricity	1.00	11.8	1.1	1.0	0.9	0.9	1.0	1.1
	Pumps	Steel	8.91	0.5	0.3	0.3	0.2	0.2	0.2	0.3
		Steel refining	8.65	0.4	0.3	0.3	0.2	0.2	0.2	0.3
	Filters	Polyethylene, HDPE	41.87	0.6	0.4	0.3	0.3	0.3	0.3	0.4
		Extrusion plastic pipes	13.80	0.2	0.1	0.1	0.1	0.1	0.1	0.1
End-of-life	Transport	Diesel	45.80	3.9	4.7	4.5	4.4	4.3	3.3	2.2
	Demolition services	Diesel	45.80	45.0	55.2	53.1	51.1	50.5	39.0	26.0
TOTAL EXERGY PER M^3 (MJ)				**207.0**	**171.5**	**162.3**	**153.4**	**153.0**	**131.9**	**116.6**

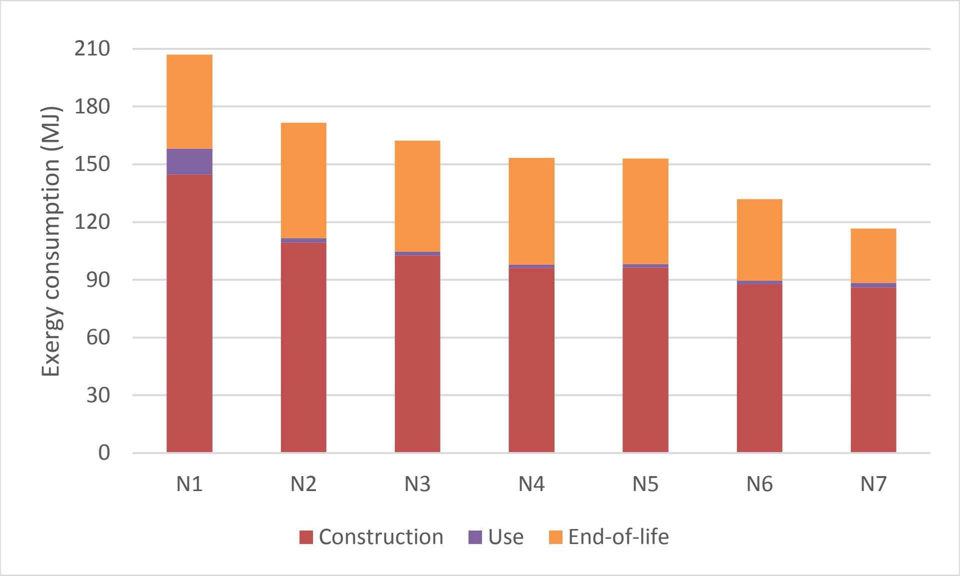


FIG 4.2 NEIGHBORHOOD EXERGY CONSUMPTION BY LIFE CYCLE STAGE

4.4 Conclusions

Exergy analysis (ExA) is a useful tool to evaluate the environmental load related to RWH systems in neighborhood scenarios, also to identify the stage with the highest resource consumption and that is especially useful in finding potential for improvement in energy savings and material consumption reduction.

ExA has also been a useful tool to detect the most resource consuming inputs in the RWH system. Two inputs have been spotted as the highest resource consumers in the lifetime of the system: Pipes and accessories and construction services.

As expected, the scenario with the higher neighborhood housing area is the one with major exergy consumption, this is especially affected for the construction and use stage. Furthermore, the end-of-life stage is comparatively smaller than in the rest of neighborhoods, except for N7.

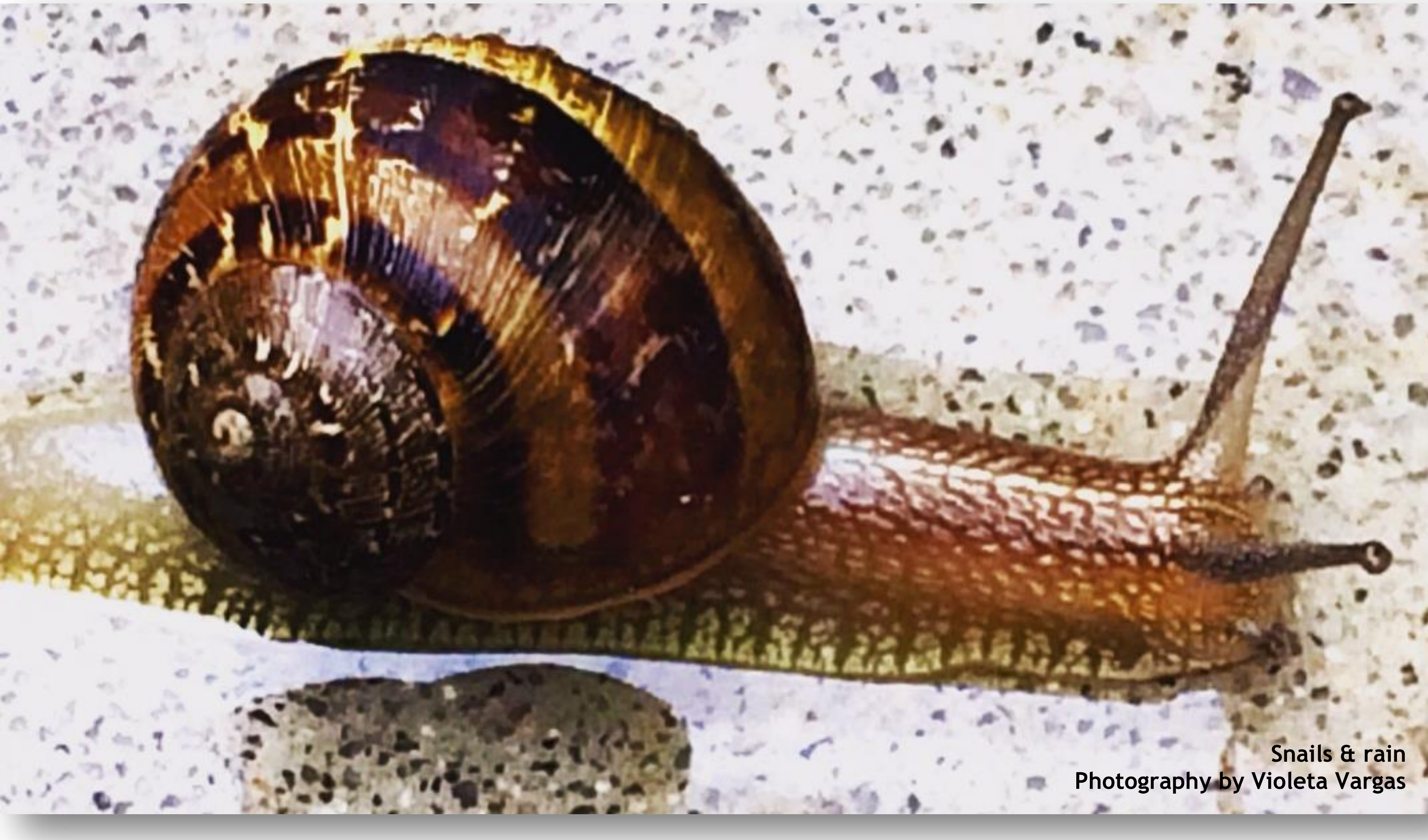
Scenario N7 is the most efficient scenario with 307 buildings, 11,062 households and a 5,000 m^3 storage tank. N7 supplies 70,335 m^3/year fulfilling almost 50% of the water demand.

Part III.

Economic and environmental analysis

5

Cost effective analysis in buildings



Snails & rain
Photography by Violeta Vargas

Chapter 5 Cost effective analysis in buildings.

based on the following paper: M. Violeta Vargas-Parra M. Rosa Rovira-Val, Xavier Gabarrell and Gara Villalba, “Cost-Effective Rainwater Harvesting System in the Metropolitan Area of Barcelona,” Journal of Water Supply: Research and Technology—AQUA 63, no. 7 (April 9, 2014): 586–595, doi:10.2166/aqua.2014.108.

Abstract

Expected population growth will result in increasing water demand. The consequences could potentially jeopardize water resource availability especially in urban areas and significantly increase costs. Rainwater harvesting (RWH) systems can aid not only in meeting water demand partially, but also doing so in a more cost-effective and environmentally-friendly manner than other techniques. Although the reduction of environmental burdens is fairly obvious, the question for urban planners and consumers remain: are RWH systems economically feasible?

This paper investigates cost-effectiveness of eight different scenarios in the Metropolitan Area of Barcelona. To do so, monetary investment is quantified to provide rainwater for laundry purposes. Results indicate that High Density scenarios are financially the most suitable choices (higher Net Present Value and shorter Payback time) given that: more users mean more savings from laundry additive consumption.

Further studies should consider which are the variables that have a greater effect on the financial appraisal. Just as inflation rate, specific attention should be paid to the costs associated to the storage tank location. And, on the savings side, include the no tap water consumption effect on the water bill, along with special attention to tap water prices in the area of study.

6

LCA and LCC in buildings

Gaudi Puddles
Photography by Paco Zotto

Chapter 6 LCA and LCC in buildings.

based on a manuscript by: M. Violeta Vargas-Parra, M. Rosa Rovira-Val, Gara Villalba and Xavier Gabarrell.

Abstract

Due to population growth in cities, urban water demand is expected to increase significantly, as well as the environmental and economic costs required to supply it. Rainwater harvesting (RWH) systems can play a key role in helping cities meet part of their water demand as an alternative to conventional water abstraction and treatment. However, the economic feasibility and the environmental impact of RWH system implementation are not always clear. This paper presents an environmental and economic analysis of RWH systems used to provide households with water for laundry purposes in a life cycle thinking perspective.

Eight urban RWH system scenarios are defined with varying population density and storage tank layout. Storage tank volume required was calculated using Plugrisost software, based on Mediterranean precipitation and catchment area, as well as water demand for laundry. Life cycle assessment (LCA) and Life cycle costing (LCC) methodologies are applied for this study. Environmental impacts were obtained using the ReCiPe 2008 (hierarchical, midpoint) and the cumulative energy demand methods. Net present value (NPV), internal rate of return (IRR) and payback time (PB) were used in LCC.

LCA results indicate that the best scenario is the one consisting of a building with the tank spread on the roof (HD3), providing up to 96% lower impacts than the rest of scenarios considered. These results are mainly related to the absence of pumping energy consumption and greater ratio of rainwater collection to storage tank capacity. Furthermore, avoided environmental impacts from the reduction in detergent use are more than 20 times greater than the impacts generated by the RWH system. LCC indicates that RWH system in clusters of buildings or home apartments offer up to sixteen times higher profits than individual installations. RWH systems in clustered scenarios have higher NPV, higher IRR and lower PB periods. Another important finding is that 80% of the savings come from the reduction of detergents and other additives avoided by the use of soft rain water. Both studies, LCA and LCC, present better results for high density scenarios. In addition to this and the most surprising finding is that the avoided environmental and economic impacts from detergent reduction clearly surpass environmental impacts (in all categories except terrestrial acidification) and economic cost of the RWH system in most cases (except LD1 and LD3). Moreover, three variables were evaluated through a sensitivity analysis: variations in the inflation rate, climate change effect on precipitation and tap water price increment.

6.1 Introduction

Water has limited availability although it is a renewable resource. Less than one percent of fresh water resources is usable for ecosystems and human consumption (World Water Assessment Programme (WWAP) 2006; United Nations Environment Programme (UNEP) 2007). During the XX century, global water consumption has increased at twice the rate of population growth (Food and Agriculture Organization of the United Nations (FAO) 2012). Moreover, "water stress" (European Environment Agency 2014) will be further intensified due to climate change. For example, precipitation of the Mediterranean area of southern Europe is expected to decrease 5% by 2020 in comparison with the climatology of 1979-2001 (Met Office Hadley Centre for Climate Change 2009). Accordingly, higher water supply vulnerability is expected in urban areas (The World Bank 2009; Leflaive 2012; World Water Assessment Programme (WWAP) 2012).

Water resource management is an essential component for the sustained development of society and economy (United Nations Development Programme 2006) and the unsustainable exploitation of this resource represents an increasing threat for human development (World Water Assessment Programme (WWAP) 2009). Furthermore, water depends on energy for treatment and distribution, and energy depends on water in all phases of energy production and electricity generation (also known as the water-energy nexus) that further accentuates the need for a more sustainable water management.

Rainwater harvesting (RWH) could help lower environmental and economic burdens, especially in urban areas where meeting water demand will be more energy and costly. Aside from dissolved carbon dioxide or dust, rainwater contains no dissolved minerals, and hence, it is normally softer than surface or groundwater (WHO, 2008) and even tap water (Farreny et al., 2011b; Rygaard et al., 2011a, 2011b, 2010). Since rainwater contains a low concentration of minerals, such as calcium and magnesium, it is ideal for laundry use in areas with high levels of water hardness and/or limited water availability because soft water requires less detergent, softener and machinery maintenance. For example, tap water in Barcelona has a significantly high level of hardness at 315 ppm (AGBAR, 2013) which results in heavy use of detergents. For all these reasons, RWH can potentially become a fundamental contributor towards urban water self-sufficiency (Rygaard et al. 2011b; Fragkou et al. 2015).

Several studies have determined significant advantages for RWH for the metropolitan area of Barcelona, a Mediterranean climate city of 2 million people. Farreny et al. (2011b) determined that the physicochemical quality of rainwater is comparable to that of tap water. A life cycle assessment quantified the avoided impact of Global Warming Potential (GWP) when rainwater substitutes main water treatment and distribution (Angrill et al. 2011). In another study by Farreny, the cost-efficiency of RWH systems was evaluated in a dense neighborhood in a city near Barcelona (Granollers) concluding that RWH systems should be installed at the neighborhood level, since it enables economies of scale (Farreny et al. 2011a). In Greater Sydney, Australia, (Rahman et al. 2012) financial viability was explored for single-family detached homes. However, none of the studies includes the savings on detergent consumption during the lifetime of the system. This work aims to fill this research gap by performing a Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) of a RWH system as an alternative supply of domestic laundry water. The metropolitan area of Barcelona serves as the case study for the analysis, but eight different scenarios varying in population density and tank location are used in order for the study to have applicability to other urban systems.

6.2 Methodology

The LCA methodology used is the ISO 14040 (ISO 2006). And life cycle impact assessment (LCIA) results are calculated at midpoint level using ReCiPe (Goedkoop et al. 2013) and cumulative energy demand methods for each life cycle stage for selected impact categories Climate Change (CC; kg CO_2 eq), Ozone Depletion (OD; kg CFC-11 eq), Terrestrial Acidification (TA; kg SO_2 eq), Freshwater Eutrophication (FE; kg P eq), Photochemical Oxidant Formation (POF; kg NMVOC), Particulate Matter Formation (PMF; kg PM10 eq) based on the ReCiPe hierarchical midpoint characterization approach and the single method Cumulative Energy Demand (CED; MJ).

The economic analysis is based on the LCC methodology as described by ISO 15686-5 (ISO 2008) according to which, different financial techniques or indicators may be used in LCC (ISO 2008) depending on the requirements of the investors. Nevertheless, Net Present Value (NPV) is considered a standard criterion to decide if an option can be justified on economic principles.

NPV (Euros) is the sum of the discounted future cash flows, defined as the difference between the present value of inflows and outflows and determines the current value of the initial investment and all future incomes/outcomes over the 50 years of lifespan of the system (Equation 6.1).

$$\boldsymbol{NPV = -I + \sum_{i=0}^{T} \frac{C_i}{(1+r)^i}} \qquad \text{EQUATION 6.1}$$

Where:

I = Initial cost or initial investment.

C_i =Cash flow at year i. (cash inflows minus cash outflows at year i)

r = Discount rate.

p =The value of discounted cash flow at which the first positive value of discounted cumulative cash flow occurs.

n =The value of discounted cash flow at which the last negative value of discounted cumulative cash flow occurs.

y_i =The number of years after the initial investment at which last negative value of discounted cumulative cash flow occurs.

Cumulative cash flow= $\sum_i^T C_i$

Another, commonly applied financial tool is the internal rate of return (IRR, %) , that appraises how financially attractive the investment of each scenario is by indicating the rate at which NPV becomes zero as is expressed by Equation 6.2.

$$\boldsymbol{NPV = \sum_{i=0}^{I} \frac{C_i}{(1+r)^i} = 0} \qquad \text{EQUATION 6.2}$$

The payback period (PB, years) gives an estimate of the time required to recover the cost of investment. It is calculated based on the number of years elapsed between the initial investment, its subsequent cash outflows and the time at which cumulative cash inflows offset the investment (Equation 6.3).

$$\boldsymbol{PB = \frac{(p-n)}{p} + y_i} \qquad \text{EQUATION 6.3}$$

In this study we consider an inflation rate of 3%, given by the International Monetary Fund (IMF) (IMF, 2012) during a lifetime of 50 years and a discount rate of 4% published by the National Bank of Spain (Banco de España, 2013).

Potential rainwater supply and storage tank size were calculated using Plugrisost®, a free simulation model developed by Gabarrell et al. (2014), which evaluates the RWH potential and environmental impact of different water supply alternatives for urban use. The model estimates the potential rainwater supply based on historical daily rainfall statistics from 1991 to 2010 for Barcelona (Catalonia Meteorological Service (SMC) 2011), a roof-runoff coefficient of 0.9, and the catchment area defined in Table 6.1 for each scenario. Storage tank sizing calculations are a function of water demand of 25 m^3 per year per household.

6.3 System boundaries

The LCA and LCC are based on a cradle-to-grave approach as depicted by Figure 6.1. The construction stage includes the energy (including transport) and materials required for the fabrication and installation of the RWH system, which can have three different rainwater storage configurations: a) underground, b) top floor but inside the building, and c) the entire roof area. More details about the various catchment configurations are available in Table II.1 and Table II.2 in the Appendix II.

The use stage considers the use and maintenance of the system during its entire lifetime. Based on the durability of the materials and machinery employed, the lifetime for the RWH system considered in this study is 50 years. Materials with shorter lifetimes require replacements. Normally the use stage is less material-intensive than the construction phase, but still requires some materials due to maintenance and energy. Also, laundry detergents and other additives are included in this stage for the 50-year period.

At the end of 50 years, the end-of-life (EOL) stage includes the energy and materials required for the dismantling of the system and transport of the materials to a waste management plant. Recycling or final disposal of the used materials is not considered as part of the system under study.

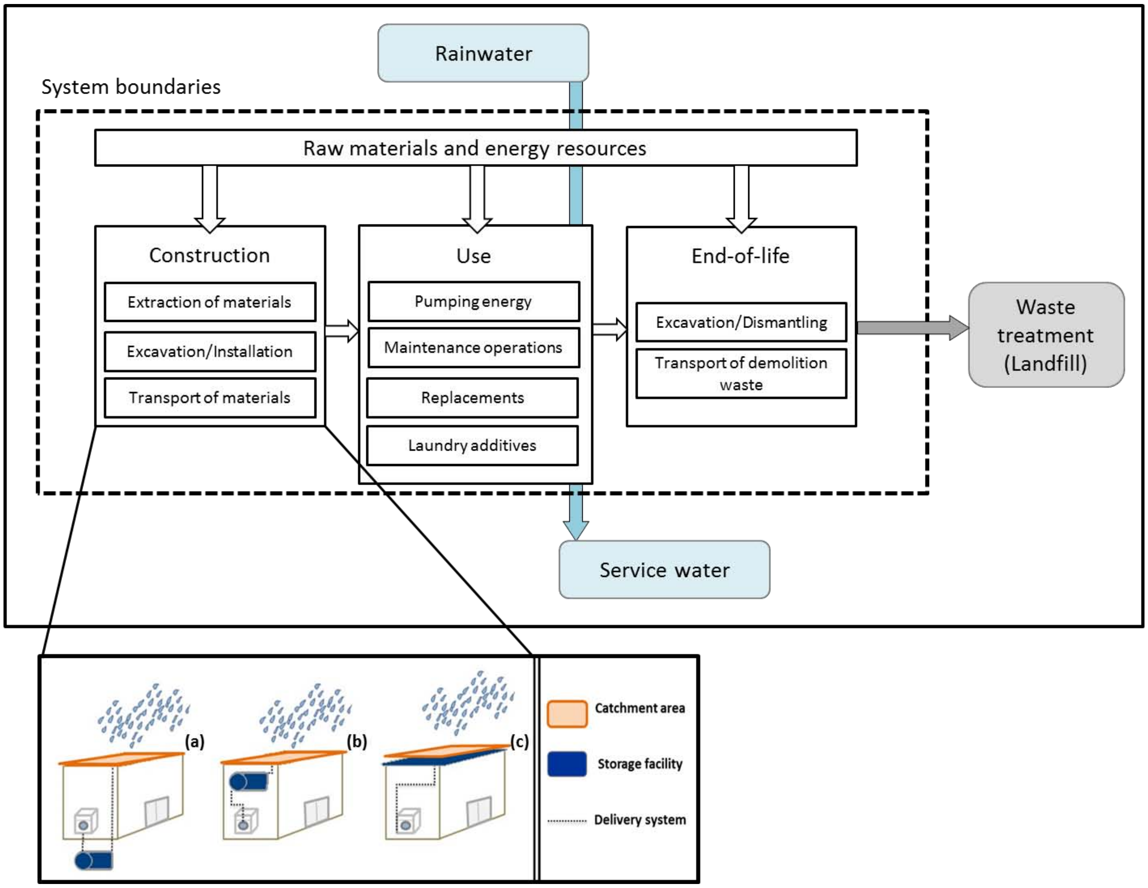


FIG. 6.1 RWH SYSTEM BOUNDARIES AND BASIC COMPONENTS WITH THREE DIFFERENT STORAGE POSITIONS.

6.3.1 Functional unit

The functional unit is 1 m^3 of rainwater supplied for domestic laundry purposes. Since NPV, IRR and PB are project-oriented financial tools, these were first calculated based on the construction, use and dismantling of a RWH system as a unit. Subsequently, results were divided by the amount of water supplied, in order to obtain the same functional unit: 1 m^3 of rainwater supplied for domestic laundry purposes.

6.3.2 Goal and scope

As illustrated by Figure 1, domestic RWH systems are commonly composed of three main parts, namely: a catchment area, which is placed on the rooftop for all cases considered in this study; a storage facility (it can be installed underground or aboveground); and a delivery system to transport the rainwater from the catchment area to the storage facility and also from the storage facility to the building, and in this case, directly to the laundry machine within the building.

Urban areas are understood as territorial units with a large number of inhabitants living mostly in built-up areas which may include villages and towns in rural districts (Eurostat 2013). European Union (EU) regions population density ranges from 21 464 inhabitants/km^2 (Paris, France in 2011) to 10 inhabitants/km^2 (Soria, Spain in 2011) (Eurostat 2014a) and within regions and cities, population density can also vary amongst neighborhoods. To represent urban areas, two densities are proposed: 1) low density of 10 inh/km^2 (LD) and 2) high density of 63,600 inh/km^2 (HD). The LD model considers a single-family home with a 250 m^2 rooftop (catchment area) (Figure 6.2a and 6.2b). The HD model considers a five-story building with 24 home-apartments with 700 m^2 of catchment area (Figure 6.2c and 6.2d). For each density model, we consider several scenarios, which vary in the location of the storage; as was shown in Fig. 6.1, for LD the storage can be underground, below or above the roof. These three scenarios are represented by Figure 6.2, where the catchment area and volume of collected rainwater is the same. A fourth scenario of a cluster of four LD houses with the tank installed underground is also included (Figure 6.2b), which has a larger catchment area and consequently greater rainwater collection. Similar scenarios are created for HD, for a single building (Figure 6.2c) or for a cluster of buildings (Figure 6.2d).

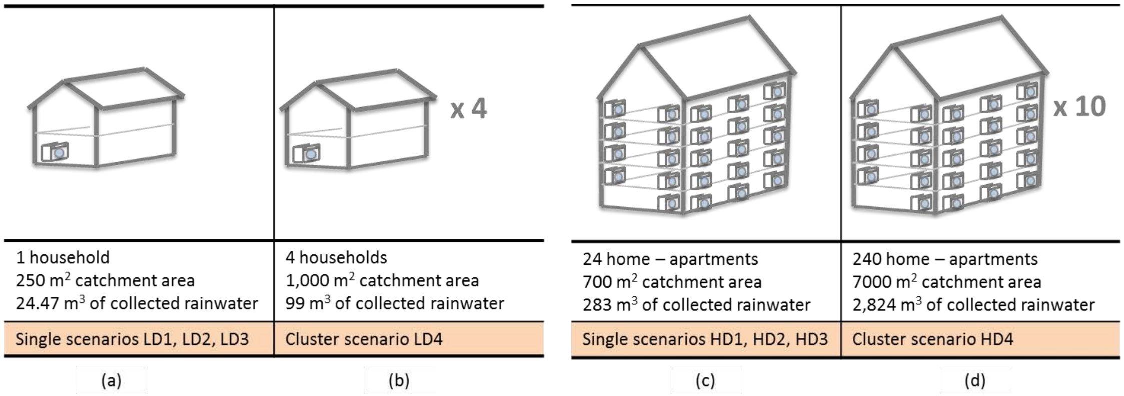


Fig. 6.2 Low and High density models: (a) and (c) single scenarios; (b) and (d) cluster scenarios. Adapted from: (Vargas-Parra et al. 2013b)

Table 6.1 summarizes the eight different scenarios, showing the two density models, storage size and location, and the relation between the provided rainwater and the laundry needs of each household.

TABLE 6.1 SCENARIOS DESCRIPTION.

Scenario	Construction type	Scale		Tank size (m^3)	Tank layout	Catchment area (m^2)	Rainwater supply (m^3/year)	Laundry demand (m^3/year)	Rainwater supply / Laundry demand
LD1	Individual	1 Household		5	Underground	250	24.5	25	98%
LD2				5	Below roof	250	24.5	25	98%
LD3				9	Spread on roof	250	24.5	25	98%
LD4	Cluster	4 Household		20	Underground	1000	99	100	99%
HD1	Individual	1 Building	24 households	20	Underground	700	283	600	47%
HD2				20	Below roof	700	283	600	47%
HD3				21	Spread on roof	700	283	600	47%
HD4	Cluster	10 Buildings	240 households	209	Underground	7000	2824	6000	47%

6.4 Data

6.4.1 Life Cycle Inventory

Inventory data for the environmental assessment was obtained from several sources. Material and energy requirements for each life cycle stage were gathered from the publicly available data from the project PLUVISOST (Angrill et al. 2011). Material and processes were selected from Ecoinvent 3. Table 6.2 presents the input data per functional unit considered in the environmental assessment.

TABLE 6.2 INVENTORY OF MATERIALS AND ENERGY PER FUNCTIONAL UNIT.

Stage	Short name	measuring unit	LD1	LD2	LD3	LD4	HD1	HD2	HD3	HD4
Construction	Recycled wood formwork	m^3	1.05E-03	7.66E-04	0.00E+00	6.36E-04	2.29E-04	1.64E-04	0.00E+00	1.07E-04
	Concrete CEM II/A-L 32.5R	m^3	3.47E-03	4.81E-03	3.36E-03	3.05E-03	1.11E-03	1.11E-03	1.28E-03	1.03E-03
	Steel frame	kg	3.22E-01	6.54E-01	1.03E-01	2.38E-01	2.33E-01	2.33E-01	2.29E-02	9.24E-02
	Waterproofing sheet	kg	0.00E+00	0.00E+00	4.25E-02	0.00E+00	0.00E+00	0.00E+00	1.52E-02	0.00E+00
		kg	0.00E+00	0.00E+00	4.25E-02	0.00E+00	0.00E+00	0.00E+00	1.52E-02	0.00E+00
	Brick	kg	0.00E+00	0.00E+00	3.37E-01	0.00E+00	0.00E+00	0.00E+00	6.83E-02	0.00E+00
	Mortar lining	kg	0.00E+00	0.00E+00	4.05E-02	0.00E+00	0.00E+00	0.00E+00	8.20E-03	0.00E+00
	Polypropylene	kg	3.04E-03	2.35E-03	2.35E-03	2.03E-02	7.08E-03	4.10E-03	4.10E-03	1.31E-02
	Stainless Steel	kg	1.93E-02	0.00E+00	0.00E+00	9.54E-03	7.35E-03	0.00E+00	0.00E+00	1.47E-03
	Diesel	kg	2.69E-02	0.00E+00	0.00E+00	1.11E+00	4.01E-01	0.00E+00	0.00E+00	6.15E-01
	Transport lorry 7.5-16 tons	tkm	2.60E-01	3.67E-01	2.59E-01	2.28E-01	8.74E-02	8.73E-02	9.63E-02	7.77E-02
Use	Electric power	kWh	4.90E-01	0.00E+00	0.00E+00	9.70E-01	4.90E-01	0.00E+00	0.00E+00	8.40E-01
EOL	Diesel	kg	1.97E-02	4.79E-01	2.39E-01	6.68E-01	2.34E-01	1.53E-01	8.67E-02	5.91E-01
	Transport lorry 7.5-16 tons	tkm	4.56E-01	6.42E-01	4.54E-01	3.99E-01	1.53E-01	1.53E-01	1.69E-01	1.36E-01

6.4.2 Cost data

Data on cost of materials, labor, tools and equipment were obtained from three different sources: (i) The Technology of Construction of Catalonia Institute database (ITeC 2012), (ii) the Guadalajara's mid-level Architecture official college database (Colegio Oficial de Aparejadores 2012) and (iii) internet catalogues were consulted for tank and pump prices (AGUADELLUVIA 2012; Baeza Group 2012; EBARA 2012; GRAF Ibérica 2012; HASA 2012; REMOSA 2012; SACI 2012). Furthermore, the costs were validated by a senior professional of water installations in Barcelona. Table 6.3 shows the description and general cost of the items considered in each life cycle stage: construction, use, and EOL. Table II.1 in the Appendix II contains the inventory of all costs considered for each scenario.

TABLE 6.3 ITEM DESCRIPTION AND COST IN EUROS.

CONSTRUCTION STAGE		**LD1**	**LD2**	**LD3**	**LD4**	**HD1**	**HD2**	**HD3**	**HD4**
Storage tank	Different capacities of prefabricated tanks for scenarios LD1, LD2, LD4, HD1, HD2, HD4. For scenarios LD3 and HD3 all necessary materials to construct and install the tank distributed over the roof.	2,083	2,083	2,288	5,670	5,670	5,670	9,355	60,155
Emplacement materials	Sand from recycled materials, waterproofing sheet, steel frame to reinforce structure.	29	0	3,356	58	58	0	13,172	116
Polypropylene pipes	Polypropylene copolymer PP-R 25 mm y 4.2 mm S 2.5	66	51	51	1,774	307	156	156	4,987
Pump	Multi-stage, integral, centrifugal, horizontal electric pumps	500	0	0	500	500	0	0	500
Filters	Universal external filter strainer with DN 100 inlet ring	390	390	390	390	390	390	39	390
Construction services	Manpower for excavation, installation and dirt transportation	310	186	40	623	640	329	44	4,316
Transport of materials	Transport of the materials from industry to site of construction <30 km.	60	0	0	239	251	0	0	2,502
USE STAGE		**LD1**	**LD2**	**LD3**	**LD4**	**HD1**	**HD2**	**HD3**	**HD4**
Electricity (yearly)	Electricity consumption for pumping water. Prices from http://www.energy.eu/ consulted in 2013	123	0	0	989	6,113	0	0	12,226
Pump replacement (every 10 years)	Multi-stage, integral, centrifugal, horizontal electric pumps	500	0	0	500	500	0	0	500
Filter replacement (every 5 years)	Universal external filter strainer with DN 100 inlet ring	390	390	390	390	390	390	390	390
Maintenance services (every 5 years)	Cleaning tank and filter, and replacement of pump and filter when necessary	134	38	38	153	152	57	57	171
END OF LIFE STAGE		**LD1**	**LD2**	**LD3**	**LD4**	**HD1**	**HD2**	**HD3**	**HD4**
Deconstruction services	Manpower for excavation and dismantling	858	870	1,515	3,374	3,538	3,538	6,311	34,903

6.4.3 Costs and savings by life cycle stages

Construction stage costs

This stage considers, what in financial terms would be, the initial costs, including all the necessary materials and labor costs associated to construct and install a RWH system in Barcelona. Table 6.3 describes the items considered as inputs to the system. Each scenario requires a different amount and configuration of these items; details and costs are available in Table II.1 in the Appendix II.

Use stage costs and savings

The use stage considers the maintenance and replacement costs, associated to the operation of the RWH system during its lifespan. In our study, an examination of all the costs associated to the suitable performance of the facilities during their lifetime was considered (Table 6.3). These costs include the electricity for pumping water on a yearly basis (necessary for scenarios where the tank is installed underground) as well as the equipment and material replacements necessary to keep the system in proper operating conditions, i.e. replacement of the pumps and filters every ten and five years respectively, as well as the labor costs associated to this activities.

During the use stage, two different aspects are considered in the calculation of savings. First, using soft rain water reduces the amount of detergent, fabric softeners, and de-calcifying additives, thereby reducing the cost of doing laundry. Based on the prices of more than ten brands of each product available in supermarkets in Barcelona in 2015, we calculated the following averages: detergents 0.24 euros per dose, fabric softeners 0.06 euros per dose and water softeners 0.42 euros per dose (65 ml per dose). The second aspect contributing to the savings is the reduction in tap water consumption for laundry. The average cost of tap water in Spain in 2014 was 1.7 Euros/m^3 (RTVE 2014) .

Water demand for laundry was calculated at 25 m^3 per year and household, considering an average of 96 liters per washing. The doses of additives are those recommended by the manufacturer for the different ranges of water hardness. Barcelona’s tap water is considered hard (315 ppm), and the doses are 1.59 detergent, 1 water softener, and 1.59 fabric softener.

End-of-life costs

The costs associated with the dismantling of the facilities are taken into account, including the transportation costs as well as the labor necessary for excavation and dismantling. The deconstructed materials (rubble) are sent to a waste management plant located at a maximum distance of 50 km from where it was installed.

6.5 Results

6.5.1 Environmental Impacts

Environmental analysis results are presented in Figure 6.3 for all eight scenarios for selected impact categories Climate Change (CC; kg CO_2 eq), Ozone Depletion (OD; kg CFC-11 eq), Terrestrial Acidification (TA; kg SO_2 eq), Freshwater Eutrophication (FE; kg P eq), Photochemical Oxidant Formation (POF; kg NMVOC), Particulate Matter Formation

(PMF; kg PM10 eq) based on the ReCiPe hierarchical midpoint characterization approach and the single method Cumulative Energy Demand (CED; MJ).

The best environmental performer is scenario HD3 (Figure 6.3) for all impact categories except for OD, where scenario HD2 has the lowest impact due to the tank that in HD3 is distributed over the roof and that requires a waterproofing foil that no other scenario uses.

Within low density scenarios, LD1 is the best option, mainly due to two facts: First, because as the tank is smaller than LD3 and LD4, the disposal of rubbish material is proportionally lower, comparing a 5 m^3 tank to a 9 and 20 m^3 tanks respectively. And second, because even though it has energy consumption during the installation of the tank underground, the impacts of reinforcement materials in LD2 are higher than those of the energy needed to install the tank underground.

The highest impacts within low density scenarios are given by scenario LD3 for five out of the seven categories (CC, OD, TA, POF and PMF), this is because this scenario requires reinforcement materials and waterproofing materials to have the tank spread on the roof. On the other hand, for high density scenarios, the least favorable scenario is HD1 mostly due to energy consumption during the use stage for pumping water to a five-story building.

Scenarios with no needs for pumping the rainwater (i.e. LD2, LD3, HD2 and HD3) concentrate 90% of their environmental impacts on the construction stage. The other four scenarios LD1, LD4, HD1 and HD4 which need pumping during the use stage shift 70% of their impacts to the construction stage. Thus, approximately 20% of the overall impacts are associated to the energy consumption required for pumping. Table II.2 in the Appendix II shows all environmental impact results for the eight scenarios by life cycle stage.

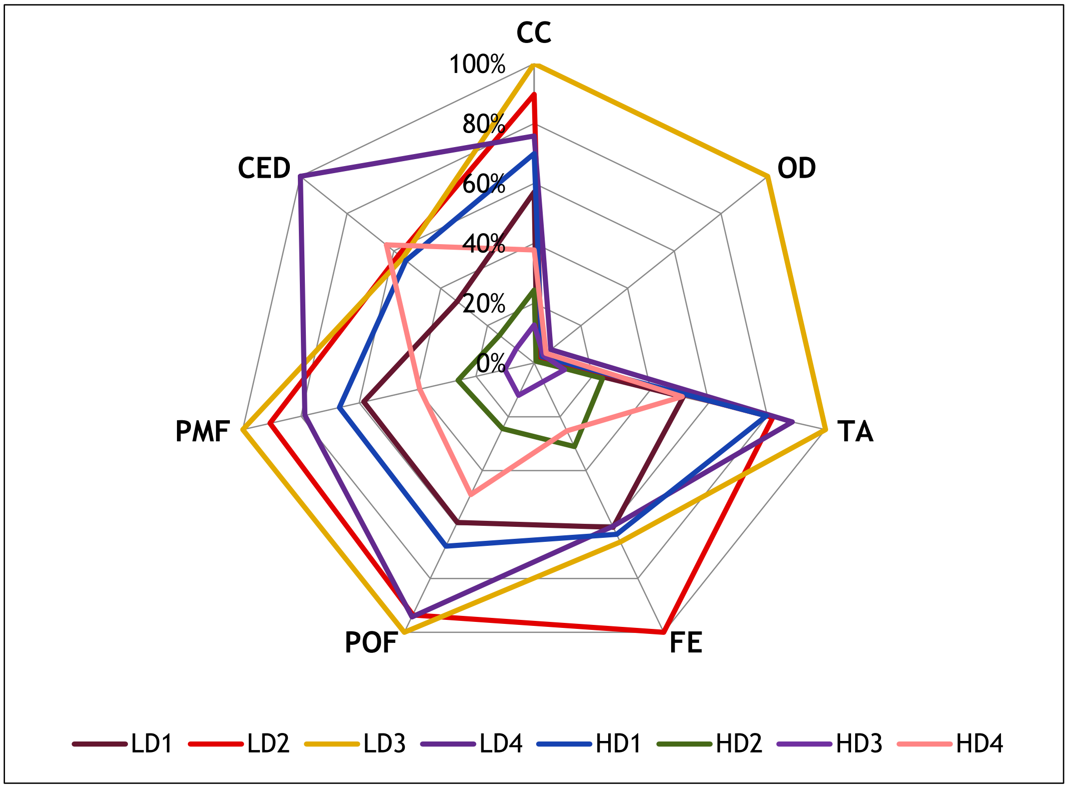


FIG 6.3 COMPARISON OF ALL EIGHT SCENARIOS

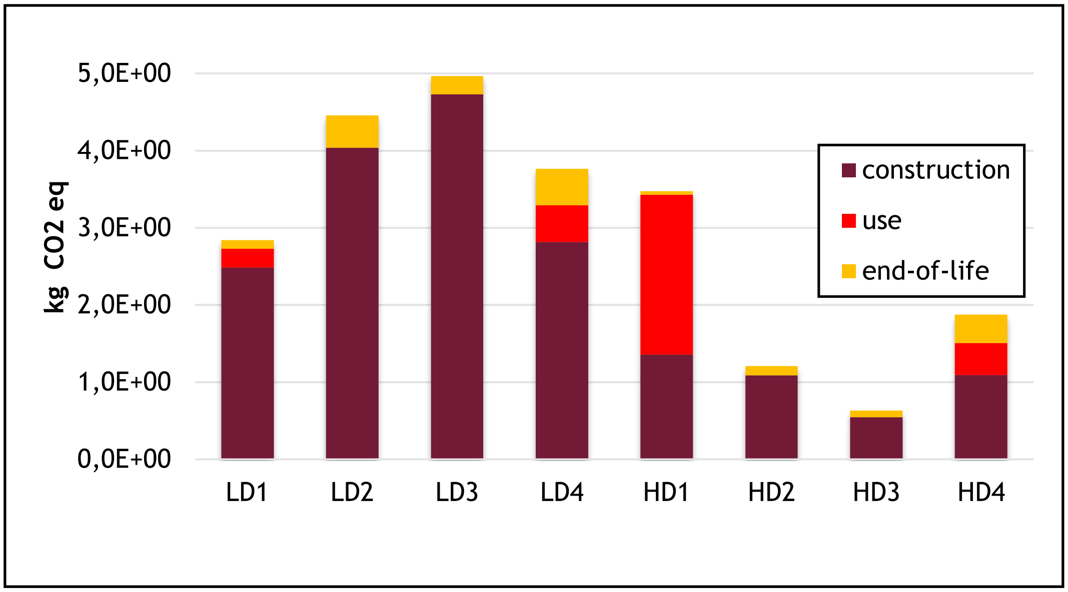


FIG 6.4 RESULTS IN CLIMATE CHANGE IMPACT CATEGORY AND LIFE CYCLE STAGE CONTRIBUTION FOR EACH SCENARIO.

HD3 presents the best environmental performance for almost all impact categories except for OD, with no needs for pumping the total impact is reduced significantly, between three to seven times lower impacts than scenarios HD1 and HD4. Figure 6.4 represents the environmental performance of almost all categories for the eight scenarios by life cycle stage. Contrarily, LD3 presents the highest environmental impacts in five out of seven categories (CC, OD, TA, POF and PMF). In scenarios LD3 and HD3 construction stage is responsible for more than 80% of the total impact and this is due to construction materials, specifically the waterproofing sheet that contains PVC and fiberglass (both materials have high environmental costs). The difference between these two scenarios is the volume of water that can be collected in each. HD3 requires double the amount of waterproofing sheet than LD3, but is able to collect more than ten times more rainwater, resulting in lower impacts per functional unit (cubic meter).

Furthermore, worst low density scenario (LD3) is notoriously affected by the production stage, particularly by the waterproofing sheet used for the storage tank that in this scenario is spread on the roof. Then, for the best low density scenario (LD1), even though production stage still is 80% of the total CC impact, the impact in all categories for this scenario is about half of those on LD3 and up to 30% of the other two low density scenarios, this is because the tank is smaller in LD1 than the other low density scenarios, it does not use the waterproofing sheet and the energy for pumping rainwater is not as high as in LD4.

In high density scenarios, worst environmental outcome for most of the categories is given by scenario HD1, except for categories OD and CED, this is mainly due to impacts related to energy consumption during the stage of use where electricity is required for pumping. As can be seen in Figure 6.4, approximately 60% of the total CC impact is given by the stage of use.

6.5.2 Avoided impacts

As a result of the difference in water hardness between Barcelona’s tap water and rainwater, the consumption of laundry detergent and other additives can be reduced significantly. In this section, environmental impacts avoided by the reduction in laundry detergent consumption are assessed.

Inventory data was obtained from P&G detergent (Saouter and Hoof 2002).Table 6.4 presents the input data per cubic meter of water for laundry purposes.

TABLE 6.4 DETERGENT INVENTORY PER CUBIC METER.

gr	Input
147.9	Water
2.1	Fluorescent whitening agent, DAS1
177.1	Sodium percarbonate
119.8	Sodium perborate, tetrahydrate
90.6	Sodium perborate, monohydrate
209.4	Zeolite

31.3	Layered sodium silicate, SKS-6
20.8	Ethoxylated alcohol (AE11)
41.7	Ethoxylated alcohol (AE7)
81.3	Alkylbenzene sulfonate
5.2	Fatty alcohol sulfate
4.2	Sodium sulfate, anhydrite
41.7	EDTA, ethylenediaminetetraacetic acid

Avoided environmental impacts were calculated per cubic meter of water used for laundry purposes. Detergent dosage is 1 dose per load for soft water and 1.59 for hard water, the difference between these two are the savings in laundry detergent, since rainwater is consider as soft water.

Table 6.5 presents the environmental impacts that were avoided when using rainwater instead of Barcelona's tap water. Subtracting these impacts from the environmental impacts of the RWH system, environmental impacts are significantly reduced. In the best case scenario, impacts are reduced more than two times (HD3) in all impact categories.

TABLE 6.5 AVOIDED ENVIRONMENTAL IMPACTS FROM SAVINGS IN DETERGENT PER CUBIC METER AND FOR SCENARIOS LD1 AND HD3.

Impact	per m^3	LD1	HD3
Climate change	1.45E+00	3.54E+01	4.09E+02
Ozone depletion	3.54E-05	8.68E-04	1.00E-02
Terrestrial acidification	1.33E-02	3.25E-01	3.76E+00
Freshwater eutrophication	1.71E-01	4.19E+00	4.85E+01
Photochemical oxidant formation	5.35E-03	1.31E-01	1.51E+00
Particulate matter formation	1.07E-07	2.63E-06	3.04E-05
Cumulative Energy Demand	2.56E+01	6.27E+02	7.25E+03
Cumulative Exergy Demand	2.86E+01	6.99E+02	8.09E+03

6.5.3 Life cycle cost results

Results are grouped in Table 6.6 by Low density (LD) and High density (HD) scenarios, further disaggregated by position of storage area and also by single construction or a cluster construction according to the scenarios summarized in Table 6.1. Results show that all HD scenarios (single and cluster construction) are economically feasible and result in positive Net Present Value (NPV). The HD scenarios also have higher Internal Rate of Return (IRR) than all LD scenarios and have a payback period (PB) of less than 3 years, except for the single building HD scenario with roof storage (HD3), which is 9 years. High density cluster scenario (HD4) is the best overall performer because it offers the highest NPV, a high IRR and the shortest PB.

For Low density scenarios, only LD2 and LD4 have positive NPVs. However, results show elevated PB of 17 and 12 years, resulting less desirable investment projects than HD but still viable options. Contrary to this, LD1 and LD3 with negative NPV are not viable.

TABLE 6.6. NPV, IRR, AND PB FOR LOW DENSITY AND HIGH DENSITY MODELS.

		Financial analysis		
		NPV (Euros)	IRR* (%)	PB* (years)
Low density scenarios				
Individual construction	LD1	- 1,800.1		-
	LD2	1,045.9	2.5%	21.23
	LD3	- 2,794.4		-
Cluster construction	LD4	12,603.9	6.0%	14.40
High density scenarios				
Individual construction	HD1	66,192.6	31.3%	2.9
	HD2	74,694.1	45.8%	2.1
	HD3	56,302.0	9.2%	10.4
Cluster construction	HD4	753,896.5	37.8%	2.6

* When the investment project does not overcome the initial expenses, the project has a negative NPV and IRR and PB cannot be calculated.

The cluster construction scenarios for both low and high density (LD4 and HD4) have the highest cumulative cash flows as illustrated by Figure 6.5. Figure 6.5 also illustrates how cluster scenarios compensate initial investment faster and with higher cumulative cash flows at the end of the study even after having a slight decrease due to the dismantling costs.

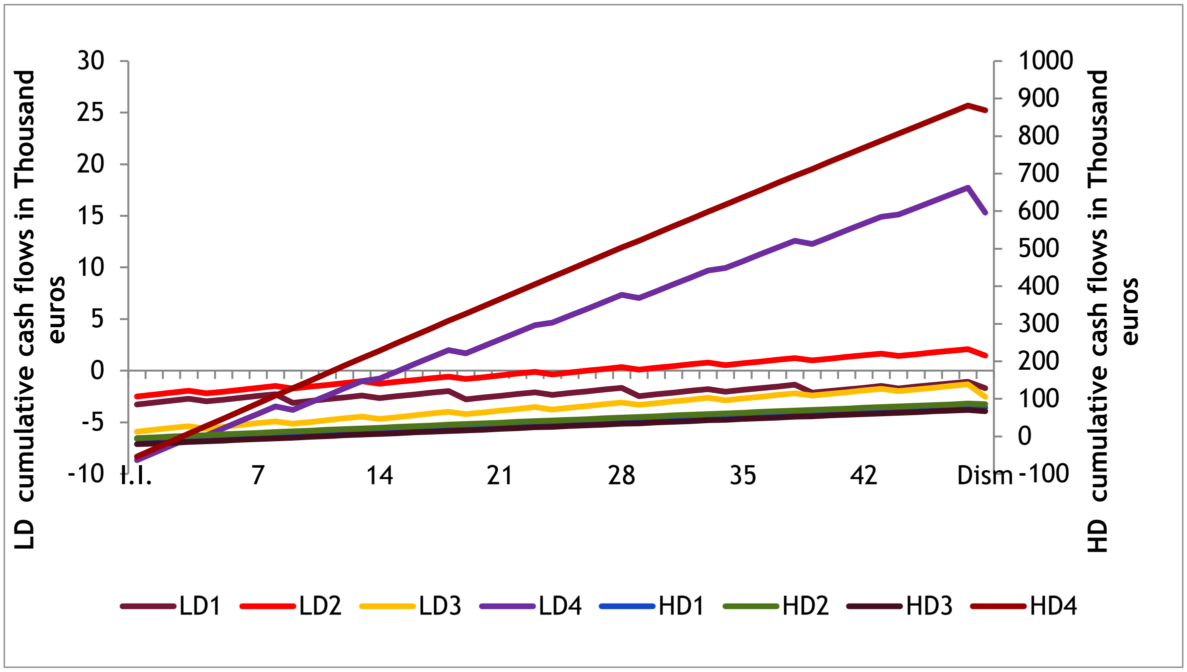


FIG 6.5 CUMULATIVE CASH FLOWS (50 YEARS) FOR LD AND HD SCENARIOS.

These results clearly indicate a preference for a large number of users given by the cluster scenarios in both low and high density models (LD4 and HD4). Infrastructures should be used to the maximum to get the maximum advantages of it. This is due to the fact that the costs associated to the construction and use phase for single building scenarios, are higher (on a per-m^3 basis) than for the cluster scenarios. For example, the cost of waterproofing materials in scenarios LD3 and HD3 is highly elevated, causing NPV to decrease up to 130% in regard to scenario LD4. Scenarios where the tank is installed underground (LD1 and HD1) result in high costs related to the electricity required for pumping and the replacement and maintenance of the pump, decreasing cumulative cash flows in an average of 80% compared to scenarios with the same amount of users and savings, as LD2 and HD2.

Moreover, 80% of the savings are achieved by minimizing, from 1.59 doses to 1 dose per laundry, the consumption of detergent, fabric conditioner and water softener, and the remaining 20% comes from replacing the tap water consumption for laundry purposes.

The life cycle approach taken by this study is especially useful in quantifying the contribution of costs and savings during the entire lifetime of the infrastructure. This is illustrated by Figure 6 for the cluster scenarios which were the best performers in terms of the financial indicators discussed above. During use stage, costs due to maintenance barely affect the high density scenario as compared to low density scenario because yearly savings represent about 10% of initial investment in low density LD4 and almost

40% for high density HD4 initial investment; therefore, initial investment is recovered easily within a few years in HD4. Moreover, maintenance occurs every five and ten years (filters and pumps respectively) representing 70% of savings every five years and 150% of savings every ten years in LD4 and since savings are higher in HD4, maintenance for LD4 represents a 4% of savings every five years and 6% every ten years.

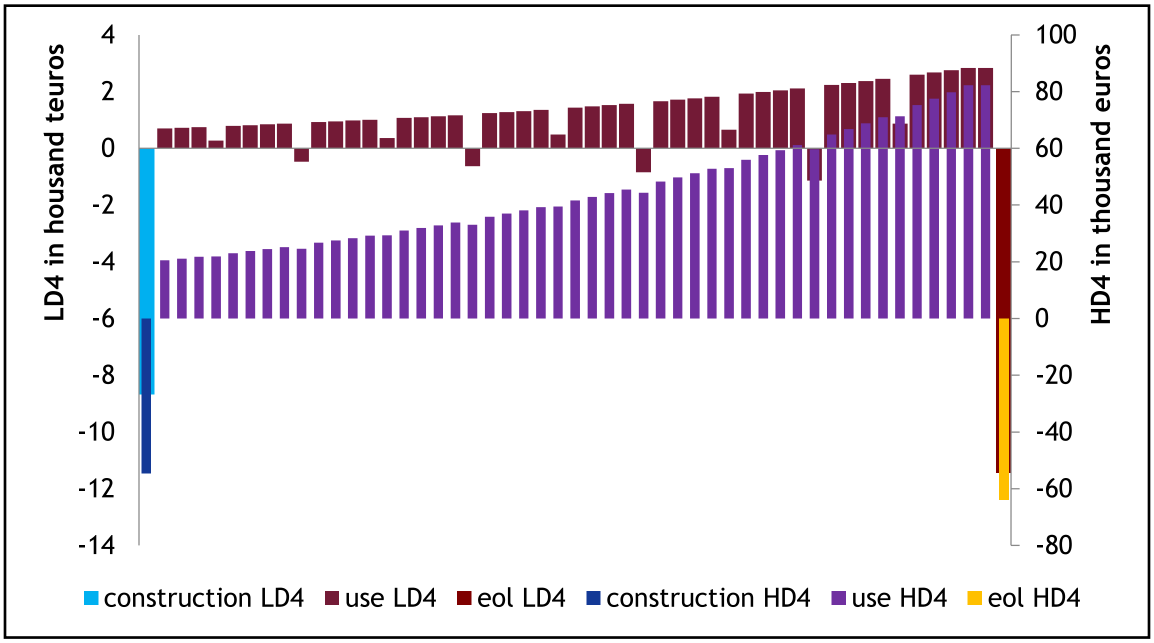


Fig 6.6 Cash flows by life cycle stage of scenarios LD4 and HD4.

Sensitivity analysis

Material and labor cost were considered as high quality data with a low degree of uncertainty since two data sources were used and were validated by field experts. Discount rate published by the National Bank of Spain was deemed of high quality and certainty. Likewise, water hardness was taken as a fixed data. However, inflation rate, precipitation and tap water price may vary over time and cause uncertainty in the results. The cumulative effect of inflation rate can play an important role in the costs of the RWH system and thus a sensitivity analysis was performed to quantify to what extent changes in inflation rate can alter NPV, IRR and PB. Secondly, a sensitivity analysis is performed evaluating the precipitation forecasts affected by climate change for the Mediterranean area based on two scenarios defined by IPPC (IPCC 2000). Finally, a third sensitivity analysis was carried out to evaluate the effect of an increase in tap water price reflected directly in the savings from no tap water consumption.

Inflation sensitivity analysis.

Due to uncertainty in inflation rates, LCC studies can be based on actual market price instead of selecting an inflation value, see for example Cellura, Ardente, & Longo, 2012; Debacker, Allacker, Spirinckx, Geerken, & De Troyer, 2013; Peri, Traverso, Finkbeiner,

& Rizzo, 2012; and Wong, Tay, Wong, Ong, & Sia, 2003. In order to be representative of these options, the sensitivity analysis is based on two alternatives:

Alternative 1: IMF forecasts for the next five years (until 2020) and after that a constant inflation rate equal to the value of 2020, that is: -0.73% for 2015, 0.68% for 2016, 0.81% for 2017, 1.15% for 2018, 1.32% for 2019 and 1.51% for 2020.

Alternative 2: No assumptions made; instead, all calculations are based only on the current market price (neglecting time value of money).

For both alternatives, a discount rate of 0.75% published by the National Bank of Spain is applied (Banco de España 2013). Since NPV and IRR are directly proportional to the inflation rate. Thus a higher inflation rate results in higher profits and higher rate of return. Consequently, the lowest NPV and IRR values are given when no inflation rate is considered. This proves that the inflation rate value is significant and should be included in feasibility studies since this could affect the profitability of the project and the investor's decision process. Table 6.7 exemplifies the behavior of the three financial tools with scenario HD4. Focusing on one scenario (in this case HD4) it becomes evident that inflation makes a big impact in financial results showing differences of around 20 to 50 percent in NPV values and from 5 to 10 percent in IRR results. For PB the differences are less than 1%. The results of the inflation sensitivity analysis are given in the Appendix II (Table II.3), and are summarized in Table 6.7.

TABLE 6.7 SENSITIVITY ANALYSIS OF INFLATION RATE APPLIED TO CLUSTER SCENARIO FOR HIGH DENSITY (HD4).

INFLATION SENSITIVITY ANALYSIS

Financial tool	BASE (-0.2%)	ALTERNATIVE 1 (IMF forecast)	ALTERNATIVE 2 (none)
NPV (euros)	753,896	1,162,355	791,841
IRR (%)	37.7%	39.6%	38.0%
PB (years)	2.6	2.6	2.6

Precipitation sensitivity analysis.

It is important to establish how sensitive the economic analysis is to varying precipitation patterns given the negative influence of greenhouse gas concentration (Solomon et al. 2007). Based on historical precipitation data (1991-2010), precipitation has decreased about 1% every year, resulting in a 19% decrease over the 20 years. Figure II.1 shows the precipitation of 20 years historical data (1991-2010), presented yearly and monthly specifically to demonstrate the tendency of the data. The sensitivity analysis is based on the following alternatives:

- Alternative 1 considers that this tendency of 1% yearly decrease is continued for the next 50 years.

- Alternatives 2 and 3 are based on the report made by the Meteorology Service of Catalonia (SMC) (Barrera-Escoda and Cunillera 2011), where two climate change scenarios are considered for Catalonia region based on scenarios A2 and B1 proposed on IPCC 2000. A2 is a regionally oriented economic development scenario, with a decreasing precipitation trend of 8% for 2011-2040 and 8% for 2041-2070. B1 is based on a trend towards global environmental sustainability resulting in a decreasing precipitation rate of 1.4% for 2011-2040 and 3.8% for 2041-2070. Table of the results is given in the Appendix II in Table II.4.

From the sensitivity analysis shown in Table 6.8, it is evident that even with the climate change effect taken into consideration in the financial calculations, there are no significant changes in NPV, IRR and PB. The highest differences are given in scenarios HD1, HD2 and HD3 when alternative 1 is considered, resulting in a maximum of a 30% reduction of the NPV, a maximum reduction of 10% of the IRR and an increase in PB of 8 months maximum. This analysis, not only proves that this is not an input of uncertainty to our study, but it also proves that even when precipitation tends to diminish, RWH will continue to be an advantageous supply of water for laundry.

TABLE 6.8 SENSITIVITY ANALYSIS FOR THREE ALTERNATIVE CHANGES IN PRECIPITATION FOR SCENARIOS HD1, HD2 AND HD3.

PRECIPITATION SENSITIVITY ANALYSIS				
SCENARIO	BASE	ALTERNATIVE 1 (-1%)	ALTERNATIVE 2 (IPCC A2)	ALTERNATIVE 3 (IPCC B1)
		NPV (euros)		
HD1	57,974	42,965	53,519	57,115
HD2	65,863	50,854	61,408	65,004
HD3	48,268	33,259	43,813	47,408
		IRR (%)		
HD1	33.9%	32.4%	33.5%	33.8%
HD2	48.1%	46.6%	47.7%	48.0%
HD3	12.3%	11.0%	11.9%	12.2%
		PB (years)		
HD1	2.9	3.0	3.0	3.0
HD2	2.1	2.1	2.1	2.1
HD3	9.1	9.8	9.5	9.4

Tap water price sensitivity analysis.

As water scarcity and shortage become an issue, costly mechanisms are emerging to help allocate water more efficiently. Statistical evidence shows that water price tends to increase, reflecting the growing scarcity of water supplies (Maxwell 2010). Based on water prices report from the Catalan Water Agency (Agència Catalana de l'Aigua), water price has increased 50% over the last 10 years, resulting in a mean yearly increment of 5%. Figure II.2 shows the water price evolution of the past 10 years (2005-2015), presenting the yearly price and increment in relation to the year before. The sensitivity analysis is based on this past increment of 5% in the water price annually and it is applied for the next years.

Table 6.9 shows the results for NPV, IRR and PB from the water price sensitivity analysis, where evidently, savings from no tap-water consumption have a great effect in financial outcomes. Alternative scenario presents an increase of up to 30% in LD scenarios and up to 45% in HD scenarios. Results from the water price sensitivity analysis are given in Table II.5.

TABLE 6.9 SENSITIVITY ANALYSIS FOR A 6% YEARLY INCREASE ON WATER PRICE FOR SCENARIOS LD1, LD2 AND HD4.

WATER PRICE SENSITIVITY ANALYSIS		
SCENARIO	BASE	ALTERNATIVE (6%)
	NPV (euros)	
LD1	-1,800	5,736
LD2	1,045	8,582
HD4	753,896	1,623,449
	IRR (%)	
LD1		4.0%
LD2	2.5	6.6%
HD4	37.8%	39.9%
	PB (years)	
LD1	50	30.4
LD2	21.2	19.4
HD4	2.6	2.5

6.6 Conclusions

The environmental assessment helps to point out the high impacts associated to the production stage, more specifically to the materials and energy needed to install the tank. Even though scenario HD2 has no pumping energy requirements, the fact that it uses more reinforcement materials results in higher impacts than scenario HD3. In the case of low density scenarios, saving energy from pumping is not always the best option, reinforcement materials in the case of scenario LD2 and waterproofing foil in scenario LD3 have a negative effect even though this scenarios use gravity to supply water.

The high density scenario HD3, constituted by 1 building and 24 households with the tank spread on roof has the lowest environmental impacts in most categories, except for Ozone Depletion (OD; kg CFC-11 eq). HD3 collects 283 m^3 per year and has no pumping needs nor structural reinforcement. Even though high density scenarios can only provide 50% of the demand, these collect a higher amount of rainwater than those in low density and have in general lower environmental impacts, because all the water is consumed, a higher demand allows more benefit. In addition to this, avoided environmental impacts from detergent that is not consumed when soft rainwater is used for laundry, reduce the impacts in around half in most scenarios.

Results from the economic study lead us to conclude that a Rainwater Harvesting (RWH) system is potentially economically viable for domestic laundry for the residences considered. The high density cluster construction configuration (HD4), which consisted of ten buildings and 240 households with the tank installed underground, had the best overall results. Financial results present the highest NPV of 753,896 euros, an IRR of 38% and a PB of 2.6 years. The high density construction scenarios have better outcomes because they require a lower rate of initial investment per m^3 of water and also because the high expenses of the construction stage are compensated by the savings resulting from less detergent use.

The location of the storage facility also plays an important role in both, the economic and the environmental analysis. In low density scenario LD3 and high density scenario HD3, where the tank is installed spread on the roof, the waterproofing materials increase construction cost, as well as the environmental impact, though in HD3 this impact is inversely proportional to the amount of m^3 of collected rainwater.

Along with this, scenarios with the tank installed underground (LD1, LD4, HD1 and HD4) incur in pumping-related economic and environmental negative impacts during the stage of use, such as electricity consumption and the costs associated to the replacement of the pump every 10 years.

The highest savings in both, environmental and economic studies are achieved from the reduction in detergent and other additives used in laundry and that are reduced by the use of soft rainwater instead of Barcelona’s hard tap water. Comparing the recommended dosage of detergent, for hard (1.59 doses per laundry) and soft water (1 dose per laundry), a difference of half the environmental impacts and of 0.57 euros per laundry, are gained. This way, when more users (more washing machines) are considered, more savings the system gets. Accordingly, the scenario with the higher amount of users (240 households or 240 washing machines) is the best scenario, mostly because the savings can faster cope with the high construction cost and obtain profits after that. This outcome is noticed in the rest of high density scenarios (HD1, HD2 and HD3) with 24 households each. This finding is significant because more cities around the world suffer from hard water problems due to limestone watersheds like Barcelona.

In previous LCA study by Angrill et al., 2011 results conclude that in general, scenarios with more users per installation have three time less environmental impact in selected impact categories (Abiotic Depletion Potential, Acidification Potential, Eutrophication Potential, Global Warming Potential, Human Toxicity Potential, Ozone Depletion Potential, and Photochemical Ozone Creation Potential) than scenarios with single-family users. The most environmentally friendly scenario was found to be a building of 24 home-apartments with the tank distributed over the roof, mainly because of the reduced need for structural components and the use of gravity flow instead of pumping. These results are consistent with the actual study, and it was already expected after updating the study by means of the Ecoinvent database and changing from CML method to ReCiPe.

From a resource accounting perspective Vargas-Parra et al., 2013 found that the scenario with the lower resource (material and energy) consumption, using Exergy analysis, was a building of 24 home-apartments with the tank installed on the roof. And that, in general, scenarios with more users (24 home-apartments or 240 home-apartments) consume 3-5 times less resources per cubic meter than those scenarios considering a single-family user.

Although, the best results differ from one study to another, in essence all three studies (LCA, Exergy analysis and LCC) conclude that buildings of 24 home-apartments are more resource efficient than those with a single-family user. In LCA the reduced need for structural components to reinforce the building in order to absorb the weight of a full tank, was the decision point between the two scenarios with the tank installed on or distributed over the roof, resulting in a more environmentally friendly scenario with the tank distributed over the roof. In the case of Exergy analysis, the crucial element was the waterproofing foil, resulting in a more resource efficient scenario with the tank spread on the roof. In LCC we could say “the more, the merrier” since the savings are calculated based on the number of users and this is the main source of savings and therefore profitability.

Best scenarios form both LCA and Exergy analysis, benefit from the use of gravity flow to supply water instead of electricity for pumping, having the tank installed below roof or distributed over the roof. Here lies the difference between these two studies and the economic study. In LCC the best scenario has 10 buildings of 24 home-apartments and the tank installed underground with pumping related costs due to electricity consumption, and saves more money from laundry additives than the electricity consumed. Either way, any of the building scenarios are viable in LCC.

There are other factors not considered in this study which could play a significant role in the economic feasibility of RWH system, such as potential technology improvement. Technological advance will doubtless continue to reduce energy and water consumption.

Other potential savings that are not considered in this study are the avoided CO_2 emissions. Tap water production process can incur on a life cycle carbon footprint of 0.1-0.7 kg of CO_2 equivalent/m^3 treated water in Barcelona Metropolitan Area (Marín et al. 2012). Considering the current carbon market pricing (13.5 euros per ton of CO_2 emissions (Kossoy and Guigon 2012)), the savings from avoided CO_2 emissions by using RWH system can range from 0.03 to 26 euros per year per scenario (depending on the scenario), and representing a 0.02% of the yearly savings.

This work has shown the environmental and economic performance of installing RWH system in a highly populated Mediterranean city. As with any effort in making urban metabolism more sustainable, it is important that local and regional factors are taken into consideration when applying to other regions. However, we hope to provide a protocol that can be used by other cities in assessing RWH system.

7

LCA and LCC in neighborhoods

Wet floor
Photography by Violeta Vargas

Chapter 7 LCA and LCC in neighborhoods.

based on a manuscript by M. Violeta Vargas-Parra, Xavier Gabarrell, Gara Villalba and M. Rosa Rovira-Val.

Abstract

Water availability is a main issue that requires prompt attention, otherwise social and economic development will be threatened. Over the last decade, rainwater harvesting has been proposed as a feasible option to mitigate water supply problems. The main features that advocate for the use of rainwater are its low levels of minerals and the fact that does not need extraordinary efforts to attain. Moreover, it is thought to be especially helpful in urban areas.

This study was focused on the evaluation of environmental and economic performance of rainwater harvesting systems in seven different types of neighborhoods (scenarios), defined by their density of population. In order to accomplish this task, LCA (using a cradle to grave approach) and LCC methodologies were applied. Actual data from neighborhoods and daily time series of rainfall from Barcelona city were used. Water demand was calculated for laundry purposes. Net present value, internal rate of return and payback time were used to evaluate economic performance. Furthermore, the sensitivity of the economic analysis was assessed contrasting different levels of water hardness.

Here we demonstrate that rainwater harvesting systems in urban neighborhoods with high density of population would generate less environmental impacts than low density ones. At the economic analysis, we saw that this strategy was feasible for the different scenarios. Nevertheless, feasibility decrease when tap water is soft and increase when the difference in mineral concentration between tap water and rainwater is higher.

7.1 Introduction

Earth surface is mostly water-covered, however, only less than one percent is usable for ecosystems and human consumption (WWAP 2006; UNEP 2007). Water is a limited resource in spite of being renewable. The water cycle can guaranty us the quantity but it does not guaranty the availability at all time and space.

Population is expected to reach 9.7 billion by 2050 (UN 2015) and 66% of it will be living in urban areas. Moreover, water stress will be further intensified due to climate change effect (European Environment Agency 2014). For example, in the Mediterranean area of Southern Europe, is expected that precipitation will decrease 5% by 2020, in comparison with the climatology of 1979-2001(Met Office Hadley Centre for Climate Change 2009).

In this modern era, water is not only vital; it is also the ground of social and economic development. Water management has become a main issue for society and the unsustainable exploitation of this resource represents an increasing threat for human development (WWAP 2009).

Additionally, consequences of climate change and urban population intensification aggravate the water problem in the cities (The World Bank 2009; Leflaive 2012; WWAP 2012). Water supply and management represents a big problem for society, forcing us to develop alternative systems to obtain water. Rainwater harvesting (RWH) could help alleviate water supply problems, especially in urban areas where meeting water demand will be more and more costly.

In domestic laundry, detergent dosage is conditioned to two aspects: water hardness and soil level. When compared to hard tap water, rainwater contains less concentration of minerals, such as calcium and magnesium, therefore, it is ideal for laundry because it requires less detergent, softener and machinery maintenance. For all these reasons, RWH is expected to become a fundamental contributor toward urban water self-sufficiency (Rygaard et al. 2011b; Fragkou et al. 2015).

To evaluate the economic and environmental performance, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are effective approaches (Heijungs et al. 2012; Sanyé-Mengual et al. 2015). In this study LCA and LCC are performed for seven different scenarios of RWH systems as an alternative water supply for domestic laundry. Scenarios are based on actual data from Barcelona neighborhoods and systems are designed based on a centralized tank from which rainwater is supplied to a washing machine per household.

7.2 Methodology

Three tools of evaluation were selected based on LCC methodology (ISO 2008), to evaluate the economic performance of a RWH system: Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Time (PB).

LCA methdology (ISO 2006) and life cycle impact assessment (LCIA) results are calculated at midpoint level using ReCiPe (Goedkoop et al. 2013) and cumulative energy demand methods.

7.2.1 System boundaries

A cradle to grave approach was followed to set the system boundaries. From the construction of the system, through 50 years of use until the end of its useful life.

For the construction stage the use of energy and materials were accounted to build and install a RWH system.

The next stage considers the use of the system during 50 years of useful life, calculated based on the durability of the materials. Materials with shorter lifetimes require replacements. Also, laundry additives necessary to do laundry are included in this stage

At the end of 50 years, the end-of-life (EOL) stage includes the dismantling of the system and transport of the materials to a waste management plant, again requiring energy and materials.

Figure 7.1 shows the system boundaries for this study and its life cycle stages. Each scenario requires a different amount and configuration of these items.

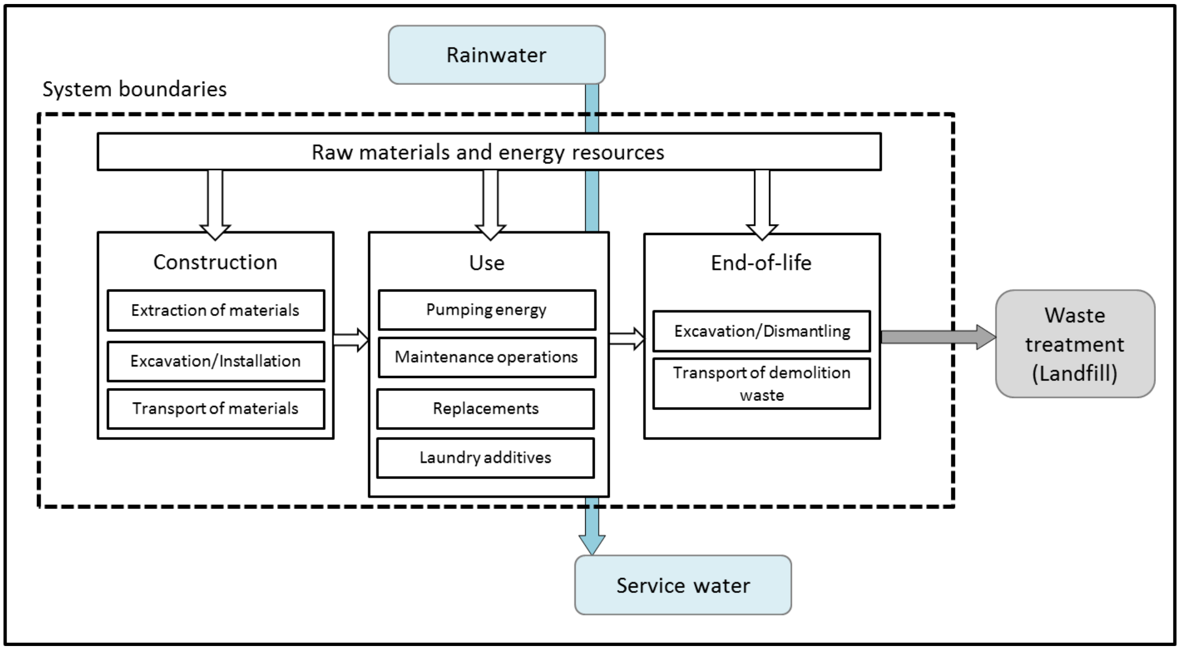


FIG 7.1 SYSTEM BOUNDARIES.

Scenarios have been designed based on actual data from Barcelona's neighborhoods. Basic statistics were applied to population density data from Ajuntament de Barcelona (2014) for 73 neighborhoods, represented in Figure 7.2.

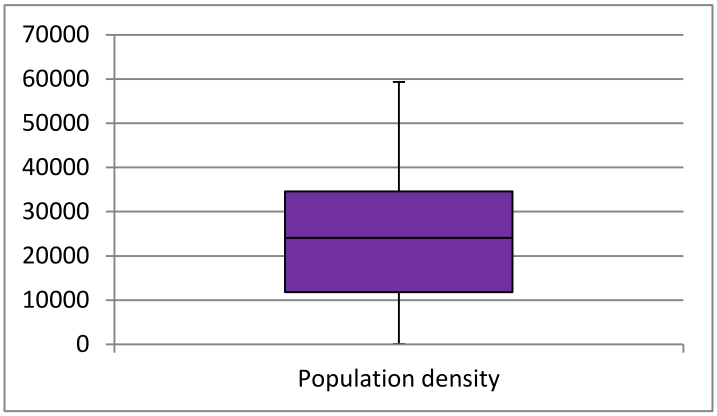


FIG 7.2 BARCELONA'S POPULATION DENSITY BOX PLOT (INH/KM^2)

Applying the formulas from Sturges (1926) and assuming a normal distribution of data, equation 7.1 was applied to calculate number of classes, the results are stated in Table 7.1.

$$K = 1 + 3.3 \log n \qquad \text{EQUATION 7.1}$$

Where K is the number of classes and n is the size of the sample.

TABLE 7.1 RANGE, CLASS AND CLASS WIDTH.

Statistical values	
Min	100
Max	59300
Range	59200
# of class	7
Class width	8457

The case study was developed from the seven statistical classes. This classes, represent real neighborhoods in Barcelona and are listed in table 7.2. These statistical classes are a representation of Barcelona neighborhoods and will be the seven scenarios of this study.

TABLE 7.2 BARCELONA'S NEIGHBORHOOD REPRESENTATION BY SCENARIO

Name	N1	N2	N3	N4	N5	N6	N7
Population density (inhabitants/km^2)	< 8557	8558 -17015	17016 -25473	25474 - 33931	33932 - 42389	42390 - 50847	50847 - 59305
Frequency in Barcelona	11	14	14	11	10	8	5
Neighborhoods in Barcelona	12. la Marina del Prat Vermell - AEI Zona Franca	43. Horta	70. el Besòs i el Maresme	73. la Verneda i la Pau	14. la Font de la Guatlla	9. la Nova Esquerra de l'Eixample	64. el Camp de l'Arpa del Clot
	22. Vallvidrera, el Tibidabo i les Planes	11. el Poble Sec - AEI Parc Montjuïc	71. Provençals del Poblenou	35. el Guinardó	5. el Fort Pienc	46. el Turó de la Peira	63. Navas
	54. Torre Baró	49. Canyelles	47. Can Peguera	26. Sant Gervasi - Galvany	62. el Congrés i els Indians	52. la Prosperitat	51. Verdun
	56. Vallbona	67. la Vila Olímpica del Poblenou	2. el Barri Gòtic	45. Porta	27. el Putxet i el Farró	1. el Raval	32. el Camp d'en Grassot i Gràcia Nova
	40. Montbau	69. Diagonal Mar i el Front Marítim del Poblenou	29. el Coll	55. Ciutat Meridiana	38. la Teixonera	44. Vilapicina i la Torre Llobeta	17. Sants - Badal
	42. la Clota	58. Baró de Viver	24. les Tres Torres	61. la Sagrera	72. Sant Martí de Provençals	33. el Baix Guinardó	
	39. Sant Genís dels Agudells	25. Sant Gervasi - la Bonanova	4. Sant Pere, Santa Caterina i la Ribera	60. Sant Andreu	18. Sants	10. Sant Antoni	
	21. Pedralbes	3. la Barceloneta	7. la Dreta de l'Eixample	16. la Bordeta	31. la Vila de Gràcia	6. la Sagrada Família	
	59. el Bon Pastor	20. la Maternitat i Sant Ramon	30. la Salut	19. les Corts	15. Hostafrancs		
	41. la Vall d'Hebron	28. Vallcarca i els Penitents	68. el Poblenou	8. l'Antiga Esquerra de l'Eixample	65. el Clot		
	23. Sarrià	57. la Trinitat Vella	34. Can Baró	37. el Carmel			
		66. el Parc i la Llacuna del Poblenou	13. la Marina de Port				
		53. la Trinitat Nova	50. les Roquetes				
		36. la Font d'en Fargues	48. la Guineueta				

7.2.2 Functional unit

The functional unit (FU) is 1 m^3 of rainwater supplied for domestic laundry purposes.

7.2.3 Goal and scope

Domestic RWH systems are commonly composed of three main parts: a catchment area, in this case the rooftop is the collection surface; a storage facility, that in this case is installed underground, and a delivery system to transport the rainwater from the catchment area to the storage facility and also from the storage facility to the building, and in this case, directly to a laundry machine per household. Table 7.3 summarizes the seven different scenarios.

Data

Water demand was calculated for laundry purposes. A laundry demand of 5 wash loads per week and a water consumption of 50 liters per load were considered in the calculations. Storage tank size and potential rainwater supply were calculated using Plugrisost®, a free simulation model developed by Gabarrell et al. (2014). The model estimated the potential rainwater supply based on a daily time series of rainfall (from 1991 to 2010), a roof-runoff coefficient estimated at 0.9 (Singh 1992) and the area of collection, defined in Table 7.3 for each scenario. Statistical data was obtained from the Barcelona statistics department (Ajuntament de Barcelona 2014). Storage tank sizing calculations are a function of water demand.

TABLE 7.3 NEIGHBORHOOD SCENARIO DESCRIPTION

Scenario	N1	N2	N3	N4	N5	N6	N7
Building height in layers	3	4	5	6	7	8	9
Average neighborhood area (km^2)	3.68	1.48	0.91	1.12	0.7096	0.80	0.4926
Average neighborhood housing area (m^2)	134905	78065	53454	69830	46293	51673	34374
Average household area (m^2)	120	75	75	75	75	75	61
Households per layer	4	4	4	4	4	4	4
Households per building	12	16	20	24	28	32	36
Average households per neighborhood (2013)	2580	6307	7704	13778	10858	14866	11062
Buildings per neighborhood	215	394	385	574	387	464	307
Building collection area (m^2)	480	300	300	300	300	300	244
Average Inhabitants per household	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Average Inhabitants per building	31.8	42.4	53	63.6	74.2	84.8	95.4
water demand household (l/household/day)	35.7	35.7	35.7	35.7	35.7	35.7	35.7
water demand building (l/building/day)	428.6	571.4	714.3	857.1	1000.0	1142.9	1285.7
water demand neighborhood daily (l/neighborhood/day)	92149.4	225250.0	275125.0	492081.2	387775.0	530933.0	395071.4
collection area (m^2)	103207.3	118256.3	115552.5	172228.4	116332.5	139369.9	74975.8
Tank capacity (m^3)	4000.0	7500.0	9000.0	7000.0	7000.0	8000.0	4500.0
% demanda cubierta	82%	60%	54%	39%	38%	33%	25%
rw supply (m^3/year)	27427.6	49268.4	54108.6	70232.0	53453.5	64722.6	36411.7

7.3 LCA

7.3.1 Life Cycle Inventory

Inventory data per FU for the environmental assessment is presented in table 7.3.

Table 7.4 Life cycle inventory per FU

Life cycle stage	Description	Input	units	N1	N2	N3	N4	N5	N6	N7
Construction	Supply pipe	Polyvinylchloride	m	2.10E-01	1.32E-01	1.29E-01	1.27E-01	1.37E-01	1.50E-01	1.94E-01
	Pipe accessories	Polyvinylchloride	unit	2.10E-01	1.32E-01	1.29E-01	1.27E-01	1.37E-01	1.50E-01	1.94E-01
	Collection pipe	Polyvinylchloride	m	1.51E-01	7.28E-02	6.93E-02	6.14E-02	6.19E-02	6.52E-02	7.64E-02
	Downspout	Polyvinylchloride	m	5.95E-02	5.95E-02	5.98E-02	6.56E-02	7.49E-02	8.48E-02	1.18E-01
	Downspout accessory	Polyvinylchloride	unit	5.95E-02	5.95E-02	5.98E-02	6.56E-02	7.49E-02	8.48E-02	1.18E-01
	Tank	Concrete, normal	m3	9.55E-03	1.10E-02	1.05E-02	9.97E-03	9.98E-03	7.73E-03	5.43E-03
		Cast iron	kg	1.35E-02	9.54E-03	8.49E-03	6.53E-03	7.81E-03	6.24E-03	6.96E-03
		Plywood, outdoor use	m	1.08E-02	7.63E-03	6.79E-03	5.22E-03	6.25E-03	4.99E-03	5.57E-03
		Bitumen	m2	4.10E-02	5.03E-02	4.83E-02	4.66E-02	4.60E-02	3.55E-02	2.37E-02
		Polyethylene terephthalate, granulate, amorphous	m2	4.10E-02	5.03E-02	4.83E-02	4.66E-02	4.60E-02	3.55E-02	2.37E-02
	Neighborhood pump	Steel, low-alloyed	unit	3.07E-05	1.26E-05	1.04E-05	6.35E-06	9.20E-06	7.61E-06	1.42E-05
	Building pump	Steel, low-alloyed	unit	6.61E-03	4.95E-03	3.99E-03	3.65E-03	3.56E-03	3.53E-03	4.36E-03
	Tank filter	Polyethylene, HDPE, granulate	unit	3.07E-05	1.26E-05	1.04E-05	6.35E-06	9.20E-06	7.61E-06	1.42E-05
	Building filter	Polyethylene, HDPE, granulate	unit	6.61E-03	4.95E-03	3.99E-03	3.65E-03	3.56E-03	3.53E-03	4.36E-03
	Downspout filter	Polyethylene, HDPE, granulate	unit	6.61E-03	4.95E-03	3.99E-03	3.65E-03	3.56E-03	3.53E-03	4.36E-03
	Construction services	Diesel, burned in building machine	MJ	5.42E+01	5.87E+01	5.45E+01	5.20E+01	5.13E+01	4.15E+01	3.27E+01
Use	Electricity	Electricity, low voltage, production ES	kWh	2.20E+00	1.12E+00	1.02E+00	8.91E-01	9.13E-01	9.58E-01	1.15E+00
	Neighborhood pump replacement	Steel, low-alloyed	unit	3.07E-05	1.26E-05	1.04E-05	6.35E-06	9.20E-06	7.61E-06	1.42E-05
	Building pump replacement	Steel, low-alloyed	unit	6.61E-03	4.95E-03	3.99E-03	3.65E-03	3.56E-03	3.53E-03	4.36E-03
	Tank filter replacement	Polyethylene, HDPE, granulate	unit	3.07E-05	1.26E-05	1.04E-05	6.35E-06	9.20E-06	7.61E-06	1.42E-05
	Building filter replacement	Polyethylene, HDPE, granulate	unit	6.61E-03	4.95E-03	3.99E-03	3.65E-03	3.56E-03	3.53E-03	4.36E-03
	Downspout filter replacement	Polyethylene, HDPE, granulate	unit	6.61E-03	4.95E-03	3.99E-03	3.65E-03	3.56E-03	3.53E-03	4.36E-03
End-of-life	Transport	Diesel, burned in building machine	MJ	3.85E+00	4.73E+00	4.55E+00	4.38E+00	4.33E+00	3.34E+00	2.23E+00
	Demolition services	Diesel, burned in building machine	MJ	4.50E+01	5.52E+01	5.31E+01	5.11E+01	5.05E+01	3.90E+01	2.60E+01

7.3.2 Environmental Impacts

Results are presented in Figure 7.3 for all scenarios and for selected impact categories Climate Change (CC; kg CO_2 eq), Ozone Depletion (OD; kg CFC-11 eq), Terrestrial Acidification (TA; kg SO_2 eq), Freshwater Eutrophication (FE; kg P eq), Photochemical Oxidant Formation (POF; kg NMVOC), Particulate Matter Formation (PMF; kg PM10 eq) based on the ReCiPe hierarchical midpoint characterization approach and the single method Cumulative Energy Demand (CED; MJ).

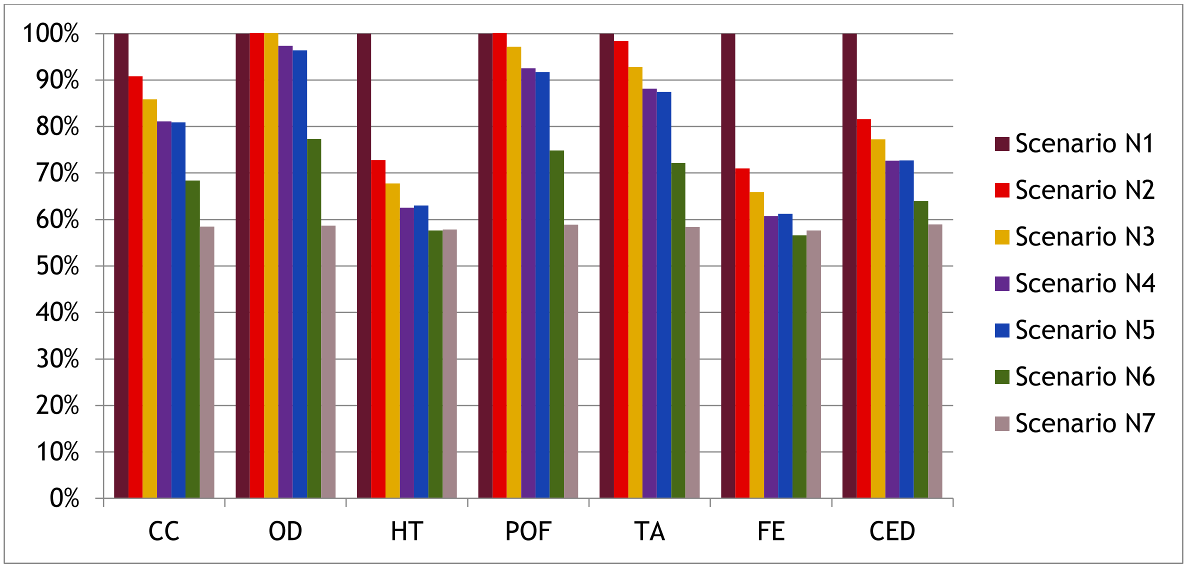


FIG 7.3 ENVIRONMENTAL IMPACTS. SCENARIO COMPARISON

Environmental analysis results are presented in Table 7.5 for all seven scenarios, each further subdivided by life cycle stage.

TABLE 7.5 CHARACTERIZATION OF RESULTS PER LIFE CYCLE STAGE CONTRIBUTIONS.

	Life cycle stages	N1	N2	N3	N4	N5	N6	N7
CC	Construction (%)	70%	65%	65%	65%	65%	67%	71%
	Use (%)	8%	5%	4%	4%	4%	5%	7%
	End-of-life (%)	22%	30%	31%	31%	31%	28%	22%
	Absolute value (kg CO2 eq)	2.00E+01	1.82E+01	1.72E+01	1.62E+01	1.62E+01	1.37E+01	1.17E+01
OD	Construction (%)	56%	54%	54%	54%	54%	54%	57%
	Use (%)	6%	3%	3%	3%	3%	4%	6%
	End-of-life (%)	38%	43%	43%	44%	44%	42%	37%
	Absolute value (kg CFC-11 eq)	1.48E-06	1.60E-06	1.51E-06	1.45E-06	1.43E-06	1.15E-06	8.71E-07
HT	Construction (%)	64%	64%	65%	65%	65%	65%	66%
	Use (%)	27%	20%	19%	18%	18%	21%	25%
	End-of-life (%)	9%	16%	16%	17%	17%	14%	9%
	Absolute value (kg 1,4-DB eq)	2.63E+00	1.91E+00	1.78E+00	1.64E+00	1.65E+00	1.51E+00	1.52E+00
POF	Construction (%)	60%	55%	54%	54%	54%	56%	61%
	Use (%)	4%	2%	2%	2%	2%	2%	3%
	End-of-life (%)	36%	43%	44%	45%	45%	42%	36%
	Absolute value (kg NMVOC)	1.70E-01	1.75E-01	1.65E-01	1.57E-01	1.56E-01	1.27E-01	1.00E-01
TA	Construction (%)	57%	54%	53%	53%	53%	54%	58%
	Use (%)	11%	6%	5%	5%	5%	7%	10%
	End-of-life (%)	32%	41%	41%	42%	42%	39%	32%
	Absolute value (kg SO2 eq)	1.11E-01	1.10E-01	1.03E-01	9.83E-02	9.75E-02	8.05E-02	6.51E-02
FE	Construction (%)	60%	60%	61%	61%	61%	61%	62%
	Use (%)	31%	24%	23%	22%	22%	25%	29%
	End-of-life (%)	9%	16%	16%	17%	17%	14%	9%
	Absolute value (kg P eq)	2.40E-03	1.70E-03	1.58E-03	1.46E-03	1.47E-03	1.36E-03	1.38E-03
CED	Construction (%)	78%	69%	69%	68%	69%	72%	78%
	Use (%)	3%	2%	2%	2%	2%	2%	3%
	End-of-life (%)	19%	29%	29%	30%	29%	26%	19%
	Absolute value (MJ)	3.55E+02	2.90E+02	2.74E+02	2.58E+02	2.58E+02	2.27E+02	2.09E+02

Scenario N7 presents the lowest environmental impacts for almost all impact categories except for HT and FE in which N6 has better results in 1% and 9% respectively. On the opposite side, N1 has obtained the highest environmental impacts of the seven scenarios. This can easily be seen in Figure 7.3.

Impacts are more or less distributed in construction and end-of-life stages with 40-50% of the total impact by scenario. Use stage, in most of categories, only contributes with 5% of the impact, except for HT and FE impact categories where use stage contributes with around 20% of the impact.

Scenarios N1 and N7 are opposite ends also in design, N1 is the least densely populated neighborhood of all seven scenarios and N7 is the most dense. N7 has 30% less area of collection than N1 and has a tank 10% bigger than N1. With these characteristics, N1 can supply 82% of the demand and N7 can only supply 25%. Still, N7 supplies 30% more rainwater than N1 and total impacts are given by functional unit (m^3).

7.3.3 Avoided impacts

As a result of the difference in water hardness between Barcelona’s tap water and rainwater, the use of laundry detergent can be reduced.

Inventory data for laundry detergent was obtained from P&G detergent (Saouter and Hoof 2002), a detailed inventory and avoided environmental impacts can be consulted in Chapter 6, tables 6.3 and 6.4.

7.4 Life cycle costs

7.4.1 Data sources

Cost of materials, labor, tools and equipment were primarily obtained from the Technology of Construction of Catalonia Institute database (ITeC 2012) and secondly from internet catalogues (AGUADELLUVIA 2012; Baeza Group 2012; EBARA 2012; GRAF Ibérica 2012; HASA 2012; REMOSA 2012; SACI 2012). The cost inventory was then revised by a senior professional of water installations in Barcelona. Table 7.6 shows the cost inventory for each scenario in euros.

TABLE 7.6 COST INVENTORY IN EUROS PER NEIGHBORHOOD SCENARIO

Stage	Material	N1	N2	N3	N4	N5	N6	N7
Construction	Supply pipes	119123	183125	217027	347915	258719	343171	237878
	Collection pipes	102508	120938	139744	201653	140376	178929	112176
	Downspout	29434	71949	87880	157180	123862	169590	126193
	Tank materials	55435	151218	174650	267303	186278	174602	67694
	Pump for tank	2881	2881	3435	3435	3435	3435	2881
	Pump for building	125990	250830	245101	394482	265966	385862	255301
	Tank filter	1425	1425	1425	1425	1425	1425	1425
	Building filter	112875	206850	202125	301350	203175	243600	161175
	Downspout filter	12900	23640	23100	34440	23220	27840	18420
	Construction services	153895	415531	471056	734530	500013	485583	199403
Use	Electricity	14743	18376	20374	28927	20451	25951	16644
	Maintenance services	12402	22631	22117	32918	22231	26632	17659
	Pump & filter replacement	256071	485626	475186	735132	497221	662163	439202
End-of-life stage	Transport to waste management plant	4038	12114	14133	22209	15143	14133	5048
	Construction services	662760	1988280	2319660	3645180	2485350	2319660	828450

7.4.2 Costs and savings by life cycle stages

Construction stage costs

This stage includes all the necessary materials and labor costs associated to construct and install a RWH system in Barcelona. Table 7.6 describes the items considered as inputs to the system. Each scenario requires a different amount and configuration of these items.

Use stage costs and savings

Use stage considers the electricity for pumping and the costs of maintenance and replacement of pumps and filters every five and 10 years respectively.

For the calculation of savings, two aspects were considered: first, the reduction in tap water consumption for laundry considering that the average cost of tap water in Spain is 1.7 euros/m^3 (RTVE 2014); second, the reduction in detergent, fabric softener and water softener.

End-of-life costs

Two items were considered in this stage: costs associated with the dismantling of the facilities, and the transport of this rubble to a waste management plant, located at no more than 50 km from the site of construction.

7.4.3 Financial tools

Net present value (NPV, Euros), internal rate of return (IRR, %) and payback period (PB, years), were calculated for the LCC study.

7.4.4 Life cycle cost results

Results are presented in Table 7.7 showing that all scenarios are economically feasible with positive NPV, very high IRR and PB of 1-2 years. Scenario with the best results is N4, with higher NPV than all other scenarios. The lower value is obtained by scenario N1 that is 80% less than N4.

TABLE 7.7 LCC RESULTS

	NPV (euros)	IRR	PB (years)
Scenario N1	12,798,278	58%	1.8
Scenario N2	32,966,755	73%	1.4
Scenario N3	40,851,441	81%	1.3
Scenario N4	67,175,722	84%	1.2
Scenario N5	46,392,875	83%	1.2
Scenario N6	56,041,016	85%	1.2
Scenario N7	29,452,117	77%	1.3

Scenarios 4 and 6 obtained the highest NPV and curiously, these two scenarios have the highest number of households of all scenarios, so even though the installation of these big tanks of 7000 and 8000 m^3 is high, savings from additive consumption are higher with more households.

7.4.5 Sensitivity analysis

This study was built on the premises of Mediterranean climate conditions, and this means that for the calculation of the tank and potential supply an average rainfall of 650 mm using Plugrisost and 20 years of historic pluviometry. Then for the savings, the hard tap water of Barcelona was used for comparison with soft rainwater, but there are many other cities that share this climate conditions. Our next objective was to evaluate the financial outcomes in the event that problems of hard tap water were affecting in a lesser extent.

Two different levels of hardness were considered:

Alternative 1. Medium-hard tap water. Additive dosage for this quality of water is 1.31 per load of laundry on average. Savings were calculated per m^3 of potential rainwater supply.

Alternative 2. Soft water. Detergent consumption would be the same with tap water than with rainwater and therefore, there would be no savings from detergent consumption.

Results are presented in Table 7.8 for alternative 1 and 7.9 for alternative 2. Results show that all scenarios are economically feasible when a small difference in water hardness is affecting the population's additive consumption for laundry. However, when tap water is soft water, savings from only tap water consumption (no savings from additive consumption) are not enough to return the initial investment needed to install RWH systems in any of these scenarios.

TABLE 7.8 ALTERNATIVE 1 MEDIUM-HARD TAP WATER

	NPV	IRR	PB
N1	10,782,172	50%	2.0
N2	28,038,583	63%	1.6
N3	34,869,303	70%	1.4
N4	57,419,651	73%	1.4
N5	39,658,150	72%	1.4
N6	47,897,762	74%	1.4
N7	25,093,762	67%	1.5

TABLE 7.9 ALTERNATIVE 2 SOFT WATER

	NPV	IRR	PB
N1	-1,143,748	-	-
N2	-1,113,153	-	-
N3	-516,983	-	-
N4	-290,673	-	-
N5	-179,932	-	-
N6	-272,227	-	-
N7	-687,322	-	-

7.5 Conclusions

Specific features of Mediterranean regions and special hardness of Barcelona’s tap water are biases to be considered previous to the extrapolation of the results from the present study.

Results from LCA prove that more densely populated areas obtain better environmental outcomes, with up to 40% lower environmental impacts in all impact categories. Dissimilarly, LCC favors scenarios with more rainwater collection rather than population density changes.

From the environmental assessment, the construction stage has been identified as the higher contributor in environmental impacts, primarily due to the pipes to collect rainwater from the rooftop of each and every building to a common storage tank and then to supply it to each and every laundry machine. Other important responsible factor is the energy required for construction.

Scenario N7, comprised by 307 buildings, 11,062 households and a 4,500 m^3 storage tank has the lowest environmental impacts in all categories. N7 supplies 36,411 m^3/year fulfilling almost 25% of the demand, and compared to the rest of scenarios, N7 has one of the smallest storage tanks after N1 that has a 4,000 m^3 tank. The major difference between N1 and N7 scenarios is that N1 potentially supplies half the amount of water of N7 and therefore, the impacts per cubic meter are higher.

Results from the economic assessment lead us to conclude that the higher the rainwater collection, the better results are obtained, and this is due to savings in detergent consumption when hard tap water is substituted by soft rainwater for laundry. Scenario N4, which consists of 574 buildings, 13,778 households and a 7,000 m^3 storage tank and a potential rainwater supply of 70,232 m^3/year has the best economic performance with the highest NPV amongst all scenarios.

Important finding is that economic performance is highly dependent on the quality of tap water and when tap water has the same quality as rainwater and are no savings from detergent consumption, negative economic results are obtained for all scenarios.

8

LCA and LCC in arid areas

Hermosillo rain
Photography by Violeta Parra

Chapter 8 LCA and LCC in arid areas.

based on a manuscript by: M. Violeta Vargas-Parra, M. Rosa Rovira-Val, Gara Villalba and Xavier Gabarrell.

Abstract

Water scarcity is a serious problem of global concern and in dry arid areas like the Sonora Desert this is already a reality directly affecting the social and economic activities. Moreover, Sonora state (Mexico) population is expected to increase 22% by 2030 and the consequent water demand could jeopardize its availability.

As a solution to reduce water demand, Hermosillo city has reduced the number of hours that tap water is available to the population to 3-5 hours a day, and this has been happening recurrently since 1998. Nonetheless, water consumption is expected to increase 57% by 2030 compared to 2006. The disparity between water demand and water availability generates a severe problem affecting the possibilities for economic and social growth as well as increasing environmental impacts.

In this study, we explore the different possibilities of applying rainwater harvesting systems to single-houses in the city of Hermosillo which has an average yearly precipitation of 250 mm. To examine and compare the environmental and economic implications of having a rainwater harvesting system in dry arid urban areas, a life cycle assessment and a life cycle cost analysis are performed.

Two possible end uses of rainwater are examined: laundry and car washing; along with this, a third option where all rainwater is collected was studied. Also, 6 different system configurations are evaluated by varying the position of the tank: underground or at ground level; and considering 3 housing typologies.

Results indicate that installing the rainwater tank at ground level instead of underground derives in lower environmental impacts, as well as, lower costs of installation. In the best case scenario, which corresponds to a 210 m^2 household with a tank installed at ground level, collected rainwater can meet more than twice the demand for laundry water. This is a significant contribution since laundry water accounts for 40% of the water consumption for an average household in Mexico.

8.1 Introduction

World water is a renewable resource but particularly water available for human and ecosystem demand is a scarce resource (Molle and Berkoff 2009). Moreover, regions that experience rapid population growth are facing sustainability challenges (Meinzen-Dick and Ringler 2008) and this is more evident when global water consumption has increased at twice the rate of population growth during the XX century (FAO 2012).

Economic and social development are directly linked to water availability, development is restricted when water supply is limited (Furumai 2008). Hermosillo city, located at the northwest of Mexico, has been struggling with water shortages for more than two decades (Ojeda de la Cruz et al. 2014).

Hermosillo is the capital city of Sonora state, with a population of 784,342 inhabitants (INEGI 2010) represents 27% of Sonora's population. Hermosillo has an annual precipitation of 250 mm and is mostly concentrated in July, August and September. Domestic water demand is mostly supplied from underground resources, 68 wells.

Hermosillo has been struggling with water scarcity for decades and as a measure to reduce water demand, Hermosillo has reduced the number of hours that tap water is available to the population to 3-5 hours a day, and this has been happening recurrently since 1998 (Ojeda de la Cruz 2013). Nonetheless, water consumption is expected to increase 57% by 2030 compared to 2006. The disparity between water demand and water availability generates a severe problem affecting the possibilities for economic and social growth.

Rainwater harvesting (RWH) is an ancient technique (Gould and Nissen-Petersen 1999) that has been especially adopted in areas with limited water availability either for rural or urban areas. Different studies evaluate the RWH performance in different approaches and different climates; some study the environmental aspects (Angrill et al. 2011; Farreny et al. 2011c), others the quality and quantity aspects (Farreny et al. 2011b; Rygaard et al. 2011b; Morales-Pinzón et al. 2012c) while others study the economic feasibility (Rygaard et al. 2010; Morales-Pinzón et al. 2014; Vargas-Parra et al. 2014).

In this study Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodologies are performed for six different scenarios of RWH system as an alternative supply of domestic water in Hermosillo.

8.2 Methodology

Potential rainwater supply and storage tank size were calculated using Plugrisost®, a free simulation model developed by Gabarrell et al. (2014), which evaluates the RWH potential and environmental impact of different water supply alternatives for urban use. The model estimates the potential rainwater supply based on historical daily rainfall statistics from 1971-1992 (CONAGUA 2011), a roof-runoff coefficient of 0.9, and the catchment area of each scenario, defined in table 8.1. Storage tank sizing calculations are a function of water demand.

LCA methdology (ISO 2006) and life cycle impact assessment (LCIA) results are calculated at midpoint level using ReCiPe (Goedkoop et al. 2013) and cumulative energy demand methods.

Based on LCC methodology (ISO 2008) two tools are selected to evaluate the economic performance of a RWH system: Initial Investment (II) and Present Value (PV).

8.2.1 System boundaries

System boundaries are set from a cradle to grave approach. Starting with the construction stage using materials that like-wise have required extraction and production and workforce. Each scenario requires a different amount and configuration of these items.

The next stage (use) considers the use of energy and materials during the useful life of the system. Based on the durability of the materials the lifetime of the RWH system was considered as 50 years.

At the end of 50 years, the end-of-life (EOL) stage includes the workforce to dismantle the system and transport of the materials to a waste management plant. Figure 8.1 shows the system boundaries for this study and its life cycle stages.

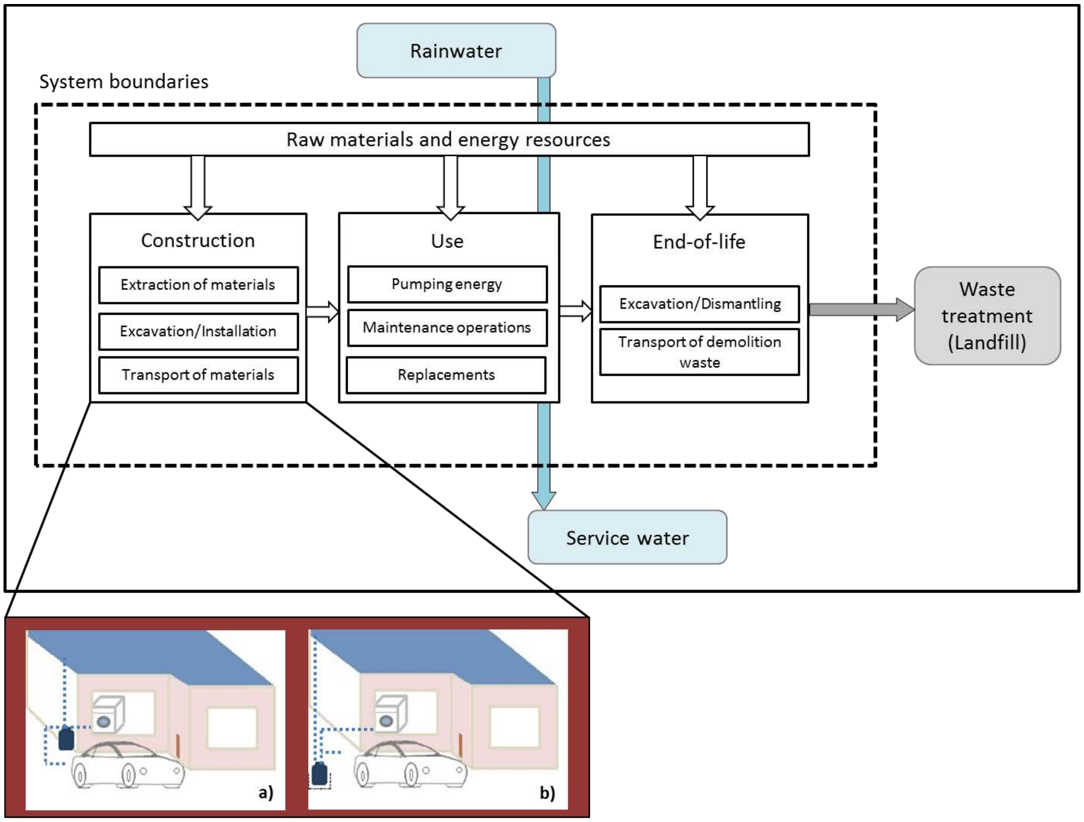


FIG 8.1 RWH SYSTEM BOUNDARIES AND BASIC COMPONENTS WITH THREE DIFFERENT STORAGE POSITIONS.

8.2.2 Functional unit

The functional unit for this study is 1 m^3 of rainwater supplied for domestic purposes, including laundry and car-washing. For the LCC study, NPV, IRR and PB were first calculated based on the construction, use and dismantling of a RWH system as a unit. Subsequently, results were divided by the amount of water supplied, in order to obtain the same functional unit: 1 m^3

8.2.3 Goal and scope

Three basic components were included: the rooftop was considered as the catchment area; the storage tank, installed at ground level or underground; and a delivery system to transport the rainwater from the catchment area to the storage facility and also from the storage facility to the house.To represent Hermosillo's most common house size in residential areas, three sizes were contemplated: 78 m^2,130 m^2 and 210 m^2. Varying the tank location, makes a total of 6 scenarios under study.

TABLE 8.1 SCENARIO DESCRIPTION.

Scenario	Catchment (m^2)	tank size (m^3)	max yield	demand (m^3/year)	demand (l/h/day)	offer (m^3/year)
78G 78U	78	1.1	95.6%	15.7	43.1	15.0
130G 130U	130	2.5	96.9%	15.7	43.1	15.2
210G 210U	210	2.5	99.0%	15.7	43.1	15.6

Data

Water demand was calculated for laundry and car-washing purposes. A laundry demand of 3 wash loads per week and a water consumption of 80 liters per load were considered in the calculations. Added to this, car-washing demand was calculated based on a weekly basis for one car in the case of 78-G and 78-U and two cars in the other four scenarios (130-G, 130-U, 210-G and 210-U). Each car-wash was calculated as 3.5 buckets per car and 18 liters per bucket.

Storage tank size and potential rainwater supply were calculated using Plugrisost®, a free simulation model developed by Gabarrell et al. (2014). The model estimated the potential rainwater supply based on historical daily rainfall data provided by CONAGUA (2011) from 1979 to 1998 for Hermosillo, a roof-runoff coefficient of 0.9, and the catchment area defined in Table 8.1 for each scenario. Storage tank sizing calculations are a function of water demand.

8.3 LCA

8.3.1 LCI

All inputs for the life cycle assessment are presented in Table 8.2 per functional unit.

TABLE 8.2 INVENTORY OF MATERIALS AND ENERGY PER FUNCTIONAL UNIT.

Stage	Input	Material description	Measuring unit	78-G	78-U	130-G	130-U	210-G	210-U
Construction	Steel, low-alloyed Metal working, average for steel product manufacturing	Pump aquor 0.5 HP	kg	2.96E-01	2.96E-01	2.46E-01	2.46E-01	2.41E-01	2.41E-01
	Polyethylene, HDPE, granulate Injection molding	Filter (units)	kg	4.02E-02	4.02E-02	3.35E-02	3.35E-02	3.28E-02	3.28E-02
	Polyvinylchloride, at regional storage/RER S Extrusion, plastic pipes	Pipe 4" (m)	kg	4.42E-01	5.30E-01	3.68E-01	4.41E-01	3.60E-01	4.32E-01
		Ball valve 4" (units)		1.77E-02	1.77E-02	1.48E-02	1.48E-02	1.45E-02	1.45E-02
		Pipe 3/4" (m)		1.57E-01	2.24E-01	1.30E-01	1.87E-01	1.28E-01	1.83E-01
		Ball valve 3/4" (units)		1.18E-02	1.18E-02	9.84E-03	9.84E-03	9.64E-03	9.64E-03
		Elbow 90 std 3/4" (units)		1.77E-02	2.66E-02	1.48E-02	2.21E-02	1.45E-02	2.17E-02
		Elbow 90 std 4" (units)		5.91E-02	4.73E-02	4.92E-02	3.94E-02	4.82E-02	3.86E-02
		T std 3/4" (units)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		T std 4" (units)		2.37E-02	1.18E-02	1.97E-02	9.84E-03	1.93E-02	9.64E-03
		Control unit		5.91E-02	5.91E-02	4.92E-02	4.92E-02	4.82E-02	4.82E-02
	Polyethylene, HDPE, granulate Injection molding	HDPE storage tank (0.75 m^3)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		HDPEstorage tank (1.1 m^3)		1.30E+00	1.30E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		HDPE storage tank (2.5 m^3)		0.00E+00	0.00E+00	2.46E+00	2.46E+00	2.41E+00	2.41E+00
Use	Electricity, low voltage {Mexico}	Electricity	kWh	1.02E+00	1.02E+00	8.49E-01	8.49E-01	8.32E-01	8.32E-01
	Steel, low-alloyed Metal working, average for steel product manufacturing	Pump aquor 0.5 HP	kg	8.87E-01	8.87E-01	7.38E-01	7.38E-01	7.23E-01	7.23E-01
	Polyethylene, HDPE, granulate Injection molding	Filter	kg	3.62E-01	3.62E-01	3.01E-01	3.01E-01	2.95E-01	2.95E-01
End-of-life	Transport, freight, lorry 3.5-7.5 metric ton, EURO3	Transport debris	tkm	1.18E+00	1.18E+00	9.84E-01	9.84E-01	9.64E-01	9.64E-01

8.3.2 Environmental impacts

Results are presented in Table 8.3, for each life cycle stage for selected impact categories Climate Change (CC; kg CO^2 eq), Ozone Depletion (OD; kg CFC-11 eq), Terrestrial Acidification (TA; kg SO^2 eq), Freshwater Eutrophication (FE; kg P eq), Photochemical Oxidant Formation (POF; kg NMVOC), Particulate Matter Formation (PMF; kg PM10 eq) based on the ReCiPe hierarchical midpoint characterization approach and the single method Cumulative Energy Demand (CED; MJ). Simapro 8 software was used to perform the LCA. Environmental analysis results are represented in Figure 8.1 for CC (kg CO^2 eq) impact category for all six scenarios in representation of the performance in most of the seven impact categories.

TABLE 8.3 ENVIRONMENTAL IMPACTS FOR SELECTED IMPACT CATEGORIES.

Impact categories	Unit	78-G	78-U	130-G	130-U	210-G	210-U
Climate change	kg CO2 eq	1.52E-03	1.59E-03	1.69E-03	1.75E-03	1.65E-03	1.71E-03
Ozone depletion	kg CFC-11 eq	1.75E-03	2.06E-03	1.46E-03	1.72E-03	1.43E-03	1.69E-03
Human toxicity	kg 1,4-DB eq	2.35E-03	2.47E-03	2.55E-03	2.65E-03	2.50E-03	2.60E-03
Photochemical oxidant formation	kg NMVOC	1.28E-02	1.30E-02	1.22E-02	1.24E-02	1.20E-02	1.22E-02
Terrestrial acidification	kg SO2 eq	1.14E-03	1.19E-03	1.28E-03	1.32E-03	1.25E-03	1.29E-03
Freshwater eutrophication	kg P eq	2.69E-03	2.82E-03	2.73E-03	2.84E-03	2.68E-03	2.78E-03
Cumulative Energy Demand	MJ	3.32E+02	3.45E+02	4.19E+02	4.29E+02	4.10E+02	4.21E+02

As seen on results table 8.3 and figure 8.2, scenario with best overall environmental outcomes is scenario 78-G, even though, for categories OD, POF and FE this is the second best scenario after 210-G. The higher impacts are obtained in scenario 130-U and in general scenarios with the tank installed underground have a slightly higher impacts than scenarios with the tank at ground level.

Construction stage contributes a 60% of all impact categories in average for all scenarios, reaching up to 99% in OD.

All scenarios have a need of electricity for pumping during the use stage, representing 30% of the total impact in most of impact categories and replacement materials considered within the use stage contribute a 90% in average for the use stage impact for all impact categories and all scenarios.

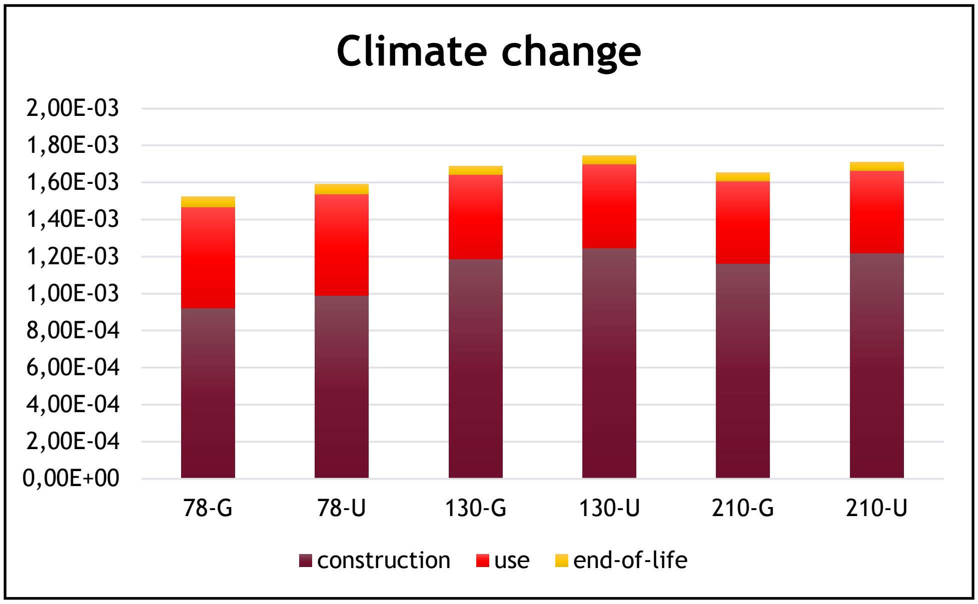


FIG 8.2 CLIMATE CHANGE IMPACT ASSESSMENT.

8.4 LCC

8.4.1 Data sources

Data on cost of materials, tools and equipment were obtained from Matarín Lobatón and Martínez Mendoza (2012) and from direct consultation with supply stores. Labor cost was obtained from (BIDECO 2015) next to this we validated the data by consulting a senior professional of water installations. Table 8.4 shows the description and general cost of the items considered in each life cycle stage: construction, use, and EOL.

TABLE 8.4 ITEM DESCRIPTION AND COST IN MEXICAN PESOS (MXN).

Stage	Input	Description	Unitary cost			Scenarios					
			Material	labor	Total	78-G	78-U	130-G	130-U	210-G	210-U
Construction	Materials	Pump aquor 0.5 HP (units)	1021.0		1021.0	1021.0	1021.0	1021.0	1021.0	1021.0	1021.0
		Downspout filter (units)	501.6		501.6	501.6	501.6	501.6	501.6	501.6	501.6
		Pipe 4" (m)	86.8		86.8	429.8	515.7	429.8	515.7	429.8	515.7
		Ball valve 4" (units)	850.0		850.0	850.0	850.0	850.0	850.0	850.0	850.0
		Pipe 3/4" (m)	7.0		7.0	23.7	34.0	23.7	34.0	23.7	34.0
		Ball valve 3/4" (units)	64.0		64.0	64.0	64.0	64.0	64.0	64.0	64.0
		Elbow std 3/4" (units)	6.0		6.0	12.0	18.0	12.0	18.0	12.0	18.0
		Elbow std 4" (units)	90.0		90.0	450.0	360.0	450.0	360.0	450.0	360.0
		T std 4" (units)	176.0		176.0	352.0	176.0	352.0	176.0	352.0	176.0
		Control unit (units)	3334.4		3334.4	3334.4	3334.4	3334.4	3334.4	3334.4	3334.4
		PVC storage tank (0.75 m3)	1499.0		1499.0	0.0	0.0	0.0	0.0	0.0	0.0
		PVC storage tank (1.1 m3)	1825.0		1825.0	1825.0	1825.0	0.0	0.0	0.0	0.0
		PVC storage tank (2.5 m3)	4099.0		4099.0	0.0	0.0	4099.0	4099.0	4099.0	4099.0
	Services	underground tank installation (unit)	0.0	350.0	350.0	0.0	350.0	0.0	350.0	0.0	350.0
		Construction workers (laborer and foreman) (hours)	0.0	291.7	291.7	2333.3	6999.8	2333.3	6999.8	2333.3	6999.8
Use	Energy	Electricity (kWh/year)	0.6	0.0	0.6	10.2	10.2	10.2	10.2	10.2	10.2
	Services	Maintenance workforce	0.0	216.7	216.7	216.7	216.7	216.7	216.7	216.7	216.7
	Materials	Pump aquor 0.5 HP	1021.0	0.0	1021.0	1021.0	1021.0	1021.0	1021.0	1021.0	1021.0
		Filter	501.6		501.6	501.6	501.6	501.6	501.6	501.6	501.6
End-of-life	Transport	Transport debris up to 3 m3 (unit)	1125.0	400.0	1525.0	1525.0	1525.0	1525.0	1525.0	1525.0	1525.0
	Services	Construction workers (laborer and foreman) (hours)	0.0	291.7	291.7	2333.3	4666.6	2333.3	4666.6	2333.3	4666.6

8.4.2 Costs and savings by life cycle stage

Construction stage costs

This stage considers all the necessary materials and labor costs associated to construct and install a RWH system in Hermosillo. Table 8.4 describes the items considered as inputs to the system. Each scenario requires a different amount and configuration of these items.

Use stage costs and savings

The use stage considers the maintenance and replacement costs, associated to the operation of the RWH system during its lifespan. In our study, an examination of all the costs associated to the suitable performance of the facilities during their lifetime was considered (Table 8.4). These costs include the electricity (an average of 0.59 Mexican pesos per kWh (COEES 2012)) for pumping water on a yearly basis as well as the equipment and material replacements necessary to keep the system in proper operating conditions, i.e. replacement of the pumps and filters every fifteen and five years respectively, as well as the labor costs associated to this activities.

During the use stage the reduction in tap water consumption for laundry was considered as savings. Tap water cost was obtained from Hermosillo's water services webpage for each scenario.

Water demand for laundry was calculated for each scenario per year and household, considering an average of 75 liters per washing cycle and 3 cycles per week and household.

End-of-life costs

Dismantling the RWH system was considered as labor and transport of rubble to landfill within a maximum distance of 20 km from where it was installed.

8.4.3 Financial tools

According to the ISO 15686-5, different financial techniques or indicators may be used in LCC (ISO 2008) depending on the requirements of the investors. Nevertheless, Initial Investment (II) and Present Value (PV) are commonly used to evaluate among different options.

Initial Investment (II, MXN pesos) accounts for all costs incurred to set a RWH system, including material and labor.

Present value (PV, MXN pesos) indicates the discounted value of all revenues generated by each scenario. It accounts for all future incomes/outcomes over the 50 years of lifespan of the system, and it can be expressed as follows in Equation 8.1:

$$\boldsymbol{PV} = \frac{C_i}{(i+r)^n} \qquad \text{EQUATION 8.1}$$

Where:

C_i= Cash flow at period i.

r= discount rate

n= number of periods

In this study we consider an inflation rate of 4.08% during a lifetime of 50 years and a discount rate of 3% published by the National Bank of Mexico (Banco de México 2014).

8.4.4 LCC results

Results are presented in Table 8.5 for each scenario in MXN. As expected, II is slightly higher in scenarios with the tank installed underground compared to those at ground level while PV depends more on the water savings and therefore is higher in scenarios 130 and 210 since this scenarios have the same tank size and same water savings. Figure 8.3 shows the cash flows before inflation for each scenario disaggregated by life cycle stage, demonstrating one more time that the construction stage is the one with more weight with a contribution of 70% in cost of materials and labor, next to this is the use stage that accounts for savings in tap water and costs of electricity for pumping and all replacements and maintenance services, and in balance it accounts for a 7% of cash flow, lastly, end-of-life contributes with a 23% of all cash flow due to labor and transport of rubble.

TABLE 8.5 LCC RESULTS

Scenario	II	PV
78-G	11,196.76	16,120.40
78-U	16,049.50	16,120.40
130-G	13,470.76	16,123.76
130-U	18,323.50	16,123.76
210-G	13,470.76	16,123.76
210-U	18,323.50	16,123.76

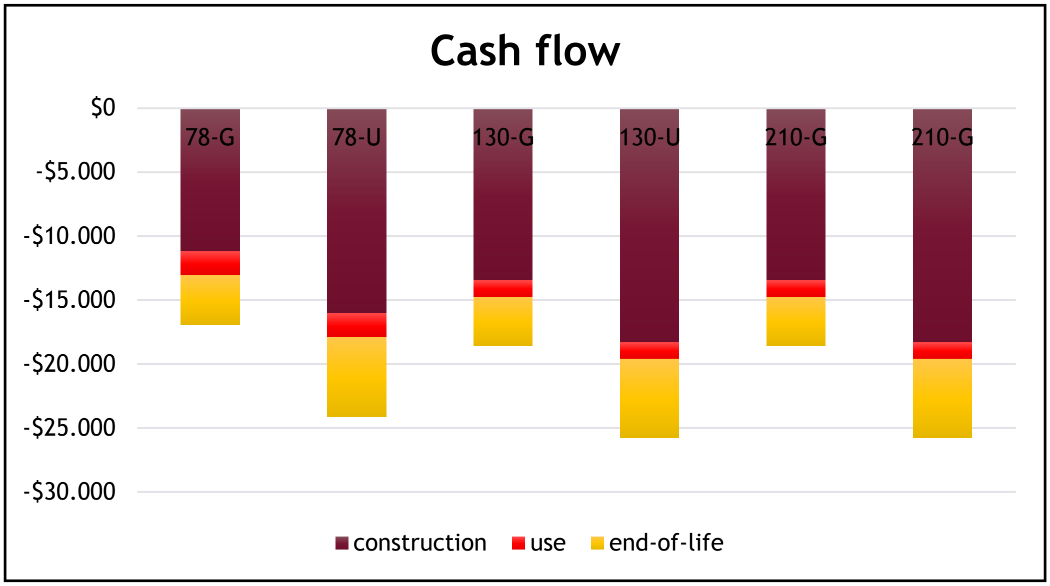


FIG 8.3 CASH FLOW BY LIFE STAGE FOR EACH SCENARIO.

8.5 Sensitivity analysis for LCA and LCC

All calculations were based on the demand of rainwater, but what would happen if that demand was different, for instance, we can presume that it is easier to connect the rainwater tank directly to the washing machine or we could try to benefit from all available rainwater and use it later for other purposes, like garden watering. Based on these assumptions, two different studies are proposed for a sensitivity analysis.

Alternative “Only laundry”: Rainwater is only used for laundry and therefore tank sizing is based on this demand, characteristics of this alternative are presented in table 8.6.

TABLE 8.6 ALTERNATIVE “ONLY LAUNDRY” DESCRIPTION

Scenario	tank size (m^3)	max yield	demand		offer
			(m^3/year)	(l/viv/dia)	(m^3/year)
78	0.75	95.65%	12.48	34.19	11.94
130	1.1	96.97%	12.48	34.19	12.10
210	1.1	97.14%	12.48	34.19	12.12

Alternative “All in”: Maximum collection of rainwater was calculated based on the area of collection, average pluviometry of 250 mm/m^2/year, a 0.9 runoff coefficient and 0.9 filter efficiency, and then assumed as demand. Details for this alternative are described in table 8.7.

TABLE 8.7 ALTERNATIVE “ALL IN” DESCRIPTION

Scenario	tank size (m^3)	max yield	demand (m^3/year)*	demand (l/viv/dia)	offer (m^3/year)
78	1.1	95.65%	15.76	43.17	15.07
130	2.5	96.97%	15.76	43.17	15.28
210	2.5	99.01%	15.76	43.17	15.60

8.5.1 Sensitivity LCA results

LCI for both alternatives can be found in Appendix III tables III.1 and III.2.

Results are represented in figure 8.4 for climate change impact assessment for all scenarios. Full results can be found in Appendix III table III.3 and III.4. As seen on figure 8.4 for climate change, alternative “only laundry” has higher impacts in all scenarios. Alternative “all in” shows lower climate change impact, reducing impacts in 7%, 30% and 60% compared to “laundry and car-washing” first study 78, 130 and 210 scenarios respectively. These results reflect the increase in rainwater collection, since with the same tank size as “laundry and car-washing” the system can supply more 7%, 50% and 100% more in alternative “all in”.

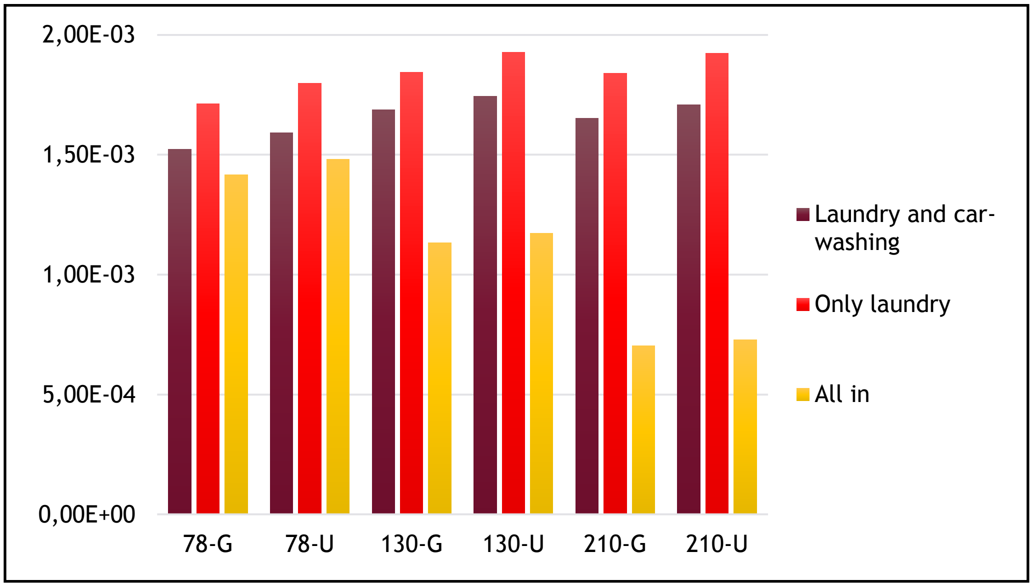


FIG 8.4 CLIMATE CHANGE FOR ALL OPTIONS.

8.5.2 Sensitivity LCC results

Item description and costs for both alternatives can be found in Appendix III tables III.5 and III.6.

Results for the sensitivity analysis in LCC are presented in table 8.8 for II per m^3. From this table we can clearly see that II can vary in a 20% up or down in "all in" and "only laundry" alternatives. LCC's sensitivity results are not far from the first option, Table III.7 in Appendix III shows that scenarios with the tank installed at ground level need an II of 10,870 – 13,470 MXN and those with the tank underground need an II of 15,723 – 18,323 MXN with slightly lower needs when is only calculated for laundry purposes.

The lowest investment per cubic meter of rainwater supplied is found in scenario 210-G alternative "all in". Alternative "all in" is the best option for all scenarios. The most expensive option for all scenarios is alternative "Only laundry" with the highest II (Table 8.8)

TABLE 8.8 INITIAL INVESTMENT RESULTS FROM SENSITIVITY ANALYSIS IN MXN PER M^3.

Scenario	Laundry and car-washing	Only laundry	All in
78-G	14.86	18.21	14.85
78-U	21.30	26.34	21.29
130-G	17.63	18.50	10.72
130-U	23.99	26.52	14.58
210-G	17.27	18.47	6.67
210-U	23.49	26.48	9.07

8.6 Conclusions

This study provides an accurate inventory of materials and labor necessary to install a RWH system in Hermosillo with an average precipitation of 250 mm/year, along with the results from the environmental and economic analyses.

Results show that for both environmental and economic studies, the best option is to design RWH systems to collect all rainwater possible, no matter what the size of collection area is.

Both environmental and economic analyses for all scenarios were found very similar among each other, and the difference is made when the demand and therefore the tank size is gauged.

Environmental impacts are reduced in up to 60% when the system is designed to collect all possible rainwater.

Initial investment costs are comparable to the cost of a washing machine, however, current savings are not correspondent with costs of maintenance.

Future research should consider several factors to extend this study:

1. A comparison with alternative solutions such as the “Independencia” aqueduct that is currently supplying 35% of Hermosillo’s demand and other alternatives as desalinated water.
2. Climate change effect in pluviometry, since this could affect greatly.
3. Water price forecasts.
4. Tap water quality conditions: contamination and hardness.

Part IV.

Integration

9

DEA for Mediterranean cases

Chapter 9 DEA for Mediterranean cases.

based on a manuscript by: M. Violeta Vargas-Parra, Francisco Vargas-Serrano, Xavier Gabarrell, Gara Villalba and M. Rosa Rovira-Val..

Abstract

Environmental and economic costs related to water supply are expected to increase as urban water demand rises with urban population growth. As an alternative to conventional water treatment, cities can benefit from rainwater harvesting (RWH) systems to meet part of urban water demand. However, the performance of RWH systems in different ambits is not always clear, especially if the target is to obtain the best results in all ambits.

The aim of this study is to evaluate Rainwater Harvesting (RWH) systems performance in, in terms of exergy as input and rainwater supply, avoided environmental impact and value creation as outputs, through an input-oriented variable returns to scale (VRS) data envelopment analysis (DEA) model applied to 15 decision making units (DMUs) located in urban areas with Mediterranean climate conditions

DMUs have been classified in three classes, LD group considers single family houses, HD group considers buildings of 24 apartments and N group considers large groups of buildings in representation of actual neighborhoods in Barcelona.

After applying DEA, three DMUs were found at the frontier, belonging to the HD and N classes. LD group was not able to reach the exergetic-efficient benchmark. HD2, N4 and N6 met the efficient use of exergy resources to supply rainwater for laundry purposes, avoiding environmental impacts with a value creation.

9.1 Introduction

As population increases and standards of living improve, limited natural resources become insufficient to satisfy human demands. However, engineering has been adapted to the demands of a society more concerned with environment, by adding sustainability as a general objective. The essentials for sustainability are environmental protection as well as economic and social development.

Within natural resources, freshwater and energy are indispensable for human well-being and socio-economic development (WWAP 2009). Moreover, water and energy are tightly interlinked and are highly interdependent, this linkage is known as the water-energy nexus. Water is required in production, transportation and energy generation. Likewise, energy is necessary for extraction, treatment and distribution of water, as well as to discharge wastewater. Furthermore, water supply in urban areas will be more costly and energy intensive as urban population increases.

Rainwater harvesting (RWH) could reduce environmental and economic loads associated to water supply in urban areas. Additionally, efficiency is directly linked to cost containment and cost reduction. Moreover, increases on energy prices and environment pollution concerns, highlight the need for processes improvement.

Measuring the efficiency of a RWH system is difficult and challenging. Different methodologies and approaches have been recently used to assess RWH systems. From an environmental approach, Angrill et al. (2011) assessed 8 different urban scenarios using a Life Cycle Approach (LCA), Vargas-Parra et al. (2013) did it from a resource consumption approach using exergy analysis and exergy efficiency. From a social perspective Domènech and Saurí (2011b)analyzed the perception of society towards the implementation of RWH systems. Farreny et al. (2011a) and Vargas-Parra et al. (2014) performed a cost-effective analysis of RWH systems in the Metropolitan Area of Barcelona. The quantitative potential has been studied in different countries with different approaches: (Farreny et al. 2011b; Rygaard et al. 2011a; Morales-Pinzón et al. 2012c) are only a few. This diversification in criteria and methodologies tends to limit the identification of best practices that could be of reference towards sustainability.

Data Envelopment Analysis (DEA) can lead to a best-practice-frontier (Cook et al. 2014).This methodology has been applied to evaluate other water related practices, such as wastewater treatment (Hernández-Sancho and Sala-Garrido 2009). In this study we aim to find the best-practice frontier analyzing 15 different Rainwater Harvesting (RWH) Systems for urban areas.

9.2 Methodology

DEA is a linear programming method that aims to measure the efficiency of different units, called decision-making units (DMUs). Each unit consumes inputs to produce outputs, and are the object of analysis.

In DEA, the efficiency score can never exceed the value of 1. An efficient DMU is the one that cannot increase its outputs quantities while its inputs are fixed, and vice versa. These efficient DMUs will act as reference for the rest of DMUs.

9.2.1 Variable returns to scale model

According to Zhu (2014), in this model, the identified best-practice frontier envelops all the observations (DMUs). The shapes of best-practice (or efficient) frontiers obtained from these models can be associated with the concept of variable returns to scale (VRS). As a result, this best-practice frontier is called VRS frontier. A DMU is considered not efficient, when it can produce more output with fixed inputs or when it can reduce its inputs to produce the same outputs. In fact, there are two ways to improve the performance of DMUs. One is to reduce its input to reach the frontier, and the other is to increase its output to reach the frontier. As a result, DEA models will have two orientations: input-oriented and output-oriented. An input orientation refers to the emphasis on the evaluated DMUs inputs that can be proportionally expanded without altering the output quantities (Fukuyama 2014). The following set of equations describes the input oriented VRS model (Equation 9.1):

$$\Theta^{*} = \min \Theta$$

Subject to

$$\sum_{j=1}^{n}\lambda_j x_{ij} \leq \Theta x_{\iota o} \qquad i=1,2,\ldots,m;$$

$$\sum_{j=1}^{n}\lambda_j y_{rj} \geq Y_{RO} \qquad R=1,2,\ldots,S;$$

EQUATION 9.1

$$\sum_{j=1}^{n}\lambda_j = 1$$

$$\lambda_j \geq 0 \qquad j = 1,2,\ldots,n.$$

Where DMU_{Θ} represents one of the n DMUs under evaluation, and $x_{\iota o}$ and y_{ro} are the i_{th} input and r_{th} output for DMU_{Θ}, respectively.

Since $\Theta=1$ is the optimal value to 9.1 equation, $\Theta^{*} \leq 1$. If $\Theta^{*} = 1$, then the current input levels cannot be reduced proportionally, indicating that DMU_{Θ} is on the frontier. Otherwise, if $\Theta^{*} \leq 1$, then DMU_{Θ} is dominated by the frontier. Θ^{*} represents the input oriented efficiency score of DMU_{Θ}.

The goal of this study is to evaluate the DMU's efficiency in exergy use in order to reach a given level of outputs, under three criteria, rainwater supply, environmental protection and economic value.

9.2.2 Data and variables

According to our goal, four variables have been selected, one input: exergetic resource consumption (X1;MJ), and three outputs: potential rainwater supply (Y1;m^3), avoided climate change effect (Y2;kg CO2 eq) and net present value (Y3;euros)

Information for 15 DMUs has been compiled and it has also been classified in three classes: LD, HD and N. DMU’s description is shown in table 9.1 and statistical information in table 9.2.

TABLE 9.1 DMUS DESCRIPTION.

Scenario	Construction type	Scale		Tank size (m^3)	Tank layout	Catchment area (m^2)	Rainwater supply (m^3/year)	Laundry demand (m^3/year)	Rainwater supply / Laundry demand
LD1	Individual	1 Household		5	Underground	250	24	25	98%
LD2				5	Below roof	250	24	25	98%
LD3				9	Spread on roof	250	24	25	98%
LD4	Cluster	4 Household		20	Underground	1000	99	100	99%
HD1	Individual	1 Building	24 households	20	Underground	700	283	600	47%
HD2				20	Below roof	700	283	600	47%
HD3				21	Spread on roof	700	283	600	47%
HD4	Cluster	10 Buildings	240 households	209	Underground	7000	2824	6000	47%
N1	Cluster	215 Buildings	2580 households	4000	Underground	103207	27428	33542	82%
N2	Cluster	394 Buildings	6307 households	7500	Underground	118256	49268	81991	60%
N3	Cluster	385 Buildings	7703 households	9000	Underground	115553	54109	100146	54%
N4	Cluster	574 Buildings	13778 households	7000	Underground	172228	70232	179118	39%
N5	Cluster	388 Buildings	10858 households	7000	Underground	116333	53454	141150	38%
N6	Cluster	465 Buildings	14866 households	8000	Underground	139370	64723	193260	33%
N7	Cluster	307 Buildings	11062 households	4500	Underground	74976	36412	143806	25%

TABLE 9.2 DMUS SUMMARY STATISTICS.

Variable	Inputs	Outputs		
	X1	Y1	Y2	Y3
Statistics	Exergetic resource consumption (MJ)	water supply (m^3)	climate change avoided impacts (kg CO^2 eq)	NPV (euros)
Mean	1.61E+02	3.47E+04	4.54E+04	1.86E+07
Standard error	3.51E+01	1.37E+04	1.93E+04	8.07E+06
Median	1.49E+02	4.09E+03	2.82E+03	7.58E+05
Standard deviation	9.92E+01	3.88E+04	5.46E+04	2.28E+07
Sample variance	1.05E+04	1.62E+09	3.19E+09	5.58E+14
Kurtosis	-1.15E+00	-1.59E+00	-8.56E-01	-8.04E-01
Skewness Asymmetry coefficient	2.14E+00	5.15E-01	8.06E-01	8.45E-01
Range	4.27E+02	1.02E+05	1.57E+05	6.57E+07
Minimum	4.82E+01	3.54E+01	2.45E+01	1.21E+03
Maximum	4.75E+02	1.02E+05	1.57E+05	6.57E+07
Sum	2.41E+03	5.20E+05	6.80E+05	2.78E+08
Count	15	15	15	15

Calculations and all assumptions made in the design of DMU's can be found in previous chapters, for exergy input calculations consult chapter 3 and 4, and for RWH systems design and all outputs consult chapters 5, 6 and 7.

9.3 DEA Results

Table 9.3 shows the exergy efficient results under input oriented VRS data envelopment model. The DMUs who reached the number one score, represents the best performance.

TABLE 9.3 EFFICIENCY SCORE.

Exergy Efficiency		
Number	DMUs	Score efficiency
1	HD1	0.646428
2	HD2	1
3	HD3	0.911522
4	HD4	0.511777
5	LD1	0.209069
6	LD2	0.224417
7	LD3	0.336729
8	LD4	0.101381
9	N1	0.404297

10	N2	0.655021
11	N3	0.730633
12	N4	1
13	N5	0.770671
14	N6	1
15	N7	0.816271

Figure 9.1 shows the DMUs relative exergy efficiency results. HD2, N4 and N6 reaching the best performance.

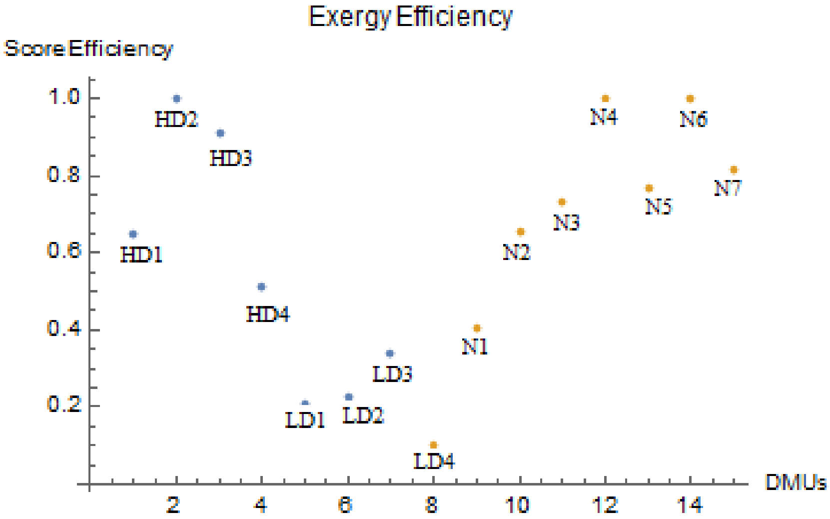


FIG 9.1 RELATIVE EXERGY EFFICIENCY.

It can be observed that the lowest exergy efficiency is achieved by the LD scenarios. The lowest exergetic inputs by outputs are found in the efficient DMUs HD2, N4 y N6

The VRS DEA model discriminatory power is confirmed by the dendrogram plot as can be seen in Figure 9.2

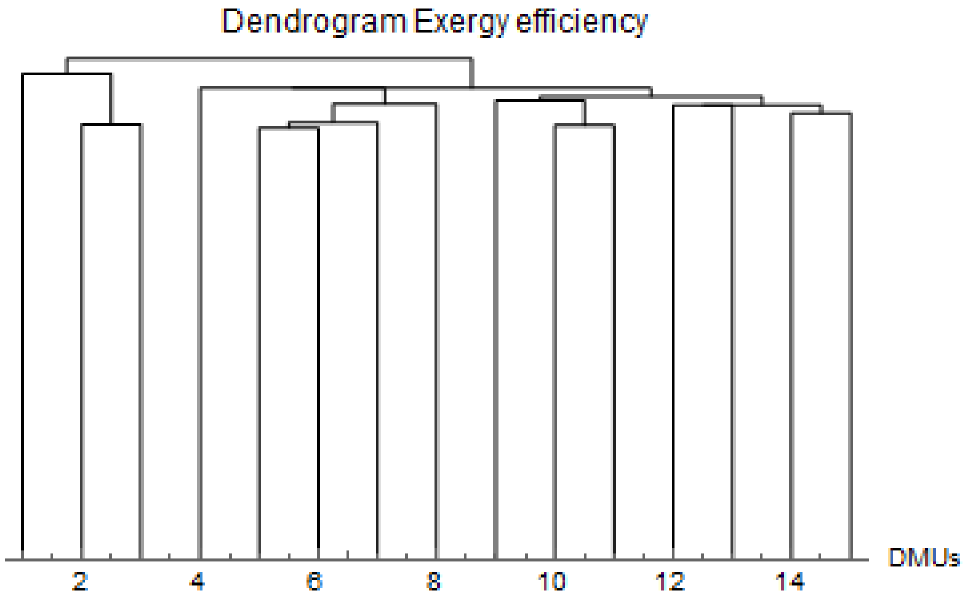


Fig 9.2 Dendrogram exergy efficiency.

There are two clusters, the best performance exergy efficiency DMUs are located in the first cluster from the left to right.

The DMUs location over the exergy efficiency frontier can be seen in Figure 9.3 for rainwater supply and for the other outputs in Appendix IV figures IV.1 and IV.2

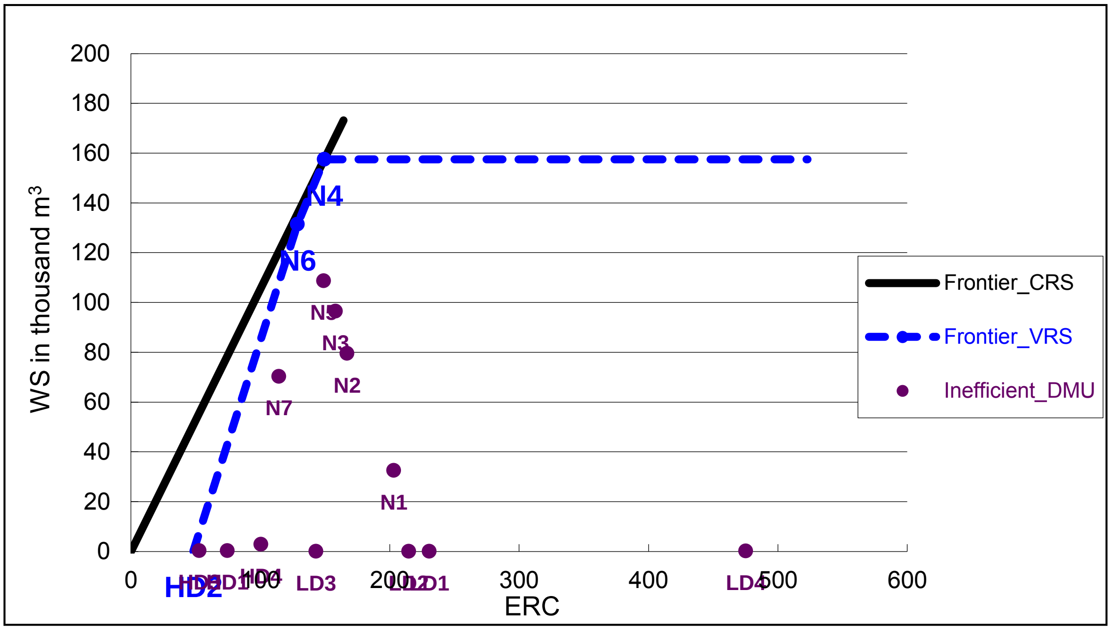


Fig 9.3 Exergy efficiency frontier

Efficient DMUs correspond to those scenarios with better use of resources in order to supply rainwater and therefore avoid CO^2 emissions from detergent consumption and also obtain an economic profit.

HD2 is an efficient DMU because compared with the other DMUs it has the lowest exergy input and obtains a relatively high amount of outputs. N4 and N6 on the other hand do not hold the lowest inputs yet they do have the highest outputs of all DMUs

9.4 Conclusions

Given the need of a tool that helps evaluate different options of RWH systems in different contexts in order to find best-practice, DEA has proven to be a practical decision support tool.

An input-oriented variable returns to scale (VRS) model has been run in order to identify the best performance of 15 decision making units (DMUs), operating in Barcelona as options for rainwater collection in urban areas, classified in three groups: LD, HD and N.

LD, HD and N are differentiated by the scale; LD considers single family houses, HD considers buildings of 24 apartments and N considers large groups of buildings in representation of actual neighborhoods in Barcelona.

In the model, DMUs are conceived to consume exergy to generate value through rainwater supply, avoiding environmental impacts. Therefore, exergy is an input and rainwater supply (WS), value creation (NPV) and CO^2 avoided are outputs.

It is found that DMUs HD2, N4 and N6 are at the benchmark, meanwhile, none of the DMUs from LD group reached the exergetic efficiency frontier.

Part V.

Conclusions

10

Discussion

Chapter 10 Discussion

From the study of the environmental and economic aspects of Rainwater Harvesting (RWH) systems in different configurations and climates in this thesis, a potential reduction in environmental impacts and a capability of increase in economic savings have been identified from a sustainable perspective.

In this chapter, a summary of the relevant findings will be discussed.

10.1 Objective achievement.

Objective I – To assess the environmental performance of rainwater harvesting systems.

From the application of Life Cycle Assessment (LCA), larger and more densely populated scenarios proved to obtain better environmental outcomes in **Chapter 6** and **Chapter 7**. **Chapter 8** does not include a population density variation, though, it also indicates that larger scales lead to improved results when “all in” alternative is analyzed.

Chapter 6 determined that scenario HD3, which is constituted by one building and 24 households with the tank spread on the roof and collects 283 m^3/year, has the lowest environmental impacts in most categories, except for Ozone Depletion (OD). This chapter also shows the avoided impacts from the difference in detergent consumption when soft rainwater is used instead of hard tap water for domestic laundry, reaching around 50% impact reduction in most scenarios.

This chapter also identified the importance of the location of the storage facility and the positive effect of avoiding energy consumption during the stage of use to pump rainwater for laundry and also the elusion of all impacts associated to the replacement of the pump itself. Furthermore, the waterproofing materials were proven to increase environmental impacts during the construction stage.

Chapter 7 continued increasing population density and scenarios were based on real Barcelona neighborhoods with densities ranging from 8557 to 59305 inh/km^2 studied in seven scenarios. In this chapter all scenarios have the tank installed underground and therefore differing from previous chapter in tank location and tank materials.

This chapter proved once more that larger and more densely populated areas obtain better environmental results, with up to 40% lower environmental impacts than the other scenarios in all impact categories. Also, during the construction stage, pipes and energy consumption were found the highest charges in environmental impacts. Other important factors are the size of the tank, which in the best environmental scenario N7 is a 5,000 m^3 storage tank, and the amount of rainwater that can potentially be supplied. Scenario N7 is comprised by 307 buildings and 11,062 households and the major difference with the rest of scenarios is the small size of the tank that is up to five times smaller than the other scenarios except for N1 that has the smallest of all the tanks with a capacity of 4,000 m3, in this case the disparity is given by the amount of potential rainwater supply, that is half of N7 potential supply, resulting in higher environmental impacts per Functional Unit (FU).

Considerably different and at the same time, to a certain point expected, **Chapter 8** differs from **Chapters 6** and **7** greatly. Environmental impacts of all arid scenarios are very similar in almost all impact categories, except for Cumulative Energy Demand, where a small difference is spotted as a result of the tank size difference.

One of the main findings of this chapter is that environmental impacts are reduced in a 60% per FU when the demand is calculated for “all in” option, where the tank is sized to harvest as much as possible rainwater doubling the tank capacity and increasing the potential supply per year in a 30% for scenarios 78-G and 78-U and increasing more than three times in scenarios 210-G and 210-U.

In general, avoided environmental impacts account for 50% of the environmental burdens of a RWH system life cycle. Increasing potential rainwater supply reduces environmental impacts per FU.

Objective II – To assess the economic performance of rainwater harvesting systems. (Chapters 5, 6, 7 and 8)

As a result of the economic assessment of RWH systems, feasibility and viability are determined through the application of financial tools. **Chapter 5** determined the cost-efficiency of eight scenarios under Mediterranean conditions from a life cycle perspective. Scenario HD4 was demonstrated as the best option with the highest Net Present Value (NPV) of €983,227 and a short Payback time (PB) of 3 years.

Through the use of Life Cycle Costing (LCC), again as in LCA, more densely populated scenarios demonstrated better results in **Chapters 5**, **6** and **7**.

Chapter 6 demonstrated that scenario HD4, which is constituted by ten buildings and 240 households with the tank underground and potentially supplying 2824 m^3/year, has the best economic performance with a NPV of €664,645 and a PB of 2.59 years because it requires a lower rate of initial investment per FU and also because savings from less detergent consumption are the highest with the highest number of users/washing machines.

Location of the tank was identified as an influential factor in the viability of RWH systems, as energy for pumping and replacement materials during the use stage can result in lower profits (savings).

Chapter 7 proved that as higher the amount of potential rainwater supply, the better results are obtained, and this is due to savings in detergent consumption when hard tap water is substituted by soft rainwater for laundry. Scenario N4, which consists of 574 buildings, 13,778 households and a potential rainwater supply of 157,444 m^3/year has the best economic performance with the highest NPV amongst all scenarios.

Chapter 8 showed that in arid areas with soft tap water, savings from substituting tap water with rainwater for only laundry are not as high as the initial investment and maintenance expenses during the lifetime of the RWH system. However, increasing the demand and recalculating the tank size, the potential rainwater supply can be tripled in scenarios with 210 m^2 of collection surface.

In **Chapters 5**, **6** and **7** the more densely populated, the better results are obtained because savings depend on the number of washing machines that are reducing detergent consumption when tap water is harder than rainwater.

Objective III. To assess the resource use efficiency in rainwater harvesting systems.
Through the application of Exergy Analysis (ExA) in **Chapter 3** and **Chapter 4**, resource consumption efficiency was evaluated for eight and seven scenarios correspondingly. **Chapter 3** found that scenario HD2, which is composed of one building and 24 households with the tank installed on the roof, is the most resource efficient scenario, mainly as a result of the absence of energy requirements in the construction stage, and also due to a higher quantity of useful output. ExA was found especially useful identifying the sensitivity to the transport of materials, making evident that production of materials represents a minor contribution against the transport. **Chapter 4,** which studies seven neighborhood scenarios determined scenario N7 as the best scenario in resource consumption. It also identified the construction stage as the highest resource consuming stage and that is especially useful in finding potential for improvement in energy savings and material consumption reduction.

Objective IV – To study the productive efficiency and estimate the production frontiers of rainwater harvesting systems.
Chapter 9 determined that through an input-oriented variable returns to scale (VRS), the best performance Decision Making Units (DMUs) out of 15 DMUs are HD2, N4 and N6, corresponding to an exergetic resource consumption of 48 MJ/m3, 149 MJ/m3 and 128 MJ/m3 respectively, with three outputs: rainwater supply (WS) of 283 m3, 70,232 m3 and 64,722 m3 respectively, value creation (NPV) of €74,694, €65,648,052 and €55,068,863 correspondingly and CO^2 avoided of 409 kg CO^2 eq, 101,612 kg CO^2 eq and 93,641 kg CO^2 eq respectively.

10.2 Methodological aspects

The methodologies applied in this thesis were useful in the assessment of RWH systems and its comparison in different scenarios.

Exergy Analysis (ExA) has been proved as a useful tool to evaluate and identify origin and potential resource consumption reduction, main contributions linked to ExA are listed below:

- Major finding is that the exergetic inefficiency of the RWH systems derives from the transport of materials and not from the materials per se.

- From a life cycle perspective an exergy inventory was calculated for all scenarios.
- Exergetic efficiency was identified for each scenario, showing opportunities for improvement.

Life Cycle Assessment (LCA) was an effective tool to evaluate the environmental performance of RWH systems, the following outcomes are directly associated to LCA:

- One of the main contributions is the inclusion of the detergent savings in the environmental performance of RWH systems in urban areas with hard water problems. Results exhibit Barcelona's environmental impact avoidance, although, could be applied to other areas with similar conditions of hard water.
- The use of LCA to evaluate a RWH system with a lifespan of 50 years including the construction, use and dismantling of the system, considering all materials and energy needed through the entire lifetime.
- LCA was useful to compare different scenarios, detecting the most environmental friendly solution amongst a variety of configurations.
- An accurate Life Cycle Inventory (LCI) of all materials and energy was provided for all scenarios.

Life Cycle Costing (LCC) was a convenient tool to assess the economic performance of RWH systems,

- Data collection and validation process for the economic inventories was very meticulous, thus providing an accurate cost inventory.
- Savings on detergent consumption turn out to be a main advantage for scenarios in areas with hard tap water problems.
- "The more, the merrier". In areas with hard tap water more users means more savings from detergent consumption and therefore better economic results.
- In dry arid areas with soft tap water, savings are not comparable to the cost of implementation, even when all rainwater is collected the initial investment is much higher than the life savings.

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Appendix I. Supplementary material related to Chapter 3.

TABLE I.1. EXERGY FLOW ANALYSIS CONSIDERING MATERIAL PRODUCTION.

STAGE	INPUT	LD1	LD2	LD3	LD4	HD1	HD2	HD3	HD4
Production	Materials	6.734,14	9.804,09	4.460,80	43.778,73	40.193,78	36.951,78	19.593,05	347.521,77
	Material production	37.567,40	58.124,13	22.670,68	144.878,10	201.531,58	196.130,68	93.647,27	1.311.807,90
	Energy	64.674,02	-	-	941.523,56	258.389,09	-	-	4.991.606,65
	Transport	71.127,34	99.145,21	69.139,18	189.154,02	198.611,60	198.521,38	295.636,67	1.783.880,87
Use	Energy	600,00	-	-	4.800,00	59.304,96	-	-	118.609,92
End-Of-Life	Energy	47.327,79	26.704,58	13.309,94	842.328,01	150.608,63	98.879,12	55.901,76	3.806.471,91
	Transport	91.561,72	127.083,35	88.191,82	330.974,86	347.525,62	347.367,72	376.767,18	3.121.746,85
TOTAL EXERGY CONSUMPTION (50 years)		319.592,41	320.861,37	197.772,43	2.497.437,30	1.256.165,26	877.850,68	841.545,93	15.481.645,86
EXERGY CONSUMPTION (1m3/year/household)		261,16	262,20	161,61	504,53	88,77	62,04	59,47	109,64

	LD1	LD2	LD3	LD4	HD1	HD2	HD3	HD4
PRODUCTION Efficiency	24,60%	40,66%	28,18%	14,30%	34,60%	54,00%	34,47%	19,67%
USE Efficiency	0,28%	100,00%	100,00%	0,14%	0,03%	100,00%	100,00%	0,16%
End-Of-Life Efficiency	24,18%	30,64%	21,09%	13,85%	32,67%	34,31%	20,74%	19,32%
TOTAL SCENARIO EFFICIENCY	0,02%	12,46%	5,94%	0,00%	0,00%	18,53%	7,15%	0,01%

TABLE I.2. GLOBAL EXERGY EFFICIENCY CONSIDERING MATERIAL PRODUCTION.

Appendix II. Supplementary material related to Chapter 6

TABLE II.1. COST INVENTORY

Stage	Input	units	Material cost	Labor cost	Total	LOW DENSITY								HIGH DENSITY							
						LD1		LD2		LD3		LD4		HD1		HD2		HD3		HD4	
						QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST
Construction stage	5.800 litres, prefabricated concrete tank	unit	2083.00		2083.00	1.00	2,083.00	1.00	2,083.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-
	21.000 litres, (3) prefabricated concrete tank	unit	5670.00		5670.00	0.00	-	0.00	-	0.00	-	1.00	5,670.00	1.00	5,670.00	0.00	-	0.00	-	0.00	-
	40.000 litres, (5) prefabricated concrete tank.	unit	11298.00			0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	1.00	11,298.00	0.00	-	4.00	45,192.00
	11.600 litres, (2) prefabricated concrete tank.	unit	3665.00			0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	1.00	3,665.00
	Pavement & installation	m2	14.09	7.42	21.51	0.00	-	0.00	-	100.00	2,150.56	0.00	-	0.00	-	0.00	-	420.00	9,032.34	0.00	-
	Sand backfilling	m3	27.72	1.26	28.98	1.00	28.98	0.00	-	0.00	-	2.00	57.95	2.00	57.95	0.00	-	0.00	-	4.00	115.90
	Reinfo	kg	0.85	0.2	1.1	0.00		0.00		126.00		0.00		0.00		0.00		324.32		0.00	

rced concrete for pillars			5	0		-		-		138.62		-		-		-		356.81		-
Reinforced concrete for walls	kg	0.85	0.40	1.25	0.00	-	0.00	-	126.00	157.63	0.00	-	0.00	-	0.00	-	324.32	405.72	0.00	-
Reinforced concrete for slabs	kg	0.85	0.29	1.13	0.00	-	0.00	-	126.00	142.86	0.00	-	0.00	-	0.00	-	324.32	367.72	0.00	-
Waterproofing sheetPVC-P with fibreglass.	m2	19.82	8.22	28.05	0.00	-	0.00	-	104.00	2,916.84	0.00	-	0.00	-	0.00	-	429.36	12,042.07	0.00	-
Double air brick (10 cm)	m2	4.95	13.90	18.85	0.00	-	0.00	-	4.00	75.41	0.00	-	0.00	-	0.00	-	9.36	176.47	0.00	-
Amorphous isolation (2 cm), with mortar and concrete.	m2	1.89	13.74	15.63	0.00	-	0.00	-	4.00	62.51	0.00	-	0.00	-	0.00	-	9.36	146.28	0.00	-
Polypropylene copolymer pipeline	m	15.79	7.35	23.14	2.85	65.95	2.20	50.91	2.20	50.91	76.65	1,773.78	13.25	306.62	6.75	156.20	6.75	156.20	215.50	4,986.94
Multistage centrifugal electric	unit	500.00	0.00	500.00	1.00	500.00	0.00	-	0.00	-	1.00	500.00	1.00	500.00	0.00	-	0.00	-	1.00	500.00

pump																				
Basket type filter pit surface max. collection: 350m2	unit	390.00		390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00
Excavation of trenches and pits.	h	0.00	7.70	7.70	5.00	38.50	5.00	38.50	9.00	69.30	20.00	154.00	21.00	161.70	21.00	161.70	37.80	291.06	209.00	1,609.30
7 tons truck for soil transportation to a waste management plant	h	0.00	7.75	7.75	5.00	38.75	5.00	38.75	9.00	69.75	20.00	155.00	21.00	162.75	21.00	162.75	37.80	292.95	209.00	1,619.75
Earthmoving with shovel	h	0.00	15.77	15.77	5.00	78.85	5.00	78.85	9.00	141.93	20.00	315.40	21.00	331.17	21.00	331.17	37.80	596.11	209.00	3,295.93
24 tons truck for soil transportation to a waste management plant	h	0.00	4.22	4.22	5.00	21.10	5.00	21.10	9.00	37.98	20.00	84.40	21.00	88.62	21.00	88.62	37.80	159.52	209.00	881.98
12 tons, self-propelled crane	h	0.00	48.98	48.98	2.00	97.96	3.00	146.94	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-
20 tons, self-	h	0.00	57.07	57.07	0.00	-	0.00	-	0.00	-	3.00	171.21	3.00	171.21	5.00	285.35	0.00	-	0.00	-

Use stage	propelled crane 60 tons, self-propelled crane	h	0.00	109.89	109.89	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	8.00	879.12
	Journeyman Plumber	h	0.00	19.05	19.05	5.00	95.25	0.00	-	0.00	-	5.00	95.25	5.00	95.25	0.00	-	0.00	-	5.00	95.25
	Electricity (yearly)	kWh			0.21	600.00	123.69	0.00	-	0.00	-	4800.00	989.52	59304.96	6,112.86	0.00	-	0.00	-	118609.92	12,225.72
	Journeyman Plumber (every 5 years)	h	0.00	19.05	19.05	2.00	38.41	2.00	38.41	2.00	38.41	3.00	57.62	3.00	57.15	3.00	57.15	3.00	57.15	4.00	76.20
	Journeyman Plumber (every 10 years)	h	0.00	19.05	19.05	5.00	96.03	0.00	-	0.00	-	5.00	96.03	5.00	95.25	0.00	-	0.00	-	5.00	95.25
	Multistage centrifugal electric pump (every 10 years)	unit	500.00	0.00	500.00	1.00	500.00	0.00	-	0.00	-	1.00	500.00	1.00	500.00	0.00	-	0.00	-	1.00	500.00
	Basket type filter pit surface max. collection:	unit	390.00		390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00

	350m2. (every 5 years)																				
End-of-life stage	12 tons transport truck	h	0.00	38.50	38.50	1.00	36.30	0.00	-	1.00	36.30	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-
	20 tons transport truck	h	0.00	48.25	48.25	0.00	-	1.00	48.30	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-
	45 tons semi trailer truck	h	0.00	88.32	88.32	0.00	-	0.00	-	0.00	-	1.00	88.32	1.00	88.32	1.00	88.32	0.00	-	0.00	-
	60 tons semi trailer truck	h	0.00	100.95	100.95	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	1.00	100.95	0.00	-
	25 tons semi trailer truck with platform	h	0.00	37.74	37.74	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	15.00	566.10
	Full demolition, no sorting of waste and load on truck	m3	0.00	10.57	10.57	5.00	52.85	5.00	52.85	9.00	95.13	20.00	211.40	21.00	221.97	21.00	221.97	37.80	399.55	209.00	2,209.13
	Demolition of retaining wall, load on truck	m3	0.00	147.81	147.81	5.00	739.05	5.00	739.05	9.00	1,330.29	20.00	2,956.20	21.00	3,104.01	21.00	3,104.01	37.80	5,587.22	209.00	30,892.29
	Demolition of slope formation, load on	m3	0.00	5.91	5.91	5.00	29.55	5.00	29.55	9.00	53.19	20.00	118.20	21.00	124.11	21.00	124.11	37.80	223.40	209.00	1,235.19

truck

TABLE II.2. CHARACTERIZATION RESULTS PER FUNCTIONAL UNIT.

		CC	OD	TA	FE	POF	PMF	CED
LD1	TOTAL	2.84E+00	2.54E-07	1.15E-02	8.42E-04	1.00E-02	5.75E-03	4.99E+01
	PRODUCTION	2.48E+00	1.86E-07	9.82E-03	7.84E-04	8.83E-03	5.17E-03	4.19E+01
	USE	2.42E-01	3.66E-08	1.30E-03	4.93E-05	7.27E-04	4.01E-04	5.18E+00
	END-OF-LIFE	1.12E-01	3.17E-08	4.21E-04	9.03E-06	4.58E-04	1.76E-04	2.76E+00
LD2	TOTAL	4.45E+00	6.30E-07	1.85E-02	1.38E-03	1.58E-02	8.91E-03	8.76E+01
	PRODUCTION	4.04E+00	2.74E-07	1.56E-02	1.34E-03	1.35E-02	8.00E-03	5.77E+01
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	4.17E-01	3.56E-07	2.86E-03	3.97E-05	2.28E-03	9.07E-04	2.99E+01
LD3	TOTAL	4.96E+00	2.06E-05	2.25E-02	9.17E-04	1.69E-02	9.82E-03	8.52E+01
	PRODUCTION	4.73E+00	2.04E-05	2.10E-02	8.95E-04	1.56E-02	9.33E-03	6.98E+01
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	2.38E-01	1.83E-07	1.52E-03	2.21E-05	1.25E-03	4.96E-04	1.54E+01
LD4	TOTAL	3.76E+00	1.46E-06	2.00E-02	8.37E-04	1.59E-02	7.73E-03	1.51E+02
	PRODUCTION	2.81E+00	9.09E-07	1.38E-02	6.92E-04	1.17E-02	5.83E-03	1.01E+02
	USE	4.79E-01	7.24E-08	2.57E-03	9.75E-05	1.44E-03	7.94E-04	1.02E+01
	END-OF-LIFE	4.73E-01	4.78E-07	3.65E-03	4.69E-05	2.76E-03	1.11E-03	4.00E+01
HD1	TOTAL	3.47E+00	6.89E-07	1.80E-02	8.78E-04	1.15E-02	6.57E-03	8.30E+01
	PRODUCTION	1.36E+00	3.54E-07	6.64E-03	4.53E-04	5.05E-03	3.06E-03	3.69E+01
	USE	2.07E+00	3.13E-07	1.11E-02	4.21E-04	6.21E-03	3.43E-03	4.43E+01
	END-OF-LIFE	4.69E-02	2.19E-08	2.23E-04	4.01E-06	2.13E-04	8.29E-05	1.87E+00
HD2	TOTAL	1.21E+00	1.87E-07	5.30E-03	4.29E-04	4.13E-03	2.57E-03	2.24E+01
	PRODUCTION	1.09E+00	7.51E-08	4.42E-03	4.17E-04	3.45E-03	2.29E-03	1.31E+01
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	1.22E-01	1.12E-07	8.78E-04	1.18E-05	6.85E-04	2.73E-04	9.38E+00
HD3	TOTAL	6.29E-01	8.18E-07	2.35E-03	9.63E-05	2.03E-03	9.87E-04	1.15E+01
	PRODUCTION	5.41E-01	7.52E-07	1.79E-03	8.82E-05	1.57E-03	8.06E-04	5.88E+00
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	8.73E-02	6.68E-08	5.57E-04	8.12E-06	4.59E-04	1.82E-04	5.62E+00
HD4	TOTAL	1.87E+00	1.05E-06	1.15E-02	3.48E-04	8.25E-03	3.86E-03	9.57E+01
	PRODUCTION	1.09E+00	5.77E-07	6.16E-03	2.26E-04	4.74E-03	2.26E-03	5.22E+01
	USE	4.15E-01	6.27E-08	2.22E-03	8.45E-05	1.25E-03	6.88E-04	8.87E+00
	END-OF-LIFE	3.71E-01	4.14E-07	3.07E-03	3.78E-05	2.26E-03	9.08E-04	3.46E+01

TABLE II.3. INFLATION SENSITIVITY ANALYSIS RESULTS BY FINANCIAL TOOL.

INFLATION SENSITIVITY ANALYSIS

SCENARIO	BASE (-0.2%)	ALTERNATIVE 1 (IMF forecast)	ALTERNATIVE 2 (none)
		NPV (euros)	
LD1	-1,800.07	-1,351.58	-1,754.73
LD2	1,045.99	2,536.57	1,189.84
LD3	-2,794.42	-1,875.96	-2,696.39
LD4	12,603.88	22,183.09	13,515.88
HD1	66,192.65	102,582.16	69,573.09
HD2	74,694.14	114,706.53	78,410.42
HD3	56,302.02	93,856.01	59,821.36
HD4	753,896.55	1,162,355.92	791,841.86
		IRR (%)	
LD1			
LD2	2.48%	4.23%	3.00%
LD3			
LD4	6.05%	7.84%	5.89%
HD1	31.34%	33.15%	31.60%
HD2	45.83%	47.59%	46.12%
HD3	9.20%	11.02%	9.42%
HD4	37.78%	39.59%	38.05%
		PB (years)	
LD1	50.00	50.00	50.00
LD2	21.23	21.19	25.65
LD3	50.00	50.00	50.00
LD4	14.40	13.08	14.24
HD1	2.99	3.00	3.03
HD2	2.12	2.10	2.11
HD3	10.37	9.77	10.48
HD4	2.62	2.59	2.61

TABLE II.4. PRECIPITATION SENSITIVITY ANALYSIS RESULTS BY FINANCIAL TOOL.

PRECIPITATION SENSITIVITY ANALYSIS

SCENARIO	BASE ALTERNATIVE	ALTERNATIVE 1 (-1%)	ALTERNATIVE 2 (IPCC A2)	ALTERNATIVE 3 (IPCC B1)
		NPV (euros)		
LD1	-1,800.07	-3,286.69	-2,241.79	-1,885.49
LD2	1,045.99	-440.63	604.27	960.57
LD3	-2,794.42	-4,281.04	-3,236.14	-2,879.84
LD4	12,603.88	12,306.94	12,524.69	12,585.85
HD1	66,192.65	49,003.17	61,085.11	65,204.96
HD2	74,694.14	57,504.67	69,586.61	73,706.45
HD3	56,302.02	39,112.55	51,194.49	55,314.33
HD4	753,896.55	745,426.44	751,637.85	753,382.41
		IRR (%)		
LD1				
LD2	2.48%		1.82%	2.36%
LD3				
LD4	6.05%	5.95%	6.02%	6.04%
HD1	31.34%	29.84%	30.94%	31.27%
HD2	45.83%	44.31%	45.43%	45.76%
HD3	9.20%	8.03%	8.89%	9.14%
HD4	37.78%	37.39%	37.67%	37.76%
		PB (years)		
LD1	50.00	50.00	50.00	50.00
LD2	21.23	50.00	24.42	23.76
LD3	50.00	50.00	50.00	50.00
LD4	14.40	14.54	14.43	14.40
HD1	2.99	3.11	3.06	3.05
HD2	2.12	2.15	2.13	2.12
HD3	10.37	11.25	10.76	10.62
HD4	2.62	2.65	2.63	2.62

TABLE II.5. WATER PRICE SENSITIVITY ANALYSIS RESULTS BY FINANCIAL TOOL.

WATER PRICE SENSITIVITY ANALYSIS

SCENARIO	BASE	ALTERNATIVE (6% increment)
	NPV (euros)	
LD1	-1,800.07	5,736.15
LD2	1,045.99	8,582.21
LD3	-2,794.42	4,741.80
LD4	12,603.88	43,087.49
HD1	66,192.65	153,332.68
HD2	74,694.14	161,834.18
HD3	56,302.02	143,442.06
HD4	753,896.55	1,623,449.39

	IRR	
LD1		4.03%
LD2	2.48%	6.64%
LD3		2.65%
LD4	6.05%	9.05%
HD1	31.34%	33.71%
HD2	45.83%	48.15%
HD3	9.20%	11.59%
HD4	37.78%	39.97%

	PB	
LD1	50	30.39
LD2	21.23	19.46
LD3	50	32.62
LD4	14.40	12.82
HD1	2.99	2.90
HD2	2.12	2.07
HD3	10.37	9.72
HD4	2.62	2.55

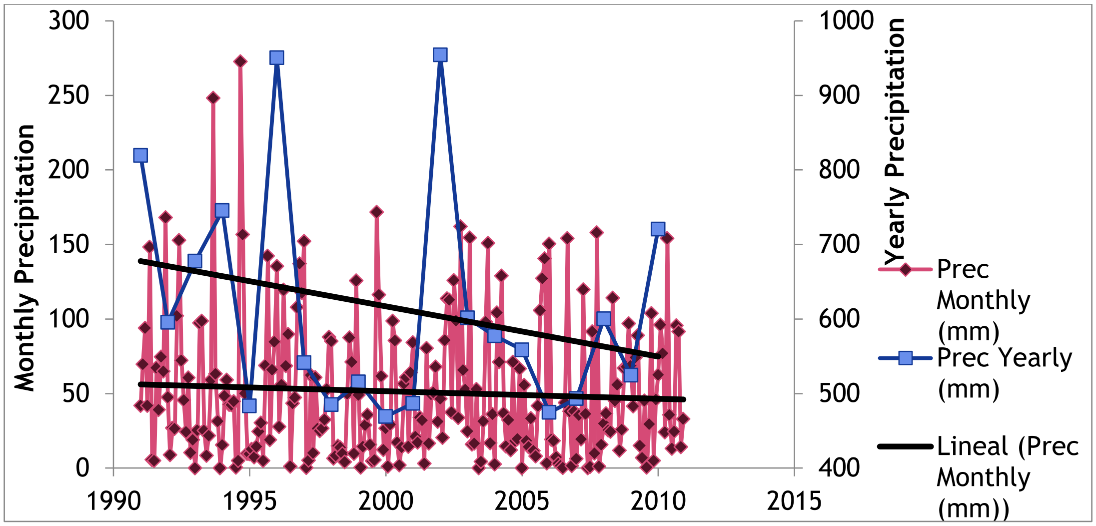

FIGURE II.1. MONTHLY AND YEARLY PRECIPITATION (1991-2010).

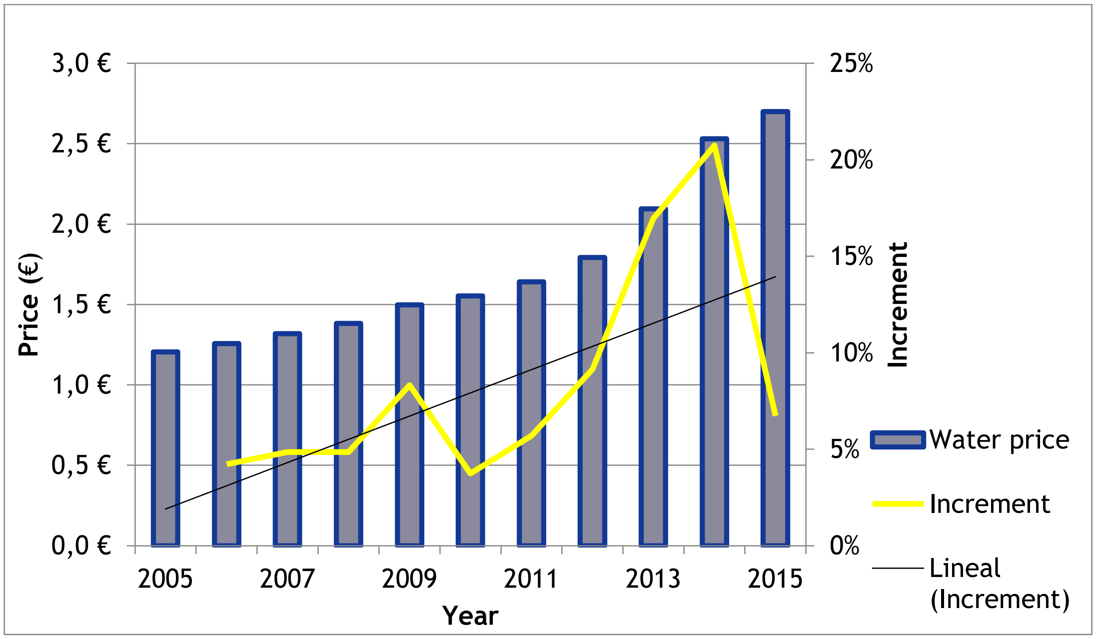

FIGURE II.2. TAP WATER PRICE EVOLUTION IN BARCELONA (2005-2015) DATA FROM: AGÈNCIA CATALANA DE L'AIGUA 2009, 2010, 2011, 2012, 2013, 2014.

Appendix III. Supplementary material related to Chapter 8.

TABLE III.1 LIFE CYCLE INVENTORY FOR ALTERNATIVE "ONLY LAUNDRY".

Stage	Input	Material description	Measuring unit	78-G	78-U	130-G	130-U	210-G	210-U
Construction	Steel, low-alloyed Metal working, average for steel product manufacturing	Pump aquor 0.5 HP	kg	3.63E-01	3.63E-01	3.58E-01	3.58E-01	3.57E-01	3.57E-01
	Polyethylene, HDPE, granulate Injection moulding	Filter (units)	kg	4.94E-02	4.94E-02	4.87E-02	4.87E-02	4.86E-02	4.86E-02
	Polyvinylchloride, at regional storage/RER S Extrusion, plastic pipes	Tubería PVC 4" (m)	kg	5.42E-01	6.51E-01	5.35E-01	6.42E-01	5.34E-01	6.41E-01
		Válvula bola 4" (units)		2.18E-02	2.18E-02	2.15E-02	2.15E-02	2.14E-02	2.14E-02
		Tubería PVC 3/4" (m)		1.92E-01	2.75E-01	1.90E-01	2.72E-01	1.90E-01	2.71E-01
		Válvula bola 3/4" (units)		1.45E-02	1.45E-02	1.43E-02	1.43E-02	1.43E-02	1.43E-02
		Codo 90 std 3/4" (units)		2.18E-02	3.27E-02	2.15E-02	3.22E-02	2.14E-02	3.22E-02
		Codo 90 std 4" (units)		7.26E-02	5.81E-02	7.16E-02	5.73E-02	7.15E-02	5.72E-02
		T std 3/4" (units)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		T std 4" (units)		2.90E-02	1.45E-02	2.86E-02	1.43E-02	2.86E-02	1.43E-02
		Control unit		7.26E-02	7.26E-02	7.16E-02	7.16E-02	7.15E-02	7.15E-02
	Polyethylene, HDPE, granulate Injection moulding	HDPE storage tank (0.75 m^3)	kg	1.09E+00	1.09E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		HDPEstorage tank (1.1 m^3)		0.00E+00	0.00E+00	1.58E+00	1.58E+00	1.57E+00	1.57E+00
		HDPE storage tank (2.5 m^3)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Electricity, low voltage {MX}	Electricity	kWh	1.25E+00	1.25E+00	1.24E+00	1.24E+00	1.23E+00	1.23E+00
Use	Steel, low-alloyed Metal working, average for steel product manufacturing	Pump aquor 0.5 HP	kg	1.09E+00	1.09E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00
	Polyethylene, HDPE, granulate Injection moulding	Filter	kg	4.45E-01	4.45E-01	4.39E-01	4.39E-01	4.38E-01	4.38E-01
End-of-life	Transport, freight, lorry 3.5-7.5 metric ton, EURO3	Transport debris	tkm	1.45E+00	1.45E+00	1.43E+00	1.43E+00	1.43E+00	1.43E+00

TABLE III.2 LIFE CYCLE INVENTORY FOR ALTERNATIVE "ALL IN".

Stage	Input	Material description	Measuring unit	78-G	78-U	130-G	130-U	210-G	210-U
Construction	Steel, low-alloyed Metal working, average for steel product manufacturing	Pump aquor 0.5 HP	kg	2.75E-01	2.75E-01	1.65E-01	1.65E-01	1.03E-01	1.03E-01
	Polyethylene, HDPE, granulate Injection moulding	Filter (units)	kg	3.75E-02	3.75E-02	2.25E-02	2.25E-02	1.40E-02	1.40E-02
	Polyvinylchloride, at regional storage/RER S Extrusion, plastic pipes	Tubería PVC 4" (m)	kg	4.12E-01	4.94E-01	2.47E-01	2.96E-01	1.54E-01	1.84E-01
		Válvula bola 4" (units)		1.65E-02	1.65E-02	9.92E-03	9.92E-03	6.17E-03	6.17E-03
		Tubería PVC 3/4" (m)		1.46E-01	2.09E-01	8.76E-02	1.25E-01	5.45E-02	7.80E-02
		Válvula bola 3/4" (units)		1.10E-02	1.10E-02	6.61E-03	6.61E-03	4.11E-03	4.11E-03
		Codo 90 std 3/4" (units)		1.65E-02	2.48E-02	9.92E-03	1.49E-02	6.17E-03	9.25E-03
		Codo 90 std 4" (units)		5.51E-02	4.41E-02	3.31E-02	2.64E-02	2.06E-02	1.64E-02
		T std 3/4" (units)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		T std 4" (units)		2.20E-02	1.10E-02	1.32E-02	6.61E-03	8.22E-03	4.11E-03
		Control unit		5.51E-02	5.51E-02	3.31E-02	3.31E-02	2.06E-02	2.06E-02
	Polyethylene, HDPE, granulate Injection moulding	HDPE storage tank (0.75 m^3)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		HDPEstorage tank (1.1 m^3)		1.21E+00	1.21E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		HDPE storage tank (2.5 m^3)		0.00E+00	0.00E+00	1.65E+00	1.65E+00	1.03E+00	1.03E+00
	Electricity, low voltage {MX}	Electricity	kWh	9.50E-01	9.50E-01	5.70E-01	5.70E-01	3.55E-01	3.55E-01
Use	Steel, low-alloyed Metal working, average for steel product manufacturing	Pump aquor 0.5 HP	kg	8.26E-01	8.26E-01	4.96E-01	4.96E-01	3.08E-01	3.08E-01
	Polyethylene, HDPE, granulate Injection moulding	Filter	kg	3.37E-01	3.37E-01	2.02E-01	2.02E-01	1.26E-01	1.26E-01
End-of-life	Transport, freight, lorry 3.5-7.5 metric ton, EURO3	Transport debris	tkm	1.10E+00	1.10E+00	6.61E-01	6.61E-01	4.11E-01	4.11E-01

Table III.3 Environmental impacts for alternative “Only laundry”.

Impact categories	Unit	78-G	78-U	130-G	130-U	210-G	210-U
Climate change	kg CO2 eq	1.71E-03	1.80E-03	1.84E-03	1.93E-03	1.84E-03	1.92E-03
Ozone depletion	kg CFC-11 eq	2.15E-03	2.52E-03	2.12E-03	2.49E-03	2.12E-03	2.49E-03
Human toxicity	kg 1,4-DB eq	2.67E-03	2.81E-03	2.85E-03	2.99E-03	2.84E-03	2.98E-03
Photochemical oxidant formation	kg NMVOC	1.51E-02	1.53E-02	1.54E-02	1.57E-02	1.54E-02	1.57E-02
Terrestrial acidification	kg SO2 eq	1.28E-03	1.34E-03	1.38E-03	1.44E-03	1.38E-03	1.44E-03
Freshwater eutrophication	kg P eq	3.13E-03	3.28E-03	3.26E-03	3.41E-03	3.26E-03	3.41E-03
Cumulative Energy Demand	MJ	3.56E+02	3.71E+02	4.02E+02	4.18E+02	4.02E+02	4.17E+02

Table III.4 Environmental impacts for alternative “All in”.

Impact categories	Unit	78-G	78-U	130-G	130-U	210-G	210-U
Climate change	kg CO2 eq	1.42E-03	1.48E-03	1.13E-03	1.17E-03	7.05E-04	7.29E-04
Ozone depletion	kg CFC-11 eq	1.63E-03	1.92E-03	9.84E-04	1.16E-03	6.12E-04	7.19E-04
Human toxicity	kg 1,4-DB eq	2.19E-03	2.30E-03	1.72E-03	1.78E-03	1.07E-03	1.11E-03
Photochemical oxidant formation	kg NMVOC	1.19E-02	1.21E-02	8.22E-03	8.34E-03	5.11E-03	5.19E-03
Terrestrial acidification	kg SO2 eq	1.06E-03	1.11E-03	8.60E-04	8.86E-04	5.35E-04	5.51E-04
Freshwater eutrophication	kg P eq	2.51E-03	2.63E-03	1.84E-03	1.91E-03	1.14E-03	1.19E-03
Cumulative Energy Demand	MJ	3.09E+02	3.21E+02	2.81E+02	2.88E+02	1.75E+02	1.79E+02

Table III.5 Item description and cost for alternative “Only laundry”.

Stage	Input	Description	Unitary cost			Scenarios					
			Material	labor	Total	78-G	78-U	130-G	130-U	210-G	210-U
Construction	Materials	Pump aquor 0.5 HP (units)	1021		1021	1021	1021	1021	1021	1021	1021
		Filtro bajante (units)	502		502	502	502	502	502	502	502
		Tubería PVC 4" (m)	87		87	430	516	430	516	430	516
		Válvula bola 4" (units)	850		850	850	850	850	850	850	850
		Tubería PVC 3/4" (m)	7		7	24	34	24	34	24	34
		Válvula bola 3/4" (units)	64		64	64	64	64	64	64	64
		Codo 90 std 3/4" (units)	6		6	12	18	12	18	12	18
		Codo 90 std 4" (units)	90		90	450	360	450	360	450	360
		T std 4" (units)	176		176	352	176	352	176	352	176
		Control unit (units)	3334		3334	3334	3334	3334	3334	3334	3334
		PVC storage tank (0.75 m^3)	1499		1499	1499	1499	0	0	0	0
		PVC storage tank (1.1 m^3)	1825		1825	0	0	1825	1825	1825	1825
		PVC storage tank (2.5 m^3)	4099		4099	0	0	0	0	0	0
	Services	underground tank installation (unit)	0	350	350	0	350	0	350	0	350
		Construction workers (laborer and foreman) (hours)	0	292	292	2333	7000	2333	7000	2333	7000
Use	Energy	Electricity (kWh/year)	1	0	1	10	10	10	10	10	10
	Services	Maintenance workforce	0	217	217	217	217	217	217	217	217
	Materials	Pump aquor 0.5 HP	1021	0	1021	1021	1021	1021	1021	1021	1021
		Filter	502		502	502	502	502	502	502	502
End-of-life	Transport	Transport debris up to 3 m^3 (unit)	1125	400	1525	1525	1525	1525	1525	1525	1525
	Services	Construction workers (laborer and foreman) (hours)	0	292	292	2333	4667	2333	4667	2333	4667

Table III.6 Item description and cost for alternative “All in”.

Stage	Input	Description	Unitary cost			Scenarios					
			Material	labor	Total	78-G	78-U	130-G	130-U	210-G	210-U
Construction	Materials	Pump aquor 0.5 HP (units)	1021		1021	1021	1021	1021	1021	1021	1021
		Filtro bajante (units)	502		502	502	502	502	502	502	502
		Tubería PVC 4" (m)	87		87	430	516	430	516	430	516
		Válvula bola 4" (units)	850		850	850	850	850	850	850	850
		Tubería PVC 3/4" (m)	7		7	24	34	24	34	24	34
		Válvula bola 3/4" (units)	64		64	64	64	64	64	64	64
		Codo 90 std 3/4" (units)	6		6	12	18	12	18	12	18
		Codo 90 std 4" (units)	90		90	450	360	450	360	450	360
		T std 4" (units)	176		176	352	176	352	176	352	176
		Control unit (units)	3334		3334	3334	3334	3334	3334	3334	3334
		PVC storage tank (0.75 m^3)	1499		1499	0	0	0	0	0	0
		PVC storage tank (1.1 m^3)	1825		1825	0	0	0	0	0	0
		PVC storage tank (2.5 m^3)	4099		4099	4099	4099	4099	4099	4099	4099
	Services	underground tank installation (unit)	0	350	350	0	350	0	350	0	350
		Construction workers (laborer and foreman) (hours)	0	292	292	2333	7000	2333	7000	2333	7000
Use	Energy	Electricity (kWh/year)	1	0	1	10	10	10	10	10	10
	Services	Maintenance workforce	0	217	217	217	217	217	217	217	217
	Materials	Pump aquor 0.5 HP	1021	0	1021	1021	1021	1021	1021	1021	1021
		Filter	502		502	502	502	502	502	502	502
End-of-life	Transport	Transport debris up to 3 m^3 (unit)	1125	400	1525	1525	1525	1525	1525	1525	1525
	Services	Construction workers (laborer and foreman) (hours)	0	292	292	2333	4667	2333	4667	2333	4667

TABLE III.7 PRESENT VALUE RESULTS FROM SENSITIVITY ANALYSIS IN MXN PER M3

Scenario	Laundry and car-washing	Only laundry	All in
78-G	21.39	27.00	21.39
78-U	21.39	27.00	21.39
130-G	21.11	26.63	12.86
130-U	21.11	26.63	12.86
210-G	20.67	26.59	8.03
210-U	20.67	26.59	8.03

Appendix IV. Supplementary material related to Chapter 9.

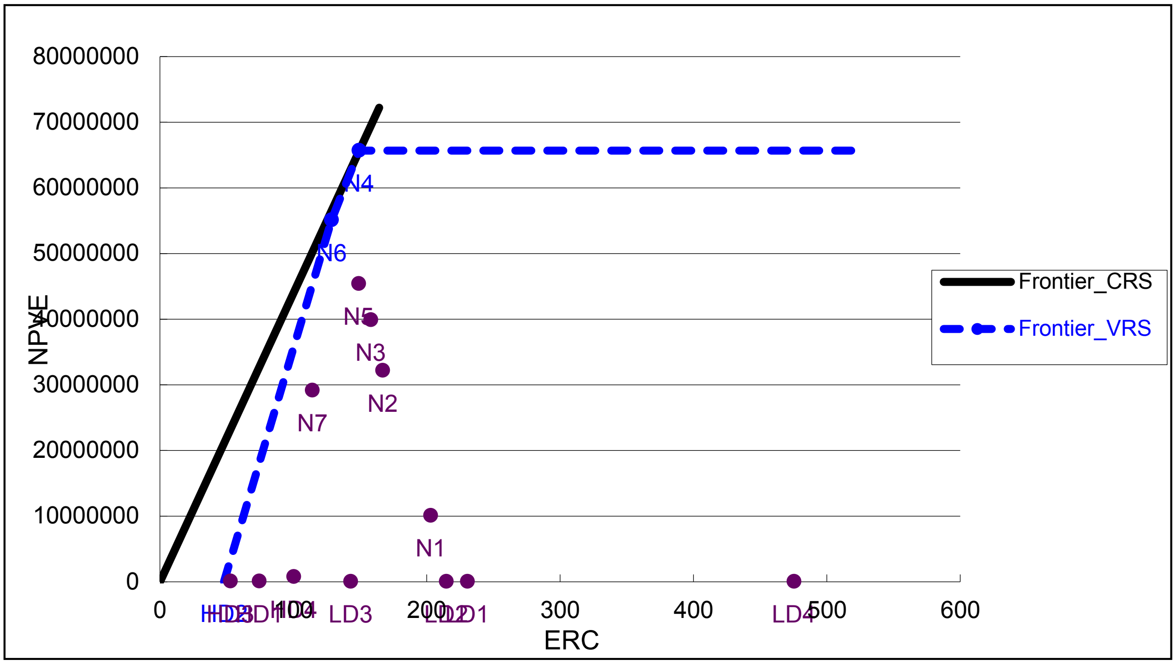

FIG IV.1 NPVE EFFICIENCY FRONTIER

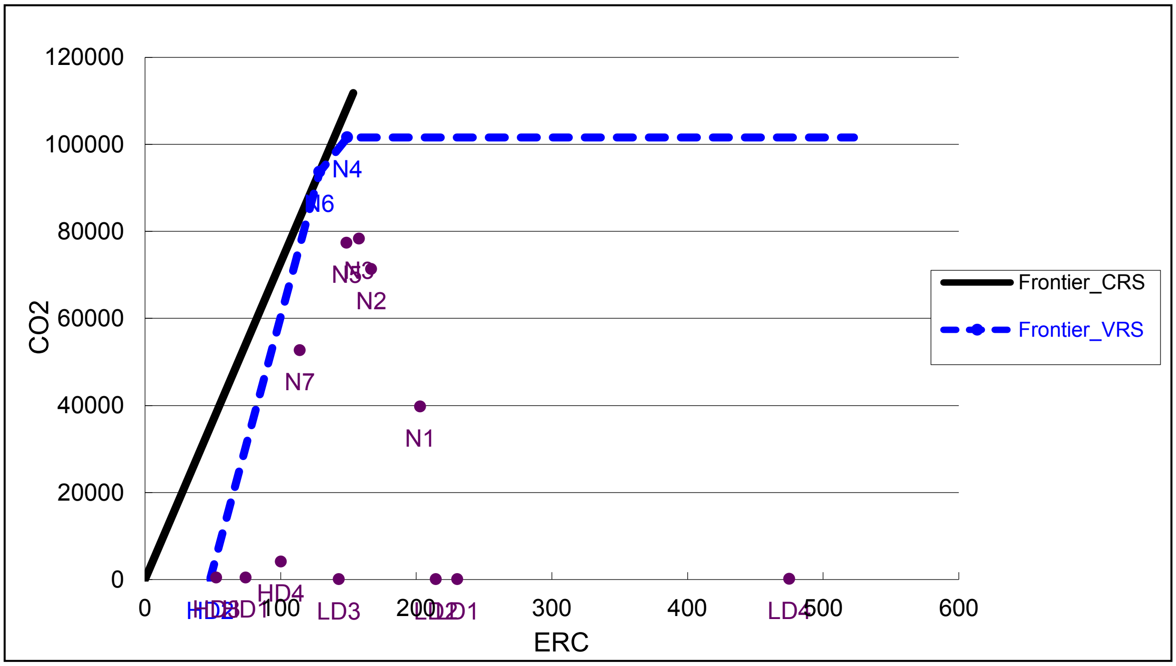

FIG IV.2 CO2 EFFICIENCY FRONTIER