Strategies for sustainable urban systems: introducing eco-innovation in buildings in Mexico and Spain

Doctoral thesis

Ileana Cerón Palma

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A thesis submitted in fulfilment of the requirements for the Doctoral degree in Environmental Sciences and Technology

Sostenipra research group
Institut de Ciència i Tecnologia Ambientals (ICTA)
Universitat Autònoma de Barcelona (UAB)

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Strategies for sustainable urban systems: introducing eco-innovation in buildings in Mexico and Spain.

By

Ileana Maria N. Cerón Palma

A thesis submitted in fulfilment of the requirements for the PhD degree in Environmental Sciences and Technology

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“Innovation distinguishes
between a leader and a follower”

Steve Jobs

This thesis entitled "Strategies for sustainable urban systems: introducing eco-innovation in buildings in Mexico and Spain" has been carried out at the Institute of Environmental Science and Technology (ICTA) at Universitat Autònoma de Barcelona (UAB). It has been carried out under the supervision of Dr. Joan Rieradevall, from the ICTA and the Department of Chemical Engineering at the UAB, Dr. Juan Ignacio Montero from the Environmental Horticulture Unit Programme at the Institute of Agriculture and Food Research and Technology (IRTA), and Dr. Jordi Oliver-Solà from Inèdit Innovació (INEDIT, spin-off of UAB research park).

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Ileana Maria N. Cerón Palma

Joan Rieradevall Juan Ignacio Montero Jordi Oliver-Solà

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List of acronyms, abbreviations and notation

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BFS	Brigth Farm Systems
CED	Cumulative Energy Demand
CFE	Comisión Federal de Electricidad
CO_2eq	Carbon dioxide equivalent emissions
CONACYT	Consejo Nacional de Ciencia y Tecnología (México)
CONAE	Consejo Nacional de Energía (México)
CONAVI	Consejo Nacional de Vivienda
CONCYTEY	Consejo de Ciencia y Tecnología de Yucatán
CTPS	Closed Transplant Production System
EEA	European Environmental Agency
EC	European Commission
Eurostat	European Statistics
EPW	Energy Plus Weather format
EWA	European Water Association
EU	European Union
EU-27	27 member states of European Union
FAO	Food and Agriculture Organization of the United Nations
FIDE	Fideicomiso para el ahorro de energía
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
ICTA	Institute of Environmental Sciencie and Technology
Idescast	Institut d'Estadística de Catalunya
IEA	International Energy Agency
INEGI	Instituo Nacional de Estadística y Geografía
INFONAVIT	Instituto del Fondo Nacional de la Vivienda para los Trabajadores
ITeC	Institut de Tecnologia de la Construcció de Catalunya
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt hour
LCA	Life Cycle Assessment
NFT	Nutrient Film Technique
NOM	Norma Oficial Mexicana
OECD	Organization for Economic Co-operation and Development
ONNCCE	Organismo Nacional de Normalización y Certificación de la Construcción y Edificación
RG	Roof Garden
RTEG	Roof Top Eco-greenhouse
RTG	Roof Top Greenhouse

SAGARPA	Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación
SEDUMA	Secretaría de Desarrollo Urbano y Medio Ambiente
SENER	Secretaría de Energía México
SHF	Sociedad Hipotecaria Federal
UADY	Universidad Autónoma de Yucatán
UN	United Nations
VSMMDF	Veces salario mínimo mensual del Distrito Federal
VF	Vertical Farming

Acknowledgments

A lo largo de estos 3 años he recibido el apoyo invaluable de amigos, profesores, familia y diversas personas que he conocido. Quiero agradecer especialmente a mis directores de tesis, el Dr. Joan Rieradevall, Dr. Juan Ignacio Montero y Dr. Jordi Oliver por el apoyo y tiempo dedicado para la realización de esta tesis así como por mi formación en el ámbito de la investigación y la confianza que depositaron en mí desde el momento que me acerqué y les manifesté mi interés de hacer el doctorado en sus líneas de investigación. A la Dra. Carmen Ponce, Dr. Carlos Quintal y Dr. Germán Giacoman quienes fueron los que me dieron el último empujón para decidirme a iniciar esta experiencia en el extranjero y quienes no han dejado de apoyarme durante este tiempo.

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A Jordi, Carles, Raúl y todos mis ahora socios que integran INÉDIT, gracias por la confianza que depositaron en mi para continuar esta aventura en México.

A todos y cada uno de mis amigos que a pesar de la distancia siempre estuvieron cerca de mi a través de internet y pude de esa manera estar presente en todos los momentos importantes de su vida que me perdí.
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Dedico esta tesis en su totalidad a la memoria de mi abuela de quien no pude despedirme pero que me ha servido de inspiración en cada línea.

Summary

This dissertation proposes strategies for sustainable urban systems, introducing eco-innovation in buildings and paying particular attention to energy and GHG emissions. The study was developed in two diferent social, economical and climatic contexts.

Firstly, environmental and energy improvement of social housing in a warm-humid climate in Merida (Mexico) is investigated, through eco-rehabilitation strategies such as ecotechnologies (efficient equipment), shading and insulation (Above roof shade, overhangs on walls, louvers in windows and green roof) and food production (tomato). Energy requirements for cooling in social housing, cumulative energetic demand and CO_2 emissions associated with the materials used in shading and insulative strategies were calculated. In food production, the expanded system is considered, in order to determine impacts related to food logistics (distribution, packaging, retail).

Secondly, Rooftop Eco-Greenhouse (RTEG) is presented as an eco-innovative system that incorporates agriculture into the rooftops of buildings in Mediterranean European cities. A list of environmental, economical, technological and social barriers, as well as opportunities for the implementation of the RTEG system, were obtained. The work method consisted of discussion seminars involving an interdisciplinary group of experts from different areas. In addition, the potential for synergies between buildings and RTEG systems in terms of heat flows was identified, focusing only on heating requirements in winter, in an office building in Barcelona (Spain).

To develop this research, multidisciplinary tools and software programs such as energy simulation (DesignBuilder, Ecotect), flow analysis (CFD), life cycle analysis (SimaPro) were used. Social tools, such as seminars and focus groups, were also utilised.

According to the results for social housing, eco-technologies could potentially provide reduce annual energy consumption by 31% (35.7kWh/m^2/year). The '*Above roof shade'* strategy can provide a saving of 126kWh/m^2/year. Production of tomatoes in social housing areas in Merida (Mexico) could provide a savings of 662 gCO_2eq per kg of tomatoes produced. In descending order, the main contributors to these savings are transport requirements (57.7%), retail phase (37.2%) and re-usable packaging (5.1%).

In respect to RTEG, we would highlight the interconnection of the building and the greenhouse as an opportunity for RTEG, making use of water, energy and CO_2 flows between both, as well as reducing food transportation requirements. The participation of experts helped to produce a global vision for the implementation of the project.

According to energy analysis, a total of 87 kWh/day of heat was removed from the greenhouse, in order to reduce its temperature. This data indicates the potential

amount of heat that could be transferred to the building in a study day. Based on the results generated by this research, further lines of research can be investigated, in order to determine other energy and environmental benefits of the RTEG system.

All strategies presented in this dissertation aim to facilitate the sustainable development of urban systems, through researching eco-innovation in the field of improvement of social housing in Developing Countries and urban agriculture in compact cities.

Preface

This thesis was developed within the research group of Sustainability and Environmental Prevention (Sostenipra) at the Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), from February 2010 to November 2012.
This dissertation is the result of a multidisciplinary approach that aims to propose and assess strategies for more sustainable systems, working mainly at a building and neighbourhood scale; paying particular attention to energy and GHG emissions.
The dissertation is mainly based on the following papers (published and under review) in peer-reviewed indexed journals:

- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2013). Towards a green sustainable strategy for social neighbourhoods in Latin America: Case from social housing in Merida, Yucatan, Mexico. *Habitat International,* 38: 47-56

- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Rieradevall J, Montero JI. Strategies to reduce the energy requirements and CO_2 emissions of cooling demands on social housing in warm-humid climates of Mexico. Submitted on July 2012 to *Energy and buildings.*

- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2012) Barriers and opportunities regarding the implementation of Rooftop Eco-Greenhouses (RTEG) in Mediterranean cities of Europe. *Journal of Urban Technology,* first on line (DOI:10.1080/10630732.20).

- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Rieradevall J, Montero JI. Energy Energy and environmental analysis of heat flows in Rooftop Eco-Greenhouse: A case study in the Mediterranean City of Barcelona. Submitted on November 2012 to *Building and environment.*

This dissertation is also based on the following oral communications and posters presented at conferences:

- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2011) Strategies for reducing the carbon footprint in a social housing district in Merida, Yucatan, Mexico. Oral communication. International Life Cycle Assessment Conference in Latin-America. Coatzacoalcos (Mexico).

- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2011) LCM of green food production in Mediterranean cities: environmental benefits associated to the energy savings in the use stage of Roof Top Greenhouse (RTG) systems. A case study in Barcelona (Catalonia, Spain). Oral communication. Life Cycle Management Congress. LCM 2011. Berlin (Germany).

- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J. (2011) LCM of green food production in Mediterranean cities: environmental benefits associated to the energy savings in the use stage of Roof Top Greenhouse (RTG) systems. A case study in Barcelona (Catalonia, Spain). Poster. Life Cycle Management Congress. LCM 2011. Berlin (Germany).

- Ceron-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2011) Energy saving from a roof top greenhouse in a public building of Barcelona, Spain". Poster. 6th International Conference on Industrial Ecology. ISIE 2011. Berkeley (California).

- Cerón-Palma I, Oliver-Solà J, Sanyé-Mengual E, Gasol C, Grau L, Montero JI, Rieradevall J (2011) Agrourban: Food self-sufficiency in cities. Poster. Smart City World Congress. Barcelona (Spain).

- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J, (2012) Periurban and innovative agrourban production areas for food self-sufficiency in the Metropolitan Area of Barcelona. Oral communication. 1st International Conference on Agriculture in an urbanizing society. Wageningen (The Netherlands).

- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2012) Potential and benefits of Rooftop Greenhouse (RTG) systems for agriculture production implemented in polygons of future Smart cities: a case study in Zona Franca (Barcelona). Smart City Expo World Congress, Barcelona (Spain).

- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2012) Potential benefits of agrourban production systems as a sustainable strategy for food self-sufficiency in urban areas. 1st International Conference for Urban Sustainability and Resilience. London.

- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2013) Integrating LCA in the selection of strategies for improving thermal conditions in Mexican social housing. Accepted to CILCA 2013, Mendoza (Argentina).

During the dissertation period, the opportunity was given to work on other projects, from which the following papers in peer-reviewed journals (accepted or in review) have been written:

- Sanyé-Mengual E, Ceron-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2012) Environmental analysis of the logistics of Agricultural products from Roof Top Greenhouse (RTG) in Mediterranean urban areas. *Journal of the Science of Food and Agriculture,* first on line. (DOI: 10.1002/jsfa.5736)

- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2012) A guideline for assessing the implementation of agrourban production through Rooftop Greenhouse (RTG) systems in industrial and logistics buildings in parks. Submitted on October 2012 to *International Journal of Agricultural Sustainability*

Part of the information necessary for the results of doctoral thesis were obtained during the following extended periods of research:
Five month period (August – September 2010 /April-May 2011 / January 2012) at the Department of Environmental Engineering in the Faculty of Engineering at the Autonomous University of Yucatan (UADY). The hosting researcher was Dr. Carmen Ponce Caballero.

Within this framework, applied research projects have been developed in paralell and put into practice in real projects. For example, I have actively participated in three building sector projects which were developed jointly with a multi-disciplinary team. The main characteristics of these projects are summarized below, by means of a series of figures (A to C).

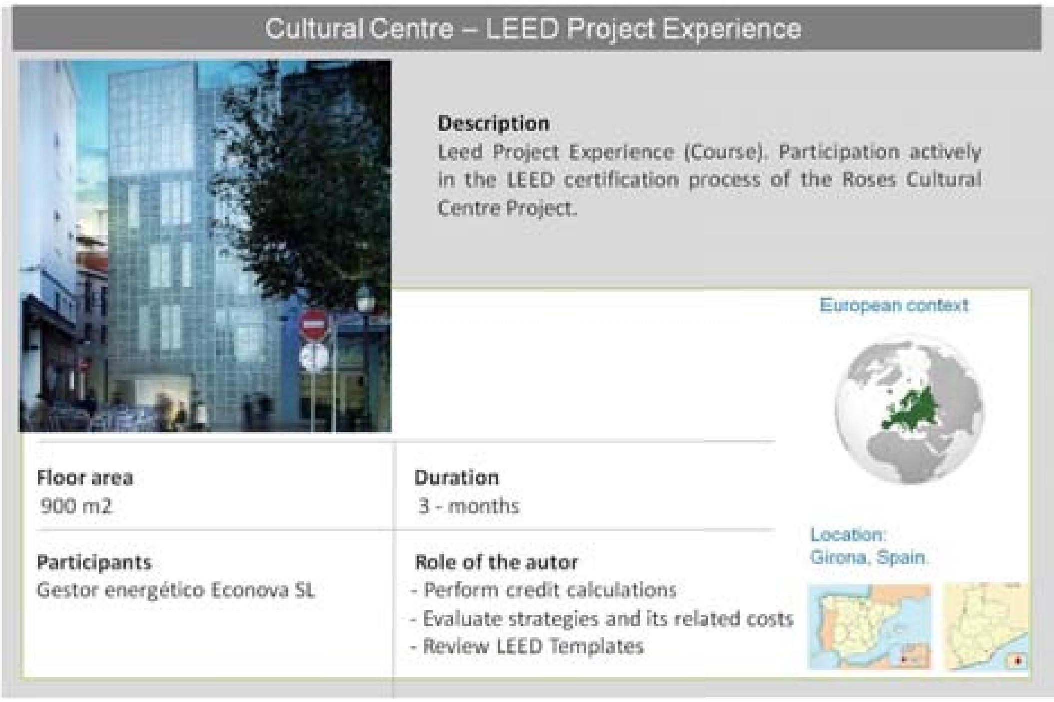

Figure A. Main characteristics of a cultural centre building - LEED certification project.

Figure B. Main characteristics of the eco-greenhouse in a catering service building project.

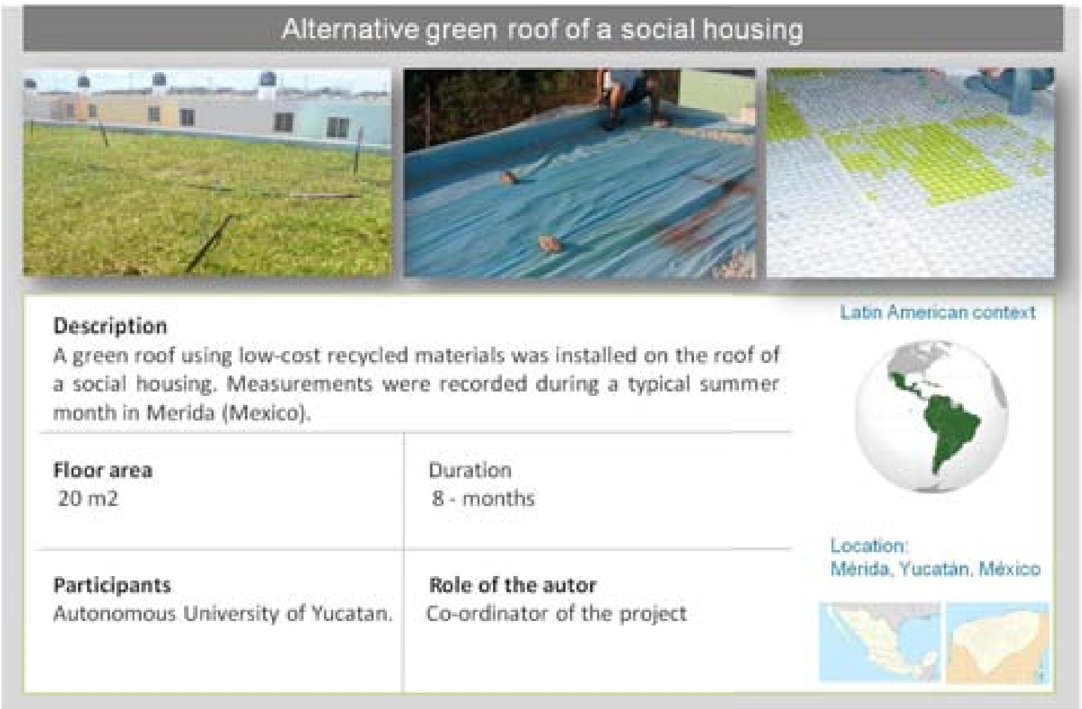

Figure C. Main characteristics of an alternative green roof project

Structure of the dissertation

The structure of the dissertation is organised into four main parts and eight chapters. For clarity, the structure of the doctoral thesis is further outlined in Figure D. This flow chart can be used throughout the reading of this manuscript as a *dissertation map*.

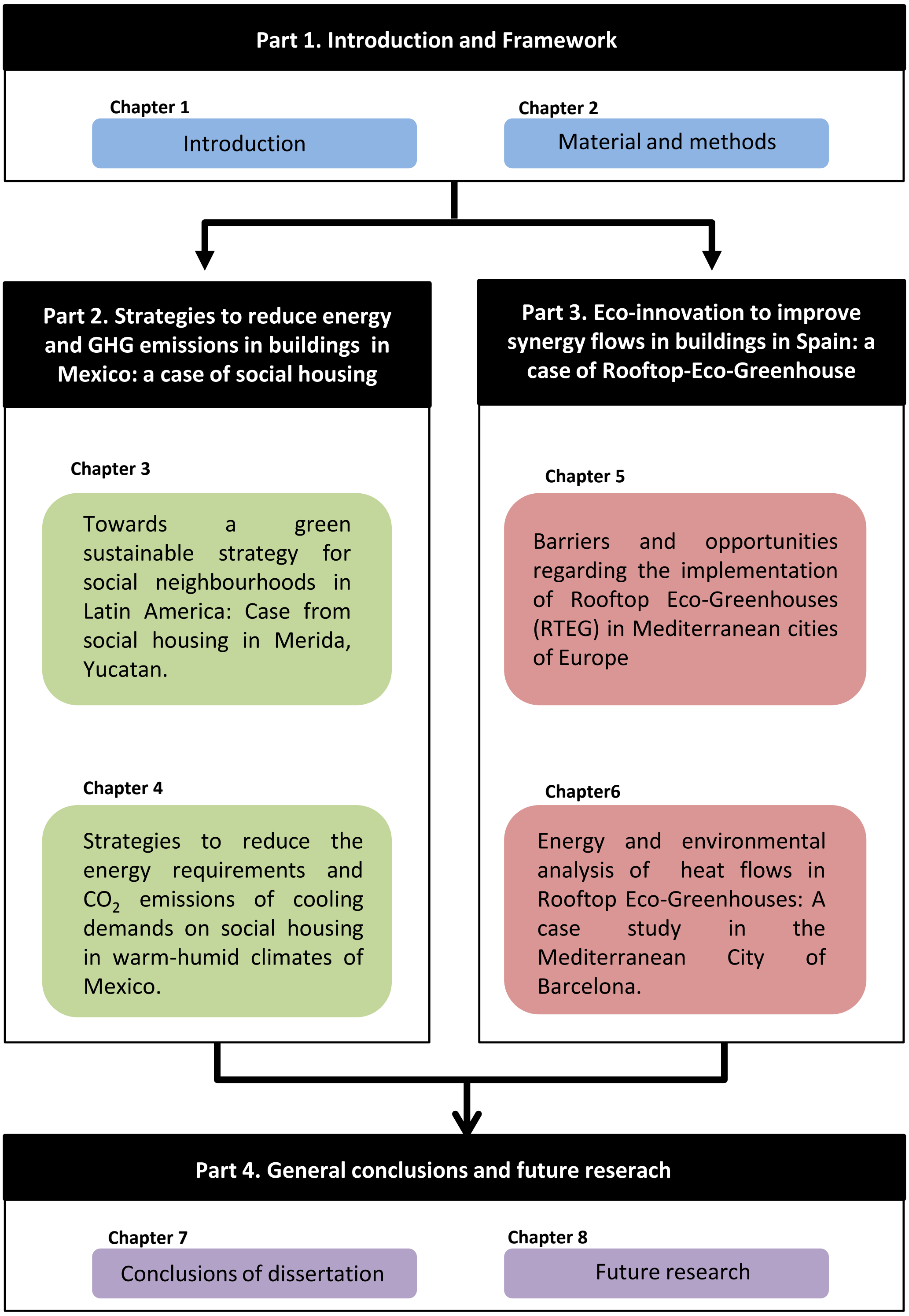

Figure D*. Map structure of dissertation*

Part 1. Introduction and framework

Part I is composed of two chapters. Chapter 1 [*Introduction*] presents an overview of sustainable cities, focusing on environmental problems in urban areas, principally in Latin American countries. Furthemore, an introduction to the concept of urban metabolism is presented and its role in the management and design of more sustainable settlements is highlighted. The importance of energy and food flows is given particular attention. The neighbourhood as a new scale of intervention is also presented. Next, the contribution of buildings to climate change and the life cycle phases of buildings are shown. Finally, the justification of this dissertation is presented and the objectives are defined. Chapter 2 [Methodology] presents environmental, social and architectural assessment tools and characteristics of the study systems.

Part 2. Strategies to reduce energy and GHG emissions in buildings in Mexico: a case of social housing

Part II focuses on the strategies applied to social housing in Mexico. It is composed of two chapters. Chapter 3 [*Towards a green sustainable strategy for social neighbourhoods in Latin America: Case from social housing in Merida, Yucatan, Mexico*] provides diverses strategies for reducing energy consumption of social housing in Merida, Mexico. Eco-technologies, green spaces and food production have been proposed and the environmental impact has been considered through the life cycle assesment. Chapter 4 [*Strategies to reduce the energy requirements and CO_2 emissions of cooling demands on social housing in warm-humid climates of Mexico*] presents passive strategies to reduced the cooling demand of social housing. The relevance of this chapter is the integration of LCA as a new tool for decisions in the construction sector.

Part 3. Eco-innovation to improve synergy flows in buildings in Spain: a case of Rooftop Eco-Greenhouse

Part III has two chapter and focuses on the integration of Rooftop grenhouses on buildings in Spain as a eco-innovative strategy. Chapter 5 [*Barriers and opportunities regarding the implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean cities of Europe*], sets the context for the research, by providing a discussion of opportunities and constraints from environmental, social and economic perspectives. Chapter 6 [*Energy and environmenta analysis of heat flows in Rooftop Eco-Greenhouse: a case study in the Mediterranean City of Barcelona*] presents a preliminary energy analysis of RTEG. The main purpose of this chapter is assess the heating demand and heat fluxes with an inter-connected system. The impact of CO_2 emissions avoided in relation to heating system is calculated.

Part 4. General conclusions and future research

Part IV includes Chapter 7**, which** provides the general conclusions of the dissertation, and Chapter 8, which proposes future fields of research associated with the objectives of dissertation.

PART 1

Introduction and Framework

Chapter 1

Introduction and framework

PHOTOGRAPHY BY ILEANA CERON

Chapter I defines sustainable development and shows how it can be applied to cities. Furthemore, it presents the role of cities in climate change, including environmental problems in developing countries. An overview of the paradigm of sustainable cities is included, focusing on urban metabolism. Initiatives at a neighbourhood scale are also presented. The importance of integrating Life Cycle Assessment (LCA) into the building sector, in order to reduce energy and GHG emissions are also be presented. Finally, the motivation of this dissertation and objectives are defined.

The chapter is structured as follows:

- Key features of sustainable cities
- Motivation of the dissertation
- Objectives of the dissertation

1.1 Key features of sustainable cities

Population growth is an urban phenomenon that is concentrated in the developing world (UN-Habitat, 2006). This has led to an increase in urban areas. It was estimated that during 2008, for the first time in history, the proportion of the population living in urban areas will reach 50 % (Figure 1.1).

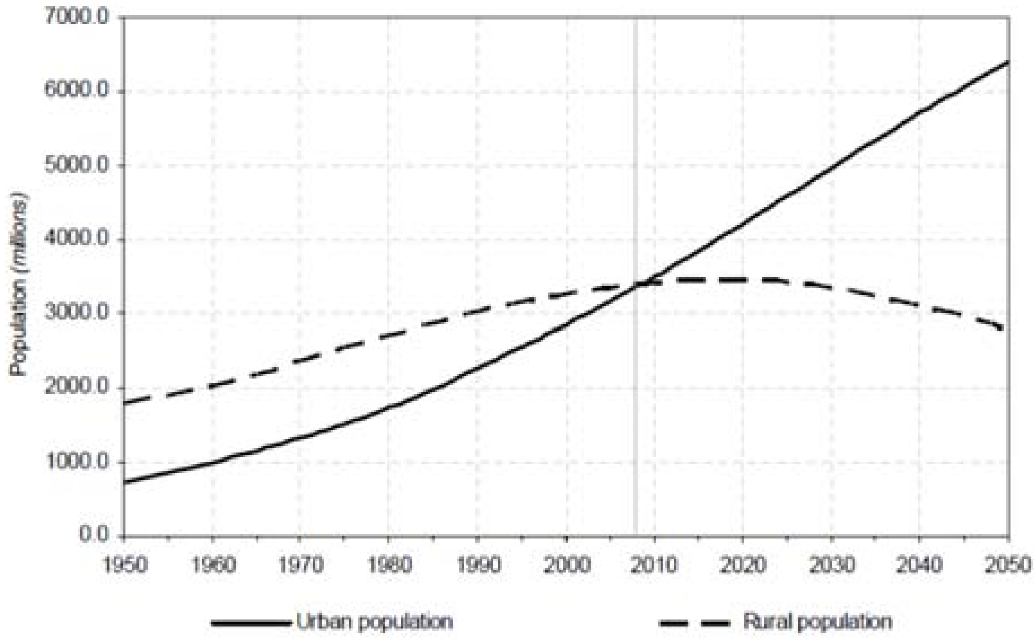

Figure 1.1 Urban and rural population of the world (1950-2050) Source: UN, 2007.

Between 2011 and 2050, the world population is expected to increase by 2.3 billion, from 7.0 billion to 9.3 billion (UN, 2012). At the same time, the world urban population is expected to increase by 72% by 2050, from 3.6 billion in 2011 to 6.3 billion in 2050. (UN, 2012).

However, cities also provide opportunities to integrate sustainability criteria into building planning and provide a better quality of life.

Since Rio's Earth Summit (1992), the concept of *Sustainable Development* (SD) has been known worldwide. However, what is the significance of sustainable development?

"*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" according to the Brutland Commission´s Our Common Future (World Commission on Environment and Development, 1987). Sustainable development can be conceptually broken down into three constituent parts: society, economy and environment (Figure 1.2). Only when all of them are fulfilled can we discuss sustainability (McGranahan et al. 2001).

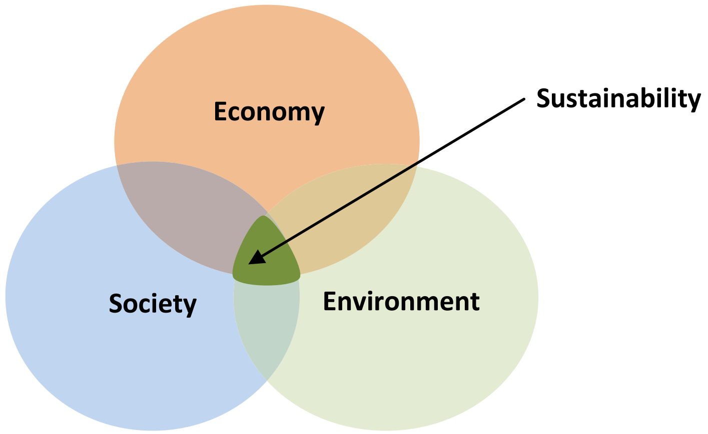

Figure 1.2 Conceptualization of sustainable development

There are different visions of the concept of sustainability in relation to cities. According to urbanist Girardet (1999), *"the cities of the 21st Century are where human destiny will be played out, and where the future of the biosphere will be determined. There will be no sustainable world without sustainable cities".*

An important factor to consider in the management and/or redesign of cities towards sustainability, is to minimize its contribution to the climate change phenomenon, through strategies to compensate, minimize or neutralize these emissions.

1.1.1 The role of cities to climate change

Currently, climate change is a natural phenomenon that affects millions of people in urban areas. The Intergovernmental Panel on Climate Change (IPCC) was created in 1988 by the World Meteorological Organization and the United Nations Environment Program in order to keep world governments informed of climate change issues. According to the IPCC, climate change is defined as: *"A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use"* (IPCC, 2007a).

Cities are seriously affected by both the impact of infrastructure and the ability of people to access basic urban services, in order to improve quality of life in cities (UNEP, 2002).

Cities use over 75% of the world´s resources (Pacione, 2009), they are responsible for 75% of the world´s energy consumption and 80% of greenhouse gas (GHG) emissions (Ash et al. 2008). Greenhouse gas emissions from cars, power plants, and other human activities are the primary cause of contemporary global warming. For example, GHG emissions associated with the provision of energy services are a major cause of climate change (Moomaw et al. 2011). The International Energy Agency (IEA) estimates that urban areas currently account for more than 71% of energy-related global greenhouse gases and this is expected to rise to 76 % by 2030 (IEA, 2011).

Since the industrial revolutions, GHG emissions from human activity have increased rapidly and are predicted to increase further by 2030 as shown in Figure 1.3.

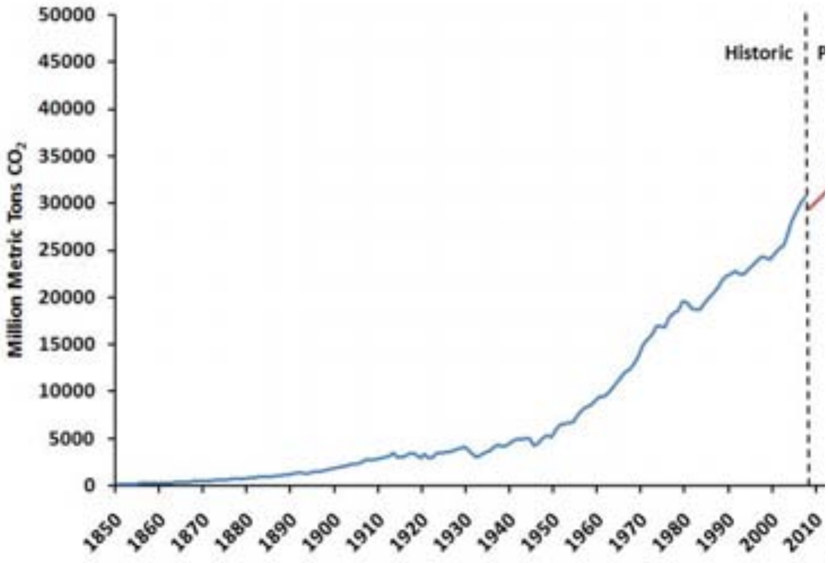

Figure 1.3 Global CO_2 emissions from 1850 to 2030. Source: C2ES (2012)

The governments of each country have acquired a great importance in mitigation and adaptation to climate change. Agenda 21 is a UN initiative that 178 governments at the United Nations Conference on Environment and Development (UNCED) adopted in 1992 under the auspices of saving the environment. In the context of the current European Climate Change policy, "Energy for a changing world", also called 20-20-20, the Covenant of Mayors (which involves local authorities from countries within the European Union), was signed with the purpose of improving energy efficiency and promoting renewable energies in services (Covenant of Mayors, 2008). The key document of the Covenant of Mayors is the Sustainable Energy Action Plans (SEAP).

Adapting to climate change is a challenge for all countries. From a global perspective, this challenge is probably greatest for developing countries. These countries are most vulnerable to climate change and its effects, such as increased temperature, drought and hurricanes. Many industries, for example, tourism, fisheries and agriculture, depend on weather conditions.

Urban change and environmental problems in developing Countries: The case of Latin America

Latin America and the Caribbean (LAC) is the most urbanized region in developing world with 80% of its relatively young population living in cities (UNFPA, 2007).

Quality of life in these countries is affected by the rapid deterioration of the urban environment, due to the degradation of the built environment and the contamination or depletion of natural resources (Bolay et al. 2005). These problems are caused by urban development and population growth. This growth is due in a large part to the abandonment of rural areas in search of new opportunities in cities. Cities occupy extensive areas and they cause significant loss of agricultural land and green areas. The high rates of urban growth during the 60s and 70s produced a rapid urbanization and various kinds of environmental problems.
A summary of important environmental data according to a study in 17 cities in Latin America by the Economist Intelligence Unit (2010) is presented. The study includes most major Latin American urban areas. Capital cities and leading business capitals were selected, both for their size and importance. The principal results observed were:

- Cities in Latin America face an enormous challenge due to the growth of informal settlements and unplanned growth of urban areas. Sustainable construction does not have a high relevance: Only 9 cities have full or partial standards for construction and only 4 cities promote energy efficiency in buildings.
- Latin American cities generate less waste per capita than European cities: 465 Kg/year versus 511 kg/year.
- Air quality is a major environmental problem. The car is the predominant mode of transport and therefore is a major source of pollution.
- On the subject of water, wastewater collection covers on average 94% of the cities in regular residential areas. However, on average, only 52% of wastewater is treated.

One of the main problems discussed by researchers and planners is the phenomenon of peripheral growth in Latin American cities. This phenomenon can be defined as a kind of growth process characterized by the expansion of borders of the city thorough the massive formation of peripheral settlements, which are, in most cases, large spontaneous low income residential areas. This expansion causes a diffuse city model unlike compact city model in Europe (Figure 1.4).

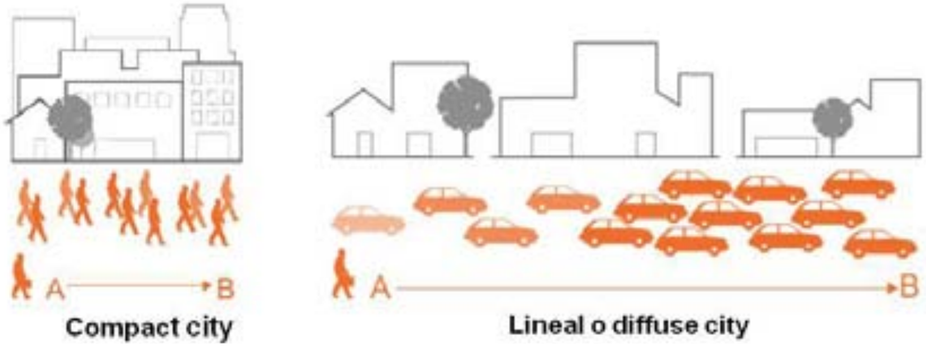

Figure 1.4 Compact and diffuse city model. Source: Rogers (1997)

In addition to irregular settlements in the periphery, in Latin American countries like Mexico, there has been a massive increase in housing construction. Social and economic housing is of greatest demand (Cerón-Palma, 2008), where a standardized prototype house is produced. This type of housing is repeated in different regions of the country, regardless climatic differences (Figure 1.5). This in turn affects the thermal comfort, energy consumption and CO_2 emissions.

Figure 1.5 Standardized prototype of social housing in Mexico.

An important strategy to be implemented in Latin America is to consider the metabolism of the city in relation to planning and construction of buildings. The following section explains the urban metabolism and other concepts of the sustainable city paradigm.

1.1.2 The sustainable city paradigm: a general overview

Several paradigms towards a new model of sustainable city have proposed the study of the impact from urban consumption patterns. One useful way to consider the impact of city activities on climate change has been through the lens of urban metabolism—the paradigm that cities have functions and processes analogous to living organisms (Livingstones, 2010). In a study that quantified the flows of energy, water, materials and waste of American cities, the concept of urban metabolism was introduced by Wolman (1965). This concept helps us consider the city as a complex system that calibrates, manages and configures various stocks and flows of resources, such as energy, water, capital, space and information (FCL, 2012). One significant flow in the cities is the food. A tremendous amount of fossil fuel is used to transport food such long distances in addition to other environmental impacts resulting from processing, packaging and distribution (Sanyé-Mengual et al. 2012).

Related to the concept of urban metabolism is the application of the ecological footprint to cities (Figure 1.6). The ecological footprint of a city is the amount of biologically productive area required to provide its natural resources and to assimilate its waste (Wackernagel and Rees, 1995).

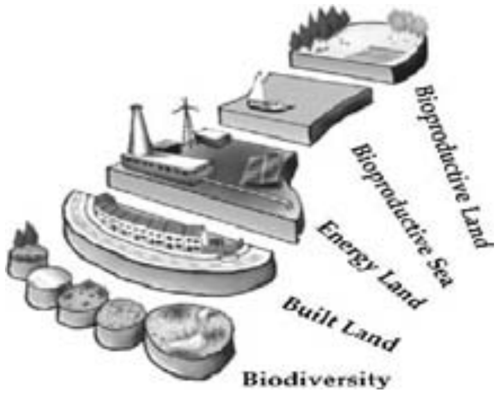

Figure 1.6 Schematic representation of the environmental footprint, and its land types. Source: Eaton et al.(2007) adapted from: Chambers et al.(2000)

Cities have been shown to be unsustainable in the sense that their footprints greatly exceed their biocapacities by typically 15–150 times (Doughty and Hammond, 2004). In order for cities to become more sustainable, they must change the linear metabolism to a more circular metabolism (Figure 1.7), creating a self-regulating sustainable relationship with the biosphere (SC, 2004).

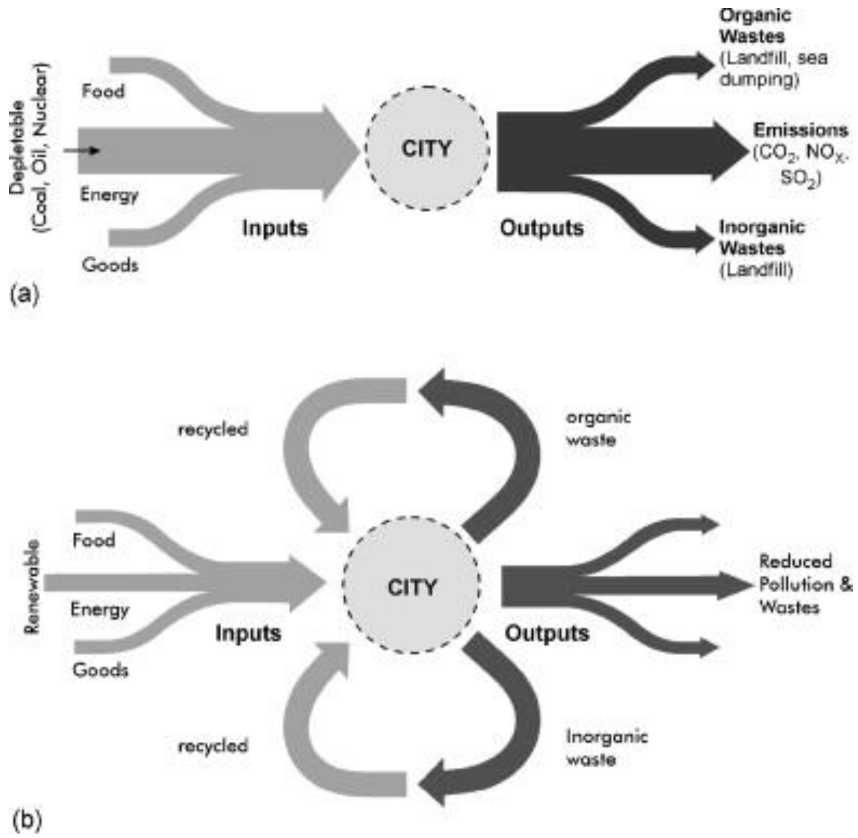

Figure 1.7 (a)Linear and (b)circular metabolism in cities – Source: Doughty and Hammond (2004); adapted from: Girardet (1999) and Rogers (1997)

Addition to energy, water and goods, in the current linear metabolism in cities, food is a significant input. The food flow model involves a tremendous amount of fossil fuels, which is used to transport food, in addition to other environmental impacts resulting from processing, packaging and distribution (Figure 1.8) (Sanyé-Mengual et al. 2012).

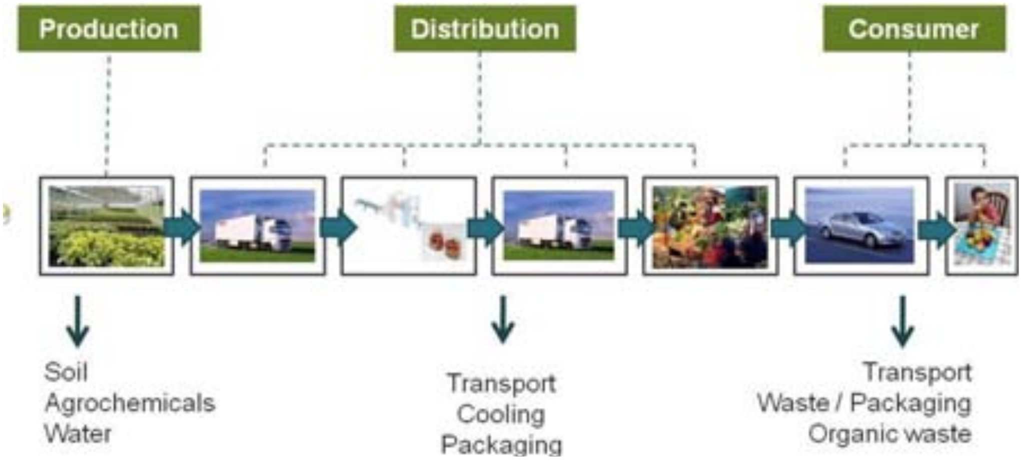

Figure 1.8 Linear system of food production. Source: Cerón-Palma et al. (2011)

Food production in isolated agricultural areas causes an increase in distance that the food has to travel to cities, thus producing large GHG emissions. There are only a few studies that quantify the benefits of the integration of food production in cities. However, the introduction of food production in cities is an issue that should be considered in future for the planning of sustainable cities.

Initiatives for sustainable cities

In cities, inhabitants are concerned about air pollution, congestion, dirty water and waste, so authorities are pressed, in order to innovate and deliver greener, cleaner, more pleasant places to live. Currently, there are programs and initiatives to promote more efficient and sustainable cities through **eco-innovation.** This is defined as "the systematic incorporation of life cycle considerations into the design of products, processes or services" (Tukker et al. 2000). Previously, the concept of eco-innovation was applied mainly to products (James, 1997). Today, eco-innovation transcends the limits of urban sustainability and climate change. It is the development of technical and management approaches to the challenge of reducing the environmental footprint of human settlement.

In Latin America, Curitiba in Brazil is one of the best examples of a sustainable city, it shows that a city can minimise its environmental impact and be attractive. Today, the city provides about 52 m^2 of green space for every inhabitant, an increase of from 1 m^2 in 1970. Some 70% of all waste is recycled (European Commission Environment, 2011). Curitiba provides the world with a model in how to integrate sustainable transport

considerations into business development, road infrastructure development, and local community development.
In Europe, Copenhagen has the largest wind turbine industry in the world. Denmark is also the leader in wind production—supplying roughly 19 percent of the country's power needs. As part of Copenhagen's goal to become the world's first carbon neutral capital by 2025, city officials have introduced a mandatory green roof policy, requiring all new developments to incorporate some type of provision for vegetation into the building's roof design (Estries, 2009).
Diverse investigations have been conducted in order to evaluate the application of new tools from industrial ecology and eco-design at different scales, for example city, neighborhood, building and urban elements. For instance, Rieradevall et al. (2009) focus on environmental optimization of urban public space through LCA, Farreny et al (2009) on ecodesign at a neighbourhood scale, Oliver-Solá et al. (2009a) on environmental impacts of infrastructure scale. Engel-Yan et al (2005) suggest that the focus should be on the design of sustainable neighbourhoods.

1.1.3 The neighbourhood as a new scale for intervention for sustainable cities

Recently, several studies relating to new and rehabilitated urban areas show the neighbourhood as a new scale for more efficient intervention for sustainable cities
Farreny et al. (2011) have applied the ecodesign methodology to plan a sustainable neighbourhood in a greenfield area called Vallbona in Barcelona, Spain. In this work, opportunities and constraints have been determined. It has been concluded that a unique path to design sustainable neighbourhoods cannot be taken, because each neighbourhood has different demands.
The first eco-district in Barcelona designed was for the municipality of Figueres in Girona. The proposed access to the neighborhood is via peripheral streets, with no cars. Car parks will be grouped in specific buildings and there will be spaces for bicycles and pedestrians. The buildings will be orientated correctly for cross ventilation. Each of the design decisions have been taken in relation to a previous study which analyzed the flows of the neighborhood (Rueda et al. 2012).
There are also existing neighbourhoods that are referred to as green because of their excellent environmental performance. The areas of Risefeld and Vauban in Freiburg (Germany) are considered important references for eco-neighbourhoods in the world.
In Risefeld, all houses are built as low-energy buildings with solar panels and climatic aspects have been considered. Green spaces, open areas, bicycle paths and other spatial aspects were considered at the planning stage. 80% of the water comes from rain harvesting (Beim et al. 2010).
The Vauban Quarter was created in an area of 38 hectares, located close to the city centre. Low-energy building is obligatory in this district; zero-energy and energy-plus building and the application of solar technology are standard for most. Parallel to private development, infrastructure was created that encompassed schools, kindergartens,

youth facilities, civic meeting places, a market place, as well as spaces for recreation and play. Vegetation-covered flat roofs store rainwater, which is collected and re-used (Field, 2010).
Other examples in Europe of sustainable neighbourhoods include Amsterdam-Ijburg, Copenhagen-Orestad and Hammarby Sjostad in Stockholm.
In United Kinston, in BedZED, located in London, homes achieved an 84% reduction in energy and footprints related to mobility decreased by 36%. Recycling reduced waste by between 17% and 42% (Barrett et al. 2006). There are several other initiatives of eco-neighborhoods in Europe and in the United States and Latin America.
There is no specific recipe for an optimal design, but it is important to include environmental and quantification tools from the planning stage. A multi-disciplinary team is needed to produce the design.

1.1.4 Building: An essential sector in climate change mitigation

The integration of the concept of sustainability to the building sector is one of initiatives that have been developed during recent years. The construction sector is associated with a number of negative environmental impacts. At the present, the sector contributes a huge amount to the global environmental load. For example, around 40% of total energy consumption in Europe and 60% of raw materials extracted from the lithosphere are attributed to this sector (Zabalzan et al. 2011). In developed countries, residential and commercial buildings account for nearly 40% of all carbon emissions and consume as much as 73% of electricity (DAC, 2011).The Intergovernmental Panel on Climate Change (IPCC) estimates that by 2030, greenhouse gas (GHG) emissions from buildings will account for over one-third of total emissions (Levine et al. 2007). This data explains the importance of implementing eco-innovative strategies and initiatives in the construction sector.

Life cycle phases of buildings

The environmental impacts of buildings occur during all stages of its life cycle.
According to Guide to Life Cycle Assessment of Buildings published by American Institute Architects (AIA) (Bayer et al. 2010), the Life-Cycle Stages of a building are:

Materials Manufacturing: Removal of raw materials from earth, transportation of materials to manufacturing locations, manufacture of finished or intermediate materials and products, and packaging and distribution of building products.
Construction: All activities relating to actual building construction.
Use and Maintenance: Building operation including energy consumption, water usage, environmental waste generation, repair and replacement of building assemblies and systems, and transport of equipment used for repair and replacement.
End of Life: Includes energy consumed and waste produced due to building demolition and disposal of materials to landfills, and transport of waste materials. Recycling and

reuse activities related to demolition waste also can be included and have a "negative impact."
ISO 21930 (2007) describes the principles and framework for environmental declarations of building products, taking into consideration the complete life cycle of a building.
Graham (2003) uses a Life Cycle Approach to link emissions to the different stages of a building's life (Figure 1.9).

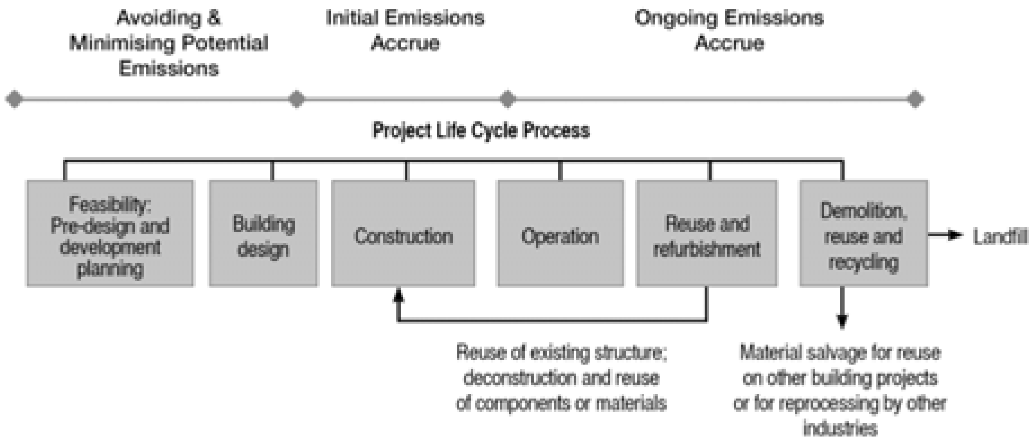

Figure 1.9 Life cycle phases of buildings. Source: Graham (2003), UNEP (2011)

Literature has emerged recently examining various aspects of environmental impact of the construction sector. For example, Oliver et al. (2009b) focus on environmental optimization of concrete sidewalks, Rieradevall et al (2008) on assessment tools, Wadel et al. (2010) on closed cycle of materials.
Life Cycle Assessment can reveal the potential for eco-innovation and substitution of traditional materials by recycling, in order to reduce the environmental footprint of buildings.
Until recently, about 20% of the carbon emitted from buildings was associated with embodied emissions (i.e. emissions that are a product of the construction, maintenance, refurbishment, including those from the extraction, transport, manufacture and assembly of building materials) and about 80% with the use of the building to maintain the level of service and comfort for inhabitants (EIO, 2011; Pages and Cuchi 2008). This indicates that the greatest contributions to climate change correspond to the phase associated with the use of the building.

Emissions associated with the use phase of building

The International Energy Agency (2009) estimates that nearly 60 per cent of the world's electricity is consumed in residential and commercial buildings. Greenhouse gas (GHG) emissions from buildings primarily arise from their consumption of fossil-fuel based energy, through the direct use of fossil fuels and through the use of electricity (UNEP, 2009).

Energy is the most important factor in order to reduce GHG emissions. Measures to reduce GHG emissions from buildings fall into one of three categories: reducing energy consumption and embodied energy in buildings, switching to low-carbon fuels including a higher share of renewable energy, or controlling the emissions of non-CO_2 GHG gases. This chapter devotes most attention to reduce energy consumption and GHG emissions in existing buildings.

Energy efficiency in buildings

In relation to the design of energy-efficient buildings, three important factors are to be considered: (a) first minimizing energy requirements through use of insulation, reducing loads, solar analysis and other passives strategies, then (b) considering equipment that consume less energy efficient offering the same service and, finally, (c) using renewable energy for what cannot be resolved through passive strategies (Levine et al. 2007). However, these strategies have to be different in each place. It is necessary to take the climate, economics, technology and the culture into account.

One of the main measures in new or existing buildings is through the thermal envelope. This term refers to the shell of the building as a barrier to unwanted heat or mass transfer between the interior (Levine et al. 2007). Three important aspects of the efficacy of the "thermal envelope" are: (a) levels of insulation and thermal bridges; (b) thermal properties of materials, windows and doors; (c) and finally, air exchanges that occur inside and outside of the building.

Reduce cooling loads and / or heating will improve the efficacy of the thermal envelope; thermal comfort inside the building is another aspect to consider.

Several initiatives have been taken in Europe and Latin America to improve energy efficiency in buildings. Further details are presented in the following chapters.

Despite the environmental and economic benefits that energy efficiency represents, there are barriers to implementation in different countries. The Carbon Trust (2005) suggests a classification of these barriers into four main categories: financial costs/benefits; hidden costs/benefits; real market failures; and behavioural/ organizational non-optimalities.

It is necessary to define eco-innovative strategies to reduce energy consumption and overcome barriers presented through research and quantification of the social, environmental and economic benefits.

1.2 Motivation of the dissertation

A large percentage of the population lives in cities and this is a key contributor to climate change. Cities and people are affected by the rapid deterioration of the urban environment, cause by degradation of the built environment, contamination and depletion of natural resources. Greenhouse gas emissions from cars, power plants, and other human activities are the primary cause of global warming. **It is necessary to define strategies to reduce consumption, emissions and improve quality of life in urban settlements.** The key is in urban infrastructure: the systems of transportation, energy, water, building, and communication that supports cities.

In addition to the current problems of cities, this dissertation is motivated by the following specific realities:

Food and energy flows in cities:

Two important problems that we need to consider in cities, in addition to water and emissions, are energy and food.

- Energy is the most important factor in reducing GHG emissions. The International Energy Agency (2009) estimates that nearly 60 per cent of the world's electricity is consumed in residential and commercial buildings. The data indicates that there is an **urgent need for new eco-innovative strategies** in order to reduce their environmental impact.
- The food flow model involves energy costs and CO_2 emissions in transport, packaging and distribution. This affects the water cycle and leads to fragmentation of the rural area and city (Arosemena, 2012). The **integration** of distant areas of the city through **agricultural activities** gives the opportunity to **reduce the environmental footprint,** which transforms spaces and leads to degradation in productive use. However, there are only a few studies that **quantify the benefits of the integration of food production in cities.**
- Integrating eco-innovative strategies in the building sector is a **priority in developing countries**. This is mainly due to the urban sprawl found in these countries. There are two important issues: the **uncontrolled action by the building sector** in order to meet housing demand and the **high consumption** by its inhabitants in order to satisfy their basic needs. It is urgent to implement these strategies, primarily for the rehabilitation of this sector, due to the large number of constructed houses.

Energy and GHG emissions in buildings in Mexico

- In Latin American countries such as Mexico, rapid urban growth and housing demand, principally of social typology, presents an opportunity to **propose and evaluate strategies to reduce the environmental impact caused by the use** of the house and **extrapolate these results to a neighbourhood and city scale.**

- Social housing provides one of the greatest demands for construction. However, there is standardized prototype constructed in different regions, regardless of differences in climate. This suggests that there is the need for **studies with tools to quantify energy saving** that can be obtained using strategies for **eco-rehabilitation** of these houses, or to be included at the **design phase for new houses**. It is necessary to consider aspects such as location, climate, insulation properties of materials and other factors. We should also consider strategies to reduce GHG emissions associated with energy use in existing houses.

Energy and GHG emissions in buildings in Spain

- In developed countries, reducing energy consumption and GHG emissions remains the goal of the construction sector. However, there is a **need to investigate new eco-innovative proposals** that could **create synergies** with existing buildings. Investigating novel methods of **food production in buildings** is a new and innovative strategy that could bring many benefits to rehabilitation.
- Considering how roofs can be used as multi-use spaces, in cities such as Barcelona (Spain), can contribute to turning gray spaces into productive spaces. At the same time this can contribute to naturalization of the city, due to the fact that green areas are reduced in the compact city model. However, there is a little information about the use of roofs in urban areas for these purposes.

1.3 Objectives of the dissertation

The main objective of this dissertation is to develop strategies for sustainable urban systems. This dissertation will focus on the assessment of eco-innovative strategies to reduce energy consumption and GHG emissions in case studies assessing buildings in two different contexts: Mexico and Spain.

Other objectives:

- Demonstrate the benefits of integrating green spaces and food production in cities.
- Demonstrate the importance of implementing environmental and energetic quantification tools such as LCA for decision making in the construction industry.
- Integrate social, environmental and architectural tools in order to evaluate strategies to be implemented in buildings.
- Evaluate rehabilitation strategies for buildings in relation to green and eco-technology criteria.

1.3.1 Specific objectives

Mexico: Eco-rehabilitation of social housing

- Propose green and passive strategies for reducing GHG emissions.
- Quantify the energy savings and GHG emissions saved with the implementation of eco-technologies (efficient equipment) and green strategies (green spaces and food production).
- Estimate CO_2 emissions fixed on green spaces (sedum) and food production (tomato) on plot and roof.
- Calculate the CO_2eq emissions saved by not transporting the food (tomato) from the production site to the consumer.
- Assess low-cost passive and insulation strategies to reduce the cooling energy demand and the equivalent CO_2 emissions.
- Quantify the cumulative energetic demand and CO_2 emissions associated with the materials used in low-cost passive strategies.
- Propose the best environmental and energetic strategies as guidelines for the eco-rehabilitation of existing social housing.

Spain: Roof Top Eco-Greenhouse (RTEG)

- Examine the barriers and social, economic, environmental and technological opportunities regarding the implementation of a new inter-connection concept called RTEG in Mediterranean cities in Europe.
- Identify barriers and opportunities for implementation in three types of buildings: multi-household, educational and industrial.
- Establish recommendations for overcoming barriers to the implementation of the RTEG system.
- Assess the energy saving potential by heating the building using a greenhouse on the roof´s building.
- Evaluate the insulating effect of using a greenhouse on the roof´s building in relation to potential energy saving with regards to heating requirements for the study building.
- Study the internal temperature in a building and a greenhouse at different time intervals during a single day during winter.
- Assesses the energy flows of RTEG interconnect in a building during a day in winter.
- Estimate the amount of residual heat available for interchange in a building and a greenhouse during a day in winter.
- Estimate CO_2 emissions avoided by minimising resource consumption generated by heating systems (electric, gas, diesel)

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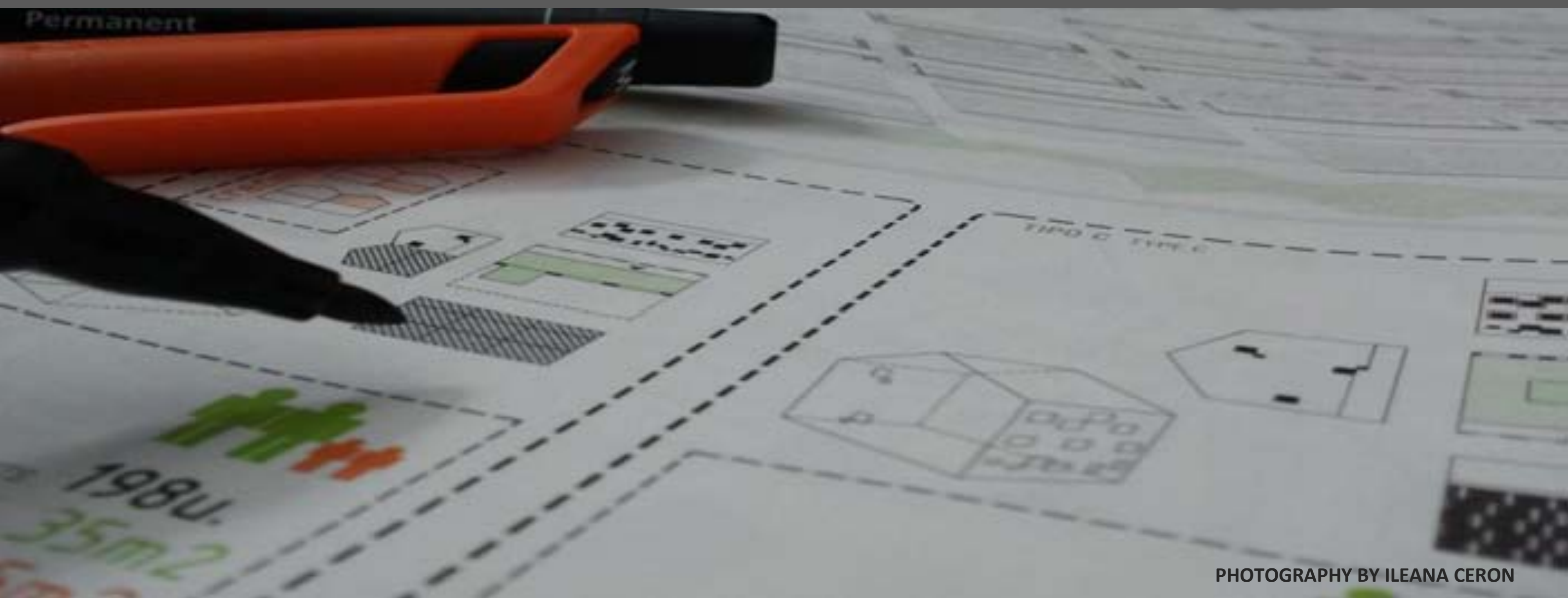
Chapter 2

Methodology



PHOTOGRAPHY BY ILEANA CERON

Chapter 2 presents the main methodological aspects that have been used in the development of this dissertation, which will be divided into assessment tools and study systems presentation. Further details will be given in following chapters.

The chapter is structured as follows:

- Assessment tools
- Systems of study

2.1 Assessment tools

The tools applied throughout the dissertation can be divided into three groups as in Figure 2.1

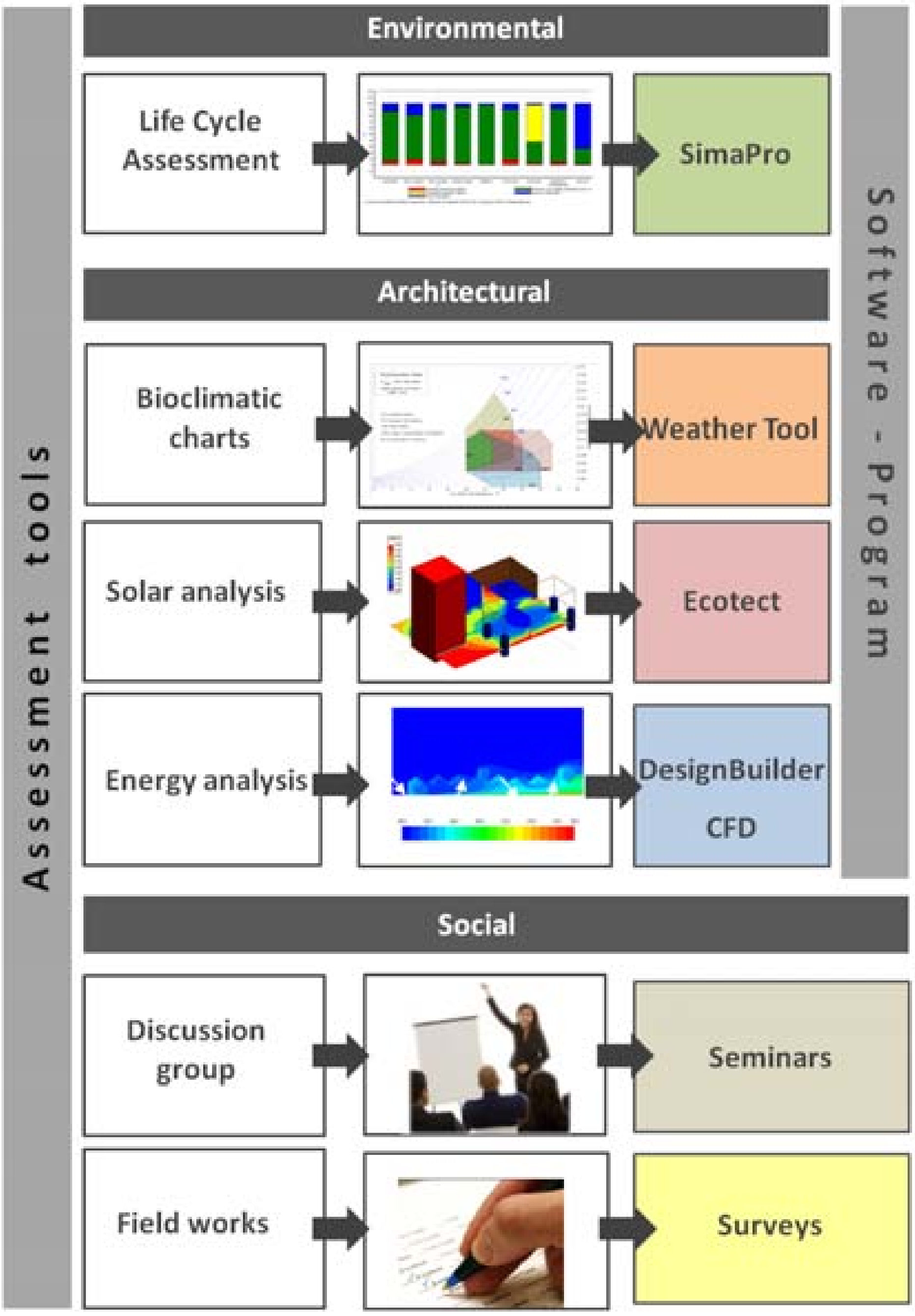


Figure 2.1 Environmental, architectural and social assessment tools

Each of the tools are presented in the following sections. Further details are provided in following chapters.

2.1.1 Environmental tools

Life Cycle Assessment (LCA)

The LCA is one of the new methodological tools used to assess the sustainability of products, processes and services. The Society for Environmental Toxicology and Chemistry (SETAC) defined LCA as :

"*an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal" (SETAC, 1993).*

The LCA research community has worked closely with the International Organization for Standarization (ISO) to produce standards for the LCA framework (ISO 14040:2006; ISO 14041:1998; ISO 14042:2000; ISO 14043:2000; ISO 14044:2006). According to ISO 14040 (2006) "*LCA is the collection and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*." Figure 2.2 shows a graphical overview of the conceptualization of LCA.

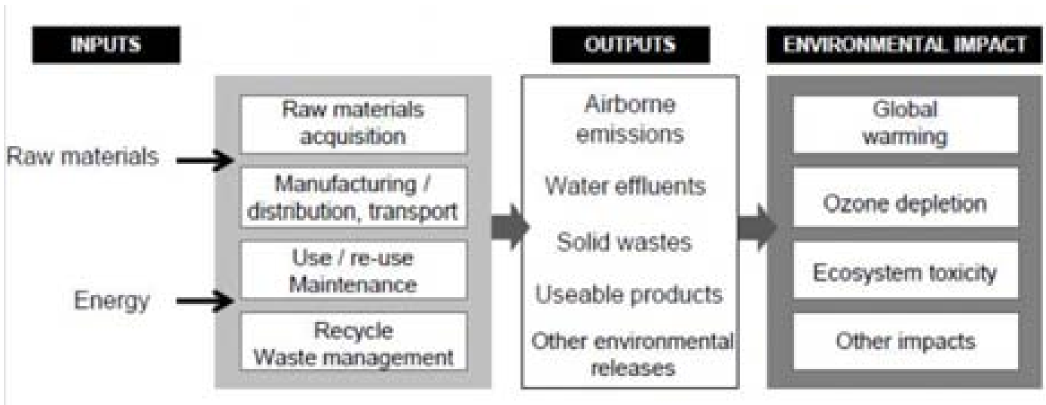


Figure 2.2 LCA Conceptualization

The standard practice of LCA includes four phases (Figure 2.3): (a) definition of the goal and scope of a project (b) inventory analysis to identify and quantify relevant inputs and outputs of a product systems (c) assessment of the impact of these inputs and outputs and (d) interpretation of the significance of impacts. (Guineè et al 2001).

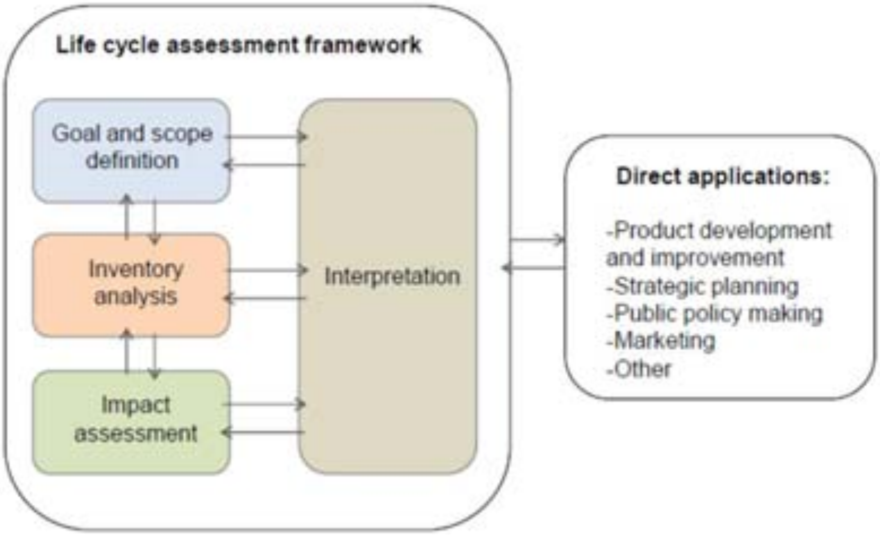


Figure 2.3 Phases of an LCA study

Further details of scope and inventory are provided in each chapter in relation to the study system.

The impact categories considered in this dissertation are Global Warming Potential (GWP) and Cumulative Energy Demand (CED). The description of these impact categories are shown in Table 2.1

Tabla 2.1 Environmental impact categories considered during the diss*ertation.*
Source: Guinée et al. (2001) and Frischknecht and Jungbluth (2003*).*

GWP **Global Warming Potential**	Climate change is related to emissions of greenhouse gases into air. The characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterisation factors. Factors are expressed as for time horizon of 100 years. Unit: kg CO_2 eq
CED Cumulative Energy Demand	It aims to investigate energy use throughout the life cycle of a good or a service. This includes direct as well as indirect uses. Characterization factors given for the energy resources were divided into: non renewable, fossil and nuclear, renewable, biomass, wind, solar, geothermal and water. Unit: MJ eq.

- **SimaPro 6**

The software program SimaPro 6 (System for Integrated environMental Assessment of Products), developed by PRé Consultants, was used as the LCA modelling and analysis tool (PRé, 2012). SimaPro is a well-known, internationally accepted and validated tool and since its emergence in 1990, it has been used in a large number of LCA studies by consultants, research institutes, and universities.

- In Chapter 3, the LCA tool is applied, in order to estimate the Global Warming Potential (GWP) of transporting food from the production site to the social neighbourhood of the study system.
- In Chapter 4, the LCA tool is applied to estimate the GWP and CED associated with the materials of the strategies proposed.

2.1.2 Architectural tools

Climate considerations are essential dimensions in the assessment of quality of outdoor built environments. Achieving thermal comfort of users is another goal of doing climate studies. According to the ASHRAE (2004), thermal comfort is fundamentally a subjective reaction or state of mind, where a person expresses satisfaction with the thermal environment.

Tools that enable us suggest strategies with entire knowledge of the climatic characteristics were used in this dissertation. Energy simulation programs are used to predict the energy performance of the buildings studied.

Below, the architectural assessment tools will be introduced. Further details are provided in each study system, in the following chapters.

Bioclimatic charts

The main objective behind the illustration of bioclimatic charts is to decide the comfort zone and the limits of the various landscape design strategies that contribute to passive energy building design. A comfort zone can be identified in terms of range of effective temperatures and a humidity level, which make a specific percentage of occupants feel comfortable (Koichi, 1996). This research applies the strategies and their application to the psychrometric chart based on the works of Givoni (1998). This chart is based on the linear relationship between temperature amplitude and vapor pressure of outdoor air. Givoni's chart identifies suitable cooling technique based on the outdoor climatic condition. Five zones are identified on Givoni's chart: thermal comfort, natural ventilation, high mass, high mass with night ventilation and evaporative cooling. Bioclimatic charts are utilized by first identifying the average monthly condition. For each month, the average daily maximum temperature is calculated and matched (Figure 2.4).

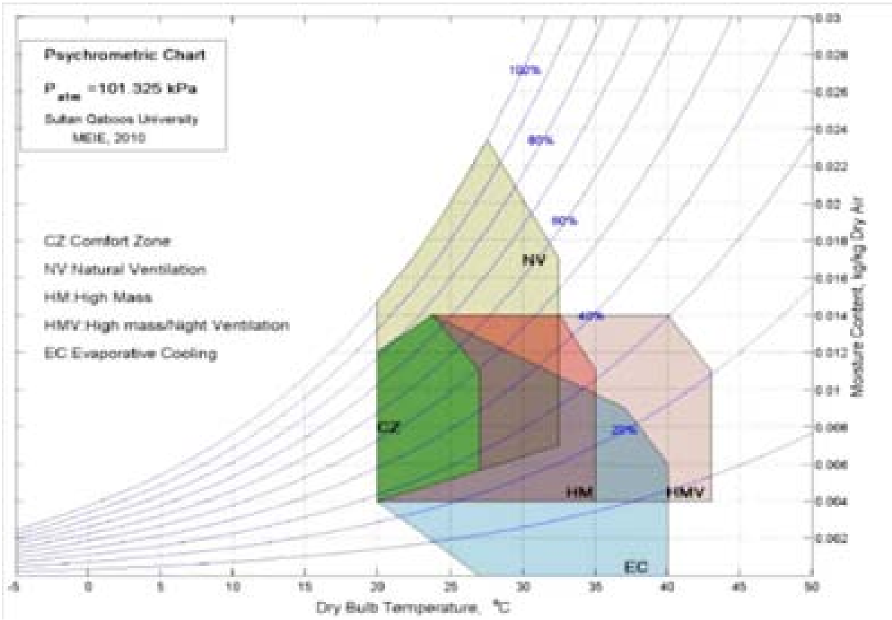


Figure 2.4 Boclimat chart

- **Weather tool software**

For this bioclimatic analysis 'The Weather Tool' software program was used (Autodesk, 2010). This is a visualisation and analysis program used to collect hourly climate data. It recognises a wide range of international weather file formats, as well as allowing users to specify customised data import formats for ASCII files. The climatic files were created with local data for each case study (Figure 2.5).

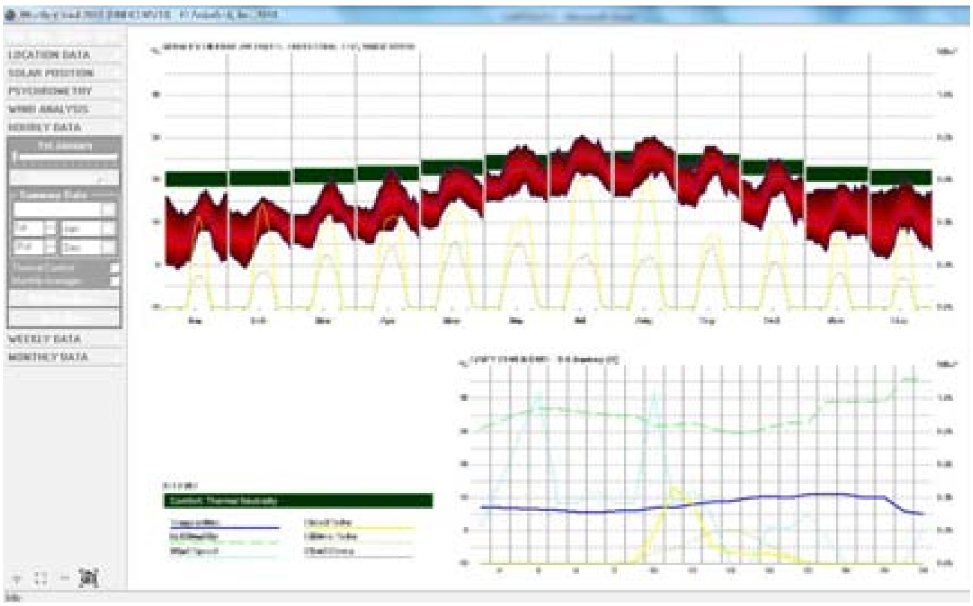


Figure 2.5 View of Weather tool´s interface

Solar analysis

The goal of solar analysis is determine the amount of radiation received on the different surfaces of the building. This allow assessment of the best location to perform, for example, an intervention of integrated photovoltaic or solar protection.

- **Ecotect**

The Ecotect software program (Autodesk, 2011) is a comprehensive sustainable building design tool. This program can visualize incident solar radiation on windows and surfaces, during any period (Figure 2.6). Following, the principal visual tools for solar analysis and calculations are described.

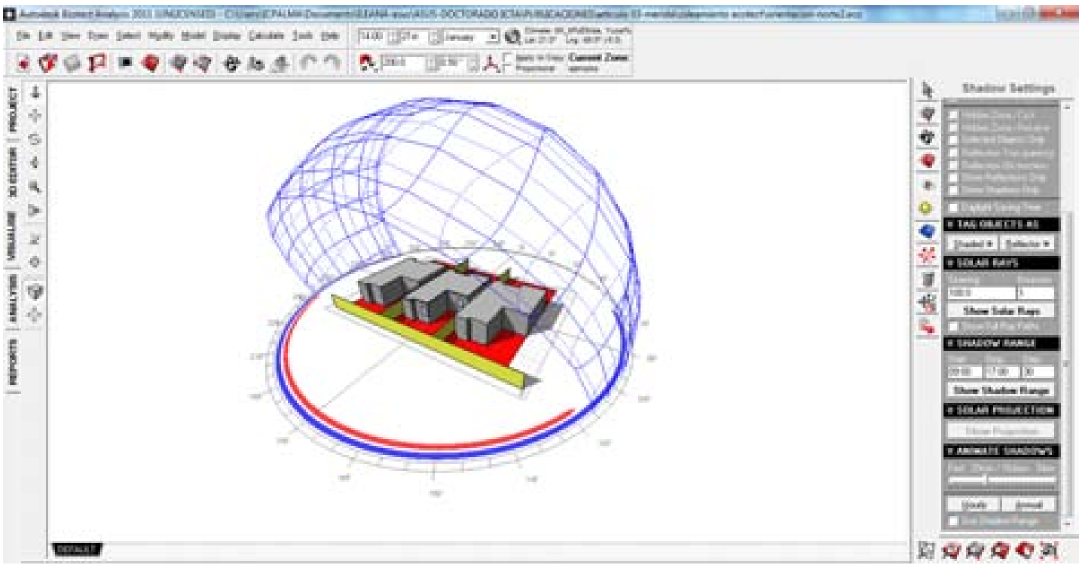


Figure 2.6 View of Ecotect´s interface

Sun path diagrams are visual representations on a flat surface, of the sun's path across the sky. They are used to determine the location of the sun easily at any time of the day, during any time of year.

- In chapter 3, sun path diagrams are used to study the sun´s path on the houses in a social neighbourhood.

Incident solar radiation, also termed ‘insolation’, refers to the wide spectrum of radiant energy from the Sun, which strikes an object or surface within the Ecotect model. This includes both a *direct* component from the sun itself (sunshine) and a *diffuse* component from the visible sky (skylight). Depending on the settings you choose, it can also contain a *reflected* component from other surfaces in the model and the ground (Autodesk, 2010).

It is important to note that insolation refers only to the amount of energy actually *falling on* a surface, which is not affected in any way by the surface properties of materials or by any internal refractive effects. Material properties only affect the amount of solar radiation *absorbed* and/or *transmitted* by a surface

- In chapter 3, incident radiation on walls and roof of a social housing is calculated

Energy simulation

The "DesignBuilder" energy simulation software program (DBS, 2011) is used to calculate the internal gains and cooling/heating demand in chapters 4 and 6. This program uses the EnergyPlus dynamic simulation process (DOE, 2011) to generate performance data based on the climatic and thermal characteristics of the materials. The program allows for the calculation of heating and cooling loads using the method adopted by ASHRAE and implemented in EnergyPlus (Figure 2.7).
The interface of CFD (Computational Fluid Dynamics) in DesignBuilder was used to evaluate temperature distribution in chapert 6

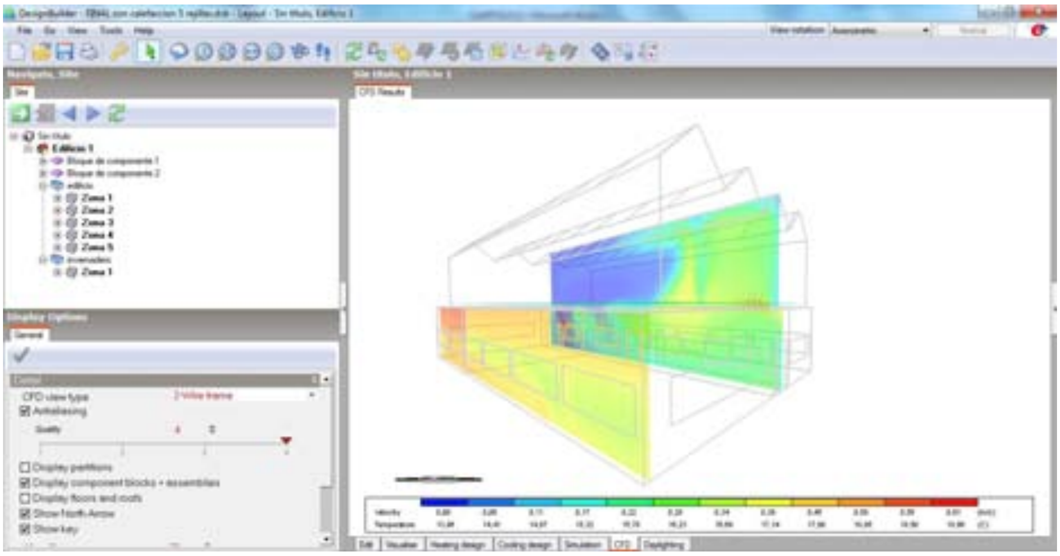


Figure 2.7 View of DesignBuilder´s interface

2.1.3 Social tools

Discussion group

A discussion or focus group is a qualitative technique that uses group interviews and discussions to collect relevant information about the research problem. Ideas will be exchanged, in order to understand the views of different participants regarding particular subjects, and conclusions will later be drawn from the discussions. The first focus groups used as a tool of social and market research were introduced in the mid twentieth century. Merton and Kendall (1946) and Edmiston (1944) wrote papers that recognized the potential of group interviews during this period.

Defining the objectives and the number of people to participate is the first step taken in setting up a discussion group. The figure of a moderator is important, as he introduces the subject, asks questions and sets standards for the participation of group members.

- In Chapter 3, a discussion group was used, in order to identify barriers and opportunities to implement greenhouses on the roofs of buildings.

Surveys

The social survey is one of the techniques used by researchers to collect and generate primary information. Researchers working with an analytical empirical approach, use the survey to obtain information from a representative group of individuals (the sample) and from there project the results to the study population.
The social survey is a questionnaire with a set of questions related to one or more variables or dimensions measured. The content of the questions varies, depending on the issues that it purports to measure. In order to have rigorous data collection, questions should be accurate, relevant and concise.

- For Chapter 3 of the thesis a survey is designed for inhabitants of social housing units in the neighborhood under study. The structure of the survey is presented below.

a) General data: Date, time and name of person interviewed
b) Housing data: m^2, time lived in house.
c) Inhabitants data: Number of inhabitants, age, sex, profession, occupancy period during the day.
d) Ventilation systems: Air conditioning, ceiling fan or pedestal fan, time of use and power.
e) Electronic equipment and household appliances: Type of equipment, power and time of use
f) Perception data: Questions regarding comfort level in relation to heating and cooling, during summer and winter.
g) Observations: Materials of house, green space, shaded areas and insulation.

2.2 Case study presentation

The research presented in this thesis is conducted in two different contexts with the same objective and applying the same assessment tools for different strategies. Part II is conducted in the context of Latin American cities and III in the Mediterranean cities of Europe (Figure 2.8).

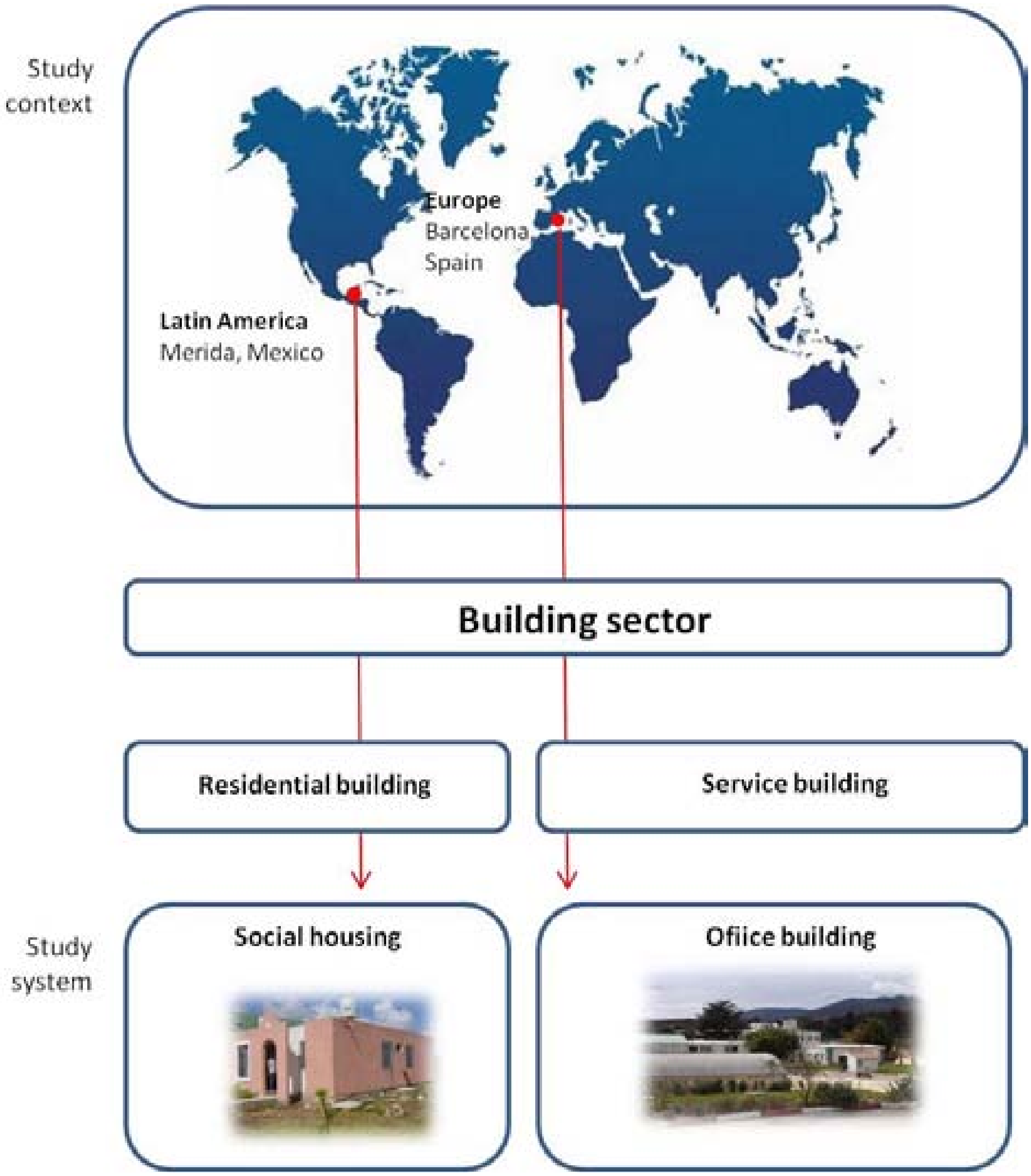


Figure 2.8 Delimitation of context and study system

The main characteristics of these case studies are summarized in Figures 2.9 and 2.10. Late, in each chapter, more details about each case study will be provided.

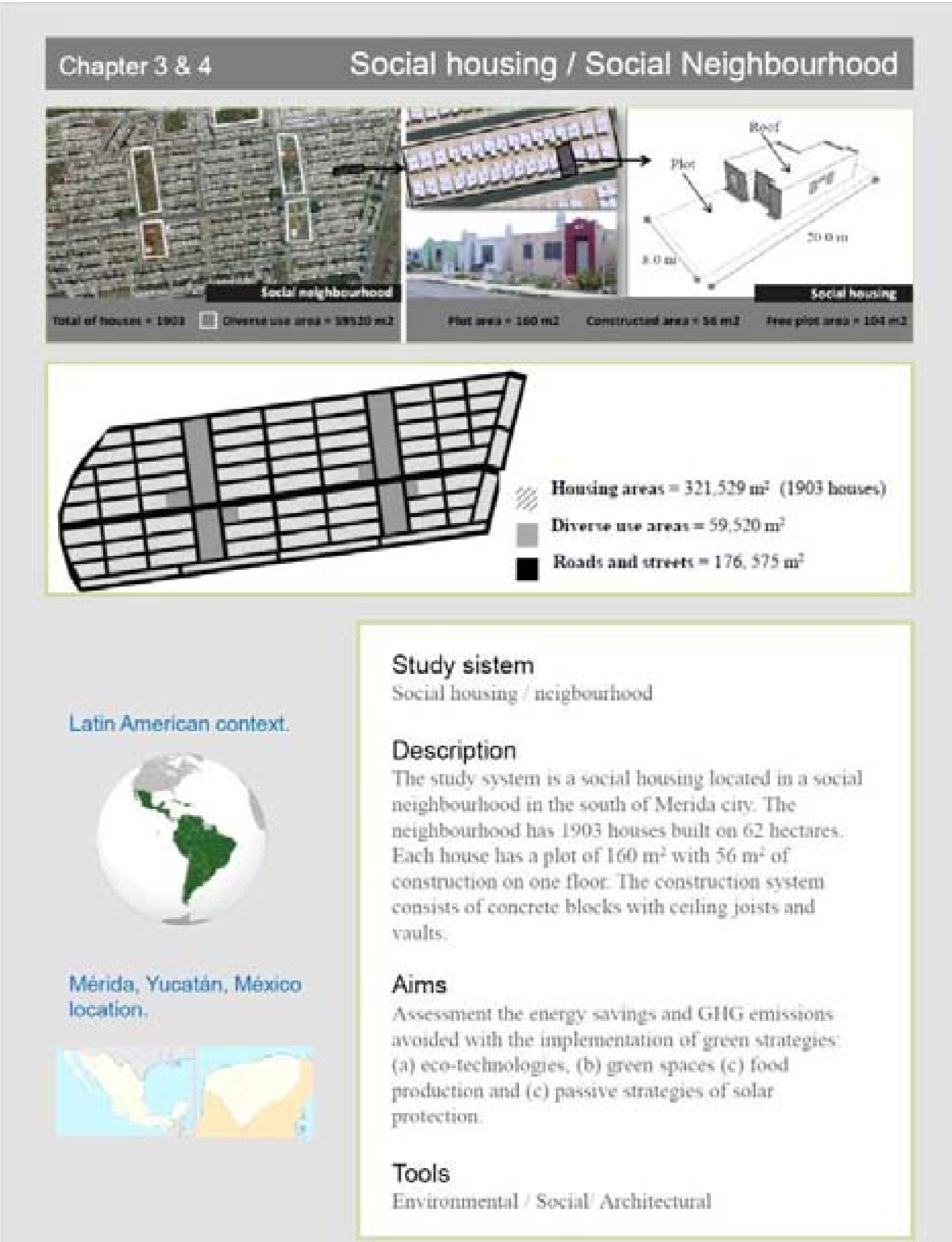


Figure 2.9 Main characteristics of the social neighbourhood and social housing case study

Figure 2.10 Main characteristics of the RTG – office building case study

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PART 2

Strategies to reduce energy and GHG emissions in buildings in Mexico: a case of social housing

As previously stated, reduction in energy consumption and GHG emission is a priority for the building sector. Social housing is an important issue that needs attention, specifically in countries such as Mexico, where there has been a huge increase in the number of houses constructed cities, due to urban growth.
Part II of this dissertation focuses on a study system, assessing social housing in Mexico in warm-humid climate. It is composed of two chapters

Chapter 3: Towards a green sustainable strategy for social neighbourhoods in Latin America: Case from social housing in Merida, Yucatan, Mexico.

Chapter 4: Strategies to reduce the energy requirements and CO_2 emissions of cooling demand on social housing in warm-humid climates of Mexico.

Chapter 3

Towards a green sustainable strategy for social neighbourhoods in Latin America: Case from social housing in Merida, Yucatan, Mexico

RENDER BY ILEANA CERON

This chaptes is based in the following paper:

Ceron-Palma I, Oliver-Solà J, Sanyé-Mengual E, Montero JI, Rieradevall J (2013) Towards a green sustainable strategy for social neighbourhood in Latin America: Case from social housing in Merida, Yucatan, Mexico. *Habitat* International, 38: 47-56, *in press*

Abstract

In developing countries, particularly in Latin America, the rapid growth of urban areas has led to complex problems, including the exploitation of natural resources, environmental pollution and greenhouse gas emissions (GHG). Massive structures are being built to meet the housing demand. Moreover, there is excessive use of energy through appliances, interior lightning and air conditioning which generate GHG.

This paper aims to propose green sustainable strategies to reduce GHG emissions associated with energy consumption in a social neighbourhood in Merida, Mexico. The strategies were eco-technology (efficient equipment) and green spaces (sedum þ food production). Once the context is set, the study collected data about energy habits and consumption. The global warming potential (GWP) was calculated through a life cycle assessment (LCA) to assess the level of GHG emissions associated with household energy consumption.

The CO_2eq emissions avoided by the transport of the food (tomatoes) from the production site to the consumer were calculated. Distribution, packaging and retail were included. All strategies combined can prevent up 1.06 tons CO_2eq/year; this represents 67% of the emissions originating from a reference household (34% avoided by eco-technology, 24.5% fixed by green spaces and 8.4% avoided by food logistics). At city scale (112,000 houses) this represents 100,352 tons/CO_2eq/year.

This study supports the importance of integrating environmental quantitative tools in planning cities.

Keywords: LCA, green roof, urban agriculture, social housing

3.1 Introduction

The design of sustainable cities is a key issue that addresses most of the global environmental problems that our society has created (Oliver-Solà et al. 2009). Currently, cities exert enormous pressure on the natural environment. The world's cities are directly or indirectly responsible for 80% of global energy consumption, generating more than 70% of the total waste and more than 60% of greenhouse gas (GHG) emissions for the planet (Ash et al. 2008). These data show the high contribution that cities make to the global warming phenomenon, which is increasing due to urban growth that is occurring worldwide (Tiwari et al. 2012).

Developing countries, particularly in Latin America, are experiencing an expansive urban growth (Cohen, 2006). This urban growth causes excessive pressure on the existing infrastructure, which affects buildings, public transportation, road networks, water quality, waste collection and public health (Grewal and Grewal, 2012). New settlements continue to be created informally at the urban periphery (Sullivan and Ward, 2012). In addition, cities occupy extensive areas and they cause significant loss of agricultural land, green areas, increased level of consumerism and larger travelling distances in people's daily lives (Turok, 2011).

In Mexico, urban and economic growth has resulted in an ever increasing demand for electricity and an increase in energy use in the transport, industry and residential sectors (Medina-Ross et al. 2005). Sheinbaum et al. (2011) conducted a study that reported a 2.2% annual increase in energy use in Mexico between 1990 and 2006. In 2011, the increase was 5.6% compared to 2010 (SENER, 2011).

In the residential sector, this increased energy use has been caused in large part by the promotion of massive housing construction that has been principally social in nature to meet the needs caused by urban growth and to reduce excessive settlement in the peripheries of cities (Aguilar and Santos, 2011). This model has been replicated in different regions of the country without considering the climatic differences between regions of Mexico (dry climate, warm, warm humid and tropical). This potentially increases the use of energy because these models do not consider the climatic requirements inherent in housing design, and there is no place for users to participate in the design (Noguchi and Hernandez-Velasco, 2005).

3.1.1 Urban planning and housing sector in Mexico

The rapid population growth in Mexican cities has economic, political, social and environmental implications. In 1980, the population was 66.8 million, and in 2010, it had increased to 112.3 million people, of which 77.8% lived in urban areas. Population growth generates greater housing needs. If in 1980 there were 12.1 million houses in Mexico, 30 years later, in 2010, this number more than doubled, reaching 28.6 million houses (INEGI, 2010a).

The construction of these houses causes a significant reduction in the area covered by vegetation, increasing the area of land covered with concrete in the form of streets, parks, roofs, etc. (Ward and Aguilar, 2003).

One notable difference between the housing sector in Mexico and that of other countries is that in Mexico, home ownership has been encouraged, while developed countries have stimulated the market for rental housing (Ferguson and Navarrete, 2003).
Of the total housing stock in Mexico in 2010, 90.6% were private and detached houses (SHF, 2010).

Energy in the housing sector

In Mexico, the growth in housing is responsible for 17% of the total energy consumption in the country and 8% of the total GHG emissions (Rosas et al. 2010).
The energy consumed in the housing sector is mainly used for water heating (29%), food preparation (52%), lighting and appliances (19%). The level of GHG emissions associated with electricity consumption in cities in Mexico varies depending on the need for artificial cooling systems and/or heating systems (SENER, 2009).
The electrical equipment and participation rates in home electricity consumption in Mexico are as follows: cooling system (44%), lighting (33%), refrigerator (14%), and heating (9%) (CONAVI, 2006).
The most important variables affecting housing energy use will be the introduction of technology, the utilisation of equipment and housing size (Rosas-Flores and Morillon, 2010).

Social housing in Mexico

The name 'social housing' is given to housing that is built for sectors of the population with lower economic resources. It consists of a standardised model constructed following the same pattern in different regions of Mexico, which ignores the different climatic conditions.
Currently, in Mexico, social housing can be classified according to its value, which is based upon how many 'times the current monthly minimum wage in Mexico City (VSMMDF)' the housing costs. This classification includes three types of social housing. The main difference between the economic, popular and traditional housing types is the size of the construction in terms of square metres (SHF, 2010).
The construction of this housing is based on conventional materials, such as beam and vault slabs, concrete and either hollow block walls, clay bricks or concrete walls, depending on the region. The lots are reduced to optimise the soil surface and are usually 8x20 m, 10x20 m or 10x25 m (Romero, 2007). Funding programs for social housing take the form of direct subsidies that require a down payment or advanced payment that represents between 15% and 25% of household income. This type of financing has led to more widespread home ownership and massive construction of this type of housing (González, 2006).

3.1.2 Initiatives in Mexico for energy efficiency and emissions reduction

Due to the importance of the housing sector in the country's energy consumption in recent years, there have been various programs and public consultation documents aimed at improving home energy efficiency. For example, The National Housing Commission (CONAVI) has drafted documents with guidelines and criteria for sustainability, energy efficiency and bioclimatic design in homes in Mexico, but these guidelines are not considered in current building regulations (CONAVI, 2008). The National Commission for Energy Conservation (CONAE) recently began work to implement a program for solar water heaters (CONAE, 2011). Morillón (2008) developed the technical basis for the Green Mortgage program, which consists of a larger credit for housing financing to incorporate new technology, including solar heaters, solar panels, insulation and saving lamps. The Federal Electricity Commission (CFE) and the Trust Fund for Electric Energy Savings (FIDE) encourage the rational and efficient use of electricity in warm climates in the country along with CONAVI and The Institute of the National Fund for Workers' Housing (INFONAVIT). The proposed actions consist of the installation of compact fluorescent lamps, double glazed thermal windows, air conditioning and the application of thermal insulation in the roofs of houses. Since 2002, these actions have reduced CO_2 emissions by 5.3 million tons (Rosas-Flores et al. 2011).

Initiatives to reduce GHG emissions have been promoted in the housing through conventional energy-saving strategies; however there have been no investigations of other strategies that can prevent and/or fix GHG emissions in neighbourhoods.

Green spaces and food production

Green spaces play a significant role in urban environments. According to studies in Merida (Mexico) by Canto (2010), higher temperatures were reported in urban areas, mainly on pavement and buildings. In these areas, the phenomenon of thermal inertia causes heat to accumulate during the day and then be released until dawn. The lowest temperatures in the city of Merida are present in areas with considerable vegetation (Canto, 2010). Plants can reduce the ability of the heat reaching buildings by increasing the reflection of radiation and shading (Li et al. 2010). Green roofs may also fixe carbon in plants and soils. The CO_2 captured by plants is the result of differences between atmospheric CO_2 absorbed during photosynthesis and the CO_2 emitted by the atmosphere during respiration. This difference is converted into biomass and is usually between 45 and 50% of the total dry weight of the plant (Carvajal, 2008; Getter et al. 2009).

Beside the above-mentioned advantages, green spaces can produce food. Urban agriculture in western cities is starting to become a feasible option of self-sufficiency.

In recent years in Mexico, the physical separation between rural and urban areas has increased. The lack of investment and support for agriculture has meant that food production in Mexico is not in line with population growth. Insufficient food production has mainly led to an increase in U.S. imports (Torres, 2001).

In the city of Merida, Yucatan, the rapid expansion of the housing sector has increasingly led to the replacement of cropland by extensive paved surfaces and the infrastructure needed to build new neighbourhoods (Cerón-Palma, 2008).

3.2 Definition of study

3.2.1 Justification and objectives

To create sustainable cities, it is essential to evaluate strategies involving a reduction of impacts to the environment. The reduction of GHG emissions through neighbourhoods will be a first step of transition to the sustainable city concept.

One way to minimize the environmental impact is to bring food production into the city. Projects in new neighbourhoods and rehabilitation projects in existing neighbourhoods have incorporated food production and flow synergy techniques. Farreny et al. (2011) carried out an interdisciplinary study of concepts for a sustainable district in Barcelona, Spain that considered the incorporation of agriculture into the urban structure.

In Latin American cities, urban agriculture has been introduced to reduce poverty by means of small vegetable gardens in homes; the space and types of crop are determined by each family (Pretty et al. 2003).

Recently, strategies for integrating food production into cities have mainly arisen through urban agriculture and initiatives in buildings. However, the environmental benefits have not been quantified (Cerón-Palma et al. 2011a).

There is still a large information gap on energy-use strategies for social housing as well as the performance of green spaces and their potential to fix carbon and produce food locally. This paper addresses some of the initiatives mentioned previously in the context of the warm-humid climate of Yucatan (Mexico) and can be replicated in other climatic regions of Mexico.

This case study of a social neighbourhood in Yucatan is the first of this region that uses quantitative environmental tools, like LCA, for assessing the environmental benefits.

The specific objectives of this study of sustainable strategies for social neighbourhoods were the following: (1) the environmental and energy study of the use of popular social housing in a representative area with a warm and humid climate in Mexico and (2) the analysis of energy savings and GHG emissions avoided with the implementation of two strategies, eco-technologies (efficient equipment) and green spaces (sedum and food production) on the roof and house plot.

3.2.2 Case-study: social neighbourhood in Merida (Yucatan, Mexico)

The study was conducted in the city of Merida, located in the state of Yucatan, in southeast Mexico. Merida is a dense and expansive city with a population of approximately 830,732 inhabitants and an area of 883 km2. The city lies at a longitude of 89^{o}58' W and a latitude of 20^{o}58' N (INEGI, 2010b). It has a warm-humid climate with an average annual rainfall of 990 mm and an average annual temperature of 29^{o}C (UADY, 2011).

The urban area of Merida has experienced a process of expansion through horizontal growth of the floor area (OECD, 2007). The impact of this expansion can be seen from the 1970s, when massive construction of housing began. In the last 10 years, the construction area has been extended by 10,255 ha (SEDUMA, 2008). This growth is mainly attributed to the housing boom that emerged due to the acquisition of land at a low cost by construction companies, thus promoting the massive construction of new neighbourhoods.

The study system is a social housing located in a social neighbourhood in the south of Merida city. The neighbourhood has 1903 houses built on 62 ha. In this type of neighbourhood, tree planting and vegetation is limited or nonexistent. According to Canto and Pérez (2003), the sparse arborization is due to the size of the housing and the plot.

According to the "Neighbourhood's Law of the State of Yucatan" any housing development has to consider a donation area (Gobierno del Estado de Yucatán, 1985). In this donation area (diverse use area) parks, equipment or green areas are being constructed. However, in the areas of donation of the social neighbourhoods, preference is given to the commercial use of soil, reducing the possibility of implementing green spaces in them. In the case study a high percentage of these areas are abandoned (Cerón-Palma, 2008).

Figure 3.1 shows the study area and summarises the features of social neighbourhood.

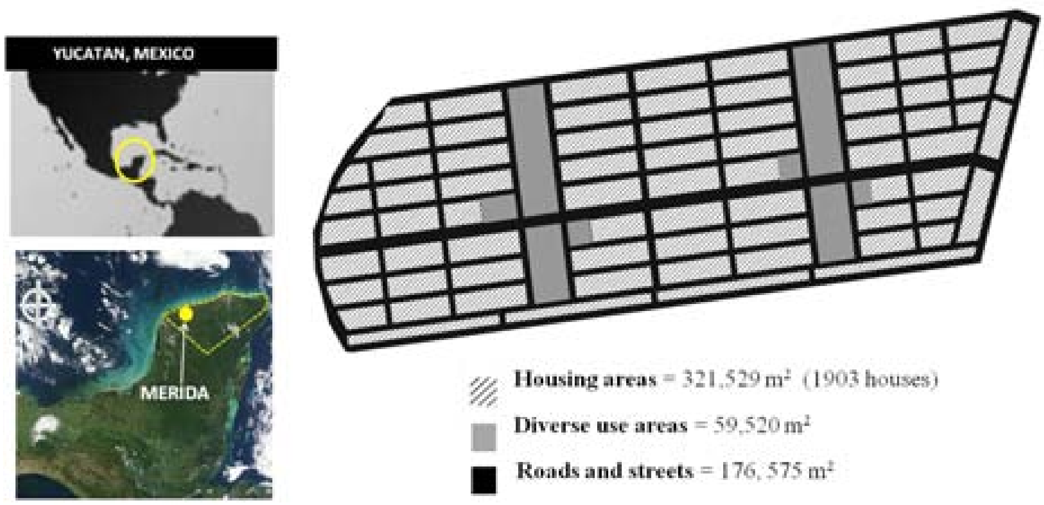

Figure 3.1 Social neighbourhood. The figure shows the limit of the neighbourhood and main characteristics

Each house has a plot of 160 m^2 with 56 m^2 of construction on one floor. The construction system consists of concrete blocks with ceiling joists and vaults. Each house has two bedrooms, one bathroom and a living room with a kitchen and is usually occupied by young families consisting of 4 or 5 members.

Figure 3.2 summarises the architectural features of social housing in Merida, Mexico, which was chosen as the reference system for this study.

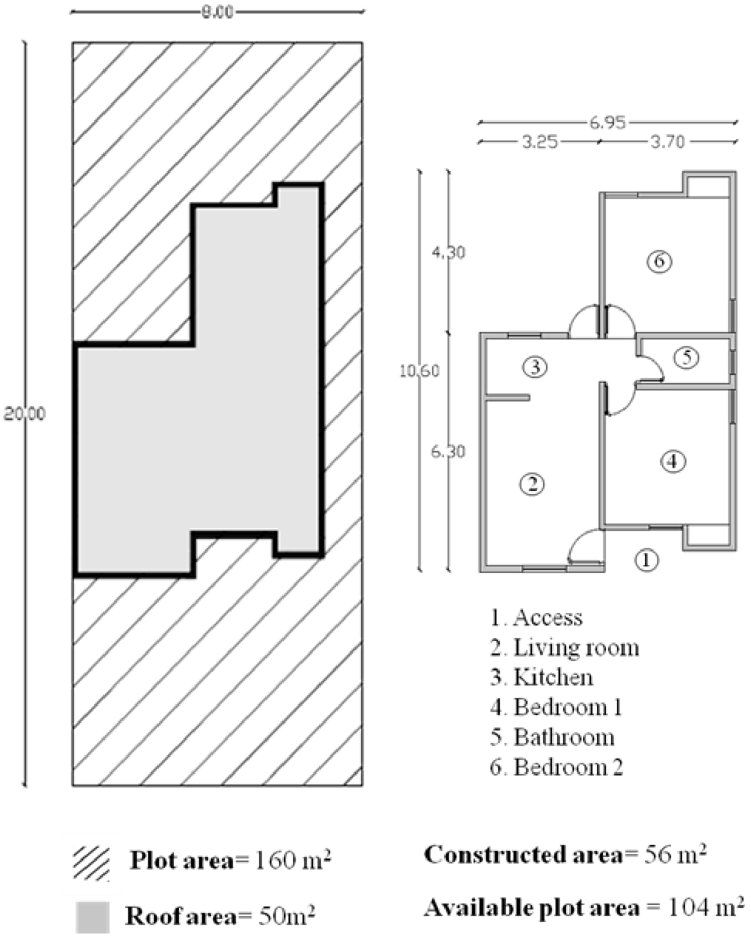

Figure 3.2 Dimensions and distribution of social housing.

The surfaces considered in the study are 100% of the roof (50m^2) and a reasonable estimation of the useful plot area for green spaces is 70% (72.8 m^2) since the rest surface is used for the house entrance, paths and others.

3.3 Materials and methods

After characterising the reference system (energy consumption and GHG emissions) in the first part of the study, two strategies for reducing GHG emissions were studied. Finally, the system was expanded to consider the emissions savings achieved by bringing food production closer to consumption, thereby avoiding the need for regional transport.

Figure 3.3 shows a summary of the methodology and tools.

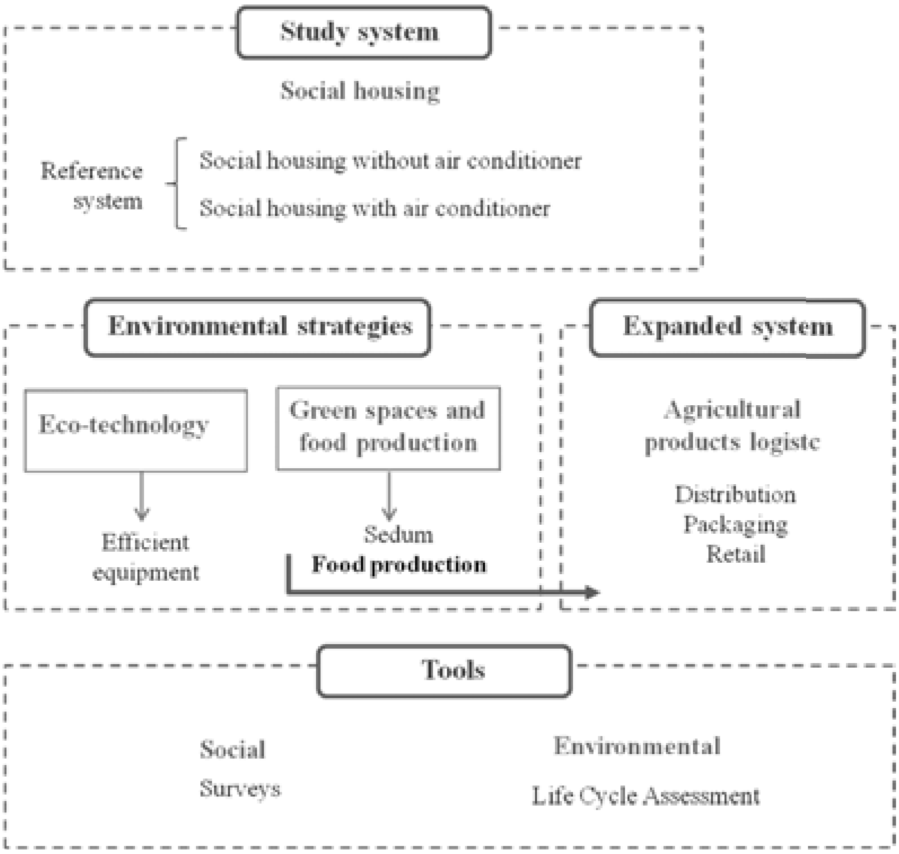

Figure 3.3 Summary of the method and tools used in the study.

3.3.1 Characterisation of the use phase of reference system

A characterisation of the housing systemis needed to obtain data regarding energy consumption. Data from field work through surveys conducted in Mexico (Cerón-Palma, 2008) were used to characterize the reference system. A survey was carried out in 90 randomly selected houses within the study site. Cerón-Palma et al. (2011b) collected data on the habits of energy consumption including the number, the model and operating hours of the following equipment: (1) households products, including a blender, iron, washer, mobile charger, TV, stereo, computer and refrigerator; (2) lighting, including incandescent light bulbs in all rooms of the house; (3) mechanical ventilation, including a pedestal fan and ceiling fan; and (4) air conditioner. These data are used as a reference system in this paper and are presented for social housing with and without air conditioning as the results differ between these two types of housing.

3.3.2 Environmental strategies

Two types of strategies for GHG emissions reduction are proposed for implementation in social housing in Merida. The first strategy is based on active eco-technology, while the second consists of introducing different types of green spaces within the area of the social housing plot and roof (Figure.3. 4).

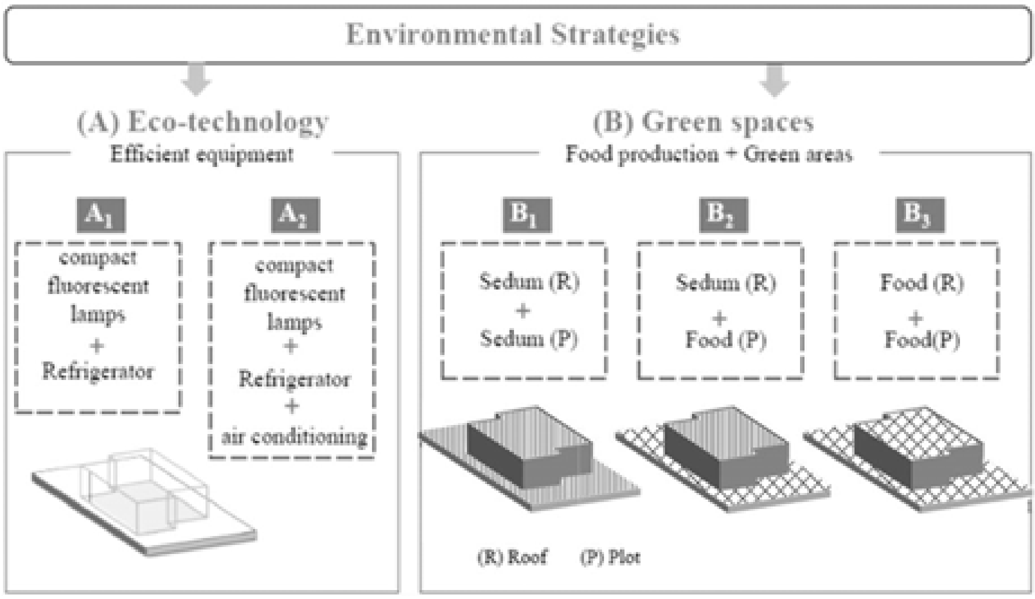

Figure. 3.4 Scenarios presented in the study strategies: eco-technologies and urban green spaces.

Eco-technology

Eco-technology means any technology or efficient equipment to generate savings of energy consumption in housing. The objective of this strategy is to quantify the CO_2 equivalent avoided through the use of efficient equipment in social housing. Such a strategy is concerned with the indoor use of the social housing. Two scenarios are defined. In each scenario, the existing equipment is replaced by more efficient equipment.

Scenario A_1: social housing without air conditioning. The proposal for this scenario considered replacing incandescent 60 W bulbs with 12 W compact fluorescent lamps and replacing the refrigerator with a more efficient model (140 W).

Scenario A_2: social housing with air conditioning. The proposal for this scenario considered the changes of scenario A and included a more efficient air conditioner (1.4 - 1 kW).

Green spaces and food production

This strategy aims to fix CO_2 emissions by implementing vegetation systems within the social housing plot and on the roof. The analysis considers green spaces planted with sedum species or for food production. Such strategy concerns with the outdoors of social housing and does not imply any change on the construction elements of the house.

An extensive green system with sedum species is proposed for the available spaces (roof and plot) as this system requires a simple installation and low maintenance for the home building system.

Food production considers the integration of horticultural crops in plots and on roofs. The tomato crop was analysed as an example of a common food product in the study area. Three scenarios are defined depending on the species and area of deployment: Scenario B_1, roof and plot with sedum; Scenario B_2, roof with sedum and plot with tomato; and Scenario B_3, roof and plot with tomato.

For the estimation of the potential carbon fixation that occurred as a result of the urban green spaces strategy, the following data from the literature have been used: sedum, 1.37 $kgCO_2/m^2$/year (Getter et al. 2009) and tomato crop, 3.18 $kgCO_2/m^2$/year (Carvajal, 2008). Fruits, leaves, root and stems are included in the data of tomato crop for the purpose of considering the annual biomass and associated carbon fixation. The time that the carbon remains in the soil is not included in these reference data.

In scenarios with tomatoes crop (B_2 and B_3), the system analysed has been expanded to include the impact avoided because of not transporting food (tomatoes) from the production site to the consumer.

The production of tomatoes within the city of Mérida would garner additional CO_2 equivalent savings as the transport and distribution stages are avoided. These environmental savings were also quantified through LCA. The functional unit select for the LCA studywas1 kg of tomatoes consumed in Merida. Tomatoes consumed in Mérida come from the states of Puebla, México, Veracruz, Nayarit and Sonora; and are distributed through distribution centers in Mexico D.F. (comm. verb. Central de frutas y verduras de Mérida).

Therefore, the analysis assumes that tomatoes are produced in these areas and transported to Mérida, where they are sold and consumed.

The tomatoes are transported by 30t-trucks and an average distance of 1500 km is used in the transport calculations (SAGARPA, 2011). Life cycle inventory data were obtained through local surveys and from a European database. The results of CO_2 fixation were excluded to the LCA. This is because the results of fixation were estimated with nonlocal data and as the fixation is less than 100 years, it cannot be counted according to the IPCC (2006a). The systems boundaries are limited to the distribution, packaging and retail stages.

Distribution. The distribution stage considers a trip from the producer to the supply centre of Mérida. The return trip is excluded from the system as it is considered that the truck is filled with other products. During transportation, a loss of 6% of the product is included due to the dry air refrigeration. The data about the loss of product were obtained from contact with the manager of a tomato distribution firm (Sanyé, et al. 2012).

Packaging. A wood packaging with a lifetime of 20 uses and a capacity for 6 kg is considered. Data for the LCI were obtained from the ecoinvent database 2.0 (Werner et al.2007).

Retail. Up to 30% of the product is damaged during the retail stage and is landfilled. Data about final disposal was obtained from ecoinvent 2.0 database (Doka, 2009), but methane (CH4) emissions were adjusted for organic matter in the Mexican context (IPCC, 2006b, Chapter 3: Solid waste disposal). The production stage is excluded of the analysis as the tomato is produced in different areas and inventory data is unavailable.

3.3.3 Environmental tools

The LCA methodology (ISO, 2006), following the method of baseline CML 2000 (Guinee et al. 2001) to characterise impact factors, has been used in this study. The Global Warming Potential (GWP) of the energy use in social housing has been calculated through LCA.

In Mexico, fossil fuels account for approximately 79% of the total primary energy; renewable energies contribute 16.5% (hydropower 13.5%, geothermal 3% and wind 0.02%), and the remaining 4.5% is from nuclear power (Santoyo-Castelazo et al. 2011).

As a reference, the average emission factor for grid electricity in Mexico in 2008 is 0.47 kgCO_2eq/kWh (SEMARNAT, 2008).

3.4 Results

This section describes the results of the quantitative evaluation obtained with the different tools and methodologies. The results are presented in three stages: (i) Characterisation of energy consumption and GHG emissions, (ii) eco-technology and (iii) green spaces.

3.4.1 Characterisation of energy consumption

Table 3.1 presents the list of the main electrical equipment used in social housing and their frequencies of use per year according to data from the field surveys (Cerón-Palma et al 2011b). The equipment presented was the most repeated and the frequency is the representative average. It is important to mention that 30% of the houses included in the field work had an air conditioner, and therefore, this cooling system was considered in the study due to the almost 50% increase in energy consumption in housing with air conditioning.

Table 3.1 Annual energy consumption and emissions associated with the use stage of housing.

Concept	Number	Uptime Hours/year	Power kW	Consumption kWh/year	Emissions $kgCO_2eq/year$
Household products					
Blender	1	62	0.65	40	19
Iron	1	106	1	106	50
Washer	1	216	0.50	108	51
Mobile charger	2	438	0.005	4	2
TV	1	1460	0.25	365	172
Stereo	1	157	0.03	5	2
Computer	1	1095	0.30	329	154
Refrigerator	1	2920	0.30	876	412
			Subtotal	**1833**	**862**
Illumination. Incandescent bulbs					
Living room	2	1825	0.06	219	103
Kitchen	1	1095	0.06	66	31
Bedrooms	4	1825	0.06	438	206
Bathroom	1	365	0.06	22	10
Patio	1	365	0.06	22	10
Access	1	1460	0.06	88	41
			Subtotal	**855**	**401**
Mechanical Ventilation					
Pedestal fan	1	2190	0.08	175	82
Ceiling fan	2	4380	0.06	526	247
			Subtotal	**701**	**329**
Artificial cooling					
Air conditioner	1	2190	1.4	3066	1441
			Subtotal	**3066**	**1441**
Social housing with air conditioner			**Total**	**6455**	**3033**
Social housing without air conditioner			**Total**	**3389**	**1592**

3.4.2 Eco-technology

Table 3.2 summarises the results of scenarios A_1 and A_2 in each category compared to the reference system.

Table 3.2 Annual energy consumption and GHG emissions ($kgCO_2eq$. per year) with the Eco-technology strategy.

Concept	Reference system		Scenario A_1		Scenario A_2	
	[kWh]	[$kgCO_2eq$]	[kWh]	[$kgCO_2eq$]	[kWh]	[$kgCO_2eq$]
Appliances	1833	862	1395	656	1395	656
Illumination	855	401	171	80	171	80
Mechanical ventilation	701	329	701	329	701	329
Artificial cooling	3066	1441	--------	--------	2190	1027
Total	***3389** ****6455**	**1592** **3033**	**2267**	**1065**	**4457**	**2092**

*Housing without air conditioning **Housing with air conditioning

Replacing the refrigerator by a more efficient accounted for a 24% reduction in energy consumption in the appliances category in the reference system. Replacing the incandescent 60 W bulbs with the 12Wcompact fluorescent lamps yielded an 80% savings of the energy consumption related to lighting, and a more efficient air conditioning system resulted in a 29% energy savings related to artificial cooling system.
Consequently, the eco-technology strategy resulted in a 33% reduction in the total annual GHG emissions, representing 1065 $kgCO_2eq$/year for scenario A_1 (housing without air conditioning).
For scenario A_2 (housing with air conditioning), this strategy resulted in a 31% reduction in total annual GHG emissions.

3.4.3 Green spaces

Table 3.3 presents the results of the green spaces strategy in scenarios B_1, B_2 and B_3.
For the green spaces strategy, Scenario B3 resulted in the greatest carbon fixation (391$kgCO_2eq$/year). This is because the biomass dry weight of food products is greater than grass (Sedum sp.), and these results also reflect a higher carbon fixation rate. However, scenario B_2 yielded higher values compared to scenario B_1.
Scenario B_1 demonstrated a lower carbon dioxide fixation as a result of the green roof strategy.

Table 3.3. Annual carbon dioxide emissions fixed in green spaces.

Area	Scenario B_1	Scenario B_2	Scenario B_3
	[kgCO_2eq/year]		
Roof	69	69	159
Plot	100	232	232
Total	**169**	**301**	**391**

Agricultural products logistics (expanded system)

According to the results, the production of tomatoes in social housing areas in Mérida could represent a savings of 662 gCO_2eq per kg of tomatoes produced. In descending order, the main contributors to these savings are the transport requirements (57.7%), the retail phase (37.2%) and the reusable packaging (5.1%).

Table 3.4 presents the results in detail.

Table 3.4. Value, emission factor, total emissions and contribution by flow of the expanded system

Flow	Unit	Value	CO_2 emissions factor [kgCO_2eq/unit]	Total emissions [kgCO_2eq]	Contribution [%]
Transport 30t, lorry	tkm	2.07E+00	1.85E-01	3,82E-01	57.7
Wood packaging	kg	3.50E-02	1.05E-01	3,67E-03	5.1
Retail (Damaged product landfill)	kg	3.00E-01	8.18E-01	2,46E-01	37.2
Total				**6.62E-01**	**100**

If we consider a 1.7 kg/m^2 tomato production (SAGARPA, 2011), scenario B_2 would produce 98.6 kg of tomatoes and would avoid 65.3 kgCO_2eq associated with food logistics. For scenario B_3, 221.2 kg of tomatoes are produced, and 146.4 kgCO_2eq associated with food logistics are avoided.

Figure 3.5 shows the emissions avoided by implementing the proposed strategies in comparison with the reference system (with and without air conditioning).

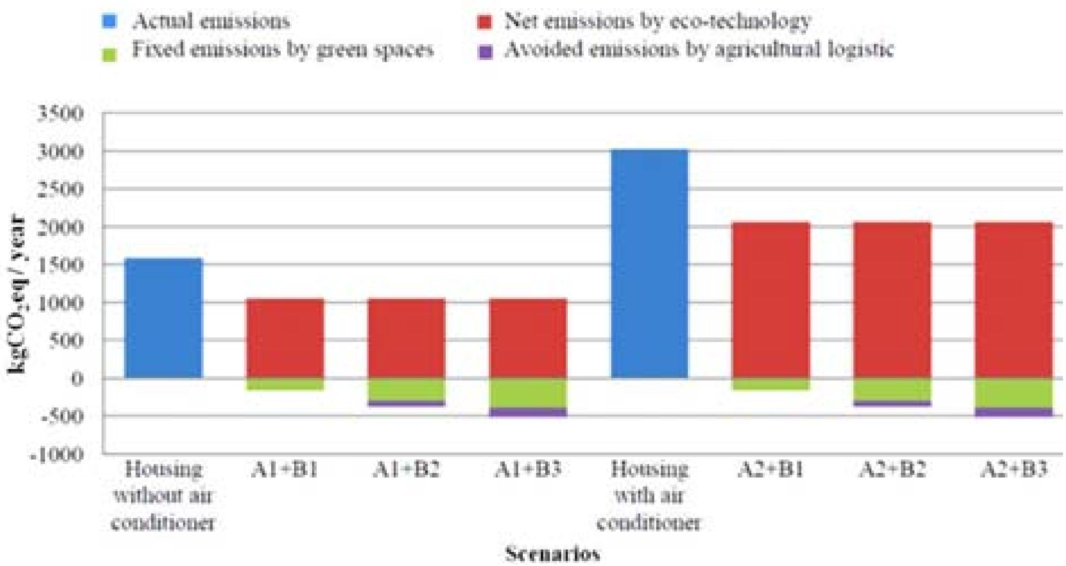

Figure 3.5 Summary results of emissions avoided and fixed by the different strategies proposed in the study.

These results show the importance of using eco-technologies in housing and in food production in cities. Scenario A_1+B_3 eliminate 1064 kgCO_2eq/year, which accounts for 67% of the emissions from social housing (33% avoided by eco-technology and 24.6% fixed by green spaces and 8.4% avoided by logistic food). Scenario A_1+B_2 eliminates 893 kgCO_2eq/year, which accounts for 56% of the emissions from social housing (33% avoided by eco-technology and 19% fixed by green spaces and 4% avoided by logistic food). In the case of scenario A_1 + B_1 compensates 44% of the emissions from social housing and only 11% is fixed by green spaces.

For an isolated house results presented in the study may not be significant, but if the study was expanded to the neighbourhood (1903 social housing) and the city (112,000 social housing) it would prevent a significant amount of GHG emissions. Table 3.5 shows this projection with scenario A_1+B_2.

The results indicate that in a city scale almost 100,352 ton/CO_2eq/year could be avoided.

Table 3.5. Projecting results of avoided GHG emissions per household at neighbourhood and city

Scale	Number of housing	Avoided by eco-technology [tonCO_2eq / year]	Fixed by green spaces [tonCO_2eq / year]	Avoided by transport [tonCO_2eq / year]
Housing	1	0.53	0.30	0.066
Neighbourhood	1903	1000	571	125
City	112,000	59,360	33,600	7392

3.5 Discussion

The results demonstrate the importance of applying the eco-technologies and green spaces strategies proposed in this study to social housing. Based on previous studies, we know that due to the low quality of social housing in Mexico, air conditioning is necessary in order to maintain comfort (Cerón-Palma, 2008).

According this study the air conditioning was responsible for 48% of the energy consumption and associated GHG emissions. For eco-technology strategy, the results projected a 31% reduction in the total annual of energy consumption and GHG emissions in housing with air conditioning.

The green-space strategies also produced significant achievements in GHG emission reductions, particularly scenarios B_2 and B_3. The green roof strategy (B_1) was the strategy that achieved the lowest result of CO_2 fixation. It is worth mentioning that the time that carbon remains in the soil is not included in this study and carbon fixed in green spaces is only an estimation.

However, there is no reason for not considering this strategy because it may have other benefits in energy consumption by functioning as insulation and reduce the heat load of the roof. It is worth mentioning that the study did not consider the effect of the green roof as a thermal insulation system for the housing that would reduce its energy demand and GHG emissions.

Other passive means such as the use of thermal insulation, best house orientation, window shading, etc., can be implemented in conjunction with the measurements suggested in this study. Such research on passive means and their effect on energy consumption are currently under investigation.

Respect to the production of food, the type of crop and its management is another issue that deserve further considerations.

For instance citrus trees can represent a more favourable strategy for food self-sufficiency and fixation of carbon emissions. According to previous studies by Carvajal (2008), the lemon and orange trees may fix between 49 $kgCO_2$ and 106 $kgCO_2$ per year respectively. If we use this data in the social neigbourhood under study, and we propose this strategy for half of the donation area (diverse use area), lemon tree crops at a density of 0.028 tree/m^2 would fix around 88 $tonCO_2$/year.

According to the results of this study, the amount of GHG avoided by the eco-technology strategy is higher than that avoided by the green space strategy and by the reduction in food logistics. Nevertheless, the integration of food production within cities in addition to the environmental benefits that were quantified in this study, could contribute to other economic and social benefits to the neighbourhoods. For example, promote a sense of community (Flores, 2006), increase access to healthy and nutritious food (Blaine et al. 2010; Duchemin et al. 2008), and strengthen local economies (Masi, 2008; Moustier, 2006). Also, this strategy can lead to develop food self-sufficiency communities with less CO_2 emissions; for instance, Doron (2005) calculates that local production in UK could reduce CO_2 emissions by 22%.

Thus, we stress the importance of conducting studies that take into account other impacts of food production in social neighbourhoods.

3.6 Conclusions

There has been significant growth in construction activity of social housing the last years in Latin American. Nevertheless, sustainable or green strategies are not considered in regulations for this housing typology. This study contributes to identifying strategies to reduce de energy consumption and GHG emissions to implement inside and outside the house without this implying change in the structure of it.

In terms of energy consumption the results show that the eco-technological strategies applied indoor of social housing with air conditioning may reduce up to 1998 kWh/year and 1122 kWh/year to social housing without air conditioning.

Expanding the results at neighbourhood scale this represents one million of electrical kWh/year saved as well as 470,000 kgCO_2eq avoided. For the green space and food production proposed outdoor of social housing, the results demonstrate that this strategy could fix up to 391 kgCO_2eq/year and 744,000 kgCO_2eq/year to neighbourhood scale. In the study area of social housing in Mérida, Mexico, the combined strategies of eco-technology and green-space at city scale could prevent more than 1 million tons of GHG emissions and provide additional environmental, economic and social benefits. For this reason it is important to include environmental strategies, energy and quantification of emissions since the early planning stage of neighbourhoods in cities.

The savings quantified in this study will provide useful strategies for applied in Latin America's social neighbourhoods as Mexico that has been facing immense development of social housing and has been producing a large amount of GHG emissions. Efforts should be focused on providing incentives for users and/or housing developers to integrate eco-technologies and green spaces into all existing social housing and to those that will be developed.

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Chapter 4

Strategies to reduce the energy requirements and CO_2 emissions of cooling demand on social housing in warm-humid climates of Mexico.

PHOTOGRAPHY BY ILEANA CERON

This chaptes is based in the following paper:

Ceron-Palma I, Sanyé-Mengual E, Oliver-Solà J, Rieradevall J, Montero JI (2012). Strategies to reduce the energy requirements and CO_2 emissions of cooling demands on social housing in warm-humid climates of Mexico. Submitted to Energy and buildings

Abstract

This article is focused on the eco-rehabilitation of existing social housing in Mexico with the goal of reducing the equivalent CO_2 emissions and the energy requirements due to cooling demands. The objective is to evaluate local passive strategies for social housing in a warm-humid climate and to quantify the potential savings these measures could yield by reducing the cooling demand and equivalent CO_2 emissions. Four strategies were selected: green roof, roof shade made with jute-based fabrics, overhangs on walls and louvers in windows.

For the investigation, bioclimatic analysis tools, the quantification of heat contributions and energy and environmental evaluations were integrated with the support of the programmes Ecotect, EnergyPlus, DesignBuilder and Simapro.

The results indicate that wall overhangs and louvers in windows reduce the annual requirements of energy for cooling by 5 and 11%, respectively. Although green roofing provides only a 13% reduction in the cooling energy requirements, this strategy reduces the annual roof heat contributions by 51%, due to its insulating effect. Roof shade with jute fabric can conserve up to 27% of the annual cooling energy required to house, and jute materials have a small environmental impact and low energetic amortisation time.

4.1 Introduction

Currently, the construction sector contributes approximately one-third of the global energy consumption and greenhouse gas (GHG) emissions worldwide. At the same time, carbon emissions related to the construction sector are expected to increase from 8.6 billion tonnes in 2004 to 11.1 billion tonnes by 2020 (UNEP, 2011). Several initiatives have emerged throughout the world to improve energy efficiency and reduce GHG emissions in the construction sector.

Bioclimatic architecture emerged in the middle of the last century as an alternative method for constructing, through passive strategies to adapt to climatic conditions of the site and promote energy efficiency (Tzikopoulos et al. 2005). Due to the potential savings, the integration of bioclimatic aspects in construction design has received considerable attention in recent years through various research studies (Radovic, 1996). It is important to mention that each climate requires specific strategies to achieve comfort and minimise energy consumption (Vale, 1993). An integration of the assessment of the environment and climatic parameters in the initial design phase can lead to a better efficiency of the thermal behaviour of houses (Dahlan et al. 2010).

In developing Latin American countries, such as Mexico, the residential construction sector is responsible for 17% of the energy consumption (Rosas et al. 2010). In Mexican cities, the rapid growth of urban areas has caused a huge increase in housing construction. These houses are built in the same way in different regions of the country, regardless of climatic differences. This causes an increase in energy consumption in warm regions due to the large amounts of energy required for domestic cooling and heating during long periods in order to maintain comfort (Cerón-Palma, 2008). To address this serious problem in Mexico, there has been a renewed interest in studies that aim to improve the energy efficiency of newly constructed social houses. There is also interest in the development of voluntary standards, to ensure the proper use of materials and in order to limit heat gains. For example, the objective of regulation NOM-020-ENER-2011 (CONAE, 2011) is the rationalisation of the use of energy in cooling systems via the house envelope. Regulation NMX-C-460-ONNCCE-2009 (ONCE, 2009) establishes specifications for the total thermal resistance (‘R’) to be met by houses through their envelope, in order to improve living conditions and reduce the energy demand of the thermal conditioning of interior spaces according to the thermal zone of the country where the house is located.

The National Housing Commission (Comisión Nacional de Vivienda - CONAVI) has developed guidelines in order to improve energy efficiency and incorporate bioclimatic analysis into new social housing developments from the design stage. Few guidelines exist in respect to the rehabilitation of existing housing (CONAVI, 2006). In Merida, Yucatan, results from studies of the annual temperature and humidity trends inside and outside four existing social houses showed a low resistivity of the thermal envelope at higher temperatures during the warmer months (Cerón-Palma et al. 2008). Within the same study the comfort of 160 people was assessed according to the ISO 7730 (2005). The results showed people experienced a discomfort level of 90%. A green roof was installed on the roof of a bedroom of a social housing unit using low-cost recycled materials. Measurements were taken during a typical summer month in Merida (Mexico), and a temperature difference of 2°C was observed in the interior bedroom compared to a housing unit without a green roof (Cerón-Palma et al. 2010).

4.2 Justification and objectives

The majority of previous studies have focused on different strategies used in existing housing than can be applied in new construction. Considerable efforts are being made in Latin American countries to incorporate norms that include the thermal behaviour and energy efficiency in the development of new housing complexes. Nevertheless, in 2010, the existence of more than 35 million houses in Mexico, was reported as being an important contributing factor to the country's total energy consumption (Sheinbaum et al 2011). Currently, there are a large number of social housing projects constructed in the last few years, which need to be studied in order to determine strategies for eco-rehabilitation. These studies will need to be conducted in order to quantify the environmental and energetic impact of such modifications. According to data reported by the National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía - INEGI), more than 112,000 social housing units have been constructed in the city of Mérida, Yucatan, a zone representative of warm-humid climate (INEGI, 2006). Social housing projects do not consider environmental or energy aspects. The incorporation of eco-rehabilitation strategies represents an important local and global action to reduce energy consumption, lower the associated CO_2 emissions and improve the quality of life of people living in these houses. The energy savings attributed to the internal thermal loads (e.g. households, lighting) in this type of social housing have been previously studied (Cerón-Palma et al. 2011). Strategies that lead to thermal loads reductions provided by the house envelope (walls, windows and roof) are analysed in this study.

The main objective of this study is to evaluate the changes in the thermal behaviour of a social housing unit in a warm-humid climate, when eco-rehabilitation strategies are applied using passive approaches in the house envelope. The purpose is to reduce the cooling energy demand and decrease the equivalent CO_2 emissions. Passive strategies were selected and adapted to the resources and local technologies, in order to incorporate these measures into the house exteriors. The following additional objectives were also studied: to quantify the cooling energy requirements of the house when applying the proposed strategies; to quantify the cumulative energetic demand and CO_2 emissions associated with the materials used in each strategy; and to propose the best environmental and energetic strategies as guidelines for the eco-rehabilitation of existing social housing.

4.3. Definition of the study system

4.3.1 Study site: general data on the geography and climate

The study was conducted in the city of Merida, located in the state of Yucatan, in the southeast of Mexico. Merida is a dense and expansive city, with a population of approximately 900,000 inhabitants. In recent years, large social housing complexes have been developed, which is why this city was selected as the study area. Merida is located at latitude of 20°58N and longitude of 89°58 W. According to the bio-climatic classification of Mexico, the city of Merida has a semi-humid warm climate with an annual precipitation of 990 mm and an average temperature of 29ºC. The highest temperatures occur between April and September (OECD, 2007). The highest monthly average temperatures are in May with a value of 29.1ºC and maximum temperatures of 38.4ºC during this month. The lowest relative humidity and greatest solar radiation are found in April and May. The minimum monthly average temperature occurs in January, with a value of 23.1ºC. This data explains the need for cooling during most of the year. Moreover, the high relative humidity values cause evaporative air conditioning systems to have a low efficacy, thereby leading to a large consumption of energy.

4.3.2 Object of study: social housing

An eco-rehabilitation study was developed using a standard social housing unit, representative of the current social housing landscape in Mexico. It is located in a neighbourhood in the south-eastern part of Mérida, Yucatan. This district consists of 1,903 houses. The lots are of 8 x 20 m, 10 x 20 m and 10 x 25 m, with the majority of lots being 160 m^2. The lateral space separating the houses from each other is 1.0 m. The typical distribution of houses within the neighbourhood is shown in Figure 4.1. The house selected for this study is orientated north.

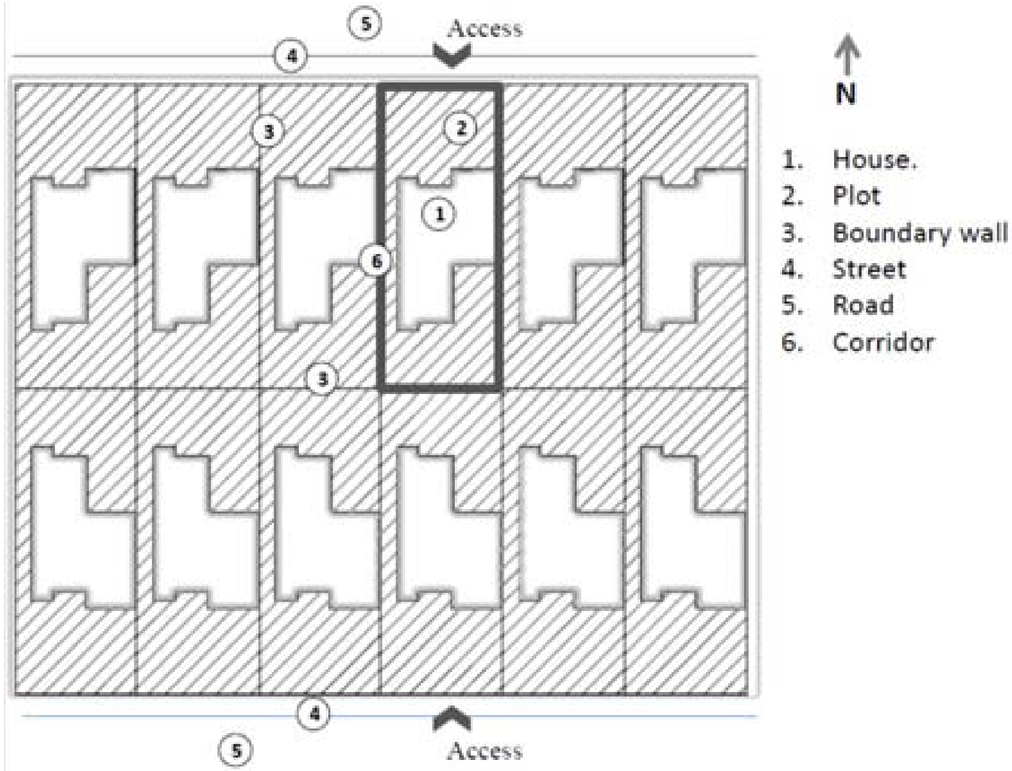

Figure 4.1. Main characteristics of the distribution of houses in the social housing neighbourhood

Social housing units without improvements have been called the “base case”. The unit consists of a single floor of 56 m^2, which is inhabited by four people. The house is divided into four zones: adult´s room, children’s room, bathroom and a living-dining area that includes a kitchen. The construction system is based on conventional materials, such as concrete block walls, joist and slab coverings. The interior height of the unit is 2.50 m. The house has windows on the north, south and east facades. The dimensions and main housing characteristics are summarized in Figure 4.2.

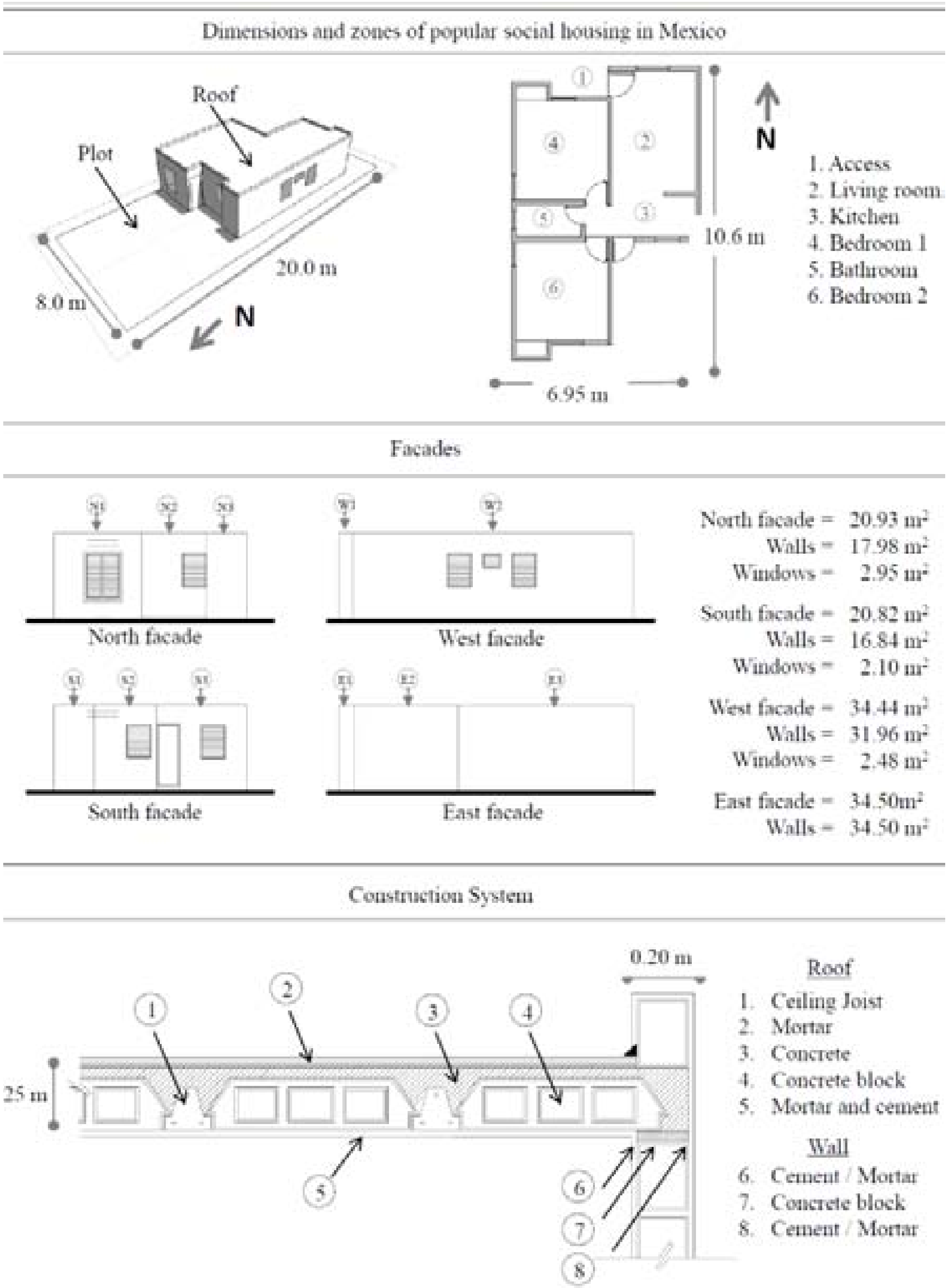

Figure 4.2 Main characteristics of the social housing unit: dimensions and construction system.

4.4 Methodology and tools

Figure 4.3 describes the methodology of this study, which is composed of four steps. A summary of the tools used in each step is also presented.

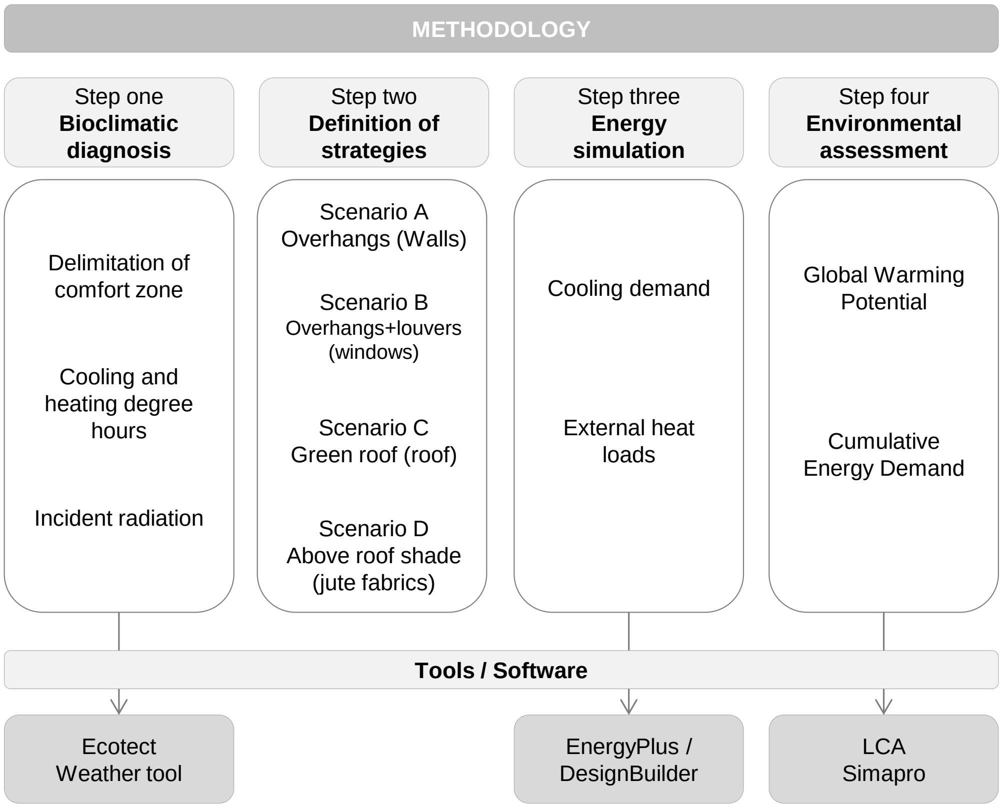

Figure 4.3 Description of the methodology and tools employed in the study

4.4.1 Step one: Bioclimatic diagnosis

In addition to the aforementioned climatic data, the climate classification for Merida was defined using Meteonorm v6.0 (2012) in order to generate hourly climatic data, which was then imported into Weather Tool v1.10 (Autodesk, 2011). Givoni psychrometric chart was used to indicate the hourly temperature and humidity values for the entire year and to present the comfort zone and main bioclimatic strategies (Givoni, 1998). The solar radiation incidence received by the house´s envelope was assessed during the second stage of bioclimatic diagnosis.

Ecotect v5.0 was used to calculate solar incidence. April 11th , a sunny summer day was selected for the analysis of sun exposure. All calculations considered the total sunlight hours between 06:00 and 17:00, using average daily values and a detailed shading mask.

The results are presented in kWh and kWh/m^2, showing values for a typical day in summer and winter, and the annual total. Sun path diagrams were used to show the path of the sun.

4.4.2 Step two: definition and selection of strategies

After the cooling or heating needs of the study house were assessed using the bio-climatic analysis and solar incidence, the strategies for this study were defined. Strategies were proposed under the premise of being suitable for introduction in to social housing unit, without affecting the housing habitability during implementation. Solar protection strategies using locally available materials were considered for the walls, roof and windows (Figure 4.4).

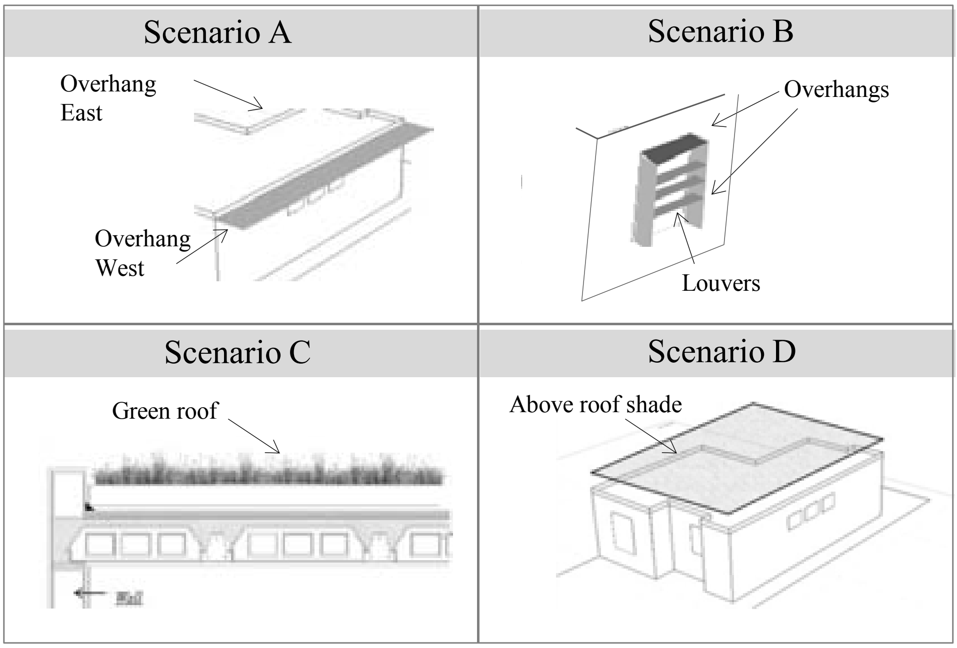

Figure 4.4 Graphic representation of the study scenarios

The strategies that were applied to each of the studied scenarios are presented in detail in the following section.

Scenario A: Overhangs on walls

For this scenario, overhangs on the eastern (E2) and western (W2) walls with a thickness of 0.10 m, at a height of 2.5 0 m were used. The eastern and western facades were the ones that received more solar radiation during the day, and therefore were chosen for this scenario.

The design variable was the projection length of the overhang, which was 0.30, 0.50 and 0.70 m in scenarios A_1, A_2 and A_3, respectively. Panel W is the system proposed by this scenario. It is a building system based on the tridimensional structure of steel wire with polystyrene, where the structure is covered with concrete. The area of Panel W employed in scenarios A_1, A_2 and A_3 were 4.15, 6.93 and 9.7 m^2, respectively. The volumes of concrete were 0.41, 0.69 and 0.96 m^3.

Scenario B: overhangs and window louvers.

Overhangs formed an aluminium frame above the windows of all facades. The overhangs were 0.50 m wide and extended to the same length from both sides. Four aluminium slats with an inclination of 15°, a depth of 0.20 m and a placement of 0.30 m from the window glass were used. In total, 88 kg of aluminium were needed cover the seven windows of the house.

Scenario C: green roof

The scenario consisted of conventional and extensive green roof of 50 m^2. The treatment included water-proofing and anti-root protection, a geotextile layer, a drainage layer, a filtering layer and a vegetation substrate totalling 0.20 m in height. The lightweight substrate was composed of low cost mineral (perlite and vermiculite) and organic material. The total volume of the substrate was 5m^3.

Scenario D: Above roof shade

A shade made of jute fabric was proposed to be placed 0.35 m above the roof. This fibre is obtained from the species *Corchorus Capsularis*, which is cultivated in warm-humid climates. Therefore jute fibre can be easily obtained in the study region. In addition, the processing and extraction of *Corchorus Capsularis* fibre are performed manually and does not require the use of energy (Karmaker and Hinrichsen, 1991). The main variables of this scenario are related to the extension of the shade: D_1, perimetric shading; D_2, perimetric shading + 0.50 m of extension; and D_3, rectangular shading (Figure 4.5).

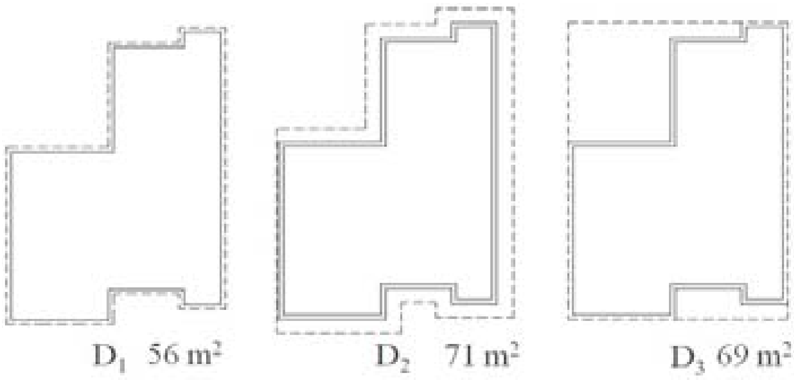

Figure 4.5 Graphic representation of the variables in scenario D

4.4.3 Step three: energy simulation

DesignBuilder simulation program

The”DesignBuilder v2.4" energy simulation program was used to calculate the external heat gains and energy cooling demand in the social housing unit (“base case” and proposed scenarios). This programme uses EnergyPlus to make dynamic simulation to generate performance data based on the climatic and thermal characteristics of the materials (EP, 2012). The programme allows for the calculation of heating and cooling loads using the method adopted by ASHRAE and implemented in EnergyPlus. The climate data for Merida was introduced into the EnergyPlus Weather (EPW) file format for use in the simulations.

Modelling the geometry

The modelling of the house was performed within the interface of DesignBuilder and was defined by four indoor operative zones: bedroom 1 (12.5 m^2), bedroom 2 (12.8 m^2), living room (19.7 m^2) and bathroom (3.6 m^2). One block of houses aligned along the backside and adjacent blocks aligned along the lateral sides (Fig. 4.1) were modelled with the purpose of characterising the social complex better, in terms of shading and reflections.

Thermal properties of the materials

The thermal characteristics of the materials of the walls and the roof were obtained based on the Mexican Normative NOM-020-ENER-2011*, Energy efficiency in constructions. – Envelope of buildings for residential use*.

For the joist and slab covering system, consisting of thermally homogenous layers and a thermally non-homogeneous layer parallel to its surface, the calculation of the insulation of each of the layers was performed. The total thermal resistance of the joist and slab system covering was R= 0.64 m^2k/W. A value of R=0.348 m^2k/W was obtained for the block walls.

The ground was considered to consist of layers of 0.50 m of compacted soil, 0.20 m of gravel and 0.10 m of concrete. The windows had a 5 mm aluminium frame and a single 3 mm glass pane. The thermal characteristics of these materials were obtained from the DesignBuilder library, derived from the ISO 10456 (2007), and the characteristics of the green roof were obtained from the EnergyPlus engineering manual.

A model AE1 RD1 emissometer with a scaling digital voltmeter was used to measure the emissivity and reflectance of the jute fabric, because this data were not available in the literature. The equipment was calibrated using two samples of materials of well-known emissivity (0.03 and 0.88). The emissivity of jute was measured and the reflectivity was calculated using calibration charts provided by the manufacturer of the emissometer. An emissivity of 0.50 and a reflectivity of 0.20 were obtained and they were introduced into the DesignBuilder library.

Internal heat gains

A house occupied by two adults and two children was studied. The bedrooms were occupied from 16:00 to 7:00, and the living area was occupied during the day. The metabolic rate consisting of the energy produce by the user when performing an activity is mainly transformed into heat. This was determined according to ISO (2005), based on the activity in each locale of the house and was represented in "met" units (bedrooms = 0.90, kitchen = 1.15 and living room = 1.2). An illumination of 4 W/m^2 for all of the zones was considered. For the electrical equipment, 4 W/m^2 were considered in the bedrooms and 16 W/m^2 in living area.

Simulation parameters

The building thermal network was solved four times per hour during simulations. A temperature of 26 ° C was used as the control temperature for the air conditioning operation (ASHRAE, 2003). For the shading calculations, all of the adjacent buildings were included and the reflections and obstructions were modelled.

4.4.4 Step four: environmental assessment

The environmental evaluation was performed according to the Life Cycle Analysis (LCA) methodology according to the ISO 14040 (2006). The classification of the flows and the characterisation of the environmental impacts followed the CML 2000 method (Guinée et al. 2001). The impact categories considered in this study are embodied energy (MJeq) according to the Cumulative Energy Demand (CED) method and, global warming potential. This quantifies the emissions of Greenhouse Gases (GHG) and their associated effects and is expressed in equivalent carbon dioxide emissions (CO_2 eq.). The Life Cycle Inventory (LCI) for panel W, aluminium, green roof and jute were extrapolated from Ecoinvent (2012) and ITEC (2012) databases, due to the absence of a specific database for Mexico. Whereas the data for concrete is specific for Mexico (Table 4.1). The lifetime assumed for each scenario is also shown in Table 1 according to data in the bibliography. However, to compare the scenarios directly, the results considered a lifetime of 30 years for each scenario.

Table 4.1 Description, inventory of materials, specific weight, assumed lifetime (years) and main sources for each scenario

Scenario	Description	Materials	Specific weight	Assumed Lifetime [years]	Main data sources
A	Overhangs with panel W	Gravel Portland cement Tap water Panel W (Polystyrene + steel)	1890 kg/m^3 300 kg/m^3 186 kg/m^3 1.6 kg/m2	30	(Ecoinvent, 2011; Oliver-Solá et al. 2009)
B	Overhang + sidefins with aluminium	Aluminium primary	6 kg/m^2	15	(Ecoinvent, 2011; ITEC, 2011)
C	Green roof	Additive Fibreglass Polyester Polyethylene Bitumen Organic material Perlite Vermiculite Water	0.25 kg/m^2 0.066 kg/m^2 0.51 kg/m^2 1.37 kg/m^2 7.57 kg/m^2 11.11 kg/m^2 115 kg/m^3 90 kg/m^3 23.12 kg/m^2	30	(ITEC, 2011; Rivela et al. 2011)
D	Above roof	Jute fabric shade	0.36 kg/m^2	10	(González, 2005)

The balance of the global warming potential of the materials and the potential savings associated with the cooling systems were obtained in order to evaluate the environmental impact of each scenario. The global warming potential associated with the materials was obtained for each of the defined scenarios. In addition the CO_2 emissions associated with cooling energy savings in each scenario has been calculated.

4.5 Results

4.5.1 Bioclimatic factors

Figure 4.6 shows the hourly temperature and humidity values for the entire year, represented in a psychrometric chart generated using the Weather Tool. The analysis of thermal comfort area indicates that 90% of the days of the year fall outside of the thermal comfort zone. The psychrometric chart for Merida shows greater requirements for cooling than heating (54,573 cooling degree hours versus 614 heating degree hours).

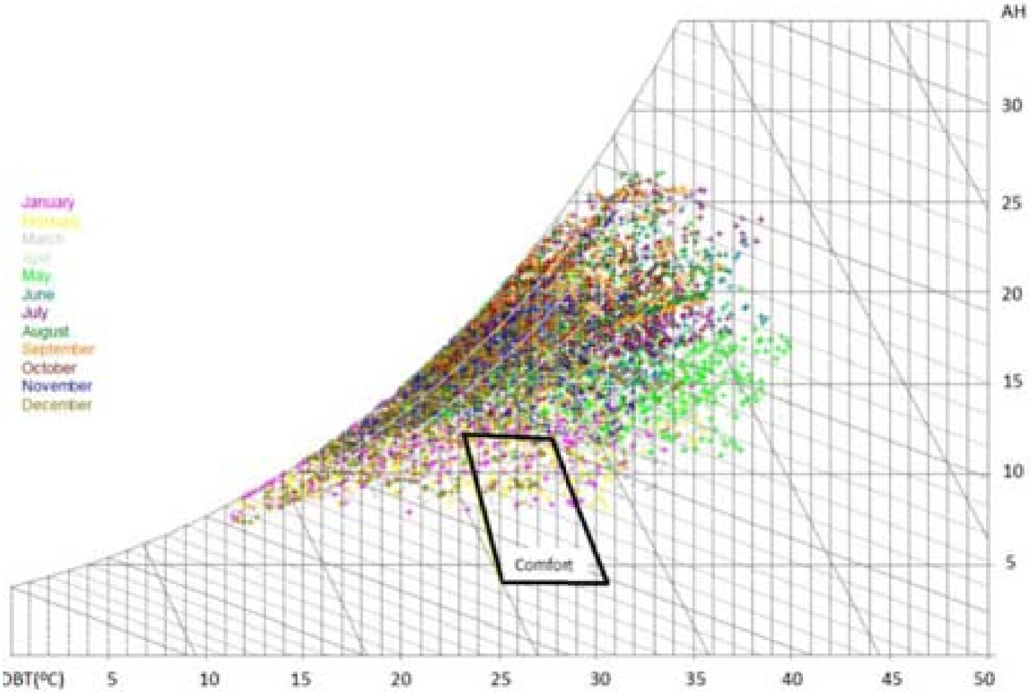

Figure 4.6 Psychrometric chart. Hourly temperature and humidity data. Comfort zone in the city of Merida. Source: prepared for this study using the Weather Tool programme and climate records of Merida, Yucatan

In the summer, only 7.3% of hours are within the comfort zone. According to Givoni psychrometric chart, the most important passive design strategy in the summer is sun shading (45.5%). Conventional air conditioning is required during 51% of summer hours.

4.5.2 Incident radiation on the facades in the base case

Table 4.2 summarises incident radiation at the facades and roof of the base case. In summer and winter, the east (E) and west (W) facades receive the greatest incident radiation. Due to the design of house, the incident radiation on the facade E2 is greater because it is not shaded unlike facades 'W2 and W3', which received shade from the surrounding houses. However, the total area of west facade causes the overall incidence is high.

Table 4.2. Incident radiation on the façades of the social housing unit (Sum of all parts of each facade)

Facade	Area [m^2]	Incident radiation [kWh]		
		Summer day	Winter day	Annual
North facade	20.93	8.68	16.06	6,600
West facade	34.44	44.77	23.55	10,644
South facade	20.82	28.45	18.39	6,836
East facade	34.5	76.25	29.74	17,057
Roof	57.31	303.74	172.5	101,574

The sun path diagrams for 21 June and 21 December are presented in Figure 4.7. These images illustrate the incidence of the sun on the envelope of the house.

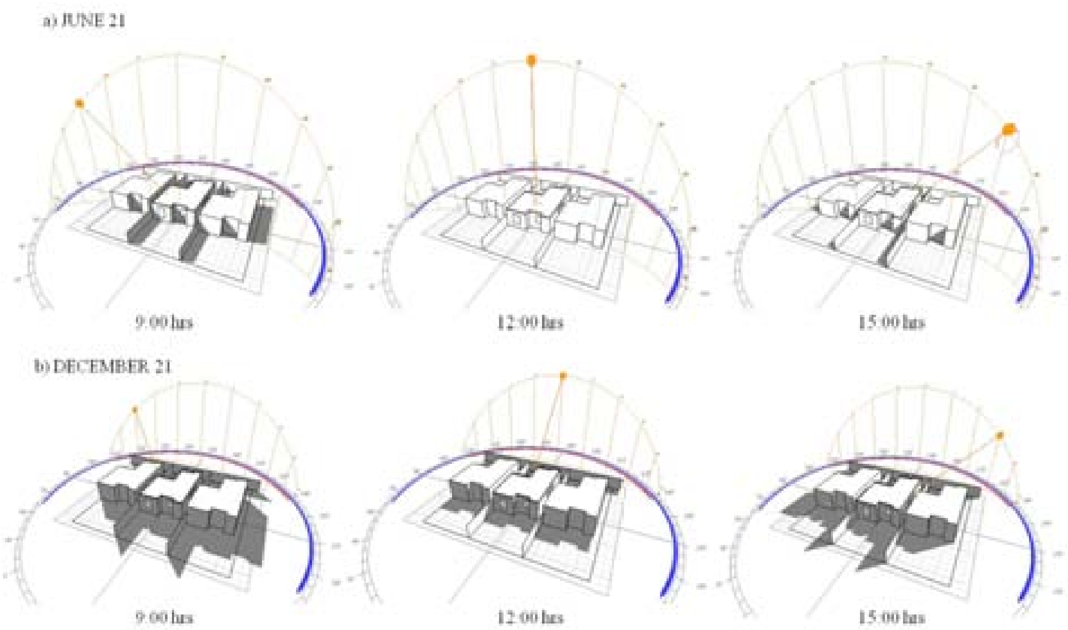

Figure. 4.7 Sun path diagram in typical summer and winter days for social housing in Merida, Yucatan, Mexico.

In summer, the angle of incidence increases, due to the more elevated trajectory, which hinders the direct entrance of sunlight into the interior space. In contrast, the solar trajectory in the winter is lower and mainly affects the S facade. In the study zone it is important to design strategies for the winter, when the area is affected by both high temperature and high solar radiation. With respect to the roof, the position of the sun dictates that long periods of shading are necessary.

4.5.3 External heat loads in the base case

Table 4.3 shows the heat transferred to the house from the walls, roof and windows for the base case on an annual basis and for typical summer and winter days.

Table 4.3 Heat transferred to the building from the envelope (walls, roof and windows)

Component	Summer day	Winter day	Annual
	[kWh]		
Wall	17.45	-3.27	1,539
Roof	14.78	2.37	2,974
Windows	9.26	11.25	3,428

Figure 4.8 shows heat transfer into the house during an entire year.

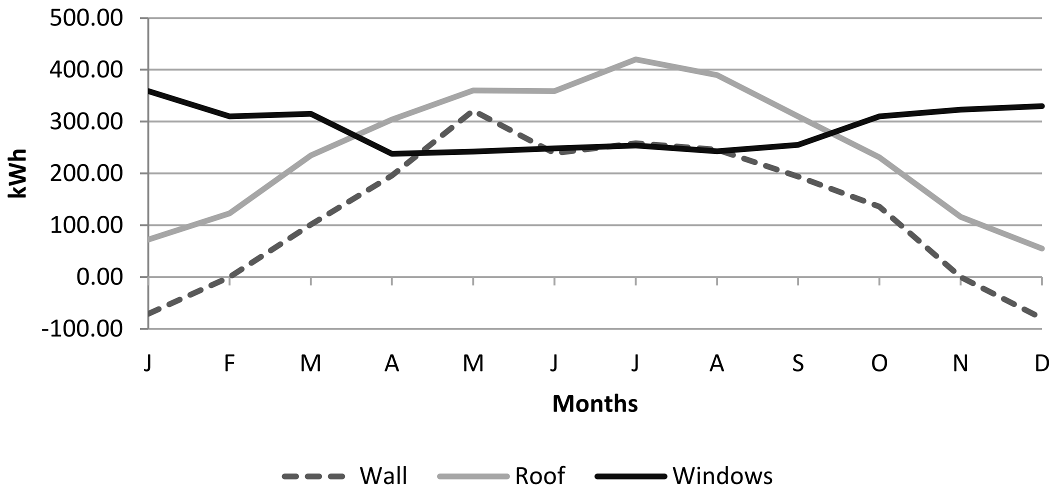

Figure 4.8 Heat transferred to the building from the walls, roof and windows during a full year in the base case

The windows show a similar behaviour throughout the year and are the main annual heat contributors. However, we can consider windows to be modifiable elements, according to the habits of the users because they can be opened or closed at will. The roof and the walls had a higher heat transfer from April to September. The roof was the main component of the heat transfer from the outside environment to the inner house air during the hottest months. The roof contributed 2974 kWh per year. A negative value indicates that this component acted as a sink of energy from the air, this was also the case for the walls during the winter period (Table 4.3 and Figure 4.8).

The exterior walls were the main source of heat input into the house on a typical summer day; they contributed a total of 17.45 kWh. The highest values occurred between 17:00 and 6:00, mainly due to the thermal inertia of the walls, which were heated during the sunny hours. The windows transferred a total of 9.26 kWh; the highest values occurred at 14:00 and 17:00, primarily due to the angle of the sun and the direct impact on the windows. In the case of the roof, the heat transfer was 14.78 kWh, and the highest values occurred from 16:00 and 19:00.

It is important to mention that although the roof received the most incident solar radiation annually, in a typical summer´s day the results yielded a greater heat contribution from the walls. This observation is attributable to the walls' smaller resistance (R= 0.348 m^2k/W) to heat transfer relative to the roof (R= 0.64 m^2k/W).

On a typical winter´s day, the walls did not transfer heat into the house, and the windows were the principal contributor of heat. The contribution from the windows was mainly associated with the sun trajectory, which was lower relative to the summer position and allowed for a greater incidence on the windows.

4.5.4 Energy demand of cooling

Table 4.4 summarises the annual energy cooling demand for social housing for the base case, as well as the scenarios studied. The energy associated with the production of the materials and the amortisation time in terms of energy are also included in Table 4.4.

Scenario	Variable	Energy balance		Materials	
		Cooling demand [kWh/year]	Scenario savings [kWh/year]	Energy embodied [kWh]	Energy payback [years]
Base case		9,640	0	-	-
A	A_1	9,281	359	276	0.77
	A_2	9,230	410	450	1.10
	A_3	9,141	499	726	1.45
B		8,586	1,054	4,742	4.5
C		8,409	1,231	8,018	6.5
D	D_1	9,150	490	1,212	2.47
	D_2	8,600	1,040	1,536	1.47
	D_3	7,040	2,600	1,500	0.57

Table 4.4 Energy requirements for cooling demand

The energy requirement for cooling in the base case was 9,640 kWh/year. Scenarios A_1 and A_2 corresponded to a 4% reduction in the annual energy cooling demand relative to the base case, whereas scenario A_3 corresponded to a reduction of 5%. It is apparent that the effect of an 'overhang' is limited and that the various studied projection lengths do not yield a significant improvement. The solar protection of the windows (scenario B) reduced the total annual cooling load by 11%. This scenario has the greatest built-in energy demand due to the materials, i.e., the production of aluminium. Thus, the amortisation time of scenario B is 4.5 years. If we consider a lifetime of 30 years for all scenarios, the amortisation time of scenario B is not significantly different. For scenario C, the results indicate a saving of 13%, solely due the insulating effect of the roof. The total energy incorporated in the materials of the green roof is greater than that of aluminium in scenario B and the amortisation time is 6.5 years. Scenario D_3 resulted in a lower energy cooling demand of 7,039 kWh/year, which represents a 27% reduction relative to the base case. Scenarios D_2 and D_1 yielded reductions of 11% and 5%, respectively. Other simulation results of scenario D, which are not included in this article, showed small differences between shading at heights of 0.30 m and 1.80 m. Therefore, the decreased energy cooling demand was due to the reduction of the solar incidence by shade, rather than a convective effect of the movement of air at the roof of the house. Although the above roof shade proposed in scenario D is made of a natural fibre and its production does not require large amounts of energy, the results of this scenario show that a greater amount of energy is incorporated into the materials relative to scenario A (Panel W). These results are most likely attributed to the relatively short lifetime of jute (10 years) compared to concrete (30 years). However, due to the significant savings in the energy cooling demand of scenario D_3, the amortisation time was the lowest of all the scenarios.

Figure 4.9 shows how the monthly results of each strategy compared to the base case. For scenarios A and D, only the variables with the greatest savings were compared (i.e., scenarios A_3 and D_3). A similar behaviour is observed in the energy cooling requirements throughout the year for all scenarios, which presented greater requirements during March to October. The highest values were observed in May.

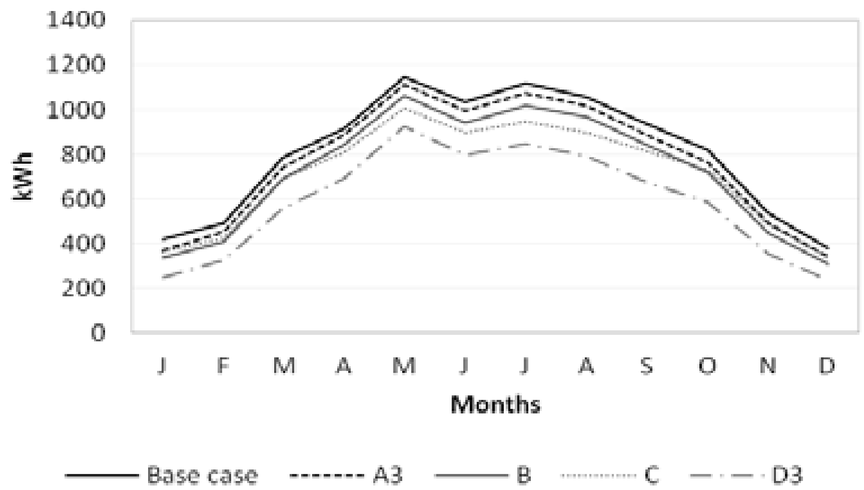

Figure 4.9 Energy requirements for cooling demand during the year

Due to the fact that energy requirements for cooling are mainly attributed to the heat contributions of the house envelope (e.g., roof, walls and windows), this analysis has been included in order to understand the behaviour of the cooling demands.

4.5.5 External heat loads in the proposed scenarios

The annual heat load was reduced by 13% for the walls and 16% for the windows within scenario A_3, relative to the base case values presented in Table 4.3.
Scenario B only affected the windows. This produced a heat contribution of 926 kWh corresponding to a 73% reduction relative to the heat contribution of the windows in the base case, according to values in Table 4.3. For a typical summer´s day, the contribution was 2.33 kWh, representing a 75% reduction compared to the base case.
The green roof (scenario C) reduced the annual heat contributions produced by the roof by 51% compared to the base case. According to the hourly analysis shown in Figure 4.10, for a typical summer´s day, the heat contribution without the 'green roof' is 14.78 Kwh and 3.78kWh with the green roof, which represents a 74% reduction and clearly shows an insulating effect from 8:00 to 21:00. This effect occurs because the thermal resistance of the roof with green roof is 1.29 m^2 K/W, as opposed to the thermal resistance of 0.64 m^2 k/W for the base case. In this scenario, the heat contributions of the walls and windows are not reduced, which implies that the contribution of the green roof to the annual energy savings is not particularly high.

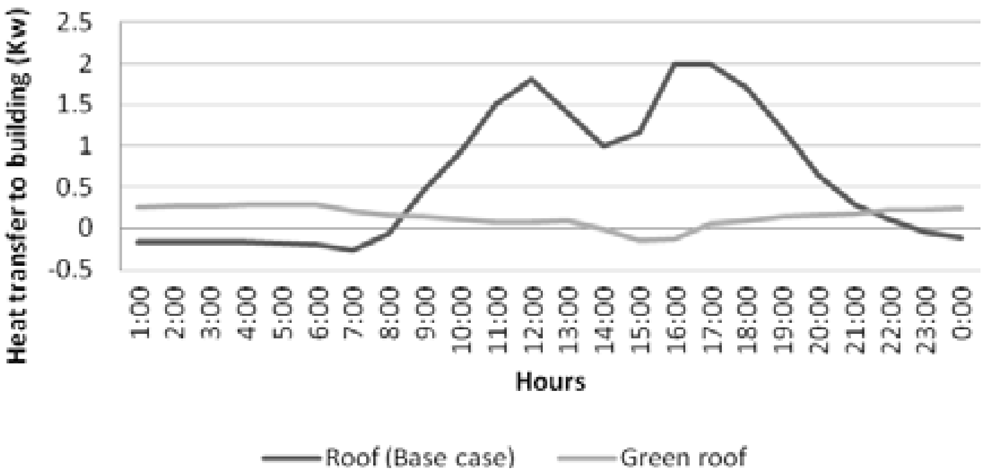

Fig. 4.10 Heat transferred to the building from the roof (base case and green roof) on a typical summer day

Scenario D_3 reduced the annual heat contributions through the walls to the interior of the house by 20%, of which 58% and 34% were attributed to the roof and windows, respectively. This reduction is also apparent in the analysis for the typical summer´s day, where this strategy affected the walls, windows and roof. In this scenario, none of the elements contributed more of 1.4 kWh during the day, unlike the base case, where the walls and roof contributions were approximately 2 kWh during certain hours of the day.

4.5.6 Global warming potential

The environmental analysis provided the GHG emissions associated with the energy cooling demand and the materials of the different strategies, their potential for global warming (kg CO_2 eq.) was analysed (Table 4.5). The environmental analysis also provides a quantification of the GHG emissions that are avoided due to the energy cooling savings of the strategies. The environmental amortisation for each scenario is identified according to the lifetime of the materials.

Table 4.5 Global warming potential, GHG emissions avoided and the total balance for each scenario and variable.

Scenario	Variable	CO_2 balance		Materials	CO_2 payback
		Cooling demand [kgCO_2eq/year]	Scenario savings [kgCO_2eq/year]	CO_2 embodied [kgCO_2eq]	[years]
Base case		4,724	0		
A	A1	4,548	176	95	0.54
	A2	4,523	201	153	0.76
	A3	4,479	245	217	0.89
B		4,207	517	2,098	4.05
C		4,120	604	482	0.80
D	D1	4,484	240	181	0.75
	D2	4,214	510	230	0.45
	D3	3,450	1,274	224	0.17

The scenarios using jute fabric (D) showed the greatest positive balance amongst the different strategies. In general, although the jute fabric had the shortest lifetime as an exterior shading element (10 years), the environmental impact associated the manufacture of the material is between 80 and 90% less than the impact of scenarios B and C (aluminium and green roof). Of the specific scenarios, scenario D_3 showed the greatest reduction of GHG emissions (kg CO_2eq) because this scenario entails a greater energy savings when used as a shading element in the house. The time of amortisation of scenario D_3 was the lowest of all studied cases. However, it is important to mention that all of the proposed scenarios present a rapid amortisation and offer significant reductions in CO_2 emissions.

4.6 Discussion

The results of this study demonstrate that on an annual basis, the main contributors of heat to the indoor environment were the windows (3,428 kWh), roof (2,974 kWh) and walls (1,539 kWh).

The strategies evaluated in this work allowed annual energy cooling demand reductions of up to 27% for the studied house. This reduction corresponds to scenario D_3, where the roof shade made of jute is proposed to provide solar protection to the walls and windows of the posterior facade (south and east orientation); this shade not only reduces the heat gain of the roof but also that of the walls and windows.

Scenario C, corresponding to the green roof, reduced the annual energy demand of cooling by 13%. This strategy directly affected the roof by reducing its heat contribution to the interior by 74%, which indicates that green roof functions as a suitable insulator and increases the resistance (R value) of the roof from 0.64 m^2-K/W to 1.29 m^2-K/W. It is noteworthy that this strategy has other benefits, such as restoration of the habitat and CO_2 fixation. According to a recent study, CO_2 fixation of 69 kgCO_2/year take place in a social housing unit with a green roof (Cerón-Palma et al. 2012). Also, it is important to mention that the green roof would present the greatest complexity to build, as well as the highest installation and maintenance costs relative to the other studied scenarios. Nevertheless, it is recommended that laboratory studies using vegetation of the region and lightweight substrates take place in order to determine the most appropriate installation strategy.

Overhangs and window louvers (scenario B) resulted in an 11% reduction in the energy cooling demand in relation to the base case.

Regarding scenario A, a maximum energy reduction of 5% was obtained using overhangs of 0.70 m long (A_3). This result indicates that further study is necessary to determine other low-cost strategies to reduce the heat contribution from the outer walls of the house, such as vegetation screens. A 32% reduction in the energy demand for cooling is expected, if scenarios B (which affects the heat contributed by the windows of the house) and D_3 (which affects the roof and walls of the posterior façade) are combined.

With respect to the emissions of CO_2eq from the materials proposed in each scenario, the results demonstrate that the annual savings associated with any of the scenarios are greater than the impacts caused by their manufacture, due to an amortisation time of greater than four years. In the proposed shading strategy using jute fabric (scenario D_3), the amortisation of energy and CO_2 emissions occur in less than a year.

Future investigations will consider the integration of eco-designs as a tool for the proposal and evaluation of new shading elements and insulating materials.

4.7 Conclusions

There is a significant potential for the eco-rehabilitation of the social housing sector in Mexico. This study identified strategies such as: wall overhangs, green roof, jute fabric roof shade and window louvers, which reduce the energy cooling demand in a social housing unit in a warm-humid climate by up to 1,274 kWh per year. The LCA was demonstrated to be an important factor in proposing materials by considering CO_2 emissions caused by their production, as well as the time of energetic amortisation. The integration of the strategies presented in this study could be an economic driver for the transformation of existing social housing, as well as the integration of environmental criteria in evaluation and decision making. Similarly, the results of this study can contribute to improvements in the competitiveness of developing new housing, when these strategies and methodologies are integrated from the design stage. We expect that the methodology of this work will allow other investigators and designers to apply similar studies to other climatic regions. This well contribute to the spread of bio-climatic analysis, the use of passive strategies and a reduction in energy consumption and CO_2 emissions for a sustainable rehabilitation of the social housing sector.

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PART 3

Eco-innovation to improve synergy flows in buildings in Spain. The case of Rooftop Eco-greenhouse

As previously stated, buildings have been detected as a priority area for reduction of the total energy consumption within the European Union. Eco-innovation is an alternative strategy that can contribute to improving resource efficiency in the building sector.
Part III of this dissertation focuses on an eco-innovation project in a European context: The integration of food production in buildings through the synergy concept called 'Rooftop Eco-Greenhouse'(RTEG). It is composed of two chapters

Chapter 5: Barriers and opportunities regarding the implementation of Rooftop Eco-Greenhouses (RTEG) in Mediterranean cities of Europe.

Chapter 6: Energy and environmental analysis of heat flows in Rooftop Eco-Greenhouses: A case study in the Mediterranean City of Barcelona.

Chapter 5

Barriers and opportunities regarding the implementation of Rooftop Eco-Greenhouses (RTEG) in mediterranean cities of Europe.

This chaptes is based in the following paper:

Ceron-Palma I, Oliver-Solà J, Sanyé-Mengual E, Montero JI, Rieradevall J (2012) Barriers and opportunities regarding the implementation of Rooftop Eco-Greenhouses (RTEG) in Mediterranean cities of Europe. ***Journal of Urban Technology, in press*** **(DOI:10.1080/10630732.20).**

Abstract

Today 50% of the population live in cities. This entails an excessive exploitation of natural resources, an increase in pollution and an increase in the demand for food. One way of reducing the ecological footprint of cities is to introduce agricultural activities to them. In the current food and agriculture model the fragmentation of the city and the countryside means energy use, CO_2 emissions from transport and large scale marketing requirements.

Roof Top Eco.Greenhouses (RTEG) consist in a greenhouse interconnected to building in terms of energy, water and CO_2 flows; is a new model for a sustainable production an eco-innovative concept for producing high quality vegetables and improving the sustainability of buildings in cities. The main objective of this study is to examine the barriers and opportunities regarding the implementation of RTEG in Mediterranean cities in Europe. The work method consisted of discussion seminars involving an interdisciplinary group of experts in the area of agronomy, architecture, engineering, environmental sciences, industrial ecology and other related disciplines. The barriers and opportunities of RTG take into account social, economic, environmental and technological aspects and were determined and analysed according to three scenarios of implementation: residential buildings, educational or cultural buildings and industrial buildings

We would highlight the interconnection of the building and the greenhouse as an opportunity of RTEG, making use of water, energy and CO_2 flows between both, as well as the decrease in food transportation requirements. The methodology applied to the study was positive due to the interdisciplinary participation of experts which facilitated a global vision of the implementation of the project.

Keywords: Greenhouses, food self-sufficiency, eco-cities, urban agriculture

5.1 Introduction

In recent years, cities have increased pressure on local and global natural ecosystems, a result of an increase in the urban population, the expansion of urban land, the exploitation of natural resources, the increase in the demand for food, water, and energy flows, as well as an increase in the pollution of the atmosphere and water (Lee, 2008).

The world's cities are directly or indirectly responsible for 75 percent of global energy consumption and 80 percent of greenhouse gas (GHG) emissions (Ash et al., 2008). The urban population is projected to be roughly 60 percent of the total world population by 2030 (United Nations, 2008), while global primary energy demand and related GHG emissions are predicted to increase 40 percent relative to the 2007 reference values (IEA, 2009). With these data, the incorporation of sustainability criteria in this process of urban growth will be one of the main
challenges of the twenty-first century (Alberti, 2008).

The sustainable urban model for the future should facilitate the exchanges of flows between cities, the natural environment, and urban subsystems from an industrial ecology perspective. In order to improve urban systems, analysis and quantification data are required of the inflows of energy, water, materials, natural resources, and the outflows of emissions from the urban system (Saheley et al., 2003). The most common city model has linear ingoing and outgoing
flows, characterized by imported resources and exporting emissions without closing cycles (Wadel et al., 2010). Currently, the flow of food to cities follows a linear model, causing a high consumption of energy resources and the generation of waste and CO_2 emissions per food unit (kg) throughout its life cycle (EEA, 2010). At the same time, cities use over two-thirds of the world's energy production and account for more than 80 percent of global greenhouse gas (GHG) emissions (IEA, 2008). Figure 5.1 shows the flows of resources and emissions as well as the fragmentation and disconnection of cities from rural areas.

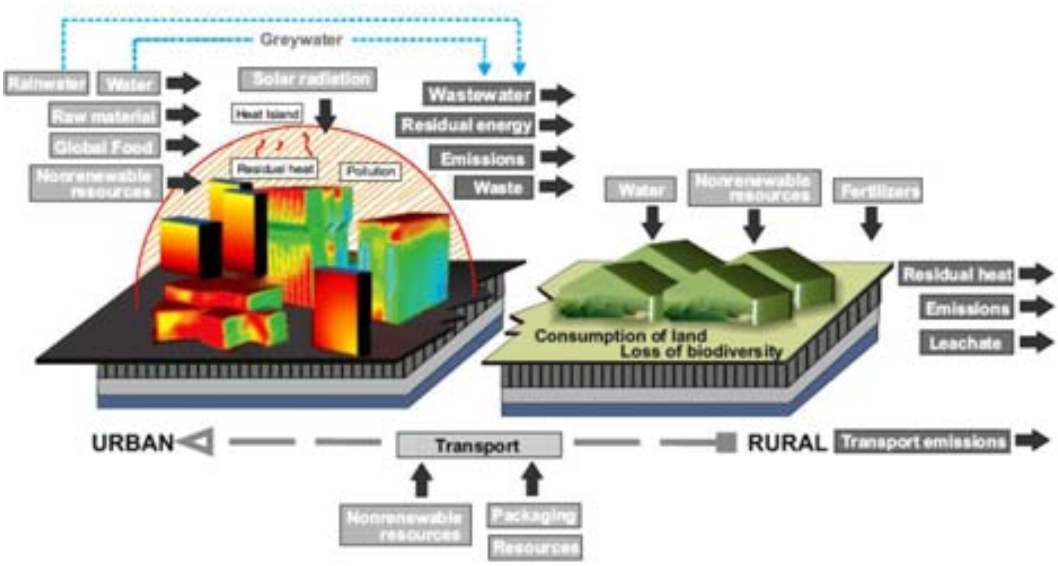

Figure 5.1 Lineal flow system in urban and agricultural systems.

The growth and concentration of the population in cities are associated with the increase in commercialization on a global scale, the exploitation of new lands for agricultural use, and as a result, the loss of biodiversity (Winston, 2010).
According to the Food and Agriculture Organization of the United Nations (FAO), over the next 30 years, many of the environmental problems associated with agriculture will remain serious, such as the loss of biodiversity caused by the expansion and intensification of agriculture in developed countries (FAO, 2010).

5.2 Food production initiatives in cities.

Apart from agriculture in rural areas, there is an incipient development of agriculture in urban and peri-urban areas that is incorporated into urban economic and ecological urban systems (Viljoen et al., 2005). Community gardens, school gardens, urban farms, among others, are some forms urban agriculture is taking (Grewal and Grewal, 2012). Incorporating agriculture into urban lands and buildings can optimize urban space.

5.2.1 Initiatives to incorporate food into urban and peri-urban lands.

Initiatives to introduce agriculture into urban lands exist in countries around the world. Cities in Latin American countries such as Brazil, Colombia, and Peru, have used urban agriculture to alleviate urban poverty and improve food security at the local level (Davila, 2006). In Vietnam, geographical research has been carried out about increasing the surface area of urban agriculture in order to satisfy the population’s food needs (Thapa and Murayama, 2008).
In Africa, various studies have demonstrated the need to increase the production of vegetables
in the future because of urban growth, and the idea of incorporating urban agriculture to be managed by communities themselves is being considered (Parrot et al., 2008).
In Europe, various projects in new neighborhoods and restoration projects in existing neighborhoods have incorporated food production and flow synergy techniques, based on the conviction that incorporating agriculture into urban spaces would provide the area with fresh produce and promote sociability among the community of neighbors; an example of this strategy is the community gardens in East London (Sustain, 2012). Farreny et al. (2011) carried out an interdisciplinary study of concepts for a sustainable district in Barcelona, Spain, and Jansma et al. (2010) did the same thing for the city of Almere in The Netherlands. Catalonia in northeast Spain offers an example of land protected from development by the creation of agricultural parks—some of which are planned and others are already in operation. These include the Agricultural Park of Llobregat, in operation since 1998, the Agricultural Park of Sabadell, and the Rural Space of Gallecs, among others (Ruralcat, 2009).

5.2.2 Initiatives to incorporate food into buildings

Currently, actions to promote introducing food into buildings are being implemented by different strategies. Rooftop farming is the practice of cultivating food on the rooftops of buildings, and this is done in roof gardens (RG) and rooftop greenhouses (RTG).
The RG is sometimes confused with the term "green roof," but a green roof requires a complicated multi-layer structure to support it and usually covers a large area. RG is an area that is generally used for the recreation of a building´s resident and is available for local food production (Ong, 2003). Examples of buildings with a roof garden are Trent University in Ontario, Canada; Chicago City Hall (Schwartz, 2009), and Changi General Hospital in Singapore (Wilson, 2005).
RTGs have as their objective more intensive production than rooftop gardens (Puri and Caplow, 2009). In New York, greenhouses were built in two educational centers—Eleanor Roosevelt School and New York Harbor School—to provide students with information and practical training about sustainability, the environment, food production, and nutrition in cities (BFS, 2009). Similar efforts have been made in the European Union (EU) to integrate greenhouses and buildings with the construction of facade and/or rooftop greenhouses. For instance, the second prototype of the Watergy project funded by the EU and consisted of the experimental assembly of a greenhouse on the facade of a building constructed in Berlin, Germany with the aim of reducing energy consumption in Northern European cities (Zaragoza et al., 2007).
Vertical Farming (VF) is other initiative and the concept refers to skyscrapers used to produce food within the skyscrapers (Despommier, 2010). Despommier (2008) defined the VF technique as a future model of agricultural production in cities using hydroponic cultivation systems. One obstacle to the implementation of VF is the limited availability of sunlight for vegetable production on multiple layers, besides the major investment needed to construct and integrate technologies in the case of new buildings exclusively designed for producing food.
There has been some research on how RG produces energy savings in buildings. Ekaterini and Dimitris (1998) found that, from the total solar radiation on the rooftopwith a garden, 27 percent was reflected, 60 percent was absorbed by plants and soil, and 13 percent was transferred into the building. The effect of RG on reducing the energy consumption of commercial buildings was measured to be up to 14.5 percent in Singapore (Wong et al., 2003). In the case of VF, the projects are still at the design level and currently no demonstrative prototype is available.
There are demonstrative and operational models for RTG, but there is no quantification data regarding energy savings in the buildings where they are used.

5.2.3 Initiatives to develop greenhouse technology for cities

New technical developments in horticulture aim at achieving a zero-environmental-impact greenhouse (Montero et al. 2008). This is particularly important in urban environments, where emissions from greenhouse production must be strongly minimized if food production is to be compatible with urban living.

The closed or semi-closed greenhouse concept is a less-input, low-emission greenhouse production system that reduces energy for heating and recycles the drainage water from irrigated crops (Montero et al., 2009) so it is a suitable concept for urban food production.

Some closed greenhouse technologies have been implemented and researched in urban greenhouses. For example, a solar desalination system by the Seawater greenhouse was implemented in United Arab Emirates in 2000 (Seawater, 2000). This system is primarily focused on water efficiency and proposes produced fresh water for irrigation by evapo/condensation, using only seawater and sunlight (Davies and Paton, 2005). The advantages of CO_2 accumulation and non-chemical pest control could not be provided.

A new humid air solar collected is proposed in the Watergy project financed by the European Union (Buchholz et al., 2004). The first experimental prototype of greenhouse focuses mainly on reduced energy and water consumption in Southern European greenhouses; it allows 85 percent recycling of irrigation water. (Buchholz et al., 2008). The collector is formed by a greenhouse connected with a solar chimney, inside of which a cooling duct contains an air-to-water heat exchanger connected to a heat accumulator (Zaragoza et al., 2007). Economically the system was not viable because of the high costs of heat exchangers. The GeslotenKas system, developed by Innogrow Company, is a closed greenhouse system for increased horticultural production, using CO_2 accumulation. It is designed to collect and store energy from the sun without releasing it into the environment. The climate control system is mainly focused on primary energy (heat pump) and this is a disadvantage because it uses fossil fuels (Opdam et al., 2005) The first commercial-scale Innogrow system was built in Holland in 2004 on 5.4 ha. This greenhouse, occupying 27 percent of the production area resulted in 36 percent energy savings in the first year of operation (Timmenga, 2009).

In Sweden, the Plantagon company developed a vertical greenhouse, the Plantagon Greenhouse. It is a spiral-shaped transport mechanism that moves soil-filled planting boxes upward. With the boxes resting on a pair of rails that corkscrew through the entire volume of the structure, a third rail carries a device that continuously cycles from the top of the spiral to the bottom, nudging each box a few centimeters upward. When they reach the top, the mature plants are pushed out onto the harvest platform, and new boxes of soil and seed are pulled in at the bottom (Plantagon, 2011). This system requires large economic investments in construction and technology.

A plant factory is another initiative in which all the environmental elements are artificially controlled. There are three types of plant factories, one with complete artificial lighting in a totally-enclosed environment, another with combined use of solar and artificial lighting, and a third with solar lighting alone (Yano Research Institute, 2011). This initiative was designed to decrease costs and introduce special varieties of plants. A Closed Transplant Production System (CTPS) at Chiba University is a materially-closed system for producing a maximum number of high-quality transplants, with a minimum use of resources and a minimum emission of environmental pollutants and

heat (Chun and Kozai, 2001). The CTPS is a warehouse-like structure covered with opaque thermal insulators.
Further research in needed in this system to elaborate the utilization efficiencies of light and water of the CTPS, in comparison with those in the greenhouse and the fields (Kozai, 2006).

5.3 Justification and objectives of the study

In Barcelona, a number of studies have identified a surface area of 95 ha of roofs on private and public buildings in the city with the potential for green and farming use (BCN Ecologia, 2010). If considering that in the city, buildings are one of the priority areas for reducing energy consumption for the European Union, since 40 percent of the total consumption corresponds to this sector (European Parliament and Council, 2010); then establishing new synergies seems to be an advantageous way to make cities more sustainable and self-sufficient.
RTG and VF are strategies that propose the integration of food production into buildings; however, these strategies are in an emerging stage of research and development. In Mediterranean cities in Europe there is another concept, “greenhouse-buildings” that we have called Rooftop Eco-Greenhouses (RTEG).
RTEGs are greenhouses interconnected with buildings in terms of energy, residual heat, water, and CO_2. The aim of this study is to examine the barriers and social, economic, environmental, and technological opportunities regarding the implementation of this new interconnection concept called RTEG in Mediterranean cities in Europe.

5.4 Definition of the study system

5.4.1 Conceptualization

RTEG is presented as an eco-innovative system that incorporates agriculture into the rooftops of buildings in the city from an industrial ecology perspective, as a new approach to sustainable food production in urban settings. It is defined by three main aspects: (1) the eco-innovation represented by the greenhouse-building incorporation as a model for producing food and as a new option of occupying territory for agriculture, using a rooftop; (2) the eco-design of the greenhouse with the criteria of low environmental impact and energy efficiency; (3) the incorporation of the concept of symbiosis and industrial ecology into the exploitation of flows. Figure 5.2 presents the conceptualization of the project.
Future research will attempt to determine whether food produced in rooftop greenhouses that share energy, water, and CO_2 flows in a common metabolism with a connecting building can generate significant economic, environmental, and social benefits.

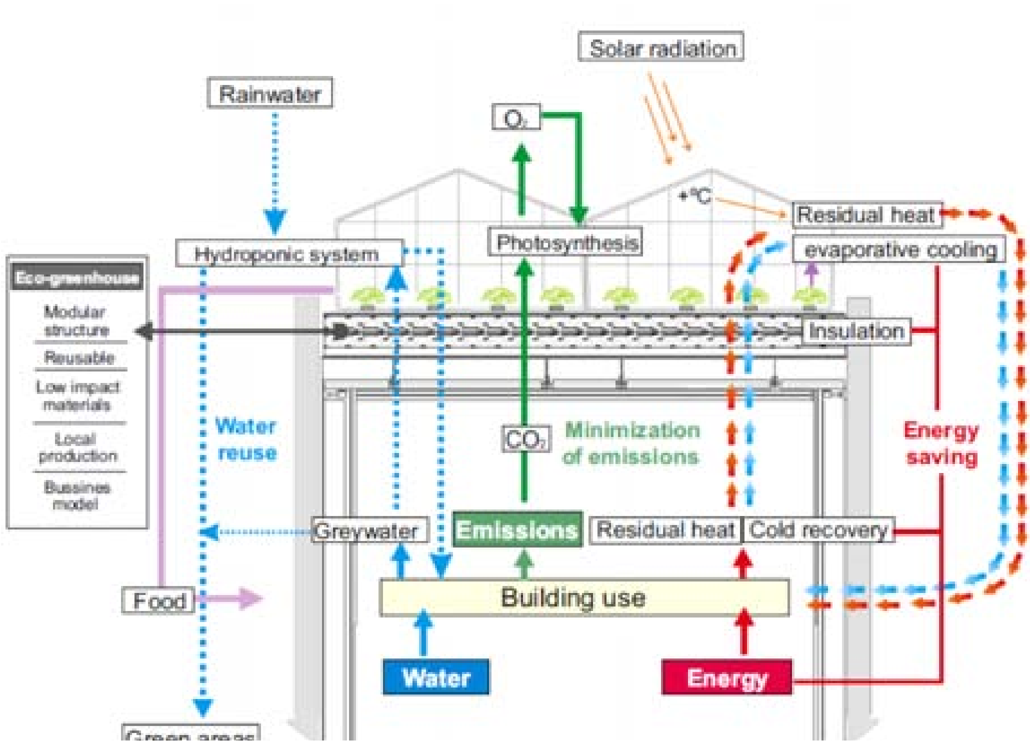

Figure 5.2 Conceptualization of RTG. The illustration emphasizes the interchange of water, energy and gas (e.g. CO_2) flows between the rooftop greenhouse and the associated building.

5.4.2 Type of greenhouse and growing system

In this study, the setting for the RTEG was the Mediterranean city of Barcelona, Spain. The RTEG system examined had a Mediterranean design, which means that the greenhouse weight was approximately 7.7 kg/m2 (Montero et al. 2008) and was a relatively light structure adapted to the mild climatic conditions of the Mediterranean. It was designed to withstand the wind more than the snow. Mediterranean greenhouses are usually a plastic film rooftop with a large surface area of windows to eliminate excess heat. In some cases, they have heating systems, although in the Southern Mediterranean, heating is not usually essential. It is a predominantly passive greenhouse, meaning that it has low energy consumption and little air conditioning equipment, since the Mediterranean climate is by nature very favorable for growing crops. Two main hydroponic systems could be used: aggregate culture, where the plants are grown in containers of various shapes and sizes filled with inert (perlite, pumice, rockwool) and/or organic (peat, coconut coir, etc.) substrate; and water culture, where bare-rooted plants are cultivated in stagnant (floating system) or flowing (nutrient film technique or NFT) nutrient solution. Aggregate culture is generally used for growing row crops such as fruit and vegetables (e.g., tomatoes and strawberries), while water culture is more appropriate for leafy vegetables and herbs that are grown at high crop density.
For this study, tomatoes were grown. Tomatoes are the most important crop in terms of production in the EU-27 (around 14 million tons produced per year), particularly for

Mediterranean countries; Spain is the second largest producer of tomatoes in the EU-27, contributing 27 percent of the total European tomato production (EUROSTAT, 2009).

5.5 Materials and methods.

The perception study of the barriers and opportunities regarding RTEG in Mediterranean cities in Europe was carried out through discussion seminars. An interdisciplinary team was set up of 15 people who specialize in agriculture, environmental sciences, engineering, and city lanning. They came from both private companies and research institutes such as ICTA of Autonomous University of Barcelona, IRTA and companies within the consortium "Vertical Farming S.L." Figure 5.3 summarizes the areas of knowledge and the actors involved in the study.

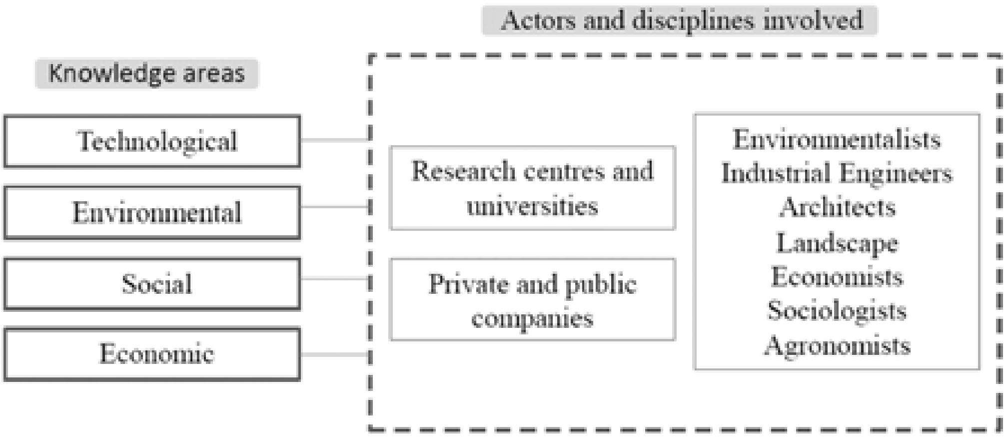

Figure 5.3 Areas of knowledge involved in the RTEG study

Once the interdisciplinary team of experts had been formed, the work sessions began. Figure 5.4 show the methodology applied to evaluate and analyze the study system.

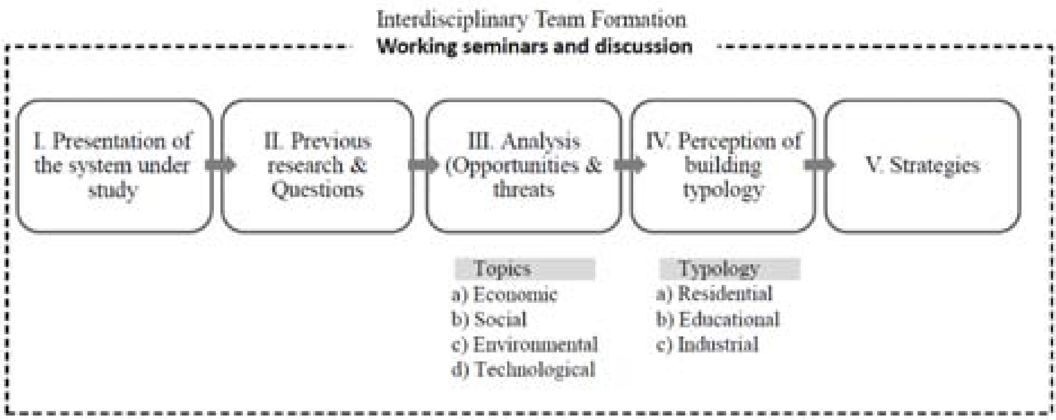

Figure 5.4 Methodology of work sessions regarding the perception study of the RTEG Project

Phase 1. In the first session, each of the actors introduced themselves and specified their field of work. Then a coordinator gave (I) the spoken and visual presentation of the RTEG study system. After the general presentation of the RTEG (II) a series of questions were drafted (see Table 5.1) from the first impressions of the actors involved in these discussions.

Table 5.1 Work group's initial questions.

Questions
(1) Will the economic, environmental, social and technological aspects of agricultural systems improve through the production of food on building rooftops?
(2) What degree food self-sufficiency can be reached in cities?
(3) How technologically complicated is the adaptation of RTEG in existing buildings or new buildings?
(4) How will thermal flows perform in the greenhouse-building?
(5) Will aspects of foods production and quality improve with the greenhouse-building flow synergy?

Once the initial questions were examined, an analysis was performed regarding the implementation of the proposed system in terms of four aspects (III): environmental, social, economic, and technological. This analysis consisted of determining the opportunities or positive aspects that could be exploited in RTEG, as well as the barriers or negative situations that can affect RTEG and, in this case, suggest strategies to overcome these in each of the aspects. Subgroups were formed to discuss each of these subjects in various sessions. Each group had a sub-coordinator who was in charge of the analyses as well as of recording the main contributions. At the end of each session, each sub-coordinator gave a summary, in front of the whole meeting, of the matters discussed, conclusions, and actions to be taken or researched before the next session for each group.

Phase 2. Once the barriers and opportunities regarding RTEG were defined, a specific perception study (IV) was performed for different building typologies to be used for the RTEG system. (Table 5.2)

Table 5.2 Scenarios in which RTEG can possibly be implemented

	Scenario A	Scenario B	Scenario C
Use	Multi-family residential	Education and/or cultural	Industrial
Ownership	Private	Public	Private
Location	City	City	Industrial estate
Layout	Attached blocks	Between dividing walls	Isolated
Structural system	Concrete	Concrete	Light steel structure

The scenarios were chosen on the basis of the main building type in the city of Barcelona, blocks of multi-family residential buildings (Idescat, 2009). Scenarios B and C were defined mainly taking into account the use and structural system.

Phase 3. In order to bring the work sessions to an end, a final debate on the results obtained was held, and strategies to overcome the barriers to implementing the project were considered.

5.6 Results.

This section describes the results of the qualitative evaluation obtained from the work sessions. The results are presented in the following order: opportunities and barriers regarding the implementation of RTEG in Mediterranean cities of Europe; perception accords to the building typology, and strategies to overcome the barriers to implementing RTEG.

5.6.1 Opportunities of RTEG

Economic opportunities

The results indicate that for the majority of the members of the work group, the economic opportunities of the RTEG project in urban systems are the following: the present proposal will help to decouple the use of resources from economic growth: the production chain will be switched to a local scale, thus radically reducing transport needs. In addition, with local production, the product acquires an added value since it brings the consumer closer to the product, avoiding transport. The surface area of the building rooftops also acquires an added value for the owner since it becomes a mixed-use space. It is another space and, therefore, provides additional income, increasing the economic profitability of the building. Urban horticulture has very considerable potential to supply the city's needs (at least partially); depending on the crop type, urban greenhouses may yield from 10 to 50 kg/m2 per year of fresh fruit (tomatoes, cucumbers, etc.) and leafy vegetables (lettuce, herbs, etc.) for fresh consumption. Vegetable consumption in EU- 27 at present is around 84 kg per capita per year (230 g/day). This means that a 1,000 m^2 greenhouse could provide fresh vegetables to approximately 120 to 600 people. This means that a city of three million such as Berlin would require approximately 1,000 ha of a greenhouse that represents approximately 1 percent of the city's area.

Lastly, the group of experts agreed that the project could reduce energy costs by improving the energy efficiency of the building through adapting the ecogreenhouse, as well as reducing water costs through reusing rain water and greywater.

Social opportunities

Regarding opportunities in the social context, most notable is the promotion of sociability among the community of neighbors through the creation of jobs in the case of residential buildings because tenants would be in charge of managing this new space. In the educational context, incorporating greenhouses into buildings would be a tool to demonstrate not only food selfsufficiency policies, but also energy and water saving policies. In this way, environmental education is strengthened. Also, there would be easy access to fresher products of better quality in terms of safety, taste, and nutritional values.

This would be achieved through the hydroponic cultivation of cultivars with better organoleptic and nutritional properties, the application of crop-specific bio fortification strategies, and the adoption of biological control of pests and diseases (so, no pesticides would be used).

Environmental opportunities

The reduction of the carbon footprint of horticultural products by minimizing the distance between growers and consumers (the km 0 approach) is one of the main environmental opportunities of the RTEG system. At present, the carbon footprint of shipping tomatoes from producers in southern Spain to consumers in Barcelona is 166 gCO^2 per kg of tomato(Sanyé-Mengual et al. 2012). Also notable in this system would be the reduction in the flow of water resources and fertilizers through the incorporation of hydroponic systems compared to current peri-urban agriculture and the collection and use of rain water and greywater fromthe building. Annual per capita water consumptionmay exceed 90 m^3 (EWA, 2010) and the proportion ofgreywater may reach 80 percent of the total wastewater generated by households.

Water consumption of year-round greenhouse cultivation is 0.7–1.5 m^3/m^2, depending on crop and site. Therefore, the irrigation water from a rooftop greenhouse operation of 1,000m^2 can be wholly supplied by the greywater produced by fewer than 200 inhabitants. Grey water is suitable for reuse in horticulture because of its low organic pollutant and pathogen content.

Also, greenhouse gas emissions frombuildings can be decreased by fixing the CO_2 of the air coming from the ventilation systems in the greenhouse caused by the photosynthetic activity of the crops. CO_2 concentration in non-residential buildings is normally around 2,700 ppm, making this a rich source for plant carbon dioxide enrichment. Lastly, of the environmental opportunities, most notable are the reduction of the building's energy demands through the insulation of the rooftops and the "naturalization" of the city by creating new urban green spaces for food production.

Technological opportunities

Regarding technological opportunities, the group of experts highlighted the reduction of the demand for urban infrastructures that would come with RTEGs, making cities more self-sufficient. Also, they noted there is a growing body of information on the technologies associated with RTEG, including information, climatic architecture, lightweight materials, and energy control systems. Also, the European Union, in particular, has devoted considerable efforts to devising strategies to integrate new technologies and “smart city” concepts (Caragliu et al., 2011). RTEG can be part of this technology and of eco-innovation in cities.

5.6.2 Barriers of RTEG

Economic barriers

There were several barriers to implementing RTEG in Mediterranean cities according to the majority of the members of the work group. In the economic context, investors perceive a low profit margin for agricultural products, a high investment cost as well as long-term repayment. It would also be expensive to rehabilitate existing buildings to accommodate RTEG. Implementing this system makes it difficult to develop other rooftop business models such as those related to renewable energy (thermal or photovoltaic), and presents legal difficulties when being installed on rooftops, considering the legal framework surrounding greenhouses. Furthermore, it presents installation difficulties in cities due to local regulations concerning the maximum building height, surface area, and volume that can be built in a certain place. It can involve a high supply cost of drinkable tap water if rain water and greywater resources are not sufficient. In addition, drinkable water is normally not permitted by law for agricultural use.

Social barriers

Of the social barriers, most notable is the functional incompatibility that can be created in urban buildings when an agricultural activity is mixed with industrial and service activities. Another barrier is consumers’ lack of trust in the quality of urban agricultural products since it is a new model of food production, and not enough data exist about how it performs in view of the environmental pollution in cities. The lack of agricultural professionals qualified in urban systems and the possible job losses in rural areas are also considered as social barriers to the implementation of RTEG.

Environmental barriers

Of the main environmental barriers, most notable is the reduction of surface areas available on building rooftops for other environmental purposes such as renewable energy (photovoltaic installation, thermal solar panels). Likewise, the impacts associated with the life cycle were also highlighted, such as: materials, building and dismantling the greenhouse with a high environmental impact. Lastly, local resources such as rain water would not be sufficient to meet the crops’ needs, and in a semi-arid atmosphere, its contribution would bevery low.

Technological barriers

Of the technological barriers, most notable was the complexity of incorporating flows of food, energy, water, and emissions between the greenhouse and buildings, as well as the complicated rehabilitation that would be required in the building's structure in order to adapt it to the excess loads generated by the greenhouse and the crops. The lack of simulation models of these agro-architectural hybrid systems was considered to be a technological barrier.

Table 5.3 presents a summary of the results shown in this section.

Table 5.3 Barriers and opportunities regarding implanting RTEG in Mediterranean cities

Fields	Opportunities	Barriers
Economic	• Reduced transport costs • Cost savings related to energy and water consumption • Revaluation of unproductive space • Innovative project attractive to investors • Existence of financial aid for new products	• High cost of supporting infrastructure • High cost of management and investment • Narrow profit margin for horticultural products • Investor distrust of new products • Long-term repayment • Labor availability
Technological	• Trend of self-sufficiency in cities • Experience in greenhouses and climatic architecture • Minimizing consumption through regulating or controlling energy systems	• Technological complexity • Complexity of adapting existing buildings / Rehabilitation • Building overloading • Possible need to strengthen the structure • Lack of simulation models for these agro-architectural hybrid systems
Environmental	• Reducing impacts associated with transport • Reuse of gray water and rainwater • Minimization of resource use in hydroponic systems • Carbon fixation • Naturalization of the city • Reduction of energy demand in the building	• Reduction of surface area for rooftop Solar panels • Environmental impact on the greenhouse construction materials
Social	• Development of sociability • Value of fresh produce • Food safety • Integration in education system	• Incompatible uses • Need to train qualified personnel

5.6.3 Perception of incorporating RTG according to different urban building typologies.

The opportunities regarding the implementation of RTEGs on building rooftops without specifying the activity or the typology of the building are applied to the three study scenarios outlined in Table 5.2, highlighting the promotion of sociability in scenario A and incorporation into the educational system in scenario B. Of the implementation barriers, most notable is that concerning the rehabilitation of existing buildings when the structure needs to be strengthened due to the extra weight of the greenhouse. This would mainly affect scenario C due to the type of light metal structure commonly used in this type of industrial building in industrial estates. Furthermore, the type of activity carried out in these scenarios could bring about an incompatibility of uses with the production of food.However, it could be positive in terms of the logistic aspects of food production due to the large surface areas of these industrial estates for maneuvering as well as the greater surface area of rooftops.

5.6.4 Recommendations and observations of the work group regarding actions to overcome the barriers to implementing RTEG

As the final part of the evaluation process of the RTEG project, recommendations and observations to facilitate the implementation were presented:

- Consider the rooftop greenhouse as part of an installation in the building (like ventilation towers, cooling system, solar panels, etc.) so that it is not affected by the local regulations that limit its implementation. Infrastructure and new technology has become an integrated and necessary part of urban life, and today's urban dwellers use many types of technology to keep the urban environment civilized, habitable, and comfortable (Tschangho et al. 2009).
- The problem of the water cycle is crucial. One constraint may be the source of the water: rainwater alone will not be sufficient to meet crop needs, and in a semi-arid environment its contribution will be very small. On the other hand, drinkable water cannot be used for crop production as this is normally prohibited by law and in any case the price is too high. The project will consider the use of greywater for the greenhouse. For this, a fraction of the building's greywater will be treated before being used for irrigation. Research must be done on developing technology to collect rain and condensation water and, more importantly, to treating the greywater from the building and processing the drainage water from crop irrigation.
- The energy cycle is particularly important: the greenhouse can act as a solar collector during the day, providing heat for the building; at night the building's residual heat can help to maintain a given set-point greenhouse temperature to favour plant growth. During warm periods plant transpiration and roof shading can help to reduce the heat load of the building. All of these energy exchange processes need to be quantified and modelled. They also require new

technologies for the interchange of flows. Moreover, innovative and specific control systems are needed to manage the greenhouse-building combination.

- In order for RTEGs to be profitable a business model describing the types of investments required and the benefits offered must exist, defining a new value chain for the sustainable city of the future with less waste, emissions, and energy consumption, and drafting a marketing plan with sales forecasts, profits and losses.
- The technological solutions of the project in all building typologies must present the least environmental impact possible during the entire life cycle. Therefore, eco-design methodologies and environmental tools such as life cycle analysis are recommended prior to construction in order to guarantee the use of low environmental impact materials and techniques.
- RTEGs must be able to operate in new buildings and existing buildings. This means they must overcome the technological and integration barriers presented, as well as technical problems related to water, energy and gas exchange.

5.7 Conclusions

This investigation presents the results of a participative experience through work seminars with an interdisciplinary group of experts to determine the barriers and opportunities regarding the implementation of the Rooftop Eco.Greenhouse (RTEG) project in Mediterranean cities in Europe. RTEGs are greenhouses interconnected with buildings for producing high-quality vegetables and improving the sustainability of buildings in European urban environments by integrating buildings and food production. A goal of this project is to demonstrate that buildings having food produced in rooftop greenhouses can reduce energy, water, and CO_2 flows and generate significant economic, environmental, and social benefits.

The experts agreed that the reduction in the transport of foods is one of the main opportunities of the project in favor of the environment since the energy consumption and CO_2 emissions were reduced in the three implementation scenarios studied. Furthermore, RTEG would be the start of a trend of self-sufficiency in cities. For scenario A most notable is the sociability between the community of neighbors, as well as an environmental education tool for scenario B. One of the largest barriers in the three scenarios concerns local regulations regarding building the project on the rooftop. Therefore, it was suggested that the greenhouse should be considered as another building installation. In order to overcome the investment and long-term repayment of the project, a business model was created that would define a new value chain for the sustainable city of the future with less waste, emissions, energy consumption. Also drafting a marketing plan was recommended if it included forecasts of sales, profits, and losses. For scenario C, the complexity of strengthening the structure involves a greater investment, but at the same time the larger surface areas are in industrial zones. To minimize the possible environmental impact on materials to strengthen the structure, the use of environmental tools to quantify the impacts on stages prior to building is advised.

The methodology applied to the study provided positive results, studying the barriers and opportunities of the project from environmental, economic, social, and technological points of view. The interdisciplinary character of the experts who participated in this study provided a broad and comprehensive perspective on the topic.

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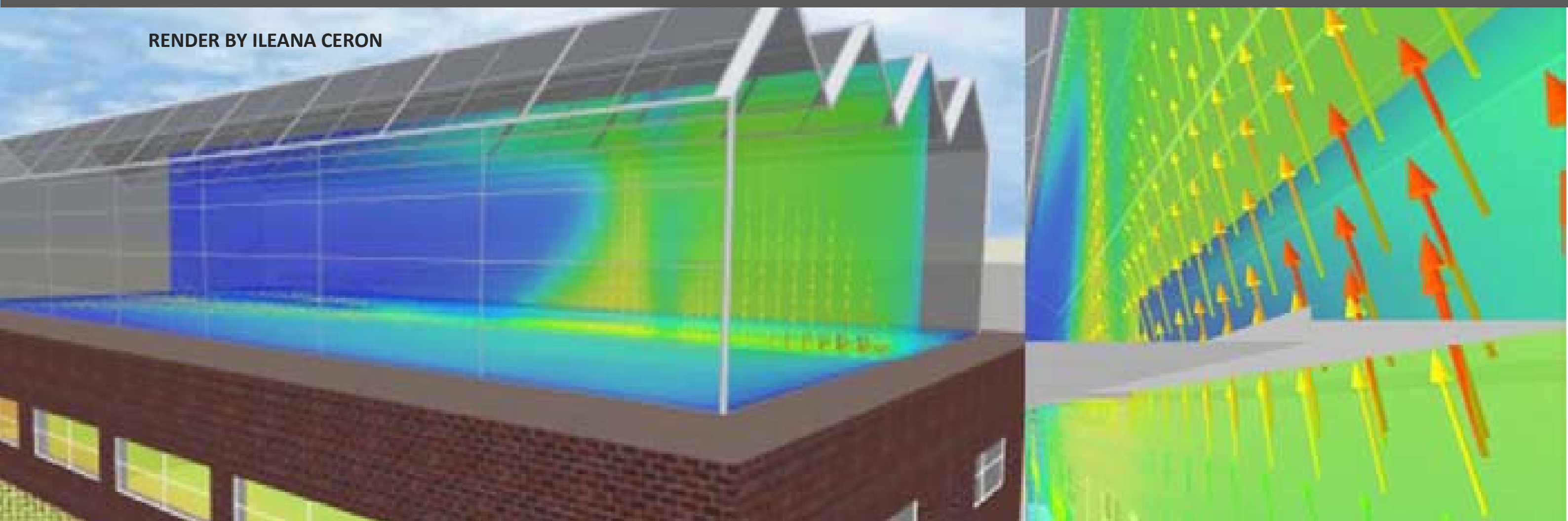
Chapter 6

Energy and environmental analysis of heat flows in Rooftop Eco-Greenhouse: A case study in the Mediterranean City of Barcelona.



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Abstract

The building sector has been accused of excessive energy consumption in terms of use, operation and maintainance. Cooling and heating requirements to improve comfort in buildings has a great impact on energy consumption. Insulation strategies and the incorporation of renewable energy in buildings has been evaluated and implemented in Europe. In order to reduce the energy consumption and CO_2 emissions in buildings, it is necessary to development and research new synergies in this sector. Rooftop Eco-Greenhouse (RTEG) is presented as an eco-innovative system that incorporates agriculture into the rooftops of buildings in the city from an industrial ecological perspective, as a new approach for sustainable food production in urban systems. This paper report results of a preliminary energy analysis of RTEG in a public building in Barcelona, Spain. The main purpose of the study was to assess the heating demand and heat flow behaviour in an interconnected RTEG system. The building and greenhouse have been modeled in Designbuilder simulation software.

The analysis was divided into three stages. First, we determined insulation effect of greenhouse in the building, through the amount of heat energy saved. Then, we analyzed the behaviour of indoor temperature in the system and the thermal balance in the building, without heating. Finally, we determined the residual heat potential that could be transferred through the interconnected system.

In addition, a sensitivity analysis of CO_2 emissions associated with heating demands has been quantified using the Life Cycle Assessment (LCA) method.

The results indicated that the insulative effect of the greenhouse on the building in terms of energy saved represents a small percentage (less than 5%) of heating demand in the building.

Preliminary results indicate the existence of residual heat in the building and greenhouse. The potential of residual heat to transfer from the greenhouse to the building was estimated as 87kWh for a day in winter. This could represent a saving of 79% in energy requirements for heating, during a day in winter.

CO2eq emissions avoided by heating systems would represent 34.45KgCO_2eq/day, 29.66KgCO_2eq/day and 23.88KgCO_2eq/day in electrical, gas and diesel systems respectively.

Keywords: smart cities, RTEG, eco-innovation, synergy flows, food in buildings

6.1 Introduction

Worldwide, 30-40% of all primary energy is used in buildings (UNEP, 2007). The building sector, like other industries, is based on the production model defined by the linear sequence: mining, manufacturing and residue (Wadel et al. 2010).

Internationally, the negative impact of the current energy model on the environment has led governments of the states and cities to consider various measures, through agreements such as the Rio de Janeiro Summit (UNCED, 1992), Kyoto (UNFCC, 1998), Johannesburg (UN, 2002), Aalborg (ICLEI, 2004) and more recently Rio+20 (UN, 2012).

Currently, buildings use about one-third of the world´s energy (Griffith et al, 2007) and this has been detected as a priority area for reduction of the total energy consumption within the European Union (EU). According to the IPCC, buildings provide the most economic mitigation potential for reduction of CO_2 emissions (Roche, 2010). One initiative of European Commission (2007a) has been the European Energy Policy Plan (20-20-20) to 2020. This consists of a 20% reduction in CO_2 emissions; 20% improvement in energy processes; and a 20% replacement of primary energy with renewable energy (Fiashi et al. 2012).

In addition to energy, food provides another significant energy flow within the urban system. The flow of food to cities follows a lineal model, causing a high consumption of energy resources, generation of waste and CO_2 emissions per food unit (kg), throughout its life cycle (EEA, 2010).

At present, the carbon footprint of shipping tomatoes from producers in Southern Spain to consumers in Barcelona is 166 g of CO_2 per kg of tomato (Sanyé-Mengual et al., 2011). Multifunctional landscape management and integration of agriculture into cities will help to reduce the carbon footprint of food production and make urban systems more sustainable (FAO 2012; Arosamena, 2012).

6.1.1 Energy efficiency and food production in buildings: An overview

Energy efficiency is a factor of great importance for sustainable buildings (Chwieduk, 2003). Energy saving is without doubt the fastest, most efficient and most profitable way to reduce emissions and improve air quality. Therefore it is necessary to promote the implementation of new policies and new technologies (Delgado et al. 2009).

In the European Mediterranean area, buildings standards play an important role. In the case of Spain, the Building Technical Code, with particular reference to the closure of buildings and their envelope is crucial in saving energy through insulation, thermal inertia and exposure to radiation (CTE, 2011). The use phase of the building is where most energy is consumed. The energy consumption during the operational phase of a building depends on several factors, such as the level of thermal demand, location and climate, materials and building design (UNEP, 2007). Cooling and heating demands are significant parameters for evaluating the energy performance of buildings in Europe (Tsikaloudaki et al. 2012).

Considerable efforts are being made in the building sector to incorporate initiatives that can improve energy efficiency. The Institute for Diversification and Saving of Energy in Spain (IDEA, 2011) is currently implementing the "Energy Saving and Efficiency Action Plan 2011-2020". It involves measures to control, in terms of energy consumption, not only for industry, but also for agricultural holdings, particularly greenhouses. The energy demand of a greenhouse depends on the relationship between the outdoor climate and the environmental needs of the crops. The climate control is used in order to improve the conditions for plants and helps to reach production goals.

Eco-innovation is an alternative strategy that can contribute to improving resource efficiency in the building sector. "Eco-innovation is any form of innovation aiming at significant and demonstrable progress towards the goal of sustainable development, through reducing impacts on the environment or achieving a more efficient and responsible use of natural resources, including energy" (European Commission, 2007b). Integrating eco-innovation in building is not solely about improve energy efficiency or resources use, but also about finding new and better ways to achieve the same or even higher functionality with new technologies and new synergies with other buildings or by using less resources (EIO, 2011). One eco-innovation strategy that could be used to improve energy efficiency and synergy with food in buildings is the implementation of Rooftop Greenhouses (RTGs).

Integrating food production using greenhouses on the roofs of buildings has started to be studied in different countries. As part of the "inFARMING" project in Germany, a prototype of the so called "Rooftop Farming" is being developed by the Fraunhofer in Haus Center (2012) in collaboration with BrightFarm Systems (2011). The goal is to demonstrate the possibility of implementation in Germany. In the private sector, local food suppliers are planning new projects such as car parks on the roof of service buildings in Vancouver, and a project called "Fresh from the roof" on a former factory roof in Berlin (Frish Von Bach, 2012). The first commercial-scale rooftop greenhouse was recently built in Montreal (Lufa Farms, 2011). This 3000m^2 greenhouse started to offer weekly vegetable baskets to local residents in Spring 2011. To our knowledge, there are no residual flow connections between the RTG and the building below. These initiatives, and others, are still in the development phase. However, it is still necessary to study proposals for the integration of greenhouses that allow quantified benefits and synergies with the building and urban system.

This study presents the preliminary energy and environmental analysis of one eco-innovation project in a European context: The integration of food production in buildings through the synergy concept called 'Rooftop Eco-Greenhouse'(RTEG)(Figure 6.1).

RTEG is defined by three main aspects: (1) Eco-innovation represented by greenhouse-building incorporation as a model for producing food and as a new option of utilising territory for agriculture, using a rooftop; (2) the eco-design of the greenhouse with criteria of low environmental impact and energy efficiency; (3) the incorporation of the concept of symbiosis and industrial ecology into the exploitation of flows (Cerón-Palma et al. 2012).

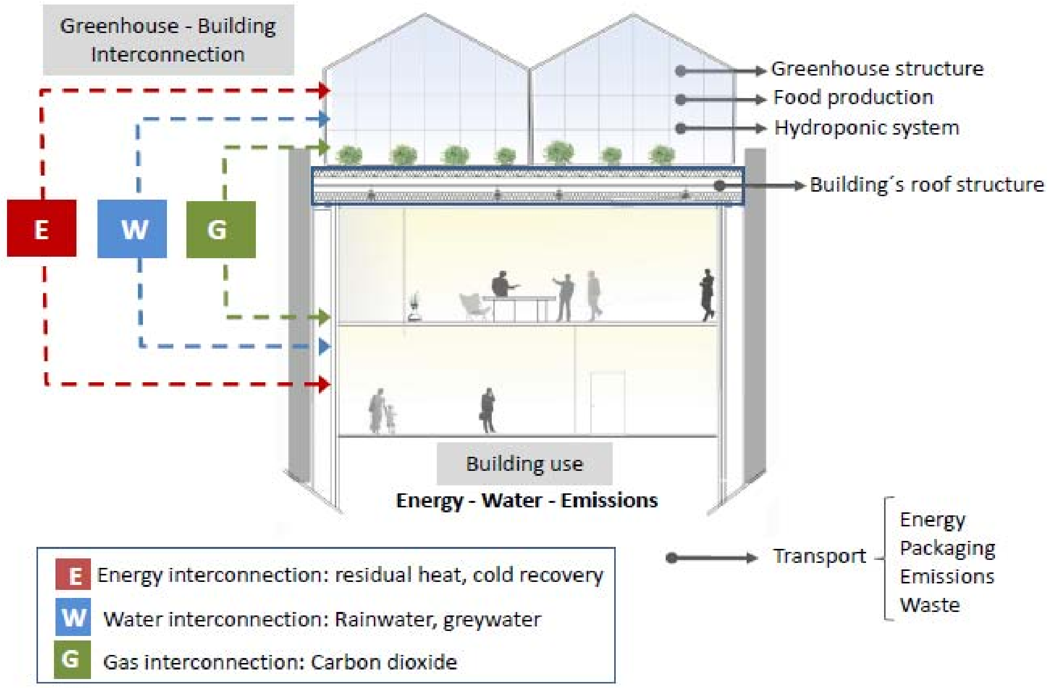

Figure 6.1. Conceptualization of RTEG

In a previous study, barriers and opportunities to the implementation of RTEG in European Mediterranean cities have been found (Ceron-Palma et al 2012). The environmental impact of the current linear supply system compared to an RTG has also been evaluated in a case study in Barcelona (Sanyè-Mengual et al 2012).

At present, there are no preliminary studies of the behavior of energy flows in the interconnected RTEG system. Therefore, this paper provides the first contribution to this type of energy analysis and this can lead to future development of this system.

6.2 Goal and scope

The main objective of this research is to identify the potential synergies between buildings and RTEG systems in terms of flows, focusing only on energy heating requirements in winter in a study system, in a service building (office). In order to achieve this main aim, several goals are outlined.

- To quantify the contribution of the greenhouse in terms of the insulative effect for the building, in order to reduce the building´s energy heating requirements.
- To analyze the internal temperatures in RTEG (greenhouse and building) on a day in winter.
- To identify the building´s residual heat that can be used by the greenhouse.

- To identify the greenhouse´s residual heat that can be used by the building.
- To estimate CO_2 emissions avoided by minimizing resource consumption of heating systems (electric, gas, diesel).

6.3 Methodology

6.3.1 The site

The study was conducted in an office building located in the South of Europe in the municipality of Cabrils, in the county of Maresme, in Barcelona, Spain (Figure 6.2). Cabrils is located at latitude 41^o 31´N and longitude 2^{o}22’ E. It has a population of approximately 7196 inhabitants, and an area of 7.1 km^2. It has a Mediterranean climate with mild temperatures in winter and warm temperature in summer.

Figure 6.2. Location of the building in Cabrils

6.3.2 Definition of study system

This section describes the main features of the building and greenhouse that compose the RTEG study system.

Office building

The building has a rectangular shape (27m long by 15.20m wide) with a total area of about 410m^2 with five zones (Figure 6.3). The outer walls are constructed of a double concrete block (0.20m) with air gap (0.10m). The roof is a concrete waffle slab (0.40m). There is a false ceiling with an air gap of 0.50m (Figure 6.4).

The office spaces are separated from the corridor (zone 3) by partitions of plywood and single glazed glass. The corridor has a suspended ceiling, which is necessary for air ducts, electricity and other installations. The exterior windows are double glazed, with glass of 6mm, with an air gap.

Fig. 6.3. Zonification of the office building.

Greenhouse

The greenhouse is a Mediterranean prototype of 325m^2. It consists of four spans of 5.6 m of height, constructed with a lightweight metal frame and polyethylene plastic film. The floor has a gravel layer of 0.03m. Figure 6.4 shows a section of RTEG and the materials of the building and greenhouse.

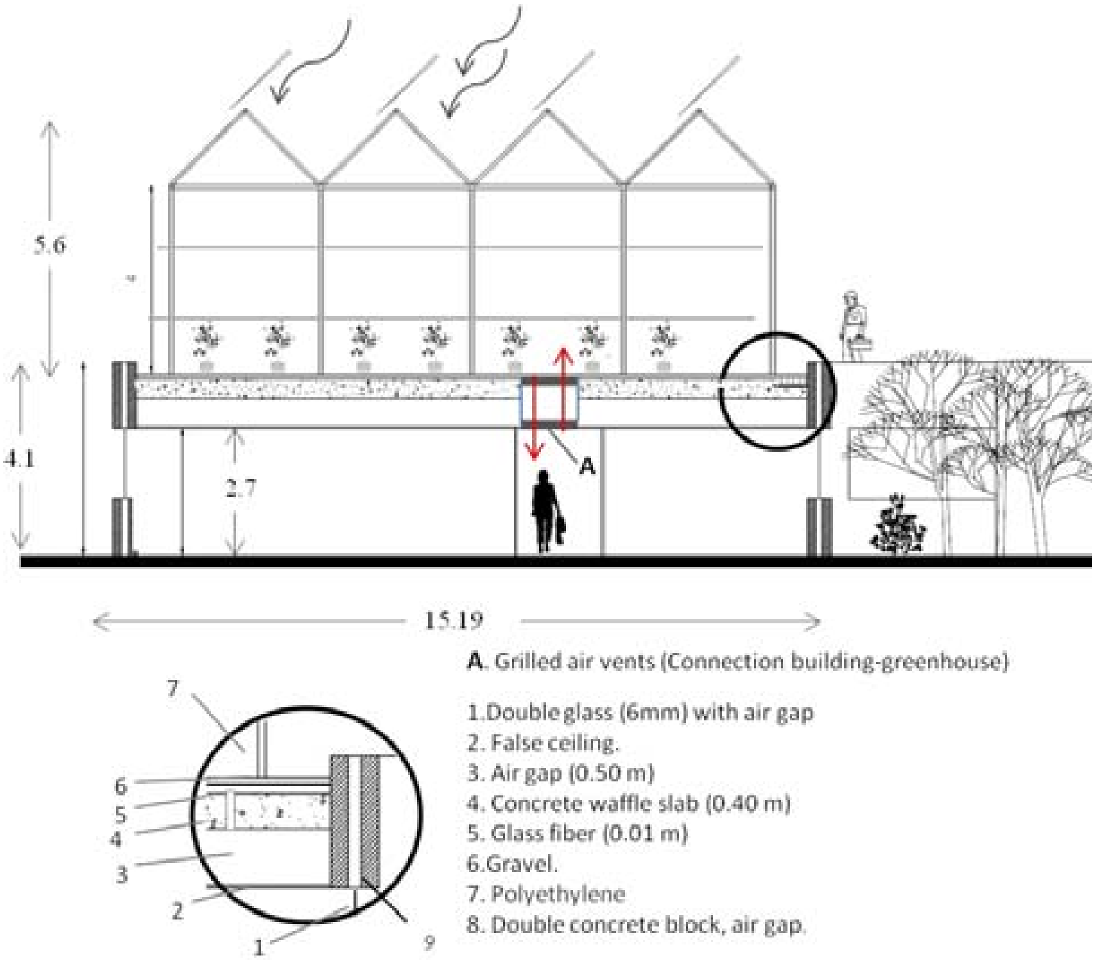

Figure 6.4. Section of study system

6.3.3 Scenarios of the study

Three stages for RTEG energy analysis are proposed (Figure 6.5). Stage A evaluates the insulative effect of the greenhouse on the building through calculating the heating demand of the building. Stage B consists of analysing indoor temperatures and heat balance in the building and greenhouse without a heating system. Stage C consists of analysing potential heat flows exchanged through two scenarios. The scenario C_1 analyses the heat flows from greenhouse to building and scenario C_2 from building to greenhouse.

A sensitivity analysis was included, in order to determine the environmental benefits associated with insulative effect (Stage A) and heat transfer from greenhouse to building (Stage C).

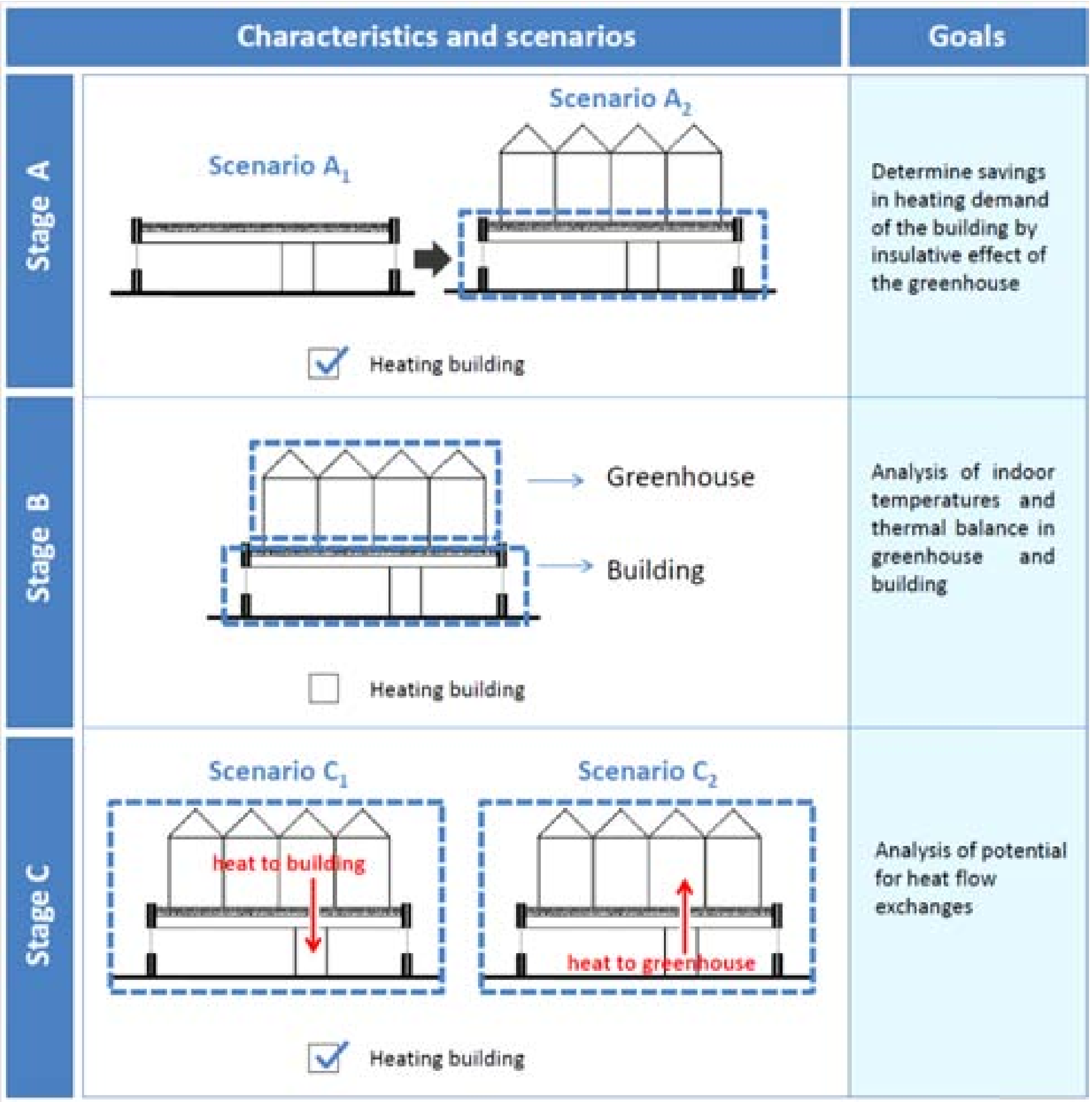

Figure 6.5. Summary of stages to be evaluated in RTEG system

6.3.4 Energy simulation

Software program

The "DesignBuilder" energy simulation program (DB, 2011) was used to calculate the internal gains and heating demand in the study system. This program uses the EnergyPlus dynamic simulation process (DOE, 2011) to generate performance data based on the climatic and thermal characteristics of the materials. The program allows for the calculation of heating loads using the method adopted by ASHRAE and implemented in EnergyPlus. The geometric model of the building and greenhouse were drawn in DesignBuilder. The interface of CFD (Computational Fluid Dynamics) in DesignBuilder was used to evaluate temperature distribution in Stage C.

Data input and simulation assumptions

Climatic data of the municipality of Cabrils were obtained using the 'Ruralcat' platform and introduced into DesignBuilder (Ruralcat, 2011).

The office was occupied from Monday to Friday, 8:00 to 19:00. A density of 0.05people/m^2 was considered. People perform sedentary office activity. A gain of 11W/m^2 was considered for equipment and computers.

The heating during the occupation period of the building was considered as 20 °C as a setpoint temperature according to ASRHAE(2010) (Stages A and C).

The greenhouse is presented empty and the effect of evapotranspiration from plants was not included in the heat balance.

In stage C, three grilled air vents (0.60 x 1.60m) were used to analyse interchange of heat between the building and greenhouse in zone 3. Each grilled air vent has a fan which forced the air to flow when required. In this same phase, a CFD analysis was conducted in order to visualize the indoor temperature distribution in zone 3 of building. The grilled air vents are opened from 13:00 to 17:00. Boundary conditions have been assigned from a previous EnergyPlus simulation of a day in winter. Design and analysis of mechanical ventilation is not considered in this research; only as an estimation of heat interchange potential for RTEG system.

Preliminary simulation: validation of input data

Surface temperature of the floor, ceiling and glass in zone 3 of the building were collected using HOBO data loggers with thermocouple connectors from February to June 2012. Preliminary simulation a day in winter was conducted in order to obtain surface temperature of the floor, ceiling and glass and will be compared with temperature obtained with data loggers.

Figure 6.6 shows the temperature behaviour of the three surfaces studied during a day in winter. During the occupation period, the heating system is activated. This is reflected in the graph, from 8:00, where it can be observed that the temperature increases in the partition and the roof. The three surfaces show similar behaviour and differences in values obtained are of less than 2^{o}C. The simulation model respond quicky to a time step change, in the same manner as when the heating is activated at 8:00. Also, the inertial thermal differences between the roof, partition and floor are shown. The floor is the most stable with fewest thermal oscilations during a day.

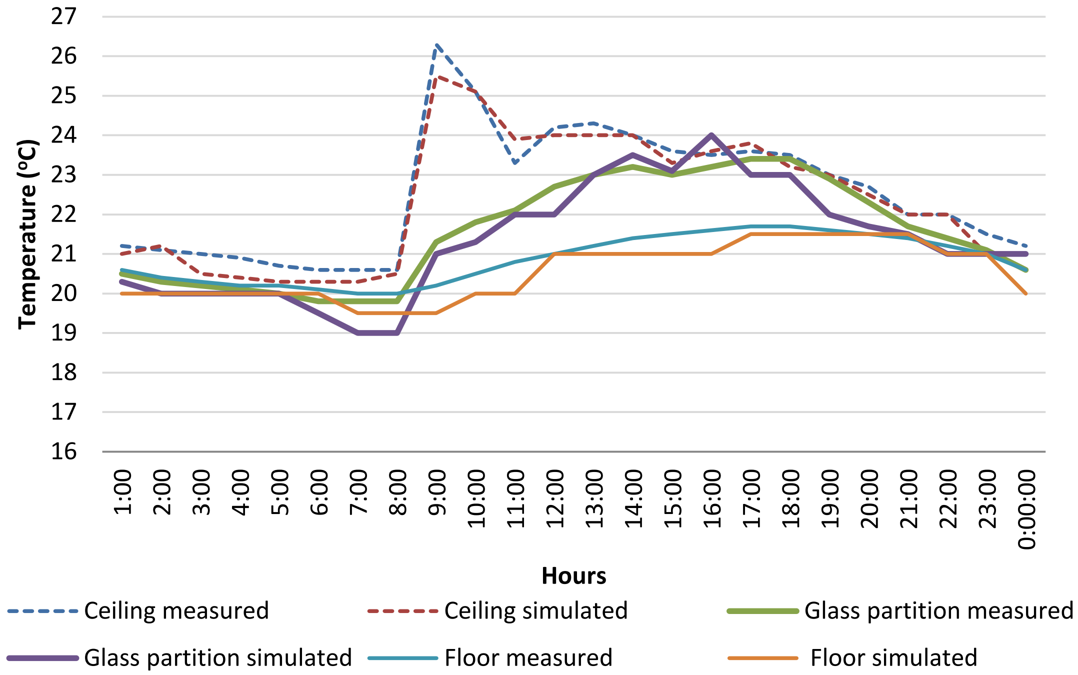

Fig. 6.6 Validation input data

A one way ANOVA was conducted for each surface, in order to determine the variance between temperature measured and temperature obtained from simulation.
According to ANOVA results for ceiling, since the P-value of the F-test is greater than or equal to 0.05, there is not a statistically significant difference between the mean surface temperature from one method to another (measured and simulated) at 95% confidence level (Table 6.1).

Table 6.1. ANOVA Table for ceiling surface temperature by method

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0,12	1	0,12	0,05	0,8222
Within groups	108,117	46	2,35036		
Total (Corr.)	108,237	47			

The results for floor and glass also indicate there is not a statistically significant difference.

In summary, the simulation model is valid because from a qualitative viewpoint, it predicts the thermal behaviour of the building´s surfaces and qualitatively predicts values that match those obtained from the experimental data.

6.3.5 Environmental analysis

Sensitivity analysis of environmental benefits.

The heating demand of office buildings can be met by electricity or a boiler (gas or gasoil). In this sense, a sensitivity analysis is carried out in order to analyse how the environmental benefits vary according to the heating system. The assessment was done according to the Life Cycle Assessment (LCA) methodology. The classification and characterization steps use the Global Warming Potential (GWP) impact category (kg CO_2 eq.) (IPPC, 2007). The electricity mix (peak) of Spain considered for the analysis is obtained from 'Red Eléctrica Española' (REE, 2011) (Table 6.2).

Table 6.2. Electricity production mix (peak) in Spain. Source: REE, 2011

Electricity production	Coverage (%)
Nuclear	17.5
Coal	14.3
Combined cycle	22.9
Eolic	14.7
Hydraulic	15.1
Solar	1.9
Thermal renewable	1.4
Thermal non-renewable	12.3

6.4 Results

This section presents results of the energy and environmental analysis.

6.4.1 Stage A: Heating demand (Insulative effect)

Heating demand results in winter are presented in Table 6.3. January is the month with the greatest heating demand. In this month scenario 'A_1' has a heating demand of 3,286 kWh and scenario 'A_2' 3,181 kWh. This represents a saving of 3%.

The variation observed for each month between the scenarios is no greater than three to five percent. From October to March, the heating demand was 11,329 kWh for scenario 'A_1' and 10,904 kWh for scenario 'A_2'. This represents savings of 3.7% during the winter period (October to march). For a typical day in winter, heating demands were 112 kWh for scenario A_1 and 110 kWh for scenario A_2.

Table 6.3. Comparison of the heating demand in a building with and without a greenhouse

Months	Building without greenhouse (A_1)		Building with greenhouse (A_2)		Saving
	[kWh]	[kWh/m^2]	[kWh]	[kWh/m^2]	
October	252	0.61	241	0.59	4%
November	1514	3.70	1451	3.50	4%
December	2721	6.60	2631	6.40	3%
January	3286	8.00	3181	7.75	3%
February	2085	5.10	2007	4.90	4%
March	1471	3.60	1393	3.40	5%
Total Winter	11329	27.63	10904	26.60	4%

Energy savings of lower than 5% between scenarios A_1 and A_2 show the need to explore new forms of interconnection, in order to enable greater energy saving. The results of stage B are presented below, which provides a first approximation of the potential residual heat in the RTG system in this study system.

6.4.2 Stage B: Variation of indoor temperatures and thermal balance

Building

Figure 6.7 shows the hourly behavior of indoor temperature during a day in winter. In the occupancy period, heating is required from 8:00 to 15:00. At 15:00, the air temperature is 20^o C remaining in the comfort zone until 18:00. This is attributed mainly to external solar gains, according to Figure 6.8. Heat is mainly lost through the walls and partitions in the period of highest radiation. Partitions are made of glass and plywood; their thermal inertia means that during daytime the partitions are cooler than the surrounding internal air and so they absorb energy from the air.

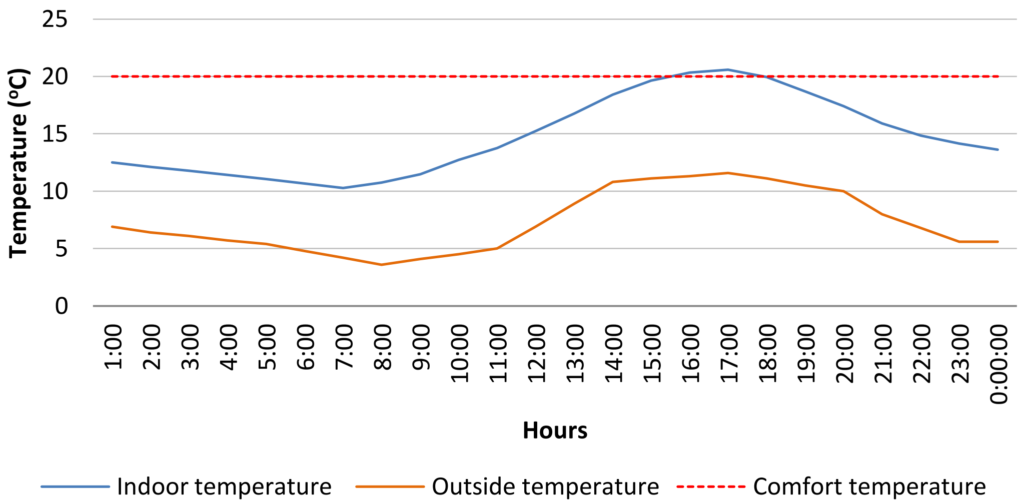

Figure 6.7. Results of temperatures in a building with greenhouse during a day in winter. The building was unheated.

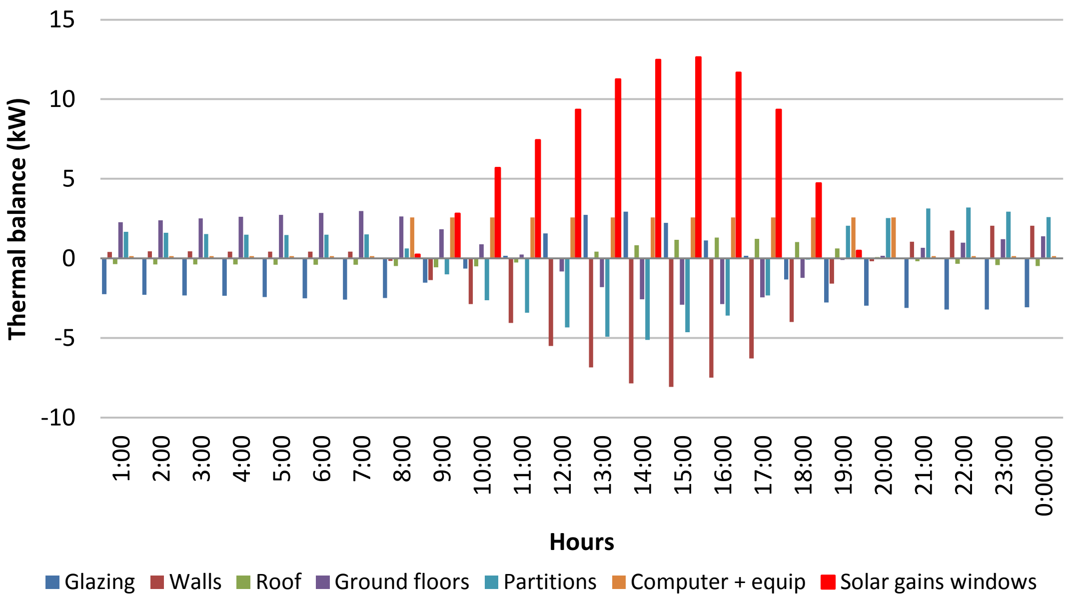

Figure6.8. Thermal balance of building during a day in winter

The building does not have residual heat during the occupation period. The results presented are variables and dependent on the characteristics of the building, such as the percentage of glazing, insulation in walls and ceilings. These aspects have an impact on the level of comfort and heating requirements.

Greenhouse

Figure 6.9 shows the hourly behavior of the indoor temperature. The red line in the graph represents an optimal temperature that is required for adequate growth of most vegetable crops such as tomato.

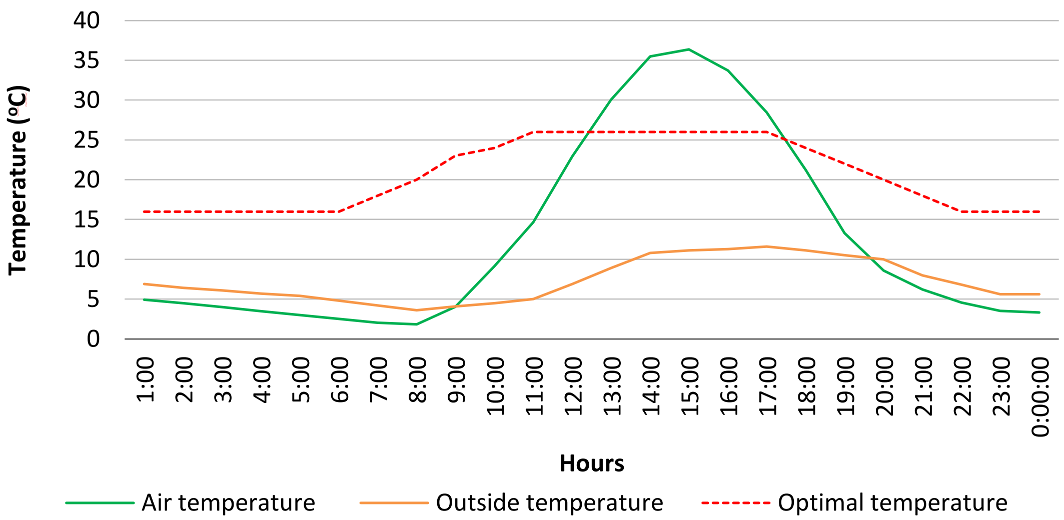

Figure 6.9. Temperature analysis in a greenhouse in a day during winter

From 21:00 to 9:00 hours, the greenhouse has a slightly lower indoor temperature in respect to the outside temperature. This is known as thermal inversion and has been observed previously in studies of nocturnal climate in unheated greenhouses, particularly under clear skies (Piscia et al. 2012). The main reason is that the greenhouse cover is cooler than the greenhouse air and the outside since the cover emits more thermal radiation than it receives from the clear sky.

From 13:00 to 17:00, the greenhouse has a residual heat with an indoor temperature that increases to 36°C at 15:00. This temperature is clearly detrimental for most crops.

Outside temperature at this time was 12°C. The largest heat gains at this time were provided by solar radiation through the transparent envelope.

As discussed in this stage, the building has no residual heat during the occupation period and does not provide comfort conditions from 8:00 to 15:00. This represents a heating demand of 110 kWh/day (0.27 kWh/m^2/day) according to results of stage A. The greenhouse has residual heat from 13:00 to 17:00, which indicates the need to ventilate, in order to remove the excess heat. The following section presents the results of stage C, which analyses the potential use of residual heat in the building and greenhouse.

6.4.3 Stage C: Potential of heat flows interchange

Results of stage C are organized into two scenarios:

Scenario C_1: Residual heat from greenhouse to building

Scenario C_2: Residual heat from building to greenhouse

Figure 6.10 summarises the residual heat of RTEG system. In stage 3, the building is heated in order to improve comfort during the occupancy period.

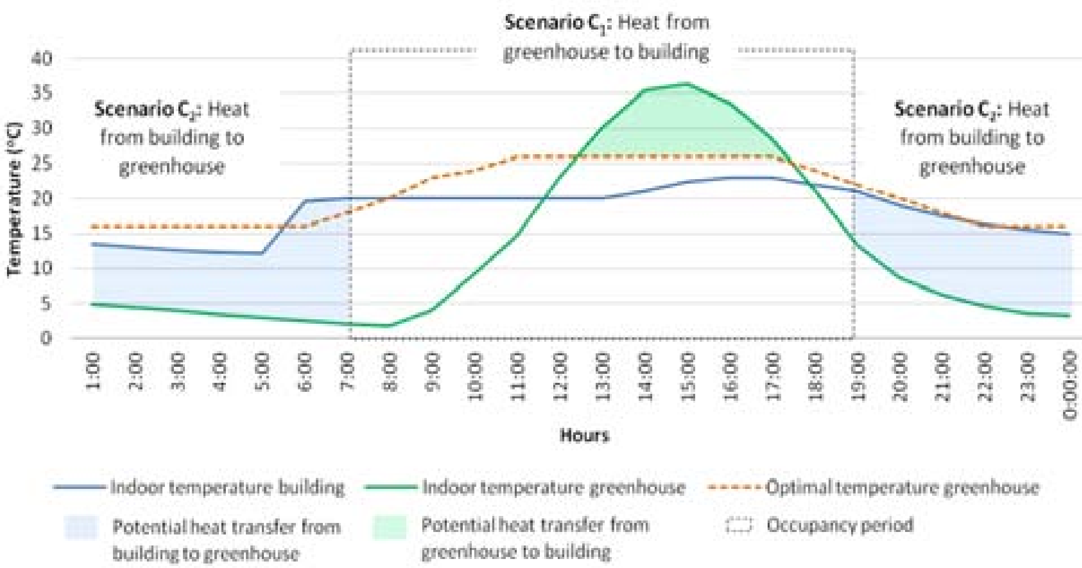

Figure 6.10. Graphical representation of residual heat in RTEG system

Figure 6.10 shows that the greenhouse can benefit from the building´s residual heat during most of the night, whilst the building can benefits from using heat from the greenhouse during the central part of the day.

Scenario C_1: Residual heat from greenhouse to building

Figure 6.11 shows the indoor temperature behaviour in the greenhouse when mechanical ventilation (Fans) was applied. A total of 87 kWh/day of heat was removed from the greenhouse in order to decrease its temperature. This data indicates the potential amount of heat that can be transferred to the building in a study day.

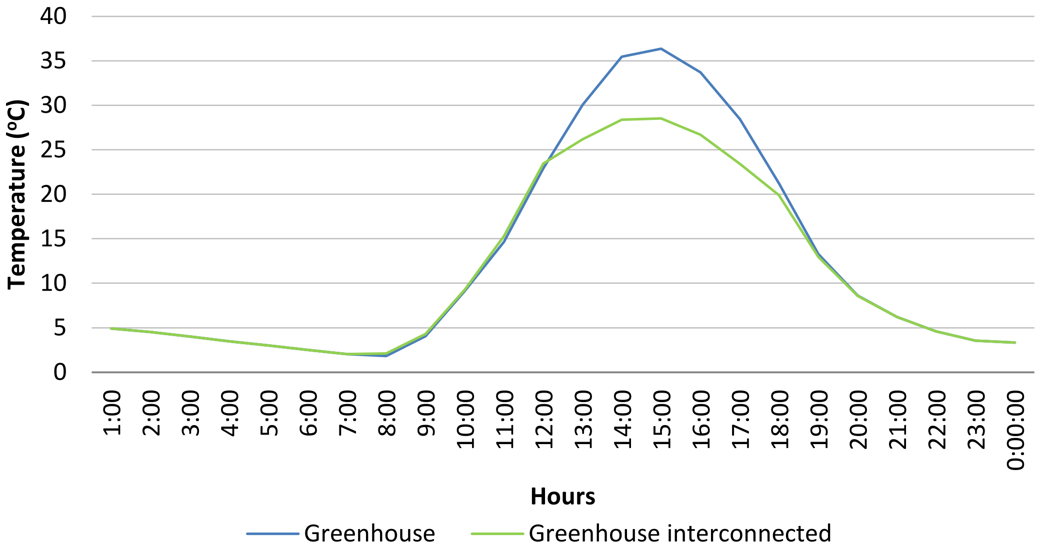

Figure 6.11 Results of temperature analysis in a greenhouse with mechanical ventilation during a day in winter.

If we assume that the building has an energy requirement for heating of 110 kWh according to the results from stage A, introducing heat recovered from the greenhouse would represent an estimated saving of 79% of the energy requirements for heating.
This percentage represents the total heat energy saving for the building if heat from greenhouse could be transferred and distributed effectively. The design of a system to transfer the heat from greenhouse to building or to distribute the heat once it is in the building, is beyond the scope of this study.

Figure 6.12 shows the distribution of indoor temperature in greenhouse and zone 3 of the office building interconnected through grilled air vents at 14:00. At this time, a greenhouse without interconnection has a temperature of 35°C. The grilled air vents were opened at 13:00, which means that by 14:00, the temperature in the greenhouse has decreased by 5 °C (Figure 6.11).

Figure 6.12 also shows that indoor temperatures were between 23°C and 26°C just below the ceiling of building. At this time, the temperature was 22°C for the building without connection.

According to Figure 6.12, there is a lack of uniformity in terms of distribution of temperature in the building. There is also a variance in internal air speed, particularly in the greenhouse area. This suggests that better air interconnections than the grilled air vents simulated in this study are needed to improve the efficiency of interconnections and air flow. Designing such devices for air flow is beyond the scope of this study.

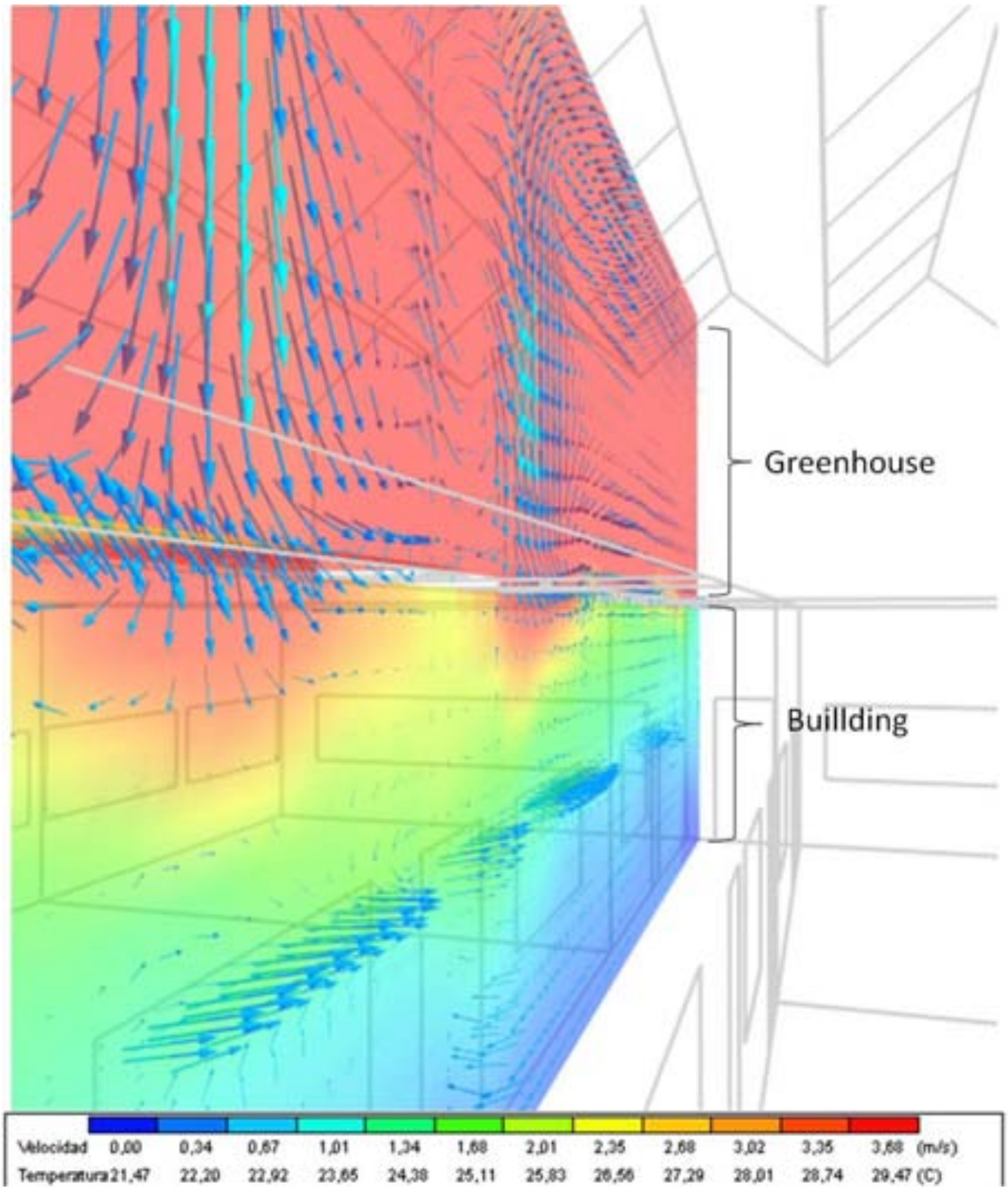

Figure 6.12 Results of CFD analysis in greenhouse and zone 3 of building at 14:00

The results of this scenario indicate that it is possible that heat flows interchange and energy requirements for heating with RTEG interconnected could be reduced to approximately 79% for building. This energy saving score should only be taken as an estimation, as the analysis was done for a single day in winter at a conventional office building, whose characteristics significantly differ from other typologies and uses.

Scenario C_2: Residual heat from building to greenhouse

In scenario $C_{2,}$ there is no residual heat during the occupation period. Outside this period, there is residual heat that the greenhouse requires in order to achieve optimal conditions at night. In Figure 6.13, heat exchange with greenhouse at 20:00 can be observed. The distribution of indoor temperatures corresponds to one hour after that grilled air vents are opened. The indoor temperatures of building oscillates between 16 and 18^{o}C. This represents 2 to 4^{o}C less than the results reported in Figure 6.10.

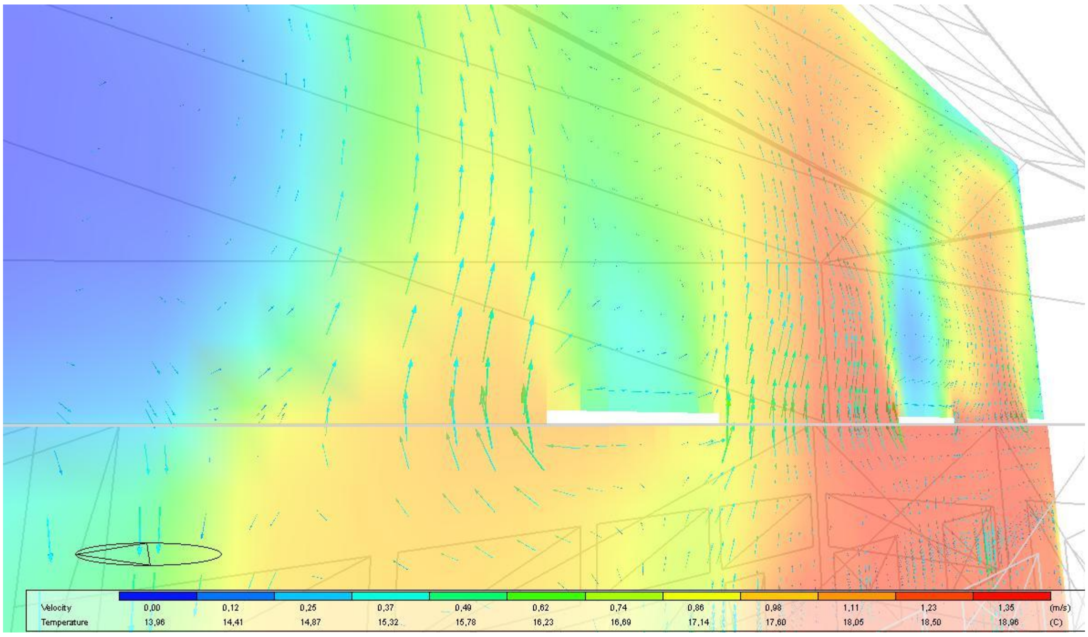

Figure 6.13. Results of temperature analysis in a greenhouse with mechanical ventilation during a day in winter at 20:00

The lack of temperature uniformity is even more evident than for scenario C_1, and supports the necessity of designing interconnection systems.

6.4.4 Sensitivity analysis of environmental benefits.

Table 6.4 shows the results of GHG emissions (kg CO2eq) prevented from the insulative effect produced by the greenhouse on the building (scenario A_2). Also shown are the results for different heating systems. In addition, the table presents the potential of CO_2

saved if all the heat recovered from the greenhouse (scenario C_1) could be used in the building, in order to reduce energy requirements for heating.

For both scenarios, the results show that the CO_2eq saved are higher for electric heating systems than a gas boiler (≈ 144%) or diesel (≈ 115%).

Table 6.4: Results of sensitivity analysis of CO_2eq avoided in the heating system

Months	**CO_2 saved due to insulation effect (A_2)**		**CO_2 saved due to heat transfer (C_1)**	
	[KgCO_2eq/day]	[KgCO_2eq/m^2/day]	[KgCO_2eq/day]	[KgCO_2eq/m^2/day]
Electricity	0.79	0.002	34.45	0.08
Gas	0.55	0.001	23.83	0.06
Diesel	0.70	0.0017	29.66	0.07

Results are presented for a day in a winter (Table 4). However, an annual analysis for scenario A_2 (all winter) shows that emissions of CO_2eq saved in electric heating systems would be 168 KgCO_2eq/year, whilst gas and diesel would be 116 and 136 KgCO_2eq/year respectively. Comparing annual values with daily results, it is observed that the amount of emissions avoided by heating systems during the year (winter) is lower, if we consider that in a single day, residual heat can avoided the use of 34.45 KgCO_2eq/day in electrical systems. Further research is needed to determine an appropriate design of connections and heat transfer systems, which is beyond the scope of this study.

Local production of hydroponic tomatoes in RTEG system in the study area on site provides environmental savings of 0.44 kg kgCO_2eq related to distribution of tomatoes (transport and loss of product avoided and optimised packaging) (Sanye-Mengual et al. 2012). With a productivity of 15 kg/m^2 (Anton et al., 2005), the annual savings would be 6.6 kgCO_2eq/m^2. Compared to the scenario $_{A2,}$ the insulative effect is equivalent to a 6% (0.41 kgCO_2eq/m^2/year) saving of distribution.

6.5 Discussion and future research

As previously described, this paper introduced a research of energy flows in the RTEG system. The main constraints found during the research were related to the variety of buildings with different characteristics that could be considered as a study systems. The office had limitations in relation to exploration the exchange of heat from the building to the greenhouse (scenario C_2). This is because the building needed to be heated during part of occupation period. Moving the heat from the building to greenhouse could produce an increased demand for heating.

For this study system, further research is needed in order to evaluate if removing heat from the building has an implication in the supply of heat through the heating system in order to meet comfort conditions

However, similar research could have been conducted using other climate data and other typologies of building. In context of service buildings, how restaurants and gyms could provide residual heat for greenhouses is of great interest to study. In this same scenario (C_2), we also noticed the importance of an air quality study for the viability of using heat flows from building to greenhouse. According to CTE (2011), the transfer or re-circulation of air can only be used if it contains a low level of contamination or less than 400ppm of CO_2 (UNE-EN 13779, 2005). Building air quality would be important to analyse in future research, in order to provide optimal CO_2 conditions for plants in greenhouses.

In scenario C_1, the potential of residual heat to transfer from greenhouse to building was estimated as 87kWh for a day in winter. This residual heat recovered in its entirety and efficiently distributed through a system designed for the interconnection of the building with the greenhouse (which is not considered in the scope of this study), could provide savings of 79% in daily heating demand (110 kWh/day) according to the results of this investigation. An important issue to be considered in future research is the assessment of the energy consumption that is required by fans systems to move heat.

The results of the environmental study related to GHG emissions (kg CO_2eq) avoided in different heating systems (electrical, gas and diesel) on a day in winter were 98% higher in stage C (residual heat potential) compared to stage A (insulation effect). However, it is necessary to consider annual simulations for energy and environmental global balance of benefits of the system. An extend annual study could assess the heat flows savings compared with other RTEG flows such as transport.

CFD analysis showed that the indoor temperature increased between 2 and 4^{o}C in building when residual heat of the greenhouse was transferred through grilled air vents. This provides improved building comfort conditions by increasing the temperature to 20^{o}C. According to ASHRAE, comfort limits in winter are 20 to 24^{o}C. If there is heat left over in one of the spaces, another option is to transfer it to nearby buildings. This is within the concept of industrial ecology, which focuses on how to change a waste product into a raw material.

Areas of future research are presented:

- Conduct studies of RTEG in summer to analyse the potential of residual cold connection. This may provide an energy and environmental annual balance of RTEG integrated in buildings in a Mediterranean climate.
- Extend energy analysis in buildings with different construction systems, percentage of glazed and/or double skin facade.
- Extend the study with greenhouses made from other materials such as glass or polycarbonate film.
- Design and evaluate connection systems in buildings of several levels and the distribution of heat within each of them.
- Compare the importance of interconnection with other RTEG system benefits, such as logistics of food.
- Expand the study to cold areas of Central Europe

- Conduct a parametric study to determine the optimal percentage of surface system components (building and greenhouse).

6.6 Conclusions

In this article, we have analyzed how RTEG provides synergy with energy flows in a office building.

As part of the methodology, the preliminary simulation demonstrated the validity of the model which did not find significant differences between the surface temperature (floor, ceiling and partitions) data found on site and the results obtained using DesignBuilder. This validates the use of the model for future research.

The energy analysis identified that the RTEG system without interconnection has low energy saving in the heating demand of the building during winter (425kWh/year).

The heat balance of the building showed that the main heat gains during the day occur from the high percentage of glazed surface of the building. It is necessary to expand the study in the future, using other types of glass facades (with a lower glazed percentage), as this may affect the heating demand.

The energy analysis determined the existence of residual heat in the greenhouse during 4 hours in the study day. Estimated data of 87 kWh/day of residual heat available to be transferred from the greenhouse to the building was obtained. This would represent a 79% savings in the energy required to heat the building in the same day, if there was an effective connection system that would allow the retrieval and distribution of all residual heat from the greenhouse. CO_2eq emissions avoided by heating systems would represent 34.45KgCO_2eq/day, 29.66KgCO_2eq/day and 23.88KgCO_2eq/day in electrical, gas and diesel systems respectively.

The building shows residual heat during periods in which it remains unoccupied. The exchange of heat flows from the building to the greenhouse is possible in this study system, as shown by the CFD analysis. However, future studies are needed to determine how movement of heat would affect heating demand during periods of occupation. Based on the results generated by this research, further lines of research can be investigated, in order to determine other energy and environmental benefits of the RTEG system.

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PART 4

Conclusions and future research

Chapter 7

Conclusions of dissertation

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This dissertation has presented eco-innovative strategies for buildings, with special attention paid to energy and CO_2 emissions. We are now in a position to formulate general conclusions.

9.1 Conclusions of methodological aspects

The conclusions regarding several tools applied in the Chapters 3 to 6 can be summarized as follows:

Integration of multidisciplinary tools as a strategy to introduce eco-innovation in buildings.

- LCA has been demonstrated as a tool for decision making in the construction sector, considering environmental factors in the selection of materials, in relation to GHG emissions and cumulative energy demand.
- The main complexity of the use of LCA in this study was the absence of a materials database in building sector in Mexico.
- It has been observed in the investigation that energy simulation analysis could help to define better strategies to reduce energy requirements for cooling and/or heating. It could be used from the planning stage for new buildings or in the rennovation of existing buildings.
- Bioclimatic diagnostic tools could help to determine the need for heating or cooling in a study site and propose strategies in relation to climatic conditions, in order to improve comfort in buildings and reduce the use of cooling or heating systems.
- Interdisciplinary participation of experts in seminars can provide a global vision of the implementation of strategies as a 'Rooftop Eco-Greenhouse'. The importance of these ‘social tools’ should not be underestimated.

9.2 Eco-innovation in buildings as strategy for sustainable urban systems.

Eco-innovation could reduce the impact that the building sector has on the environment and energy efficiency could also be improved in this area. General conclusions of several strategies evaluated in this dissertation can be summarised as follows:

Strategies to reduce energy and GHG emissions in social housing in Mexico

Indoor strategies of social housing: Eco-technologies

- Eco-technologies could potentially provide an annual reduction of 31% of energy consumption and GHG emissions in social housing. In terms of energy consumption, the results of this dissertation show that the eco-technological strategy applied indoors in social housing (scenario with air conditioner) could provide a reduction of up to 35.7kWh/m^2/year, compared with 20kWh/m^2/year in social housing without air conditioning.

- Efforts should be focused on providing incentives for users and/or housing developers to integrate eco-technologies into existing social housing and to those that will be constructed in the future.
- Expanding the results to a social neighbourhood scale (1903 social houses in a warm-humid climate) show one million of electrical kWh/year could be saved and 470,000 kgCO_2eq emissions could be avoided.

Outdoor (building envelope) strategies for social housing: Shading and insulation

- From the four strategies evaluated (Above roof shade, overhangs on walls, louvers in windows and green roof), above roof shade made with jute-based material performed the best in relation to the environment and energy. Strategies were proposed under the premise of being suitable for introduction in to a social housing unit, without affecting habitability during implementation.
- Social house with '*Above roof shade'* strategy can provide a saving of 27% compared to a standard house in a warm humid climate (126kWh/m^2/year). This strategy can be installed using local resources and can be implemented at a low cost.
- The embodied energy for jute of '*Above roof shade'* strategy was 1500 kWh. This represented a greater energy input in comparison to aluminium, Panel W and green roof materials. However, this strategy presented major savings in relation to annual energy cooling requirements, and therefore the payback time was less than one year. It also showed the greatest reduction of GHG emissions (kg CO_2eq), with savings of 22.8 kg CO_2eq/m^2/year.
- Green roof was other strategy that provided energy benefits, solely due to the insulating effect. This strategy reduced the annual heat contributions produced by the roof by 51%, compared with the house without a green roof. The results show a saving of 22 kWh/m^2/year in relation to energy requirements for cooling. However, this strategy needed the largest amount of energy for materials and the payback period was 6.5 years.
- The payback period for CO_2 embodied for green roof materials in relation to CO_2 emissions avoided associated with the use of cooling systems, was less than one year.
- Aluminium used for louvers in windows was the major contributor to Global Warming Potential (2098 KgCO_2eq).

Innovation strategy for social housing: Food production in low density cities

- Food production in plot and the roof of social house can represent a favourable strategy for food self-sufficiency and fixation of carbon emissions. This can also increase security in relation to food production in urban areas.
- In expanding the study system (social house) to food production, we have observed that in this new system-product, it is crucial consider the

environmental impact avoided in relation to food logistics as one of the benefits gained by introducing food production into cities. According to the results, the production of tomatoes in social housing areas in Merida (Mexico) could provide a savings of 662 gCO_2eq per kg of tomatoes produced. In descending order, the main contributors to these savings are transport requirements (57.7%), the retail phase (37.2%) and re-usable packaging (5.1%).

- Carbon fixation for food production (tomato) on plot and roof was 391 kgCO_2eq/year. This represents 56% more than the green spaces strategy that used sedum.
- Food production in plot and sedum on roof was the scenario recommended for social housing. This is in relation to accessibility issues and also prevents logistical problems of installation. Carbon fixation for this scenario was 301 kgCO_2eq/year.

Rooftop Eco.Greenhouse (RTEG) as a synergy concept in relatoin to buildings in Spain

A list of environmental, economical, technological and social barriers (and the ways to counter-act the barriers) to the RTEG system have been obtained.

Barriers to implementation RTEG

- Several constraints in RTEG challenged the implementation. One of the largest barriers concerns local regulations regarding installing the greenhouse on the rooftop. Therefore, it was suggested that the greenhouse should be considered as a part of the building equipment, instead of a permanent construction. These legal barriers have been verified and overcome in the pilot project in a catering service building (Xiringuito Escriba) in Barcelona (See preface section page XIV).
- Another constraint was the source of the water: rainwater alone will not be sufficient to meet crop needs, and drinkable water cannot be used for crop production. Therefore, some greywater needed to be treated and moved from the building to the greenhouse.
- The lack of simulation models of these agro-architectural hybrid systems was considered to be a technological barrier.
- Eco-design methodologies and environmental tools are recommended, in order to guarantee the use of low environmental impact materials and techniques. This will reduce the environment impact of the technologies used in the scenarios.
- In terms of rehabilitation strategies, the structures of some buildings would need to be strengthened, due to the extra weight of the greenhouse. This would mainly affect industrial buildings, due to the type of light metal structure commonly used.

Opportunities to implementation of RTEG

- Several benefits, such as the reduction in the transport of foods, provided a positive environmental effect in relation to reduction of energy consumption and CO_2 emissions.
- The existence of financial aids for new eco-innovative products is considered to be an important incentive for companies.
- The surface area of the building rooftops acquires an added value for the owner since it becomes a mixed-use space.
- RTEG could reduce energy costs by improving the energy efficiency of the building through adapting the eco-greenhouse, as well as reducing water costs through re-using rain water and grey water.
- The promotion of sociability in multi-household buildings and incorporation into the educational system in educational buildings were considered opportunities for implementation of these typologies. There would be a positive effect for industrial buildings in relation to food production and logistics.
- The RTEG system has significant potential to be investigated and implemented.

Energy and environmental analysis of RTEG

The conclusions of the energy and environmental analysis of RTEG, are in relation to the the Mediterranean climate context, during the winter period. The RTEG system is composed of an office building (410m^2) and a mediterranean greenhouse of 310m^2.

- The energy analysis results indicate that an RTEG system without interconnection provides contribution of 1kWh/m^2 in heating demand saving, in the study building during winter.
- Energy analysis has determined there is a potential of 87 kWh of residual heat created during in greenhouse during winter day. This energy could be transferred to the building, in order to reduce heating demand and improve comfort conditions. However it is necessary to conducted studies in order to design and evaluate distribution systems.
- An efficient system to recover and distribute heat flows in the building could provide a saving of 79% of the current heating demand of the building, which is 110 kWh for the study day.
- The insulation effect represents a savings of 0.80, 0.50 and 0.70KgCO_2eq/day in electric heating, gas and diesel respectively.
- The estimated savings in heating demand for the building associated with heat transferred from greenhouse represents a savings of 34.45, 23.83 and 29.66 KgCO_2eq/day in electric heating, gas and diesel respectively.
- This study has determined the presence of residual energy in both the greenhouse and the building. However, it is necessary to increase the period of simulation and also the number of study systems, in order for more conclusive results to be obtained.

Chapter 8

Future research

PHOTOGRAPHY BY ILEANA CERON

Chapter 8 focuses on further work that could be undertaken following this dissertation, and focuses particularly on two potential areas of study. Actions that could lead to the implementation of research outcomes and the expansion of the research into other areas are highlighted.

8.1 Strategies to reduce energy and GHG emissions in social housing in Mexico.

- Proposed integration of strategies to reduce energy and GHG emissions with multidisciplinary assessment tools. Expand assessment of strategies investigated and propose new strategies in other regions and other orientations of social housing.
- Environmental improvements through the eco-design of each of the strategies proposed.
- Expand the study to evaluate all strategies with an economic approach, paying special attention to time for payback according to energy saving in houses.
- The green roof study could be extended, in order to quantify environmental and economic benefits and impacts.
    - Determine the substrate and appropriate plants according to the study site through laboratory and field studies.
    - Conduct studies of carbon fixation in species of the region.
    - Determine the environmental impact of irrigation and maintenance.
- Expand social studies, in order to evaluate incentives and perceptions of 'green roof' with inhabitants of social neighbourhoods. Positive aspects, such as improving the quality of life of the people that work in agriculture, and negatives aspects, such as the perception that food produced in the city is more contaminated, should be studied.
- Expand the materials proposed for eco-rehabilitation strategies in order to have a wider range of possible materials and understand their environmental impacts.
- Expand the LCA of materials to all impact categories.
- Generate life cycle inventories for the building sector in Mexico.

8.2 Rooftop Eco-Greenhouse in mediterranean cities of Europe

The RTEG system has significant potential to be investigated. There are a number of avenues for research:

- An environmental, economic and social assessment of RTEG could take place, in order to demonstrate the advantages of RTEG in comparison with current systems of vegetable production.
- Design and evaluate an efficient connection and control for exchange of residual energy, water and CO_2 between the RTG and the building below.
- Develop a combined set of top-down and bottom-up indicators for measuring the sustainability performance of RTEG based on attributional LCA, Material and Energy Flow Analysis (MEFA) and consequential LCA.

- Test and evaluate the RTEG operation through pilot tests in different locations with varied climates.
- Develop technology to collect rain water and condensation, and more importantly, to treat the greywater in the building and process the drainage water from crop irrigation.
- Demonstrate that food produced in rooftop greenhouses connected to the building below can generate significant benefits, in terms of energy, water and CO2 flows within a common metabolism.
- Determine the technical, agriculture, legal, planning and economic criteria for facilitating the implementation of RTEG
- Analyse in detail each flow that is integrated into the system: water, energy, CO_2, food and materials.

Future research of energy analysis of this dissertation could be summarised as follows:

- Expand the number of simulations and energy flow analysis to all year.
- Design and assess different interconnection systems and equipment of heat recovered.
- Develop an air quality study for the viability of using heat fluxes from building to greenhouse.
- Extend the study to other building typologies, different construction systems and percentage of glazed or double skin facade.
- Assessment of the energy consumption that is required by the fans to retrieve and move heat to and from the building.
- Extend CFD analysis to all zones of the building and the greenhouse.
- Conduct studies in the summer period, in order to analyse the existence and potential of residual cold for interchange. This would provide an assessment of the annual balance of RTEG connected to buildings in a Mediterranean climate.
- Develop a parametric study to determine the optimal percentage of surface area of system components (building and greenhouse)
- Compare the importance of interconnection with other benefits of RTEG system, such as food logistics.

All these enhancement strategies aim to facilitate the sustainable development of urban systems, through researching eco-innovation in the field of improvement of social housing in developing countries and urban agriculture in compact cities.