icta Institut de Ciència i Tecnologia Ambientals·UAB

Universitat Autònoma de Barcelona

SosteniPrA

2009 Maria Christina Fragkou

Evaluation of urban sustainability through a metabolic perspective

Evaluation of urban sustainability through a metabolic perspective

Application in a Mediterranean coastal region

PhD thesis

Maria Christina Fragkou

Supervising directors:
Dr. Xavier Gabarrell i Durany
& Dra. M. Teresa Vicent i Huguet

SosteniPrA Research Group
Institut de Ciència I Tecnologia Ambientals (ICTA)
Universitat Autònoma de Barcelona

“Amb el suport del Departament d’Universitats, Recerca i Societat
de la Informació de la Generalitat de Catalunya”

Universitat
Autònoma
de Barcelona

Evaluation of urban sustainability through a metabolic perspective

Application in a Mediterranean coastal region

PhD thesis

“Amb el suport del Departament d’Universitats, Recerca i Societat de la Informació
de la Generalitat de Catalunya”

PhD Thesis

Maria Christina Fragkou

Supervising Directors: Dr. Xavier Gabarrell i Durany
& Dra. Teresa Vicent i Huguet

Date of deposit: April 2009

PhD Programme in Environmental Sciences

SosteniPrA Research Group
Institut de Ciència I Tecnologia Ambiental (ICTA)
Universitat Autónoma de Barcelona

“Sólo sé que nada sé”

Sócrates

“Yo no sabia que sabía todo lo que sabía”

Maitena

PREFACE

The scale of the system studied in this dissertation could classify this work as focused on local or regional sustainability, yet I find the term ‘urban’ more appropriate; although the case study is a region studied as a unit, it is an aggregation of municipalities and data in every case has been found on a municipal level. Moreover, comparisons were made between municipalities, finally assessing sustainability on a municipal level. What characterises these municipalities is that they are coastal, industrial, tourist, overpopulated and, what I consider of greatest importance, urban. This is the feature that most conditions their sustainability and I would most like to stress and focus on. Apart from the evident and well-discussed frenetic and dominant urbanisation of earth, my personal interest in the urban lies in the fact that it is my environment, being the ambient that surrounds me and the place where I live and act, where I look for optimum living conditions and quality of life.

Although there is a clear distinction in bibliography between the terms *urbanisation*, *cities* and *urban*, these terms are used here without distinction. The process of urbanisation can be considered as a process against both the rural and the cities. Bookchin (1995)[1] finds the terms *urbanisation* and *cities* not only variant, but antagonistic. When I refer to cities and the urban environment I refer to a common perception of the ‘city’ throughout its history, meaning dense population, organised social life, lack of contact with nature, massive scales of production and consumption.

A city is a complex system and an interdisciplinary approach is required when this is examined. The issue tackled here is only a fragment of urban studies; in the whole spectrum of the urban phenomenon I select, according to my discipline and educational background, to dwell on urban sustainability. Similarly, considering the complexity of this matter, this work is focused on its ecological or environmental aspect; social and economical sustainability dimensions are not thoroughly tackled. More concretely, a practical approach is followed, trying to measure urban sustainability by proposing two methodologies and

---

[1] See references of the Introduction Chapter

corresponding indicators, based on the concept of urban metabolism. These are applied on the area containing 27 coastal municipalities of the Barcelona metropolitan region, examined as a single system.

This thesis is organised as follows; it has an introductory chapter, focusing on the conceptual and methodological framework of this work, substantiating its focus. Unlike most theses there is no separate Methodology Chapter, as the intention of this work is the creation and proposal of new methodologies. The objectives set for this thesis are presented subsequently. Three main chapters follow each one as a complete work with its own methodology and findings. In the next Chapter, the key results presented so far are compared and discussed. The last Chapter summarises the main conclusions of this research.

The Introduction Chapter emphasises on the importance of the city for its dwellers and on its central role in sustainable development through a short review on the city's formation, evolution and associated environmental problems. A review of international initiatives on urban sustainability is presented, followed by the way it is tackled in related bibliography. The ecological metaphors used for studying cities, which form the conceptual basis of this thesis, are discussed and relevant methodologies are presented. Next, the use of indicators in measuring urban sustainability is analysed. Finally, Material Flow Accounting (MFA) is presented, being the groundwork of the methodologies proposed and applied in this dissertation. These methodologies are explained in detail in each of the following Chapters; within the Introduction the key concepts and guidelines of MFA that have been employed to be further expanded and complemented are presented. The concepts that were crucial for and stimulated and shaped this investigation were:

- the definition of the system's limits
- the accounting and categorisation of flows and
- the importance and position of water and waste flows in MFA

The Objectives Chapter presents the main goals of this work, its aspirations and contribution to the field of urban sustainability and the social metabolism studies.

Chapter Three presents a study on artificial water flow accounting. Water flows are of extreme importance in the metabolic performance of any socioeconomic system, yet they are excluded from typical MFA studies because of their magnitude; a methodological framework focused exclusively on piped water is proposed, that sets guidelines for conducting the artificial water balance accounting of a system, with MFA as a departure point. The suggested indicator draws on the results of the flow accounting and compares them to the renewable water the system receives in the form of rainwater.

The fourth Chapter is a study on the evaluation of municipal solid waste (MSW) management from a metabolic perspective. The importance of waste flows, as a system's outputs, is analysed and their role in MFA and metabolic studies is discussed. A methodology useful for the revision of MSW management plans that takes into account issues of social equity is proposed. The derived indicator reflects the quantitative and qualitative aspects of a MSW management plan's metabolism.

Chapter Five presents a preliminary study on the energetic profile of the studied system, complementing the findings of the two previously proposed indicators, in order to have a more comprehensive picture on the system's ecological sustainability through the assessment of its self-sufficiency in these three important issues.

In Chapter Six the two proposed methodologies are applied on each of the 27 municipalities that belong to the studied area, studying them as independent systems. The aim is to identify the urban characteristics that most influence the aspects of sustainability studied here, based on the performance of these municipalities with regards to the two suggested indicators.

The conclusions drawn in the final Chapter are not only related to the metabolic performance and the sustainability of the system, but on the idea of urban sustainability as a whole.

Acknowledgements

A mis profesores, Teresa Vicent y Xavier Gabarrell, por el trabajo y el esfuerzo común y sobre todo por ayudarme conseguir la beca que me permitió venir a Barcelona y completar este doctorado.

A mis compañeros de ecología industrial por compartir tiempo, espacio, opiniones, crisis y alegrías. Los amigos y amigas de economía ecológica por las conversaciones, por confundirme y encontrar difícil ubicarme en ambas ramas y darme su punto de vista que cambio el mío por bien. A todos y todas en el ICTA y a los torturadores de tortugas.

Maria y Eleni por ser mi familia aquí, y que nada sería igual sin ellas. A Darko por los paseos y la compañía. A Christos y Laura por la amistad y los consejos. A Ainhoa por ofrecerme refugio en los momentos más críticos. A Emilio por estar siempre y compartirlo todo.

A toda mi familia en Grecia.
Μαμά Άννα, μπαμπά Λάκη, Έφη, Γεράσιμε, σας ευχαριστώ για όλα!!!

Στη γιαγιά μου και τον παππού μου!

Abstract

Recognising the important role of cities in global sustainable development, this thesis focuses on two urban sustainability aspects through a metabolic perspective. Based on the Material Flow Accounting (MFA) methodological guidelines presented by Eurostat in 2001, two new methodologies are developed with the aim to assess water and Municipal Solid Waste (MSW) management. These are applied on the coastal municipalities of the Barcelona metropolitan region for a period of eight years, not only examining the system as a whole but assessing in addition each municipality separately.

The first methodology complements MFA and accounts for all artificial water flows of a system, referring to the flows consisting of piped and drained water; input and output related indirect flows are also considered, corresponding to water losses. The second methodology describes efficiently the flows of MSW, not only within a given system but between neighbouring systems as well, accounting of the MSW imports and exports and the secondary waste generated in the MSW treatment plants, following each residue until its final sink.

Accordingly, two indicators are suggested for the measurement of urban sustainability regarding these issues:

- A water indicator that assesses the potential of a system for sustainable water management, based on the system's demands in terms of water and the renewable water it receives in the form of rainwater.
- An indicator suitable for the revision of MSW management strategies, in line with basic waste management principles, that reflects the capacity of a system to manage the amount of MSW it accepts and the grade of sustainability of the treatment practices followed within the system, valuing as the best option the use of residues as prime materials.

The energetic profile of the studied system is also analysed, employing a more simplified methodology for the description of its energetic flows, for the importance of these flows in an urban area and with the aim of providing a more complete view on the case study's metabolism.

The studied system has a poor metabolic performance in terms of MSW management and energy, on both spatial levels. The results reveal low recycling and reuse rates of MSW and extended transport of these. A great degree of dependence on energy imports is demonstrated while the contribution of renewable sources is trivial. Concerning water, results on the case study's metabolism demonstrate the importance of these flows for the system and the significant magnitude of water losses. Encouraging indicator values indicate that the system could cover its needs exploiting rainfall; yet, the lack of required facilities in the majority of municipalities indicates the need for more daring water management decisions in this region suffering from severe droughts.

The proposed tools are proved to be able to detect drawbacks and changes in relevant infrastructure and policies. The two indicators finally, can serve as valuable tools for the planning or redesigning of urban areas, supporting decision-making on determining population size, density and urban growth, in combination with other indicators.

Resumen

Reconociendo la importancia de la urbe en el desarrollo sostenible global, esta tesis se enfoca en dos aspectos de la sostenibilidad urbana mediante una perspectiva metabólica. De acuerdo con las pautas metodológicas de la Análisis de Flujos de Materiales (Material Flow Accounting - MFA) presentadas por Eurostat en 2001, dos nuevas metodologías se desarrollan con el objetivo de evaluar la gestión de agua y de residuos Sólidos Urbanos (RSU). Ellas se aplican en los municipios litorales de la región metropolitana de Barcelona por un período de ocho años, no solamente examinando el sistema en su totalidad, sino también evaluando cada municipio por separado.

La primera metodología complementa MFA contabilizando todos los flujos artificiales de agua de un sistema, refiriendo a los flujos que consisten en el agua de tuberías y el agua drenada; se consideran también los flujos indirectos relacionados con las entradas y las salidas, correspondiendo a las pérdidas de agua. La segunda metodología describe eficientemente los flujos de RSU, no sólo dentro del sistema examinado sino entre sistemas vecinales también, contabilizando de las importaciones y exportaciones de RSU y los residuos secundarios generados en las plantas de tratamiento de RSU, siguiendo cada residuo sólido hasta su deposición final.

Consecutivamente, dos indicadores se proponen para la evaluación de la sostenibilidad urbana en relación con estos asuntos:

- Un indicador de sostenibilidad del uso del agua, basado en las demandas del sistema en términos del agua y del agua renovable que eso recibe en la forma de agua de lluvia.
- Un indicador adecuado para la revisión de las estrategias de la gestión de RSU, en línea con principios básicos de la gestión de residuos, que refleja la capacidad de un sistema para gestionar la cantidad de RSU que acepta y el grado del sostenibilidad de las prácticas del tratamiento dentro del sistema, valorando como la mejor opción el uso de residuos como materias primas.

El perfil energético del sistema estudiado se analiza también, empleando una metodología más simple para la descripción de sus flujos energéticos, por la importancia de estos flujos en un área urbana y con el objetivo de proporcionar una visión más completa sobre el metabolismo del caso de estudio.

Los resultados revelan un pobre funcionamiento metabólico para el sistema estudiado en términos de gestión de RSU, en ambos niveles espaciales, con bajos porcentajes de reciclaje y de reutilización. El sistema tiene un gran grado de dependencia de importaciones energéticas mientras la contribución de fuentes renovables es trivial. Con relación al agua, los resultados de su metabolismo demuestran la importancia de estos flujos para el sistema y la magnitud significativa de las pérdidas de agua. Los satisfactorios valores del indicador muestran que el sistema podría cubrir sus necesidades explotando el agua precipitada; sin embargo, la carencia de instalaciones relevantes en la mayoría de los municipios indica la necesidad de decisiones más atrevidas sobre la administración del agua en esta región que sufre de sequías severas.

Las herramientas propuestas en esta tesis se demuestran capaces de detectar las problemáticas y los cambios en relación con relevante infraestructura y políticas. Los dos indicadores finalmente, pueden servir como herramientas valiosas para el planeamiento o la remodelación de áreas urbanas, contribuyendo a/apoyando la toma de decisiones para la determinación del tamaño de la población, densidad y crecimiento urbano, conjuntamente con otros indicadores.

Table of Contents

List of Figures

List of Tables

List of mostly used acronyms

EEA	European Environmental Agency
EMSHTR	Entitat Metropolitana de Serveis Hidràulics i Tractament de Residus
EU	European Union
GDP	Gross Domestic Product
IDESCAT	Institut d'Estadística de Catalunya
MFA	Material Flow Analysis and Accounting
MSW	Municipal Solid Waste
OECD	Organisation for Economic Co-operation and Development
PEC	Pla Energètic de Catalunya
PEL	Pla Estratègic Litoral de Barcelona
PWTP	Potable Water Treatment Plant
UN	United Nations
UNCSD	United Nations Commission for Sustainable Development
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

1.1. On urban sustainability

Cities [...] are many things to many people.

Walsh et al., 2006

A city is an extremely complex system. It forms and is formed by social, economical and environmental conditions, relations and processes. Harvey (2008) identifies the question of *what kind of city we want* with that of *what people we want to be*, embracing the issues of social relations, relation to nature, style of daily life, appropriate technologies at our service and our aesthetic values. Bookchin (1995), in order to define (and recover the original meaning of) 'city', first gives his interpretations of 'politics', 'citizenship' and 'democracy', passing from 'power' and the 'state'. The structure of a city does not only define quality of life, but social equity, the type of citizenship for its dwellers (Mega, 2000; Ditchev, 2005), the relation with public spaces and state control (Gandy, 2004; K'Akumu, 2007).

The conventional, and maybe dominant, view on city's formation links this to technological conditions; it names the beginning of food cultivation and agricultural production that resulted in the concentration of people in the most fertile lands, as a reference starting point in city's history (Bairoch, 1988; Bookchin, 1995). Others interpret its origins and further evolution from an energetic point of view (e.g. Huang and Chen, 2005) or see it as a surplus product and a class phenomenon (Harvey, 2008).

Lefebvre (1970) emphasises three important benchmarks in city's history: the *political city*, which closely followed organised social life, agriculture and the village, where merchants were still outsiders and only visiting cities. With the gradual centralisation of the marketplace the *merchant city* aroused in Western Europe around the 14th Century and succeeded its political form; commercial exchange became then an urban function[2]. It is

---

[2] Bookchin (1995) notes on this, that capitalism and its effects, even in these earliest forms, slowly penetrated from its sphere (market places) into domestic life (neighbourhoods or families) and changed the cities' functions, turning them, "*from civilised forms of humane consociation into anonymous market places, developing a growth-oriented economy in which production and consumption became ends in themselves*"

with this transition that the shift from the countryside's importance over the urban took place. Cities no longer were 'urban islands' in the middle of rural landscapes; nature is now the environment and at the service of the city. This was followed up with the appearance of industrial capital and, consequently, the *industrial city*. The industry penetrated the city gradually, "*…in search for capital [...], markets and an abundant supply of low-cost labour…*" (Lefebvre, 1970).

Lefebvre continues his analysis on the urban predicting a new stage of total urbanisation, being this the *urban revolution* that is following the industrial one. This view has been expressed by others; Doxiadis for example predicted with *ekistics*[3], based on urbanisation and population growth trends, that all cities would fuse in a single continuous worldwide city (*ecumenopolis*) (Doxiadis, 1970). Actually, frenetic urbanisation is taking place globally - not only in the form of urban sprawl, as in the United States of America and Europe, but through the construction of new cities, with China as a striking example. This vast urban expansion has, naturally, brought an increase in the number of urban dwellers worldwide. Urban quality of life now affects directly more than half of the planet's population[4].

There are numerous interpretations on the evolution of cities and equivalent terms to characterise each phase of this process, until they reach the form they have today. In every case though, their origin and further development is viewed as inherently linked to the dominant modes of production and energy sources of each era, hence to market relations and technological progress. These parameters are essentially associated with environmental problems, such as pollution and depletion of non-renewable natural resources. Hence, cities have directly, or not, been a central factor in environmental degradation and a key factor in sustainable development, long before the concept was invented.

---

[3] An interdisciplinary science on the study of all human settlements (with a view to geography and ecology - the physical environment- , and human psychology and anthropology, and cultural, political, and occasionally aesthetics) proposed by Doxiadis (1970), but not accepted by academic circles.

[4] According to the UN (2008), the percentage of world population living in areas classified as urban was 48.6% in 2005, expected to surpass 50% in 2010 and reach 69.6% in 2050.

1.1.1. *The importance of cities in global sustainable development and related initiatives*

Environmental concerns have been transformed following the changes in the relation between city and environment, the urban and the rural over history. The major environmental battles of the past were fought outside cities and the original focus of sustainability concerns was on the issues of wilderness preservation, renewable resource extraction and natural management. In the second half of the 20th century they included and centred on the issues of pollution, non-renewable resources depletion and population growth (Robinson, 2004), that were originally associated with urban centres. The need to include cities in the global sustainability agenda is now universally recognised by environmentalists, governments and industry (Newman, 1999).

The interest of modern cities, in terms of sustainability, lies in the urban processes' intensive natural resources use. Urban centres are characterised by their routine use of energy as a driving force for power production, transportation of goods, construction of buildings and infrastructure, as well as for domestic comfort. Moreover, a large amount of materials is processed, consumed or accumulated there and resides while in use. Their vast energy and material demands do not allow cities to be self-regulating without maintaining stable links with the hinterland from which they draw energy, food and materials and into which they release their wastes. In comparison with other ecosystems, urban systems are relatively immature due to their rapid growth and inefficient use of resources (Huang and Hsu, 2003). Based on these remarks, Huang and Hsu (2003) relate the major environmental problems and associated social costs of an urban ecosystem to the rapid increase of resource inputs for urban consumption.

Nevertheless, environmental problems arousing from urban activities are not only associated with urban production and consumption patterns, but with a city's infrastructure, planning, buildings and transport systems (Satterthwaite, 1997); old pipe networks and disaggregation of the cities according to activities (residence, work, leisure, commerce zones) for example, are related to poor efficiency in energy and water use and great dependence on automobile mobility.

What is most interesting is that the consequences of these environmental problems are not restricted on having an impact on a city's immediate and surrounding environment, but have regional and global effects. Localised problems are mainly health related and include poor local environmental quality, inadequate household water and sanitation, indoor air pollution and excessive crowding (IIED, 2001), affecting directly the quality of life of a city's inhabitants. Regional problems that surpass urban limits are air pollution, inadequate waste management, pollution of bodies of water and coastal areas and the loss of green areas. These effects have as a consequence more large-scale problems like ecological disruption, resource depletion and emissions of greenhouse gases, which still affect urban dwellers.

It is on these grounds that large urban centres have gained importance in the field of sustainable development, not only as an object of local studies but as a key component for global sustainability. They may be the places where pollution has the potential to cause the most harm, but it is also where opportunities for recycling and reuse are the most vivid and according to Harper and Graedel (2004) where the concept of sustainability must in the long term succeed or fail.

The recognition of the urban environment's importance by all related actors has lead to a series of global summits and urban sustainable development initiatives in the course of the last years. Although the first time that the international community was brought together to discuss matters related to global environment was in the Stockholm Conference on Human Environment, in 1972, the urban environment was included and prioritised much later as a United Nations (UN) initiative; Habitat 1976 officially launched the worldwide dialogue on cities (Holden et al., 2008). In 1992 the United Nations Conference on Environment and Development (UNCED), held in Rio, resulted in Agenda 21, that set guiding principles on urban sustainability; this included strategies for sustainable energy and transport, shelter for all, conservation of historical and cultural heritage, combating poverty, community empowerment, promoting local labour and responsible fiscal policies (Holden et al., 2008; UN Habitat, 2002). However, it was only in 1996, at the UN Habitat II summit that took place in Istanbul, when the issues related to cities' living environment were clearly brought to the core of the global environmental agenda. Moreover, this was the first UN conference where city representatives, and not solely heads of states, were invited to deal with the problems of an urbanising world. The outcome was the Habitat Agenda, a programme with similar lines with Agenda 21, calling for adequate shelter and sustainable human settlements for all, directed at nation states, but with a designated role for cities and local authorities (UN Habitat, 1996). Six years later, in the Johannesburg World Summit on Sustainable Development, there was special focus on local and urban environments in addressing global sustainability, as an aftermath of Habitat II. The two previous documents on local scale were brought to the fore and the formulation of local development agendas, the Local Agenda 21, was initiated. Furthermore, a new action agenda resulted, WEHAB, for water, energy, health, agriculture and biodiversity.

Another relevant initiative is the World Urban Forum (WUF), a biannual global forum on cities, that started in 2002 in Nairobi, Kenya and its last version took place in 2008 in Nanjing, China. The WUF was established by the United Nations to examine rapid urbanisation and its impact on communities, cities, economies and policies, through the promotion of open dialogue among a wide range of partners (Holden et al., 2008). Other global projects that have included the urban issue in their agenda include the World Social Forum held in Porto Alegre, Brazil, since 2001, organised and attended by world alternative social movements, and the United Nations Millennium declaration (UN General Assembly, 2000) setting eight Millennium Development Goals (MDG). These aim to promote and ensure sustainability and improve the lives of slum dwellers in modern cities, between others.

Numerous projects and initiatives related to sustainability on the local or regional level have appeared since; the Organisation for Economic and Cultural Development, the European Commission and even the World Bank now have sustainable cities programmes (Newman, 1999). The UN Habitat has a series of international programmes related to health and environmental quality in cities, such as the Sustainable Cities Programme, Safer Cities Programme, Water and Sanitation Programme, Rapid Urban Sector Profiling for Sustainability and the Global Urban Observatory[5]. At the European level, the Sustainable Cities and Towns Project helped formulate a set of guidelines for sustainable local development and their main principles were adopted by a large number of cities signing a charter during a meeting held in Aalborg, Denmark, in 1994 (European Commission, 1996; Mega, 2000). Similar programmes were put in place by local authorities in North America

---

[5] For a review see UN Habitat (2008)

in pursuit of improving their environment and regulate resources use and waste generation (UNCHS, 1996). Long-term programmes on combating urban environmental problems are also applied in Latin America (Satterthwaite, 1997).

1.1.2. Defining urban sustainability

The term urban sustainability and the notion of sustainable cities are based on two basic concepts: sustainability and sustainable development. In order to define the terms under question and analyse the application of sustainable development in the urban context, this should be defined first. The concept of sustainability emerged from the need for reducing environmental pressures stemming from human activities. Worldwide discourse on sustainability was launched with two documents: the Club of Rome's Limits to Growth (Meadows et al., 1972) and the Brundtland Commission's Our Common Future (World Commission on Environment and Development, 1987). The Club of Rome warned about reaching the limits to growth on the planet, based on the growth trends in world population, industrialisation, pollution, food production and resource depletion, and called for the establishment of "*…a condition of ecological and economic stability that is sustainable far into the future…*" However, it was not taken into consideration in any major governance and policy plans, and the only economist to publicly accept it was Herman Daly (Holden et al., 2008). It was Brundtland's report that achieved that and initiated a dialogue from the international down to the local scale that continues to this day and lead to global summits on the topic.

Regardless of the immense literature on the subject and the extensive use of the term, in the majority of related texts the definition of sustainable development is either taken for granted or described very loosely (Yanarella and Levine, 1992). The origin of the term "sustainable development" is in an International Conservation Union's (IUCN) report, presented in 1980, responding to the Limits to Growth study (Atkinson, 2007). It was with the Brundtland Report, in 1987, that was popularised and its most widespread definition was given, described as *''...development that meets the needs of the present without compromising the ability of future generations to meet their own needs...''* (World Commission on Environment and Development, 1987), becoming a milestone of global environmental discussion. Following that, the Rio Declaration, emerging from the UN Conference on

Environment and Development (Earth Summit, 1992) in Rio de Janeiro in 1992, identified the social, economic and ecological dimensions of sustainable development.

Whilst well established, applied and studied, the concept of sustainable development is still considered to be quite vague and can be interpreted in various ways (Huesemann, 2004). Considerations on the opacity of the concept include the lack of specification of neither the mentioned "needs", nor the time frame for their satisfaction, or a particular role for the environment (Bartelmus, 2003). Given these difficulties, amongst others, debates have erupted between those who prefer the three pillars approach (emphasising the social, ecological and economic dimensions of sustainable development), or a more dualistic typology (emphasising the relationship between humanity and nature), reflecting the political and philosophical position of those proposing the definition more than any unambiguous scientific view (Robinson, 2004). A similar division has occurred between those that support 'weak sustainability' and those opting for 'strong sustainability'. The difference between these two perceptions of sustainability lies in the idea of natural capital compensation for manufactured capital. While weak sustainability supports that manufactured capital can substitute natural capital, strong sustainability emphasises on maintaining biophysical capital intact and recognises that manufactured and natural capital "*…are really not substitutes but complements in most production functions…*" (Daly, 1990, in Rees and Wackernagel, 1996)[6].

For the interpretation of sustainable development it is useful to examine each of its components separately, representing its physical and social dimensions respectively. The word "sustainable" states that "*...the environment should continue its normal natural cyclic functions without disruption or overburdening...*" (K'Akumu, 2007). This implies the existence of limits in the use of natural resources, either imposed by nature, society or the functioning of the planet (Walsh et al., 2006). "Development" describes "*…a social change process for fulfilling human needs, advancing social equity, expanding organisational effectiveness, and building capacity towards sustainability…*" (Roseland, 2000). Human needs refer to material needs, that include the physical necessities of life, and nonmaterial needs related to quality of life issues (Holden et al., 2008). The issue of equity is central in

---

[6] In a more extended analysis on the subject, Ayres et al. (2001) distinguish two different assumptions of weak sustainability on the subject; the first one assumes the substitutability between natural, human and manufactured capital. The second assumption claims that economic well-being supersedes all other concerns.

the sustainable development discourse and includes both current (intragenerational) and future (intergenerational) equity. Current equity has a social sense as it refers basically to the relations between the world's rich and poor, both between and within countries. Future equity on the other hand is equity in a physical sense, implying the maintenance of ecological integrity (Holden et al., 2008).

Just like sustainable development itself, although the terms 'sustainable cities' and 'sustainable human settlements' have been much discussed, and despite being a main theme for research, policy initiatives and programmes, there was no clear and widely accepted definition as to what they mean even after Habitat II (Satterthwaite, 1997). The majority of definitions encountered in bibliography focuses on urban sustainability's environmental, economic and social aspects and stresses the importance of humanity-nature interactions. Yet, it is the physical dimension that dominates the discourse in most definitions, in terms of natural resources conservation and their efficient use.

After completing her bibliographical research, Mega (2000) concludes that the common elements that form the pillars of urban sustainability are agreed to be "*…healthy environment, social cohesion, and economic efficiency, in harmonious co-evolution and with processes of democratic participation…*" . Under a metabolic, and physical, perspective, Girardet (1990), cited in Huang et al. (1998), proposes that the priority of urban sustainability should be "*…re-designing urban metabolism by `closing the circle' to make it truly compatible with the process of the living world…*" From the same perspective, Newman (1999) uses the metabolism concept only to extend it and include aspects of human livability, meaning the requirement for social amenity and health, and gives a more comprehensive description of urban sustainability. Approaching the city as an ecosystem he identifies increased inputs and outputs as the main urban environmental problems. He defines the goal of sustainability in a city as "*…the reduction of the city's use of natural resources and production of wastes while simultaneously improving its livability, so that it can better fit within the capacities of the local, regional and global ecosystems…*" (Newman, 1999).

Myllyla and Kuvaja (2005) define and discuss the concepts of 'eco-city', 'ecological city' and 'sustainable city'. They attribute the values of postmodern societies to the eco-city and argue that it can only be relevant in the North, as the concept is built on societal structures and relations only existent there (i.e. democracy, strong civil participation, etc). Following the ecological city supposition, environmental problems associated to cities are recognised but their resolution or alleviation is assumed to be feasible through technocratic and industrial solutions. The authors understand the concept of ecological city as the description of "*…processes which will ensure that a city can carry out its basic functions in an ecologically sensitive manner without risking the possibilities of the future generations to take care of their needs…*" This commitment links the ecological city to the concept of sustainable development (Myllyla and Kuvaja, 2005). Finally, a sustainable city is perceived as an urban entity that produces ecologically sustainable processes without endangering national, regional or global natural resources and ecosystems (Myllyla and Kuvaja, 2005).

Van Dijk and Mingshun (2005) finally, distinguish five urban sub-systems; namely the social, economic, environmental, institutional and urban hinterland. They argue that urban sustainability requires that a city takes all these five sub-systems into account, minimises its negative impact on urban environment and maintains the resources consumption and emissions within the resources regeneration ability and environmental load-capacity.

Local or urban approaches on sustainable development facilitate the creation of policies and plans of action that are sensitive to regional differences. The need for a local focus is even imperative when we consider the varying conditions between the cities of the North and the South. Myllyla and Kuvaja (2005) point out that in the North, sustainability is achieved through technocratic means and with certain societal conditions (democratic institutions, political transparency, etc) taken for granted. Environmental problems are recognised and it is believed that they can be solved through ecological and technocratic innovations; urban sustainability is then based on technological solutions and the purchasing power of the urban dwellers (the ability to buy organic food or live in the suburbs for example). In the South urban sustainability is expressed with the creation of 'ecological islets' that come as an opposition to the polluted and low quality of life slums. These are naturally inhabited by people that have the resources to invest in environmental services and consequently in their well-being. These cities then demonstrate a partial development that is limited to exclusive areas, generating conditions of exclusion and inequality (Myllyla and Kuvaja, 2005). The authors' conclusion is that an 'eco-social' morality should exist between city dwellers, referring to "*...a principle or practise of adjusting values or way of life according to the* *principles of sustainable development…*" (Järvelä and Kuvaja-Puumalainen, 1998). Holden et al. (2008) also stress the need for different approaches to the transition to sustainable development, depending on the class and development context.

Whilst urban sustainability stems from sustainable development, and in analogy with the characteristics of the latter, we should expect it to guarantee the same quality of life for all urban dwellers in the same city as well as between rich and poor cities, or cities in the North and the South, regardless a city's size and economic development, the race, age or the social status of its inhabitants. The condition of inter-city equality discards then the creation of selected ecological neighbourhoods while the remaining city is lacking basic quality of life standards. In the same line, the physical dimension of urban sustainability demands sustainable function of the cities, i.e. cyclic and efficient resources consumption, renewable energy sources and minimisation of pollution and waste generation, which would result to minimal impact on the environment's natural cycles.

It is important to underscore that a sustainable city should not, in any case, be identified with an environmentally pleasant city. Although there is a concern of local authorities on the physical characteristics of cities (Huang and Hsu, 2003), expressed with its 'greening' and obsessive cleaning of public spaces, these attempts have little to do with sustainability. These actions normally result in the reduction of green spaces to decorative urban elements and the restriction of civil rights in public spaces[7]. The necessary changes for the achievement of sustainable development go much deeper than the mere existence of parks in a city, something that, as Huang and Shu (2003) comment, is understood by environmental planners and resource managers but is not inherent to conventional economists and urban planners.

Regardless of the plethora of bibliography, various initiatives and even 'successful' practical examples of sustainable development and cities, there are many doubts on the feasibility of a development that can indeed be sustainable; an economic development that will be sustainable in a social, environmental and social manner. This dialogue started with the club of Rome's Limits to Growth (Meadows et al., 1972) and carries on until nowadays

---

[7] A typical example is the 'Ordenança de Civisme' in Barcelona (Ajuntament de Barcelona, 2006)

with the 'degrowth' term[8] (Latouche, 2004; Fournier, 2008). These oppositions on one hand derive from the vagueness of the term and the difficulty to set concrete goals and the practical infeasibility to achieve this on the other. As far as the 'sustainable development' definition is concerned, Tainter (2006), for example, wonders (i) what is that we have to sustain, (ii) for whom, (iii) for how long and (iv) at what cost. He claims that sustainability is essentially a function of problem solving (and not a passive consequence of consuming less) and this requires energy. Consequently, in the effort to achieve sustainability we reach the contradiction of needing to increase resource use. Kastoriadis (1984), setting the same questions as Tainter, argued that development is a concept to which western societies have given a positive meaning and refers to the ability of a society (or an economic system) to increase its economy infinitely. He also stressed the prevalence of the idea that the infinite increase of production and productive forces is indeed the central objective of human beings. He claimed finally, that 'development' (*ανάπτυξις)* entails (the definition of) natural limits; if development is infinite it is also incomplete and vague. It therefore needs to have goals; a reference state; a final state as nature has for every being.

On another basis, Huesemann (2001; 2003) uses the second law of thermodynamics to demonstrate that industrial production and the modern way of life cannot continue without burdening the environment regardless of whichever 'green' or 'sustainable' solutions. He recognises that "*...even if it were possible to design 'zero-emission' industrial processes by completely closing the materials cycle...*", when we try to cover our energetic needs with renewable sources the environmental disturbances will not be negligible. He points out that "*...the capture and conversion of solar energy will still have significant negative environmental impacts, especially if used on a large scale...*", as this is required to maintain the complexity of organisms, ecosystems, biodiversity, and the carbon and nitrogen cycles.

These doubts are certainly expanded to the concept of sustainable cities; not only for challenging the idea of sustainable development in general, but for the cities' special features as well. Herman Daly (1991, in Alberti, 1996) suggests three criteria to assess sustainability:

- Rates of use of renewable resources do not exceed replacement rates.

---

[8] Following Latouche's (2004) explanation of what degrowth is, the word *term* instead *of concept* is used to define it

- Rates of use of non-renewable resources do not exceed rates of development of renewable substitutes.
- Rates of pollution emissions do not exceed the assimilative capacity of the environment.

When we apply these conditions to cities, the sustainable demand on resources and waste generation is required by its inhabitants. Nevertheless, even if a city achieves not to burden its local environment in the long term, it is impossible not to extend the area of its sources and sinks beyond its hinterland, causing environmental problems elsewhere. Furthermore, cities are demonstrably disruptive of the earth's life-support system with linear characteristics in their use of materials, low recycling rates, no recycling of nutrients and no reuse of raw materials (Girardet, 1990). What more, their great energetic needs are based on depleting fossil fuels that are burned and released in the atmosphere, with small renewable energy contribution.

1.1.3. *Ecological metaphors of the city and derived methods used for the measurement of urban sustainability*

> *The city is like a body and has its own discourses on arteries on the horizontal element, in the case of the vertical elements there are the walls, the towers. [...] When you define a city you are defining a body.*
>
> Miquel Navarro, 2003
> *Your world, your city* Project
> Guggenheim Museum of Bilbao,
> November 2008

Ecological metaphors have been used in sustainability studies after the observation of similarities between ecosystems and socioeconomic systems, giving these organic qualities. In the context of industrial ecology, researchers view modern industrial economies as living organisms that ‘ingest’ raw materials, which are ‘metabolised’ to produce goods and services, and they ‘excrete’ wastes in the form of discarded materials and pollution (Matthews et al., 2000). Similarly, the industrial system is considered analogue to the natural one; the difference in this analogy lies in the linearity of industrial systems' material flows, unlike nature's closed loops material circles.

Similar analogies are used for studying urban sustainability; cities have both been perceived as ecological systems and living organisms. The urban is now perceived as a new type of ecosystem that differs completely from the 'natural' ones though, with regards to resource and energy use (Sukopp, 1998). Since one of the most profound problems cities are up against, in terms of sustainability, lies in the linearity of their material flows, there is a need for understanding how they function in terms of resources consumption. Energy demands, use of water resources, population increase, land use and food production are interrelated problems that have essentially to do with resources management. It is also necessary for urban and global sustainability to know the quantities of resources that are available, both in total quantity and on a spatial basis, to understand how much is needed by humans and other organisms and evaluate ways to make the rate of use match availability more closely (Walsh et al., 2006). The use of the metabolism concept helps spot unsustainable practices in cities' use of natural resources. The discussion on issues of urban metabolism started in the 1960s focusing on water use and water and air pollution of cities (Wolman, 1965). According to Fischer-Kowalski (1997), the roots of 'societal metabolism' go back to the 1860's, when the concept of 'metabolism' was almost simultaneously born in both biology and social theory. Although the term has been used in social and anthropological sciences since that time, also recognising the 'metabolism between man and nature' (Marx and Engels, 1867, in Fischer-Kowalski, 1997), it was not used in the framework of environmental problems until much later[9].

In addition, the view of the city as a complex ecosystem helps describe and better understand the complex interrelations between its elements and substructures, and its relation with the natural environment.

> *"The concept of urban ecosystems is helpful to investigate the relationships between urban systems and the environment [...]* and *ecologists have described the city as an eterotrophic ecosystem, highly dependent on large*

---

[9] See Chapter Three for a detailed literature review on the concept of social metabolism and studies on urban metabolism

> *inputs of energy and materials and a vast capacity to absorb emissions and waste*"
>
> (Alberti, 1996).

Urban systems are open and interactive, in a constant interchange of energy and materials with the natural environment. As such, they are not only connected to systems in the immediate hinterland, but have connections, in an ecological sense, with regions at national and global levels (Sukopp, 1998). Tjallingii (1993, in Newman, 1999) goes beyond the concept of metaphor and mentions that:

> "*The city is (now) conceived as a dynamic and complex ecosystem. This is not a metaphor, but a concept of a real city. The social, economic and cultural systems cannot escape the rules of abiotic and biotic nature. Guidelines for action will have to be geared to these rules*"

There are, however, views opposite to these metaphors of the cities (and socio-economic systems as a consequence). Alberti (1996) recognises the limitations of the urban ecosystem approach as it cannot integrate into one analytical framework the biological and socio-economic concepts. Newman (1999), as mentioned earlier, recognised the same problem and added the omitted human basis, along with the physical and biological ones, to the metabolism model. He accurately notes that "*...the metabolism approach to cities is a purely biological view, but cities are much more than a mechanism for processing resources and producing wastes, they are about creating human opportunity...*"

K'Akumu (2007) finally, is very critical with the 'living organism' metaphor of cities; he considers this incomplete because the logic of death "*...is always ignored or avoided...*" As all organisms "*...have a known life cycle of life, death and decay...*" he supports that the same logic should be applied to cities instead of trying to perpetually sustain them. The infinite growth and maintenance of these linear systems that interfere with the natural cycles of carbon and water cannot be ecologically sustainable. He concludes that "*...the city as an organism [...] should die and decompose to release the nutrients for use by other living organisms, whether fellow cities or plants and animals...*"

Regardless their limitations, the usefulness of these ecological conceptualisations of the city are broadly accepted and various methodologies have been developed based on these concepts. Urban carrying capacity, ecological footprint and Material Flow Accounting (MFA) are used for the assessment of urban sustainability and the cities' impact on the ecosphere.

In the field of ecology, carrying capacity is defined as the maximum number of individuals that can be supported in an environment without the area experiencing decreases in the ability to support future generations within its limits (Chung, 1988). The application of the concept to the management of urban growth was developed in the 1970's and applied to water resources and urban planning (Mar, 1981). The concept of carrying capacity derives from the recognition that the natural environment has a limit for human activities which when exceeded can cause serious and irreversible damage to the natural environment (Mar, 1981). In these lines, Oh et al. (2005) define urban carrying capacity as the level of human activities, population growth, land use and physical development, which can be sustained by the urban environment without causing serious degradation and irreversible damage. Broadening the ecological view, they also distinguish the urban facilities, public perception, and institutional aspects of urban carrying capacity. Suggested factors affecting ecological (or environmental) carrying capacity include soil, slope, vegetation, wetlands, scenic resources, natural hazards, air and water quality, and energy availability (Godschalk and Axler, 1977), while constraints of environmentally sensitive areas, availability of water resources and capacities of water related infrastructures, are relevant in the urban context (Huang and Chen, 2005).

Nevertheless, the relevance of carrying capacity to human populations is quite controversial (Mar, 1981; Munda, 2006; Yanarella and Levine, 1992). First, there is no standard per capita resource consumption by humans, as this factor is regulated by cultural habits, social class, etc. Technology is another parameter that does not exist in nature but is crucial in human societies. Trade is another limiting factor that makes the application of the carrying capacity to humans a difficult task, as the territory that each group occupies is hard to identify. Mar (1981) utterly rejects the idea of carrying capacity with the 'dead-is-dead' strategy, proposing the concentration of people in areas that have already surpassed their carrying capacity limits. He contends that higher densities do not necessarily cause further degradation of environmental quality and that once a threshold is violated, "*…it is better to* *continue to concentrate activity in the 'dead' area, than to encourage development on other areas that have not been forced across similar thresholds…*" He substantiates his argument on the theory that claims that density population reduces the environmental burden per capita, a position held by many contemporary urban planners.

The ecological footprint index overcomes the objections to the carrying capacity concept with a reverse logic; instead of asking what population a certain area can support, the question now is how much land is required per person. This refers to the necessary land, on a continuous basis, for the provision of water, energy and materials and the deposition and absorption of waste generated. Formally defined, the ecological footprint (EF) is "…*the total area of productive land and water required continuously to produce all the resources consumed and to assimilate all the wastes produced, by a defined population, wherever on Earth that land is located...*" (Rees, 1992). The concept was applied in the urban environment for the calculation of "*...how large a pasture is necessary to support that city indefinitely- to produce all its 'feed' and to assimilate all its wastes sustainably...*" (Rees and Wackernagel, 1996).

Material Flow Accounting and analysis (MFA) is one of the central set of tools and methodologies that industrial ecology developed and has been using, along with life-cycle assessment, substance flow analysis and other material and energy flow models, all deriving from metabolic aspects of the analogy to natural systems (Ehrenfeld, 2004). MFA can provide a framework for analyzing the urbanisation process and the way cities are transforming the earth's ecosystems as a consequence of human activities (Huang and Hsu, 2003). MFA forms the methodological basis of this thesis and is discussed in further detail in Section 1.2.

1.1.4. Sustainability indicators in the service of urban sustainability

...in a few words, what counts [...] is whatever can be counted.

Kastoriadis, 1984

The abovementioned methodologies for the assessment of urban sustainability are completed with the extraction of corresponding indicators. Indicators have been widely used in the scientific field and in many public policy areas as feedback mechanisms for decision making. They accurately depict the situation and the processes of real world and their value goes beyond their numerical value itself (Huang et al., 1998). The use of indicators is also crucial in the effort to assess sustainable development and monitor the progress towards sustainability.

Following the same line with the attitude towards environmental problems, sustainability indicators were initially focused on environmental performance and then included social, economic and institutional perspectives. Sustainability indicators differ from classical environmental indicators as "*...they do not simply reflect environmental conditions or pressures on the environment, but indicate interactive characters between socio-economic and ecological systems...*" (Opschoor and Reijnders, 1991, in Huang et al., 1998). Sustainability indicators are used for describing a given system in a certain moment or to be used with reference values to measure a system's evolution towards a reference or ideal situation. Many argue that sustainable development, being a process and not a state, must be quantified and therefore measured. Walsh et al. (2006) state that urban sustainability only has sense when numerical goals are proposed; they base this on the fact that:

> "*Quantification encourages discussion of the correctness of the quantification itself and of urban sustainability more generally, and because a transition to sustainability cannot be designed and implemented until numerical goals are agreed upon and targets and timescales established*"

The role of indicators, in combination with public participation, are crucial for fostering the interaction among experts and the local community and help influence lifestyles and economic activities (Diamantini and Zannon, 2000). Alberti (1996) distinguishes two dimensions of urban sustainability: the *quality* of urban systems and their *impact* on both the local and global resource framework. She argues that, from an ecological perspective, "*...the interaction between urban systems and the environment can be described by indicators of sources, sinks, ecological support systems, and human health and welfare...*" (Alberti, 1996).

Understanding the importance of sustainability indicators has led to numerous initiatives by international organisations that have proposed such indicators[10]. The United Nations Centre for Human Settlements and the World Bank (UNCHS and the World Bank, 1995), in pursuit of a 'well-functioning city', have developed a broad set of indicators on seven categories[11]. The OECD (1993; 1994) has worked extensively on the proposal of urban indicators to help national policymakers to monitor urban policies. It developed the Pressure-State-Response (PSR) framework, distinguishing indicators in these three corresponding categories. The European Environment Agency (EEA) used OECD's PSR approach in order to report on the state of Europe's environment and a core set of indicators on ten sectors is suggested (EEA, 1995)[12]. There are also 'urban environment' related indicators that touch upon issues of municipal waste, land use, water quality and consumption, and transport. The World Health Organisation has also developed specific urban health indicators as part of its Healthy City Project (WHO, 1993), improving the Health for All strategy at the local level.

The UN Commission for Sustainable Development (UNCSD, 1996), based on Agenda's 21 definition of sustainable development, has proposed sustainability indicators for its monitoring:

> "*Chapter 40 of Agenda 21 calls on countries and the international community to develop indicators of sustainable development [...], needed to increase focus on sustainable development and assist decision-makers at all levels to adopt sound national sustainable development policies*"

---

[10] For an extensive review see Alberti (1996)

[11] Namely (1) socioeconomic development, (2) infrastructure, (3) transport, (4) environmental management, (5) local government, (6) affordable and adequate housing, and (7) housing provision.

[12] That is Agriculture, Air pollution, Biodiversity, Climate change, Energy, Fisheries, Terrestrial, Transport, Waste and Water

The final UNCSD indicator set was proposed in 2006 and is based on the previous two editions (UN, 1996; 2001). The revised edition contains 96 indicators, including a subset of 50 core indicators. Apart from international organisations, many local initiatives have taken place, where cities in Europe and North America have developed environmental performance indicators to help them report on the state of the environment (McLaren, 1996).

Taking for granted the complexity of the sustainability issue, the selection of adequate, relevant and robust indicators is quite challenging. The sets of criteria for indicators selection are almost as numerous as the indicators sets. The UN sustainable indicators programme (UN, 2007) recommended that indicators for sustainable development must be:

- primarily national in scope;
- relevant to assessing sustainable development progress;
- limited in number, but remaining open-ended and adaptable to future needs;
- broad in coverage of Agenda 21 and all aspects of sustainable development;
- understandable, clear and unambiguous; science, health, economics and many public policy areas as feedback mechanisms to decision making
- conceptually sound;
- representative of an international consensus to the extent possible;
- within the capabilities of national governments to develop;
- dependent on cost effective data of known quality.

With regards to sustainability indicators in the urban environment, Alberti (1996) proposes that a useful set of indicators should be able to tell us both (i) whether urban quality and performance in cities is improving or deteriorating in relation to certain sustainability criteria or desirable targets and (ii) how these trends in urban quality and performance are linked to trends in spatial structures, urban organisation, and lifestyles.

Although one of the assets of using indicators is the simplification of complex phenomena (EEA, 1995), critiques on the use of indicators for the measurement of urban sustainability basically focus on their simplistic view. Atkinson (2007) claims that indicators "*...had the effect of fragmenting and dispersing the focus on what might be the main issues and generally became a technical exercise that attempted to assess the state of the environment—and hence economy and society...*" He continues by arguing that the problem lies in the absence of a reference state or the recognition of the practical steps required to lead us to a direction that would be sustainable. Commenting on intercity comparisons using indicators, Satterthwaite (1997) notes that "*...there is a danger that this reduces intercity comparisons on environmental performance to those indicators that are easily measured...*" Finally, overcoming these limitations and in an attempt to measure degrowth by combining all aspects of sustainable development, Du Crest (2008) proposes three comprehensive indicators for the three relationships: (i) Social/economic: Time spent on non-commercial activities/time spent for paid work, (ii) Social/environment: Space occupied for human needs/space dedicated to other species and (iii) Environment/economic: Ecological footprint.

1.2. Presentation of the methodological framework – Material Flow Accounting and Analysis and derived indicators

The foundations of MFA were set on the concepts of material and energy balancing presented by Ayres and Kneese in 1969 (Ayres and Kneese, 1969). Being a truly interdisciplinary enterprise, MFA links several social and natural science disciplines together, serving to support several issues of environmental concern and institutions involved in promoting sustainable development (Fischer-Kowalski, 1997). Consequently, MFA can be used as a tool for monitoring environmental pressures, contribute to the integrated environmental and economic accounting, plan and evaluate policies for sustainability. The information provided through MFA can be used by statistical offices, governmental and non-governmental organisations, as well as by industry (Bringezu, 1997).

MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2004). A major field of MFA represents the analysis of the metabolism of cities, regions, and national or supranational economies, connecting the sources, the pathways and the intermediate and final sinks of the total material flows within the system (Hinterberger et al., 2003), based on the mass conservation law. The principle concept underlying the economy-wide MFA approach is a simple model describing the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment dependent on a constant throughput of materials and energy, as shown in Figure 1-1.

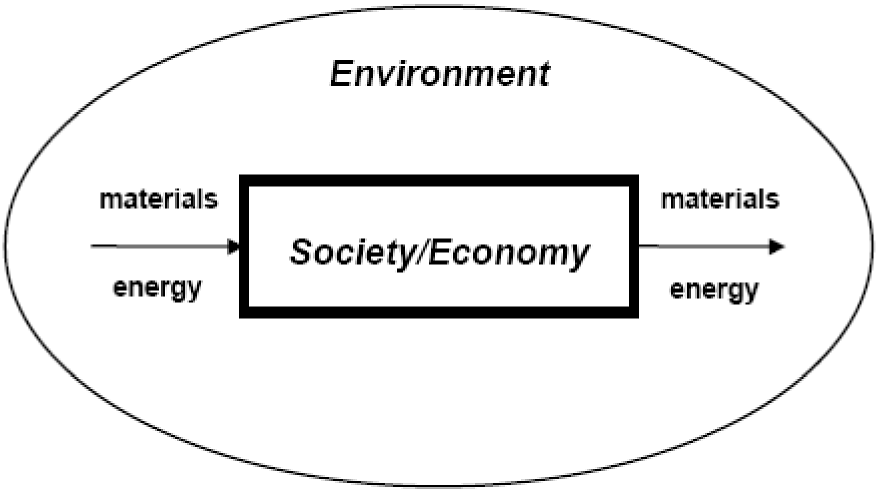


Figure 1-1 The economy/environment system
(Source: Eurostat, 2001)

MFA is applied with the purpose to provide aggregate background information on composition and changes of the physical structure of socioeconomic systems (Hinterberger et al., 2003), acknowledging the importance of resource flows that constitute the material basis of the economy. At the same time, these flows carry and induce an environmental burden associated with resource extraction and the subsequent material flows and stocks, which finally end up as waste and emissions. In this context, raw materials, water and air are extracted from the natural system as inputs, which are then transformed into products and finally re-transferred to the natural system as outputs (waste and emissions).

By analysing the weight and structure of one (e.g. MFA for biomass) or more materials' (e.g. bulk MFA) throughput of economies, their metabolic performance can be assessed in terms of sustainable development (Bringezu, 2003). As MFA is based on the mass conservation principle, missing flows along substance pathways can be identified and the need for final sinks to accommodate substances that are lost along the pathway or that have no economic value at the end of the consumption cycle can be assessed (Bruner, 2004). Furthermore, the flows of wastes and environmental loadings become visible, and their sources can be identified, through balancing inputs and outputs. As a result, MFA represents a very useful methodological framework for analysing economy-environment relationships and deriving environmental and integrated environmental/socio-economic indicators (Hinterberger et al., 2003)[13].

According to different study subjects and various methods followed, MFA covers approaches such as substance flow analysis, product flow accounts, material balancing, and overall material flow accounts. Furthermore, there are different MFA approaches, regarding the study period, the type and size of the system under study and the focus of the study. The main distinction lies in the latter parameter. As the material balance principle constitutes the logical basis of MFA, it can be applied from two different perspectives, according to Eurostat (2001), distinguishing two broad categories:

- The *system* perspective deals with the overall throughput of firms, sectors, regions or national economies and following the material balance principle, what goes into the system is either accumulated or leaves it as an output. This type of studies includes the study of the metabolic performance of industrial sectors and national and regional economies and follows the target of dematerialisation, meaning the reduction of the total material and energy demands of the system under study (Luks and Hammer, 2003). Still, the accounting can be restricted to the calculation of selected materials and substances or of the total material input, output or throughput.

---

[13] Although Wolman (1965) conducted a first empirical study of the metabolism of a model U.S. city in the 1960´s, the idea of a statistical approach towards national material flows and balances was not formulated and first applied until the next decade (e.g. Gofman et al., 1974, in Eurostat, 2001). Still, the idea was only put into statistical practise more broadly in the beginning of the 1990’s when the first studies on a national level were performed for Austria (Steurer, 1992), Japan (Japanese Environmental Agency, 1992), the USA (Rogich, 1992) and Germany (Schütz and Bringezu, 1993) and since then many more have been presented on various countries globally. In the framework of the two MFA projects co-ordinated by the World Resources Institute (Adriaanse et al., 1997; Matthews et al., 2000), MFAs were presented for the USA, Japan, Austria, Germany and the Netherlands. Selected bibliography on nation wide MFA includes studies for Italy (de Marco et al., 2001; Femia, 2000), Denmark (Gravgaard Pedersen, 2000), Finland (Muukkonen, 2000), Sweden (Isacsson et al., 2000), the United Kingdom (Bringezu and Schütz, 2001a; Schandl and Schulz, 2000), the Czech Republic (Scasny et al., 2003) and Australia (Poldy and Foran, 1999). Considering Spain, a study was published in 2004 (Cañellas et al., 2004), covering a time period of 20 years (1980 – 2000), mainly focusing on the country’s dematerialisation tendency. Sendra (2004) adapted MFA and presented studies on various systems: construction sector, industrial areas and regional level. Studies on the European Union level (EU-15) have been carried out as well, including a calculation of its Total Material Requirement indicator (Bringezu and Schütz, 2001b) and a first material balance (Bringezu and Schütz, 2001c), published by the EEA and Eurostat, respectively. Finally, and what is interesting for this study, a MFA of Catalonia was presented for the years 1996-2004 (Sendra et al., 2006).

- Following the *physical flow* perspective, the environmental problems related to certain impacts of substances, products or materials are studied. This approach supposes that the sum of masses by origin must equal to the sum of masses by destination and follows the concern of detoxification. These studies include Substance Flow Analysis (SFA), selected bulk material flows and Life Cycle Analysis (LCA) type studies.

A more detailed classification, expanding the one in the Eurostat guide (Eurostat, 2001), is presented in Bringezu and Moriguchi (2002).

As far as the methodological guidelines on conducting a national-wide MFA are concerned, these were set by a first methodological guidebook that was published by the European Statistical Office (Eurostat, 2001). In 2008, the Organisation for Economic Cooperation and Development issued guidelines on measuring material flows and resource productivity (OECD, 2008). However, at the launch of this study only the Eurostat guide had been published and forms the only methodological basis.

1.2.1. System Definition

As the focus of economy-wide MFA and balances is on the flows between a given economy and the environment, Eurostat (2001) defines the system's boundary:

- by the extraction of primary materials from the national environment and the discharge of materials to the national environment;
- by the political (administrative) borders that determine material flows to and from other economies (imports and exports).

1.2.2. The general material balance scheme

Economy-wide MFA and balances basically provide an aggregate overview, in tonnes, of annual material inputs and outputs of an economy (Eurostat, 2001). The economy as a system, including production and consumption activities, is viewed as a single black box and only flows that cross its boundaries are recorded; flows within or outside the system are not taken into account. The recorded flows generally include inputs from the national environment and the physical amounts of imports, and outputs to the environment and exports. Apart from these flows, the indirect flows associated with them are also accounted. The term 'indirect flows' refers to upstream flows associated to imports and exports of an economy. The basic methodological concept of a MFA study is illustrated in Figure 1-2.

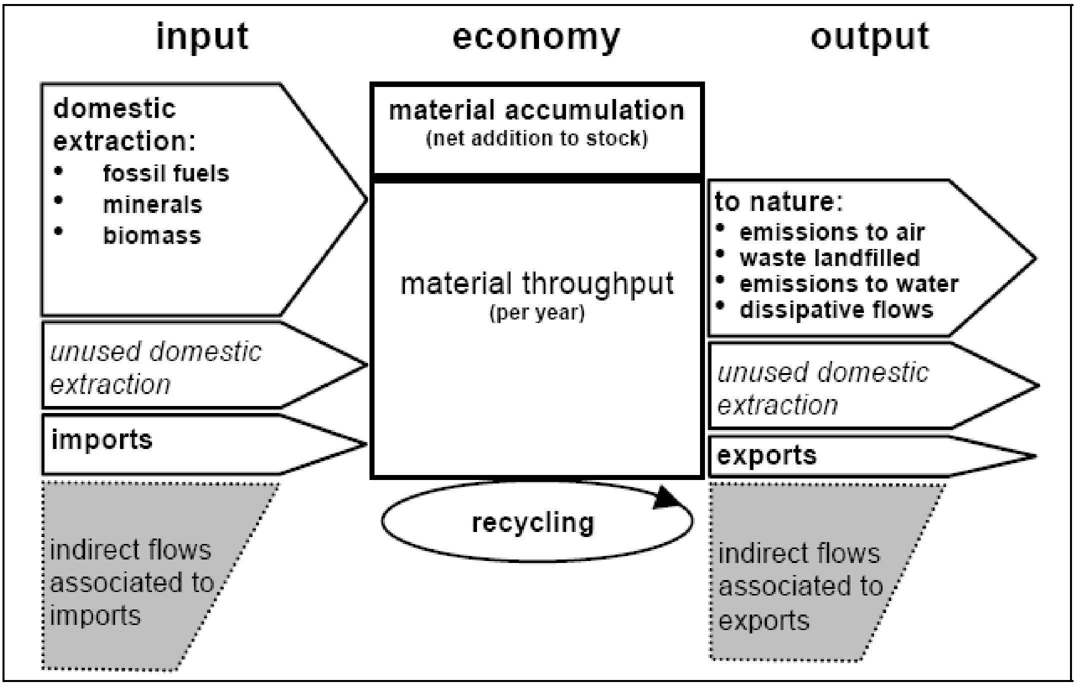


Figure 1-2 Economy-wide material balance scheme (excluding air and water)

(Source: Eurostat, 2001)

According to the first law of thermodynamics on the conservation of matter, mass or energy is neither created nor destroyed by any physical transformation (production or consumption) process. This material balance principle constitutes the logical basis of MFA and the consistent and complete recording of inputs, outputs and material accumulation. Based on that principle, what goes into the system either leaves it as output or is accumulated in the system. Consequently, the net stock change (net accumulation) for a given system is equal to the difference between inputs and outputs, expressed by the following equation:

(Equation 1-1) **Inputs = Outputs + material accumulation**

1.2.3. Main categories of flows

Eurostat (2001) uses three different dimensions in order to characterise and categorise material flows, as presented in Table 1-1. The first one is the *territorial dimension*, referring to the origin or destination of the flows, distinguishing them into domestic or foreign. The second is the *product-chain or life-cycle dimension*, separating flows into direct and indirect. Direct flows are the accounted flows that are directly observed and physically enter the economy as input (Luks and Hammer, 2003). Indirect flows occur up-stream in the production process.

Table 1-1 Classification and terminology of material flows

(Modified from Luks and Hammer, 2003 and Eurostat, 2001)

Life cycle dimension	***Product dimension***		***Territorial dimension***	***Input category***	***Output category***
	Inputs	***Outputs***			
Direct	Used	Processed	Domestic	Domestic extraction (used)	Domestic processed output to nature
Not applied	Unused	Non-processed	Domestic	Unused domestic extraction	Disposal of unused domestic extraction
Direct	Used	Processed	Foreign	Imports	Exports
Indirect	Used	Processed	Foreign	Indirect flows associated to imports	Indirect flows associated to exports
Indirect	Used	Processed	Foreign		

Finally, the *product dimension* indicates whether materials enter the economic system under study or not. With regards to input flows, these are separated into used and unused, the former referring to an input for use in any economy, while the latter to materials that have been extracted from the environment but do not finally enter the economy for use or further processing. Concerning outputs, the processed / non-processed distinction is used, referring to the flows stemming from an economic system or not.

1.2.4. Water and waste flows in MFA

As the purpose of this thesis is to dwell on water and municipal waste flows, it is of special interest to examine how the MFA methodological guidelines deal with these flows. Although this subject is thoroughly discussed in the corresponding chapters, the main guidelines are resumed at this point.

Water flows represent enormous mass flows in any socioeconomic system with one order of magnitude more than all other materials. For this reason, these are not accounted for in national MFA studies (Eurostat, 2001); Eurostat's recommendation is the drawing up and separate presentation of water flow accounts. Nevertheless, water is included in a typical MFA as a memorandum item for balancing. This usually includes water in the form of:

- Water vapour from combustion (H_2O); this includes vapour from water (H_2O) and hydrogen (H) contents of fuels
- Water evaporation from products; this includes the water content of biomass and other materials

Residues form part of the outputs to the environment, as clearly demonstrated in Figure 1-2. Flows of recycled materials are neither counted as inputs nor as outputs as they do not cross the economy's boundaries, but can be included in imports and exports or the net addition to stock (that is if they are imported by the system or exported from this to be recycled for example). Yet, Eurostat proposes the monitoring of recycling flows to prevent double counting, although it is not recommended to make recycling accounts part of a standard set of economy-wide MFA. As far as landfilled waste is concerned, this is considered an output to nature. It is important though to make a clear distinction between 'controlled' and 'uncontrolled' landfills, as the former can be included within the system's boundary. In this case the landfill air emissions and leakages are to be recorded as an output to the environment rather than the disposed waste. Finally, it is important to assess when the controlled landfills are abandoned due to the fact that they are treated as stock

1.2.5. MFA derived Indicators

Among the main purposes of economy-wide material flow accounts and balances is the derivation of a set of aggregated indicators on resources use (Eurostat, 2001). When they are combined with population size and other demographic indicators, indicators on the material intensity of lifestyles are provided. If they are related to GDP and other economic and social indicators, resource productivity and eco-efficiency indicators are conveyed. MFA manages to successfully describe the biophysical metabolism of societies with the use of the derivable indicators that provide insights into the structure and change over time of the physical metabolism of economies. These are associated with the studied flows and were originally established by the Eurostat methodological guide (Eurostat, 2001). MFA derived indicators can be grouped into (i) input, (ii) output and (iii) consumption indicators and their main representatives, based on the suggestions given by Eurostat (2001), are given below.

A. Input indicators

- *Direct Material Input (DMI)* measures the direct input of all materials which are of economic value and are used in production and consumption activities, into the economy. DMI equals domestic (used) extraction plus imports.
- *Total Material Input (TMI)* includes, in addition to DMI, also unused domestic extraction
- *Total Material Requirement (TMR)* includes, in addition to TMI, the indirect material flows that are associated to imports. According to Hinterberger et al. (2003), TMR comprises the most comprehensive input indicator, including the totality of input flows.

B. Consumption indicators

- *Domestic material consumption (DMC)* measures the total amount of material directly used in an economy (i.e. excluding indirect flows). DMC equals DMI minus exports.
- *Total material consumption (TMC)* includes, in addition to DMC, indirect flows associated to imports and exports. TMC equals TMR minus exports and their indirect flows.

- *Net Additions to Stock (NAS)* measures the 'physical growth of the economy', describing the annual accumulation of materials within the economic system.
- *Physical Trade Balance (PTB)* measures the physical trade surplus of an economy and could also be defined for indirect flows associated to Imports and Exports. PTB is equal to imports minus exports.

C. Output indicators

- *Domestic Processed Output (DPO)* describes the total weight of materials, extracted from the domestic environment or imported, which have been used in the domestic economy, before flowing to the environment. DPO includes emissions to air, industrial and household wastes deposited in landfills, material loads in wastewater and materials dispersed into the environment as a result of product use (dissipative flows). Recycled material flows in the economy are excluded from DPO.
- *Total Domestic Output (TDO)* is the sum of DPO and disposal of unused extraction, representing the total quantity of material outputs to the environment caused by economic activity.
- *Direct Material Output (DMO)* is the sum of DPO and exports, representing the total quantity of material leaving the economy after use.
- *Total material output (TMO)* - measures the total of material that leaves the economy. TMO equals TDO plus exports.

1.2.6. Regional MFA

The MFA framework can be applied on a variety of spatial scales (Haberl et al., 2004) and in the course of smaller than the national scale studies, material flows of neither global nor national importance are detected[14]. There is a special interest between the flows of a city or a region and the national economy in which this is embedded; Eurostat (2001) states that a motivation for performing regional MFA lies in the need to produce a regional dataset following the logic of a national-wide MFA.

---

[14] According to Friege (1997), water supply, erosion and land use must be linked to local or urban planning and materials transported over short distances, such as stone or clay, are principally important on a regional level.

Moreover, regional MFAs are also inherently associated with the dematerialisation strategy, as in the course of its achievement a regionalisation of the economy is required (Hammer et al., 2003). Through the study of regional material and energy flows, considering at the same time the regional particularities, increased use of regional resources and improved resource efficiency of regional products and services can be achieved, resulting in a reduction of the material and energy throughput of a region.

Regionalised material flow accounts, when these are combined and correlated with economic and social indicators, also support policy makers working towards sustainable development (Friege, 1997). What's more, regional MFA studies facilitate the definition of regional action targets, which are necessary for the completion of national environmental quality targets associated with urban planning and development.

Even though MFA on a regional or local level is considered to be an important scientific tool on the way to regional and local sustainability (Hinterberger and Schneider, 2001), published studies are still limited in number compared to the ones conducted on the national level[15]. This could be linked to the lack of methodological guidelines on the regional level, such as those proposed by Eurostat (2001) for the national level. Recognising this need, Hammer et al. (2003) aimed to develop a method for applying the MFA framework on the regional level after the review of already published regional MFA case studies discussing the different methodological approaches followed. In addition, Grünbühel (2003) made some basic suggestions on the conduction of local level MFA studies.

---

[15] Considering urban metabolism and related MFA studies, a bibliographical review is presented in Chapter Three. International bibliography on regional MFA includes several empirical studies focused on the methods employed and the data sources. Selected works include the study of two regions in Switzerland (Brunner et al., 1994; Hendriks et al., 2000) that follows a different methodological approach as the one suggested by Eurostat (2001), accounting for flows within the regions as well. Bringezu and Schultz (1996a; 1996b) calculated aggregated regional MFA indicators (like DMI and TMR) for the Ruhr area and compared with results from North-Rhine-Westphalia and Germany. Furthermore, local full bulk MFAs were carried out for the municipality of Amsterdam (Gorree et al., 2000) and Trinket Island (Singh et al., 2001), while the Total Material Requirement of the Basque country was accounted for the years 1989-1998 in a MFA study of the region (IHOBE, 2002). Finally, three local MFAs were carried out for Bolivia, Colombia and Brazil, not following a bulk MFA methodology, but taking into account only important input and stocks categories (Hammer et al., 2003).

Concerning their methodology, there are two main differences between national and regional level MFA studies. The first one concerns import and export flows; although national level trade flows are accounted by official statistics, trade flows in a regional level have to be separated into interregional, or intra-national, trade flows and international trade flows; between the region and the rest of the country and between the region and the rest of the world, respectively. As a consequence, there is a need for use of different statistical sources and estimation methods for both kinds of flows (Hinterberger et al., 2003).

The other difference lies in the confidentiality and availability of data on a regional level. In the case that the production structure in a certain branch within the region is dominated by a small number of firms, data could be confidential. Additionally, while on national level the majority of data can be obtained from national statistic offices or the United Nations, data availability is much poorer on a regional level. Consequently, data collection is usually a time consuming process, as data is not centrally available, but dispersed among several institutions. Moreover, data on some material flows may not be available in physical units at all and would have to be estimated from more general data (Hinterberger et al., 2003). Scarce and disperse data sources is a drawback related to the conduction of regional MFA studies and could be associated with the lack of these studies.

1.3. Case Study presentation

The selected system is comprised of the 27 municipalities included in the 'Strategic Plan of the coast of the Barcelona Metropolitan Region'. They are situated along the coastline of Catalonia, an autonomous community of Spain located in the North-east corner of the Iberian Peninsula (Figure 1-3). Covering about 32 000 km² and with 580 km of coastal strip, Catalonia currently has approximately seven million inhabitants. The selected region occupies an area of 478 km^2, representing 1.5% of Catalonia's surface and 118.6 km of coastline.

Figure 1-3 Location of Catalonia in Spain and Europe and the coastal municipalities under study

With a population of 2.5 million residents, the area hosts 36% of the Catalan population, with a density of more than 5 000 inhabitants per km^2, while the equivalent value for Catalonia is around 200 inhabitants per km^2 and for the European Union some 115 inhabitants per km^2 in 2004. The region extends from the municipality of Malgrat de Mar in the North, to that of Cubelles in the South, with Barcelona in the centre of the studied coastline, as illustrated in Figure 1-4. Concerning political administration, the study area includes municipalities belonging to four different Catalan counties; that of Maresme, Barcelonès, Baix Llobregat and Garraf. Eight of these municipalities belong to the Metropolitan Area of Barcelona (namely Montgat, Badalona, Sant Adrià de Besòs, Barcelona, El Prat de Llobregat, Viladecans, Gavà and Castelldefels). A summary of the administrative division, data on population and the surface covered by each municipality for 2005 is given in Table 1-2.

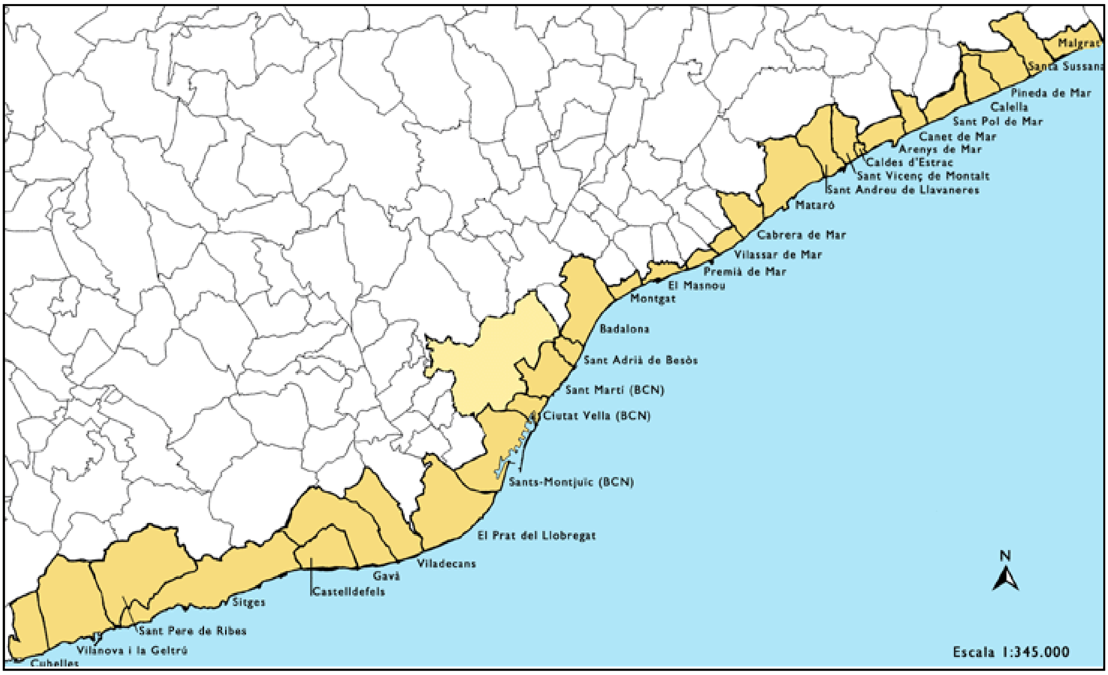


Figure 1-4 The coastal municipalities of Barcelona's metropolitan region (Source: Observatori del Litoral, 2008)

Nevertheless, concerning the authorities responsible for their environmental management, a different division is followed. The eight municipalities belonging to the Barcelona Metropolitan Area are under the administration of the Metropolitan Water Services and Waste Treatment Authority (Entitat Metropolitana de Serveis Hidràulics i Tractament de Residus - EMSHTR); the remaining municipalities of Maresme are under the administration of the Maresme County Council (Consell Comarcal de Maresme). Finally, the municipalities of Sitges, Sant Pere de Ribes, Vilanova i la Geltrú and Cubelles are under the management of the Community of municipalities of Penedès and Garraf (Mancomunitat Intermunicipal del Penedès i Garraf).

Table 1-2 Administrative division and basic data on the studied municipalities, for 2005 [a]

	County	*Municipality*	*Population*	*Surface (km^2)*	*Population density (inh/km^2)*
	Garraf	**Cubelles**	**10 617**	**13.7**	**775**
		Vilanova i la Geltrú	**61 427**	**34**	**1 807**
		Sant Pere de Ribes	**26 108**	**40.8**	**640**
		Sitges	**24 470**	**43.8**	**559**
Metropolitan Area of Barcelona	***Baix Llobregat***	**Castelldefels**	**56 718**	**12.9**	**4 397**
		Gavà	**44 210**	**30.8**	**1 435**
		Viladecans	**61 043**	**20.4**	**2 992**
		el Prat de Llobregat	**63 190**	**31.2**	**2 025**
	Barcelonès	**Barcelona**	**1 593 075**	**100.4**	**15 867**
		Sant Adrià de Besòs	**32 940**	**3.8**	**8 668**
		Badalona	**218 553**	**21.2**	**10 309**
	Maresme	**Montgat**	**9 112**	**3.0**	**3 037**
		el Masnou	**21 464**	**3.4**	**6 313**
		Premià de Mar	**27 653**	**2.1**	**13 168**
		Vilassar de Mar	**18 900**	**4.0**	**4 725**
		Cabrera de Mar	**4 119**	**9.0**	**458**
		Mataró	**116 698**	**22.5**	**5 187**
		Sant Andreu de Llavaneres	**9 180**	**11.8**	**778**
		Sant Vicenç de Montalt	**4 771**	**8.1**	**589**
		Caldes d'Estrac	**2 508**	**0.9**	**2 787**
		Arenys de Mar	**13 860**	**6.9**	**2 009**
		Canet de Mar	**12 429**	**5.6**	**2 219**
		Sant Pol de Mar	**4 597**	**7.5**	**613**
		Calella	**16 927**	**8.0**	**2 116**
		Pineda de Mar	**24 702**	**10.8**	**2 287**
		Santa Susanna	**2 868**	**12.7**	**226**
		Malgrat de Mar	**16 833**	**8.9**	**1 891**
		Entire system	**2 498 972**	**478.2**	**5 226**

[a] Source: IDESCAT, 2008

[b] Average value

1.3.1. The system's economic structure

The studied system has a strong economy as an important commercial and tourist attraction centre with an important industrial basis. Similarly to the rest of Catalonia, it is a region of limited natural resources, hence with a weak primary economic sector. On the other hand, the manufacturing industry is quite strong, mostly concentrated in the municipalities around Barcelona. This is clear in Table 1-3, which contains the gross value added per sector in each of the studied municipalities, in percentages, an indicator that reflects the contribution of each sector to the studied economy. Another significant sector, related to the system's tourist development is construction. Finally, the tertiary sector has experienced considerable development the last years, including tourism and services and a great number of publicity and new technologies companies as well, contributing significantly to the GDP and employment offer (Observatori del Litoral, 2008).

Table 1-3 Gross value added per sector, in percentages, for municipalities with population superior to 5 000 inhabitants, for 2001 [a]

Municipality	*Agriculture*	*Industry*	*Construction*	*Services*	*PIB index – Catalonia=100*
Cubelles	**0.4**	**36.6**	**16.1**	**46.9**	**87.8**
Vilanova i la Geltrú	**1.7**	**26.2**	**9.5**	**62.6**	**88.6**
Sant Pere de Ribes	**0.2**	**15.5**	**14.1**	**70.2**	**53.3**
Sitges	**0.0**	**12.1**	**10.9**	**77.0**	**99.3**
Castelldefels	**0.0**	**9.4**	**11.0**	**79,6**	**59.8**
Gavà	**0.9**	**43.3**	**6.7**	**49.1**	**109.2**
Viladecans	**1.2**	**25.5**	**10.2**	**63.2**	**58.7**
el Prat de Llobregat	**0.0**	**21.8**	**3.1**	**75.1**	**204.6**
Barcelona	**0.0**	**18.8**	**5.5**	**75.7**	**129.3**
Sant Adrià de Besòs	**0.0**	**45.1**	**6.2**	**48.6**	**79.1**
Badalona	**0.0**	**23.5**	**8.3**	**68.2**	**59.0**
Montgat	**0.2**	**33.1**	**9.8**	**56.9**	**59.5**
el Masnou	**1.0**	**34.5**	**5.7**	**58.7**	**66.8**
Premià de Mar	**0.5**	**17.5**	**8.4**	**73.6**	**53.8**
Vilassar de Mar	**9.2**	**15.6**	**6.0**	**69.1**	**76.4**
Mataró	**0.4**	**24.7**	**8.8**	**66.1**	**83.5**
Sant Andreu de Llavaneres	**2.7**	**9.0**	**12.6**	**75.8**	**58.4**
Arenys de Mar	**5.8**	**12.2**	**9.5**	**72.5**	**67.4**
Canet de Mar	**0.9**	**24.2**	**10.3**	**64.6**	**57.6**
Calella	**0.2**	**7.5**	**9.5**	**82.8**	**83.2**
Pineda de Mar	**0.1**	**19.6**	**15.6**	**64.7**	**64.9**
Malgrat de Mar	**0.1**	**33.5**	**11.7**	**54.7**	**97.1**

[a] **Source: IDESCAT, 2008a**

1.3.2. The Strategic Coastal Plan of the Metropolitan Region of Barcelona

The significance of coastal regions is not restricted to their ecological importance; they demonstrate a special interest for the variety and intensity of human activities developed there. More specifically, they have been historically attractive for human occupation, facilitating the creation, expansion and development, in every economical and socio-political aspect, of urban centres. This is confirmed by the fact that, nowadays, coastal zones accommodate more than 60% of the world's population, while they occupy less than 15% of the Earth's land surface. Furthermore, in the European Union about one-third of the population is concentrated near the coasts (EEA, 1999a) while, particularly in the South, heavy populated areas are usually connected with regions with large cities, as the example of Barcelona and its Metropolitan Area amongst others. Spain is not an exception to this pattern, with 36.5% of the total population residing in coastal regions (Martin and Miguelez, 2004). Regarding Catalonia, in the year 2003, 70% of its population resided in areas within a 20km distance from the shore (Ulied and Xalabarder, 2004).

As a result of their elevated urbanisation, these regions contain the majority of humanity's infrastructure and demonstrate high industrial, commercial, transport and tourism activity, followed by a big share of global consumption and waste production (CRC, 2001). These intense human activities always produce, in the long term, a strong environmental impact on coastal regions (EEA, 1999b).

Coastal regions host a large range of industrial activities, including heavy industry complexes, big commercial harbours and waste treatment plants, as in the case of the studied region. The impacts caused by these activities can be direct, as air pollution, industrial effluents and contribution to hot spot creation by pollution for instance, or indirect, like further concentration of activities and urban development.

Regarding tourism, this deeply affects coastal regions, not only because of the high seasonal increase in population, but due to the need for related infrastructure as well. Impacts include changes in land use, through the limitation of nature and agricultural land as there is augmented need for tourist facilities, over-consumption of water resources and increased generation of waste and discharges to the sea due to increased population. According to the EEA (1999b) "*…coastal tourism causes reduction of natural sites and open spaces,* *substantial alteration of coastal landscapes and conflicts on the use of land, water and other resources…*"

It is not hard to comprehend the importance and complexity of coastal regions, both in sociological and ecological terms, and as a result, the need to control the equilibrium between the human and natural systems, coexisting and evolving together. Recognising the pressure coastal zones face by development, many initiatives have been taken the last years in order to ensure the protection of these areas of important environmental resources from human activities[16].

The initiative of the Strategic Plan of the coast of the Barcelona Metropolitan Region (Pla Estratègic per al litoral de la Regió Metropolitana de Barcelona - PEL) is based on the common problems and characteristics that the municipalities involved share. Apart from their common history and culture, all municipalities are, to some extent, affected by their vicinity to Barcelona. The vast development and growth of the city could not but influence its surrounding areas, resulting in both advantages and inconveniences, as consequences of the extended transport networks, advanced infrastructures and the development of high economical activities.

An initiative promoted by the Fórum de Municipis del Litoral de la Regió Metropolitana de Barcelona, the PEL was constituted in February 2004 with the objective to propose clear and concise strategic lines that would facilitate the town councils in the management of

---

[16] The United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992, recognised the need and utility of global and unified integrated coastal governance (Earth Summit 1992). The implementation of the Rio Principles along with Chapter 17 of Agenda 21, demanding the formulation and execution of coastal management programmes, resulted in almost doubling their number in 2000, compared to the number of programmes existing in 1993 (CRC, 2001). The EU has also recognised the importance of coastal areas and the need for protecting them. Since 1996, the European Commission has been working on the promotion of measures for the protection of coastal areas and in the period between 1996 and 1999, it operated a Demonstration Programme on Integrated Coastal Zone Management (ICZM) designed around a series of 35 demonstration projects and 6 thematic studies (http://ec.europa.eu/comm/environment/iczm/). This programme was focused on the provision of technical information about sustainable coastal zone management and the stimulation of a debate among actors involved in the planning, management or use of European coastal zones, with the ultimate aim to stimulate ICZM in Europe. Key areas of action for ICZM are environmental impact assessment, coastal land planning, habitat management and pollution control (EEA, 1999b). The projects cover the whole territory of the EU and include the regions of the Baltic Sea, the North Sea, the North-West Europe Metropolitan Region, the Atlantic Area, The Mediterranean and the French and Italian Alps and finally, the Central and Eastern Mediterranean (http://ec.europa.eu/comm/environment/iczm/).

their coastal territories (Pla Estratègic Litoral, 2008). The plan emerged from the will of the 27 coastal municipalities to work together and reach common strategies, as the territory has numerous problems that, in particular the ones that affect the coast as a system, require a joint approach. In this way, a strategic Plan offered the possibility to deal with collective problems of the area, currently not dealt by any other administrative body. The strategies planned are divided in the following six sectors:

- Culture and Society
- Natural environment and sustainability
- Economic development and employment
- Urban planning and demography
- Infrastructures, communications and highway administration (Mobility)

References

Adriaanse, A., Bringezu, S., Hammond, A., Moriguchi, Y., Rodenburg, E., Rogich, D. and Schütz, H. (1997) Resource Flows: The Material Basis of Industrial Economies. Ed. by World Resources Institute, Wuppertal Institute, Netherlands Ministry of Housing, Spatial Planning, and Environment, National Institute for Environmental Studies, Japan. WRI Report: Washington.

Ajuntament de Barcelona (2006) Projecte d'ordenança de mesures per fomentar i garantir la convivència ciutadana a la ciutat de Barcelona. Butlletí Oficial de la Província de Barcelona, 24/1/2006. Num. 20, Annex I, pp 14-30

Alberti, M (1996) Measuring Urban Sustainability. Environmental Impact Assessment Review 16: 381-424

Atkinson, A. (2007) Cities after oil—1. "Sustainable development and energy futures". City 11 (2): 201–213

Ayres, R. U. and Kneese, A. V. (1969) Production, Consumption and Externalities. American Economic Review 59 (3): 282-97

Ayres, R. U., van der Bergh, C. J. M. and Gowdy, J. M. (2001) Strong versus Weak Sustainability: Economics, Natural Sciences and "Consilience". Environmental ethics 23: 155-168

Bairoch, P. (1988) Cities and Economic Development: From the Dawn of History to the Present. ISBN 0226034658

Bartelmus, P. (2003) Dematerialization and capital maintenance: two sides of the sustainability coin. Ecological Economics 46: 61-81

Bookchin, M. (1995); From Urbanization to Cities: Toward a New Politics of Citizenship. Cassell: London; New York

Bringezu, S. (1997) Introduction. ConAccount workshop, Leiden, the Netherlands. Wuppertal Institute for Climate, Environment and Energy Science Centre North Rhine-Westphalia: Wuppertal

Bringezu, S. (2003) Industrial ecology and material flow analysis: Basic concepts, policy relevance and some case studies. Greenleaf Publishing

Bringezu, S. and Moriguchi, Y. (2002) Material flow analysis. In: Ayres, R. U. and Ayres, L. W. (eds.), A Handbook of Industrial Analysis. Edward Elgar Publishing: Cheltenham

Bringezu, S. and Schütz, H. (1996a) Der ökologische Rucksack des Ruhrgebiets. Report No. 61. Wuppertal Institute: Wuppertal

Bringezu, S. and Schütz, H. (1996b) Die stoffliche Basis deWirtschaftsraumes Ruhr. Ein Vergleich mit Nordhein-Westfalen und der Bundesrepublik Deutschland. RuR, 6.

Bringezu, S. and Schütz, H. (2001a) Total material resource flows of the United Kingdom, Final report. EPG 1/8/62. Wuppertal Institute: Wuppertal

Bringezu, S. and Schütz, H. (2001b) Total material requirement of the European Union. Technical part. Technical Report. No. 56. European Environmental Agency: Copenhagen

Bringezu, S. and Schütz, H. (2001c) Material use indicators for the European Union, 1980-1997. Eurostat Working Paper 2/2001/B/2. Eurostat: Luxemburg

Brunner, P. H. (2004) Materials Flow Analysis and the Ultimate Sink. Journal of Industrial Ecology 8 (3)

Brunner P. H., Daxbeck H. and Baccini P. (1994) Industrial metabolism at the regional and local level: A case study on a Swiss region. In: Ayers, R. U. and Simonis, U. E. (eds.), Industrial Metabolism: Restructuring for Sustainable Development. United Nations University Press: Tokyo

Brunner, P. H. and Rechberger, H. (2004) Practical handbook of material flow analysis. Lewis Publishers, CRC Press: London, New York, Washington, DC

Cañellas, S., González, A., Puig, I., Sendra, C. and Sojo, A. (2004) Material Flow Accounting of Spain. International Journal of Global Environmental Issues 4 (4): 229-241

Chung, S. (1988) A conceptual model for regional environmental planning centred on carrying capacity measures. Korean Journal of Regional Sciences 4 (2): 117–128.

CRC (2001) Future Directions in Integrated Coastal Management: The Consensus from Block Island. Coastal Resources Centre Coastal Resources Centre; University of Rhode Island: Narragansett

Daly, H. E. (1990) Sustainable development: From concept and theory towards operational principles. Steady State Economics, 2nd ed. Island Press: Washington

Daly, H. E. (1991) Steady State Economics. Island Press: Washington

De Marco, O., Lagioia, G. and Pizzoli Mazzacane E. (2001) Materials Flows Analysis of the Italian Economy. Journal of Industrial Ecology 4 (2): 55-70

Diamantini, C. and Zanon, B. (2000) Planning the urban sustainable development. The case of the plan for the province of Trento, Italy. Environmental Impact Assessment Review 20: 299–310

Ditchev, I (2005) Communist urbanization and conditional citizenship. City 9 (3): 341-354

Doxiadis, C. A. (1970) Ekistics, the Science of Human Settlements. Science 170 (3956): 393-404

Du Crest, A. (2008) What will be the indicators for tomorrow? First international conference on Economic De-growth for Ecological Sustainability and Social Equity: Paris, April 18-19th 2008

Earth Summit (1992) United Nations Conference on Environment and Development (UNCED): Rio de Janeiro, Brazil, 3-14 June 1992

EEA (1995) Europe's Environment: The Dobris Assessment. European Environment Agency; Earthscan: London

EEA (1999a) Environment in the European Union at the turn of the century, State of Environment report No 1/1999. European Environmental Agency: Copenhagen

EEA (1999b) State and pressures of the marine and coastal Mediterranean environment (Summary). European Environmental Agency: Copenhagen

Ehrenfeld, J. R. (2004) Can Industrial Ecology be the "Science of Sustainability"? Journal of Industrial Ecology 8 (1-2)

European Commission (1996) European sustainable cities. Office for Official publications of the European Communities: Luxemburg

Eurostat (2001) Economy-wide material flow accounts and derived indicators. A methodological guide. Office for Official Publications of the European Union: Luxembourg.

Femia, A. (2000) A material flow account for Italy, 1988. Eurostat Working Paper Nr. 2/2000/B/8. Eurostat: Luxemburg

Fischer-Kowalski, M. (1997) Society's Metabolism - Origins and Development of the Material Flow Paradigm. ConAccount workshop, Leiden, The Netherlands, Wuppertal Institute for Climate, Environment and Energy Science Centre North Rhine-Westphalia

Fournier, V. (2008) Escaping from economy: the politics of degrowth. International Journal of Sociology and Social Policy 28 (11/12): 528-545

Friege, H. (1997) Requirements for Policy Relevant Material Flow Accounting - Results of the German Bundestag's Enquête Commission. ConAccount workshop, Leiden, the Netherlands. Wuppertal Institute for Climate, Environment and Energy Science Centre North Rhine-Westphalia

Gandy, M. (2004) Rethinking urban metabolism: Water, space and the modern city. City 8 (3): 363-379

Girardet, H. (1990) The metabolism of cities. In: Cadman, D. and Payne, G. (eds.), The Living City: Towards a Sustainable Future. Routledge: London, pp. 170-180.

Godschalk, D.R. and Axler, N. (1977) Carrying Capacity Applications in Growth Management: A Reconnaissance. Department of Housing and Urban Development: Washington, DC

Gofman, K., Lemeschew, M. and Reimers, N. (1974) Die Ökonomie der Naturnutzung – Aufgaben einer neuen Wissenschaft. Nauka I shisn 6

Gorree, M., Kleijn, R.. and van der Voet, E. (2000) Materiaañstromen door Ámsterdam. CML: Amsterdam

Gravgaard Pedersen, O. (2000) Material flow accounts and analysis for Denmark. Paper presented at the 26-27 June 2000 meeting of the Eurostat Task Force on Material Flow Accounting

Grünbühel, C. M. (2003) Analysis at the local scale. In: Schandl, H., Grünbühel, C. M., Haberl, H. and Weisz, H., Handbook of Physical Accounting: Measuring bio-physical dimensions of socio-economic activities. Federal Ministry of Agriculture and Forestry, Environment and Water Management: Vienna

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H. and Winiwarter, V. (2004) Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 21: 199-213

Hammer, M., Giljum, S., Bargigli, S. and Hinterberger, F. (2003) Material Flow Analysis on the regional level: Questions, Problems, Solutions. Working NEDS Papers 2. Hamburg University: Hamburg

Harper, E. M. and Graedel, T. E. (2004) Industrial ecology: a teenager's progress. Technology in Society 26: 433-445

Harvey, D. (2008) The right to the city. New Left Review 53: 23-40

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P. and Brunner, P. (2000) Material flow analysis: a tool to support environmental decision making. Two case studies on the city of Vienna and the Swiss lowlands. Local Environment 5: 311-328

Hinterberger, F. and Schneider, F. (2001) Eco-Efficiency of Regions: Toward Reducing Total Material Input. 7th European Roundtable on Cleaner Production: Lund

Hinterberger, F., Giljum, S. and Hammer, M. (2003) Material Flow Accounting and Analysis (MFA): A Valuable Tool for Analyses of Society-Nature Interrelationships. SERI Background Paper Nr. 2. Sustainable Europe Research Institute (SERI): Vienna

Holden, M., Roseland, M., Ferguson and K., Perl, A. (2008) Seeking urban sustainability on the world stage. Habitat International 32: 305-317

Huang, S.-L. and Chen, C.-W. (2005) Theory of urban energetics and mechanisms of urban development. Ecological Modelling 189: 49–71

Huang S. and Hsu, W. (2003); Materials flow analysis and emergy evaluation of Taipei's urban construction. Landscape and Urban Planning 63: 61–74

Huang, S.-L., Wong, J.-H. and Chen, T.-C. (1998) A framework of indicator system for measuring Taipei's urban sustainability. Landscape and Urban Planning 42: 15-27

Huesemann, M.H. (2001) Can pollution problems be effectively solved by environmental science and technology? An analysis of critical limitations. Ecological Economics 37 (2): 271-287

Huesemann, M.H. (2003) Recognizing the limits of Environmental Science and Technology. Environmental Science and Technology 37 (13): 259A–261A

Huesemann, M.H. (2004) The Failure of Eco-Efficiency to Guarantee Sustainability: Future Challenges for Industrial Ecology. Environmental Progress 23 (4): 264-270

IDESCAT (2008) Territori: Banc d'estadístiques de municipis i comarques: Dades bàsiques. Web de l'estadística ofocial de Catalunya. Institut d'Estadistica de Catalunya. Available at: http://www.idescat.cat/territ/BasicTerr?TC=9

IHOBE (2002) Total Material Requirement of the Basque Country. IHOBE: Bilbao

IIED (2001) Briefing Paper Series on Urban Environmental Improvement and Poverty Reduction. International Institute for Environment and Development. Danida: London

Isacsson, A., Jonsson, K., Linder, I., Palm, V. and Wadeskog, A. (2000) Material Flow Accounts - DMI and DMC for Sweden 1987-1997. Eurostat Working Paper 2/2000/B/2. Eurostat: Luxemburg

Japanese Environmental Agency (1992) Quality of the Environment in Japan 1992. Japanese Environmental Agency: Tokyo

Järvelä, M. and Kuvaja-Puumalainen, K. (1998) Environmental Impact Assessment. Encyclopedia of Applied Ethics, Volume 2. Academic Press: New York, pp. 83–91.

K'Akumu, O. A. (2007) Sustain no city: An ecological conceptualization of urban development. City 11 (2): 221-228

Kastoriadis, C. (1984) Thoughts on 'development' and 'rationality'. Ypsilon publications: Athens (in Greek)

Latouche, S. (2004) Degrowth economics: why less should be much more. Le monde diplomatique, 14 November 2004

Lefebvre, H. (1970) La Révolution urbaine. Editions Gallimard: Paris

Luks, F. and Hammer, M. (2003) Material Flow Analysis, Discourse Analysis and the Rhetorics of (Ecological) Economics. Working NEDS Papers 1, March 2003. SERI: Vienna

McLaren, V. W. (1996) Urban Sustainability Reporting. Journal of the American Planning Association 62(2): 184-202.

Mar, B.W. (1981) Dead is dead - an alternative strategy for urban water management. Urban Ecology 5: 103-112

Marcouse, P. (2005) "The city" as a perverse metaphor. City 9 (2): 247-254

Martin, F. and Miguelez, F. (2004) Las ciudades, sumideros de energia. Archipielago No 61/2004, Julio

Matthews, E., Amann, C., Bringezu, S., Fischer – Kowalski, M., Hüttler, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Schütz, H., van der Voet, E. and Weisz, H. (2000) The Weight of Nations: Material Outflows from Industrial Economies. World Resources Institute: Washington

Meadows, D. H. Meadows, D. L., Randers, J. and Behrens, W. W., III (1972) Limits to Growth. A report to the club of Rome. Universe books: New York

Mega, V. (2000) Cities inventing the civilisation of sustainability: an odyssey in the urban archipelago of the European Union. Cities 17 (3): 227-236

Munda, G. (2006) Social multi-criteria evaluation for urban sustainability policies. Land Use Policy 23: 86-94

Muukkonen, J. (2000) TMR, DMI and material balances, Finland 1980-1997. Eurostat Working Paper Nr. 2/2000/B/1. Eurostat: Luxemburg

Myllyla, S. and Kuvaja, K. (2005) Societal premises for sustainable development in large southern cities. Global Environmental Change 15: 224–237

Newman, P. W. G. (1999) Sustainability and cities: extending the metabolism model. Landscape and Urban Planning 44: 219-226

Observatori del Litoral (2008) Pla Estratègic Litoral de la Regió Metropolitana de Barcelona: Informes sectorials: La transició econòmica. Available at: http://www.elfar.diba.cat/observatori/plalitoral/subpag3/capt3.2.html

OECD (1993) Core Set of Indicators for Environmental Performance Reviews. Environmental Monograph No. 38. OECD: Paris

OECD (1994) OECD Core Set of Environmental Indicators: A Summary of the Work Group on the State of the Environment. OECD Environment Directorate: Paris

OECD (2008) Measuring material flows and resource productivity: Synthesis report. OECD: Paris

Oh, K., Jeong, Y., Lee, D., Lee, W. and Choi, J. (2005) Determining development density using the Urban Carrying Capacity Assessment System. Landscape and Urban Planning 73: 1–15

Opschoor, H. and Reijnders, L. (1991) Toward sustainable development indicators. In: Kuik, O. and Verbruggen, H. (eds.), In Search of Indicators of Sustainable Development. Kluwer Academic Publishers: Dordrecht, pp. 7-27

Pla Estratègic Litoral (2008) Pla Estratègic Litoral de la Regió Metropolitana de Barcelona: Presentació. Consorci El Far. Available at: http://www.elfar.diba.cat/observatori/plalitoral/

Poldy, F. and Foran, B. (1999) Resource flows: the material basis of the Australian economy. Working Document. No. 99/16. CSIRO: Canberra

Rees, W. (1992) Ecological footprints and appropriated carrying capacity: What urban economics leaves out. Environment and Urbanization 4 (2): 121-130

Rees, W. and Wackernagel, M. (1996) Urban ecological footprints: why cities cannot be sustainable and why they are a key to sustainability. Environmental Impact Assessment Review 16: 223-248

Robinson, J. (2004) Squaring the circle? Some thoughts on the idea of sustainable development. Ecological Economics 48: 369-384

Rogich, D.G. (1992) Trends in Material Use - Implications for Sustainable Development. Paper presented at the Conference on Sustainable Development: Energy and Mineral Resources in the

Circum-Pacific Region and the Environmental Impact of their Utilization: Bangkok, 9-12 March 1992

Roseland, M. (2000) Sustainable community development: Integrating environmental, economic and social objectives. Progress in Planning 54 (2): 71-132

Satterthwaite, D. (1997) Sustainable Cities or Cities that contribute to sustainable development. Urban Studies 34 (10): 1667-1691

Scasny, M., Kovanda, J. and Hak, T. (2003) Material flow accounts, balances and derived indicators the Czech Republic during the 1990s: results and recommendations for methodological improvements. Ecological Economics 45 (1): 41-57

Schandl, H. and Schulz, N. (2000) Using Material Flow Accounting to operationalise the concept of Society's Metabolism. A preliminary MFA for the United Kingdom for the period of 1937-1997. ISER Working Paper 2000-3. University of Essex: Colchester

Schütz, H. and Bringezu, S. (1993) Major Material Flows in Germany. Fresenius Environmental Bulletin 2: 443-448

Sendra, C. (2004) Anàlisis dels fluxos de materials de Ctalunya en el periode 1996-2000. Departament d'Enginyeria Quimica. Bellaterra, Universitat Autònoma de Barcelona. Doctorat de Ciències Ambientals

Sendra, C., Gabarell, X. and Vicent, T. (2006) El análisis de los flujos de materiales en la ecología industrial: una herramienta para alcanzar el desarrollo sostenible. Ingeniería Química 435 (11): 115-121

Singh, S.J., Grünbühel, C.M., Schandl, H. and Schulz, N. (2001) Social metabolism and labour in a local context: Changing Environmental Relations on Trinket Island. Population and Environment 23 (1): 71-104

Steurer, A. (1992) Stoffstrombilanz Östereich 1988. Schrift. Sozial Ökologie des iff, Wien. Vol 26

Sukopp, H. (1998) Urban Ecology – Scientific and Practical Aspects. In: Breuste, J., Feldmann, H. and Uhlmann, O. (eds.), Urban Ecology. Springer-Velarg: Berlin; Heidelberg

Tainter, J. A. (2006) Social complexity and sustainability. Ecological complexity 3: 91-103

Tjallingii, S. P. (1993) Ecopolis: Strategies for Ecologically sound urban development. Backhuys Publishers: Leiden

Ulied, A. and Xalabarder, M. (2004) Pla Estratègic per al Litoral de la Regió Metropolitana de Barcelona: Informe de Situació. Fórum de Municipis del Litoral de la Regió Metropolitana de Barcelona: Barcelona

UN (1996) Indicators of Sustainable Development Framework and Methodologies. United Nations Sales Publication No.E.96.II.A.16: New York

UN (2001) Indicators of Sustainable Development: Guidelines and Methodologies, Second Edition. UN Sales Publication No.E.01.II.A.6: New York

UN (2007) Indicators of Sustainable Development: Guidelines and Methodologies, Third Edition. United Nations: New York

UN (2008) World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. Available at: http://esa.un.org/unup

UNCHS and the World Bank (1995) Indicators Programme: Monitoring Human Settlements. UNCHS: Nairobi

UNCSD (1996) Working List of Indicators of Sustainable Development. United Nations Commission on Sustainable Development: New York.

UN General Assembly (8 September 2000) 55/2 United Nations millennium declaration. United Nations: New York

UN Habitat (1996) Istanbul Declaration on Human Settlements. United Nations: Istanbul

UN Habitat (2002) Sustainable urbanization bridging the green and brown agendas. DPU: London

UN Habitat (2008) UN Habitat Programmes. Available at: http://www.unhabitat.org/categories.asp?catid=33

van Dijk, M. P., Mingshun, Z. (2005) Sustainability indices as a tool for urban managers, evidence from four medium-sized Chinese cities. Environmental Impact Assessment Review 25: 667– 688

Walsh, E, Babakina, O, Pennock, A., Shi, H.,Chi, Y., Wang, T. and Graedel, T. E. (2006) Quantitative guidelines for urban sustainability. Technology in Society 28: 45-61

WHO (1993) Healthy City Indicators. World Health Organization: Copenhagen

Wolman, A. (1965) The metabolism of the city, Scientific American 213: 179-190

World Commission on Environment and Development (1987) Our common future. Oxford University Press: New York

Xing, Y., Horner, R. M. W., El-Haram, M. A. and Bebbington, J. (2008) A Framework Model For Assessing Sustainability Impacts Of Urban Development. Accounting Forum doi:10.1016/j.accfor.2008.09.003

Yanarella, E. J. and Levine, R. S. (1992) Does sustainable development lead to sustainability? Futures October 1992

2. OBJECTIVES

This research has three basic objectives; the first one deals with the development of two new methodologies adequate for the description of flows not accounted for in classical MFA studies. The next goal is the derivation of new indicators resulting from each methodology. The third objective is the application of the proposed tools on the case study in order to demonstrate their viability and test the system's performance with reference to the considered sustainability issues. The analysis of the energy flows of the case study is also included in the objectives of this work.

This thesis has its conceptual basis on social metabolism and uses the methodological framework of Material Flow Accounting and Analysis. Although these tools are not really new, their application on the urban scale is not that widespread as it is on nationwide studies. A thorough literature review on how they have been used so far in the field of urban sustainability is necessary for their further understanding, enhancement and focus on aspects that have not been investigated so far. The aim of this thesis is to employ and further develop these tools for the assessment and measurement of urban sustainability. With the use of MFA's basic notions and methodological guidelines, the intention is to give a new perspective on how this framework can be used and open the way for new applications in the fields of local, regional and urban sustainability.

The focus of the study is on the artificial water flows and the municipal solid waste flows. These have been selected for their importance in the metabolic performance of any given system and their crucial role in sustainable development, not only on the urban but on the global scale as well. They are certainly issues that have been extensively studied, but the suggestion of this thesis is the development of methodologies for the separate accounting and analysis of these flows, able to be applied in a variety of spatial and temporal scales. This leads to the derivation of new sustainability indicators for the assessment of these flows' management, useful for the planning or redesigning of a system, the monitoring of its evolution and for comparisons between systems. Their main intention is to test a system's self-sufficiency in terms of water use and MSW management respectively and help in the revelation of new aspects of water and waste flows management that have not been studied yet.

Finally, these methodologies and indicators will be applied on a rather complex system with high population density and intense touristy and industrial activities that faces great environmental pressures. They shall be first used for the assessment of the entire system for a series of years, aiming to reveal changes in management strategies on the studied issues. They will then be applied on each of the urban subsystems comprising the case study separately with the objective to define the parameters that assist a better sustainability performance on the urban scale. This process shall demonstrate the grade of applicability and simplicity of the suggested methodologies and indicators and the quality of their results.

3. REGIONAL WATER FLOW ACCOUNTING AND A NEW INDICATOR AS TOOLS FOR SUSTAINABLE WATER USE ASSESSMENT IN URBAN REGIONS[17]

---

[17] This chapter builds on a paper published as Fragkou, M., Vicent, T. and Gabarrell, X. (2008) Artificial water flow accounting in a Mediterranean coastal region. In Malhotra, G. (ed.) Environmental Growth: A Global Perspective. Macmillan Publishers India: New Delhi. ISBN: 9780230636835

Abstract

This study is focused on the development and establishment of a methodology adequate to describe efficiently the artificial water flows in a regional system, referring to the water flows consisting of piped and drained water. Following that methodology, a water balance accounting is conducted for a time period of eight years in the region compiled of 27 coastal municipalities of the Barcelona metropolitan region, with a population density of more than 5 000 inhabitants per km^2. The methodology suggested is based on the Material Flow Analysis methodology presented by Eurostat, basically complementing it as it accounts of all artificial water flows of the studied system. At the same time, a simple water use sustainability indicator is suggested, based on the system's demands for water and the renewable water it receives in the form of rainwater.

3.1. Introduction

It has been noted that, like the human metabolism, socioeconomic systems require inputs of material and energy flows, which the system's physical and biological processes transform into products and services. These in turn produce outputs in the form of wastes and emissions. According to Martinez-Alier (2004), the first precursors of a biophysical approach to the economy appeared at the end of the 19th century; Podolinsky's work on agricultural energy flows and Marx's and Engels' interest in the interactions between the human economy and the natural environment, both expressed the concept of metabolism.

Urban ecology studies rooted in this concept have been developed and usually examine the ecology and evolution of cities. They characterise their metabolism (Harper and Graedel, 2007) as rapidly developing open systems that inevitably depend on their surroundings for the provision of natural resources and waste assimilation (Bai, 2007). Wolman originally introduced the concept of urban metabolism in 1965 (Wolman, 1965) considering the provision of adequate water supply, the effective disposal of sewage and the control of air pollution as the three metabolic problems that have become increasingly acute as a result of urban growth. Nowadays, urban metabolic issues such as high resource consumption and waste production not only concern urban sustainability but have an effect on the question of sustainable global development as well (Satterthwaite, 1997).

Since Wolman's first work numerous urban metabolism studies have been carried out in order to assess a city's progress towards sustainability and dematerialisation. A few years later two pioneering studies were published for the cities of Sydney (Aston et al., 1972) and Hong Kong (Newcombe, 1977). Two more studies have dealt with the latter, carried out by Boyden (1980) and Warren-Rhodes and Koenig (2001). Later on, Obernosterer et al. (1998) and Daxbeck et al. (2001) assessed the urban metabolism of the city of Vienna with the objective of identifying and quantifying the key material flows and stocks within the city and its dependence on resources provided by its surroundings. A study on the Taipei metropolis was presented in 1998 (Huang, 1998) and the material and energy flows of the city of Barcelona for the period between 1985 and 1991 were presented by Barracó et al.

(1999). More recently, urban metabolism studies conducted in five metropolitan areas worldwide were analysed over the course of the last 20 years (Kennedy et al., 2007). They concluded that there is a general tendency of increasing per capita metabolism in terms of water, materials, energy and nutrients.

Water is by far the largest component of urban metabolism in terms of mass. Kennedy et al. (2007) single out water flows because they consider changing ground water levels one of the resulting consequences of urban metabolism that can have significant impact on the sustainability of cities. Complementing this view, we detect a need to account for water flows in order to understand how cities function in terms of water consumption, their effects on water resources depletion and finding possible solutions to management problems. Urban water flows can be differentiated into natural flows including surface water, groundwater, precipitation and evaporation, and artificial flows corresponding to piped and drained water (Stanners and Bourdeau, 1995)

A balance sheet of inputs and outputs can be analysed because the processes of a city system are based on the laws of thermodynamics; Material Flow Analysis (MFA) can be a useful tool for satisfying the need for analyzing the urbanisation process and the way cities and metropolitan areas are transforming the earth’s ecosystems as a consequence of human activities (Huang and Hsu, 2003). MFA is based on the concept of societal metabolism and its foundations were set on the concepts of material and energy balancing presented by Ayres and Kneese in 1969 (Ayres and Kneese, 1969). MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2004). Based on the mass conservation law, a major field of MFA represents the analysis of the metabolism of cities, regions, and national or supranational economies by connecting the sources, the pathways and the intermediate and final sinks of the total material flows within the system. The principle concept underlying the economy-wide MFA approach is a simple model describing the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment dependent on a constant throughput of materials and energy (Eurostat, 2001). Considering methodological guidelines on conducting a national-wide MFA, these were set by a first methodological guidebook that was published by the European Statistical Office (Eurostat, 2001). According to this, one of the main uses of MFA is the derivation of indicators, which can give an aggregated picture of ‘societal metabolism’. These indicators have been introduced to official reports with the aim to identify and describe socioeconomic activities which cause pressures on the environment and provide an overview on the issues of resource use, waste disposal and emissions to air and water (Hinterberger et al., 2003).

Because it is a significant flux in a city's metabolism and one of the key issues in sustainable development (EEA, 2001), the sustainable supply of water along with its demand and administration is an important and complex component of sustainability. According to the European Environmental Agency (EEA, 2001), "*...sustainability must seek to balance the water available at any particular point in time and space with the demand for water for various 'uses', and the need for enough water to safeguard human health and the aquatic ecosystem...*" Gleick et al. (1996) define sustainable water use as "*...the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it...*"

The abovementioned definitions of sustainable water use can be summarised as an environmental balance of supply and demand. The need for quantifying this ratio has resulted in the establishment of various indicators, both on the European and the international level. These indicators attempt to evaluate the sustainability of a determinate system in terms of water use and management.

One of the most widely used indicators for assessing the stress on water is the Falkenmark Indicator (Falkenmarck et al., 1989). It compares the total freshwater resources with the total population in a country and indicates the pressure that population puts on water resources, including the needs of natural ecosystems. Alternatively, the EEA proposes the Water Exploitation Index (Lallana and Marcuello, 2004), defined as the mean annual total abstractions of freshwater (equal to the mean annual precipitation minus the mean annual evapotranspiration plus the mean annual inflows in each country) divided by the mean annual freshwater resources. This indicator describes how the total water abstractions put pressure on water resources, identifying those countries having high abstractions in relation to their resources. Other established indicators include the Dependency Ratio (UN, 2003) which expresses the part of the total renewable water resources originating outside a country, calculated as the ratio between the external renewable resources and total natural renewable resources. Finally, the Consumption Index suggested by Margat (1996) expresses the ratio between water consumption and total renewable resources.

In this paper we propose the establishment of a new indicator that does not assess the stress on water resources, as most already existing indicators do, but examines a system's self-sufficiency in terms of water consumption by evaluating its sustainable water use. In other words, instead of considering the actual use of freshwater resources, it explores whether sustainability could be achieved using the renewable water a region receives in the form of rainwater. The indicator takes into account factors such as population statistics (because water consumption is strongly related to the number of inhabitants of an area), and land use data, (it only considers rainfall on urbanised areas). The latter assumption allows remaining rainfall to be available for agricultural uses and the natural water cycle. Unlike some of the abovementioned indicators that neglect temporal and spatial variations (WSM, 2004), this indicator is simple to calculate and can be used for applications and comparisons in a wide range of temporal and spatial scales.

3.2. System Description

With regards to water management in the system under study, the responsible body is the Catalan Water Agency (Agència Catalana de l'Aigua), a public organisation attached to the Ministry of the Environment and Housing of the Government of Catalonia, with full authority over the water cycle in the inland basins of Catalonia.

The main water sources for the region until 2003 were superficial and included the Tordera, Ter and Llobregat rivers, while the majority of municipalities complemented their supply with water obtained from local wells and aquifers. Volumes of water extracted and consumed from the latter sources are very hard to measure and control, which make accurate resources contribution and water accounting a difficult task. During 2003, the Tordera desalinisation plant was put in service, providing with water seven of the studied municipalities; still, as it was a start-up period, it is not taken into account in this study.

The whole region is supplied with water from the four different potable water treatment plants (PWTPs) of Palafolls, Abrera, Cardedeu and Sant Joan Despí. These are all located outside the area under study. The plants of Sant Joan Despí and Abrera treat water originating from the Llobregat River. The Cardedeu plant is under the management of the Aigües Ter Llobregat (ATLL) Company and treats water from the Ter River. Lastly, the Palafolls plant distributes water from the Tordera River. Two private companies (AGBAR and SOREA) are the main administrators of the secondary water supply networks in the study region while only one municipality is under the administration of a public system (Aigües del Prat).

Yet, the prolonged drought period that the region experienced recently, had as a consequence important policy shifts on water management and distribution issues with the objective to complement its freshwater sources. The implementation of extreme measures for the resolution of this situation included the provision of drinking water from France through seaborne shipments or the consideration of the diversion of the mouth of the Ebro River in the region of Aragon for the transfer of water in cases of emergency (el Periodico, 2008).

With the exception of the municipality of Castelldefels, all municipalities have a unitary network sewerage system that has been in development since the urbanisation of the area. The majority of treatment plants installed in the zone during the study period have primary and secondary treatment and all discharge treated water into the sea through outfalls. All wastewater treatment plants (WWTPs) serving the studied municipalities are located inside the system.

3.3. Methodology

The suggested methodology uses the MFA methodological guidelines presented by Eurostat (2001). Economy-wide MFA and balances basically provide an aggregate overview, in tonnes, of annual material inputs and outputs of an economy. The whole economy including production and consumption activities is viewed as a single black box and only flows that cross the system boundary of the economy are recorded; these generally include the inputs and outputs of an economy, as well as the upstream flows associated with them (indirect flows).

Water flows are not accounted for in national MFA studies because they represent enormous mass flows with one order of magnitude more than all other materials (Eurostat, 2001). In a typical MFA, water is counted as a memorandum item for balancing purposes. Usually this is in the form of the water content of biomass or mineral inputs or waste outputs. Eurostat's recommendation is the drawing up and separate presentation of water flow accounting.

In this study, all artificial water flows of the system are accounted for. In addition, a part of the natural input flows (i.e. rainwater) not included in the water balance has been calculated and used as a useful tool for assessing the system's sustainability in terms of water consumption. It must be noted that all calculations have not been done for the system as a whole, but in a disaggregated manner at a municipal level. After calculations were made on a municipal level, the sum of results for the municipalities gave an aggregate view on the system.

System Definition The system boundaries were defined in line with the Eurostat methodological guidelines. According to them (Eurostat, 2001), the system boundary is defined:

1. by the extraction of primary materials from the national environment and the discharge of materials to the national environment;
2. by the political (administrative) borders that determine material flows to and from other economies (imports and exports).

Study Period The study period selected is an eight-year series between 1996 and 2003. The specific period was chosen because we expected to find more data for later time periods. This factor is of critical importance since, according to Hammer et al. (2003), data availability is one of the crucial points for the success of regional MFA studies. Furthermore, a time period of eight years is sufficient to detect changes in the metabolic profile of a region and to analyze impacts of changed political frameworks on regional material flows.

Data Sources Given that the data needed to be obtained on a municipal level, their collection was a rather difficult and time-consuming task. Although data were ample on a national and county level, few factors were available on a municipal level. As expected, centralised data were not available, but rather dispersed among different sources. Most data were found for municipalities that had performed environmental audits or had Agenda 21 reports published (these municipalities are Badalona, Castelldefels, Gavà, Malgrat de Mar, Montgat, Pineda de Mar, Vilanova i La Geltrú). Similarly, some environmental audits at a county level contained very useful information for both system description as well as numerical data (Innova, 2000). Sufficient data were also found for the eight coastal municipalities that are under the administration of the Metropolitan Environmental Authority (Entitat Metropolitana del Medi Ambient - EMMA), as this entity issues annual environmental reports (Entitat Metropolitana del Medi Ambient, 2004). Finally, some data were acquired through personal communication with employees of public entities and private companies.

Data on the PWTPs were found in the annual ATLL reports, which are available on the company's website (ATLL, 2008). For reports on the years 1996-2000 that were not available online, hard copies were sent by post by the company after personal communication with ATLL personnel. Data on population statistics and basic demographical characteristics on a municipal level were encountered through the two statistical offices covering the area under study, namely the Spanish National Statistics Institute (INE, 2006) and the Statistical Institute of Catalonia (IDESCAT, 2006).

Database creation After all data were collected, a database was created, including all artificial water flows at a municipal level. These included artificial input and output flows and their associated indirect flows. Necessary data should be at the municipal and plant level, referring to PWTPs and WWTPs. Data on plants must include volumes of freshwater treated and distributed to each municipality by the PWTPs and the wastewater treated in WWTPs. The combination of this data allows for the calculation of water losses in the primary and secondary distribution networks. Municipal level data must include the total volume of water distributed in the primary water supply distribution network, the total volume of recorded water use and data on local wells and aquifers (i.e. domestic extraction). All data must be yearly and, referring to water flows, should be in m^3/y.

Artificial water metabolism description and accounting The annual artificial water flow metabolism of each municipality is described based on the database created. These disaggregated municipal data compose the system's overall metabolism and a comprehensive artificial water flow accounting can be then made.

Calculation of the water self-sufficiency indicator By combining data on artificial water input flows and renewable water inputs in the system, the overall water self-sufficiency indicator can be calculated.

3.3.1. Artificial water balance accounting

The sea and the rivers crossing the system analysed are considered to be outside its boundaries. Therefore, all flows originating from or directed to these bodies are counted as imports and exports respectively. As a consequence, precipitation and water evaporation are omitted from the water balance accounting methodology suggested here. Figure 3-1 demonstrates a complete schematic diagram of the water flows and infrastructures of an assumed regional system. It also includes functions inside the system's boundaries, whose limits are indicated with the dotted line. The abovementioned components that are not taken into account, such as rainwater inputs and evaporation outputs, are included as well with the aim to give a more comprehensive picture of the system. The phases where water losses can take place in both primary and secondary water supply networks are indicated with the small twisted arrows.

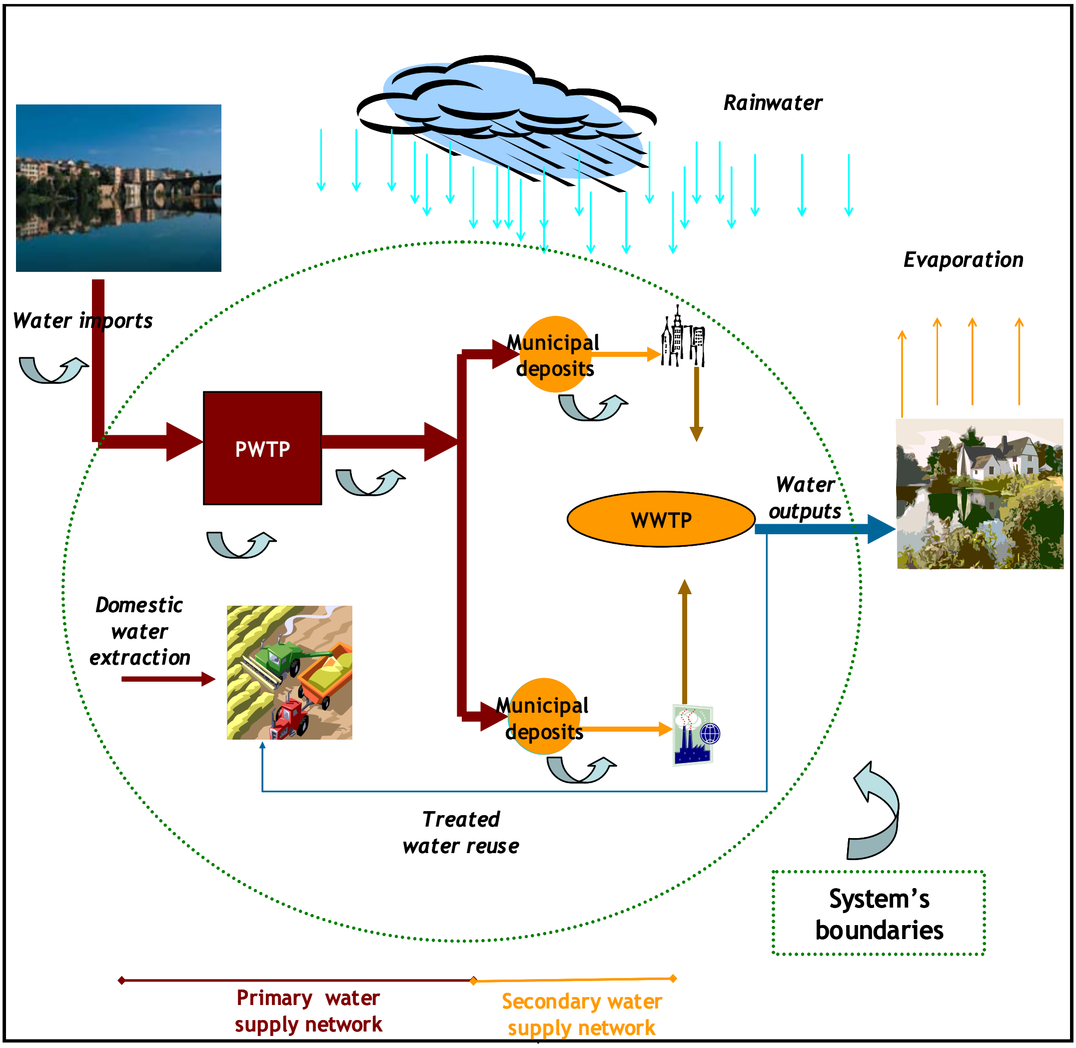


Figure 3-1 Schematic diagram of a regional system, in terms of water, including its basic elements, flows and infrastructures and the phases where losses occur

The term 'indirect flow' is used for both import and export associated flows when considering up-stream material input and output flows. This term perfectly describes the flows analysed here, which are defined by Eurostat (2001) as "*...the up-stream material input flows that are associated to imports but are not physically imported...*" on the input side and as "*...the upstream material output flows associated to exports but not physically exported...*" on the output side. In this study, we consider as indirect flows the water losses in both primary and secondary water distribution networks. The calculation, control and restriction of these losses are essential for a more sufficient and sustainable water use.

3.3.2. Input flows

The volume of water used by the system, within its boundaries, is counted as water input flows. Total water input flows include water imports and domestic extraction of water. Water that enters the system originating from sources outside its boundaries and consumed by it, is counted as imports. These imports can represent various sources, such as PWTPs located outside the system's boundaries, imports of bottled water and water transferred by vessels or container trucks. Water obtained from local wells and aquifers is counted as domestic extraction. Total artificial water input flows for a single municipality are calculated according to the next equation:

(Equation 3-1) $$I_{m,x} = DE_{m,x} + IM_{m,x}$$

Where,

I $_{\mathbf{m,x}}$ total artificial water input flows for municipality *m* and year *x*, m^3/y

DE $_{\mathbf{m,x}}$ domestically extracted artificial water input flows for municipality *m* and year *x*, m^3/y

IM $_{\mathbf{m,x}}$ imported artificial water input flows for municipality *m* and year *x*, m^3/y

It should also be noted that water used for electricity production is not counted. This is because it leaves the system after its use and the rivers crossing the system and the sea are considered outside the system's limits.

Concerning the case study, the water supplied by the four PWTPs serving the area is counted as water imports. Bottled water consumed is also considered an import since there are no bottling plants located in the system. Domestic extraction is the water acquired by local wells and aquifers. The values for bottled water consumption were extrapolated from per capita data found on national level at the European Federation of Bottled Water website (EFBW, 2007), including the consumption of containers of more than 10 litres.

3.3.3. Indirect flows associated with water inputs

The indirect flows associated with water inputs are the water losses in the primary distribution network that occur between the water's capture and its storage in the holding reservoirs. There are three different types of water losses detected in this stage. The first is calculated as the difference between the volume of water for treatment captured from the river basin or underground reservoir and the actual volume of water entering the plant. The second takes place during the water's treatment in the plant and is associated with the type of treatment the plant performs, its unit operations and pipeline maintenance; these losses are primarily associated with the treatment in decanters and carbon and sand filters. Finally, the last type of water losses equals the difference between the volume of water treated and the volume of water sent to the reservoirs. The sum of these types of losses provides us with the total annual water losses taking place during primary water supply for each plant.

A common methodology was followed in order to calculate all types of input associated with indirect flows; first, an annual coefficient was derived for each PWTP based on the total annual volume of water distributed to the total of the municipalities that it serves (Equation 3-2). After a coefficient was obtained per m^3 of water distributed each year, it was applied to each municipality, multiplying it by the volume of water that was distributed to it by the plant, using Equation 3-3.

(Equation 3-2)

$$ctr_{p,x} = Vdi_{p,x} \div Ven_{p,x}$$

Where,

ctr $_{p,x}$ performance coefficient for PWTP p and year x

Vdi $_{p,x}$ total volume of water distributed by PWTP p for year x, m^3/y

Ven $_{p,x}$ volume of water entering in PWTP p to be treated for year x, m^3/y

(Equation 3-3)
$$IFP_x = \sum_{\substack{p=0\\m=0}}^{n} \left(ctr_{p,x} \times PI_{m,x} \right)$$

Where,

IFP $_x$ total indirect flows associated with primary water distribution network for the system for year x, m^3/y

ctr $_{p,x}$ performance coefficient for PWTP p and year x

PI $_{m,x}$ volume of water provided by PWTP p to municipality m for year x, m^3/y

3.3.4. Output flows

Water outputs include the total volume of water leaving the system's boundaries. This includes wastewater that is either directly discharged in the sea or rivers without prior treatment, or treated water leaving the WWTPs. Treated water that is recycled or reused is not counted as part of output flows since it is always reused inside the system. However, if it is used for irrigation purposes it is considered as an output to the environment. Water outputs consist of the total volume of recorded water consumed for domestic, municipal, commercial and industrial uses in the system's secondary water supply networks, together with the volume of bottled water consumed, less reused water. The percentage of water reuse for each WWTP serving the system is also taken into account. Total artificial water outputs for a single municipality are calculated with the equation below.

(Equation 3-4)
$$O_{m,x} = Vre_{m,x} + Vbo_{m,x} - \left(Vre_{m,x} \times xre_{p,m,x} \right)$$

Where,

O $_{m,x}$ total artificial water output flows for municipality m and year x, m^3/y

Vre $_{m,x}$ volume of recorded water use in municipality m for year x, m^3/y

Vbo $_{m,x}$ volume of bottled water consumed in municipality m and year x, m^3/y

xre $_{p,m,x}$ percentage of water reuse for the WWTP p serving municipality m for year x, %

It must be noted that although rainwater is collected by most municipalities' sewage system and ends up in WWTPs, this contribution to total water outputs is not considered in this methodology.

3.3.5. Indirect flows associated with water outputs

Indirect flows associated with water outputs include secondary water supply losses that are related to each municipality's secondary distribution network, defined as the difference between the volume of water supplied to the network and the volume of water recorded by the users (Miralles and Porta, 2002), as expressed in Equation 3-5. Losses in this stage are associated with distribution pipe leakages, recording errors and malpractices, and users without a consumption measurement system. With regards to the entirety of Catalonia, the total distribution network efficiency, measured as the difference between the volume of water distributed and the volume of recorded water, was 74.6% in 2003[18]. Based on the above remarks, Figure 3-2 illustrates the water balance for a regional system including input, output and associated indirect flows.

(Equation 3-5)

$$IFS_x = \sum_{m=0}^{n}\left(Vse_{m,x} - Vre_{m,x}\right)$$

Where,

IFS $_x$ secondary supply losses for municipality *m* for year *x*, m^3/y

Vse$_{m,x}$ total volume distributed in the secondary water supply network to municipality *m* for year *x*, m^3/y

Vre $_{m,x}$ volume of recorded water use in municipality *m* for year *x*, m^3/y

---

[18] This value is translated into 53.11 m^3 of water not counted annually per user. Furthermore, under-registration of costumers' meters alone can reduce the network's performance between 5% and 12%.

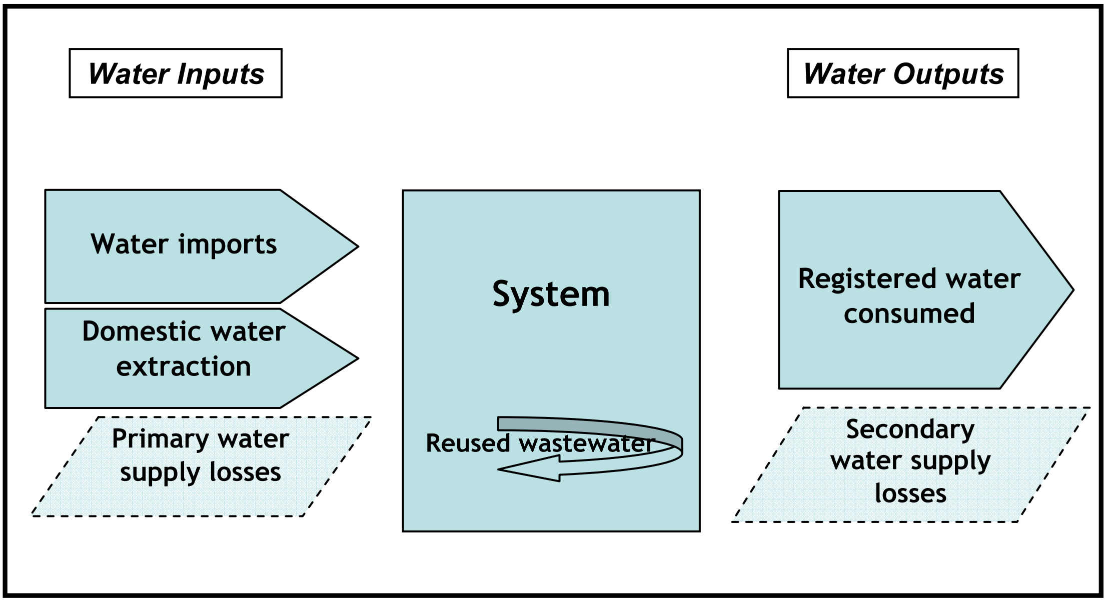


Figure 3-2 General artificial water balance scheme, including inputs, outputs and associated indirect flows

3.4. Water self-sufficiency indicator

In order to test the system's sustainability in terms of water consumption, a self-sufficiency indicator was identified by using the system's renewable resources inputs as a sustainability metric. The indicator is defined as the ratio of the system's water consumption to the volume of renewable water it receives. For a system comprised of various municipalities the overall indicator is expressed by the following equation:

(Equation 3-6)

$$wss_x = \sum_{m=0}^{n} \left[\left(I_{m,x} + IFP_{m,x} \right) \div RW_{m,x} \right]$$

Where,

wss_x water self-sufficiency indicator value for the whole system for year *x*

$I_{m,x}$ total artificial water input flows for municipality *m* and year *x*, m^3/y

$IFP_{m,x}$ total indirect flows associated with primary water distribution network for municipality *m* and year *x*, m^3/y

$RW_{m,x}$ total renewable water inputs for municipality *m* for year *x*, m^3/y

I, IFP We consider as total artificial water inputs the total volume of piped water used by the system, including both water imports and domestic water extraction. This figure aims to represent the needs of the studied system in terms of water consumption. The indirect flows associated with these inputs are also taken into account.

RW Renewable water inputs are equal to the rainwater precipitation in function with land use, in the system. We consider as a possible renewable water resource only the volume of water that falls on the urbanised areas of the system and that can be collected in rainwater storage tanks. Rainwater that falls on non-urbanised surfaces is directly used by nature through processes such as surface runoff and groundwater recharge. It is included in the natural cycle of water, which is outside the scope of this paper.

The total rainwater input to the system was calculated using monthly municipal precipitation data in mm provided by the Meteorological Service of Catalonia (Meteocat, 2006). Land use data on a municipal level were provided by the Statistical Institute of Catalonia (IDESCAT, 2006). Annual precipitation values were calculated by adding up the municipal monthly precipitation data. The total amount of rainwater the system received that year was acquired by multiplying this number with the urbanised surface of each municipality. Precipitation on urban areas in m^3/cap·y was calculated by dividing the latter figure with the equivalent population.

3.4.1. Interpretation of the indicator

We consider unity as the optimum value for the proposed water self-sufficiency indicator for an urban system that could be self-sufficient in terms of water use without the need to extract water from its surrounding area. A value of the indicator equal to or very close to unity (i.e. in the range of: $0.75 < wss < 1.25$) means that the rainwater received on sealed surfaces exceeds, and can theoretically cover, the water needs of the studied area. This suggests sustainable water consumption and a self-sufficient system in terms of water management. Indicator values higher than unity correspond to systems consuming more water than the equivalent renewable water they receive, implying dependence on water imports and/or domestic extraction.

Based on the mathematical expression of the indicator, the lower a system's indicator value, the more sustainable it should be. Nevertheless, wss indicator values much lower than unity could imply a highly urbanised system that does not form a suggested sustainability indicator or an objective for an urban system in this work. Although rainwater falling on concrete is seen as a renewable water resource, it must be noted that the unrestrained expansion of sealed areas in cities and urban systems is not suggested as a solution to water use sustainability nor as a water management sustainability indicator. Our proposal is to construct, expand and/or make use of the possible existing facilities for rainwater capturing, making the most of this fraction of rainwater that has no biological function in the natural ecosystem between its precipitation and its recharge to the sea or other waterways. What's more, in combination with poor urban planning and deficient drainage systems, rainwater often causes floods in the urban environment and this could turn a problem into a sustainable solution at various levels.

3.5. Results and discussion

Although the study period for the region's water balance accounting was originally planned from 1996 to 2003, data scarcity restricted the study to a shorter time period. Consequently, only data regarding the years from 1998 to 2003 are presented in this section.

3.5.1. Indirect flows associated with water inputs and outputs

Annual per capita water losses associated with primary and secondary water supply distribution are given in Table 3-1[19]. As can be seen, losses associated with secondary water supply appear to be much higher than the ones taking place during primary distribution and

---

[19] It must be noted that Table 1 does not include year 2003 with reference to primary supply losses as this year includes data from municipalities supplied with water from the Palafolls PWTP and the Tordera desalinisation plant. No assumptions could be made on the treatment and distribution losses of that plant, still they are considered to be important aspects relevant to this work that will be developed in the future.

display a general downward tendency, demonstrating an improvement in municipal distribution network efficiency. With reference to primary water supply, losses mainly occur in the distribution stage where they are up to 10 times higher than the ones occurring during water treatment. Augmented efficiency in the primary water supply network serving the system is observed as well.

Table 3-1 Treatment, distribution and total primary water supply losses and total secondary water supply losses in the studied system, in m^3/cap·y

Year of study	*Treatment losses*	*Distribution losses*	*IFP* *Total primary water supply losses*	*IFS* *Total secondary water supply losses*
1998	**-**	**-**	**8.56**	**32.37**
1999	**-**	**-**	**7.86**	**26.87**
2000	**1.82**	**5.06**	**6.88**	**19.51**
2001	**2.17**	**4.76**	**6.93**	**22.24**
2002	**1.24**	**3.85**	**5.10**	**21.97**
2003	**-**	**-**	**-**	**21.35**

3.5.2. Water Balance Results

Table 3-2 includes total annual water inputs, also separated into volumes of imported water and domestic extraction, and the contribution of imports to total inputs. These figures reveal the region’s dependence on water imports, since domestic water extraction only contributes to 10% of total annual water inputs. This lack of self-sufficiency in water supply is quite stable, with no annual fluctuations. Up to 2000, total water inputs show a steady decrease during the first three years, while a small increase in water demand is demonstrated for 2001. On the contrary, total water outputs showed a slight increase between years 1998 and 1999, and 2000 and 2001. Because outputs are directly related to secondary supply networks’ efficiency, this stability in their annual volume could be attributed to the fact that relatively stable values were used for municipal networks’ performance.

The sum of the results presented in this chapter can be summarised in the form of water balance schemes, illustrating a full water flow analysis of the region for each of the years selected.

Table 3-2 Total annual inputs, disaggregated in imports and domestic extraction, and total annual outputs, in m3/cap•y

Year	*I* *Total water inputs*	*IM* *Water imports*	*DE* *Domestic water extraction*	*Imports contribution to water inputs (%)*	*O* *Total water outputs*
1998	**105.5**	**94.3**	**11.1**	**89.4**	**72.4**
1999	**100.3**	**90.2**	**10.2**	**89.9**	**72.8**
2000	**94.4**	**84.9**	**9.5**	**89.9**	**74.2**
2001	**96.6**	**86.8**	**9.8**	**89.9**	**73.7**
2002	**95.0**	**84.2**	**10.9**	**88.6**	**71.0**
2003	**92.3**	**77.3**	**9.3**	**89.3**	**68.5**

3.5.3. Water self-sufficiency assessment

In order to calculate the system's water self-sufficiency indicator, the rainwater entering the system was estimated using precipitation data for the year 2002. The results, presented in Table 3-3, reveal that the total rainwater received by the system has a total volume considerably higher than the total water demands of the system for each year studied. Furthermore, urban precipitation in m^3 per capita and day greatly exceeds the average water consumption in the area. Total water outputs are easily covered by the equivalent volumes of precipitation on urbanised areas. In agreement with the above result, the water self-sufficiency indicator has a value of 0.72, clearly demonstrating the system's self-sufficiency and sustainable water consumption.

Table 3-3 Calculation of the water indicator for the studied system and three selected municipalities, for 2002

Studied system	*Total surface covered (km^2)*	*Percentage of urbanised surface* [a, b] *(%)*	*Total Precipitation (m^3/y)*	*Precipitation on urbanised surface (m^3/y)*	*RW* *Precipitation on urbanised surface ($m^3/cap·y$)*	*(I+IFP)* *Water Consumption ($m^3/cap·y$)*	*wss*
Entire system	**478.2**	**76.1**	**433 743 600**	**330 453 219**	**139**	**100.1**	**0.72**
Barcelona	**100.4**	**89.6**	**94 094880**	**84 301 100**	**55.2**	**97.2**	**1.76**
Sitges	**43.8**	**53.5**	**38 989 446**	**20 865 600**	**976**	**83.5**	**0.09**
Sant Adrià de Besòs	**3.8**	**100.0**	**3 679 540**	**3 679 540**	**113**	**108**	**0.96**

[a] Source: IDESCAT (2008)

[b] As urban area is accounted the total area of the municipality excluding the used agricultural land, non used agricultural land and the terrain covered by forests, desert, grass and thicket

In addition to the study for the whole system, the wss indicator was calculated in a disaggregated manner for three of the municipalities included in the system under study (Table 3-3). Barcelona is a highly urbanised municipality and the most densely populated among the studied ones. Sitges is a residential tourist area predominated by semi-detached houses resulting in low density population, on the contrary to the industrialised municipality of Sant Adrià de Besòs that has a small surface but elevated population. Barcelona appears to be much less self-sufficient than Sitges, although it has a much higher percentage of sealed surfaces, attributed to the lower per capita consumption in the latter and the high population density of Barcelona (30 times higher than that of Sitges). The self-sufficiency of Sant Adrià de Besòs is clearly attributed to the absolute domination of sealed surfaces, regardless of the fact that it has the highest per capita consumption of all three municipalities. Studying these results it appears to be quite difficult to plan individual water management strategies at municipal level. Since the system as a whole is served by four PWTPs, it seems more viable design a global strategic scheme for a sustainable provision and management of water.

We have tried to propose a feasible water management strategy that can consider and take advantage of this renewable water resource. As an example, we compared the above results with the existing rainwater storage reservoirs of the municipality of Barcelona (which covers 21% of the system's surface) with a capacity of 522 400 m^3 in 2008. In 2002, the year of the study, these deposits had a volume of 274 400 m^3. Yet, according to the Sewerage of Barcelona Company (CLABSA, 2006), they only retain rainwater for flood prevention purposes and gradually release this water to the sea. Our suggestion is a different use of the existing infrastructure and a change in the administration's goals and priorities. This possibility has been studied in depth by others and various ways of collecting and utilizing rainwater in urbanised areas, both for potable and non-potable purposes, have been suggested (see for example Kim et al., 2004; Herrmann and Schmida, 1999; Villarreal and Dixon, 2005). These studies cite examples that have been applied to other urban areas demonstrating the viability of this proposal.

3.6. Conclusions

In this work, a methodology for the description of artificial water metabolism and a new water use sustainability indicator have been suggested and applied on the coastal municipalities of the Barcelona Metropolitan Area. Results of interest in the area of artificial water flow accounting are mainly found in the primary and secondary water supply losses. Compared to the total water inputs of the system, including water imports, domestic extraction and primary water supply losses, the amount of lost water represents approximately 30% of the total annual water inputs; this results in enough water to cover the annual needs of almost 700 000 residents of that area.

Results demonstrate that water flows have a great significance for the studied system. The municipalities included in it merely occupy 1.5% of Catalonia's surface and represent 36% of its population. Still, the system's demands in water are more than 200 million tonnes of water annually, while there were only about 160 millions of tonnes of material input for all of Catalonia in 2000 (Sendra et al., 2006).

The suggested indicator evaluates the use of a fraction of rainwater that not only is neither exploited nor has a biologic function in the ecosystem, but in many cases causes flooding problems. It appears to be a useful evaluation tool for existing urbanised systems because it can detect drawbacks and changes in relevant infrastructure. Furthermore, in combination with other planning and sustainability indicators, it can serve as an urban planning tool for future urbanisations.

Although some flows related to industrial and agricultural uses and domestic extraction could have been omitted, the results in the study system reveal that our system is indeed sustainable in terms of consumption. On the other hand, this volume of unexploited renewable water input, in conjunction with the important water distribution losses and the low percentages of water reuse, imply an unsustainable water management policy. This result, together with a self-sufficiency indicator value of less than 1, is of great importance when the special features of the selected area are taken into account. It is a coastal tourist area in a Mediterranean region with no intense rainfall that receives great pressures in terms of water consumption. We can subsequently deduce the main results of the sustainability evaluation as sustainable water consumption by the people, but an insufficient and unsustainable water management from the part of the governing bodies. These facts can give us an idea of how sustainability and efficient resource use are not impossible objectives to achieve in a highly populated and industrialised region. Furthermore, they show us the paths to do so.

References

Aston, A. R., Millington, R. J. and Kalma, J. D. (1972) Nutrients in the Sydney area. Proceedings of the ecological society of Australia 7 (The city as a life system?), pp. 117-91

ATLL (2008) Aigües Ter Llobregat: Publicacions: Memòria. Aigües Ter Llobregat. Available at: http://www.atll.net/ca/page.asp?id=73

Ayres, R. U. and Kneese, A. V. (1969) Production, Consumption and Externalities. American Economic Review 59 (3): 282-97

Bai, X. (2007) Industrial Ecology and the Global Impacts of Cities. Journal of Industrial Ecology 11 (2): 1-6

Barracó, H., Parés, M., Prat, A. and Terrades, J. (1999) Barcelona 1985-1999. Ecologia de una ciutat. Ajuntament de Barcelona: Barcelona

Boyden, S. (1980) Ecological study of human settlements. Nature Resources 16 (3): 2-9

Brunner, P. H. and Rechberger, H. (2004) Practical handbook of material flow analysis. Lewis Publishers, CRC Press: London, New York, Washington, DC

CLABSA (2006) Activitats i realitzacions: Clavegueram: Dipòsits de BCN. Sewerage of Barcelona. Available at: www.clabsa.es

Daxbeck, H., Kisliakova, A. and Obernosterer, R. (2001) Der ökologische Fußabdruck der Stadt Wien. Ressourcen Management Agentur: Vienna

EEA (2001) Sustainable water use in Europe Part 2: Demand management. The European Environmental Agency: Copenhagen

EFBW (2007) European Federation of Bottled Waters: Facts and Figures. European Federation of Bottled Waters. Available at: www.efbw.org

El Periodico (2008) Una flota de 10 vaixells salvaran BCN de les restriccions a l'estiu. El Periodico, March 4, 2008. Available at: http://www.elperiodico.cat/comunes/crisisagua/cat/medidas6.asp

Entitat Metropolitana del Medi Ambient (2004) Metropolitan Environmental Data 2003. Entitat Metropolitana dels Serveis Hidràulics i del Tractatament de Residus (EMSHTR): Barcelona

Eurostat (2001) Economy-wide material flow accounts and derived indicators. A methodological guide. Office for Official Publications of the European Union: Luxembourg

Falkenmark, M., Lundqvist, J. and Widstrand, C. (1989) Macro-scale water scarcity requires microscale approaches: aspects of vulnerability in semi-arid development, Natural Resources Forum. 13 (4): 258-267

Gleick, P. H., Loh, P., Gomez, S. V. and Morrison, J. (1996) California Water 2020: A Sustainable Vision. Pacific Institute for Studies in Development, Environment and Security:

Oakland

Hammer M., Giljum S., Bargigli S. and Hinterberger, F. (2003) Material Flow Analysis on the regional level: Questions, Problems, Solutions, Working NEDS Papers 2. SERI: Hamburg

Harper E. M. and Graedel, T. E. (2004) Industrial ecology: a teenager's progress. Technology in Society 26: 433–445

Herrmann, T. and Schmida, U. (1999) Rainwater utilization in Germany: efficiency, dimensioning, hydraulic and environmental aspects. Urban Water 1: 307-316

Hinterberger, F., Giljum, S. and Hammer, M. (2003) Material Flow Accounting and Analysis (MFA): A Valuable Tool for Analyses of Society-Nature Interrelationships. SERI Background Paper Nr. 2. Sustainable Europe Research Institute (SERI): Vienna

Huang, S. (1998) Urban ecosystems, energetic hierarchies and ecological economics of Taipei metropolis. Journal of Environmental Management 52: 39-51.

Huang, S. and Hsu, W. (2003) Materials flow analysis and emergy evaluation of Taipei's urban construction. Landscape of Urban Planning 63: 61–74

IDESCAT (2006) Territori: Banc d'estadístiques de municipis i comarques: Cens agrari: Distribució de la superfície agraria. Web de l'estadistica oficial de Catalunya. Institut d'Estadistica de Catalunya. Available at: http://www.idescat.cat/

INE (2006) Instituto Nacional de Estadistica. Databases available at www.ine.es

Innova (2000) Environmental audit of the Baix Maresme. Document available at http://www.maresme2015.net/documents/auditoria_ambiental_sintesi_bm.pdf

Kennedy, C., Cuddihy, J. and Engel-Yan, J. (2007) The Changing metabolism of cities. Journal of Industrial Ecology 11 (2): 43-59

Kim, R-H., Lee, S., Kim, Y-M. and Suh, J-Y. (2004) Developing technologies for rainwater utilization in urbanized area. Environmental Technology 26: 401-410

Lallana, C. and Marcuello, C. (2004) Indicator Fact Sheet (WQ1): Water exploitation index, European Environment Agency: Copenhagen

Margat, J. (1996) Les ressources en eau: conception, évaluation, cartographie, compatabilité. Manuels & Méthodes 28, FAO/BRGM. Editions BRGM: Orleans

Martinez-Alier, J. (2004) Marx, Energy and Social Metabolism. Encyclopaedia of Energy. Doi:10.1016/B0-12-176480-X/00155-8

Meteocat (2006) Climatic Atlas of Catalonia. Meteorological Service of Catalonia. Available at: www.meteo.cat/ marcs/marcclima.html

Miralles, H. and Porta, E. (2002) El abastecimiento de agua en Barcelona, Sociedad General de Aguas de Barcelona, S.A. (Agbar) Fundacion Canal de Isabel Ii Seminario; El agua en las grandes ciudades europeas: La gestión de la demanda

Newcombe, K. (1977) Nutrient flow in major urban settlement: Hong Kong. Human Ecology 5

(3): 179-208

Obernosterer, R., Brunner, P., Daxbeck H., Gagan, T., Hendriks C., Morf L., Paumann R. and Reiner, I. (1998) Materials accounting as a tool for decision making in environmental policy - Urban metabolism of Vienna. Technical University of Vienna: Vienna

Satterthwaite, D. (1997) Sustainable cities or cities that contribute to sustainable development. Urban Studies: 34 (10): 1667–1691

Sendra, C., Gabarell, X. and Vicent, T. (2006) El análisis de los flujos de materiales en la ecología industrial: una herramienta para alcanzar el desarrollo sostenible. Ingeniería Química 435 (11): 115-121

Stanners, D. and Bourdeau, P. (eds) (1995) Europe's Environment – The Dobris Assessment. The European Environmental Agency: Copenhagen

UN (2003) UN World Water Development Report: Water of people, Water for Life. UNESCO and Berghahn Books: Barcelona

Villarreal, E. L. and Dixon, A. (2005) Analysis of a rainwater collection system for domestic water supply in Ringdansen, Norrköping, Sweden. Building Environment 40: 1174-1184

Warren-Rhodes, K. and Koenig, A. (2001) Escalating Trends in the Urban Metabolism of Hong Kong: 1971–1997. Ambio 30 (7): 429-438

Wolman, A. (1965) The metabolism of the city. Scientific American 213: 179-190

WSM (2004) Water Strategy Man Newsletter: Issue 4. Available at: http://environ.chemeng.ntua.gr/WSM/ Newsletters/Issue4/Indicators_Appendix.htm

4. A NEW SUSTAINABILITY ASSESSMENT INDICATOR ON MUNICIPAL WASTE MANAGEMENT STRATEGIES

Abstract

In this paper we propose a new indicator suitable for the revision of municipal solid waste (MSW) management plans in line with basic waste management principles. The study is based on the concept of social metabolism and the methodology employs the monitoring of MSW flows. The value of the MSW management self-sufficiency indicator proposed reflects the capacity of a system to manage the amount of MSW it accepts and the grade of sustainability of the treatment practices followed within the system, valuing as the best option the use of residues as raw materials. Compared with waste recovery rates, the suggested indicator proves to be more comprehensive in assessing the sustainability of MSW management plans in medium-scale urban regions. In combination with information provided by other urban sustainability indicators, as water use and air pollution, the indicator can be a useful tool in decision making. In this paper, the case of a highly urbanised coastal Mediterranean area (the city of Barcelona and its surroundings) is studied and assessed for a time period of eight years.

4.1. Introduction

In the context of urban sustainability, MSW management is a multifaceted subject and problems associated to it are not restricted to the issues of waste minimisation, conservation of resources or the application of the best treatment technique. Special importance is given to the social aspects of waste management (Furuseth and O'Callaghan, 1991; Hsu, 2006; Joos et al., 1999; Pol et al., 2005).

The study of the output (waste) flows in a society's metabolism can provide useful information on waste generation, import and export flows, energy recovery and recycling rates, as well as on the depletion of raw materials (AWAST Project, 2003). According to the Material Flow Accounting (MFA) principles, inputs can either be added to an economy as socioeconomic stocks, or they can end up as outputs of socioeconomic metabolism (Haberl et al., 2004). Therefore, every material extracted from the environment to be used by the economy finally ends up in the environment and the final amount of outputs is ultimately determined by the magnitude of the inputs. The relation between the input and output flows of a socioeconomic system can help evaluate the course of dematerialisation. As this is directed towards the reduction of primary inputs into an economy (Bringezu and Moriguchi, 2002), the reduction of waste disposal can be considered as an indicator of dematerialisation as well. According to Friege (1997), data on waste streams and statistical inquiries into material flows must be standardised and combined. The amount of waste produced can also be seen as an indicator of a society's efficiency, particularly in relation to the use of natural resources and waste treatment operations (EEA, 2005).

A series of indicators has been proposed for the monitoring of MSW generation and treatment. The majority of the indicators are merely quantitative statements that mainly focus on MSW generation rates, treatment rates and prevalence of disposal options (Danish EPA, 2003). Typical examples of generation indicators are the total and per sector (e.g. household and commercial) annual MSW generation rates, either expressed in totals or per capita values. The amounts of MSW that is landfilled, incinerated or recycled, either in absolute values or percentiles are the most common waste management related indicators, while the landfilling of biodegradable waste and the recycling of packaging waste indicators are also monitored by the European Environmental Agency (EEA, 2007). Eurostat, the Statistical Office of the European Communities, uses the abovementioned generation and management indicators and complements them with data on the number, total area and remaining capacity of available waste recovery and disposal installations (Eurostat, 2004a; Eurostat, 2007). Similar indicators are proposed and used by the Organisation for Economic Co-operation and Development (OECD, 2004) and the UN Commission on Sustainable Development (UNCSD, 2001) among others.

Some institutions, such as the Danish Environmental Protection Agency, recognise the variety of environmental issues linked to waste management and the need for the establishment of new indicators based on a life cycle analysis (LCA) perspective (Danish EPA, 2003). These take account of energy and resource consumption and concerns on a global, regional and local level (e.g. global warming, acidification/eutrophication and ozone depletion respectively). MSW management plan evaluations using the LCA approach include the case studies of the Bologna district in Italy (Buttol et al., 2007), the city of Ankara in Turkey (Özeler et al., 2006) and the Basque region of Gipuzkoa (Muñoz et al., 2004).

Local, regional or national plans on waste management handle municipal solid waste, industrial solid waste, municipal and industrial wastewater and air emissions separately. Similarly, this study is focused exclusively on the MSW flows of a system, aiming to evaluate the corresponding management plans and policies. The objective is to complement the existing quantitative statements related to waste management with an indicator that allows the revision of a MSW management plan in line with basic waste management principles, based on the theory of social metabolism. Furthermore, the carrying capacity of a social system in terms of MSW treatment is assessed, which corresponds the amount of waste that this is capable of accepting, not only in technical terms but in terms of social equity as well[20].

A general methodology for calculating the MSW management self-sufficiency indicator is proposed and then applied to a selected area of study. This is a densely populated coastal

---

[20] The term 'carrying capacity' in this work exclusively refers to the capacity of a socioeconomic system to manage and recycle, within its limits, the MSW this generates. There is absolutely no intention of identifying the carrying capacity of a system with its MSW treatment capacity. The latter is, however, considered to be one of the dimensions of 'carrying capacity'.

zone, highly intensive in terms of industrial, commercial and tourist activities, which we consider to be a representative sample of a developed European urban region.

4.2. Methodology

The basis of the methodology presented here is Material Flow Accounting. Using some main MFA methodological concepts, as the input, output flows and the definition of system limits, a new methodology is developed to investigate some aspects of MSW management. MFA is an instrument for the macro-analysis of a socioeconomic system, examining it as a black box; the suggested methodology is a tool for analysing a system on a lower level, in terms of MSW management, taking into account the function of the MSW treatment plants included in the system under study. At this level of analysis we propose a new indicator that assesses in more detail a MSW management plan and its sustainability.

In the MFA methodology (Eurostat, 2001) there are three gateway flows for Domestic Processed Output (DPO) or Total Domestic Output (TDO) that is air, water and land. We choose in this study to follow the solid flows of a MSW management plan and focus on the way these are managed and the sustainability of these practices. The methodology follows the municipal solid waste flows generated in a system and the secondary waste flows occurring during their treatment.

As the methodology proposed is based on an accounting of municipal solid waste flows in terms of weight, air emissions and water flows generated by a socioeconomic system are omitted as they are of several magnitudes larger than the studied flows. Consequently, either municipal or industrial wastewater generated in a system is not a focal point for this study. However, flows of wastewater generated in MSW treatment plants are relevant as they are generated during the treatment of MSW flows. In other words, their weights are considered because they form part, as outputs, of the MSW management plan that is under evaluation.

➢ Definition of system limits

The indicator proposed is developed for urban systems of micro- to meso- level, ranging from municipalities to metropolitan areas. For matters of data availability, the system boundaries must correspond with current administrative regions. In line with the Eurostat methodological guidelines (Eurostat, 2001), we define the system boundaries by the political borders that determine material flows to and from other economies (imports and exports).

A system diagram is given in Figure 4-1 displaying all internal and external MSW flows of a hypothetical system. Of all residues generated during the production and consumption processes of a socioeconomic system, only municipal solid waste is taken into account (G). This can either be treated in the system's plants (I_{dom}), treated in plants outside the system (I_{exp}), or be landfilled (I_{landf}) or directly used as raw material (R), either inside or outside the system.

The system input flows included in the weight balance consist of all the solid municipal waste flows this receives to be treated in its plants (I_{imp}). Input flows not accounted for include wastewater flows to be treated in the system, externally generated air emissions and waste landfilled within its limits without previous treatment. System output flows taken into account consist of the municipal solid waste directly sent to be treated in external plants (I_{exp}) and the solid and liquid secondary waste flows generated in the system's MSW treatment plants (O_B) that are either exported for further treatment or deposited to the environment. System outputs not considered in the methodology are the wastewater flows treated in external plants and the air emissions dismissed to the environment (either from the production/consumption processes or during the operation of the MSW treatment plants).

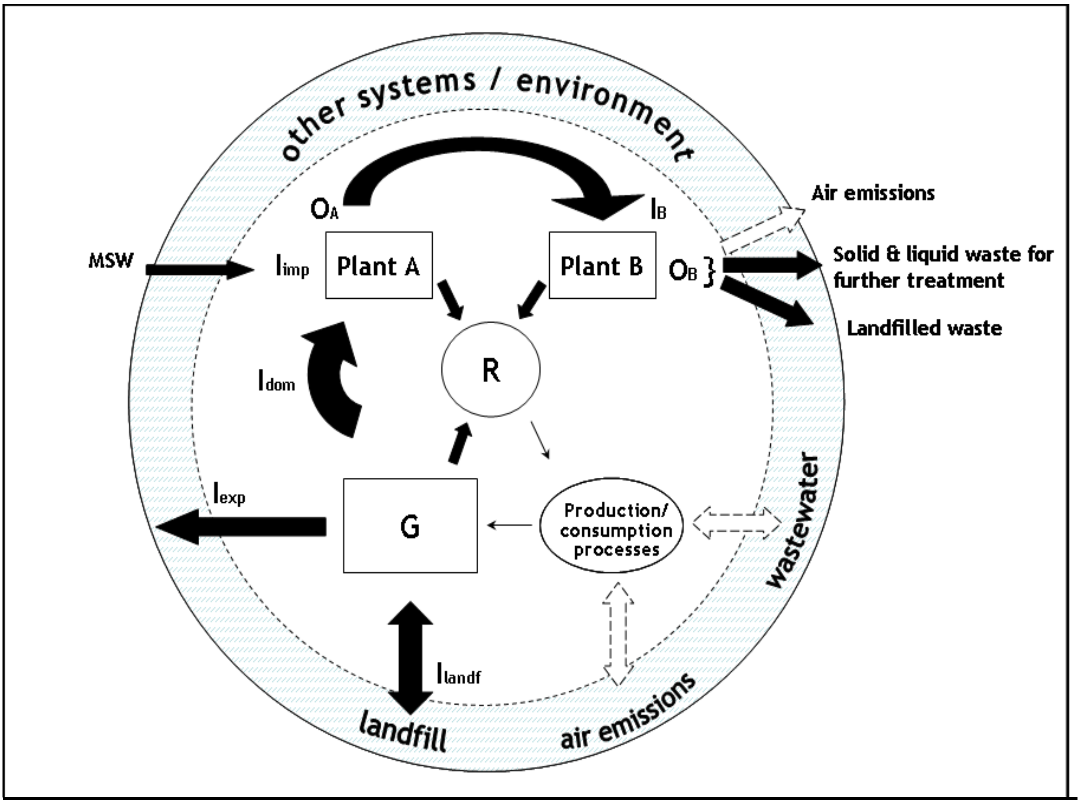


Figure 4-1 Schematic representation of a hypothetical system with two MSW treatment plants (A and B). The system limits are represented by the inner discontinuous circle. Black, solid arrows represent flows included in the material accounting; the flows not considered are indicated by white arrows in dashed line. G stands for the municipal solid waste flow occurring from the production and consumption processes. R corresponds to the fraction of municipal or secondary solid waste directly used as raw material, either inside or outside the system's limits.

➢ Data collection and sources

The first step of the methodology is the collection of the necessary data. This must be yearly and collected on two different levels: the municipal and the treatment plant level. Municipal data required include MSW generation rates both in total weight generated per year and disaggregated data on the fractions of MSW collected. Treatment data not only have to provide information on the type of treatment each fraction of each municipality receives, but the place of treatment as well, with respect to the system's limits. In addition, the secondary waste generated in the MSW treatment facilities has to be known, along with their place and type of treatment or final disposal.

Three different sources of data are used: (i) local and regional statistical institutes and waste agencies, basically providing data on MSW production and management, as well as on infrastructure information and the amount of MSW (in weight) treated annually in each plant, (ii) Agenda 21 reports and environmental audits on a regional or county level that contain data on disposal routes and plant emissions and (iii) private sector sources, such as the companies managing the MSW treatment facilities, which provide data on plants' inputs and refuse generation. All quantitative data is in tonnes per year.

4.3. Definition of the municipal solid waste management self-sufficiency indicator

4.3.1. *Definition of the indicator*

The indicator proposed, applied on an urban area that consists of various municipalities, is defined, for a specific time period, as the ratio of the sum of MSW treated in the given system and the fraction directly used as raw materials, to the amount of MSW generated in it. The amount of MSW treated is equal to the inputs of all MSW treatment plants located in the system, minus the waste generated by these facilities. The indicator, ws_x, is the MSW management self-sufficiency indicator for year x and is calculated as:

(Equation 4-1)

$$ws_x = \left(\sum_{p=0}^{n} \left(I_{x,p} - O_{x,p} \right) + R_x \right) / G_x$$

The terms are described below.

- ***$I_{x,p}$* is the input of MSW treatment plant *p*, located inside the system, for year *x*, in tonnes per year**

A treatment plant’s input flows are equal to the total amount of waste treated in it, regardless of its origin, either inside or outside the system. This could either be collected MSW or waste produced at waste treatment facilities (secondary flow refuse). The solid or liquid reactants used in the treatment processes are not included in a plant’s inputs. In accordance with the mass conservation law the inputs of a plant should be equal to their outputs, so the reactants that form part of the refuse generated by the plant are included in the output side.

- **$O_{x,p}$ is the amount of waste generated by MSW treatment plant *p*, located inside the system, for year *x*, in tonnes per year**

We consider as outputs from a treatment plant to be the solid and liquid waste generated during MSW treatment that has no further use, cannot be recovered and therefore has to be treated by a new process or sent for final disposal. Plant outputs include the secondary waste that is either landfilled or sent for further treatment, either inside or outside the system. Consequently, materials recovered during the treatment process, wastes that are recycled and outputs that have a market value are not accounted as O_x. It should be noted that the secondary waste of a plant (accounted as plant output, O_x) that is treated by another plant in the system (accounted as plant input, I_x) does not change the value of the indicator, on condition that the same amount in weight that exits the first plant enters the second (see for example flows O_A and I_B in Figure 4-1).

- ***Rx* is the amount of separately selected MSW used directly as raw materials for year *x*, in tonnes per year**

This parameter represents the separately selected fraction of MSW, typically paper and glass, which is directly used as a raw material in manufacturing plants, either inside or outside the system, without prior selection or treatment. This fraction does not include MSW treated in recycling plants.

- **G_x is the total amount of MSW generated by the studied system for year *x*, in tonnes per year**

The total amount of MSW generated in the system is defined as the sum of the MSW collected within its boundaries. Air emissions, residues treated as wastewater and industrial and construction waste are excluded from this definition. In the proposed methodology it represents the sum of MSW generated and collected in each of the municipalities included in the system.

4.3.2. Assumptions and calculation methods used to estimate the indicator

MSW generated by other socioeconomic systems but handled in the studied system's MSW treatment plants are considered to be waste imports and are included in these plants' inputs.

The amount of MSW generated by the system but treated outside its limits is not included in the numerator of the mathematical expression of the indicator, as it is considered as an export of the system. Nonetheless, this category of MSW is reflected in the indicator value by not being included in the plants' inputs, although it is so in the MSW generation (G_x).

Compost plants' inputs are equal to the amount of organic waste treated there (I_x). Their outputs (O_x) consist of the solid and liquid refuse from the composting process, excluding the compost produced that is of a value. When no market is available for the generated compost due to low quality, this is landfilled and included in the plant's waste output flows.

Anaerobic digestion plants treat organic waste (I_x) by transforming it into biogas through a methanisation process that is then converted into electricity. Their output (O_x) is the remainder of this process sent for further treatment or for final disposal.

Incineration plants (with energy recovery) usually accept waste that cannot be re-used or has not been collected separately. The inputs (I_x) of an incineration plant correspond to the waste this receives. Its outputs (O_x) consist of the bottom and flying ash generated during the incineration process, and occasionally wastewater, depending on the plant's technical characteristics and the type of treatment followed.

Separately collected recyclable materials, predominantly glass, paper, plastic and metals are sent to recycling plants to be recycled (I_x). We account the refuse occurring from the recycling processes as outputs (O_x) from these plants.

Landfills finally, are considered to be outside the limits of a socioeconomic system regardless of their position with reference to it. Consequently, landfilled waste is always regarded to be an export and imported waste landfilled inside the studied system is neither accounted for as input to plants nor as an output of the system.

In accordance with the above definitions and comments, the annual MSW generation of a system would be defined in terms of I and R as follows:

(Equation 4-2) $$G = \left(I - I_{imp}\right) + I_{\mathrm{exp}} + R + I_{landf}$$

Where,

G generation of MSW in the system, t/y

I total inputs of waste in the system's MSW treatment plants, t/y

I_{imp} the waste imported from other systems to be treated in the system's MSW treatment plants, t/y

I_{exp} the fraction of generated MSW treated outside the system's limits, t/y

R the fraction of generated MSW that is directly used as raw material, in tonnes per year

I_{landf} the fraction of generated MSW that is landfilled, t/y

The difference between I and I_{imp} represents the fraction of locally generated waste treated by the system's plants (I_{dom}).

4.4. Discussion

The indicator can theoretically take negative or positive values[21]. We consider the optimum value to be unity. This value suggests sustainability and equilibrium, in terms of MSW management, for the studied area, being autonomous and self-sufficient in its reuse, treatment and final disposal of MSW, without loading other systems with the environmental burden associated to it.

In Table 4-1 a list of possible scenarios with regards to MSW exports, imports and treatment type is analysed and the indicator value is calculated for each of them. We suppose the same MSW generation in all scenarios and that all MSW treated inside the system receives the same treatment (column 4). Export percentages represent the fraction of MSW generated by the system that is treated outside its limits. When MSW is imported into the system, this is considered equal to the system's MSW generation in weight.

In all optimum situations in Table 4-1 (scenarios 1, 5 and 11) the MSW treated by the system is 100% recovered either through recycling or direct use as a raw material. It should be noted that an indicator value equal to unity does not always suggest a sustainable society. Material recovery with a high energy demand, for example, does not favour a system's sustainability. Additionally, it alone does not guarantee non-renewable resource conservation and total waste generation has to be decreased in each case.

---

[21] In order for the indicator to take negative values, in accordance with Equation 4-1, the total outputs of plants ($O_{x,\ p}$) should be greater than their inputs ($I_{x,\ p}$) and this difference should surpass the amount of MSW to be directly used as a raw material (R_x). We consider this an improbable case. The outputs of a plant could only exceed its inputs in the case of a treatment including chemical processes, normally stabilisation of waste prior to landfilling. Stabilisation for MSW is required in the case of high carbon content. The European Agenda on waste management (European Commission, 1999) prioritises the reduction of biodegradable waste landfilling so this case is pretty unlikely to happen. We focus therefore, our analysis on the cases with positive indicator values.

Table 4-1 Possible scenarios of MSW management policies with varying place and type of treatment

Scenario	*Waste exports*	*Waste Imports* [a]	*Treatment type* [b, c ,d, e]	*Indicator value*
1	**0%**	**0%**	**Recycling- reuse as raw material**	**1**
2	**0%**	**0%**	**Incineration**	**0.78**
3	**0%**	**0%**	**Landfilling**	**0**
4	**100%**	**0%**	**Recycling**	**0**
5	**100%**	**0%**	**Reuse as raw material**	**1**
6	**100%**	**0%**	**Incineration**	**0**
7	**100%**	**0%**	**Landfilling**	**0**
8	**0%**	**100%**	**Recycling- reuse as raw material**	**2**
9	**0%**	**100%**	**Incineration**	**1.55**
10	**0%**	**100%**	**Landfilling**	**0**
11	**100%**	**100%**	**Recycling**	**1**
12	**100%**	**100%**	**Reuse as raw material**	**2**
13	**100%**	**100%**	**Incineration**	**0.78**
14	**100%**	**100%**	**Landfilling**	**0**

[a] **Waste imports are considered to be equal to the amount of waste generated by the system**

[b] **Refers to the treatment residues inside the system receive**

[c] **We suppose that all residues are treated in the same way**

[d] **In the application of the indicator in these hypothetical scenarios we consider a perfect recycling scheme with a 100% yield**

[e] **We consider the refuse of the incineration process to be the bottom and flying ash, corresponding to 22.5% of the weight of the inputs, according to Doka (2003)**

In the case of systems exporting waste, these essentially send environmental impacts abroad and are potential generators of social conflicts associated with the location of waste treatment facilities. This is clearly illustrated in Table 4-1, where the cases in which the indicator has a value lower than unity occurs in the scenarios where (i) the dominant treatment type does not promote material recovery, namely incineration and controlled disposal (scenarios 2, 3, 7, 10 and 14) and (ii) the waste generated is treated outside the system's limits (scenarios 4, 6 and 13), regardless of the type of treatment it receives.

A value higher than unity would indicate a system with the capacity to treat more MSW than it generates. Nevertheless, an increase in the value of the indicator should not be identified with an increase in the degree of sustainability for a given system. Indicator values higher than the unity entail waste transport within systems (scenarios 8, 9 and 12), a critical stage of MSW management plans that involves energy consumption and emissions of air pollutants. According to Buttol et al. (2007), when waste has to be transported over distances of more than 7 km, the transport stage contributes to more than 50% of the total energy demand and CO_2 emissions of a MSW management scheme. Similarly, Iriarte et al. (2009), use LCA to assess three different selective waste collection systems, and conclude that inter-city transport of 11 km onwards is the sub-stage which most contributes to global warming impact and energy demand in all the collection systems studied[22].

Another interesting remark is that the indicator assesses a system to be more sustainable if it incinerates its waste within its limits than if it exports it for recycling (scenarios 2 and 4 respectively, Table 4-1). This observation demonstrates that the indicator ranks higher (i) the effort of a socioeconomic system to host MSW treatment facilities and (ii) the restriction of waste transport and the environmental impacts associated to it, to the export of residues even if they are to be treated in a more sustainable manner.

An important factor in the interpretation of the indicator value is the size of the studied system in terms of population. If this is too small, it is unlikely to host any MSW treatment facilities, so its ws value could not reach the unity. On the other hand, this value could be achieved in the case of a small municipality with a good separation and collection scheme and the use of other practices as composting at home, resulting in the minimisation and recovery of all waste generated. For this reason we propose systems of 20 000 inhabitants as a minimum size of application. We consider that systems of this scale generate sufficient

---

[22] The importance of the air emissions during the transport and treatment stages (principally through incineration and emission of landfill gas) of a MSW management scheme and their association with climate change cannot be neglected. A study conducted by the World Resources Institute (WRI, 2000), using the MFA methodology to document the materials that flow through industrial economies, reveals that there has been a steady increase in the share of outflows to the atmosphere and a corresponding decrease in the share of flows going to land and water. Although air emissions from treatment processes and transport are not directly considered in this work, the practices favouring emission of air pollutants are treated in such way so that these emissions are reflected in the indicator value. The fractions of waste that are exported from a system and those that are landfilled are excluded from the numerator of Equation 4-1, penalizing residue transport and landfill correspondingly. Similarly, incineration is also penalised through the consideration of the refuse generated during this process.

amount of MSW to justify the existence of relevant treatment installations and guarantee an objective evaluation of its MSW management scheme.

4.5. Application of the indicator to the selected area of study for the years 1998-2005

Based on its collection and treatment, MSW collected in the studied system is classified as waste that is collected separately in order to be recycled or recovered and waste destined with no prior treatment for energy recovery plants and controlled disposal. The region disposes of installations for the collection, separation and treatment of both types of waste. Currently, the separately collected MSW components are glass, paper and cardboard, light packaging, organic material and voluminous articles.

The currently existing final treatment facilities on the coast of the Barcelona metropolitan region are a controlled landfill site and two incinerator plants. During the selected study period, a composting plant and the Barcelona Ecoparc were constructed, the latter disposing of a composting and an anaerobic digestion plant.

The study period selected for the calculation of the indicator for the selected area is an eight-year time series between 1998 and 2005.

The main data source on waste production rates as well as on infrastructure information and the amount of waste (in weight) treated annually at each plant was the Waste Agency of Catalonia (Agència de Residus de Catalunya). All data was provided through the Agency's website (Waste Agency of Catalonia, 2007) on a municipal level and for each of the years studied. Additional data on disposal routes were recovered for municipalities that had performed environmental audits or have had Agenda 21 reports (Municipality of Badalona, 2001; Municipality of Castelldefels, 2001; Municipality of Gavà, 2003; Municipality of Malgrat de Mar, 2003; Municipality of Montgat, 2002; Municipality of Pineda de Mar, 2003; Municipality of Vilanova i La Geltrú, 2003). Similarly, some environmental audits on a county level contained very useful information both on the description of the system and on numerical data (Auditoria Ambiental Territorial del Baix Maresme, 2001). Additional data was also encountered for the eight coastal municipalities that are under the administration of the Metropolitan Environmental Authority (Entitat Metropolitana del Medi Ambient - EMMA), as annual environmental reports are issued by this entity (EMMA, 2004; 2005).

The results obtained are presented in Table 4-2. The values of the indicator, calculated using Equation 4-1, are relatively low for the given system, demonstrating low sustainability, although they have an increasing tendency. This is attributed to large amounts of landfilled waste and the lack of adequate facilities for waste treatment in the area. The fluctuation of the indicator with respect to changes in imported and exported waste flows is demonstrated in the same Table.

Table 4-2 Annual values of the variables used for the calculation of the indicator and the results obtained for the studied system

Year	*Total MSW generation by the system (t/y)*	*Waste imported (t/y)*	*Waste exported [a] (t/y)*	*Waste treated in the system (t/y)*	*Plant outputs (t/y)*	ws_x	*Recovered waste [b] (%)*
1998	**1 045 762**	**102 639**	**668 439**	**420 832**	**-**	**0.43**	**29.5**
1999	**1 153 630**	**121 762**	**755 232**	**455 623**	**-**	**0.44**	**27.8**
2000	**1 217 617**	**99 128**	**778 093**	**480 212**	**-**	**0.44**	**36.9**
2001	**1 219 049**	**124 080**	**748 805**	**528 093**	**13 907**	**0.48**	**38.3**
2002	**1 254 794**	**143 659**	**834 769**	**493 346**	**8 880**	**0.44**	**34.4**
2003	**1 360 965**	**177 696**	**641 598**	**816 275**	**16 233**	**0.65**	**53.1**
2004	**1 413 503**	**239 701**	**670 505**	**886 846**	**202 808**	**0.55**	**54.2**
2005	**1 396 558**	**286 828**	**602 100**	**943 452**	**166 569**	**0.64**	**56.1**

[a] **Includes landfilled waste**

[b] **Recovered waste represents the percentage of MW recovered, including recycling, composting and incineration with energy recovery, according to the Eurostat Methodology (Eurostat, 2001)**

The percentage of recovered waste is also included in Table 4-2. Similar to the Eurostat methodology on MSW (Eurostat, 2004b), quantities of recovered waste include residues sent for recycling, composting and incineration with energy recovery. As one would expect, increased recovery rates bring about increases in the indicator. Nonetheless, with regards to the correlation between the fraction of waste recovered and the indicator value, some differences can be noticed in the results. Between years 1998 and 1999 the value of the indicator slightly rises while the percentage of waste recovered appears to have decreased; this can be attributed to a rise in the total amount of waste treated in the system's plants and in the amount of waste imported. The big difference in MSW generation between these two years is caused by an increase in generation per capita of about 11%. Comparing years 2003 and 2004 we notice a drop in the indicator, in contrast with the augmentation in waste recovery, reflecting the increased MSW generation and transport (i.e. increased imported and exported waste). Although there was a very small increase of 0.4% in the system's population, the total MSW generation augmentation was of 3.4%. Another crucial factor is the rise of the system's treatment capacity by 70 000 tonnes, accompanied by a significant increase in plants' outputs (Table 4-2). In other words, the system appears to be less sustainable in its entirety due to the poor performance of its treatment plants, referring to their high refuse generation. The indicator therefore evaluates the sustainability of the system more thoroughly than the recovery percentage. Additionally, although there is a rise in waste recovery between years 1999 and 2000 these present the same indicator value. This can be explained by a simultaneous augmentation in waste generation and an increase of waste exports. These factors do not favour the system's sustainability and are reflected in the indicators' value but not in the recovery rate, which would give a false impression of the progress of the system's sustainability as a unique sustainability criterion.

Based on these observations, we consider the proposed indicator to be more comprehensive in assessing the sustainability of MSW management plans in medium-scale urban regions, although more complex to calculate. The MSW management self-sufficiency indicator prioritises waste reuse and recovery inside the generating system's territory and takes into account the whole cycle of waste treatment, regarding MSW flows. It finally reflects a social dimension of sustainable MSW management as it evaluates the social effort of a given system to treat the MSW it does not generate.

4.6. Application of the indicator to selected municipalities for the year 2005

In order to apply the methodology to regions of a smaller spatial and administrative scale and make comparisons between different systems, the indicator was calculated for three selected municipalities included in the considered system. These results are included in Table 4-3. The example of the municipality of Sant Adrià de Besòs represents a small urban area with a remarkably high indicator value, attributed to the function of an incinerator plant in the area that results in high MSW imports of a scale of approximately 19 times the MSW the municipality itself generates in weight. Although Sant Adrià de Besòs is in solidarity with other systems, it bears the environmental burden associated to the function of the incinerator plant that serves a much wider area. This example reveals the dominance of the incineration option in MSW strategies in the system. Moreover, it confirms that optimum indicator values are close to unity given that really high values represent fairly unsustainable systems.

Table 4-3 Indicator values and basic statistical data for three selected municipalities contained in the studied system, for 2005

Municipality	*Population* [a]	*Residue generation* [b] *(kg/cap·y)*	*Number of WM facilities*	*Waste imported (t/y)*	ws_x
Sant Adrià de Besòs	**32 940**	**540**	**1** [c]	**326 083**	**18.37**
Gavà	**44 210**	**558**	**3** [d]	**39 495**	**1.54**
Castelldefels	**56 718**	**719**	**2** [e]	**13 631**	**0.51**

[a] Source: Barcelona Provincial Council, 2007a

[b] Source: Barcelona Provincial Council, 2007b

[c] Hosts a MW incinerator

[d] Hosts a controlled landfill, a sorting plant for light packaging, one for voluminous residues and a green point

[e] Hosts a compost plant and a green point

The case of the municipality of Gavà is fairly similar, hosting two sorting plants that consequently import MSW; however, the indicator has a lower value than Sant Adrià de Besòs due to lower imports and the nature of these installations with minor outputs to the environment. The compost plant in Castelldefels serves the neighbouring municipalities but the value of the indicator is not particularly high due to elevated MSW exports by this municipality.

Of these three municipalities, Gavà appears to be the most sustainable. The results of this comparison serve to suggest that the indicator is an urban planning tool; cities and regions like the municipality of Gavà, with indicator values higher than, but close to unity, are systems that could increase their population with a simultaneous increase in their sustainability. Using the data given for 2005, the population of this municipality was calculated in order to achieve a value of the indicator equal to unity. Maintaining residue generation (in kg/cap·y) at the same levels, the population of Gavà could be increased by 23 000 inhabitants without loading the carrying capacity of the system[23]. Obviously, this alone could not be the only criterion for planning the development of an urban region but it is a useful tool used in combination with other sustainability and socioeconomic indicators.

---

[23] It is not simple to define the carrying capacity of a system, and the smaller this is the harder the task. Urban systems are open and interactive, in a constant interchange of energy and materials with the natural environment and that is not restricted to their immediate hinterland but have connections, in an ecological sense, with regions at national and global levels (Sukopp, H., 1998). Accordingly, resources extraction and waste assimilation of urban systems nowadays extend far beyond their locality. The relevance of carrying capacity to human populations is quite controversial in general, partly for this reason (Mar, 1981; Munda, 2006; Yanarella and Levine, 1992). Nevertheless, the suggested indicator does reflect the recycling habits of a population, and as a consequence the resource use efficiency of a system; it is certainly not alone sufficient for the calculation of population growth potential, it is, however, linked to it and can be potentially used in combination with other indicators for its control.

4.7. Application of the indicator to the municipality of Barcelona for three selective years of study

The indicator was estimated for the municipality of Barcelona for three different years, with the aim to assess its temporal evolution concerning MSW management and the related policy decisions made during this time period (see Table 4-4); this municipality presents special interest due to an Ecoparc that started functioning in its premises during the studied period. For 1998, the value of the indicator is close to zero; it has no MSW treatment facilities and the fraction of recovered waste, corresponding to the fraction that is directly used as raw material, is quite low. In 2002, the Ecoparc started operating and the impressive increase in the fraction of generated MSW that is recovered in the municipality is followed by a similar tendency in the indicator's value. The increase is not equivalent in both values though, since half of the waste treated is imported. In the last year of study, the rates of imported and recovered waste have increased in analogy with the increase in the treatment capacity, compared with the equivalent 2002 values. These facts, in combination with a moderate waste generation augmentation, lead the system to its highest indicator value for the selected study period.

Table 4-4 Temporal evolution of the waste indicator for the municipality of Barcelona

Year	*Waste generated (t/y)*	*Waste treated in facilities (t/y)*	*Waste imported (t/y)*	ws_x	*Waste recovered in the municipality* [a] *(t/y)*
1998	**653 699**	**0**	**0**	**0.04**	**8 138**
2002	**797 101**	**89 709**	**47 828**	**0.17**	**59 723**
2005	**874 970**	**368 197**	**183 568**	**0.37**	**224 258**

[a] Recovered waste represents the amount of MSW recovered, including recycling, composting and incineration with energy recovery, according to the Eurostat Methodology (Eurostat, 2001)

4.8. Conclusions

The indicator proposed in this paper is a useful tool for the evaluation, in terms of sustainability, of MSW management plans, based on the monitoring of MSW flows from their generation until their final disposal. Its originality lies in the incorporation of the transport of MSW, through the monitoring of imported and exported waste, and the performance of the related treatment plants, taking into account their waste outputs and their further processing or final disposal.

It manages to provide policy makers with an assessment of higher quality and consistency than a mere recovery percentage that cannot thoroughly represent the sustainability of a MSW plan. Yearly revisions of the indicator supplemented with more disaggregate data on MSW treatment facilities, generation rates and other socio-economic indicators may reveal information on waste generation tendencies, waste management policy changes, the sustainability of a region and issues of environmental justice.

The proposed indicator follows a holistic and descriptive approach on the evaluation of a MSW management plan and is not a parameter for the election of the siting of a plant, dependant on a variety of parameters that would keep our indicator from being simple. The indicator can serve for the selection of a system (e.g. a municipality or a wider urban area) to host a MSW treatment plan but cannot predict its exact position within its limits. In other words, the indicator is not a tool for the determination of the exact location of a MSW treatment plant but it is useful for the evaluation of the current situation in a system and in reflecting the sustainability of a complete MSW management plan in a predetermined area of study.

The indicator is best applied on urban areas with a population greater than 20 000 – 30 000 inhabitants, territories that most likely host MSW treatment facilities. Its application facilitates the planning of complementary installations offering various options for improvement so that each community can decide upon its future with reference to MSW management policies and the hosting of related facilities. Furthermore, neighbouring (interrelated) systems can commonly plan joint MSW management policies and improve their management plans by recycling/reusing more MSW and/or improving the existing plants' performance. The analysis of the indicator's values can also facilitate define the limits of growth for a given system, in terms of the interrelated issues of population, use of resources and waste generation.

Finally, the application of the suggested methodology on a national or even continental level, with a focus on industrial waste, could enable us to treat the issues of hazardous waste treatment policies and sustainable management and social inequity on a larger scale.

References

Auditoria Ambiental Territorial del Baix Maresme (2001) Document V. Document de Síntesi de l'Auditoria. Available at: www.plalitoral.net/est_sectorials.htm

AWAST Project (2003) Workpackage 1 – Waste matter aspects. MFA-MANUAL. Guidelines for the use of Material Flow Analysis (MFA) for Municipal Solid Waste (MSW) Management. Contract Number: EVK4-CT-2000-0015.

Barcelona Provincial Council (2007a) Demographic municipal data. Diputació de Barcelona. Available at: http://www.diba.es/hg2/demografia/dpt.asp?IdMenu=03020101

Barcelona Provincial Council (2007b) Indicators on quality of life. Diputació de Barcelona. Available at: http://www.diba.es/hg2/indicadors/qualitat/resi_KgHab.asp?IdMenu=04030401

Bringezu S. and Moriguchi Y. (2002) Material flow analysis. In: Ayres, R. U. and Ayres, L. W. (eds.), A Handbook of Industrial Ecology. Edward Elgar Publishing: Cheltenham

Buttol, P., Masoni, P., Bonoli, A., Goldoni, S., Belladonna V. and Cavazzuti, C. (2007) LCA of integrated MSW management systems: Case study of the Bologna District. Waste Management 27 (8): 1059-1070.

Danish EPA (2003) Waste Indicators. Environmental Project No. 809. Danish Environmental Protection Agency: Copenhagen

Doka, G. (2003) Life Cycle Inventories of Waste Treatment Services. Ecoinvent report No. 13. Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland.

EEA (2005) CSI 016 Specification - Municipal waste generation. Available at: http://themes.eea.europa.eu/IMS/IMS/ISpecs/ISpecification20041007131809/full_spec#Rationale

EEA (2007) Indicators – Waste. European Environmental Agency. Available at: http://www.eea.europa.eu/themes/waste/indicators

EMMA (2004) Metropolitan Environmental Data 2003. Entitat Metropolitana dels Serveis Hidràulics i del Tractatament de Residus (EMSHTR): Barcelona

EMMA (2005) Metropolitan Environmental Data 2004. Entitat Metropolitana dels Serveis Hidràulics i del Tractatament de Residus (EMSHTR): Barcelona

European Commission, 1999. Directive 99/31/EC, 1999. Directive on landfill of waste.

Eurostat (2001) Economy-wide material flow accounts and derived indicators - A methodological guide. Office for Official Publications of the European Union: Luxembourg

Eurostat (2004a) Urban Audit – Methodological Handbook. Office for Official Publications of the European Communities: Luxembourg

Eurostat (2004b) Waste Statistics - Eurostat Metadata in SDDS format: Summary Methodology. Eurostat, Statistical Office of the European Communities. Unit E3: Environment statistics.

Office for Official Publications of the European Communities: Luxembourg.

Eurostat (2007) Data Navigation Tree - Environment and Energy Indicators. Available at: http://epp.eurostat.cec.eu.int/portal/page?_pageid=1996,45323734&_dad=portal&_schema=PORTAL&screen=welcomeref&open=/envir/env/env_was&language=en&product=EU_MAIN_TREE&root=EU_MAIN_TREE&scrollto=300

Friege, H. (1997) Requirements for Policy Relevant Material Flow Accounting - Results of the German Bundestag's Enquête Commission. In: S. Bringezu, M. Fischer-Kowalski, R. Kleijn and V. Palm (eds.), Regional and National Material Flow Accounting: From Paradigm to Practice of Sustainability. Wuppertal Institute for Climate, Environment and Energy Science Centre North Rhine-Westphalia

Furuseth, O.J. and O'Callaghan, J. (1991) Community response to a municipal waste incinerator: NIMBY or neighbor? Landscape and urban planning 21: 163-171

Haberl H., Fischer-Kowalski M., Krausmann F., Weisz H. and Winiwarter V. (2004) Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 21: 199–213

Hsu, H.-S. (2006) NIMBY opposition and solid waste incinerator siting in democratizing Taiwan. The Social Science Journal 43: 453–459

Iriarte, A., Gabarrell, X. and Rieradevall, J. (2009) LCA of selective waste collection systems in dense urban areas. Waste Management 29: 903-914

Joos, W., Carabias, V., Winistoerfer, H. and Stuecheli, A. (1999) Social aspects of public waste management in Switzerland. Waste Management 19: 417-425

Mar, B.W. (1981) Dead is dead - an alternative strategy for urban water management. Urban Ecology 5: 103-112

Munda, G. (2006) Social multi-criteria evaluation for urban sustainability policies. Land Use Policy 23: 86-94

Municipality of Badalona, 2001. Municipal Environmental Audit of Badalona: Diagnostic. Badalona City Council, Badalona, Spain.

Municipality of Castelldefels (2001) Municipal Environmental Audit of Castelldefels: Diagnostic. Foundation Castelldefels 21

Municipality of Gavà (2003) Municipal Environmental Audit of Gavà: Descriptive Report. DEPLAN, S.L.

Municipality of Malgrat de Mar (2003) Municipal Environmental Audit of Malgrat de Mar: Document IV – Summary. Municipality of Malgrat de Mar

Municipality of Montgat (2002) Diagnosis of natural and support Systems: agricultural, forestall, hydrological. Municipality of Montgat

Municipality of Pineda de Mar (2003) Municipal Environmental Audit of Pineda de Mar: Municipal Environmental Diagnosis (Provisional Document)

Municipality of Vilanova i La Geltrú (2003) Sustainability indicators system for the municipality of Vilanova i la Geltrú. Municipality of Vilanova i La Geltrú

Muñoz, I., Rieradevall, J., Domènech, X., Milà and Canals, L. (2004) LCA Application to Integrated Waste Management Planning in Gipuzkoa (Spain). The International Journal of Life Cycle Assessment 9 (4): 272-280

OECD (2004) OECD Key environmental indicators. OECD Environment Directorate: Paris

Özeler, D., Yetiş Ü. and Demirer, G.N. (2006) Life cycle assessment of municipal solid waste management methods: Ankara case study. Environment International 32 (3): 405-411

Pol, E., Di Masso, A., Castrechini, A., Bonet, M. R. and Vidal, T. (2005) Psychological parameters to understand and manage the NIMBY effect. Revue européenne de psychologie appliquée 56: 43–51

Sukopp, H. (1998) Urban Ecology – Scientific and Practical Aspects. In: Breuste, J., Feldmann, H. and Uhlmann, O. (eds.), Urban Ecology. Springer-Velarg Berlin Heidelberg

UNCSD (2001) Indicators of Sustainable Development: Guidelines and Methodologies. Available at: http://www.un.org/esa/sustdev/publications/publications.htm

Waste Agency of Catalonia (2007) Municipal waste statistics page. Available at: http://www.arc-cat.net/ca/estaddin/index.html

WRI (2000) The weight of nations – Material outflows from industrialised countries. World Resources Institute: Washington, DC

Yanarella, E. J. and Levine R. S. (1992) Does sustainable development lead to sustainability? Futures October 1992

5. ANALYSIS OF THE CASE STUDY´S ENERGY PROFILE

This study comes to complement the two previous works on the metabolism of the coastal municipalities of Barcelona's metropolitan region. After touching upon the issues of water and municipal solid waste (MSW) management under a metabolic perspective, it was considered that the energy issue should also be studied; not solely for its position in the world agenda of sustainable development and the energetic crisis we are facing, but in addition for its importance in the metabolism of an urban area and its significant interconnection with the previously studied flows. All the internal processes that maintain a city require energy, whether these are related to production and transport procedures or consumption on the residential level. Moreover, the energetic metabolic picture of a system is essential as material and energy flows are so closely interrelated that the metabolism of a society can be adequately understood only if both are considered (Krausmann and Haberl, 2002). Concerning the aspects of urban energy consumption associated with water and MSW flows, these include for example water pumping, purification and treatment, waste collection, transport, treatment and/or recycling processes.

The methodology followed for the description of the energy flows of the system under study is not as analytical as in the previous studies. The indirect flows associated with distribution and consumption of energy are not calculated and the study does not conclude with the suggestion of an energy use sustainability indicator. This work aims to describe the energy demand and generation tendencies in the area, to indicate the sectors that most energy consume, and, in the same line with the previous studies, assess the self-sufficiency of the area in terms of energy.

5.1. Introduction

There could not possibly be any attempt to tackle the energetic issue we experience today without touching upon the current social, technical and economical context. As Kastoriadis put it more than twenty years ago (Kastoriadis and Cohn-Bendit, 1981), the energetic problem is merely a problem of this society and the way this is politically and socially organised. Energy transitions throughout human history have shaped and influenced all aspects of social organisation and society-nature interrelations, bringing changes in socioeconomic metabolism and the colonisation of natural systems (Fischer-Kowalski and Haberl, 1998). The use of petrol as an efficient, cheap and abundant energy source has entailed fundamental changes, primarily in patterns of production and consumption. It has moved the human working force from agriculture to the industrial and later on to the services sector, facilitating the concentration of people and the inevitable creation of large urban centres. The resulting cheaper and faster transportation of goods and people has also affected spatial organisation and metabolic patterns both on global and local scale. Socioeconomic systems are no longer constrained by land use as they depend on fossils and they are neither restricted to their neighbouring environment for the extraction of natural resources; the cheap movement of goods in a globalised world economy allows the import of commodities from whichever region has less production costs (Sempere, 2007). In the urban setting, cheap transport had as a consequence careless urban sprawl and the facilitation of the segregation of residential, work, commercial, and leisure areas in modern cities.

Ecological problems associated with socioeconomic energy metabolism are central for sustainable development. Tracing energy flows is significant for analysing the efficiency and progress of economic structure and growth, societal organisation and technological innovation among other variables of sustainability (Krausmann et al., 2004). Comprehensive reviews of the origin and the precursors of societal energetic metabolism are presented by Martinez-Alier (1987; 2004) and Fischer-Kowalski (1998). Suh (2005) makes a review on the evolution of energy flow analysis in ecology going over the various methodologies used.

The importance of energy flows has resulted in their inclusion in national statistics (IEA, 1995; UN, 1997) and the derivation of numerous energy production and consumption indicators (see for example EEA, 1999; Eurostat, 1999; UNDESA, 2001; IAEA, 2005). However, conventional energy balances and statistics[24] only account for energy used for the production of heat, power and light (Krausmann and Harbel, 2002), omitting the fraction of biomass that is not used as fuel either for heat or electricity production, using net calorific values of materials. The Energy Flow Accounting (EFA) methodology complements these methods considering all direct socioeconomic energy inputs into the system (Haberl et al.,

---

[24] For a distinction between energy balances and energy statistics, see Haberl (2001)

2004). In particular, these account for all biomass inputs to the system, including the fraction used for human nutrition and livestock, significant even in an industrial society's metabolism (Haberl, 2006). Using this methodology some indicators can also be calculated in analogy with Material Flow Accounting (MFA), such as Direct Energy Input and Domestic Energy Extraction. Moreover, EFA accounts are calculated on the basis of the gross calorific value of all materials considered (Krausmann and Harbel, 2002). Other, often complementary, methodologies employed for the description of energy flows include multi-criteria and multi-scale approaches (Giampietro et al., 2006; Ramos-Martín et al., 2007a), input–output analysis for energy flows (Thi Anh Tuyet and Ishihara, 2006), extended exergy analysis (Sciubba, 2003), exergy flow analysis (Talens et al., 2008), emergy analysis (Ulgiati et al., 1994) and Life Cycle Analysis (Farreny et al., 2008; Gasol et al., 2009; Udo de Hayes and Heijungs, 2007).

The study of socioeconomic energy metabolism has been the subject of numerous works in various spatial and time scales, employing a wide range of tools and methodologies. A few examples include the study of Haberl (2006) on the global socioeconomic energetic metabolism of the last million years accounting for biomass inputs [25], employing EFA and the examination of Austria's transition to an industrial economy from an energy flows perspective by Krausmann and Haberl (2002). Local or regional studies have also been published (e.g. Oliver-Solà et al., 2007; Sundkvist et al., 1999), including a report on Catalonia's energy metabolism (Ramos-Martín et al., 2007b)

With regards to urban systems, according to Brugmann (1996) energy planning was the first field to be developed in urban management matters, when "*...by the 1980's urban energy planners were applying materials and energy balancing to determine the stocks, flows, and conversion efficiencies of urban energy resources...*" Since then several works have been presented on the interrelation of the urban environment with its natural surroundings and the factors that affect energy consumption in urban centres (Huang, 1998; Huang et al., 2007). In their study on the metabolism of eight metropolitan regions from all over the world, Kennedy et al. (2007), state climatic conditions, the cost of energy, the age of the city and the state of its development as factors that affect the energy consumption and the metabolic profile of a city.

---

[25] Assessing its evolution following the transitions from the hunter-gatherer, to agricultural to the industrial societies

A large number of studies has focused on the interrelation between urban density and energy consumption. Mindali et al. (2004) studied the energy consumption in the transportation system – urban density interrelation, based on the pioneering study by Newman and Kenworthy (1989) that suggested a negative correlation between urban density and energy consumption. The authors argue that this correlation cannot be taken for granted in every case. Larivière and Lafrance (1999) demonstrate through a model that high-density cities use less electricity per capita than low-density ones. Still, they note that the influence of this factor on gasoline consumption is much stronger. With regards to welfare factors, Omer (2008) notices that the quality of life practised by people is usually being represented as proportional to the per capita energy use in a particular system. Various United Nations documents also identify a relationship between energy consumption and standard of living (Dzioubinski and Chipman, 1999; Goldemberg and Johansson, 1995). Conversely, a literature review in Joyeux and Ripple (2007) demonstrates neutrality between Gross National Product (GNP) and energy consumption.

The intention of this study is to analyse the energy consumption of the studied system as a whole and per activity sector. Special focus is given on the origin of the primary materials and the grade of the system's self-sufficiency in terms of energy. In addition, a comparison between municipalities is carried out with the aim to explore the consumption patterns that exist in accordance with the urbanistic models of these. The relevance of some of the factors that have an affect on energy consumption on the urban scale is also studied.

5.2. Materials and methods

The system's energy policy is planned by the Government of Catalonia (Generalitat de Catalonia) and regulated under Spanish and European legislation. In 2006, the Energetic Plan of Catalonia (Pla Energètic de Catalunya - PEC) was published by the Department of Labour and Industry (Departament de Treball i Indústria) with the aim to regulate and set aims for the energy management of the region, with a focus on sustainable management of energy resources, the optimisation of energy use and efficiency and the maximisation of renewable uses (Generalitat de Catalunya, 2006). The system's deficiency in fossil fuels brings it in a state of high energy dependence. This implies that some sources of energy, such as nuclear and wind power, which are not locally generated but are common in Catalonia, form part of the system's energy mix. The main primary energy sources used in the system are crude petrol, natural gas and nuclear energy, all imported.

Domestic electricity generation in the system is essentially fossil fuel-based, oscillating between 80 and 100%. During the study period four thermal power plants working with fuel oil and natural gas provided the system with electricity. One situated in the municipality of Cubelles, courtesy of the Spanish Electricity Network Company (Red Eléctrica de España – REE), another in the municipality of Badalona, under the management of FECSA-ENHER and two more reactors in Sant Adriá de Besòs of the same company. The latter closed down in 2003. In 2002, a combined cycle power plant was put into function in Sant Adriá de Besòs, property of ENDESA S.A.

Other sources of energy include solar heat and photovoltaic modules in public premises, primarily in Barcelona, a mini-hydroelectric plant in the same municipality functioning since 1999, and energy recovery plants from municipal solid waste (MSW). The latter include two incineration plants, in Mataró and Sant Adriá de Besòs, the production of biogas through methanisation in the Ecoparcs of Barcelona and Sant Adriá de Besòs, since 2003 and 2006 respectively, and landfill gas from the landfill situated in the municipality of Garraf. A small amount of electricity is produced in some wastewater treatment plants (in Besòs, Mataró and El Prat de Llobregat) by cogeneration, basically for satisfying their own energy needs, which we do not include in the calculations.

The methodology used is adequate for the simple description of the energy metabolism of a regional system; this means that indirect flows associated with energy generation, distribution and consumption as well as the endosomatic energetic needs of the system are omitted. The efficiency of each energy source is not taken into account.

In order to assess the self-sufficiency of the system, it is necessary to compare its energetic needs (energy consumption) to the energy generated in its premises. Consecutively, the clear definition of the system's limits and the energy inputs and outputs are crucial parts of the methodology employed.

Definition of system limits

We have used political boundaries to define our system. The system as a whole is not politically or administratively defined, but the municipalities that form it are. Regarding the extraction of fossils and the generation of power, we use the system boundaries defined by Eurostat (2001). According to them, the system boundary is defined:

1. by the extraction of primary materials from the national environment and the discharge of materials to the national environment;
2. by the political (administrative) borders that determine material flows to and from other economies (imports and exports).

The energy accounted for is:

- The energy distributed by the electricity grid. This includes all power plants providing the system with electricity, including nuclear stations and those running on natural gas, coal and petroleum, plus the net imported electricity; electricity generated by renewable energy sources as hydroelectric plants, photovoltaic panels, and wind turbines. Solar energy provided by solar panels for water heating is not included, as it does not enter the electricity grid and cannot be measured.
- The final consumption of natural gas, propane, butane, all types of diesel (both in vehicles and heating, meaning types A, B and C) and gasoline, wood and coal.
- Other sources of energy such as biomass or municipal residues. The latter refers to electricity obtained from MSW incinerators, biogas from landfills, and the gas from the methanisation process of MSW.

Units of measurement

Data on primary and final consumption and energy sources and carriers were encountered in diverse units; still, after appropriate unit conversions, the units used in this work are Joules.

Electricity mix

For the calculation of the system's electricity mix, we consider that locally produced electricity is consumed by the system itself. First, local generation is subtracted from total electricity demand. We suppose that the rest, imported electricity, is equivalent to the Catalan mix, in accordance with other studies that have performed similar regional studies in this area (see for example Observatori de l'Energia de Barcelona, 2005). The combination of these gives the system's final mix, using the following equation:

(Equation 5-1) $$x_{T,i} = \left[\left(x_{R,i} \times E_R \div E_T\right) + \left(x_{C,i} \times \left(E_C \div E_T\right)\right]$$

Where,

$x_{T,i}$ the contribution of primary energy source *i* in the system's electricity mix, in percentage

$x_{R,i}$ the contribution of primary energy source *i* in the system's electricity generation, in percentage

$x_{C,i}$ the contribution of primary energy source *i* in the Catalan electricity mix, in percentage

E_R the amount of electricity generated inside the system's limits, GJ

E_C the amount of electricity imported from the Catalan grid, GJ

E_T the total amount of electricity consumed by the system, GJ

Domestic energy production

All energy carriers used by the system that have been extracted inside its limits are accounted for as domestic sources of energy. With regards to the local power generation plants using fossil fuels, if these have been locally extracted the energy generated is considered as domestic. In the case that the prime materials are imported, the energy produced is considered as imported.

Energy Imports

Fossil fuels consumed inside and by the system but extracted outside its limits are considered as imports. The same applies for the power generation plants; facilities situated in other regions that provide the system with energy are considered as importers of energy.

Consumption Sectors

Final energy consumption data have been disaggregated per sectors in order to better assess and interpret the results. This was also required for a more comprehensive monitoring of the evolution of the economy under study. The main distinction made here is between the domestic uses of energy and the remaining uses, that is production and services. These include the sectors of (i) primary and tertiary services and transport, (ii) industrial and energy generation uses and (iii) construction and public works.

Data Sources

Data on local energy generation, total and per sector final consumption and prime materials' origin and contribution were required. Data were collected and organised on an annual basis and per municipality; the sum of the 27 municipalities gives an aggregated view on the system. This allows the assessment of the evolution of the overall energy consumption tendencies, imports dependency and, at the same time, the conduction of comparisons on municipal level combined with other indicators.

Generation data on fossil fuel and cogeneration plants were provided by the annual reports published by the Spanish Association of Electric Industry (UNESA, 2004; UNESA, 2007). With regards to renewable energy, only data on the photovoltaic installations of the city of Barcelona have been encountered in the municipality's Energy Agency website (Agència d'energia de Barcelona, 2008). Consumption data on electricity and natural gas (only for the period between 1997 and 2004) have been provided after personal communication with the Catalan Institute of Energy (Institut Català d'Energia – ICAEN). Consumption data on propane and butane were encountered per sector on province level in the statistics database of the Ministry of Industry, Tourism and Commerce (MITYC, 2008). Data on gasoline and diesel oil consumption was encountered in Spain's National Statistics Institute database (INE, 2008).

Data estimation methods were used for information that was not available on a municipal level. The most important estimates concern fuel oil, gasoline, butane and propane consumption throughout the entire time series, and natural gas for three years of the study (2004-2006). These data were encountered either on the Catalan or County level and the calculation of the system's corresponding values was based on population statistics available by the Statistical Institute of Catalonia (IDESCAT, 2008a).

Auxiliary Statistics/Indicators

A number of auxiliary statistics and indicators were required for the thorough interpretation of the energy results. Some of these include (i) Demographic statistics, (ii) Land use statistics, (iii) GDP per capita values and (iv) Contribution of each sector to municipal GDP.

5.3. Results and Discussion

5.3.1. Contextualisation of the system's energy demand

In order to better evaluate the energy consumption of the system under study it is first useful to contextualise this. This is done through its comparison with some larger economies in which this is included, for year 2005. Catalonia, Spain and the EU-25 are selected as benchmarks, in addition to the municipality of Barcelona for its importance in the region. Per capita indicators on total final energy, electricity and natural gas consumption are compared, in addition to energy consumption for domestic uses. The results are given in Table 5-1 and reveal that the studied system is moderately energy intensive, in per capita values, with the exception of final energy consumption. Catalonia appears to have the highest per capita natural gas and total final electricity consumption, possibly attributed to the region's strong industrial sector in combination with low population density (219 inhabitants per km^2, in 2006). The highest total and domestic energy consumption per capita corresponds to the EU-25 followed by Spain. When compared with the equivalent values for Catalonia and the system under study this result could be explained by the size of the Spanish economy, resulting in increased transport energy demand and the existence of more energy intensive industries in the rest of the country.

Table 5-1 Comparison of selected energy consumption indicators between the case study and four reference systems, for 2005, in GJ/cap

Region	*Final energy consumption*	*Final energy consumption for domestic uses*	*Final natural gas consumption*	*Total final electricity consumption*
Studied system	**85.6**	**13.8** [a]	**18.2** [a]	**16.5**
Barcelona	**41.2** [b]	**14.5**	**15.6** [b]	**16.7**
Catalonia [c]	**95.4**	**13.1**	**39.7**	**23.8**
Spain [d]	**100.8**	**14.4** [e]	**17.2**	**19.8**
EU-25 [d]	**107.1**	**27.8** [e]	**25.4**	**21.6**

[a] **Data for 2004, as no analytical data for natural gas have been found for 2005**

[b] **Data for 2004; Source: Agència d'Energia de Barcelona (2005)**

[c] **Source: Ramos-Martín et al. (2007b)**

[d] **Source : INE (2008)**

[e] **Source: IEA (2008)**

The studied system demonstrates the lowest total final electricity consumption values; this could be explained by the combination of very high population density (exceeding 5200 inh/km^2 in 2005)[26] and the restricted number and variety of industries, when compared to systems of much larger scales. On the other hand, residential final energy consumption could be expected to be higher as a consequence of the tourist based economy that makes domestic consumption correspond in reality to a much higher number of energy consumers than the system's inhabitants; however, the mild climatic conditions of the region reduce domestic energetic needs. Finally, the relatively high natural gas consumption in the system reflects increased use of natural gas in the domestic and energy sector.

---

[26] The level of population density is better understood when compared with other systems; the corresponding value for Spain in 2005 for example was equivalent to 91.4 inhabitants per km^2

5.3.2. Calculation of the system's electricity mix

No results have been encountered on primary energy consumption by source for the selected system since it has no statistical data recorded, similar to any region that is not politically defined, like a county or province for example. On the other hand, trying to find disaggregated data on a municipal level was quite difficult as the spatial scale is too small and the information found mainly concerned final consumption. Therefore, and as mentioned previously, the electricity mix of the system is calculated taking into account the contribution of the Catalan mix to the system's electricity needs; the results are presented in Table 5-2. Main trends include the steady increase of natural gas and the decline of petrol use for electricity generation. We also notice the contribution of energy sources that are not generated in the system, such as nuclear, wind-power and bio-fuels. Nuclear energy has a diminishing contribution in electricity production, mainly due to the launch of numerous natural gas combined cycle plants both in the system and the wider region of Catalonia. Although the use of renewables in Catalonia is augmenting (Ramos-Martín et al., 2007b), their contribution in the system's mix is dropping, a fact attributed to the rising of local electricity generation that does not depend on renewables (see Section 5.3.2).

Table 5-2 Annual progress of primary energy consumption by source in the studied system, in percentages [a]

	1997	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004* [b]	*2005* [b]
Carbon	**1.30**	**0.76**	**0.78**	**0.85**	**0.37**	**0.58**	**0.33**	**0.41**	**0.39**
Petrol	**50.63**	**51.91**	**50.92**	**49.31**	**50.28**	**41.96**	**31.96**	**26.39**	**30.10**
Natural gas	**22.95**	**19.42**	**22.40**	**22.44**	**23.97**	**39.77**	**50.44**	**59.21**	**57.57**
Nuclear	**21.85**	**23.60**	**20.49**	**21.71**	**19.80**	**13.84**	**12.43**	**9.98**	**7.78**
Hydroelectric	**1.76**	**1.56**	**1.41**	**1.38**	**1.38**	**0.96**	**1.06**	**0.75**	**0.48**
Wind-power	**0.00**	**0.00**	**0.03**	**0.04**	**0.04**	**0.03**	**0.03**	**0.03**	**0.03**
Biomass	**0.45**	**0.44**	**0.37**	**0.33**	**0.29**	**0.19**	**0.18**	**0.16**	**0.14**
Solar energy	**0.00**	**0.00**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.02**
Electricity exchange balance	**0.43**	**0.70**	**0.77**	**1.10**	**1.17**	**0.62**	**0.65**	**0.34**	**0.89**
Renewable waste	**0.48**	**0.46**	**0.42**	**0.42**	**0.35**	**0.27**	**0.34**	**0.35**	**0.23**
Non-renewable waste	**0.15**	**1.13**	**2.41**	**2.41**	**2.32**	**1.73**	**2.48**	**2.98**	**2.97**
Bioethanol	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.04**	**0.04**	**0.03**
Biodiesel	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.02**	**0.03**
Biogas	**0.00**	**0.00**	**0.00**	**0.01**	**0.01**	**0.02**	**0.04**	**0.06**	**0.06**
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

[a] Source: Calculation based on data from Ramos-Martín et al., 2007b
[b] Provisional data

5.3.3. *Evolution of final energy consumption per source and sector*

Annual evolution of final energy consumption and percentile contribution by source are presented in Table 5-3. Electricity produced by renewable sources and non-renewable waste is included in ‘electricity’, as they are distributed through the same grid. The values presented are for year 2000 onwards due to lack of data on butane, propane, gasoline and diesel consumption for the time series between 1997 and 1999. It is necessary to comment on the absolute augmentation of natural gas consumption, rising from almost 33 840 TJ/y in 1997 to approximately 81 000 TJ/y the last year of study. This makes it the dominant energy source for the system in 2006, representing 37.5% of the final energy consumption. According to the Gas Natural Group (2008), major natural gas provider in Spain, their supply points have increased by 1.2 million in the Spanish state in the course of four years, between 2003 and 2007.

Table 5-3 Total and per capita annual final energy consumption and contribution per source

	2000	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*
Electricity (%)	**21.0**	**21.2**	**21.7**	**21.7**	**22.0**	**19.3**	**19.2**
Natural gas (%)	**24.6**	**25.7**	**24.1**	**25.3**	**24.6**	**36.0**	**37.5**
Butane (%)	**1.6**	**1.4**	**1.3**	**1.1**	**1.0**	**0.8**	**0.7**
Propane (%)	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.5**	**0.5**
Diesel/fuel oil (%)	**40.9**	**40.8**	**42.0**	**42.3**	**43.1**	**36.6**	**36.0**
Gasoline (%)	**11.3**	**10.2**	**10.2**	**9.0**	**8.4**	**6.6**	**6.1**
Total final consumption (TJ/y)	**157 055**	**168 266**	**168 366**	**180 676**	**181 433**	**213 953**	**216 652**
Total final consumption (GJ/cap·y)	**67.9**	**72.1**	**70.9**	**73.7**	**73.7**	**85.6**	**85.7**

The augmentation of natural gas consumption also explains and is directly linked to the drop in butane, diesel and gasoline consumption, as demonstrated in Table 5-3. The shift from these more 'traditional' energy sources to natural gas for heating systems has definitely influenced their consumption. Although the absolute amount of diesel oil is increased over the years, type C, used for heating, has been reduced almost by 50% dropping from 174 000 to 90 000 tonnes annually, between 2000 and 2006 (MITYC, 2008). The contribution of propane and butane gases is rather small, their sum representing less than 2% of final energy consumption throughout the study period. They are principally used in the domestic sector, where a fraction between 73% and 82% of their total consumption is destined (MITYC, 2008).

We should note here the lack of data for carbon and wood fuel consumption since no data have been found on municipal level. Nevertheless, information on Catalonia reveals a small contribution of carbon to final energy consumption for 2006, equal to 0.2% (ICAEN, 2007).

The diminution of carbon consumption is also verified by the drop of the number of houses using this fuel for central heating. According to data from IDESCAT (2008a), the percentage of houses in the studied system using carbon for this purpose has dropped from 12.6% in 1991 to 0.3% in 2001. The same applies to wood, dropping from 0.6% to 0.2% for the same years.

The total and per sector consumption of electricity in absolute values is better illustrated in Figure 5-1 and the annual variations in Figure 5-2; we can notice a steady increase of total electricity demand throughout the whole period of study with an average growth rate of 4% annually, and a more moderate growth the last three years of the study. The services and transport sector is the most demanding in terms of electricity (Figure 5-1), chiefly explained by the service based economy of the area. Taking into account that this fraction basically represents the tertiary sector, as agricultural activities are hardly developed in the area, this data reveals the great impact tourist activities developed in the area have in energy consumption. Conversely, the industrial and energy sector demonstrates a steady decline the last four years of the study. This data comes to complement the previous comment; examining the contribution per economic activity sector to the system's economy we notice a shift from industrial to service activities; in 1991 the industrial sector was representing 31.2% of total GDP and the service sector 56.2% (IDESCAT, 2008a). Ten years later, the industrial sector dropped by 8 percentile units and services rose by 7%, in an almost complementary way.

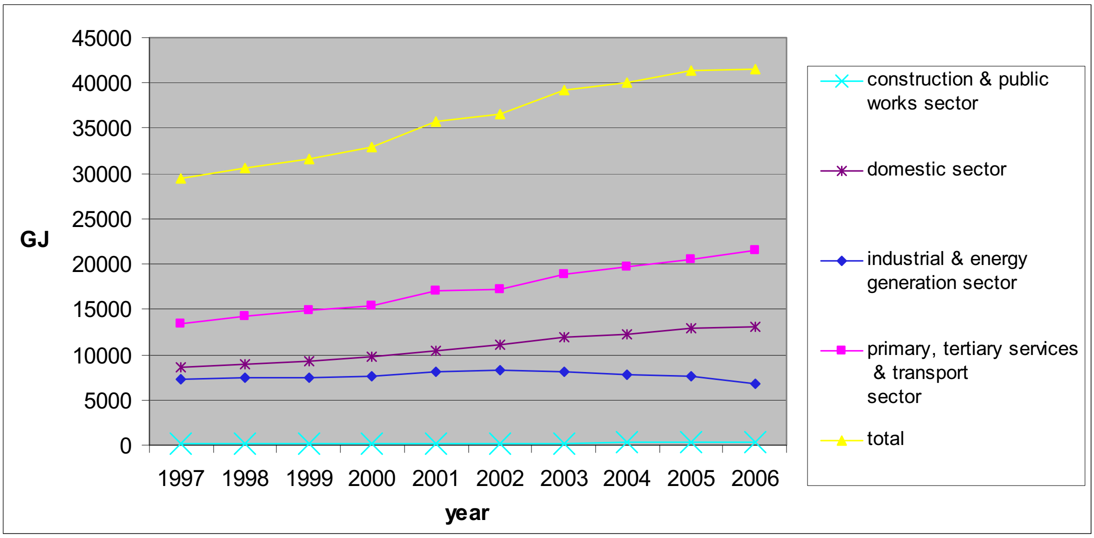


Figure 5-1 Final electricity consumption per sectors

The least energy demanding and most unstable sector is the construction and public works one, as shown in both Figures. Energy demand for this sector had an impressive increase between 2002 and 2004 only to drop again the last two years. Finally, electricity demand for domestic uses demonstrates a steady and positive growth rate throughout the whole study period.

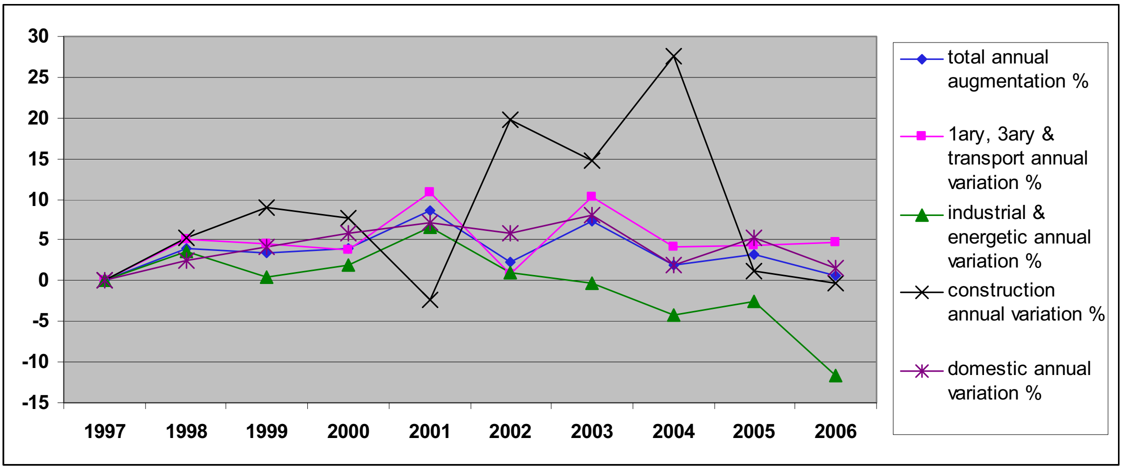


Figure 5-2 Annual variations in electricity consumption per sectors

5.3.4. Local energy generation and assessment of the system's energy self-sufficiency

The lack of domestic extraction of fossil fuels limits the system's local primary energy generation to renewable sources; official data on municipal level only stated relevant installations in the municipality of Barcelona (Agència d'energia de Barcelona, 2008). As described in Section 5.2, these include photovoltaic panels in municipal buildings, a mini-hydraulic power plant in the neighbourhood of Trinitat and the MSW energy recovery plants. The annual evolution of energy generation of these installations and their contribution to total energy and electricity consumption is given in
Table 5-4.

Apparently, the contribution of these sources to the consumption needs of the system is trivial, reaching an annual maximum contribution of 3% and 1% to final electricity and total energy consumption respectively. In contrast to the general picture of whole Catalonia, and with Spain as the second European wind energy generator, there are not any wind farms in the system. Even though it is an area compatible with the installation of wind farms (Generalitat de Catalunya, 2008) its potential does not seem to be very promising (EolicCat, 2008). In the same way, the developed services sectors dominating the system's economy and extensive urbanisation can explain the absence of bio-fuel production; agricultural production in the area is very poor, therefore there are no cultivations dedicated to energy uses.

While all primary resources are imported, electricity generation by local plants is quite elevated. Figure 5-3 shows the annual evolution of domestic electricity generation[27] compared to the system's final electricity demand. Its contribution oscillated from an average of 21.4%, for the period between 1997 and 2001, to the value of 53.4% for the following years. The highest value is noticed in 2005, when domestic plants covered 60% of the system's needs in electricity.

---

[27] Referring to all local plants, regardless of the origin of the prime materials

Table 5-4 Domestic primary energy generation, in GJ/y, and its contribution to final electricity and energy consumption, in the studied system

	Photovoltaic panels [a, b]	*Mini-hydraulic* [b]	*MSW incineration* [c, d]	*MSW methanisation* [e]	*Landfills* [e, f]	*Total energy generated*	*% of final electricity consumption*	*% of final energy consumption*
1997	**-**	**-**	**-**	**-**	**-**	**0**	**0.00**	**0.00**
1998	**-**	**-**	**298 199**	**-**	**-**	**298 199**	**0.97**	**0.45**
1999	**-**	**22 320**	**708 995**	**-**	**-**	**731 318**	**2.31**	**1.03**
2000	**144**	**20 520**	**735 401**	**-**	**-**	**756 065**	**2.30**	**0.48**
2001	**288**	**18 720**	**773 752**	**-**	**-**	**792 760**	**2.22**	**0.47**
2002	**738**	**22 680**	**592 240**	**9 572**	**-**	**625 234**	**1.71**	**0.37**
2003	**932**	**21 960**	**931 968**	**22 349**	**-**	**977 213**	**2.49**	**0.54**
2004	**2 930**	**-**	**862 517**	**62 413**	**292 194**	**1 220 058**	**3.05**	**0.67**
2005	**2 930**	**-**	**898 654**	**23 576**	**292 194**	**1 217 354**	**2.95**	**0.57**
2006	**2 930**	**-**	**317 225**	**588 269**	**187 441**	**1 095 865**	**2.64**	**0.51**

[a] Data calculated from installed potential data.

[b] Source: Canal Solar BCN (2008);

[c] Energy generation for the Mataró plant was calculated knowing the amount of residues treated and the energy generation coefficient of 1.894 GJ/t (Source: Consortium for the Management of Solid Municipal Waste in Maresme, 2008)

[d] Energy generation data for the incinerator plant of Sant Adriá de Besòs obtained from TERSA (2008)

[e] Data on the methanisation plants and landfill site obtained from the annual environmental reports issued by the Metropolitan Environmental Authority of Barcelona (EMMA, 2004; 2005; 2006; 2007)

[f] Refers to the energy obtained from landfill gas

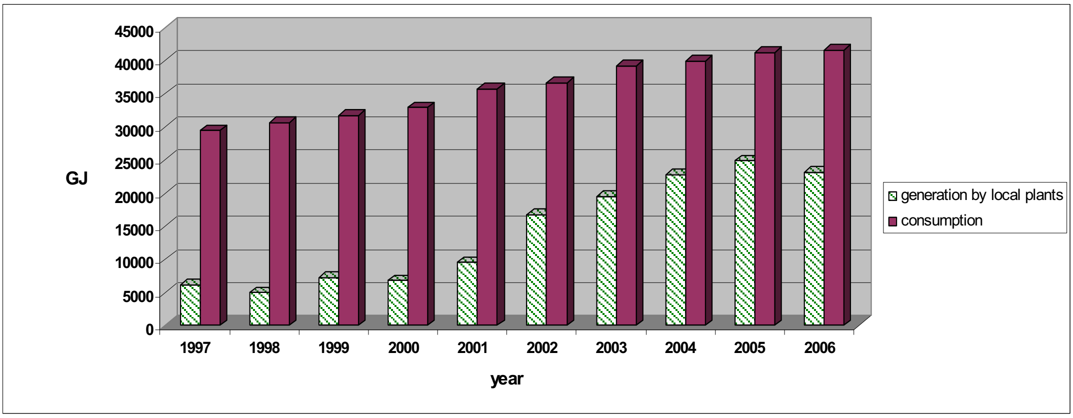


Figure 5-3 Annual progress of domestic final electricity generation and total electricity consumption

The sudden increase in 2002 is attributed to the launch of two units of a combined cycle plant in the municipality of Sant Adriá de Besòs, better illustrated in Figure 5-4. It is apparent in the same Figure, that local electricity generation is characterised by the dominance of natural gas related facilities, the small share of MSW energy recovery processes and the insignificant contribution of renewable sources.

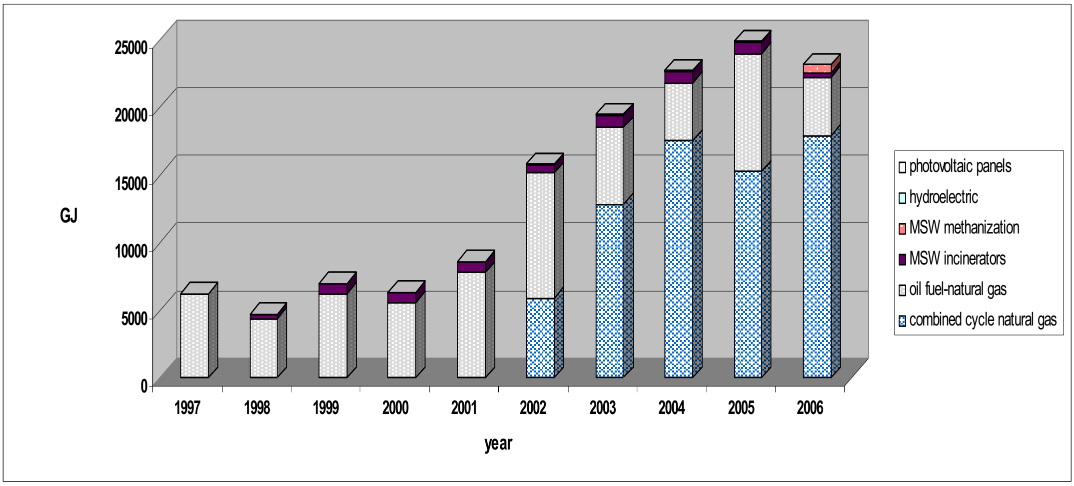


Figure 5-4 Annual progress of domestic final electricity generation per source

5.3.5. Energy consumption analysis on a municipal scale

The aim of this section is to compare energy consumption indicators on a municipal level using data on GDP and population density. This analysis can help discover possible consumption patterns linked to different types of economies and urbanisation types. The comparisons are made between the municipalities with population superior to 5 000 inhabitants for 2001. Due to the lack of analytical energy consumption data we can only make a comparison of total and per sectors final electricity consumption and total natural gas consumption. The results are given in Table 5-5.

Table 5-5 Data on energy consumption, population density and GDP for municipalities with population superior to 5 000 inhabitants, for 2001

Municipality	*Population Density (inh/km^2)*	*GDP per capita*	*Electricity consumption per sector, in GJ/cap*					*Natural Gas (GJ/cap)*
			Domestic	*Primary, Tertiary & Transport*	*Industrial & energetic*	*Construction & public works*	*Total*	
Cubelles	513	18.5	6.8	5.6	0.4	0.4	13.2	4.7
Vilanova i la Geltrú	1 571	18.7	4.6	6.1	7.8	0.1	18.6	13.3
Sant Pere de Ribes	561	11.3	4.9	3.3	1.4	0.1	9.6	8.6
Sitges	464	20.9	7.8	10.9	20.5	0.3	39.6	13.6
Castelldefels	3 627	12.6	5.4	4.0	0.2	0.1	9.8	7.7
Gavà	6 212	23	4.5	5.4	5.3	0.1	15.3	29.5
Viladecans	2 801	12.4	3.5	3.7	7.3	0.1	14.5	11.3
el Prat de Llobregat	1 933	43.1	3.5	9.3	27.4	0.1	40.3	139.7
Barcelona	14 993	27.3	4.6	8.4	2.2	0.1	15.2	15.5
Sant Adrià de Besòs	8 537	16.7	3.1	8.1	6.8	0.0	18.0	20.3
Badalona	9 858	12.5	3.4	3.4	2.0	0.0	8.8	7.7
Montgat	4 764	12.6	4.2	2.8	4.2	0.0	11.3	21.3
el Masnou	1 286	14.1	5.0	3.9	6.9	0.1	15.9	46.8
Premià de Mar	12 645	11.4	4.2	2.1	1.2	0.0	7.5	10.2
Vilassar de Mar	4 344	16.1	5.4	4.6	1.5	0.0	11.5	24.1
Mataró	1 601	17.6	4.0	6.1	3.4	0.1	13.5	15.5
Sant Andreu de Llavaneres	633	12.3	7.7	4.6	0.3	0.1	12.7	18.9
Arenys de Mar	1 858	14.2	4.9	6.8	1.2	0.1	13.0	10.9
Canet de Mar	1 890	12.2	4.7	3.4	1.4	0.1	9.6	9.3
Calella	1 727	17.5	5.4	10.7	0.4	0.1	16.6	12.4
Pineda de Mar	2 808	13.7	4.7	5.8	3.4	0.1	14.1	16.6
Malgrat de Mar	2 024	20.5	4.2	6.9	9.7	0.1	20.8	40.0

As mentioned in the Introduction of this Chapter, both electricity consumption and GDP are regarded as quality of life indicators, so a positive correlation should be expected between them. The municipalities under study however, do not demonstrate a very wide range of GDP values in order to make an interesting analysis and reach valuable conclusions regarding this issue. Examining the graphs in Figure 5-5 we can detect a positive connection in the case of total electricity consumption and the services and transport sector.

El Prat de Llobregat, a highly industrialised municipality situated next to Barcelona, presents the highest per capita GDP. Its elevated energy demand is attributed to industrial activities, judging from the relatively low consumption of the residential and construction sectors. If we take for granted that domestic electricity consumption is correlated to GDP, we could describe el Prat as a rich industrial municipality with poor residents. An interesting case is that of Sitges, a summer resort that presents consumption values surprisingly close to that of el Prat de Llobregat in graphs b, d and f. This can be explained by two reasons; the elevated domestic, service and construction sectors consumption can be attributed to a tourist-based economy that has results in high investments in these sectors and as a consequence the temporal augmentation of its population by 24% (IDESCAT, 2008b). With regards to industrial electricity consumption, that can be attributed to Sitges' low population density that raises the per capita values. The city of Barcelona has rather moderate per capita values with the exception of the services and transport sector, due to the great number of visitors it receives and the function of an electric tram line.

As far as population density is concerned, there does not seem to be a general trend with the energy consumption indicators studied here (Figure 5-6). Yet, there is a clear negative correlation with electricity consumption in the domestic and construction sectors. If we consider that the sum of municipalities is urbanised with the same pace, densely populated systems demonstrate lower per capita consumption values.

The results on the relationship between the urbanised surface of a municipality and its energy needs are analogous to the ones presented for population density. These two factors have a positive correlation, as high population density is linked with extended urbanised surface (see Figure 5-7).

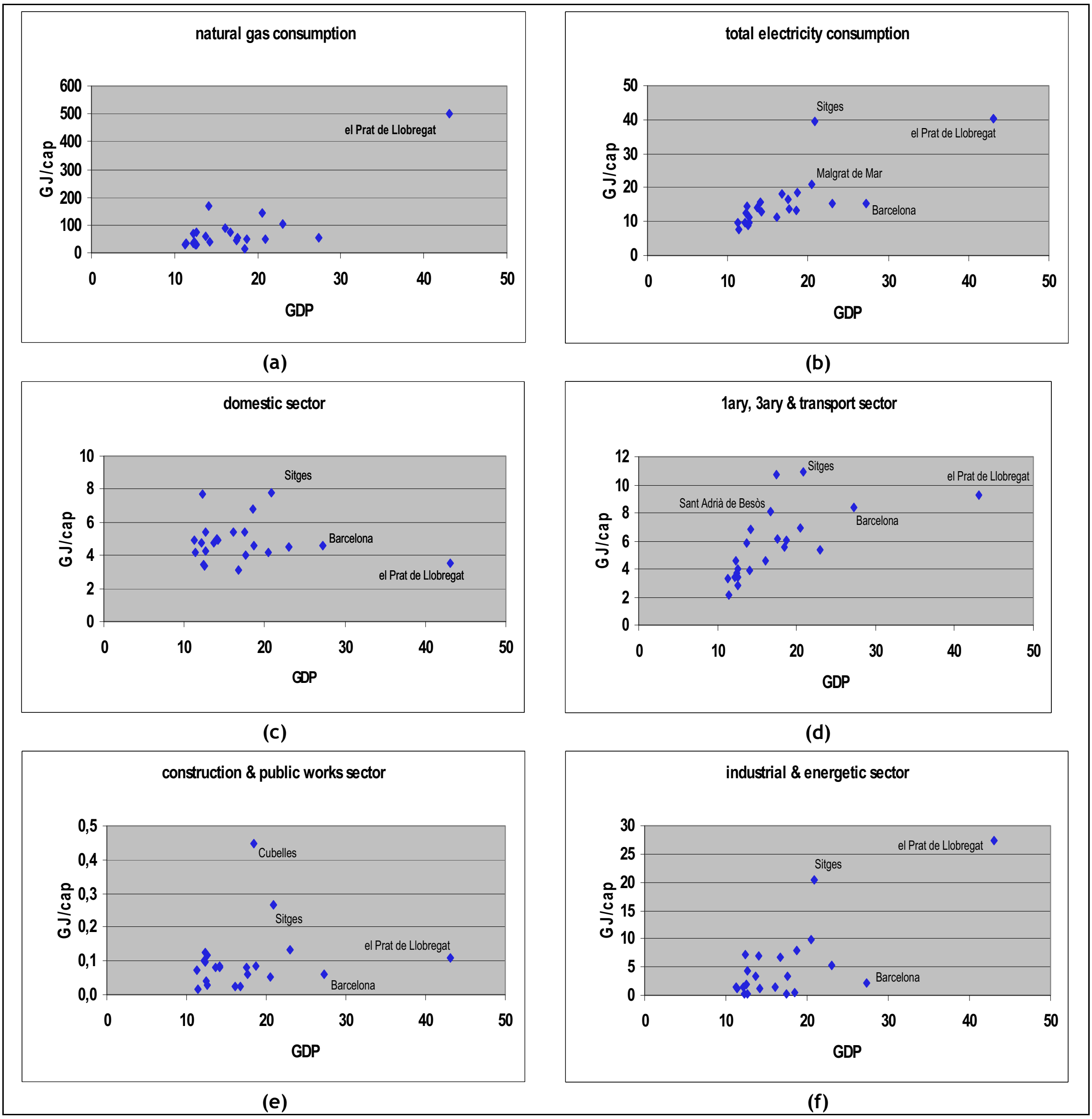


Figure 5-5 Correlation of GDP and main energy consumption indicators, for 2001

(a) annual natural gas consumption (b) total final electricity consumption (c) electricity consumption for domestic uses (d) electricity consumption for services and transport (e) electricity consumption for construction and public works (f) electricity consumption for industrial and energy production

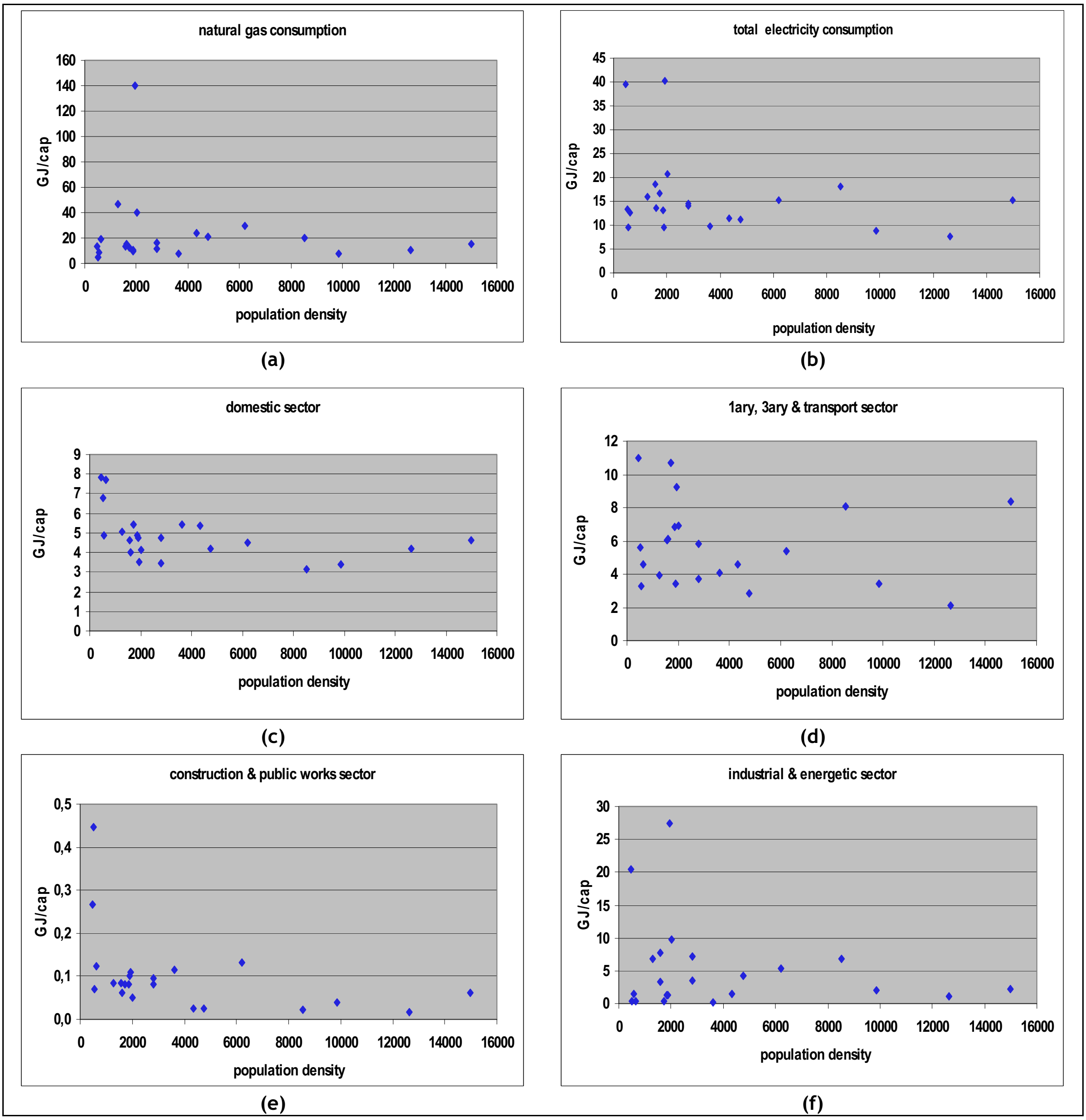


Figure 5-6 Correlation of population density, in inhabitants per km^2, and main energy consumption indicators, in GJ per capita, for 2001

(a) annual natural gas consumption (b) total final electricity consumption (c) electricity consumption for domestic uses (d) electricity consumption for services and transport (e) electricity consumption for construction and public works (f) electricity consumption for industrial and energy production

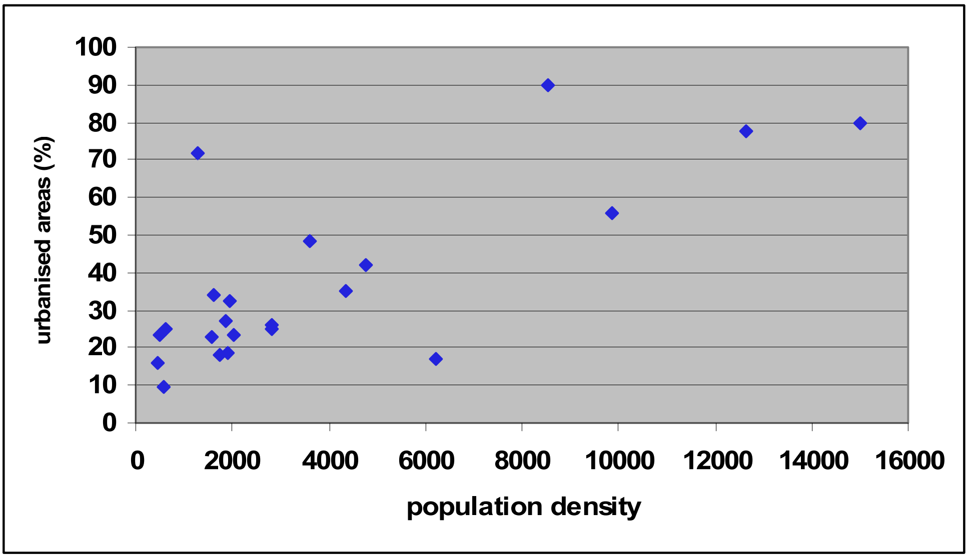


Figure 5-7 Correlation between population density, in inhabitants per km^2, and percentage of urbanised surface

5.4. Conclusions

The studied system does not seem to be very energy intensive in per capita values compared to systems of larger scale; yet, final energy consumption is increasing over the years, both in absolute and in per capita values. The results primarily reveal the system's energetic dependence on imports and the low generation of renewable energies within its limits. It heavily depends on imported natural gas for electricity generation as for direct consumption. This is in analogy with a gradual decline in the contribution of nuclear energy and petrol in the system's energy mix and in the final consumption of long-established energy sources like gasoline, petrol, butane and diesel. A transition towards natural gas has taken place in the system during the study period then. This shift, however, has neither improved its dependence on imports nor its sustainability, in terms of energy consumption, as natural gas is a depletable resource. The conduction of more specific studies on this issue would be interesting for the disclosure of some environmental aspects of this, such as a probable change in CO_2 emissions employing LCA.

No strong connection is revealed between energy consumption and population density with the exception of the electricity consumption in the domestic and construction sectors. On the contrary, the type of economy of each municipality is an important factor that forms energy consumption patterns. Touristy municipalities demonstrate elevated per capita electricity consumption in the domestic and services sector, due to seasonal population augmentation and the related infrastructure correspondingly. High GDP values are also positively related with total electricity consumption and to the electricity demand of the services and transport sector. Finally, after the confirmation of the importance of tertiary services in energy consumption, the need for more specific studies on this sector seems to be necessary.

References

Agència d'Energia de Barcelona (2005) El comptador. Informació Energética de Barcelona. Agència d'Energia de Barcelona. Num.1

Agència d'Energia de Barcelona (2008) Data available at: http://www.barcelonaenergia.cat/cas/observatorio/fotovolt/resumefv.htm

Brugmann, J. (1996) Planning for sustainability at the local government level. Environ Impact Assess Rev 16: 363-379 (in Catalan)

Canal Solar BCN (2008) http://www.barcelonaenergia.cat/canalsolar/

Consortium for the Management of Solid Municipal Waste in Maresme (2008) Consorci per al Tractament de Residus Sòlids Urbans del Maresme. Available at: http://www.plantabrossa-maresme.com/infocaps.php?id=1234

Dzioubinski, O. and Chipman, R. (1999) Trends in consumption and production: household energy consumption. DESA Discussion Paper No. 6, Economic and Social Affairs, United Nations.

EEA (1999) Environment in the European Union at the turn of the century. Environmental assessment report no. 2. Office for Official Publications of the European Union. European Environment Agency: Luxembourg

EMMA (2004) Metropolitan Environmental Data 2003. Entitat Metropolitana dels Serveis Hidràulics i del Tractatament de Residus (EMSHTR): Barcelona

EMMA (2005) Metropolitan Environmental Data 2004. Entitat Metropolitana dels Serveis Hidràulics i del Tractatament de Residus (EMSHTR): Barcelona

EMMA (2006) Metropolitan Environmental Data 2005. Entitat Metropolitana dels Serveis Hidràulics i del Tractatament de Residus (EMSHTR): Barcelona

EMMA (2007) Metropolitan Environmental Data 2006. Entitat Metropolitana dels Serveis Hidràulics i del Tractatament de Residus (EMSHTR): Barcelona

EolicCat (2008) Areas with wind potential in Catalonia. EolicCat, l'Associació Eòlica de Catalunya. Available at: http://www.eoliccat.net/_docs/zones.asp

Eurostat (1999) Towards environmental pressure indicators for the EU. Office for Official Publications of the European Communities: Luxembourg

Eurostat (2001) Economy-wide material flow accounts and derived indicators. A methodological guide. Office for Official Publications of the European Union: Luxembourg

Farreny, R., Gabarrell, X. and Rieradevall, J. (2008) Energy intensity and greenhouse gas emissions of a purchase in the retail park service sector: an integrative approach. Energy Policy 36 (6): 1957-1968

Fischer-Kowalski, M. (1998) Society's metabolism. The intellectual history of materials flow analysis. Part I: 1860–1970. J Ind Ecol 2 (1): 61–78.

Fischer-Kowalski, M. and Haberl, H. (1998) Sustainable development: socio-economic metabolism and colonization of nature. International Social Science Journal 50 (4): 573-587

Gas Natural Group (2008) Operating and Financial Statistics. Available at: http://portal.gasnatural.com/archivos/informesPDF/280508_Estadisticas_de_explotacion_financieras_ing.pdf

Gasol, C. M., Martínez, S., Rigola, M., Rieradevall, J., Anton, A., Carrasco, J., Ciria, P. and Gabarrell, X (2009) Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renewable and Sustainable Energy Reviews 13 (4): 801-812

Generalitat de Catalunya (2006) Pla de l' Energia de Catalunya 2006-2015. Generalitat de Catalunya. Departament de Treball i Indústria: Barcelona

Giampietro, M., Mayumi, K. and Munda, G. (2006) Integrated assessment and energy analysis: Quality assurance in multi-criteria analysis of sustainability. Energy 31: 59–86

Goldemberg, J. and Johansson, T.B. (eds.) (1995) Energy as an instrument of socio-economic development. United Nations Development Programme. Available at: http://www.undp.org/seed/energy/policy

Haberl, H. (2001) The energetic metabolism of societies. Part I: Accounting concepts. Journal of Industrial Ecology 5 (1): 11-33

Haberl, H. (2006) The global socioeconomic energy metabolism as a sustainability problem. Energy 31: 87-99

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H. and Winiwarter, V. (2004) Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 21: 199-213

Huang, S.-L. (1998) Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. Journal of Environmental Management 52: 39-51

Huang, S.-L., Kao, W.-C. and Lee, C.-L. (2007) Energetic mechanisms and development of an urban landscape system. Ecological Modelling 201 (3-4): 495-506

IAEA (2005) Energy Indicators for Sustainable Development: Guidelines and Methodologies. International Atomic Energy Agency: Vienna. ISBN 92–0–116204–9

ICAEN (2007) Balanç energètic de Catalunya 2006. Institut Català d' Energia.Generalitat de Catalunya. Setmana de l'energia 2007. 19 of October 2007. Document available at: http://www.gencat.cat/economia/doc/doc_29565278_1.pdf

IDESCAT (2008a) Institut d'Estadística de Catalunya. Databases available at: www.idescat.cat

IDESCAT (2008b) Database of municipalities and counties: Sitges. Institut d'Estadística de Catalunya. Available at: http://www.idescat.cat/territ/BasicTerr?TC=5&V0=1&V3=863&V4=435& ALLINFO=TRUE&PARENT=1&CTX=B&V1=08270&VOK=Confirmar

IEA (1995) Energy balances of OECD countries 1992–1993. International Energy Agency: Paris

INE (2008) Instituto Nacional de Estadistica. Databases available at: www.ine.es

Generalitat de Catalunya (2008) Ministry of the Environment: Pla de Parcs eòlics de Catalunya. Available at: http://mediambient.gencat.net

Joyeux, R and Ripple, R. D. (2007) Household energy consumption versus income and relative standard of living: A panel approach. Energy Policy 35: 50–60

Kastoriadis, C. and Cohn-Bendit, D. (1981) From ecology to autonomy. Kedros publishing: Athens.

Kennedy, C, Cuddihy, J. and Engel-Yan, J. (2007) The changing metabolism of cities. Journal of Industrial Ecology 11 (2): 1-17

Krausmann, F. and Haberl, H. (2002). The process of industrialization from the perspective of energetic metabolism. Socioeconomic energy flows in Austria 1830-1995. Ecological Economics 41: 177-201

Krausmann, F., Haberl, H., Erb, K.-H. and Wackernagel, M. (2004) Resource flows and land use in Austria 1950–2000: using the MEFA framework to monitor society–nature interaction for sustainability. Land Use Policy 21: 215–230

Larivière, I. and Lafrance, G. (1999) Modelling the electricity consumption of cities: effect of urban density. Energy Economics 21 (1): 53-66

Martinez-Alier, J. (1987) Ecological economics: energy, environment and society. Basil Blackwell: Oxford

Martinez-Alier, J. (2004) Marx, Energy and social metabolism. Encyclopaedia of Energy 3: 825-834

Mindali, O., Raveh, A. and Salomon, I. (2004) Urban density and energy consumption: a new look at old statistics. Transportation Research Part A 38: 143–162

MITYC (2008) Estadísticas y Balances Energéticos – Publicaciones Estadísticas Gas. Ministerio de Industria, Turismo y Comercio. Available at: http://www.mityc.es/Balances/Seccion/Publicaciones/Estadisticas/Gas/

Newman, P. and Kenworthy, J. (1989) Cities and Automobile Dependence: An International Sourcebook. Avebury Technical: Great Britain

Observatori de l'energia de Barcelona (2005) Observatori de L'energia de Barcelona. Balanç 1999 – 2003. Observatori de l'energia de Barcelona: Barcelona

Oliver-Solà, J., Núñez, M., Gabarrell, X., Boada, M. and Rieradevall, J. (2007) Services sector metabolism, Integrated Energy Flow Analysis and Life Cycle Analysis of the technical energy consumption at the Montjuic Park. Journal of Industrial Ecology 11(2): 83-98

Omer, A., M. (2008) Energy, environment and sustainable development. Renewable and Sustainable Energy Reviews 12 (9): 2265-2300

Ramos-Martín, J., Giampietro, M. and Mayumi, K. (2007a) On China's exosomatic energy metabolism: An application of multi-scale integrated analysis of societal metabolism (MSIASM). Ecological Economics 63: 174-191

Ramos-Martín, J., Cañellas Boltà, S. and Russi, D. (2007b) Anàlisi del Metabolisme Energètic de l'Economia Catalana (AMEEC). Bloc 2: Energia Primària a Catalunya. Resum executiu. Consell Assessor pel Desenvolupament Sostenible (CADS). Generalitat de Catalunya: Barcelona

Sciubba, E. (2003) Extended exergy accounting applied to energy recovery from waste: The concept of total recycling. Energy 28: 1315–1334

Sempere, J. (2007) Los riesgos y el potencial político de la transición a la era post-petróleo. In: Sempere, J. and Tello, E. (eds.), El final de la era del petróleo barato. Icaria editorial: Barcelona

Suh, S. (2005) Theory of materials and energy flow analysis in ecology and economics. Ecological Modelling 189: 251-269

Sundkvist, Ǻ., Jansson, A., Enefalk, Ǻ. And Larsson, P. (1999) Energy flow analysis as a tool for developing a sustainable society—a case study of a Swedish island. Resources, Conservation and Recycling 25: 289–299

Talens, L., Villalba, G. and Gabarrell, X. (2008) Exergy análisis of integrated waste Management in the recovery and recycling of used cooking oils. Environmental Science and Technology 42 (13): 4977-4981

TERSA (2008) TERSA: Solucions ambientals: Planta de Valorització Energètica (Sant Adrià de Besós): Dades de producció 2003-2007. Grupo TERSA. Data available at: www.tersa.com

Thi Anh Tuyet, N. and Ishihara, K., N. (2006) Analysis of changing hidden energy flow in Vietnam. Energy Policy 34: 1883–1888

Udo de Hayes, H., A. and Heijungs, R. (2007) Life-cycle assessment for energy analysis and management. Applied Energy 84: 817–827

Ulgiati, S., Odum, H.T. and Bastianoni, S. (1994) Emergy use, environmental loading and sustainability. An emergy analysis of Italy. Ecological Modelling 73: 215-268

UN (1997) Energy statistics yearbook 1995. United Nations: New York

UNDESA (2001) Indicators of Sustainable Development: Guidelines and Methodologies, 2nd edition, September. United Nations Department of Economic and Social Affairs: New York

UNESA (2004) Memoria Estadística Eléctrica de UNESA. 2004. Asociación Española de la Industria Eléctrica. Available at: www.unesa.es

UNESA (2007) Memoria Estadística Eléctrica de UNESA. 2007. Asociación Española de la Industria Eléctrica. Available at: www.unesa.es

6. APPLICATION OF THE PROPOSED TOOLS ON THE MUNICIPAL LEVEL

6.1. Inter-municipal comparison for the two indicators for 2003

Both indicators presented in this work reflect natural resources consumption habits and related management strategies on a local or regional level. Along these lines, they are able to monitor the transition of the actual models of urbanisation towards more sustainable systems. The water indicator is related to water consumption habits and the efficiency of the water distribution networks; the waste indicator correspondingly, is linked to MSW generation and management, hence with natural resources use efficiency, and the effectiveness of MSW management plans. The two indicators have one fundamental difference; whereas the waste indicator assesses the sustainability of existing management schemes, the water indicator also reflects the opportunities for the exploitation of the available renewable water from precipitation. In other words, the latter demonstrates, or even quantifies, the potential of a system for sustainable water management. Both indicators can serve as useful planning tools for urban regions, in combination with other indicators, revealing aspects of carrying capacity with reference to the issues they assess.

The performance of all municipalities in the two indicators is presented in Table 6-1. Results for the waste indicator are only provided for municipalities with a population superior to 20 000 inhabitants; as mentioned in Chapter Four, this is the minimum system size that the indicator should best be applied to. From the comparison of the results in both indicators we can notice an overall better performance in the water indicator. Waste indicator data vary between extreme high and low values that imply excessive imports or exports of MSW and weak recycling policies respectively, with the externalisation of environmental problems associated to MSW treatment as a consequence. These results also imply important transport of waste, entailing augmented CO_2 emissions and energy demand[28]. Few municipalities have moderate results; still none of them appears to perform really well in this indicator reaching the unity.

---

[28] As stated in Chapter Four, transport of waste is the stage of a MSW Management plan that most contributes to atmospheric emissions and consumption of energy

Table 6-1 Results on the two indicators for the 27 municipalities, where applicable, for 2003

Municipality	*Water indicator*	*Waste indicator*
Cubelles	-	-
Vilanova i la Geltrú	0.42	0.10
Sant Pere de Ribes	0.15	0.67
Sitges	0.15	0.06
Castelldefels	0.78	0.49
Gavà	2.34	0.50
Viladecans	0.45	0.05
el Prat de Llobregat	1.24	0.08
Barcelona	2.93	0.32
Sant Adrià de Besòs	1.48	23.96
Badalona	1.38	0.05
Montgat	0.12	-
el Masnou	0.14	0.05
Premià de Mar	1.36	0.05
Vilassar de Mar	1.05	-
Cabrera de Mar	0.24	-
Mataró	5.38	2.96
Sant Andreu de Llavaneres	0.12	-
Sant Vicenç de Montalt	0.13	-
Caldes d'Estrac	0.54	-
Arenys de Mar	0.23	-
Canet de Mar	0.27	-
Sant Pol de Mar	0.72	-
Calella	0.43	-
Pineda de Mar	0.15	0.03
Santa Susanna	0.13	-
Malgrat de Mar	0.08	-
Entire System	1.03	0.65

On the other hand, most municipalities demonstrate water indicator values below the unity, with the exception of seven of them, indicating strong potential for covering their needs in water using rainwater. Even though the systems are closely situated in an area of Mediterranean climate facing similar weather conditions with moderate precipitation, there is no homogeny in the values of this indicator due to the variety of urban models among the studied systems.

A positive water indicator value for a system does not necessarily indicate this as sustainable; the indicator assesses the potential of a system to cover its needs with rainwater but the sustainability of that is dependent on the exploitation of this resource. However positive the results obtained for these municipalities, these are not sustainable in their water management if the rainwater they receive is not properly exploited. The success of this proposal lies in the existence and appropriate use of the necessary infrastructure and during the study period, only the city of Barcelona disposed of underground deposits for the retention of rainwater (EMMA, 2005). Yet, these were merely used for the avoidance of floods and the control of water contamination. This water was then gradually deliberated to the sea or rivers, sometimes having been treated in a wastewater treatment plant (CLABSA, 2006). So regardless of the indicator values all municipalities were unsustainable in the time period studied, in terms of the exploitation of renewable water they received through precipitation. In the following sections the factors that affect each indicator are examined.

6.1.1. Analysis of the performance of the water indicator for 2003 and overall evaluation of the water management strategies in all municipalities

The information presented in Table 6-2 is related to the features that shape the water indicator value with regards to land use, precipitation and water consumption habits for each municipality. As mentioned earlier, most municipalities demonstrate particularly low indicator values which suggest that the amount of rainfall they receive annually in their urbanised surfaces exceeds their needs in water.

As stated in Chapter Three, optimum water indicator values oscillate between 0.75 and 1.25, given that extremely low values could imply extended urbanised surfaces for a system which is not always desirable and does certainly not form a positive sustainability index. The revision of the characteristics of the municipalities with indicator values lower than 0.50 though does not agree with this assumption. These systems have various degrees of urbanisation with percentages of urban surface between 53.5%, for Sitges, and 91%, for Arenys de Mar and Canet de Mar. They neither seem to have any other common characteristic in terms of precipitation, water consumption or water management (i.e. water reuse and distribution efficiency).

On the other hand, many systems with extended urbanised surfaces that reach up to 100% do not seem to achieve good results; Premià de Mar, Badalona and Sant Adrià de Besòs are good examples, with a degree of urbanisation superior to 90% and high indicator values. The critical, and common for these municipalities, factor in this case appears to be high population density.

Table 6-2 Data relevant to the water indicator, for 2003 [a]

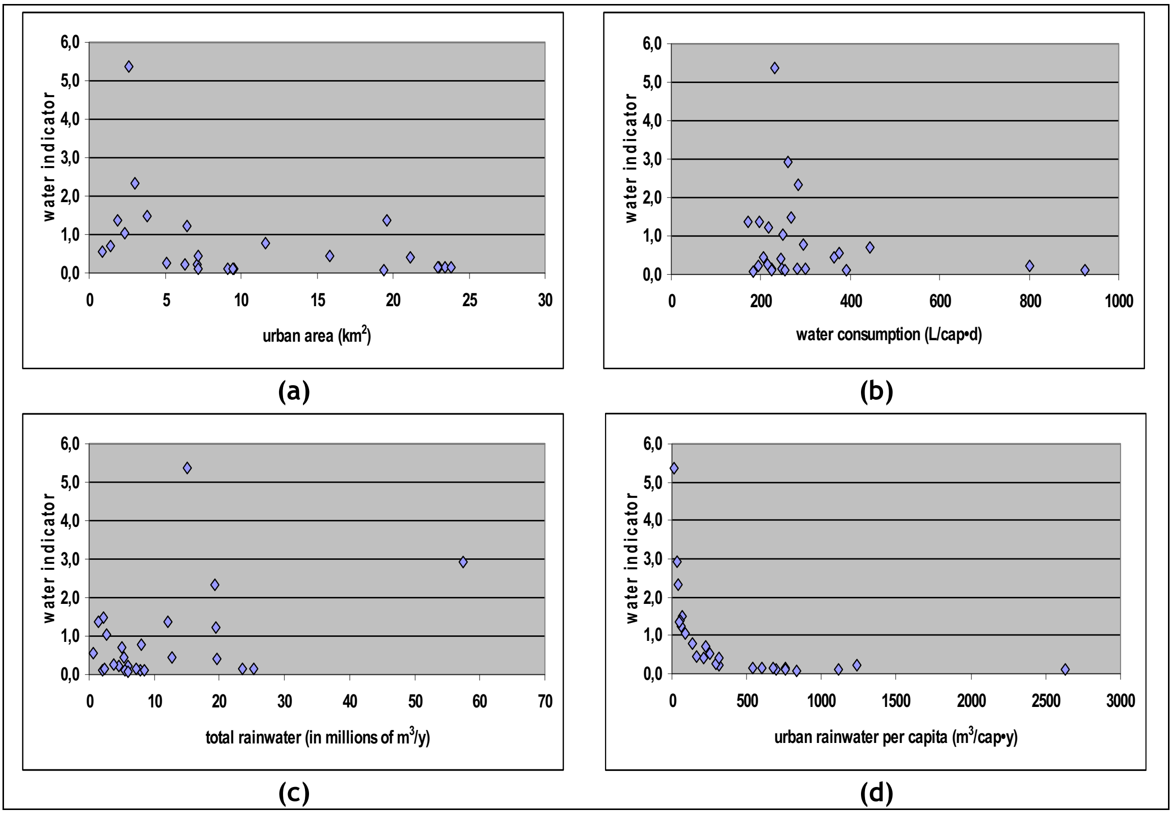
Municipality	*Population density (inh/km^2)*	*Primary water distribution (L/cap·d)*	*Total rainfall (L/cap·d)*	*Urban area (%)*	*Water reuse (m^3/y)*	*Secondary supply network efficiency*	*Water indicator*
Vilanova i la Geltrú	**1 685**	**245**	**940**	**62.1**	**0**	**79%**	**0.42**
Sant Pere de Ribes	**606**	**223**	**2 614**	**56.4**	**0**	**77%**	**0.15**
Sitges	**517**	**247**	**3 068**	**53.5**	**0**	**84%**	**0.15**
Castelldefels	**4 062**	**294**	**421**	**89.9**	**2 267 870**	**76%**	**0.78**
Gavà	**1 374**	**284**	**1 245**	**88.2**	**1 766 490**	**76%**	**2.34**
Viladecans	**2 909**	**207**	**588**	**77.6**	**1 803 060**	**76%**	**0.45**
el Prat de Llobregat	**2 029**	**216**	**843**	**72.7**	**0**	**83%**	**1.24**
Barcelona	**15 764**	**261**	**99**	**89.6**	**0**	**76%**	**2.93**
Sant Adrià de Besòs	**8 643**	**269**	**181**	**100.0**	**0**	**76%**	**1.48**
Badalona	**10 115**	**197**	**155**	**92.4**	**0**	**76%**	**1.38**
Montgat	**2 925**	**223**	**627**	**84.3**	**0**	**76%**	**0.12**
el Masnou	**6 177**	**299**	**297**	**77.4**	**1 878**	**82%**	**0.14**
Premià de Mar	**13 012**	**172**	**141**	**90.0**	**1 458**	**85%**	**1.36**
Vilassar de Mar	**4 580**	**249**	**401**	**59.3**	**0**	**77%**	**1.05**
Cabrera de Mar	**430**	**801**	**4 268**	**79.2**	**0**	**82%**	**0.24**
Mataró	**4 972**	**232**	**369**	**87.7**	**0**	**91%**	**5.38**
Sant Andreu de Llavaneres	**716**	**254**	**2 562**	**81.0**	**24 106**	**77%**	**0.12**
Sant Vicenç de Montalt	**534**	**392**	**3 435**	**88.8**	**19 581**	**79%**	**0.13**
Caldes d'Estrac	**2 567**	**376**	**715**	**97.8**	**10 397**	**82%**	**0.54**
Arenys de Mar	**1 947**	**194**	**943**	**91.3**	**0**	**68%**	**0.23**
Canet de Mar	**2 093**	**216**	**877**	**91.3**	**0**	**75%**	**0.27**
Sant Pol de Mar	**570**	**444**	**3 218**	**19.2**	**0**	**72%**	**0.72**
Calella	**1 925**	**364**	**953**	**89.6**	**0**	**72%**	**0.43**
Pineda de Mar	**2 115**	**282**	**867**	**73.6**	**0**	**81%**	**0.15**
Santa Susanna	**190**	**924**	**9 657**	**74.7**	**0**	**59%**	**0.13**
Malgrat de Mar	**1 754**	**183**	**1 046**	**86.2**	**0**	**77%**	**0.08**
Entire System	**5 000**	**253**	**318**	**76.3**	**5 894 840**	**77%**	**1.04**

[a] The municipality of Cubelles is not included due to insufficient data

In view of these first observations it is essential to examine the correlation of the indicator with each of the parameters that condition its value. The main factors affecting the indicator, taking into consideration its mathematical expression[29], are the urban surface, water consumption and precipitation of a system. The main critique this indicator has received so far is related to its connection to the degree of urbanisation of the evaluated system, as increased paved surface should bring positive results to the water indicator. However, and despite its significance in the end result of the indicator, there does not seem to be any correlation between the urban area of a system and this, either as a percentage of its total surface (see Table 6-2) or as an absolute value in km^2 (Figure 6-1(a)). Similar remarks can be made with reference to primary water distribution per capita as illustrated in Figure 6-1(b). Regarding precipitation, Figure 6-1 (c) reveals that augmented rainfall does not necessarily result in better indicator values. Per capita precipitation on urbanised areas in contrast, is clearly positively related to the indicator, designating the importance of population density in a system (Figure 6-1 (d)).

---

[29] See Equation 3-6, Chapter Three



(a) (b)

(c) (d)

Figure 6-1 Correlation between the main factors that influence the water indicator value and the results obtained for each municipality, for 2003

(a) Relation between the indicator values and the urban area of each municipality
(b) Relation between the indicator values and water consumption
(c) Relation between the indicator values and total rainwater received
(d) Relation between the indicator values and rainwater received on urbanised surfaces, per capita

Examining the correlation between population density and the water indicator values, the last assumption is confirmed indeed. Figure 6-2 reveals that all municipalities with population density superior to 5 000 inhabitants per km^2, with the exception of el Masnou, demonstrate indicator values higher than the unity, regardless of their per capita consumption and grade of urbanisation. In the case of el Masnou, even though it has elevated water consumption per capita, it is a system with extended urbanised surface that allows for a greater recollection of rainwater.

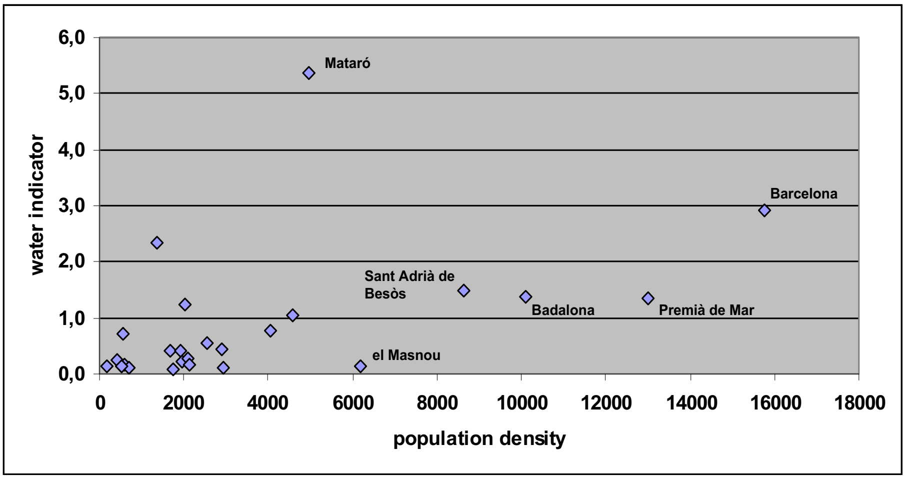


Figure 6-2 Correlation between the water indicator and population density, in inhabitants per km^2, for 2003

In fact, augmented population density seems to be the common characteristic of the systems that perform badly; Mataró, Sant Adrià de Besòs, Badalona, Premià de Mar and Barcelona are included in the six most densely populated municipalities. The case of Gavà and el Prat de Llobregat is different as they are systems of low population density but with restricted urban areas that do not favour rainwater collection resulting in high indicator values.

It is quite interesting to contrast the case of Premià de Mar, the municipality with the lowest per capita consumption, with that of Santa Susanna, the most water demanding system in terms of per capita consumption. The first reuses water and has satisfactory efficiency in its secondary supply network; yet, its indicator value is higher than Santa Susanna. Population density in combination with low available rainfall does not allow this municipality to cover its needs in water through urban precipitation.

Suggestions for the improvement in the performance of these municipalities would certainly not include augmentation of their urbanised surface (as in the case of Gavà and el Prat de Llobregat) or reduction in their population (for the most densely populated ones). Local strategies and policies can put forward sustainable solutions with relation to water resources management that will neither deteriorate the urban environment nor affect their population. An increase in the efficiency of the secondary water supply networks would minimise water distribution losses in Gavà, Barcelona, Sant Adrià de Besòs and Badalona, consequently reducing their primary water supply needs. Augmented water reuse and measures for a change in water consumption habits would lead to the same results. Nevertheless, the majority of these systems (namely Gavà, Sant Adrià de Besòs, Badalona and Mataró) have highly industrialised economies, as shown previously in Table 1-3, in a manner that a reduction in water demand would require further actions and stricter control on the industrial level too.

There are three interrelated factors critical for the water indicator value, namely available water from precipitation, urbanised surface and population density. Apparently, these factors cannot guarantee a system's sound performance individually; high urbanisation does not necessarily favour the indicator, if per capita consumption and population density is too elevated. In the same lines, systems with high water per capita consumption and low population density can demonstrate good results even if they have limited urbanised surface.

6.1.2. Analysis of the performance of the waste indicator for 2003

The MSW indicator value heavily depends on the fraction of generated MSW that is directly used as raw material (R) and, in the case of systems hosting related treatment plants, to the performance of these[30]. For systems with no MSW treatment capacity the indicator value is solely attributed, and is analogous, to the fraction of MSW directly recovered (R). The majority of waste indicator values presented in Table 6-1 are less than or equal to 0.10 and correspond to such municipalities[31]; their low values indicate small direct recovery rates (see Table 6-3). These systems export almost the totality of their MSW to be treated outside their limits (each of them exports more than 90% of its MSW), externalising this way the associated to MSW treatment environmental costs. At the same time, MSW transport is augmented with an equivalent increase in the CO_2 emissions and energy demand for their MSW management plans.

The municipalities with moderate results, meaning values between 0.30 and 0.75, are those that host material recovery facilities, such as compost and sorting plants, with small secondary waste flows that favour the indicator (Barcelona, Castelldefels, Gavà and Sant

---

[30] See Equation 4-1, Chapter Four

[31] Namely, Vilanova i la Geltrú, Sitges, Viladecans, el Prat de Llobregat, Badalona, el Masnou, Premià de Mar and Pineda de Mar

Pere de Ribes). These systems receive low fractions of MSW compared to their local generation and even though they demonstrate satisfactory R values, compared to the rest, they still need to export grand part of their MSW. Barcelona is a special case with elevated, in absolute values, amounts of MSW imported to be treated in its Ecoparc that are not reflected in the indicator's value; high local generation of MSW counterbalances the high amount of waste treated there resulting in a moderate indicator value.

Sant Adrià de Besòs and Mataró present extremely high indicator values; both host incinerator plants and their values are analogous to their plants' inputs. These plants principally serve the municipalities belonging to the Barcelona Metropolitan Area and the County of Maresme respectively. As shown in Table 6-3, the two systems share the common characteristics of very high rates of MSW imports and correspondingly low percentages of exported waste in relation to the MSW they generate. They also demonstrate small fractions of directly recovered MSW for year 2003.

The municipality that has the best performance, always considering the unity as the optimum value, is Sant Pere de Ribes. Although this municipality has a moderate direct recovery rate (R) and receives MSW equivalent to 50% of the amount it generates, it hosts a plant with trivial secondary waste flows and has low MSW generation.

Table 6-3 Data relevant to the waste indicator, on the 14 municipalities with population of more than 20 000 inhabitants, for 2003

	Plants hosted	*MSW generation (t/y)*	*Waste treated (t/y)*	*Plant outputs (t/y)*	*Imported waste (%)*	*Exported waste (%)*	*R (%)*
Badalona	**-**	**94 384**	**0**	**0**	**0.0**	**94.8**	**5.2**
Barcelona	**compost plant** **methanisation plant**	**868 325**	**228 807**	**-**	**7.6**	**75.2**	**6.0**
Castelldefels	**compost plant**	**36 010**	**15 349**	**-**	**26.9**	**78.2**	**6.1**
el Masnou	**-**	**10 842**	**0**	**0**	**0.0**	**94.7**	**5.3**
el Prat de Llobregat	**-**	**28 415**	**0**	**0**	**0.0**	**92.4**	**7.6**
Gavà	**sorting plant**	**23 231**	**12 411**	**2 201**	**52.4**	**93.1**	**5.8**
Mataró	**incinerator**	**65 518**	**190 346**	**-**	**211.8**	**15.6**	**5.7**
Pineda de Mar	**-**	**20 334**	**0**	**0**	**0.0**	**96.6**	**3.4**
Premià de Mar	**-**	**12 567**	**0**	**0**	**0.0**	**95.2**	**4.8**
Sant Adrià de Besòs	**incinerator**	**14 475**	**360 192**	**14 032**	**2404.0**	**10.8**	**5.0**
Sant Pere de Ribes	**compost plant**	**15 129**	**9 170**	**-**	**52.9**	**86.3**	**5.9**
Sitges	**-**	**20 925**	**0**	**0**	**0.0**	**93.7**	**6.3**
Viladecans	**-**	**28 641**	**0**	**0**	**0.0**	**95.4**	**4.6**
Vilanova i la Geltrú	**-**	**36 196**	**0**	**0**	**0.0**	**90.5**	**9.5**

From these observations we could conclude that the local MSW management plans of the systems that belong to the Barcelona Metropolitan Area and the County of Maresme favour incineration with energy recovery rather than methanisation or material recovery and composting. With regards to methanisation this is quite expectable as the unique plant in the area, situated in Barcelona, only started receiving MSW in 2001 on an experimental basis. Compost is a much more common practice, greatly favoured not only by the European Communities Directives but Catalan regulations as well; the Municipal Waste Management Program in Catalonia (2001-2006), in force during the period of study[32], set objectives for the separate collection of each of the fractions of MSW and planned to impose a tax on landfilling, in order to encourage separate collection and recycling (Generalitat de Catalunya, 2001). Yet, the amount of organic matter collected separately does not reach the

---

[32] A new plan has been published since, planning the actions on the issue of MSW management for Catalonia for the period between 2005 and 2012 (Generalitat de Catalunya, 2005).

amount of residues directly sent for final treatment, whether that is landfill or incineration. In 2003, 10 of the studied municipalities were not collecting organic matter separately.

Systems that host incineration plants, although they appear more self-sufficient in terms of MSW treatment capacity, are receptors of large amounts of waste from neighbouring systems and the associated environmental costs to the function of these plants. What is more, they seem to heavily rely on these facilities and demonstrate lower material recovery than most systems.

6.1.3. Overall analysis of the MSW management strategies in all 27 municipalities

The scope of this section is to analyse the results of the MSW management plans in the totality of municipalities, including the smaller ones; between the 27 municipalities, 13 of them had a population of less than 20 000 inhabitants in 2003. Examining the data presented in Table 6-4 we notice that the spatial scale of the studied systems does not favour the siting of MSW treatment plants; the municipalities that host treatment plants have a population superior to 20 000 inhabitants. Furthermore, even though the Catalan regulation obliges municipalities of more than 5 000 inhabitants to perform separate collection since 2005 (EIONET, 2007), separate collection and recycling schemes were not well developed in the smaller municipalities during the study period. Municipalities of lower than 5 000 inhabitants do demonstrate low separate collection percentages, not exceeding 10%, with the exception of Santa Susanna that reaches almost 20%. This municipality however has rather special characteristics with particularly high MSW generation and water consumption per capita. This probably reveals high touristy development that leads to equivalent increased attention to municipal environmental policies.

It is also interesting to examine the separate collection percentages in relation to the Counties that each municipality belongs to and their respective MSW management policies. There is a clear difference between the three Counties of the South and that of Maresme. Garraf has the highest percentage with 29.5 % of separate selection, possibly reflecting this County’s population distress for the landfill operating there, followed by Baix Llobregat with 24.9% and Barcelonès with 19%. Maresme only reaches 11.9% of separate collection. These values not only reflect the MSW management schemes' efficiency on a County level but the siting of treatment plants as well. Maresme only hosts a final treatment facility while the material recovery and compost plants are distributed along the rest of the studied coastline. Similarly, it is the County with less green points per municipality.

Table 6-4 Basic data relevant to MSW management on the 27 municipalities

County	*Municipality*	*Population*	*Number of MSW management plants* [a, b]	*% separate collection*
Garraf	**Cubelles**	**8 548**	**(1)**	**35.36**
	Vilanova i la Geltrú	**57 300**	**(1)**	**31.52**
	Sant Pere de Ribes	**24 741**	**1 (1)**	**32.89**
	Sitges	**22 625**	**(1)**	**18.28**
Baix Llobregat	**Castelldefels**	**52 405**	**1 (1)**	**33.45**
	Gavà	**42 304**	**2 (1)**	**17.6**
	Viladecans	**59 343**	**(1)**	**17.14**
	el Prat de Llobregat	**63 312**	**(1)**	**31.48**
Barcelonès	**Barcelona**	**1 582 738**	**2 (7)**	**20.5**
	Sant Adrià de Besòs	**32 845**	**1**	**15.71**
	Badalona	**214 440**	**(2)**	**21.04**
Maresme	**Montgat**	**8 775**	**-**	**10.77**
	el Masnou	**21 001**	**-**	**6.59**
	Premià de Mar	**27 326**	**-**	**6.11**
	Vilassar de Mar	**18 321**	**-**	**12.88**
	Cabrera de Mar	**3 869**	**-**	**10.93**
	Mataró	**111 879**	**1 (2)**	**21.24**
	Sant Andreu de Llavaneres	**8 450**	**(1)**	**9.89**
	Sant Vicenç de Montalt	**4 326**	**-**	**7.82**
	Caldes d'Estrac	**2 310**	**-**	**7.03**
	Arenys de Mar	**13 431**	**-**	**8.27**
	Canet de Mar	**11 722**	**(1)**	**8.5**
	Sant Pol de Mar	**4 276**		**10.16**
	Calella	**15 400**	**(1)**	**13.76**
	Pineda de Mar	**22 843**	**(1)**	**21.17**
	Santa Susanna	**2 413**	**-**	**19.95**
	Malgrat de Mar	**15 614**	**(1)**	**15.34**
	Entire System	**2 452 557**	**8 (24)**	**18.6**

[a] Includes compost, recycling, incineration with energy recovery, methanisation and sorting plants

[b] The number in parenthesis indicates the number of green points (deixalleries)

Figure 6-3 illustrates the relation between the fraction of MSW separately collected and the acquisitive power per capita for each municipality; a positive relation between these parameters can be detected. This demonstrates that the MSW management plan of a County is a more decisive factor than the economic condition of a municipality. Other exceptions are the municipalities of Santa Susanna, as mentioned earlier, and Sitges. The latter demonstrates low separate collection and high income although it is situated in a County with well-organised recycling schemes.

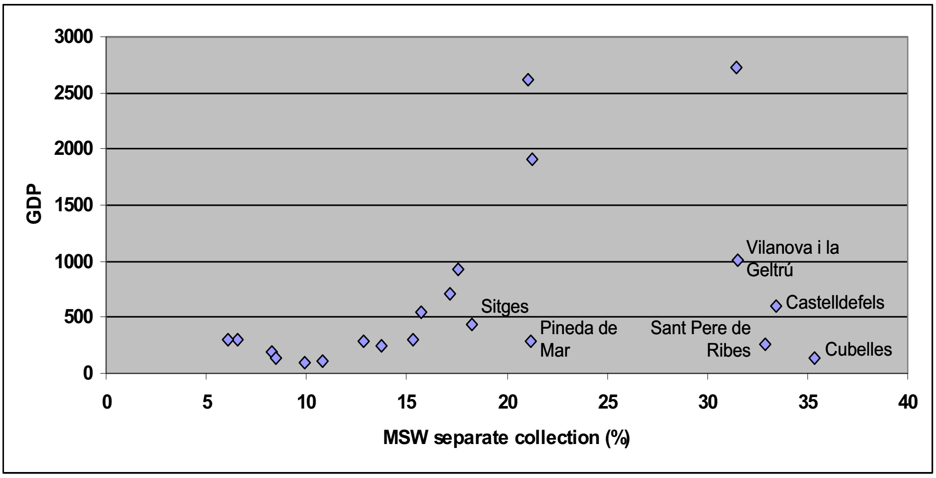


Figure 6-3 Comparison between the percentage of separate collection of MSW and GDP, per capita, for municipalities of more than 5 000 inhabitants (excluding Barcelona)

6.2. Annual evolution of the water self-sufficiency indicator

The annual progress of the water indicator for the period between 1998 and 2003 is only presented for the municipalities that have sufficient data for its calculation throughout these years. The graphic representation of these values is illustrated in Figure 6-4. It seems that most systems have a steady performance for all years, meaning that their values do not demonstrate oscillations below and above the unity. Sant Adrià de Besòs, Badalona and Vilassar de Mar are the only exceptions as they seem to be unsustainable for all years excluding 2002.

We can notice that most municipalities have a similar temporal evolution with a descending tendency between 1999 and 2001. In 2002 every system has the best performance as the indicator values drop significantly, only to rise again the following year. Precipitation for 2002 covers most systems' demand in water with the exception of Barcelona, Premià de Mar and Mataró.

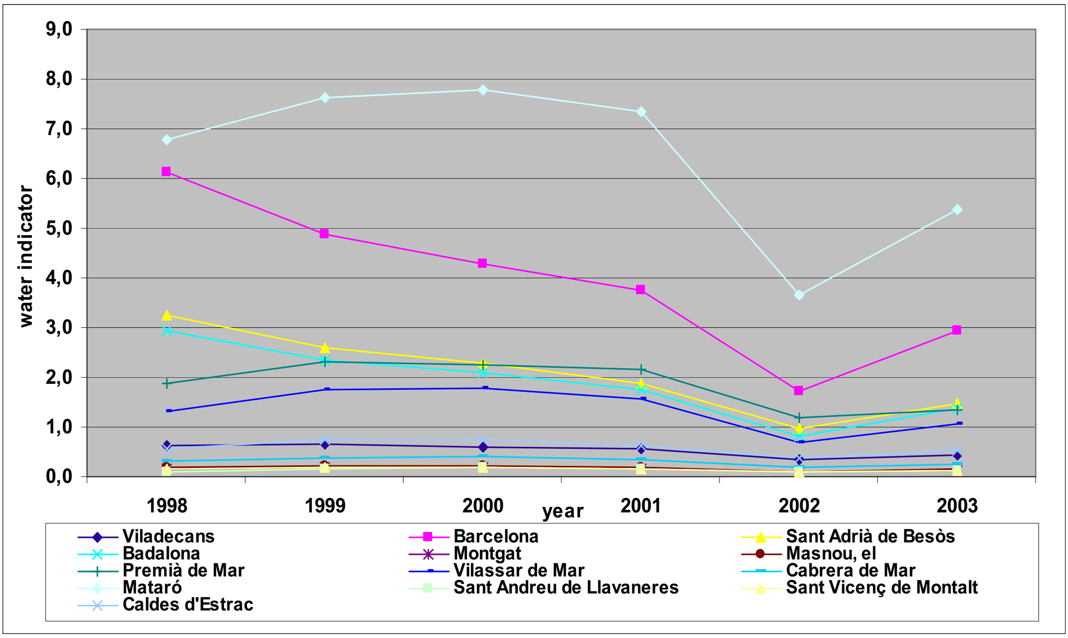


Figure 6-4 Annual evolution of the water indicator for selected municipalities

With the examination of the evolution of total annual precipitation per municipality in Figure 6-5, an extreme increase of rainfall for that year is noticed, that perfectly explains the indicator's behaviour. In 2003 annual precipitation drops again but is still higher than the equivalent values for the period between 1998 and 2001; indicator values follow the same trend.

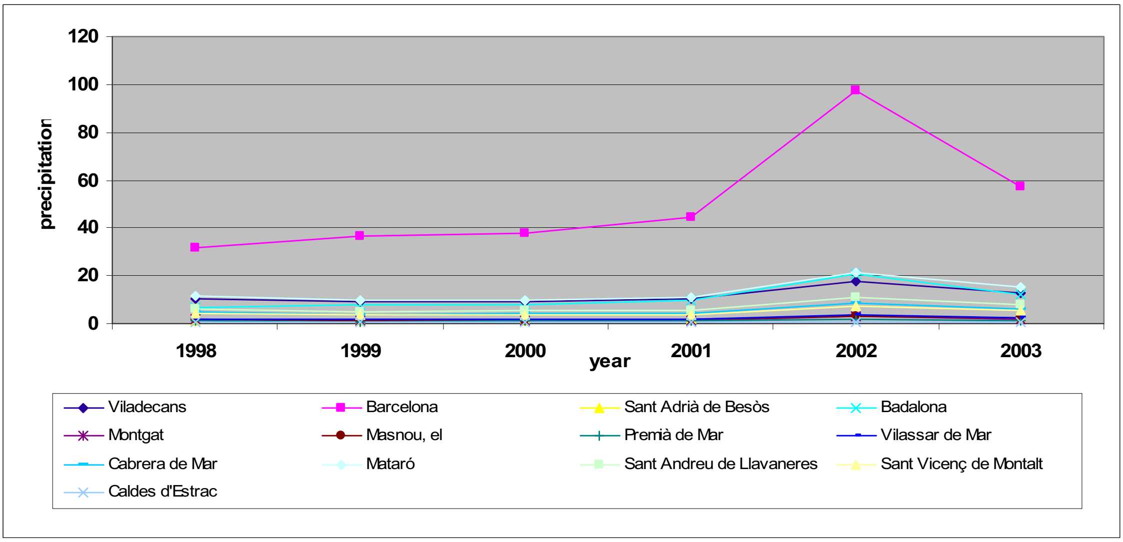


Figure 6-5 Annual evolution of precipitation in millions of m^3/y per municipality

Through the observation of water consumption data for these years (Figure 6-6) it seems that water consumption is not such a strong factor as precipitation in affecting the indicator, for the reason that there do not appear to be any changes on a management level, referring to water reuse and improvement in the infrastructures for reducing water distribution losses. In this case, fluctuation of water consumption values does not coincide with the indicator values showing that precipitation can help these systems be sustainable in terms of water use even if their consumption keeps rising. In 2002, Viladecans, Sant Adrià de Besòs, Premià de Mar, and Caldes d'Estrac present increased per capita consumption; yet, precipitation could still cover or reach these municipalities' needs in water. Nevertheless, the sustainability goal for a municipality with reference to this indicator is not to expect increased precipitation to cover its needs in water but to diminish water demands not only through reduced consumption but with the improvement of the related infrastructure and the maximum reuse possible.

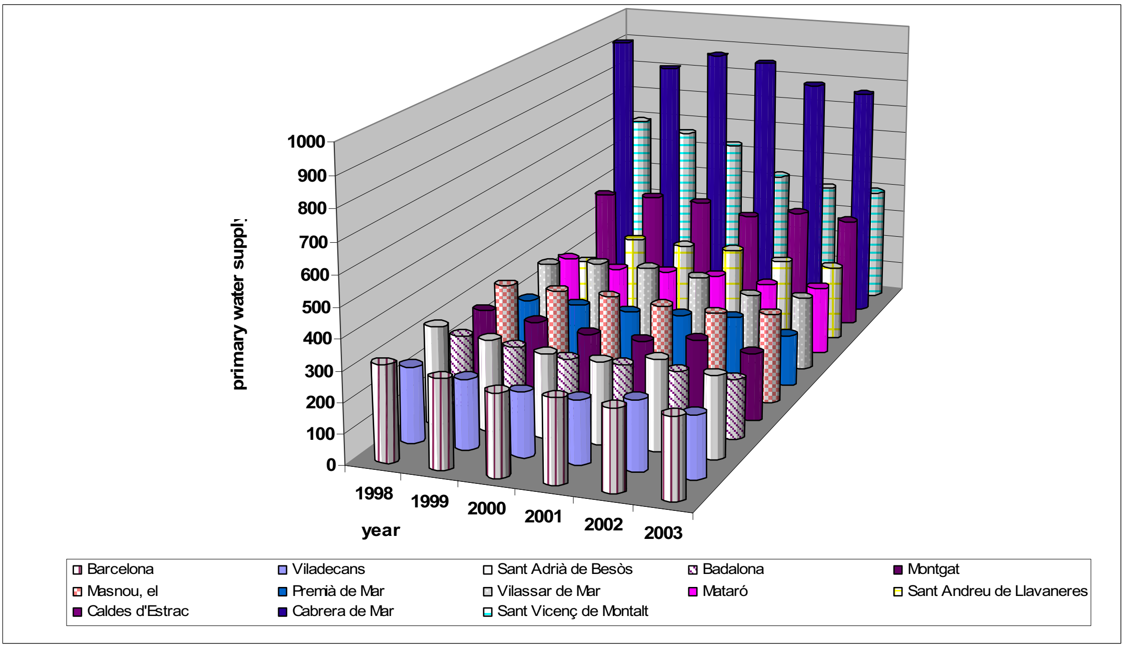


Figure 6-6 Annual evolution of primary water supply, in m^3/cap·d

6.3. Annual evolution of the MSW management indicator

Of all 27 municipalities under study, sufficient data for the calculation of the indicator throughout the whole period of study (1998-2005) have only been encountered on 14 of them. The results are presented in Table 6-5.

Table 6-5 Annual evolution of the indicator for selected municipalities

	1998	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*
Badalona	**0.04**	**0.05**	**0.04**	**0.05**	**0.05**	**0.05**	**0.05**	**0.06**
Barcelona	**0.04**	**0.05**	**0.05**	**0.07**	**0.17**	**0.32**	**0.25**	**0.37**
Castelldefels	**0.11**	**0.04**	**0.31**	**0.23**	**0.38**	**0.49**	**0.22**	**0.51**
el Masnou	**0.03**	**0.04**	**0.04**	**0.04**	**0.05**	**0.05**	**0.05**	**0.06**
el Prat de Llobregat	**0.06**	**0.07**	**0.06**	**0.06**	**0.09**	**0.08**	**0.07**	**0.07**
Gavà	**0.05**	**0.06**	**0.05**	**0.48**	**0.47**	**0.50**	**0.47**	**1.54**
Mataró	**3.59**	**3.70**	**3.32**	**3.24**	**3.70**	**2.96**	**2.97**	**2.62**
Pineda de Mar	**0.02**	**0.02**	**0.03**	**0.03**	**0.03**	**0.03**	**0.04**	**0.05**
Premià de Mar	**0.03**	**0.04**	**0.04**	**0.05**	**0.04**	**0.05**	**0.04**	**0.06**
Sant Adrià de Besòs	**17.63**	**18.81**	**19.21**	**19.56**	**12.54**	**23.96**	**16.02**	**18.37**
Sant Pere de Ribes	**0.05**	**0.05**	**0.05**	**0.06**	**0.06**	**0.67**	**0.57**	**0.66**
Sitges	**0.02**	**0.04**	**0.04**	**0.04**	**0.05**	**0.06**	**0.07**	**0.06**
Viladecans	**0.02**	**0.03**	**0.02**	**0.03**	**0.03**	**0.05**	**0.04**	**0.07**
Vilanova i la Geltrú	**0.06**	**0.07**	**0.06**	**0.07**	**0.09**	**0.10**	**0.10**	**0.11**

The majority of municipalities that do not host treatment facilities present stable yet slightly ascending indicator values which reach their peak the last year of study[33]. This tendency cannot but reveal increasing fractions of MSW directly used as raw materials, hence an increase in separate collection of MSW. Although the percentage of separately selected MSW is not included in the mathematical expression of the indicator this is directly related to R and represents its potential for increase. Figure 6-7 verifies this assumption, illustrating increasing tendencies for the fractions of separately collected MSW and R, both resulting in their highest values in year 2005.

---

[33] Municipalities that have no MSW treatment capacity demonstrate indicator values close to zero, solely attributed to the R fraction as noted earlier; in this case these are: Badalona, el Masnou, el Prat de Llobregat, Pineda de Mar, Premià de Mar, Sitges, Viladecans and Vilanova i la Geltrú

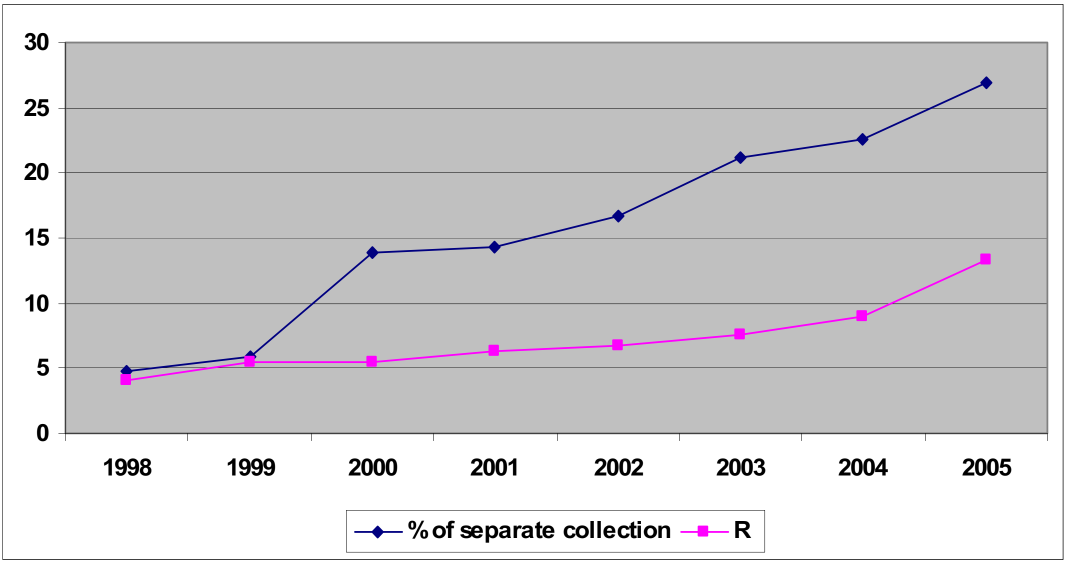


Figure 6-7 Annual evolution of the fractions of MSW separately selected, in percentage, and that directly used as prime materials, in 10^7 tonnes per year (average values of selected municipalities)

The municipalities that launched treatment facilities during the study period clearly reflect this change in their indicator value. Barcelona's Ecoparc started functioning on an experimental basis in 2001 and accepted MSW from 2002 onwards. The indicator rapidly increases from that year on, as both the treating capacity and the material recovery of the system are gradually increased (Table 6-6). The rest of municipalities of this category are those that better perform in the MSW indicator and host material recovery plants. These are Castelldefels, Gavà and Sant Pere de Ribes.

Table 6-6 Annual progress of plant inputs in the municipalities with increasing waste indicator values, in t/y

	1998	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*
Barcelona	**0**	**0**	**0**	**11 163**	**89 709**	**228 807**	**349 402**	**368 197**
Castelldefels	**2 209**	**-**	**8 656**	**7 103**	**8 961**	**15 349**	**6 063**	**18 397**
Gavà	**-**	**-**	**-**	**12 158**	**11 603**	**12 411**	**12 407**	**40 961**
Sant Pere de Ribes	**-**	**-**	**-**	**-**	**-**	**9 170**	**8 209**	**8 952**

6.4. Conclusions

With regards to the MSW management plans of the studied systems, it was made clear from the results that on a small municipality level, the objective is not for every system to host each MSW facility required to treat all the types of waste this generates. MSW management sustainability is not achieved through the existence of treatment facilities but with reduction of MSW flows and the maximisation of the materials sent for direct recovery (R); these should be the objectives of a local MSW management scheme that aims for sustainability and efficient use of resources.

In addition, the sum of the municipalities' performance, evaluated as a single system, is much better than the average value of all municipalities studied individually. This information could support the idea that MSW management plans should be designed on a larger than the municipal scale (as it is already taking place in the County of Maresme and the Barcelona Metropolitan Area); after local efforts for minimisation of waste flows and increase of separate collection, regional plans should aim to minimise waste transport and augment fractions of directly recovered MSW.

Concerning the estimation of the potential of the municipalities under study to cover their needs in water through the exploitation of rainwater, the majority of them showed good results. We see that we cannot make a simplistic analysis proposing augmented paved surfaces for municipalities for the recollection of rainwater; one of the most encouraging results is that increased urbanisation is not a requisite for sufficient rainfall recollection. Under current conditions of urbanisation, these systems have many possibilities to improve their water management sustainability by means of more decisive policies, whose changes can be monitored by the indicator.

Nevertheless, however positive the results on the water indicator, this study can only remain on a theoretical level due to the lack of the required facilities in these systems, as the success of this proposal lies in the existence and appropriate use of the necessary infrastructure. This work can be seen as the first step in the detection of sustainable solutions for water management in urban areas. The water indicator finally, can be an important tool for the planning or redesigning of urban areas, supporting decision-making on determining population size, density and urban growth, in combination with other indicators.

References

Agència Metropolitana de Residus (2003) Memòria 2002. Agència Metropolitana de Residus: Barcelona.

CLABSA (2006) Activitats i realitzacions: Clavegueram: Dipòsits de BCN. Sewerage of Barcelona. Available at: www.clabsa.es

EIONET (2007) Fact sheets: Spain. European Topic Centre on Resource and Waste Management. Available at: http://waste.eionet.europa.eu/factsheets/Spain.

EMMA (2005) Pla Director d'Aigües Pluvials: Planificació del drenatge urbà a l'àrea metropolitana de Barcelona i estudi de reducció de descàrregues de sistemes de sanejament a medi receptor. Entitat Metropolitana del Medi Ambient: Barcelona

Generalitat de Catalunya (2001) Programa de gestió de residus municipals de Catalunya (2001-2006) – PROGREMIC, Synthesis Document. Departament de medi ambient i habitatge, Junta de Residuos: Barcelona

Generalitat de Catalunya (2005) Pla D'acció Per A La Gestió de Residus Municipals A Catalunya 2005-2012. Departament de medi ambient i habitatge, Agència de Residus de Catalunya: Barcelona

7. CONCLUSIONS

In this thesis two methodologies have been proposed for the evaluation of urban sustainability from a metabolic perspective, with regards to water and MSW management. The separate accounting and analysis of artificial water and MSW flows are suggested with the aim to monitor their temporal evolution, detect their associated indirect flows and assess their importance on a local or regional scale. The results demonstrate the capacity of these methodologies to describe these flows efficiently and give a clear picture on the metabolism of a system with relation to these.

The methodologies presented build on the MFA guidelines proposed by Eurostat for the conduction of studies on a national level; the key MFA concepts used were adapted to face the needs and particularities of smaller scale studies. After the standardisation of a MFA methodology for nation-wide studies, similar guidelines should be established for analyses on lower spatial levels for the detection, monitoring and analysis of local, regional and urban flows that call for such approaches.

The main drawback throughout this research has certainly been the collection of data. Disperse and insufficient information on the municipal level only made this process more difficult. The sources were diverse, varying from national and regional statistics institutes to Agenda 21 reports carried out on a municipal level. The municipalities that belong to greater entities responsible for their environmental management, such as those of the Barcelona Metropolitan Area or the county of Maresme, had more detailed and extensive information. With reference to data collection, the significant contribution of the local Catalan agencies of water, waste and energy indicate the importance of such entities. With the completion of this work the need for a more systematised and consistent recording of environmental data on a smaller than the national level is detected, identifying this omission as a major reason for the restricted number of such studies.

In the same lines, indicators derived from local or regional scale studies are indispensable for the achievement of sustainability in such systems. It is clear that sustainability cannot be achieved with the sole help of indicators; their use, however, is indispensable for monitoring the progress of a system’s demands on natural resources and the estimation of necessary changes in consumption habits, management strategies and related policies.

The description of the artificial water and MSW flows resulted in corresponding sustainability indicators that give insight into the metabolic performance of a system in relation to these flows. These indicators have a certain degree of complexity due to the variety of factors that influence them, they are however simple to calculate. Their main asset is the inclusion of aspects that are not taken into account by related sustainability indicators proposed so far. Besides their potential use in the planning of future urban areas they appear to be useful evaluation tools for existing urbanised systems as they can detect drawbacks and changes in relevant infrastructure. They manage in addition to overcome the negative critique on indicators, including the absence of a reference state or the recognition of the practical steps required to lead us to a direction that would be sustainable, setting clear goals and proposing concrete sustainable policies.

The water self-sufficiency indicator proposed examines the potential of a system to sustainably manage the renewable water resources it receives in form of rainwater. It is calculated with the next equation:

$$wss_x = \sum_{m=0}^{n} \left[\left(I_{m,x} + IFP_{m,x} \right) \div RW_{m,x} \right]$$

Where, $\boldsymbol{wss}_{\boldsymbol{x}}$ is the water indicator value for a system for year *x*; $\boldsymbol{I}_{\boldsymbol{m,x}}$ are the total artificial water input flows for municipality *m* and year *x*, in m^3 per year; $\boldsymbol{IFP}_{\boldsymbol{m,x}}$ are the total indirect flows associated with the primary water distribution network for a system *m* and year *x*, in m^3 per year; $\boldsymbol{RW}_{\boldsymbol{m,x}}$ is the volume of rainwater on urbanised areas for municipality *m* and year *x*, in m^3 per year.

The value of this indicator is strongly linked to (i) the water demand of a system, including the water losses at the potabilisation and primary distribution stages, (ii) the rainwater this receives, (iii) the extent of its urbanised surface and (iv) its population density. Optimum values for this indicator are those below unity; values under this limit correspond to systems that they can cover their water needs with the rainwater they receive on their urbanised surfaces. On the contrary, water indicator values higher than the unity indicate systems that their demands in water exceed, and cannot be covered by, the rainfall they receive on their urban surfaces.

The waste management indicator presented assesses the capacity of a system to manage its MSW sustainably, through the examination of the metabolic performance of its MSW management plan. Its mathematical expression is the following:

$$ws_x = \left(\sum_{p=0}^{n} \left(I_{x,p} - O_{x,p} \right) + R_x \right) / G_x$$

Where, ***ws*** is the MSW management self-sufficiency indicator for year x; $\boldsymbol{I_{x,p}}$ is the amount of waste treated in MSW plant p, located inside the system, for year x, in tonnes per year; $\boldsymbol{O_{x,p}}$ is the amount of secondary waste leaving the MSW treatment plant p, for year x, in tonnes per year; $\boldsymbol{R_x}$ is the amount of separately selected MSW used directly as raw materials for year x, in tonnes per year; $\boldsymbol{G_x}$ is the total amount of MSW generated by the studied system for year x, in tonnes per year.

The performance of a system with reference to the waste indicator depends on (i) the amount of waste directly used as raw material, as paper and glass, hence the rate of MSW separate collection, (ii) the amount of waste that generates, (iii) the type of treatment the MSW generated by the system receives, (iv) the amount of waste exported and imported by the system, thus transport of waste, (v) the performance of the treatment plants, referring to the secondary waste generated. High indicator values imply elevated imports for a system, not only of MSW to be treated but of the environmental burden associated to it as well, therefore augmented MSW flows between systems and increased transport.

The indicator value that suggests sustainable MSW management practices is the unity. A system with such value would be one that does not export or send to landfill any fraction of the MSW it generates but directly reuses it or treats it with trivial secondary outputs. Indicator values close to zero indicate systems that export or landfill grand part of their MSW and recycle and/or reuse rates are minor.

With regards to the energy flow accounting, the research was much more difficult and no indicator has been suggested on that issue. This matter was much more complex to handle due to the variety of flows to be accounted and of materials involved, each with distinct energetic value and processes of use and conversion. Indirect flows were also difficult to calculate as they occur in various stages of energy transport, conversion and consumption of the energy carriers. Additionally, the fact that the case study is not an administrative entity was a big drawback. This research should best be done on well-defined systems, of either too small scale, as buildings for example, or of large enough to have relevant data recorded, meaning metropolitan areas, counties or autonomous communities. Other tools and methodologies should also be employed for a more complete study on this issue, as for example LCA or exergy analysis.

The application of these indicators on the case study gave mediocre results. Waste indicator values were increasing throughout the study period but did not exceed 0.65, implying high exports of waste and low material recovery rates. The water indicator, on the other hand, stays under unity demonstrating that the system could, in theory, cover its water needs exploiting rainfall.

Application of the proposed tools on the case study

In an overall evaluation of the system, we could characterise this as rather unsustainable with reference to the aspects studied in this dissertation. It has however many possibilities for improvement and the use of these tools show the way to more sustainable practices.

Application of the artificial water flow accounting methodology on the case study revealed the importance of these flows for the system and that of the water losses in its metabolism, reaching 30% of annual water inputs. An important result of the indicator is that the system could cover its needs in water exploiting the rainfall on urbanised areas. However, lacking the required facilities, this water source is not exploited. We can subsequently conclude to sustainable water consumption in the system, but an insufficient and unsustainable water management from the part of the governing bodies.

In terms of MSW management the system does not have a good performance even if the waste indicator value is increasing over the years. Rates of recovered waste are increased throughout the study period, yet waste generation follows a similar trend. The main MSW management characteristics of its overall assessment are low recycling and reuse rates and reliance on the final disposal facilities of the area.

The analysis of the energy flows demonstrated an absolute need for imports and trivial local generation by renewable sources. The system heavily depends on imported natural gas, for electricity generation as for direct consumption, which seems to gradually substitute nuclear energy and petrol and long-established energy sources like gasoline, petrol and butane respectively. Although it is not very energy intensive in per capita values compared to systems of larger scale, the final energy demand of the system is increasing over the years, both in absolute as in per capita values.

Application of the proposed tools on the municipal level

Results of the artificial water flow accounting on a municipal level did not demonstrate any changes concerning management that could reduce primary water supply needs. An increase in the efficiency of the water supply networks would minimise distribution losses; augmented water reuse and measures for a change in water consumption habits would lead to the same results.

With regards to MSW management on the municipal level the main conclusions point out the need for an overall reduction in the MSW metabolic flows. MSW management sustainability on such systems is not linked to the existence of treatment facilities but to the reduction of MSW flows and the maximisation of the materials sent for direct recovery (R).

What is obvious from this study is that no clear guidelines can be proposed for the ideal design or features of a sustainable urban system. All determining factors are always interrelated and the local conditions are the ones that set the limitations for such decisions. A definite conclusion is that a decrease in both input and output flows and a better efficiency in materials and energy use always guarantee a sustainable course.

Sustainability has to be global, inter- and intra-generational in order to be real and successful and ecological sustainability cannot be achieved without its social, economical and institutional aspects completed. The analysis of material and energy flows on every spatial scale proves to be a useful tool in our effort to meet this challenge.