MODELLING OF ENERGY AND ENVIRONMENTAL COSTS FOR SUSTAINABILITY OF URBAN AREAS*

by

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The principal aim of this paper is to present the results achieved by the practical application of energy modelling to urban areas based on two interrelated concepts: energy costs and environmental costs. The analysis has been carried out in three standard Municipalities located in a Mediterranean Zone (Spain) selected based on their different size and socio-economic activities in order to facilitate the extrapolation of results. Energy flows of the chosen areas have been quantified and classified. In addition, energy and environmental costs have been aggregated for each productive sector. Using the methodology proposed in this paper innovative solutions could be specially designed for different areas in order to ensure the sustainable development of urban areas. Finally, the basis for changing the present development model in the Municipalities is set out by means of the application of sustainability principles set in Agenda 21.

Key words: *sustainability, rural/urban centres, energy efficiency, S/I curves, environmental impact*

Introduction

At present, urban areas concentrate a large number of activities and population in a limited space. This implies the importation and use of massive energy resources [1]. The majority of the imported resources are not renewable and a huge quantity of waste is generated. Large imbalances are caused by the inflows and outflows of materials, altering seriously the ecosystems where resources are taken. Due to the exploitation of resources and the discharge of waste these ecosystems are doubly damaged.

Approximately 20% of world's population, most of them inhabitants of urban areas in developed geographical areas, consume 80% of the natural resources. Forecasts

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indicate that in 202,5 75% of the population will live in urban areas implying an increase of 25% over the current situation.

Cities have a complex way of functioning. They use large quantities of energy and materials in order to provide services to citizens and to create necessary infrastructure. The question is: will the future increase in energy and materials consumption be sustainable with the growth of population in urban areas?

During the last decade various authors have developed different methodologies for the calculation and analysis of energy and environmental costs of different types of systems. The study of costs in urban areas can be illustrated as a "black box" where there are big inflows and outflows of materials and energy [2] in order to supply the complex city structure.

The environmental costs can be directly analysed from the calculation of energy costs. From these costs it is possible to calculate the cities' greenhouse effect because all the end uses of energy cause gas emissions and thermal pollution. This environmental cost analysis [3], which considers the transformation of the spent energy in CO_2, allows the balance between CO_2 emissions and CO_2 consumption for a specific area to be defined.

The pollution attributed to a city can be an important indicator for determining the territory that a city needs in order to assimilate its pollution. The city's environmental costs can be measured using the territory's occupation [4]. This ratio has to be calculated considering the potential occupation [5] of the territory necessary for assimilating the pollution and not considering only the urban areas. Another way to calculate the environmental costs [6] is the use of "energy units" obtained measuring the energy that is necessary for separating and neutralising the emissions.

The study presented here has been undertaken in the framework of the "Costurbis" Project (meaning "urban areas' costs) and its principal aim is to quantify the energy inflow of cities and its environmental impact. A new vision of energy flows is proposed by this project. It analyses the real causes of massive energy consumption. Different urban areas are compared highlighting possible actions for their future sustainability. The control of energy and environmental costs in urban areas [7-8] represents, therefore, an essential instrument in order to achieve correct resource planning. Resource modelling provides a global vision of the real operation and the technological basis for the sustainable management of urban areas.

Methodology

Summary

The methodology can be summarised in the following points:

(1) Selection of the urban areas for analysis and definition of the main targeted sectors.
(2) Summary, comparison and analysis of information and energy data.

(3) Calculation of energy flows and energy and environmental costs.
(4) Energy modelling done by Savings-Investment curves [9].
(5) Improvement proposals, reflections and conclusions.

The size, Mediterranean weather conditions, and socio-economic features have been considered in the selection of urban areas.

The Municipalities analysed have been grouped in three basic types. (1) Small towns (1,000-2,000 inhabitants) located in rural areas that have as principal activities agriculture and livestock breeding, (2) Medium towns (10,000-18,000 inhabitants) whose principal sectors are industry, services and the agriculture and breeding sectors, and (3) Large towns (30,000-50,000 inhabitants) that have a socio-economic structure characterised by the primacy of the service sector and a strong industrial sector.

Residential, services and road transport sectors were mainly analysed. In the information collection phase, data related to energy consumption and equipment for the year 2000 was gathered. Likewise energy diagnosis in several centres of the services sector (including City Council's (public) buildings and public lighting) were carried out. On the other hand, in residential and transport sector the population gave useful energy information through a survey distributed through several high schools by random sampling. In this survey the energy use habits, the main consumption and energy equipment of houses, as well as the most common transport method were asked. The data collected was then extrapolated to the total population.

Data about global consumption and associated costs for the towns provided by the gas and electricity supplier companies were also used. Managing all data collected, the global energy flows and the environmental impact associated [10] (considering the emissions to the atmosphere derived from the energy generation and consumption) were calculated for the towns. After evaluating the energy flows crossing the urban areas and detecting the energy inefficiencies, some proposals to diminish the energy and environmental costs were estimated in order to obtain an energy model of the Municipality through the Law of Savings-Investment. This Law permits an estimation of the savings that a Municipality can make by going ahead with a particular investment.

Sources of error

In the development of this study various Local Administrations and High Schools were involved in the survey and distribution of questionnaires. The results of this collaboration were quite insufficient: more than 1,100 questionnaires were distributed but only 19% were collected and considered valid for analysis and extrapolation of results. This demonstrates people's lack of awareness regarding environmental issues at different levels. In order to simplify the extrapolation the sample was approximated to be normal statistical distribution. All these factors contributed to a bigger margin of error in the extrapolation of results.

Results

Energy flows in residential sector

Energy consumption in housing depends on construction features, energy systems and equipment and the habits of inhabitants. In small towns 64% of the population live in single houses which generally implies a larger house size. In medium and large towns this percentage decreases respectively to 28% and 4% respectively.

The average occupation density of homes in medium or large towns is 3.2-3.3 inhabitants/home, while in small towns in rural areas the density decreases to 2.8 inhabitants/home in contrast with the increased house size. This fact could be provoked by the social-labour change experienced in rural areas in rdecent years. The principal cause of this change was the separation of rural activities, *e. g.* small industries and family farms, from private houses with the consequent increase in house area. Moreover, the average age of houses is higher in small towns. This implies that window insulation is more inefficient. These circumstances result in greater heating consumption in small towns which represents the most significant energy consumption in private houses.

The predominance of single houses and cottages in small towns implies that almost 100% of heating systems are individual. These installations are obviously less efficient than centralised ones. The amount of individual heating systems is inversely proportional to the Municipality's size while centralised installations in building are obviously directly proportional to the city size. In medium towns centralised installations represent 9-10% while in large towns they reach 50% of the total.

The availability of natural gas (which represents cleaner emissions) increases in bigger Municipalities principally due to the already existing networks. Only 50% of homes that use electrical energy for heating have electric accumulators and night rate meters, while in the rest inefficient conventional stoves are still used. Moreover, and in spite of what we expected, firewood is rarely used for heating (3%) in the rural areas analysed.

Regarding home lighting, the use of low-consumption lamps and fluorescent tubes is only found in 45-55% of houses.

Annual energy consumption *per capita* in urban areas (fig. 1) is slightly higher than the Spanish annual average [11], that is 0.21 toe/inhabitant. Because of the different home occupation density in the analysed town, it is interesting to consider the annual energy consumption in each home, which is also higher than national annual average, that is 0.71 toe/home.

In the residential sector, the thermal consumption is predominant, representing 66% of the total energy consumption of this sector. The annual electric consumption fluctuates between 3,065 kWh/home in small towns and 3,835 kWh/home in large towns. On the other hand, the annual thermal consumption *per capita* is 0.18 toe in medium towns, 0.22 toe in large towns, and 0.33 toe in small towns. Both results are direct consequences of lower occupation density of houses in small towns.

The annual energy cost *per capita* in the residential sector reaches 240-420 €. Approximately 59% of this cost is attributed to electricity consumption.

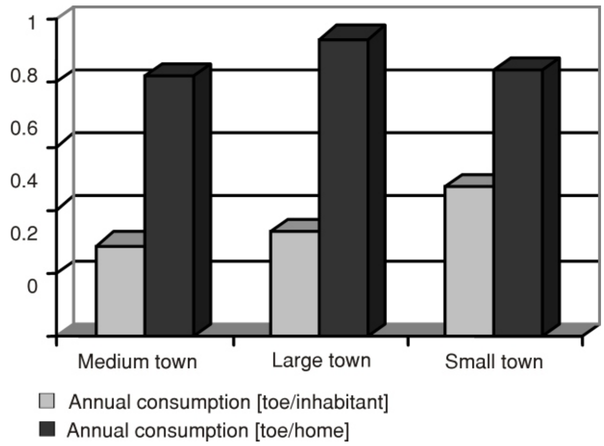

Figure 1. Energy consumption in the residential sector

In the medium and large towns the energy consumption in the residential sector implies 44-48% of the polluting emissions of the town. This percentage reaches 70% in the small towns because the residential sector is one of the largest energy consumers and the services sector is irrelevant.

Table 1 shows the pollution emissions *per capita* associated with residential sector.

Table 1. Annual environmental impacts of residential sector

Size	SO_2 [kg/inhabitant]	NO_x [kg/inhabitant]	CO [kg/inhabitant]	HC [kg/inhabitant]
Large town	2947.3	1396.0	95.8	142.1
Medium town	3026.6	1433.6	98.1	145.9
Small town	3718.3	1759.6	118.8	179.1

Energy flows in transport sector

More and more powerful cars as well as the increasing mobility of people have annulled the environmental benefits resulting from the improvements in car efficiency.

A consequence of socio-economic development is the higher prevalence of car ownership. This means an increase in the average number of vehicles *per capita*, tab. 2.

Table 2. Mobility population with own vehicle and vehicles density

Size	Annual mobility [km/inhabitant]	Vehicles density [vehicles/1000 inhabitant]
Large town	9.250	564
Medium town	7.750	542
Small town	8.500	534

The average density of vehicles in urban areas exceeds overcomes in 21% the European Union rate, that is 451 vehicles/1000 inhabitants. In the urban areas analysed citizens' mobility [12-13] in their own vehicle is above the national rate estimated as 6,000 kilometres travelled per inhabitant per year.

The largest part of the energy consumption occurs in urban areas and in large towns. This is a direct consequence of the daily work commute. However, the journeys are mainly commuting runs in the small tows and long journeys to leisure areas during the weekend are the major cause of consumption in the large towns. Moreover, in rural areas the energy consumption has increased due to the current intensive use of cars, tractors and other agriculture machines.

Public transport is six times more efficient than private transport but in the analysed towns some deficiencies were detected in the public transport system resulting in low usage rates.

In a typical home the fuel consumption for transport is the highest energy consumption. So in medium towns this consumption represents 65% of the total energy consumption of homes, while in large and small towns this proportion reaches 67% and 55% respectively.

Annual energy cost *per capita* in fuel for transport is 500 € approximately in small and medium towns. In large towns this cost is slightly higher reaching 600 €. In tab. 3 the pollution emissions derived from transport are presented.

Table 3. Annual environmental impacts of transport sector according to fuel type

Size	Fuel	SO_2 [kg/inhabitant]	NO_x [kg/inhabitant]	Particles [kg/inhabitant]	CO [kg/inhabitant]	HC [kg/inhabitant]
Large town	Petrol	0.065	4.874	0.662	116.973	9.748
	Diesel	9.546	9.069	6.348	3.150	18.138
Medium town	Petrol	0.066	5.352	0.357	128.450	10.704
	Diesel	5.581	5.302	3.665	1.841	10.604
Small town	Petrol	0.000	4.910	0.431	119.380	9.991
	Diesel	6.632	6.288	4.393	2.153	12.489

Energy flows in municipal sector

Although the municipal sector represents a small part of the total energy consumption of the Municipalities, a local policy that takes into account energy optimisation criteria can have a "multiplication effect" to encourage other users to appropriately manage energy. These local policies could be used as the basis for future environmental protection and the improvement of citizens' quality of life.

Public lighting in urban areas represents almost 50% of electricity costs in the municipal sector. Moreover, 40% of public lighting on average is wasted emitting light to the atmosphere (light pollution). Annual electricity consumption *per capita* for public lighting ranges from 100-140 kWh and the annual economic costs associated are 7-12 € per inhabitant depending on the Municipality's urban structure in both cases. The implementation of regulation systems for lighting level [14] and improvements in installation maintenance would represent an energy saving of around 20-30%.

Pollution emissions to the atmosphere resulting from the electricity generation required to provide public lighting are presented in tab. 4.

Table 4. Annual environmental impacts of public lighting

Size	Consumption [kWh/inhabitant]	SO_2 [kg/inhabitant]	NO_x [kg/inhabitant]	CO [kg/inhabitant]	HC [kg/inhabitant]
Large town	132	0.300	0.142	0.010	0.014
Medium town	101	0.230	0.109	0.007	0.011
Small town	139	0.317	0.150	0.010	0.016

Global energy flows

The annual energy consumption *per capita* for urban areas is around 1 toe per inhabitant, of which 20% is electricity consumption. In small towns the ratio is 1.13 toe/inhabitant due to the greater thermal consumption caused by lower house occupation. In medium towns the ratio is 1 toe/inhabitant and in the large towns is about 1.23 toe/inhabitant due to the greater consumption in the urban transport sector.

Regarding the participation of the different sectors in total energy consumption of the town, the transport sector is the most important energy consumer requiring 52% of the total energy. Subsequently the residential sector must be considered with an average percentage around 32%, commercial and services sector with 14%, and finally the municipal sector with 2% of total energy consumption. Annual energy cost *per capita*, fig.2, presents few variations in urban areas, always within a range of 930-1,110 €.

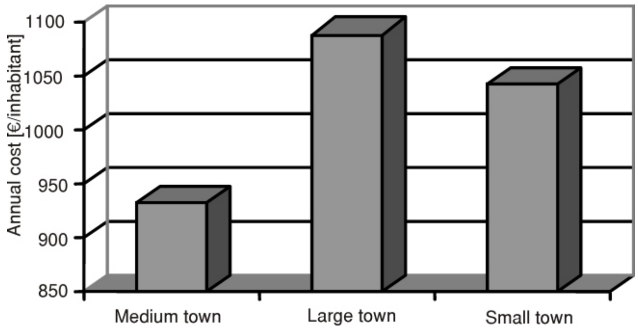

Figure 2. Energy cost *per capita* for the towns

The annual electricity cost *per capita* is similar in the urban areas analysed, about 300 €, while the annual thermal cost *per capita* is between 630-780 €, which makes up 70% of the total energy cost of the town approximately.

Table 5 shows the pollution emissions *per capita* for total energy consumption in urban areas.

Table 5. Annual environmental impacts for towns

Size	SO_2 [t/inhabitant]	NO_x [t/inhabitant]	CO [t/inhabitant]	HC [t/inhabitant]
Large town	6.63	3.15	0.33	0.35
Medium town	6.26	2.97	0.33	0.32
Small town	5.16	2.45	0.29	0.27

Energy modelling: Analysis of improvement potential

Starting from the identification and quantification of energy saving actions that are necessary for rectifying the detected inefficiencies, an energy model for each Municipality can be obtained by means of the characterisation of the Municipality's Savings-Investment curves. Considering the main inefficiencies exposed, the saving proposals quantified in this model are as follows:

(a) Automation of thermal equipment and individual management of consumption.
(b) To foment thermal solar energy technology as support to hot water systemsin all sectors.
(c) To promote more efficient technologies for heating.
(d) To better the thermal insulation in equipment and buildings.

(e) To increase the refrigeration equipment efficiency.
(f) To increase the lighting systems efficiency.
(g) To foment the public and clean transports in the urban areas.
(h) To optimise municipal electricity bills.

In order to quantify the results two different scenarios have been taken into account:

Scenario A: The possibility of carrying out the proposed actions with the population's current level of awareness.

Scenario B: The potential savings obtained by the implementation of the above mentioned actions has been evaluated taking into account the hypothetical results achieved by means of an awareness campaign directed to foment the rational and efficient use of energy among the population.

The Savings-Investment curves have been obtained arranging the proposals for energy saving according to their economic profitability, from highest to lowest.

The ratio total saving / total investment has been taken as a reference of the profitability of each action. It allows the evaluation of all the different types of investments (annual or multi-annual) with respect to the total saving obtained over the useful life time of the particular investment and normalised by unit of time.

After arranging the proposals in order, the sum total of investments and savings obtained is calculated, from the most profitable to the least and the Savings-Investment curve is obtained representing these points:

$$A(I) = A_{\mathrm{M}}(1 - \mathrm{e}^{-\varepsilon I}) \tag{1}$$

where $A(I)$ is the total saving obtained during the useful life of the project invested [€], I the total investment [€], A_{M} the maximum achievable saving [€], and ε the saturation coefficient of the Savings-Investment curve [–].

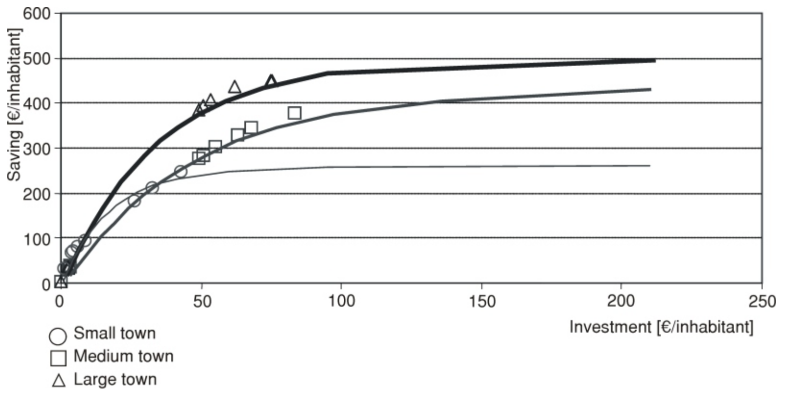

Figure 3. Savings-Investment curves for towns in scenario A

The most profitable proposals are displayed at the beginning of the model and it is possible to observe that some small investments generate big saving. Increasing the investment the saving grow too, but more moderately. The curve reaches the saturation point for a particular investment level where an increase in investment no longer results in an increase in savings. This asymptote limit coincides with the Municipality's maximum achievable saving (A_M).

In the obtained curves (figs. 3 and 4) the data are expressed in € *per capita* and they can be extrapolated to the 3 Municipalities analysed.

The increase of energy saving obtained by means of an awareness campaign can reach 54% in the large towns, tab. 6. This increase would reach 76% in the medium towns and it would join the 383% in the small towns. It means that the awareness of the population achieves better results in the small towns. Besides the *per capita* costs of the campaigns are more expensive due to the minimum costs for carrying out the campaigns.

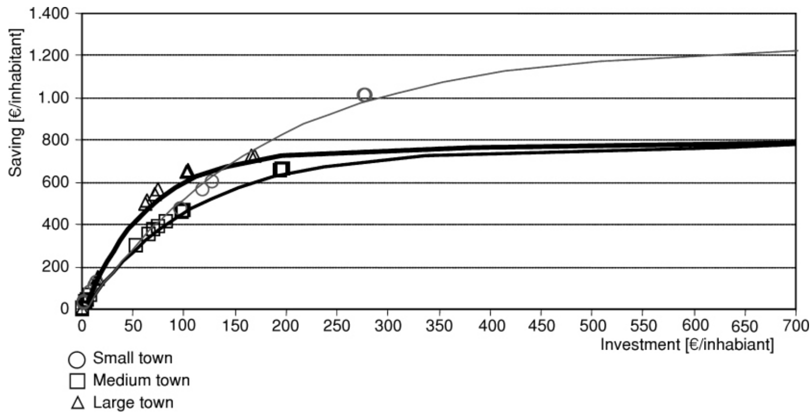

Figure 4. Savings-Investment curves for towns in scenario B

Table 6. Towns energy modelling

Size	Scenario A		Scenario B		
	Maximum saving: A_M (€/inhabitant)	Saturation coefficient ε	Maximum saving: A_M [€/inhabitant]	Saturation coefficient: ε	Awareness campaign cost [€/inhabitant]
Large town	511	0.0292	787	0.016	3.69
Medium town	443	0.022	782	0.0095	7.33
Small town	263	0.059	1273	0.00563	23.04

The saturation coefficient shows the speed with which the maximum savings, A_M, is achieved.

This coefficient is inversely proportional to the municipality size in scenario A due to the profitability of the actions carried out in each case. However, this changes radically when an awareness campaign is undertaken, reducing the three coefficients due to the greater investment *per capita*. A significant reduction is experienced in the small towns because the *per capita* dissemination cost would be more expensive, but the amount of energy savings achieved increases.

Conclusions

Analysing the above results we can conclude that the present situation of the Municipalities is very far from ideal principles of sustainable energy use. But implementing strategies orientated towards the development of new criteria of sustainability can reverse this situation. In this sense, to implement the principles of the Agenda 21 [15] the following conditions are absolutely necessary:

(a) Sustainable local policies have to be put in place by Municipalities in order to obtain a multiplying effect among the population. The implementation of awareness campaigns coordinaated with an environmental educational programme at schools could result in a significant reduction in energy consumption in the Municipalities.
(b) Municipalities have to diversify energy consumption and to exploit local resources in order to improve air quality and to reduce greenhouse gases. At present there exists a deeply ingrained use of conventional energy sources, based on a lack of information about the advantages that the use of renewable energies could represent. In this context the promulgation of a Local Ordinance for the incorporation of thermal solar energy systems in buildings and the promotion of biomass (firewood) as fuel for heating are urgent.
(c) The massive use of private cars with a low occupancy rate has to be reduced, increasing the use of more efficient means of transport. It is necessary to minimise the urban mobility necessities in the large towns encouraging efficient urban planning and compact urban structures. Likewise, it is essential to promote the use of public transport in order to reach higher usage rates similar to the rates obtained in northern and central European countries.
(d) New actions are urgent in order to promote recycling among the population, as well as materials re-utilisation and exhaustive classification of wastes.

Summarising, the analysis detected an urgent necessity to strengthen Municipalities' competencies in energy matters right across Europe. The aim is to promote renewable energies and environmental protection by means of the implementation of Agenda 21 principles. To promote an environment where energy is used efficiently does not exclude the right of the population to the use of energy. Technical innovation and R&D in this area have to be focused on their direct application in the Municipalities.

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