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Emission inventory for greenhouse gases in the City of Barcelona, 1987–1996

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Abstract

Emissions of greenhouse gases for the City of Barcelona are estimated for the period 1987–1994. The sources considered are: public and private transportation; industrial, commercial and domestic activities; and municipal solid waste disposal. The results show that the main source of CO_2 emissions in Barcelona is private vehicle transportation, which accounts, as an average for the period studied, for 35% of total emissions. The second most important source is the municipal solid waste landfill facility of the city (24% of total emissions). The percentages for the remaining sources under consideration were: 14% electricity, 12% natural gas, 5% incineration, and 3% liquefied petroleum gases. However, the values for CO_2 emissions per inhabitant over the period studied are lower than those for any other industrialized city available for comparison. This is closely related to the high percentage of electricity generation from nuclear power stations and hydro power facilities, and also to the extensive use of natural gas for domestic uses. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Background

The *Cities for Climate Protection Campaign* emerged as a contribution by local administrations to the UN Framework Convention on Climate Change (UNFCCC) established in the Conference on Environment and Development, which took place in Rio de Janeiro in June 1992. Following on from this, the European Conference of Local Authorities held in Amsterdam in March 1993 approved a statement that proposed the *European Cities for Climate Protection Campaign*. The City of Barcelona joined this campaign.

Within this process, in September 1994 the international conference "How to Combat Global Warming at the Local Level" took place in Heidelberg, co-organized by the OECD, EC, ICLEI and Heidelberg City Council, with the participation of Barcelona City Council. The mayors and local authorities that participated in the conference recognized, in the form of a statement, that (Heidelberg, 9 September 1994):

- cities consume the lion's share of total energy, so that a high share of energy demand for heating, commercial/industrial activities and transportation is concentrated in urban agglomerations;
- these trends cause local pollution and greatly contribute to environmental damage at the global level; and
- promoting more environmentally conscious energy management and reducing the negative impacts of increasing traffic are of primary importance.

In consideration of the urgent need to take actions at the local level, the signatories committed themselves to

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reducing CO_2 emissions in their areas of responsibility by at least 20% of 1987 levels by 2005.

Obviously, to reduce the possibility of increasing the greenhouse effect, it is necessary to limit the emissions of the gases that produce it. It is here that other types of questions emerge: How much is being emitted? How much has to be reduced? When and for how long? How and where can the emissions be reduced? Who must reduce them?

According to the reports published by the UNEP/WHO (1992) there is a growing tendency towards the concentration of population in large urban centers. This process means that cities are becoming the main centers of generation of man-related emissions of greenhouse gases. As a consequence, many of the corrective measures to reduce emissions will have to be taken in the cities themselves.

A previous initiative to estimate the emissions of large cities was the project called "*The Urban CO_2 Project*" (Harvey, 1993), which involved 14 cities working together to develop CO_2 emission inventories and targets, strategies, and programs for CO_2 emission reduction. Reduction strategies for the cities of Toronto (Canada), (City of Toronto, 1991), and Bologna (Italy), (Comune di Bologna, 1995) have already been proposed following this initiative.

In the Berlin Summit (March 1995), the parties to the UNFCCC were expected to decide on the percentage reduction of emissions of greenhouse gases, but the different postures of the various delegations made the agreement impossible. The parallel summit of local authorities proposed a reduction of 20% in emissions of CO_2 by the year 2005. Although this proposal was not adopted, the opening of a section in the Conference of States for cities to expound their criteria has in itself meant a degree of recognition of the important role they play in the solution of a global problem.

Delegates at the UNFCCC conference of the parties at Kyoto (December 1997) reached an agreement to curb greenhouse gas emissions in the near future. Developed countries will, on average, cut their emissions back to 5.8% below 1990 levels by 2008–2012 (7% reduction for the US; 8% for the EU; 6% for Japan and Canada; but an 8% increase for Australia). Many observers criticized that the treaty did not go far enough and that emission levels will not fall off fast enough to prevent global warming.

2. Estimation of the emissions: methodology

At the moment, there are a number of national and international guidelines for preparing emission inventories on a more or less nation-wide level. Some examples for "classical" air pollutants (SO_2, NO_x, etc.) are, for instance, the CORINAIR methodology (Bouscaren et al., 1992) and the EMEP/CORINAIR "Atmospheric Emission Inventory Guidebook" (McInnes, 1996). These original works led to other versions such as the US-EPA emission inventory guidelines (USEPA, 1977, 1979,1980,1995).

Another effort is the EUREKA Environmental Project EUROTRAC I Subproject GENEMIS (Ebel et al., 1997). One of the main tasks of this project was to put emphasis on the spatial and temporal resolution of emissions in order to provide data for macroscale dispersion modeling. At present, the Subproject GENEMIS is continuing in the context of the new Project EUROTRAC II.

Sometimes it is necessary to obtain an emission inventory with a high temporal and spatial resolution, and in these cases a special methodology is developed (Costa and Baldasano, 1996; Baldasano, 1998).

For emission inventories for greenhouse gases we have the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1995). This reference, a guideline for the development of emission inventories at a national level, uses a top-down methodology (Loibl et al., 1993; Orthofer and Winiwarter, 1998). This type of approach uses available information for greater emission areas and breaks down the overall emissions into sub-units using data for source strength and emission generating activities, or, in the absence of this information, source specific statistical data. However, the application of this approach at the urban scale is not always appropriate, a bottom-up methodology often being advisable. This second approach divides the study area into grid cells (or administrative units), for each of which all emission sources and activities are accounted for.

In order to assess the contribution of the municipality of Barcelona to the emissions of greenhouse gases, we analyzed the activities that generate non-biogenic emissions of the gases that have most incidence on the greenhouse effect: carbon dioxide (CO_2) and methane (CH_4). Methane is emitted in smaller quantities than CO_2, but its relative greenhouse effect, or Global Warming Potential (GWP), can be considered to be, over a 100 year horizon, 25 times greater than that of CO_2 (WMO/UNEP, 1990).

Non-biogenic CO_2 emissions are mainly produced by fossil fuels used for transportation and generation of power for industrial, commercial and domestic use. Other sources of CO_2 are Municipal Solid Waste (MSW) disposal facilities, such as landfills and incinerators. Emission of CH_4 from landfills is generated in processes of bacterial decomposition of organic matter under anaerobic conditions. These decomposition processes are one of the main sources of the emissions of methane into the atmosphere.

In this study, emissions of CO_2 and CH_4 were estimated, using a bottom-up methodology, from man-related activities only. The sources considered were: private and public traffic; industrial, commercial and domestic activities; and disposal of MSW. We considered not only the final amounts of fuel consumed, but also the emissions produced during their life cycle; that is, emissions related to their extraction, processing, transportation and distribution.

Finally, 10% was added to the estimated emissions of CO_2, which is intended to account for the emissions that we could not estimate due to lack of information. Under the denomination of "others" we include emissions derived from sources such as consumption in airports and harbors, flammable liquid for heating (diesel oil), use of solid fuels, etc.

2.1. Emissions from vehicle traffic

The main liquid fuels that are used for surface transportation in the City of Barcelona are products derived from oil, especially diesel oil and gasoline. Since information of sales from gas stations is often difficult to obtain due to company confidentiality policies, the annual consumption and emissions from transportation were estimated using data for vehicle traffic within the municipal area of Barcelona and its main characteristics.

The data used for the estimation of emissions from vehicle traffic was provided by the "*Servei d'Ordenació i Seguretat Vial*" (Road Planning and Safety Service) of Barcelona City Council. Annual consumption of fuel was calculated from the estimation of the average number of kilometers traveled in the City of Barcelona on a working day. For weekend days and public holidays the estimation was 80% of the volume of traffic for weekdays. We also used information about the types of vehicles (cars or trucks) circulating on the different road types in the city (streets and ring roads) and the distribution of the fuel they use (gasoline or diesel oil). We estimated an average consumption of fuel per 100 km traveled of 10.5 l for gasoline cars, 10 l/100 km for diesel cars and small trucks, and 29 l/100 km for large trucks. Finally, assuming that gasoline has a density of 0.75 kg l^{-1} (0.84 kg l^{-1} for diesel oil), with an 85.5% carbon content (85.7% for diesel oil), we calculated that the combustion of every kg of gasoline releases into the atmosphere 3.135 kg of CO_2 (3.142 kg CO_2 kg^{-1} for diesel oil).

Using all the information mentioned above, we estimated the volume of fuel used in a year, and from that the total amount of CO_2 emitted from transportation uses. The results are given in Table 1, where we have included the traffic volume (in millions of kilometers traveled per year), and the tons of CO_2 emitted. Year-to-year evolution in emissions shows a fairly steady increase of about 5% a year, broken only by a decrease in emissions in 1991.

Finally, data on consumption of fuel from the Public Transportation Company tells us that between 3.8 and 4.2% of the total CO_2 transportation emissions in Barcelona originates from public transportation.

Table 1
Estimation of the volume of consumption of fuel, and CO_2 emissions from transportation, 1987–1996

Year	Mvkm yr^{-1}	m^3gasoline	m^3 gas-oil	t CO_2 yr^{-1}
1987	3,805.8	268,540	240,529	1,533,484
1988	3,943.0	278,217	249,196	1,588,742
1989	4,080.1	287,893	257,863	1,643,999
1990	4,217.3	297,570	266,531	1,699,257
1991	3,913.3	276,121	247,319	1,576,775
1992	3,932.5	276,318	252,258	1,593,123
1993	3,951.7	276,504	257,233	1,609,556
1994	4,063.5	284,328	264,511	1,655,096
1995	4,255.7	297,774	277,020	1,733,368
1996	4,433.9	310,242	288,620	1,805,947

2.2. Emissions from use of natural gas

Natural gas (NG) is supplied to users through a distribution network that covers the whole of the City of Barcelona. The information on consumption was extracted from the Barcelona Statistical Yearbook according to data from the company Gas Natural (Ajuntament de Barcelona, 1997).

The available information is supplied in thousands of kcal (therms). To calculate the emissions of CO_2 it is necessary to use the thermal capacity of the NG, which in the case of the gas supplied by Gas Natural is 10,500 kcal N^{-1} m^{-3}. Since NG distributed in Barcelona is mostly composed of methane, the generation of CO_2 from NG combustion can be estimated at 2.5 kg of CO_2 per kg of gas.

The evolution of the total consumption of natural gas in recent years is presented in Table 2. The evolution of the emissions does not show great variability, with fluctuation of $\pm$ 10% from year to year, but the overall tendency is towards a gradual increase in the emissions.

NG in Barcelona is mostly used as fuel in industries, and for heating and cooking in private households. Quarterly information on the consumption of NG can be used as an indicator of the percentage of that consumption that is used to heat buildings. The consumption in the summer months was taken as the base value (level 0) to calculate the additional amount that is employed in heating during the remaining quarters. The calculation revealed that 31% of the total consumption of natural gas is used for heating.

2.3. Emissions from liquefied petroleum gases

The category of liquefied petroleum gases (LPG) includes gases such as propane and butane. The main users of these gases are households without a central heating installation. Other users are certain industries and some public transportation vehicles. Assuming that the estimated emissions from LPG combustion is 3 kg of CO_2 per kg of gas, emissions for the City of Barcelona were calculated from data provided by the manufacturing companies and are shown in Table 3. Emissions have decreased steadily in the period studied, mainly due to the progressive implantation of natural gas for domestic uses.

2.4. Emissions from production of electricity

For the calculation of the emissions of CO_2 from electrical consumption in the City of Barcelona the following data was used:

- Electricity consumption in Barcelona.
- Production centers that supply power to the city and percentages of participation.
- Estimation of the emissions of CO_2 for each of the primary sources of power.
- Estimation of the emissions of CO_2 attributable to electricity consumption in Barcelona.

Table 2
Consumption and CO_2 emissions of natural gas, 1987–1996

Year	Therms	$t\ CO_2\ yr^{-1}$
1987	2,083,574,233	501,204
1988	2,047,198,072	492,453
1989	2,141,864,087	515,225
1990	2,188,891,179	526,538
1991	2,525,366,041	607,477
1992	2,625,999,831	631,684
1993	2,602,550,148	626,043
1994	2,526,103,569	607,654
1995	2,435,959,921	585,970
1996	2,642,883,767	635,746

Source. Ajuntament de Barcelona (1997).

2.4.1. Electricity consumption in Barcelona

Available data on the consumption of electricity for the period 1987–1996 and its distribution according to sectors and type of supply are shown in Table 4. We have only distinguished between the total domestic consumption and the consumption for transportation uses (trains and underground). The data shows a gradual but constant increase from year to year.

2.4.2. Production of power. Power stations that supply the City of Barcelona

To calculate the emissions associated with electricity consumption in the City of Barcelona, it is necessary to know what electricity production facilities are there in the area and the amount of electricity they provide for the city's consumption. Several centers supply electricity to the city, and not all of them share the same source of primary energy. For this reason, the emissions of CO_2 per GWh produced will vary for each facility according to its production system (fossil fuel/nuclear/hydraulic), and consequently, to the type of fuel they use.

In the Barcelona region there are four power stations which cover part of demand of the Barcelona Metropolitan Area (Barcelona and the municipalities that form its "industrial belt"). These facilities are the Badalona (fuel oil), Sant Adrià (fuel oil and natural gas), and Besòs (fuel oil and natural gas) power stations and the Sant Adrià incineration plant, which uses municipal solid waste (MSW) as fuel. The electricity production of these facilities is presented in Table 5.

Only part of these productions is directly attributable to Barcelona's consumption. To calculate the percentage of this production that corresponds to Barcelona we took into account the percentage of the population of the City of Barcelona with respect to the population of the Barcelona Metropolitan Area (55.7%). The production from the incinerator of Sant Adrià was calculated from the tons of MSW that Barcelona burns in that facility.

Table 3
Estimation of the consumption of LPG (by type of user) and estimated CO_2 emissions from its use, 1987–1996

Year	$t\ yr^{-1}$	Domestic	COM.-IND	Transport	$t\ CO_2 yr^{-1}$
1987	57,119	44,926	3739	8454	207,513
1988	53,678	41,387	5989	6301	195,009
1989	50,261	37,734	8609	3918	182,598
1990	49,225	37,318	10,090	1033	178,835
1991	50,522	39,199	9706	1255	183,545
1992	51,818	41,080	9322	1416	188,255
1993	63,468	49,354	8360	5754	230,582
1994	46,464	32,996	8298	5170	168,803
1995	45,392	31,871	8216	5305	164,909
1996	39,245	31,621	2384	5239	142,576

Table 4
Electricity consumption by type of supply, 1987–1996

Year	Low tension (GWh)		High tension (GWh)		Total (GWh)
	Domestic	Com.-ind.	Com.-ind.	Transp.	
1987	1,276.43	1,626.55	976.25	146.25	4,025.47
1988	1,223.41	1,719.35	992.27	132.68	4,067.71
1989	1,314.28	1,959.49	1,064.41	138.39	4,476.58
1990	1,273.46	2,018.12	1,075.19	149.21	4,515.99
1991	1,431.03	2,098.97	1,114.93	128.730	4,773.67
1992	1,524.23	2,296.21	1,175.94	153.99	5,150.39
1993	1,548.89	2,161.22	1,084.71	163.66	4,958.49
1994	1,522.85	2,169.96	1,071.00	158.82	4,922.65
1995	1,577.82	2,153.98	1,126.87	172.48	5,031.16
1996	1,631.77	2,242.32	1,146.80	168.41	5,189.31

Table 5
Electricity production in the Barcelona area by type of fuel, 1989–1996

GWh	1989	1990	1991	1992	1993	1994	1995	1996
MSW incinerator	85	84	86	90	89	94	106	104
BESÒS fuel oil	190	87		179	56	14	56	314
BESÒS gas oil	99	267		110	2	10	5	70
Sant Adrià fuel oil	226	117		407	68	30	31	
Sant Adrià gas oil	128	136		191	17	56	113	36
Badalona fuel oil				5	9	2	3	
Total =	728	691	86	982	241	205	315	524

Table 6
Electricity consumption in Barcelona by source, 1987–1996

GWh	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
MSW INC.	51	56	33	58	38	44	38	44	34	36
Hydraulic	345	349	389	439	522	681	714	711	721	726
Coal	92	93	104	128	133	136	143	142	144	145
Fuel oil	225	225	290	175	321	410	159	110	137	262
Gas oil	227	228	185	286	295	249	96	122	152	146
Nuclear	3,016	3,047	3,398	3,326	3,326	3,455	3,625	3,611	3,659	3,688
Self-prod. (HIDR-THER)	69	70	78	105	139	175	183	183	185	187
Total =	4,025	4,068	4,477	4,516	4,774	5,150	4,958	4,923	5,031	5,189

Since the electric production in the area of Barcelona only accounts for a small amount of the total power needed in the city, to establish the percentage of each source we considered production of electricity for all Catalonia (and included other primary sources, such as hydraulic, coal-burning and nuclear stations). From the data for Catalonia we established the percentage distribution of electric power production according to its origins. This distribution is, for example for year 1994, 14.75% hydraulic, 2.95% coal, 1.76% fuel oil, 1.76% gas, 74.97% nuclear and 3.79% self-production. The difference between the power produced in the Barcelona area and the energy the city consumes (the city's power deficit) is distributed according to the percentage of Catalonia.

Consumption of electricity in Barcelona, according to energy sources, and taking into account the distribution for Catalonia described above, is shown in Table 6. The CO_2 emissions from electricity generation were calculated using the following emission factors: hydraulic energy 6550 kg CO_2 GWh^{-1}, coal 1,255,323 kg CO_2

Table 7
Emission of CO_2 from electricity consumption in Barcelona, 1987–1996

$t\ CO_2\ yr^{-1}$	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Hydraulic	2,261	2,284	2,547	2,877	3,531	4,657	4,676	4,657	4,720	4,757
Coal	115,474	116,654	130,100	160,722	172,767	170,769	179,141	178,436	180,827	182,263
Fuel oil	199,488	199,959	257,773	155,142	222,084	364,612	141,556	97,783	121,284	232,637
Gas oil	167,430	167,821	136,179	210,237	169,346	183,324	70,595	89,726	111,904	107,357
Nuclear	25,911	26,176	29,193	28,570	29,514	29,683	31,138	31,015	31,431	31,680
Self-prod (hidr -ther)	20,715	20,926	23,338	31,620	43,167	52,563	55,141	54,923	55,659	56,101
Sub-total =	531,280	533,820	579,131	589,168	640,410	805,408	482,247	456,542	505,824	614,797
Distribution Losses	47,815	48,044	52,122	53,025	57,637	72,487	43,402	41,089	45,524	55,332
Total =	579,095	581,864	631,253	642,193	698,047	877,894	525,649	497,630	551,349	670,128
$t\ CO_2\ GWh^{-1}$	144	143	141	142	146	170	106	101	110	129

GWh^{-1} (Departament d'Indústria i Energia, 1992), fuel oil 888,242 kg CO_2 GWh^{-1} (Departament d'Indústria i Energia, 1992), diesel oil 746,188 kg CO_2 GWh^{-1} (Departament d'Indústria i Energia, 1992), nuclear 8590 kg CO_2 GWh^{-1} (U.S.D.O.E., 1989), and self-production (hydro.-therm.) 300,747 kg CO_2 GWh^{-1}.

Using all the information described above we estimated the total CO_2 emissions from the generation of electricity for the City of Barcelona, which are shown in Table 7. We did not include in this table emissions from the MSW incineration facility of Sant Adrià, which will be considered in Section 2.4.

Table 7 shows that emissions from electricity, and the ratio of tons emitted per GWh, are highly variable from year to year, being strongly dependent on the particular characteristic of the production for each year. The energy system favors the use of nuclear and hydro power in preference to other sources of energy from fuel burning. Nuclear power is used more than other sources. Nuclear production is fairly constant in the years considered and covers the basic consumption of electricity (74–83%). Another important factor is the participation of hydro energy (between 9.4 and 14.7% of the total consumption). The participation of hydro energy is highly dependent on the precipitation occurring over the year. The remaining electric power facilities cover peaks of demand.

Finally, if the demand for power decreases (as it did in 1993 and 1994), the participation of hydro and nuclear power increases, to the detriment of gas, liquid fuel and coal power stations. In those years the ratios of CO_2 emitted per GWh produced were less.

2.5. Emissions from MSW disposal

MSW management in Barcelona is carried out according to the following model:

- An incineration plant located in Sant Adrià del Besòs, which also burns MSW from other municipalities. This facility allows the recovery of the energy for electricity production.
- An MSW landfill in Garraf, which does not include, at the present moment, any recovery process for the biogas produced.
- Recycling schemes are currently being implemented in Barcelona. There are containers for paper, glass, metals, and plastics, together with the normal containers for collecting most of the waste generated in Barcelona. Recycled MSW represents about 5% of the total amount produced.

The amount of MSW from the City of Barcelona incinerated in Sant Adrià was estimated from the total MSW production and the tons dumped at the Garraf landfill.

There is some controversy about the inclusion of CO_2 emissions from incineration of MSW in emission inventories for greenhouse gases. On this subject, the IPCC guidelines (IPCC, 1995) point out that a fraction of the carbon in waste combustion (mainly from paper and food waste) is derived from biomass raw materials, which can be replaced by regrowth on an annual basis. Following this reasoning, these emissions should not be considered net CO_2 emissions. However, the IPCC also suggest that if the agricultural and forestry resources are not sustainably managed, these categories should be included in the inventory as net CO_2 emissions, as they entail a reduction in biomass stocks. In our case, an emission inventory at a city level, we considered that it was correct to include Barcelona's emissions from incineration of MSW as net emissions, which we calculated from the percentage of carbon content in Barcelona's MSW composition. This percentage is 46.12%, which resulted in an emission of 1.69 kg of CO_2 for every kg of MSW incinerated.

Emissions of CO_2 per ton of MSW deposited in the landfill were estimated using Taylor's (1992) factors, which were 0.085 tons of CH_4 per ton of MSW, and 0.193

Table 8
Generation, disposal and CO_2 emissions from MSW in Barcelona,1987–1997

$t\ yr^{-1}$	1987	1988	1989	1990	1991	1992	1993	1994	1996	1997
MSW-total	542,221	581,909	604,898	625,793	656,371	675,215	666,192	649,807	622,585	627,330
MSW-inciner	154,221	169,909	100,896	176,793	113,371	134,215	116,192	133,807	102,585	107,330
MSW-landfill	388,000	412,000	504,000	449,000	543,000	541,000	550,000	516,000	520,000	520,000
CO_2 incin	305,773	336,878	196,522	344,760	224,833	264,554	230,373	265,299	203,395	212,803
CO_2 landfill	899,384	955,016	1,168,272	1,040,782	1,258,674	1,254,038	1,274,900	1,196,088	1,205,360	1,205,360
Total CO_2	1,206,157	1,291,894	1,364,794	1,385,542	1,483,507	1,518,592	1,505,273	1,461,387	1,408,755	1,418,163

tons of CO_2 per ton of MSW, which, once the CH_4 emissions have been transformed into CO_2 emissions through the global warming potential (GWP), results in an emission of 2.32 tons of equivalent CO_2 per ton of MSW deposited in the landfill.

The data for the generation and disposal of MSW and related CO_2 emissions are presented in Table 8. Emissions show a constant increase up to 1992. Since 1993 the tons of MSW generated by the city have decreased, due to a gradual decrease in the city's population and to the fact that the expenditure on food per household has not increased. The final destination of the MSW produced, either the incinerator or the Garraf landfill, will determine whether the CO_2 equivalent emissions from MSW disposal decrease or increase, respectively, due to the emission factor of the landfill being higher than that of the incinerator.

3. Global assessment of the emission of greenhouse gases in the City of Barcelona

3.1. Global emissions in the City of Barcelona

Table 9 presents the estimated emissions for the period 1987–1996, which are also shown in Fig. 1. The percentage distribution of these emissions is also included. From the results, we can see that the principal source of greenhouse gas emissions in Barcelona is vehicle traffic (30–35% of total emissions). This is followed by the emissions originating from the disposal of MSW, especially those generated in the Garraf landfill (20–25% of total emissions). Natural gas accounts for about 12% of total CO_2 emissions, whereas electricity is responsible for approximately 13%.

From the results, we can observe that annual variations are limited. To account for these differences we have calculated in Table 9 the year-to-year variability of the emissions. As we can see, CO_2 emissions showed an almost linear increase between 1987 and 1991, with year-to-year increases of between 2 and 4.5%. The year 1992 showed a more significant increase (almost 6%) with respect to the 1991 emissions. The celebration of the Olympic Games in the city that year is probably responsible for this increase, which is especially large for emissions derived from the production of electricity. Year-to-year variability is negative for the years 1993 and 1994. This is probably related to the post-Olympic economic crisis, which produced a drop in electricity consumption. Emissions from energy generation are also lower due to the reduction in the use of fossil fuels and to the increase in electricity from nuclear and hydro sources. Emissions pick up again in 1996 (with an increase of 5.1% with respect to 1995), showing that the previous year's decrease in emissions was only temporary. This rise is mainly due to the increase in vehicle traffic and the large proportion of fuel-generated power.

Finally, emissions of equivalent tons of CO_2 per inhabitant vary between 2.6 and 3.4 equivalent tons of CO_2 per person per year over the period 1987–1996. This ratio does not correspond exactly with the evolution of the emissions over the same period, since it is corrected to account for the variation in the population of the city. The slow but continuous loss of inhabitants in the city produces a small increase in this ratio for the years 1987–1991. In 1991 the value reached 3.0 tons of CO_2 per inhabitant per year and stayed there until 1995, with the exception of 1992, which as we mentioned above, can be considered as an atypical year due to the celebration of the Olympic Games. The slow decrease in population in the city compensates for the lower emissions observed over these years. The coincidence of increased emissions and lower population for 1996 results in the highest emissions-to-population ratio (3.4 tons of CO_2 per inhabitant) observed over the period studied.

3.2. Distribution of the emission by uses

The distribution of the emissions by uses and sectors is shown in Table 10, where we have included percentages for years 1993 and 1996. The distribution changed

Table 9
Total emissions of greenhouse gases in Barcelona, expressed as equivalent tones of CO_2, and percentage distribution by sources, 1987–1996

SOURCE ($t\ CO_2\ yr^{-1}$)	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Vehicle traffic	1,533,484	1,588,742	1,643,999	1,699,257	1,576,775	1,593,123	1,609,556	1,655,096	1,733,368	1,805,947
Natural gas	501,204	492,453	515,225	526,538	607,477	631,684	626,043	607,654	585,970	635,746
LPG	207,513	195,009	182,598	178,835	183,545	188,255	230,582	228,276	164,909	142,576
Electricity	579,095	581,864	631,253	642,193	698,047	877,894	525,649	497,630	551,349	670,128
MSW incineration	305,773	336,878	196,522	344,760	224,833	264,554	230,373	265,299	203,395	212,803
MSW landfill	899,384	955,016	1,168,272	1,040,782	1,258,674	1,254,038	1,274,900	1,196,088	1,205,360	1,205,360
Total =	4,026,453	4,149,962	4,337,869	4,432,365	4,549,351	4,809,550	4,497,103	4,450,043	4,444,350	4,672,560
Other (10% total)	402,645	414,996	433,787	443,236	454,935	480,955	449,710	445,004	444,435	467,256
Total =	4,429,099	4,564,958	4,771,656	4,875,601	5,004,286	5,290,505	4,946,813	4,895,047	4,888,785	5,139,816
Year-to-year variability		3.07	4.53	2.18	2.64	5.72	-6.5	-2.37	-1.22	5.13
Population	1,714,355	1,712,350	1,707,286	1,696, 795	1,643,542	1,630, 635	1,635, 067	1,630,867	1,614,571	1,508, 805
(CO_2/inhabitant)	2.6	2.7	2.8	2.9	3.0	3.2	3.0	3.0	3.0	3.4
Source (%)										
Vehicle traffic	34.6%	34.8%	34.5%	34.9%	31.5%	30.1%	32.5%	33.8%	35.5%	35.1%
Natural gas	11.3%	10.8%	10.8%	10.8%	12.1%	11.9%	12.7%	12.4%	12.0%	12.4%
LPG	4.7%	4.3%	3.8%	3.7%	3.7%	3.6%	4.7%	4.7%	3.4%	2.8%
Electricity	13.1%	12.7%	13.2%	13.2%	13.9%	16.6%	10.6%	10.2%	11.3%	13.0%
MSW incineration	6.9%	7.4%	4.1%	7.1%	4.5%	5.0%	4.7%	5.4%	4.2%	4.1%
MSW landfill	20.3%	20.9%	24.5%	21.3%	25.2%	23.7%	25.8%	24.4%	24.7%	23.5%
Other (10% total)	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%

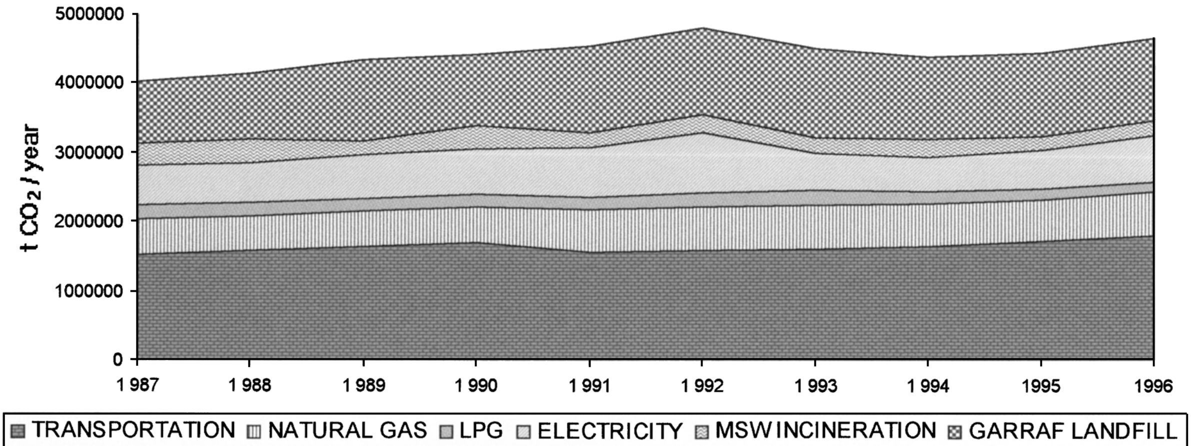

Fig. 1. CO_2 emissions by sectors in the City of Barcelona, 1987–1996.

little between the two years studied. The sectors whose participation changed most were those related to the various uses of electricity, due to the higher percentage of power produced from fuel burning in 1996.

The main characteristics of the distributions are:

Transportation: Transportation is responsible for about 38% of the total emissions of greenhouse gases. Only about 5% of these transportation emissions (2% of the total emissions) correspond to emissions from public transportation. However, public transportation accounts for 55% of the total number of trips. We should note that the percentage in these distributions do not coincide with the percentage corresponding to vehicle traffic shown in Table 9. This can be explained if we take into account that in the percentage calculated in Table 10 we have also

Table 10
Distribution of the emissions, according to uses and sectors (years 1993 and 1996)

	Equivalent t CO_2 1993	1993	Equivalent t CO_2 1996	1996
Public transportation	103,331	2.1%	114,688	2.3%
Private transportation	1,563,924	31.6%	1,757,202	35.5%
Heating	375,615	7.6%	349,817	7.1%
Refrigeration	74,116	1.5%	94,488	1.9%
Industry	488,601	9.9%	495,921	10.0%
Other uses of gas	179,661	3.6%	178,920	3.6%
Lighting. services and domestic	72,540	1.5%	92,478	1.9%
Other uses electricity	134,040	2.7%	170,883	3.5%
MSW disposal	1,505,273	30.4%	1,418,163	28.7%
Other	449,710	9.1%	467,256	9.4%
Total =	4,946,813		5,139,816	

included emissions resulting from LPG and electricity used for transportation.

Disposal of municipal solid waste (MSW): CO_2 equivalent emissions generated in the Garraf landfill (28.7% of the total emissions) places the current management model for MSW in Barcelona as the second largest source of greenhouse gases. If the methane produced in the Garraf landfill were burnt or recovered, the percentage of contribution of the disposal of MSW in the global emissions would be considerably reduced. We calculated that the contribution of MSW to total CO_2 emissions would be 10% if methane were burnt in flares without energy recovery and 13.8% if it were use for production of electric power.

The incineration of MSW has a high ratio of emission of CO_2 per GWh produced, responsible for roughly 5% of the emissions of CO_2. This ratio is due to the low thermal power of MSW and the efficiency of the present facilities.

Other activities: The remaining emissions, about 33% of the total, are mainly distributed between the industrial sector, now of little importance in the City of Barcelona, and air-conditioning of buildings (heating and cooling). A small percentage of the emissions are related to activities that use gas (such as the production of sanitary hot water, cooking stoves, etc.), and applications of electricity such as lighting and the use of home appliances.

In the future, it is expected that emissions from air-conditioning of buildings will increase, due to its progressive installation in private houses and in commerce.

4. Comparison with other cities, Catalonia and Spain

The emissions of equivalent tons of CO_2 per inhabitant in the City of Barcelona included in Table 9 vary between 2.6 and 3.4 equivalent tons of CO_2 per person per year over the period 1987–1996. These values can be considered low in comparison with values for other cities in industrialized countries (Table 11). As we mentioned above, the constant decrease in the population of the city over the period studied is responsible for the increase in this ratio, especially in recent years.

This type of comparison, however, should be made carefully because not all the inventories considered take into account the same sources of greenhouse gases or used the same methodology. Some of the characteristics that might influence the emission values for an area are, for instance, its climatic characteristics, its urban structure, the type of economic activity being developed (services versus industry), the habits of the population (use of private cars), sources of electric power and the MSW management program, among others.

The low emission levels per inhabitant can be explained by the following factors, among others:

- The economic structure of the city is mainly based on the tertiary sector (services).
- A large percentage of the electrical energy that Barcelona consumes is produced by sources that do not emit greenhouse gases (nuclear and hydro energy represent 90% of the total consumption).
- The City of Barcelona and its surrounding area adopted the general use of natural gas during the 1980's.
- Barcelona is a Mediterranean city that enjoys a mild climate. Therefore, energy consumption for heating uses will be lower in comparison with other cities (especially with respect to northern and central European cities).
- Air-conditioning systems are quite usual in offices and commercial buildings, but not very common in private homes.
- The city has a compact structure, with many flats and apartments rather than individual houses.

Finally, if we compare Barcelona with Catalonia and Spain, these major differences are maintained (see Table 12). Higher ratios for Catalonia are mainly due to a higher industrial participation in comparison with the industrial presence in Barcelona.

5. Barcelona's efforts to limit emissions

Although we show above that Barcelona's emissions of greenhouse gases are low compared to those of other cities, the city has begun to introduce measures aimed at reducing or at least avoiding a rise in its contribution to the greenhouse effect.

To this end, the City Council has founded the Sustainability Board, whose main goal is to adopt the premises of Agenda 21.

A study has been carried out to determine possible measures to be adopted by the City Council to decrease emissions (Baldasano, 1996). There is a project under consideration to collect and recover biogas from the Garraf landfill, which would mean a reduction of the total emissions of greenhouse gases because of the high GWP index of methane. Another possibility under study is the transformation of urban buses so that they can use natural gas (methane) as fuel. This methane would come from an MSW biomethanization plant.

Table 11
Comparison of CO_2 emissions per capita in different cities

	t CO_2/inhabitant yr^{-1}
Barcelona (E), 1996	3.4
Ankara (TK), 1988[a]	3.6
Bologne (I), 1988[a]	5.7
Copenhagen (DK), 1988[a]	7.5
Heidelberg (D), 1987[b]	7.9
Helsinki (Fin), 1988[a]	8.3
Turin (I), 1990[c]	8.6
Sanjosé, CA (USA), 1988[a]	8.8
Portland, OR (USA), 1988[a]	10.1
Saarbrucken (D), 1988[a]	10.4
Hanover (D), 1988[a]	10.6
Dade county, Miami, FL (USA), 1988[a]	11.6
Toronto metro, on (Can) 1988[a]	13.5
Toronto city, on (Can), 1988[a]	15.0
Minneapolis, MN (USA), 1988[a]	17.5
Denver, Co (USA), 1988[a]	22.3

[a] Harvey (1993).
[b] Schmidt (1994).
[c] SOFTECH Energía Tecnología Ambiente (1989).

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Table 12
Emissions of CO_2 per inhabitant in Barcelona, Catalonia and Spain

T/inhabitant yr^{-1}	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Barcelona	2.6	2.7	2.8	2.9	3.0	3.2	3.0	3.0	3.0	3.4
Catalonia[a]				5.7	5.9	5.9	5.7	5.8	6.4	
Spain[b]				7.0			7.0			

[a] Baldasano and Fernández (1998).
[b] Moptma (1995) and Mimam (1996).

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