LCA Case Studies

Environmental Performance of a Municipal Wastewater Treatment Plant

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Abstract

Goal, Scope and Background. Nowadays, every strategy must be developed taking into account the global impact on the environment; if this aspect is forgotten, a change of environmental loads or their effect will be caused and no reduction will be attained. For instance, a wastewater treatment plant (WWTP), which is considered *a priori* as an ecological treatment system, gives rise to an environmental impact due to its energy consumption, use of chemical compounds, emissions to the atmosphere and sludge production, the post-treatment of which will also have diverse environmental effects. The goal of this study is to evaluate the potential environmental impact corresponding to a municipal WWTP and to identify the hot spots associated with the process.

Methods. In this study, the Centre of Environmental Science (CML) of Leiden University methodology has been considered to quantify the potential environmental impact associated with the system under study. A comprehensive analysis of the WWTP was evaluated for the physico-chemical characterisation of the wastewaters as well as the inventory of all the inputs (energy, chemical compounds, ...) and outputs (emissions to air, water, soil and solid waste generation) associated with the global process. Regarding Life Cycle Inventory Assessment, SimaPro 5.0 was used and in particular CML factors (updated in 2002) were chosen for characterisation and normalisation stages.

Results and Discussion. A comprehensive inventory of empirical data from water, sludge and gas flows during 2000 and 2001 was obtained. Two impact categories arise due to their significance: eutrophication and terrestrial ecotoxicity. Consequently, the aspects to be minimised in order to reduce the environmental impact of the system are the pollutant load at the watercourse discharge (mainly NH_3, PO_4^{3-} and COD, even when all of them are below legal limits) and the emissions to soil (mainly Cr, Hg and Zn, even when they are present in low concentrations) when the sludge is used for agricultural application.

Conclusions. As far as the environmental impact is concerned, differentiation between humid and dry season is not required as results are practically equal for both situations. Water discharge and sludge application to land have turned out to be the main contributors in the environmental performance of a WWTP. Regarding the former, the removal of nitrogen by means of a nitrification-denitrification system coupled to conventional biological aerobic treatment implies a high environmental impact reduction and, as for the latter, bearing in mind the proposed legislation, heavy metals as well as pathogens are supposed to be the key parameters to define the most adequate treatment strategies for the generated sludge.

Recommendations and Outlook. This study can serve as a basis for future studies that can apply a similar policy to a great number of wastewater facilities. Besides, features such as different treatment systems and capacities can provide additional information with the final aim of including the environmental vector in the decision-making process when the operation of a WWTP is intended to be optimised. Moreover, sludge must also be a focus of attention due to the expected increase and its major contribution to the global environmental impact of a WWTP, which can determine other treatment alternatives.

Keywords: Denitrification; ecotoxicity; eutrophication; life cycle inventory (LCI); sludge; wastewater; wastewater treatment plant (WWTP)

Glossary

ADP	Abiotic resources Depletion Potential	HS	Humid Season
AP	Acidification Potential	LCA	Life Cycle Assessment
BOD_5	5-days Biological Oxygen Demand	LCI	Life Cycle Inventory
COD	Chemical Oxygen Demand	LCIA	Life Cycle Inventory Analysis
Cond	Conductivity	POFP	Photo-Oxidant compounds Formation Potential
DM	Dry Matter	ODP	stratospheric Ozone Depletion Potential
DS	Dry Season	SS	Suspended Solids
EP	Eutrophication Potential	WWTP	Waste Water Treatment Plant
GWP	Global Warming Potential	v	Volumetric flow rate

1 Introduction

The last decades have seen a general increase in environmental awareness in such a way that the environment is now recognised as one of the major factors associated with any activity. Moreover, the understanding that those environmental approaches designed for solving local-specific problems is not desirable. The interest is now focused on new methods trying to find a more global solution. Therefore, nowadays, every strategy must be developed taking into account the global nature of the environment; if this aspect is forgotten, a change of environmental loads or their effect will be caused and no reduction will be attained. For instance, a wastewater treatment plant (WWTP), which is *a priori* considered as an ecological treatment system, gives rise to an environmental impact due to its energy consumption, use of chemical compounds, emissions to atmosphere and sludge production, the post-treatment of which will have diverse environmental effects. The implementation of the European Water Act (91/271/EC) is leading to a rapid multiplication of WWTPs across Europe and, consequently, this activity must be analysed to evaluate its environmental influence. In this study, the inventory of a WWTP has been performed in order to quantify the impact of its activities from a Life Cycle Assessment (LCA) perspective.

Although the application of LCA on sewage sludge management has turned out to be fairly extensive over the last few years, wastewater treatment is still a field of limited references. Tillman et al. [1] analysed two different alternative systems (local treatment in comparison to a separation system regarding to urine, faeces and grey water) for two specific city centres in Sweden. Two specific locations from Sweden were also investigated as case studies by Lundin et al. [2], where the final aim was to compare the environmental loads from wastewater systems with different technical solutions. In Spain, Vidal et al. [3] compared three configurations of biological treatments by means of a simulation software in order to diminish the discharge of nitrogen in the treated effluent. As far as the evaluation on sewage sludge is concerned, two types of studies can be distinguished depending on the final scope: on the one hand, studies such as Suh and Rousseaux [4], where a comparative general LCA study on a variety of sludge disposal methods was carried out, and, on the other hand, some specific research papers where particular systems and locations were analysed [5].

The general aim of the research work initiated with this paper is the evaluation of the most common technical options focused on the removal of organic matter from urban wastewater in order to obtain a methodology to include the environmental vector in the decision-making process when the optimisation or the implementation of a WWTP is planned. The primary objective of the paper is to develop a reliable inventory of the WWTP. The analysis of the treatment facility begins with the definition of five subsystems, including not only the treatment of the influent but also of the solid fractions such as inert residue, municipal solid waste as well as grease waste and the generated sludge. Electrical consumption, production of chemicals and transportation by road were also considered. Extensive analysis of all the input and output flows is deemed to be presented in tables with average values as well as standard deviations in order to point out the variability in the performance of the treatment system. Moreover, the purpose of the study is also to evaluate the environmental performance of a typical configuration for a WWTP.

2 Goal and Scope

2.1 Objectives

The goal of this study is to evaluate the potential environmental impact associated with a municipal WWTP (with a treatment capacity for an equivalent population of 90,000 inhabitants) in order to identify the hot spots associated with the process.

The audience of this paper is made up of scientists and practitioners of LCA.

2.2 Functional unit

The main purpose of any WWTP is the removal of pollutants present in water and, consequently, the reduction of emissions (mainly solids, organic matter and nutrients) when the treated effluents are discharged to watercourses.

Regarding the definition of the functional unit, several options may be taken into account: for example, quantity of removed pollutants, volume of treated wastewater or volume of generated sludge. According to the recommendations by Suh and Rousseaux [6], the quantity of inflow water in a certain period of time appears to be the best choice since it is based on realistic data. Consequently, the amount of wastewater treated at the WWTP per day with the subsequent sludge disposal was selected as the functional unit.

However, it is necessary to take into consideration the fact that the performance of a WWTP commonly proceeds in two ways: summer conditions and winter conditions, and therefore, the functional unit has been quantified by means of two different reference flows: 57,349 $m^3 day^{-1}$ in the Humid Season (HS, which represents the months from October to April) and 49,214 $m^3 day^{-1}$ in the Dry Season (DS: from May to September).

2.3 Description of the system under study

The WWTP under study occupies an area of 14,000 m^2 and it has a maximum treatment capacity of 90,000 inhabitants. In fact, these facilities were built for a population of 88,000 but nowadays, due to several factors such as the increase of both population and industrial activities, the average inflow has increased to its maximum capacity treatment.

This WWTP has three different lines: water, sludge and biogas production. The first line, water, is divided in two parallel ones, each treating the same flow of wastewater. Both lines comprise preliminary, physico-chemical and biological treatments. Regarding the sludge line, the primary sludge (from the physico-chemical treatment) and the secondary sludge (from the biological treatment) are mixed after being thickened in an intermediate tank before being fed into the anaerobic digester. Afterwards, they are dewatered in a belt filter and the final product is fated for agricultural use. Biogas is generated in the anaerobic digester and it is further used in a major proportion to maintain the digester temperature constant while the rest is burned in a torch.

Considering the boundaries of the system for its evaluation by LCA, the wastewater process was divided into five subsystems (**Fig. 1**).

- **Subsystem 1:** It comprises the input of raw water, its pre-treatment and primary treatment, the discharge of the partially treated effluent to the watercourse and the transportation by road as well as the treatment of all solid fractions generated in the WWTP, bearing in mind their characteristics (inert residue, municipal solid waste and grease waste).
- **Subsystem 2:** It entails the secondary treatment (activated sludge) and the discharge of the treated water into the river.
- **Subsystem 3:** It considers the sludge line, from its generation (as primary and secondary sludge) to its storage in silos, as well as the gas line. This subsystem also includes the production and transport of chemical compounds consumed at the mechanical dewatering stage.

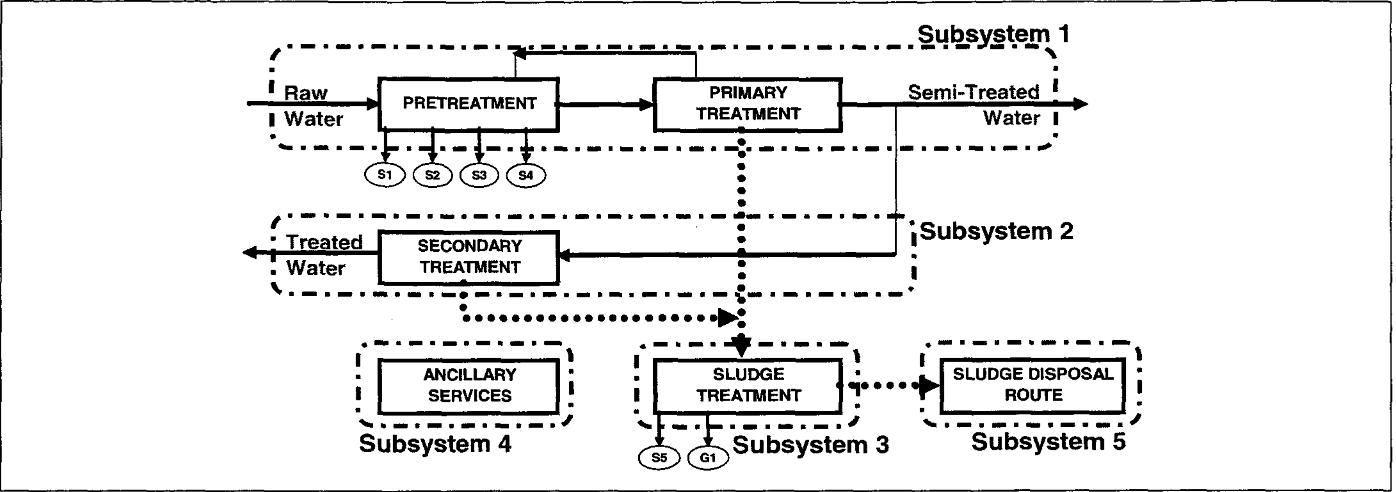

Fig.1: Simplified flowchart of the system and the subsystem defined. S1 to S5 are the different solid fractions generated in the WWTP and G1, the gas emission from the torch

- **Subsystem 4:** It is obtained from electrical consumptions that cannot be allocated to other subsystems, such as auxiliary services and general illumination.
- **Subsystem 5:** This phase includes the scenario of sludge disposal. In other words, the transport of the sludge (by trucks to farms, considering an average distance of 25 km) and its application to land as a fertiliser, where the consumption of fuel by the machinery as well as the avoided fertilisers has been computed.

2.4 Data – Sources and quality

During 2000 and 2001, a comprehensive analysis of the three mentioned lines was carried out for physico-chemical characterisation. **Table 1** presents a detailed list of the origin and quality of the data handled in this assessment. Most parameters were analysed daily or weekly according to standard methods [7]. Other parameters, such as nitrate or nitrite, were measured with water capillary ion analyser [8]. Biogas composition (methane, carbon dioxide and nitrogen) was determined by means of gas chromatography with a thermal conductivity detector [7] and sludge characterisation was obtained following the procedure established by the national legislation, which selected parameters to be determined: pH, dry matter, organic matter, nitrogen, phosphorous according to standard methods and heavy metals such as cadmium, copper, nickel, lead, zinc, mercury and chromium, by atomic-absorption spectroscopy [9,10].

Some complementary data was obtained from the SimaPro 5.0 database [11], which is described next:

- **Data from polyacrylamide production** has been considered to evaluate the polymer used at mechanical dewatering [12].
- **Electricity.** Due to the non-availability of electrical energy distribution in the process, consumption has been quantified considering the theoretical power requirement of each unit as well as the computed working hours. This is the reason why no standard deviations have been calculated for the electricity values with no differentiation for HS and DS (HS/DS column) in the inventory tables.

  In relation to the electricity production profile, an electrical percentage distribution according to data from the Institute for Diversification and Energy Saving (Spain) has been used: 35.8% of the electricity is produced from coal, 27.6% is nuclear, 13.9% is hydroelectric, 9.9% is obtained from oil power plants, 9.7% from gas power plants, 2.2% from wind power plants, 0.6% from waste use and 0.3% from biomass use [13]. However, due to the non-availability of data quantifying the environmental burdens associated with the different electricity production systems in Spain, we chose data from the database [14].
- **Generation, transport and treatment of solid waste.** At WWTP there is no system to quantify the accurate amount of each faction of solid waste generated (grease waste, inert residue and municipal solid waste), so their productions have been estimated by means of the approximate volume and frequency of each recollection tank. Consequently, no distinction between HS and DS could be established and values are presented in the HS/DS column. Although the transport distance for each solid waste has been quantified considering the real values between the WWTP and the waste treatment plant for each residue, the truck capacity selected was that available in the BUWAL database. The specific waste treatment considered was different according to the residue characteristics: inertisation for grease wastes and landfills both for inert residue as well as for municipal solid waste.
- **Air emissions** from the biological treatment were calculated by stoichiometric considerations regarding the removal of organic material (Eq. 1) [15] and the complete combustion of biogas in the torch (Eq. 2) [16]:

$$C_{18}H_{19}O_9N + 0.74 \cdot NH_3 + 8.8 \cdot O_2 \Rightarrow 1.74 \cdot C_5H_7O_2N + 9.3 \cdot CO_2 + 4.52 \cdot H_2O \quad (1)$$

$$CH_4 + 2 \cdot (O_2 + 3.78 \cdot N_2) \Rightarrow CO_2 + 7.56 \cdot N_2 + 2 \cdot H_2O + \text{heat} \quad (2)$$

Table 1: Sources, period and geographical origin of experimental and bibliographic data

Experimental Data

Element	Frequency of Measurement	Period	Method
Water			
Flow	Daily	Year 2000	Ultrasonic Flow meter
pH	Daily	Year 2000	Standard Methods [7]
COD	Daily	Year 2000	Standard Methods [7]
BOD	Fortnightly	Year 2000	Standard Methods [7]
SS	Daily	Year 2000	Standard Methods [7]
NH_3	Monthly	Year 2000	Standard Methods [7]
NO_3^-	Monthly	Year 2000	Capillary Ion Analyser [8]
NO_2^-	Monthly	Year 2000	Capillary Ion Analyser [8]
SO_4^{2-}	Monthly	Year 2000	SulfaVer 4 Method, adapted from Standard Methods [7]
PO_4^{3-}	Monthly	Year 2000	PhosVer 3 Method, adapted from Standard Methods [7]
Conductivity	Daily	Year 2000	Pt Electrode, Standard Methods [7]
Colour	Daily	Year 2000	Espectrophotometric analysis (Pt-Co method), adapted from Standard Methods [7]
Heavy Metals	Once a year	Year 2001	Atomic-Absorption Spectroscopy, Standard Methods [7]
Biogas			
Flow	Daily	Year 2001	Flow meter with an automatic data acquisition system
Composition	Monthly	Year 2001	Gas Chromatography, Standard Methods [7]
Sludge			
Amount	Daily	Year 2000	Mass measurement
pH	Twice per week	Year 2000	Standard Methods [9]
Dry Matter	Twice per week	Year 2000	Standard Methods [9]
Organic Matter	Twice per week	Year 2000	Standard Methods [9]
Nitrogen	Monthly	Year 2001	Standard Methods [9]
Phosphorous			Standard Methods [9]
Heavy Metals			Atomic-Absorption Spectroscopy, Standard Methods [9]

Bibliographic Data

Element	Geographic Area	Period	Source*
Electricity	Spain	Year 2000	IDAE
	Europe, Western	1990–94	BUWAL
Heat from Diesel	Europe, Western	1990–94	BUWAL
Transport by road	Europe, Western	1990–94	BUWAL
Diesel for machinery	Europe, Western	1990–94	BUWAL
Acrylonitrile	Europe, Western	1985–89	PRe 4
Fertilisers	Europe, Western	1990–94	SPIN
Cement	Unspecified	Unspecified	IVAM LCA
Limestone	Unspecified	Unspecified	IVAM LCA
Landfill	Europe, Western	1990–94	BUWAL

*Database References:
Pre 4 database, PRé Consultants, Amersfoort, The Netherlands, 1998.
BUWAL 250, Ökoinventare für Verpackungen, Schriftenreihe Umwelt 250, Bern, 1996.
SPIN N-fertiliser, Produktie van stikstof kunstmest, rapport 147, RIVM Bilthoven 1995.
SPIN P-fertiliser, Produktie van fosfaat meststoffen, rapport 102, RIVM Bilthoven 1992
IVAM LCA Data 2.0 Database and User's Guide, IVAM Environmental Research, Amsterdam, The Netherlands, 1998.

3 Life Cycle Inventory

An LCI step is concerned with the data collection and calculation procedures necessary to complete the inventory [17]. This is the first step to carry out a complete characterisation of the different streams in order to obtain a comprehensive inventory of all the inputs and outputs.

The inventory was mainly based on site-specific data for the period 2001–2002. Summaries for each subsystem are presented in **Tables 2–5**. All the data shown are averages over the Humid Season (HS) or Dry Season (DS) and when HS/DS is referred, no detailed data were obtained so annual average data were handled. Subsystem 4 only comprises the electricity consumption from the grid to ancillary services such as illumination, which was stated as 611.5 MJ.

Upstream system stands for the activities that take place upstream to the WWTP (household consumptions as well as collection and transport), but they have been excluded from our study. Background system includes those activities that are considered ancillary for our system and cannot be affected by the results obtained (electricity production and transport).

Table 2: Inventory Data for Subsystem 1 (pre-treatment and primary treatment)

INPUTS					
From the Upstream System			**From the Background System**		
Materials	**HS**	**DS**	**Electricity (MJ)**	**HS**	**DS**
v (m^3)	57,376 ± 3,083	49,118 ± 2,959	From the grid	10,666	9,307
pH	7.18 ± 0.22	7.22 ± 0.12			
COD (mg L^{-1})	318 ± 117	339 ± 152			
BOD_5 (mg L^{-1})	134 ± 30	145 ± 21			
SS (mg L^{-1})	235 ± 132	226 ± 137	**Transport (t·km)**	**HS / DS**	
NH_3 (mg L^{-1})	19.82 ± 6.13	23.85 ± 4.23	Of inert solids	184 ± 18	
NO_3^- (mg L^{-1})	6.84 ± 1.47	8.80 ± 2.11	Of municipal solid waste	4.00 ± 0.99	
NO_2^- (mg L^{-1})	0.606 ± 0.249	0.429 ± 0.093	Of fatty solids	49.7 ± 4.5	
SO_4^{2-} (mg L^{-1})	40.4 ± 4.2	43.3 ± 5.3			
PO_4^{3-} (mg L^{-1})	1.72 ± 0.26	2.86 ± 0.36			
Cond (S/cm)	332 ± 49	367 ± 52			
Colour (Pt-Co)	413 ± 116	405 ± 103			

OUTPUTS				
To Further Treatment		**To the Environment**		
	HS / DS	**Emissions to water**	**HS**	**DS**
Inert waste (m^3)	1.10 ± 0.10	v (m^3)	31,129 ± 3,567	22,696 ± 2,869
Water (%)	28.33 ± 3.10	pH	7.18 ± 0.13	7.23 ± 0.12
Ashes (%)	63.58 ± 0.36	COD (mg L^{-1})	177 ± 47	185 ± 61
N (%)	0.27 ± 0.04	BOD_5 (mg L^{-1})	85 ± 18	82 ± 10
C (%)	9.59 ± 2.86	SS (mg L^{-1})	93 ± 33	81 ± 28
H (%)	1.05 ± 0.25	NH_3 (mg L^{-1})	18.27 ± 1.89	22.94 ± 2.02
S (%)	0.20 ± 0.09	NO_3^- (mg L^{-1})	7.43 ± 2.19	8.80 ± 1.45
Municipal solid waste (kg)	36 ± 9	NO_2^- (mg L^{-1})	0.373 ± 0.158	0.462 ± 0.031
Metals (%)	3.46 ± 0.35	SO_4^{2-} (mg L^{-1})	37.1 ± 4.5	47.0 ± 0.7
Glass (%)	6.29 ± 1.95	PO_4^{3-} (mg L^{-1})	1.30 ± 0.11	2.43 ± 0.23
Plastics (%)	11.03 ± 1.55	Cond (S/cm)	320 ± 37	361 ± 48
Paper (%)	19.56 ± 3.59	Colour (Pt-Co)	335 ± 64	339 ± 73
Organics (%)	21.96 ± 4.54			
Others (%)	4.71 ± 2.84			
Water (%)	32.88 ± 4.31			
Fatty waste (m^3)	0.73 ± 0.07			
pH	5.84 ± 0.93			
Total Solids (%)	43.94 ± 10.68			
Volatile Solid (%)	41.78 ± 11.31			
COD (g L^{-1})	5.21 ± 1.97			
Density (kg L^{-1})	0.99 ± 0.03			

Table 3: Inventory Data for Subsystem 2 (biological treatment)

INPUTS					
From the Subsystem 1			**From the Background System**		
Materials	**HS**	**DS**	**Electricity (MJ)**	**HS / DS**	
v (m^3)	26,220 ± 1,217	26,518 ± 788	From the grid	10,516	
pH	7.18 ± 0.13	7.23 ± 0.12			
COD (mg L^{-1})	177 ± 47	185 ± 61			
BOD_5 (mg L^{-1})	85 ± 18	82 ± 10			
SS (mg L^{-1})	93 ± 33	81 ± 28			
NH_3 (mg L^{-1})	18.27 ± 1.89	22.94 ± 2.02			
NO_3^- (mg L^{-1})	7.43 ± 2.19	8.80 ± 1.45			
NO_2^- (mg L^{-1})	0.373 ± 0.158	0.462 ± 0.031			
SO_4^{2-} (mg L^{-1})	37.1 ± 4.5	47.0 ± 0.7			
PO_4^{3-} (mg L^{-1})	1.30 ± 0.11	2.43 ± 0.23			
Cond (S/cm)	320 ± 37	361 ± 48			
Colour (Pt-Co)	335 ± 64	339 ± 73			
OUTPUTS to the Environment					
Emissions to air	**HS**	**DS**	**Emissions to water**	**HS**	**DS**
CO_2 (kg)	2,345 ± 411	2,507 ± 520	v (m^3)	26,220 ± 1,217	26,518 ± 788
			pH	7.13 ± 0.17	7.30 ± 0.15
			COD (mg L^{-1})	55 ± 24	56 ± 28
			BOD_5 (mg L^{-1})	9 ± 5	6 ± 3
			SS (mg L^{-1})	12 ± 7	10 ± 7
			NH_3 (mg L^{-1})	15.84 ± 1.97	23.71 ± 1.40
			NO_3^- (mg L^{-1})	2.44 ± 0.92	3.15 ± 0.10
			NO_2^- (mg L^{-1})	0.116 ± 0.041	0.400 ± 0.442
			SO_4^{2-} (mg L^{-1})	45.2 ± 19.2	41.5 ± 0.5
			PO_4^{3-} (mg L^{-1})	1.18 ± 0.24	1.51 ± 0.02
			Cond (S/cm)	296 ± 31	348 ± 32
			Colour (Pt-Co)	58 ± 23	45 ± 13

Table 4: Inventory Data for Subsystem 3 (sludge treatment inside the WWTP)

INPUTS					
From the Subsystems 1 & 2			**From the Background System**		
Materials	**HS**	**DS**	**Transport (t·km)**	**HS**	**DS**
Mixed Sludge (m^3)(*)	379.5	420.8	Of polymer	12.62 ± 0.65	11,82 ± 0.44
Polymer (kg)	17.4 ± 0.9	16.3 ± 0.6			
Electricity (MJ)	**HS / DS**				
From the grid	2,554				
OUTPUTS					
To Further Treatment			**To the Environment**		
Avoided Product	**HS**	**DS**	**Emissions to air**	**HS / DS**	
Heat (MJ)	18,985 ± 3,038	18,985 ± 3,038	CO_2 (kg)	618.6 ± 185.6	
Waste to treatment			NO_X (kg)	13.2 ± 4.0	
PE to recycling (g)	225 ± 12	211 ± 8			

(*) 1% of Solid Content. At the evaluated WWTP, the primary and secondary sludge are separately thickened, so any experimental data regarding the mixed sludge before thickening is available.

Table 5: Inventory Data for Subsystem 5 (sludge treatment outside the WWTP)

INPUTS					
From the Subsystem 3			**From the Background System**		
Materials	**HS**	**DS**	**Transport by road**	**HS**	**DS**
Sludge Cake (kg)	10,180 ± 585	11,460 ± 1,577	Of sludge (t·km)	254.50 ± 14.62	286.50 ± 39.42
DM (%)	23.86 ± 3.49	23.50 ± 2.64			
OM (%)	38.25 ± 4.57	41.70 ± 4.83			
Diesel (kg)	1.75 ± 0.10	1.97 ± 0.27			
OUTPUTS					
As Avoided Products			**To the Environment**		
	HS	**DS**	**Emissions to soil**	**HS / DS**	
Fertilizer N	86.22 ± 4.95	97.07 ± 25.10	Cd (mg/kg DM)	1.38 ± 0.35	
Fertilizer P	49.37 ± 2.84	55.58 ± 11.00	Cr (mg/kg DM)	79.12 ± 15.99	
			Cu (mg/kg DM)	193.19 ± 43.17	
			Hg (mg/kg DM)	1.43 ± 0.01	
			Ni (mg/kg DM)	29.24 ± 8.80	
			Pb (mg/kg DM)	334.05 ± 48.37	
			Zn (mg/kg DM)	1,521 ± 57	

4 Life Cycle Inventory Analysis

In the first steps of the LCIA, classification and characterisation, emissions and resources coming from the inventory are sorted into different groups or impact categories according to their potential impact on the environment. In accordance with the default list of impact categories elaborated by Guinèe et al. [18], some of them have been chosen among the so called baseline impact categories (**Table 6**): climate change (also called global warming, GWP), stratospheric ozone depletion (ODP), acidification (AP), eutrophication (EP), photooxidant formation (POFP), depletion of abiotic resources (ADP), human toxicity (HTP) and terrestrial ecotoxicity (TTP).

Table 6: Bibliographic references of the characterisation factors for the impact categories considered

Impact Category	**References**
global warming (GWP)	J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.), 2001. IPCC Third Assessment Report: Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK.
stratospheric ozone depletion (ODP)	World Meteorological Organisation (WMO), 1992: Scientific assessment of ozone depletion: 1991. Global Ozone Research and Monitoring Project – Report no. 25, Geneva. WMO, 1995: Scientific assessment of ozone depletion: 1994. Global Ozone Research and Monitoring Project – Report no. 37, Geneva. WMO, 1999: Scientific assessment of ozone depletion: 1998. Global Ozone Research and Monitoring Project – Report no. 44, Geneva.
acidification (AP)	Huijbregts, M.A.J., 1999. Life cycle impact assessment of acidifying and eutrophying air pollutants. Calculation of equivalency factors with RAINS-LCA. Faculty of Environmental Science, University of Amsterdam, The Netherlands.
eutrophication (EP)	Heijungs, R., J. Guinèe, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin, H.P. de Goede, 1992. Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Science (CML), Leiden University, The Netherlands.
photo-oxidant formation (POCP)	Derwent, R.G., M.E. Jenkin, S.M. Saunders & M.J. Pilling, 1998. Photochemical ozone creation potentials for organic compounds in Northwest Europe calculated with a master chemical mechanism. Atmospheric Environment 32: 2429–2441. Jenkin, M.E. & G.D. Hayman, 1999: Photochemical ozone creation potentials for oxygenated volatile organic compounds: sensitivity to variations in kinetic and mechanistic parameters. Atmospheric Environment 33: 1775–1293.
depletion of abiotic resources (ADP)	Guinèe J.B. (ed.), 2001. Life Cycle Assessment an operational guide to the ISO standard. Volume I, II, III
human toxicity (HTP)	Huijbregts, M.A.J., 1999. Priority assessment of toxic substances in LCA. Development and application of the multi-media fate, exposure and effect model USES-LCA. IVAM environmental research, University of Amsterdam, The Netherlands.
terrestrial ecotoxicity (TTP)	Huijbregts, M.A.J., 2000. Priority Assessment of Toxic Substances in the frame of LCA. Time horizon dependency of toxicity potentials calculated with the multi-media fate, exposure and effects model USES-LCA. Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, The Netherlands.

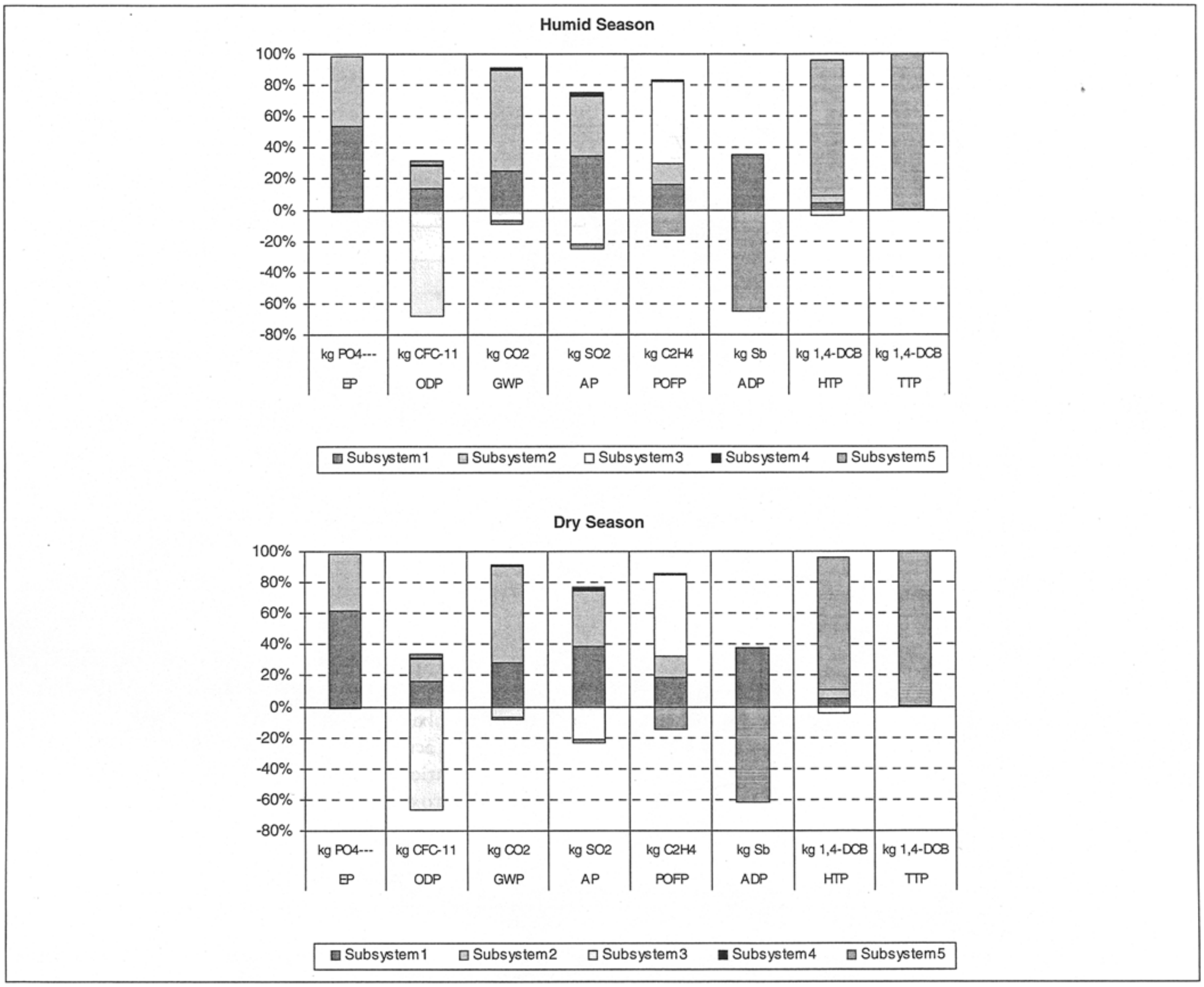

Fig. 2: Characterisation profiles for both Functional Units. Subsystem 1 is represented in dark grey, subsystem 2 in light grey, subsystem 3 with dots, subsystem 4 in black and subsystem 5 with oblique lines

Results from the characterisation phase are shown in terms of relative contribution of its life cycle steps (subsystems) to the different impact categories (**Fig. 2**), where Humid Season and Dry Season are presented separately, although they display a common tendency.

The next step: the normalisation phase (**Fig. 3**) allows us to compare all the environmental impacts on the same scale. The state-of-the-art indicates that site-dependency considerations must be taken into account at local impact categories [19,20]; however, this dependency is still non-available for Spanish conditions so accessible normalization data may be used. Up-to-date normalization figures have been recently published [21]. Among the four possibilities, Western Europe (1995) seems to be the most appropriate to evaluate a process that takes place in Galicia (Spain).

It is generally recognised that the weighting element in LCIA requires political, ideological and/or ethical values, so a high degree of subjectivity is always involved, for this reason, this stage was left out of this study.

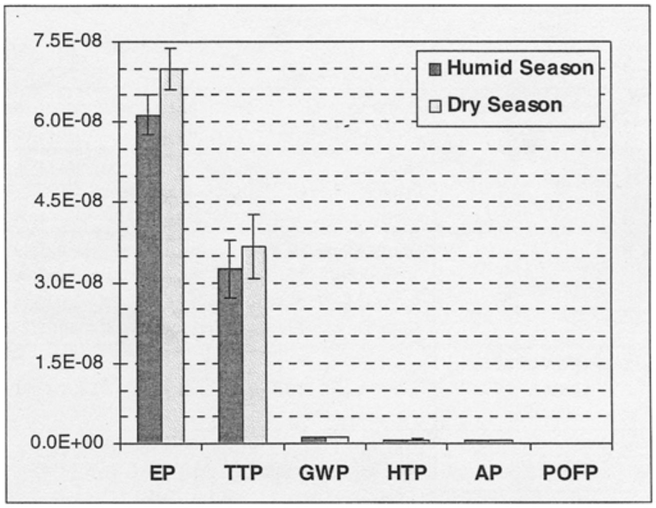

Fig. 3: Normalisation data for each impact category considered in this work. Mean values and variability due to more significant standard deviations are shown

5 Results and Discussion

Both Figs. 2 and 3 display a short variation related to the two different functional unit defined (HS and DS). In fact, the average deviation along all the impact categories studied can be established as 11%, ranging from 2% at GWP to 28% at ADP (characterisation figures).

The low potential impact due to the ancillary services (subsystem 4) is shown in Fig. 2. Even if its higher contribution is considered (AP), it stands for less than 5% of the total impact.

5.1 Improvement actions for environmental impact reduction

Among the categories studied, two of them have been reported as the most significant: eutrophication ($6.14 \cdot 10^{-8} \pm 0.38 \cdot 10^{-8}$ at HS and $6.98 \cdot 10^{-8} \pm 0.39 \cdot 10^{-8}$ at DS) and terrestrial ecotoxicity ($3.26 \cdot 10^{-8} \pm 0.53 \cdot 10^{-8}$ at HS and $3.67 \cdot 10^{-8} \pm 0.59 \cdot 10^{-8}$ at DS); so attention has to be focused on those activities which are supposed to have an essential reduction on both of them.

As far as **eutrophication** is concerned, the emission of three substances to water can be identified as the main responsible factor with a contribution of more than 95% to the overall impact. Ammonium, phosphate and organic matter (this latter measured as COD) are discharged not only at the final discharge point (treated wastewater) but also at an intermediate point (released as semi-treated wastewater after the primary treatment), so the improvement actions can be fixed on two specific directions:

- The need of the nitrogen removal in the design of wastewater treatment plants, while the removal of phosphate can be considered as a secondary objective
- An accurate over-dimension of the treatment plant is desirable considering both the amount of pluvial waters and the expected growth of the urban and industrial surrounding areas, since a major impact in this case is due to the discharge of organic matter in the intermediate site when the treatment capacity of the system is exceeded, especially in rainy weather.

We focus on the first option considering a scenario combining the removal of organic and nitrogenous matter, where the effluent from both actual primary and secondary treatments is treated in a nitrification-denitrification unit before being discharged. The air emissions from the nitrification-denitrification process were calculated by stoichiometric considerations (Eq. 3 & 4) [15]:

$$NH_4^+ + 1.86 \cdot O_2 + 1.98 \cdot HCO_3^- \Rightarrow 0.02 \cdot C_5H_7O_2N + 0.98 \cdot NO_3^- + 1.88 \cdot H_2CO_3 + 1.04 \cdot H_2O \qquad (3)$$

$$0.61 \cdot C_{18}H_{19}O_9N + 4.54 \cdot NO_3^- + 0.39 \cdot NH_4^+ + 4.15 \cdot H^+ \Rightarrow C_5H_7O_2N + 2.72 \cdot N_2 + 5.98 \cdot CO_2 + 5.15 \cdot H_2O \qquad (4)$$

Moreover, the aeration demand was estimated and expressed in electrical consumption.

The evaluation of this option implies a substantial reduction at EP: 58% for humid season (from 737 to 310 kg-eq PO_4^{3-}) and 54% for dry season (from 837 to 388 kg-eq PO_4^{3-}). Contrary to EP, other categories, such as GWP, AP or POFP are negatively affected with an increase on their values; however, these variations have less importance in comparison with the reduction at EP in terms of normalisation figures.

Regarding **terrestrial ecotoxicity** potential, the emission of heavy metals from the sludge is the unique accountable parameter, where Cr, Hg and Zn are pointed out to be the more outstanding contributors.

Unlike EP, where a technological implementation has been proposed, a new scenario will be evaluated here bearing in mind the future legislation concerning sludge and its consequences. Although Directive 86/278/EEC on the use of sludge in agriculture (Official Journal 04/07/1986; adapted to the Spanish Legislation by R.D. 1310/1990) is still valid, the document on sludge (3rd Draft, Brussels, 27 April 2000) must be taken into account because its upcoming implementation will suppose an important readjustment on sludge management due to tighter limit values for heavy metals both in sludge and in soil as well as in the inclusion of limit values for concentrations of organic compounds and dioxins in sludge.

Table 7 shows the limit values according to actual Spanish and future European legislation, where a significant revision is proposed in order to achieve the concentrations expected to be obtained in the medium (about year 2015) and long-term (about year 2025). Nowadays, the sludge generated at WWTP is typically added to lands (average dose = 80 ton/ha/year) thus, special attention to monitor the amounts of heavy

Table 7: Limit values for concentration of heavy metals according to Spanish and European legislation

Parameters	Annex I, Spanish Legislation (R.D. 1310/1990)		Working document on Sludge. 3rd Draft Long term (about 2025)	
	Limit values for concentration of heavy metals in sludge for use on land (mg/kg DM) Soil with pH < 7	Limit values for amounts of heavy metals which may be added annually to soil, based on a ten year average (kg/ha/year)	Limit values for concentration of heavy metals in sludge for use on land (mg/kg DM)	Limit values for amounts of heavy metals which may be added annually to soil, based on a ten year average (kg/ha/year)
Cd	20	0.15	2	0.006
Cr	1,000	3.00	600	1.80
Cu	1,000	12.00	600	1.80
Hg	16	0.10	2	0.006
Ni	300	3.00	100	0.30
Pb	750	15.00	200	0.60
Zn	2,500	30.00	1,500	4.50

metals supplemented to soil (measured as kg/ha/year) has to be paid to maintain the proposed limit values. Consequently, a bigger area of soil will be necessary for the same amount of sludge (sludge composition is supposed to be invariable).

Moreover, the working document on sludge puts special pressure on pathogens and their consequences on land application; so there are many factors involved in the use of sludge on agriculture. In this sense, composting will probably play a more significant role in sewage sludge treatment because the sludge could be transformed in a non-hazardous resource after a hygienisation process.

Sludge quality results from the quality of wastewater entering the WWTP; therefore, more effort should be made to ensure the quality of wastewater by enforcing stricter discharge standards for industrial wastewater. However, other recent reports show the difficulty to identify the sources of metals which contribute to the wastewater pollution; for instance, it has been reported that only a very minor fraction, 4% or less, of the present contribution of heavy metals to WWTP in Stockholm (Sweden) is derived from large size factories; surprisingly, the contribution also seems to be rather marginal from smaller ones [22]. In Gothenburg (also in Sweden), measurements in the early 1990s showed that the total contribution to WWTPs from small factories was 3% for the following heavy metals: Zn, Hg, Ni, Cr and Cd, 6% for Cu and 12% for Pb [23]. All these results suggest that there is a diffuse pollution source, which is difficult to be identified. Substance flow analysis (SFA) has been used to search for alternatives to reduce sources and conclusions regarding the opportunities for wastewater utilities to manage and to reduce sources of heavy metals are to a certain extent encouraging for only certain metals such as Ni [24]. Consequently, WWTP cannot be as a separate phenomenon in society but a part of the system of material flows since reducing the WWTP emissions might involve a reduction in the inflow of heavy metals in society and a better overview of the urban erosion processes in order to decrease the diffuse sources [25].

5.2 Future outlook

The on-going research is now focused in two main directions.

On the one hand, and as it was mentioned at the introduction to this paper, the general aim of this work is the evaluation of the most common technical options focused on the removal of organic matter from urban wastewater in order to obtain a methodology to include the environmental vector in the decision-making process when the optimisation or the implementation of a WWTP is planned; bearing in mind the concept of equivalent inhabitant, a classification of WWTPs in Galicia (Spain) will be made according to the next grouping: Group 1, fewer than 2,000 equivalent inhabitants, Group 2, from 2,000 to 10,000 equivalent inhabitants, Group 3, from 10,000 to 50,000 equivalent inhabitants and Group 4, greater than 50,000. Typical configurations will be identified for each group and an extensive fieldwork will be developed on the same lines as the inventory presented here, in order to evaluate the environmental performance of each one.

On the other hand, sludge is also the focus of attention in our work. At the present time, several different alternatives of sewage sludge post-treatment, including traditional methods (such as landfill or incineration) and alternative thermal treatment technologies (such as pyrolysis), are being inventoried in order to compare them with the actual option that takes place at the WWTP under study, which comprises anaerobic digestion plus land application [26].

6 Conclusions

In this study, a WWTP has been evaluated by means of exhaustive fieldwork. During two years, a thorough inventory of empirical data from water, sludge and gas flows were collected in order to obtain demonstrative values of the system.

At the first stage of the LCA (objectives and scope definition), two distinct functional units were defined in order to take into consideration the fact that the performance of a WWTP commonly depends on the variability of input data corresponding to the different seasons (HS, from October to April, and DS, from May to September). However, outcomes from the environmental analysis have demonstrated that such differentiation is not required as far as the potential impact is concerned. Variation due to the variability of the data in each season has turned out to be more significant than variation due to seasonability.

Water discharge and sludge application to land have turned out to be the main contributors to the environmental performance of a WWTP. Regarding the former, the removal of nitrogen by means of a nitrification-denitrification system coupled to a conventional biological aerobic treatment implies a high environmental impact reduction and, with reference to the latter and bearing in mind the future legislation, heavy metals as well as pathogens should be the key parameters to define the most adequate treatment strategies for the generated sludge.

This study can serve as a basis for future studies to be applied to a great number of wastewater facilities, considering aspects such as different treatment systems and capacities. In this way, an evaluation methodology of these types of systems can be developed once the most significant variables are established.

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[1] Int J LCA 3 (3) 145–157 (1998)
Life Cycle Assessment of Municipal Waste Water Systems
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Life Cycle Assessment was applied to municipal planning in a study of waste water systems in Bergsjön, a Göteborg suburb, and Hamburgsund, a coastal village. Existing waste water treatment consists of mechanical, biological and chemical treatment. The heat in the waste water from Bergsjön is recovered for the district heating system. One alternative studied encompassed pretreatment, anaerobic digestion or drying of the solid fraction and treatment of the liquid fraction in sand filter beds. In another alternative, urine, faeces and grey water would separately be conducted out of the buildings. The urine would be used as fertilizer, whereas faeces would be digested or dried, before used in agriculture. The grey water would be treated in filter beds. Changes in the waste water system would affect surrounding technical systems (drinking water production, district heating and fertilizer production). This was approached through system enlargement. For Hamburgsund, both alternatives showed lower environmental impact than the existing system, and the urine separation system the lowest. Bergsjön results were more difficult to interpret. Energy consumption was lowest for the existing system, whereas air emissions were lower for the alternatives. Water emissions increased for some parameters and decreased for others. Phosphorous recovery was high for all three alternatives, whereas there was virtually no nitrogen recovery until urine separation was introduced.

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An LCA Study on Sludge Retreatment Processes in Japan
Keko Iriyama Strauss, Michael Wiedemann

The majority of night soil (human excrements) is source separated from other sewage water and treated at night soil treatment plants in Japan. Efforts have been made to achieve material recovery from this organic mass, together with other organic wastes such as kitchen wastes and manure, by expanding the functions at night soil treatment plants. These facilities with expanded function are called 'sludge retreatment centers', which are promoted by the Japanese Ministry of Health and Welfare. Potential environmental impacts of sludge retreatment using two presently available systems in Japan are analyzed for comparison. Systems compared are: 1) Mebius system, a high-speed fermentation process with methane gas recovery and compost production and 2) a comparable system with a basic composting process. The functional unit for this study is concurrent treatment of 40 t/d of kitchen waste, 40 m^3/d of night soil, and 60 m^3/d of private sewage treatment tank sludge. Impact assessment on Global Warming (IPCC 1996, 20 yrs.), Acidification Potential (De Leeuv – AP), Eutrophication Potential (De Leeuv – EP) and Resource Index (Fava/SETAC & Heijungs) all indicated that sludge retreatment with Mebius system provides a better environmental performance. The main reasons are: 1) production of power using recovered methane and 2) reduction of sludge volume by digestion, which leads to reduction of fuel required for sludge drying. The collection and treatment of night soil and kitchen wastes involves many economic and social factors. Therefore, more studies with different functional units on these systems should be made to obtain a more complete picture that can be used for decision-making processes. The results of this study can be used as a starting point.

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Country-specific Damage Factors for Air Pollutants
Wolfram Krewitt, Till M. Bachmann, Thomas Heck,
Alfred Trukenmüller

DOI: http://dx.doi.org/10.1065/lca2000.12.048. An integrated impact assessment model is used to calculate the impact per tonne of SO_2, NO_x, fine particles, and NMVOC emitted from different source countries on human health, acidification, eutrophication, and the man-made environment (crop yield and building materials). Indicators on the endpoint level are used to measure the effects resulting from a marginal change in emission levels. While the assessment of impacts on ecosystems and the man-made environment is limited to Europe, damage factors for health effects are also derived for Asia and South America. For Europe, emission scenarios for the years 1990 and 2010 are considered to analyse the influence of changing background conditions on the resulting impacts. Results show that there is a significant variation in the damage resulting from a unit emission for some of the impact categories, both between countries and between base years. Depending on the scope of the study and the information available from the life cycle inventory, results from the paper can be used to consider site dependent conditions in life cycle impact assessment as a complement to the current site-independent (or global) approach.