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Environmental assessment of the integrated municipal solid waste management system in Porto (Portugal)

Marta Herva [a], Belmira Neto [b], Enrique Roca [a,*]

[a] Sustainable Processes and Products Engineering Group, Dept. of Chemical Engineering, University of Santiago de Compostela, Campus Vida, 15782 Santiago de Compostela, Spain
[b] CEMUC, Dpt. of Metallurgical and Materials Engineering, Faculty of Engineering, University of Porto, Portugal

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ABSTRACT

This paper presents the results of the environmental evaluation of the waste treatment processes occurring at LIPOR (the Inter-municipal Waste Management System of Greater Porto – Portugal) in the period 2007–2011. To this aim two methodologies are applied, namely the Energy and Material Flow Analysis (EMFA) and the Ecological Footprint (EF). The benefits of their joint application are explored, as well as the usefulness of the indicators derived to guide the company in the identification of the hot spots and in the improvement of their management practices. The Integrated Waste Management System (IWMS) at LIPOR includes several units, specifically the separation of several materials for valorization (namely, packaging materials -as metals and plastics-, glass and paper and cardboard), the incineration of waste with energy recovery, composting of the organic fraction and the landfilling of pre-treated waste.

From the EMFA, it can be highlighted that the electricity generated in the energy recovery plant is the most important energy flow and that it largely exceeds the energy demands from the LIPOR system. According to the net EF results, the composting and energy recovery units were found as very beneficial in terms of resources savings. Despite the fact that the composting plant has the largest gross EF (0.28 ± 0.02 gm^2 kg^{-1} in average for the period analyzed, where gm^2 refers to global square meters), a significant counter footprint effect associated with the production of the compost was calculated (-1.51 ± 0.10 gm^2 kg^{-1} of waste composted). The energy recovery plant shows the lower gross EF (0.05 ± 0.01 gm^2 kg^{-1} of waste combusted), but also an important contribution to the counter footprint (-0.78 ± 0.01 gm^2 kg^{-1} in average). These individual results are reported to 1 kg of waste treated at each facility. Meanwhile, the EF for the overall IWMS reaches -0.49 ± 0.12 gm^2 kg^{-1}, where this result is reported to the total wastes treated at LIPOR. The negative value means that, in terms of the EF, the global system is environmentally beneficial because of the recovery of resources such as the compost and electricity.

1. Introduction

Economic and human population growths, as well as changes in lifestyles and in consumption patterns, have been the main drivers to a progressive increase in the generation of waste. This is particularly due to the large use of packaging materials. As a consequence, one of the major challenges for municipalities in the 21st century is to collect, recycle, treat and dispose of increasing amounts of urban solid waste (Cherubini et al., 2009). Waste can cause several impacts in the environment, as the pollution of air, soil, surface and ground water. In addition, valuable space is taken up by landfills and a poor waste management may cause harm in the public health. The impact in the environment, together with the economic constraints associated with the management of residual flows, are usually the driving forces to identify solutions for the reduction of the impacts caused by the solid urban wastes (Seadon, 2010).

The waste hierarchy defined in the Directive 2008/98/EC defines priorities to be considered in legislation and policies for waste

List of abbreviations: CF, Counter footprint; CP, Composting Plant; EF, Ecological footprint; EMFA, Energy and material flow analysis; ERP, Energy Recovery Plant; IWMS, Integrated waste management system; LCA, Life Cycle Assessment; MSW, Municipal solid waste; SP, Sorting Plant; WEEE, Waste Electrical and Electronic Equipment; gha, Global hectares; gm^2, Global square meters.

* Corresponding author. Tel.: +34 881 816 774; fax: +34 881 816 702.
E-mail address: enrique.roca@usc.es (E. Roca).
URL: http://prodes.usc.es

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prevention and management. But the hierarchy is not rigid, and the Directive also addresses the possibility of altering the hierarchy for specific situations when supported by a life-cycle thinking study (European Commission, 2008). Furthermore, a holistic approach, which recognizes the relevance of all disposal options within an integrated waste management, could also be preferred (White et al., 1999).

The increasing pressure on waste managers, planners and waste regulators for sustainable systems has spanned the spectrum of new and existing waste treatment technologies and managerial strategies. These seek to maintain environmental quality at present and to meet sustainability goals in the future (Barton et al., 1996; Pires et al., 2011). This suggests the need of analytical tools to evaluate the overall environmental burdens of waste management systems (Thomas and McDougall, 2005). Due to its life cycle approach, Life Cycle Assessment (LCA) has been widely applied to evaluate environmental problems associated with municipal solid wastes (Arena et al., 2003; Cleary, 2009). There are, however, other environmental evaluation methodologies using life-cycle approaches that have been also applied. For instance, Cherubini et al. (2009) performed studies using material flows and the ecological footprint (EF) assessment. Moreover, Herva and Roca (2013a) performed a study that established a ranking of waste treatment alternatives based on two approaches: 1) use of the EF as a single composite indicator and 2) integration of the EF together with other material flow indicators related to water consumption, emissions to air and water and occupied landfill volume. This was done by using multi-criteria analysis (Herva and Roca, 2013b).

In contrast to the individual waste treatment processes, the applications to evaluate integrated waste management systems are scarcer. To this respect, there is an international expert group on life cycle assessment for integrated waste management that promotes the application of LCA methodology to identify optimal environmental solutions for managing wastes (Thomas and McDougall, 2005). den Boer et al. (2007) developed a waste management tool based on LCA (LCA-IWM) that allowed constructing and evaluating different scenarios in municipal solid waste management planning. The environmental criteria were based on the CML 2001 method and additionally social and economic criteria were defined. Cifrian et al. (2012) combined material flow indicators and the single approach of the carbon footprint to track the progress over time of the municipal solid waste management system of Cantabria. Other authors have also addressed the topic of integrated waste management systems from a LCA perspective (Muñoz et al., 2004; Rigamonti et al., 2009). Nevertheless, to the authors' knowledge, this work presents the first attempt to use the EF as and aggregated indicator of sustainability to evaluate an integrated municipal solid waste management system.

This work assesses the environmental performance of LIPOR, which is the Inter-municipal Waste Management System located in Porto (Portugal) responsible for the management and treatment of the municipal solid waste (MSW) produced in the eight partner municipalities. The environmental assessment of the Integrated Waste Management System (IWMS) of LIPOR followed a stepwise approach: 1) the modeling and scenario building in Umberto® for energy and material flow analysis; 2) assessment of the EF. This is done in order to obtain an overall measure of the environmental burdens associated with the facilities where the waste treatment processes take place at LIPOR. An additional objective is to explore the benefits of the joint application of the methodologies proposed, as well as the usefulness of the indicators derived to guide the company in the identification of the hot spots and in the improvement of their management practices, by comparing the results from the different operating years.

2. Methodology

This section describes the LIPOR's waste treatment processes as well as the environmental evaluation methodologies used.

2.1. Case study

The integrated system for MSW at LIPOR includes the separation of several materials for valorization (Sorting Plant - SP), composting of the organic fraction (Composting Plant - CP) and the incineration of waste with energy recovery (Energy Recovery Plant ERP). LIPOR receives at its SP packaging materials (metal and plastic), glass, paper and cardboard arriving from different waste collection systems, namely through eco-containers available to citizens and a door-to-door collection in some specific areas. All the materials collected separately are brought to LIPOR's sorting plant where an additional separation takes place before the materials are sent to third-party recycling plants. The glass is transported directly to the facilities without any processing at LIPOR.

In addition, a sanitary landfill is used to dispose the by-products (slag and inert ashes) from the ERP, as well as raw waste that cannot be treated in any of LIPOR's industrial treatment plants. The waste flows, treated at the different treatment plants, for the time frame considered (2007–2011) are presented in Table 1.

LIPOR's IWMS is divided in four main steps (see Fig. 1). Step I represents the generation of waste by the citizens. The councils (step II) provide the adequate infrastructure for public use for a separated disposal and collection of wastes. The flows of wastes are then sent to appropriate waste treatment facilities at LIPOR (step III) according to their characteristics. Finally, the valuable products (energy, compost and recycled materials) resulting from the valorization processes are commercialized (step IV). The activity at LIPOR also implies other processes that cannot be allocated to any specific waste treatment plant and that were grouped under the name 'general activities'. These include the administrative services or the management of hazardous wastes not treated internally but sent to authorized managers. Inventory raw data used in the environmental assessment are listed in the Appendix (Tables A.1 to A.5).

2.1.1. Energy recovery plant (ERP)

In the Energy Recovery Plant (ERP) the MSW not having a recovery potential is subjected to a thermal treatment in order to recover wastes' endogenous energy, under controlled conditions and, to produce electricity. The incineration takes place at a high temperature (1000 °C–1200 °C) under excess oxygen conditions. The incineration plant is energetically self-sufficient. This is to say that about 90% of the energy produced is sent to the Portuguese national electricity grid network.

Table 1
Annual waste streams treated or disposed of by the existing treatment processes at LIPOR (2007–2011).

	2007	2008	2009	2010	2011	Units
Population (inhabitants)	972,301	972,301	970,704	986,274	984,047	–
Waste streams:						
Sorting Plant (SP)	49,884	55,470	59,966	58,591	55,153	t
Composting Plant (CP)	30,730	37,146	42,215	47,308	46,140	t
Energy Recovery Plant (ERP)	419,389	383,553	398,392	378,693	392,140	t
Landfill	27,185	63,308	39,339	57,835	21,399	t
Total	527,188	539,477	539,912	542,427	514,832	t

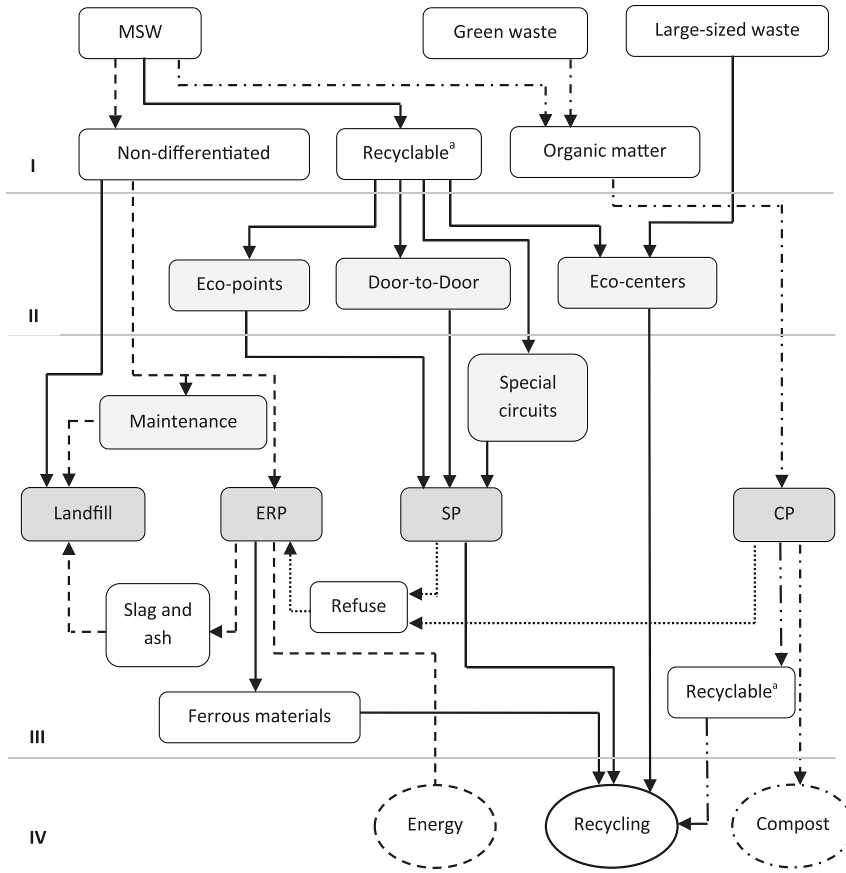

Fig. 1. The Integrated Waste Management System at LIPOR (adapted from LIPOR, 2009). ERP as the Energy Recovery Plant, SP as the Sorting Plant and CP as the Composting Plant. **I** – Citizen: production and disposal **II** – Councils: production and disposal **III** – LIPOR: valorization and treatment **IV** – Clients: products and resources [a] Recyclable are the wastes that can still be converted into valuable materials.

The air emissions released during the combustion process undergo a monitoring system control. The gases are filtered and neutralized before sent to the atmosphere as explained next. The flue gas treatment starts with the maintenance of the burning temperature in the furnace above 900 °C to prevent the formation of furans and dioxins. It is also injected urea to avoid the production of nitrogen oxides. In a reactor, slaked lime (calcium hydroxide solution) and activated carbon are added to reduce the heavy metals, dioxins and furans. Finally, the flue gas goes through several sleeve filters for particulate emission reduction (reduce the emission of flying ashes).

The flying ashes collected in the sleeve filters are sent to the inertization facility where an aluminates solution and other cement compounds are added to favor the entrapment of pollutants in the ashes and forming hard blocks. Finally, these inertized ashes are deposited in a special landfill.

2.1.2. Sorting plant (SP)

In the Sorting Plant (SP) a complementary separation of wastes is made. This process takes place in a closed building of 4000 m^2. There are three treatment lines, namely, line for bulky items (plastic and metal), mixed line (paper and cardboard) and multipurpose line (different materials).

In the former, there is a pre-sorting of plastic and metal packages that come from the several selective collection circuits. This process allows opening locked bags and remove of plastic film (through suction), mixed plastics and bulky rejected waste, so that the material reaches better quality. The feeding of the next sorting process is carried out with a shovel loader and then the material is transported by a conveyor belt. Then it follows a magnetic separator that captures iron materials and transports them into another conveyor. The sorted iron materials fall into a hopper which feeds a press machine for iron materials. The remaining bulky material falls into a vibrating screen that eliminates the unwanted material.

Regarding the paper and cardboard, LIPOR just receives the material from the selective collection. It is pressed and baled to be sent to the appropriate waste managers.

In the multipurpose line, the material is transported by a belt conveyor into a rotating trommel screen. This equipment separates paper/cardboard based on size. Throughout the sorting lines, there's a de-dusting system, which removes small dust originated by the different process stages from the material.

Additionally to the three sorting lines described above, there is a sorting platform that sorts large materials or materials that cannot be sent to the Sorting Plant due to their properties. These include: plastics, scrap, glass, large non-metal items, batteries, fluorescent lamps, wood and WEEE (Waste Electrical and Electronic Equipment).

2.1.3. Composting plant (CP)

The biowaste recovery occurs in a Composting Plant (CP) that can process nearly 60,000 t y^{-1} of organic waste. The organic fraction of the MSW is collected from a formal circuit, implemented by LIPOR. A large amount of organic waste from, among others, restaurants, hypermarkets and markets is collected every day. The resulting compost is commercialized by LIPOR.

2.1.4. Landfill

The landfill acts as a complementary facility. Waste flows occurring during maintenance or unplanned stops of the treatment plants are sent to landfill. Residual flows as the ashes and the slag formed during the operation of the ERP are also landfilled.

2.2. Environmental evaluation methodologies

The results from the application of the environmental evaluation methodologies are reported in several ways, as most convenient for the analysis: total flows in the EMFA, global EF for the overall IWMS, relative EF for the overall IWMS related to 1 kg of wastes treated at LIPOR and individual EFs for the waste treatment processes at LIPOR reported to 1 kg of wastes specifically treated at each plant.

Due to the lack of information readily available, the processes of transportation, the wastewater treatment, as well as the processes associated with the recently implemented biogas plant, were not considered in the analysis. In the following the reasoning behind these exclusions are identified. Transportation is usually identified as relevant in environmental assessments. However, the main objective of the current work was specifically the appraisal of the waste treatment processes and the transportation of the incoming materials is not of a direct responsibility of LIPOR. Despite that fact, the recognition, from an environmental point of view, of the relevance of the circuits used in wastes collection identifies them as to be assessed in a follow-up work. In respect to the wastewater treatment, currently all the effluents are sent to the municipal wastewater treatment plant. The amount generated, mostly referring to the leaching occurring in the landfill, is low (around 15,000 $m^3\ y^{-1}$) and therefore considered to be negligible. At last and concerning the plant for the valorization of biogas, this unit is still in an experimental phase. There are records of energy production since 2009 and they show that the amount of energy produced by this unit has a share of about 2% of the electricity generated in the ERP. Consequently, although considering having an environmental benefit, the contribution is here considered to be negligible when compared to the energy valorization process.

2.2.1. Modeling in Umberto®

The different processes that compose the system were modeled using the software Umberto® 5.5, developed by ifu - Institute for Environmental Informatics Hamburg GmbH and ifeu - Institute for Energy and Environmental Research Heidelberg Ltd. Umberto® allows calculating and visualizing material and energy flows (Wohlgemuth et al., 2006). Hence, a preliminary perspective of LIPOR's performance could be obtained based on an energy and material flows analysis.

The main elements used to construct the models with Umberto® are transitions, places and arrows (Fig. 2). Transitions indicate the location where a material or energy transformation occurs. A place is a site where material and energy are stored or distributed. There are four different types of places: input and output, which determine the boundaries of the network; storage, to store materials; connection, for the distribution of flows; port, that link two network layers. Finally, the arrows connect places and transitions and show the direction of the flow (ifu and ifeu, 2005).

The global IWMS of LIPOR was modeled in the main network, while the specific waste treatment facilities (namely, the ERP, CP and landfill) were included as subnets. Sankey diagrams were used to better visualize the flows. These are flow charts in which the width of the arrow is proportional to the flow quantity providing a graphical analysis of the distribution of energy and material flows in a network.

2.2.2. Ecological footprint

The EF determines the space required to support an activity by means of the area needed to provide the resources consumed and to absorb the wastes generated (Wackernagel and Rees, 1996). In this case, the component method was applied and the mutually exclusive use of land approach was adopted (Monfreda et al., 2004). The component method implies that individual EFs are calculated for each flow (V_i) in the inventory data (in a yearly basis) following Eq. (1). These are later aggregated, according to Eq. (2).

$$\mathrm{EF}_i = \sum_j \frac{V_i}{\mathrm{NP}_i} F_j + \sum_j \frac{\mathrm{EV}_i}{\mathrm{EP}_i} F_j \quad (1)$$

$$\mathrm{EF} = \sum_j \mathrm{EF}_i \quad (2)$$

EF_i is the area required for the component i; NP_i, EV_i and EP_i are, respectively, the natural productivity, embodied energy and energy productivity for component i; F_j is the equivalence factor for land type j. Equivalence factors translate a specific land type (i.e. cropland, pasture, forest, fishing ground) into a universal unit of biologically productive area, generally a global hectare -gha- (Kitzes et al., 2007). Those flows that imply the demand of resources from nature contribute positively to the EF and they constitute the gross EF. However, there are other activities that may reduce the net impact on the environment like the recycling of materials or the energy recovery. These account for the so called counter footprint (CF). Consequently, the net EF associated with an activity is calculated by Eq. (3).

$$\text{Net EF} = \text{Gross EF} - \text{CF} \quad (3)$$

Two main terms are considered for the CF. As discussed by Rigamonti et al. (2009), it is important to properly define the assumptions regarding the material and energy recovery because these may significantly alter the results. In this respect, the electricity generated in the ERP was considered to substitute an equivalent amount of energy from the national grid. Regarding the compost produced in the CP, it was assumed to avoid the production of conventional manufactured fertilizers (Simmons et al., 2006).

The flows (or components) considered to determine the EF are presented in the Tables A.1 to A.5 from the Appendix. The Eqs. [1–3] can only be used to estimate the EF of material and energy flows, as discussed in previous works (Herva et al., 2011, 2012). In addition

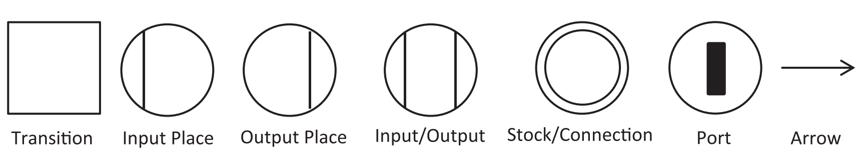

Fig. 2. Main elements used to build flow networks in Umberto®. A general representation is used for 'port' places. These can take the form of any of the other types but with a solid rectangle inside.

and to estimate the EF of final residual flows (as batteries, cartridges and toners listed in the Table A.5) not treated internally at LIPOR the model developed by Herva et al. (2010) was used. The EF for these wastes is calculated by using Eq. (4).

$$EF_{wastes} = EF_{electricity} + EF_{carbon\ emissions} - CF_{slag} \quad (4)$$

where, EF_{wastes} is the total EF estimated for the waste flow being treated in the plasma process; $EF_{electricity}$ is the contribution from the net electricity balance between the electricity consumed by the plasma torch and the electricity generated in the cogeneration unit where the syngas is combusted; $EF_{carbon\ emissions}$ calculates the area required to absorb the CO_2 released in the combined cycle and CF_{slag} is the Counter Footprint associated with the slag production (recovery of inorganic material avoiding the extraction and manufacture of new raw materials). Each of these terms depends on the carbon content of the wastes being treated.

Equivalence factors (F_j) for 2007 were used in the estimation of the EF (Ewing et al., 2010). The energy productivity factors were (EP_i) taken from Coto-Millán et al. (2008) and the embodied energy values (EV_i) considered are from Simmons et al. (2006). The Portuguese electricity consumption mix sources in 2009, collected in Table A.6, were considered in the estimation (ERSE, 2009).

2.2.3. *Benefits and drawbacks of the joint application of EMFA and EF*

The modeling in Umberto of the IWMS operated by LIPOR allows tracking all the energy and material flows occurring in the different waste treatment processes and the inter-connections among them. This offers a detailed analysis that is generally considered as a previous step to any environmental impact assessment method. The EMFA facilitates the identification of likely missing flows in the inventory so that they can be completed by introducing secondary data or by modeling equations.

Furthermore, the later application of the EF permits summarizing the environmental impact of a process into a single indicator that can be easily interpreted and compared. This is the major benefit of this methodology with respect to LCA, which handles a series of indicators more difficultly understandable and usable for communication purposes.

However, there are aspects that still cannot be properly evaluated by the EF, like emissions other than CO_2 (Herva et al., 2012). This is a drawback with respect to LCA; nevertheless, the joint application with EMFA in this case study partially permits to overcome this problem by maintaining the simplified approach proposed.

3. Results and discussion

3.1. *Energy and material flow analysis based on Umberto®*

The global network used to model the IWMS of LIPOR and the interconnections among waste treatment plants is presented in Fig. 3. The right side of this figure presents the additional process referred to as general activities, added to complete the network. For the main network, the Sankey diagram is used for the material flow analysis. The ERP, CP and landfill were included as subnets (Fig. 4). Despite the fact that the scenario for the year 2010 is used as example to discuss the results, no large differences occur in the energy and material flows for the different operating years of the period analyzed. For the sake of clarity in the analysis, only three main groups of materials were selected, namely, the materials consumed (e.g., pallets, big bags, chemicals), the solid waste flows (diverted to the different waste treatment plants) and the materials recovered for recycling (e.g., ferrous materials) or as compost.

The main flow in Fig. 3 presents the waste streams treated at LIPOR. The majority of the wastes collected are directly sent to the ERP (the amount equals 74% in average for the period studied). This is the situation in cities like Porto and Lisbon, where the majority of wastes are thermally treated. However, the picture at the national level is quite different and the landfilling is the preponderant waste management alternative (Magrinho et al., 2006; Vilão et al., 2012). The figures for 2011 indicate that 58% of the MSW produced in Portugal were landfilled, 20% were energetically valorized, 14% were sorted for recycling and 9% were sent to organic valorization processes (Vilão et al., 2012). The European Environmental Agency reports similar tendencies, with a 19% increase in the recycling rate since 2001 to 2010, mainly because of an increase in material recycling (EEA, 2013). However, it is recognized that Portugal still

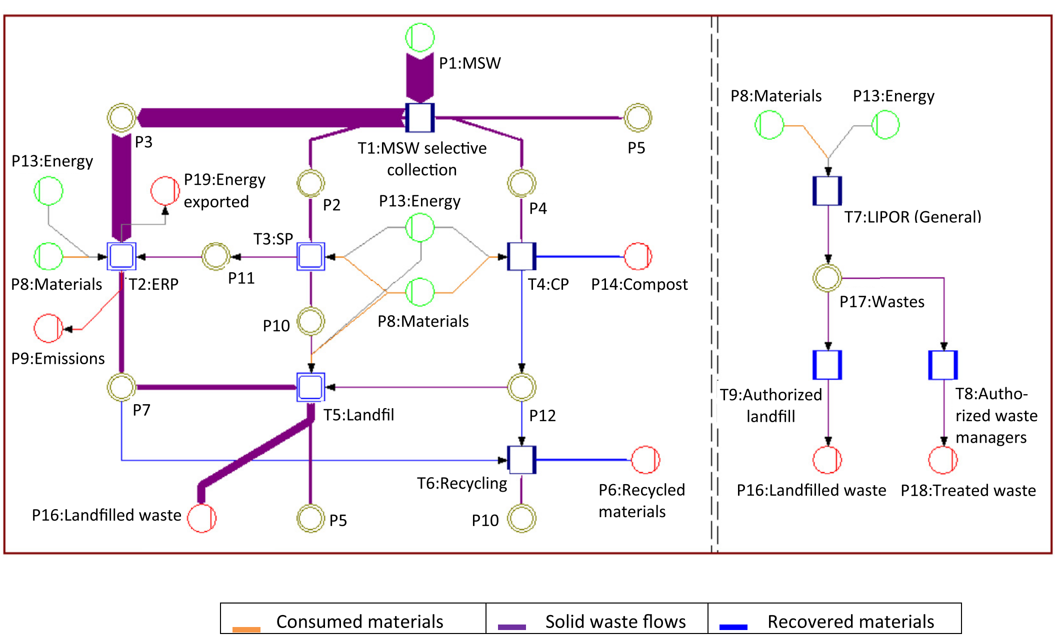

Fig. 3. Sankey diagram presenting the material flows for the LIPOR's network for 2010 modeled in Umberto®.

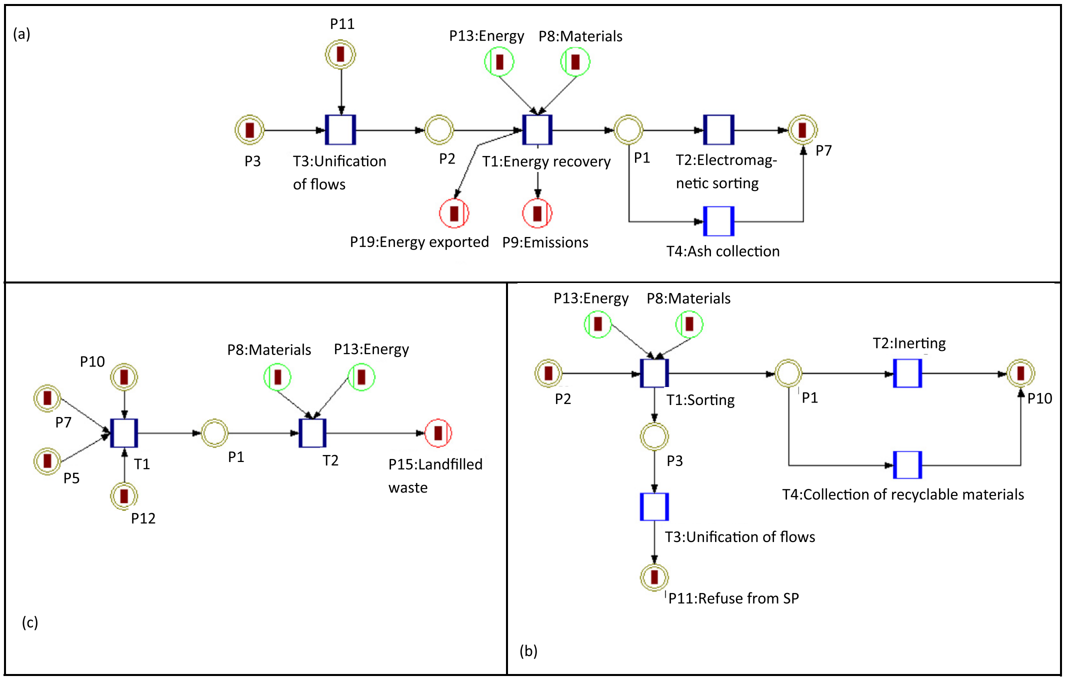

Fig. 4. Subnets from LIPOR's main network for 2010 modeled in Umberto®: (a) Energy Recovery Plant; (b) Sorting Plant; (c) Landfill.

needs to make further efforts to fulfil the 50% recycling target of the Waste Framework Directive by 2020.

After an additional selection carried out at the SP, part of the wastes are sent to the ERP while others are sent to the landfill for their final disposal, together with rejects from the ERP and CP. This means that most of waste streams are treated internally. There are five net output flows, namely, air emissions (P9), energy exported to the network (P19), compost (P14), recycled materials (P6) and waste streams treated externally (P18). Among the five output flows mentioned, the energy sent to the national electricity grid, the compost and the recycled materials (ferrous materials, scraps and light wastes) are valuable and they will contribute to the counter footprint (CF) in the EF assessment. The internal waste flows that are finally disposed in the landfill (P15) are also represented as an output flow in Fig. 3. This had to be done due to operational reasons in Umberto®; however, given that the landfill is part of LIPOR, they are not considered as net outputs from the system.

On the other hand, Fig. 5 shows the energy flows in the main network. Four types of energy sources were employed, namely,

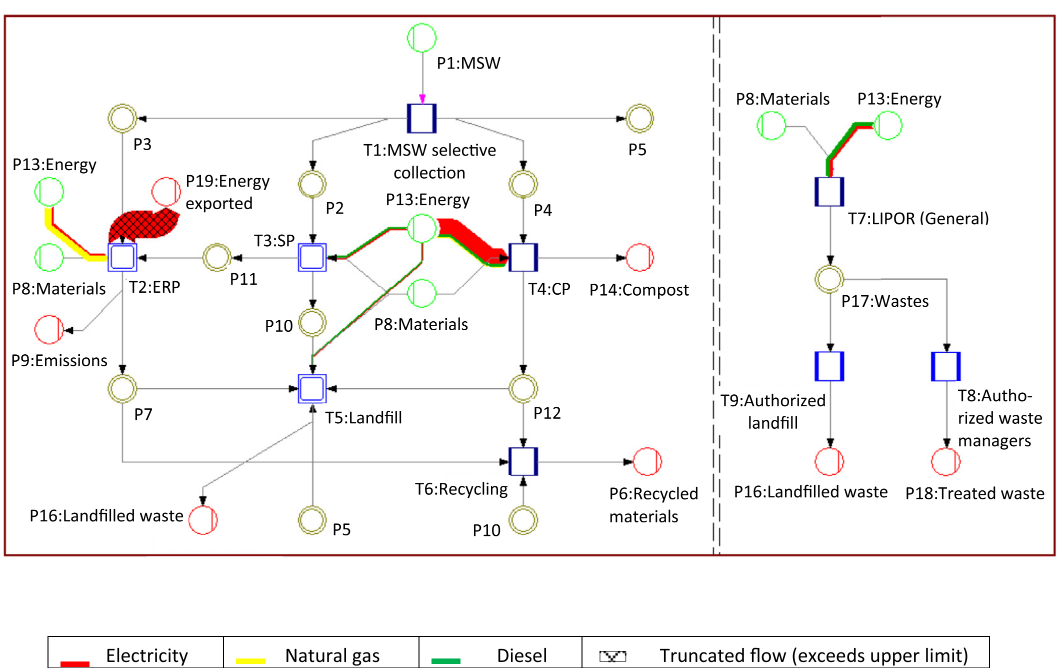

Fig. 5. Sankey diagram presenting the energy flows for the LIPOR's network for 2010 modeled in Umberto®.

electricity, natural gas, diesel and gasoline. The electricity added to the national electricity grid network resulting from ERP (named as energy exported in Fig. 5) represents the most important energy flow at LIPOR, largely exceeding the energy demands from the LIPOR system. In fact, this flow is scratched in Fig. 5 because it exceeds the upper limit (maximum is 30 GJ) established for the Sankey scaling. The reason for that was to make the other contributions visible in the presented network. Despite that, the value for gasoline consumption, which only occurs in the general activities, was small to be presented in the diagram. The CP was identified as the most energy consuming process at LIPOR. This may be mainly due to the energy consumption during the aeration of the composting piles. At the end it is important to refer that the data provided by the company in this respect might have a significant level of uncertainty. This is because it was estimated based on the global values for energy consumption registered for the overall administrative buildings.

3.2. Results for the EF assessment

As an average for the period analyzed, the global EF for the IWMS was $-25{,}780 \pm 5865$ gha (global hectares), while the relative EF was -0.49 ± 0.12 $gm^2\ kg^{-1}$ (global square meters per kg of waste). The results per year are presented in Fig. 6. The negative value means that, in terms of the EF, the global system is environmentally beneficial because of the recovery of resources such as the compost and electricity; i.e., the counter footprint exceeds the gross EF. A worse overall performance for 2008 was observed. This was mainly due to the greater value of the gross EF. A detailed analysis of the energy and material flows in the IWMS allows identifying that the reason that explains this variability is the consumption of paper in the administrative buildings. For instance, in 2008, 4019 kg of white paper were consumed, while the consumption in 2010 was 529 kg. The difference can hardly be explained based on operational reasons and may be due to errors in data collection.

A similar effect, although not so relevant, is observed for 2009 because of the same reason.

Among the aspects excluded from the analysis (section 2), the transportation of wastes to the treatment plants, together with the collection, could be the most relevant. An estimate of its likely contribution was done under a worst case scenario in which all wastes are transported the longest possible distance, i.e. 30 km. For road transport the coefficient of 0.07 ha km^{-1} $(1000\ t)^{-1}$ was considered together with the world-average carbon absorption factor of 0.271 gha tCO_2^{-1} (Niccolucci et al., 2008). With this approach, the estimated EF for the transport of wastes would be around 1119 gha and, therefore, the global EF around −24,661 gha. This means that the contribution is not noticeable and that the global EF is still negative, i.e., environmentally favorable.

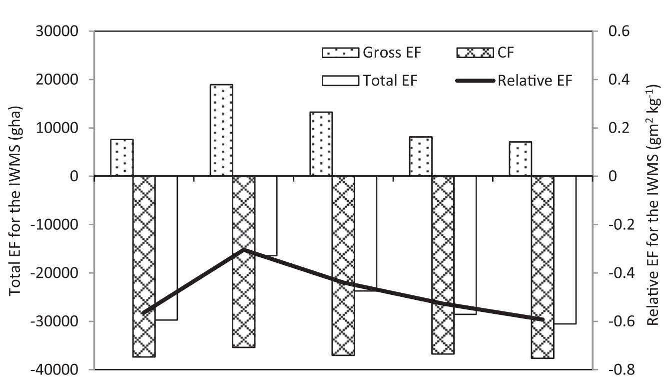

Fig. 6. Total and relative (related to the total wastes treated at LIPOR) EF estimates for the overall IWMS at LIPOR.

The results in Fig. 7 correspond with the assessment of the performance of the individual treatment plants at LIPOR. The relative EFs here are related to the amount of wastes specifically treated at each of them. The three main terms that compound the gross EF (energy, materials and waste flows not treated internally at LIPOR), the CF and the net EF are specified. Regarding the gross EF, the CP presents the largest values for the period considered being the largest contribution due to the energy consumption. However, it is important to refer that this value was estimated based on the overall energy consumption in several buildings, thus it is particularly characterized by uncertainty. The second largest value for the EF is associated with the general activities. This is mainly due to the materials use and particularly the consumption of paper. The built area of the different facilities was not taken into account in the calculations.

The results for the CP show it as having the major contribution in terms of CF associated with the avoided impact due to the production of a stabilized organic matter used as soil amendment. Actually, LIPOR commercializes this fertilizer so-called Nutrimais (LIPOR, 2013). The CF (averaged value is -1.51 ± 0.10 $gm^2\ kg^{-1}$ of waste composted for the period analyzed) largely exceeds the gross EF (0.28 ± 0.02 $gm^2\ kg^{-1}$ of waste composted) and, consequently, results in a negative value for the net EF. This means that the CP has an overall good performance in terms of ecological footprint. The ERP also conveys an important contribution to the CF due to the electricity exported (averaged value is -0.78 ± 0.01 $gm^2\ kg^{-1}$ of combusted waste), apart from presenting the lowest gross EF (averaged value is 0.05 ± 0.01 $gm^2\ kg^{-1}$ of combusted waste) among all the treatment facilities. Therefore, the composting and the incineration with energy recovery plants appear as very environmentally beneficial waste treatment alternatives at LIPOR.

The EF of independent MSW treatment processes was evaluated in a previous work published by the authors. The following scenarios were evaluated, where each option treats all the waste flows: 1) landfilling with energy recovery, 2) incineration with energy recovery, 3) biological treatment of the organic fraction (OFMSW) with energy recovery from the refuse derived fuel and 4) thermal plasma gasification. The EF figures obtained were, respectively, 13.2, 4.9, 3.3 and 3.4 $gm^2\ kg^{-1}$ MSW (Herva and Roca, 2013a). The positive calculated results were larger than the EF calculated for the waste treatment processes occurring at LIPOR. Therefore, it could be concluded that an integrated waste management system is more beneficial from an environmental point of view, so that each type of waste conducts the most appropriate treatment process. Huijbregts et al. (2008) also calculated the EF of a number of processes available in the Ecoinvent database v1.2, some of them belonging to the category of incineration (73 cases), landfill (113 cases) and recycling (28 cases). The order of magnitude of the EF values was in the range of that obtained in Herva and Roca (2013a), being 5 $m^2\ kg^{-1}$ for incineration and around 0.05 $m^2\ kg^{-1}$ for landfill and recycling.

Finally, it is important to remark that, because the EF methodology does not evaluate air emissions other than CO_2, the emissions reported by LIPOR for the ERP (Table A.3) were excluded from the analysis. Nevertheless, the exhaust gases follow a controlled cleaning process that minimizes the exit of dangerous substances and that comply with legal restrictions. Air emissions are also generated during composting; however, this process occurs in a closed building where the air is treated in biofilters.

The water used in the different waste treatment plants is analyzed independently (Fig. 8) because it is not adequately assessed by the EF methodology. Although freshwater is a natural resource cycled through the biosphere, the EF of a given quantity of

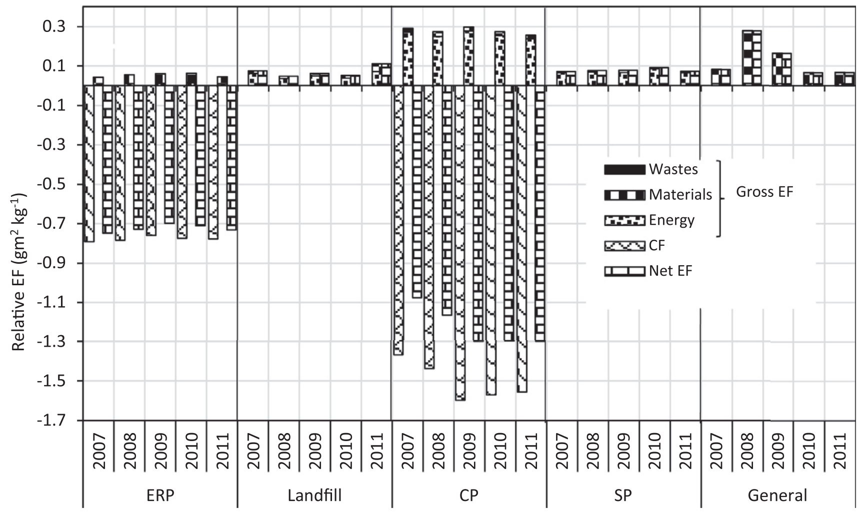

Fig. 7. Relative EF estimates for the four waste treatment processes and general activities of LIPOR, namely Energy Recovery Plant (ERP), Landfill, Composting Plant (CP), Sorting Plant (SP) and the general activities.

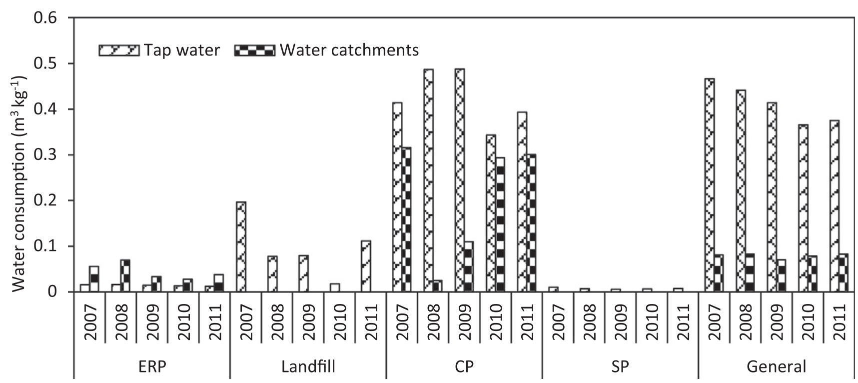

Fig. 8. Water uses at the different plants of LIPOR, namely Energy Recovery Plant (ERP), Landfill, Composting Plant (CP), Sorting Plant (SP) and the general activities.

water is not calculated having as basis yield values as it is in the case of crop or wood products. Hence, the footprint associated with water is usually reported as the volume of water consumed or the EF required for a utility to provide a given supply of water (Kitzes and Wackernagel, 2009). In the case study, tap water is the main source of water, but ground level water is also used at ERP, CP and in the general activities. The ERP has the larger water requirements (see Table A.3). Despite this, the water is recirculated in the process and the losses are in general below 3%. Hence, Fig. 8 shows the real net water consumption in the ERP (as well as for the other waste treatment processes evaluated). Results demonstrate that the CP is the larger water consumer when the consumption is reported to the mass (kg) of waste treated by this facility. The reason that can explain these results is that moisture content is carefully monitored during the composting processes. The water content of most feedstocks is not adequate or losses may occur during the decomposition process (e.g. evaporation). Due to that it is necessary the addition of water for an adequate composting process (Blengini, 2008; Cadena et al., 2009). Large quantities of water are also used in the general facilities at LIPOR.

4. Conclusions

This paper evaluated the environmental performance of the waste treatment plants included in the IWMS of LIPOR, namely the Sorting Plant (SP), Composting Plant (CP), Energy Recovery Plant (ERP) and landfill, with a combined use of EMFA and EF. The modeling of the IWMS in Umberto® facilitated the visualization of flows and the interconnections among processes. In addition, it was helpful in detecting missing data.

Based on the indicators derived, the general conclusion was that the environmental gains of the IWMS were higher than the environmental impacts. This is due to the fact that the recovery of energy from the ERP and the compost obtained from the valorization of the organic wastes (i.e., the counter footprint) largely compensated the gross EF of the waste treatment processes. This results in that an IWMS seems to be more beneficial from an environmental point of view.

The results concerning the EF for the composting plant revealed that it has a relatively larger contribution to the environmental impact when reported to the amount of waste treated. However, this impact was largely compensated by the environmental benefits associated with the compost obtained, translated into a large contribution to the counter footprint and, as a consequence, yielding a negative net EF.

The results from the EF for the ERP show it as very beneficial due to the low gross EF and the large counter footprint. This is a similar situation to that of the CP. In this case, the counter footprint is associated to the excess of electricity generated in the ERP and that is exported to the national grid. However, this conclusion must be considered cautiously given the fact that the environmental impacts associated with the air pollutants released during ERP activities were not evaluated by the EF. In this regard, emissions like dioxins or hydrogen fluoride can promote particular concerns and the identification of mitigation measures.

There were some limitations related to data availability associated with the processes occurring at the IWMS of LIPOR, as for example the biogas valorization, the wastewater treatment and the transportation. Despite these limitations, the comparison of EF results with literature values for MSW treatment processes (not belonging to an IWMS) allows us to conclude that the figures obtained are in the same order of magnitude. Nevertheless, it is important to remark that, to the author's knowledge, there are no antecedents in calculating the EF of an IWMS and, therefore, it can serve as reference to compare the results of this work with other IWMS worldwide.

EMFA and EF methods seem to be complementary to adequately evaluate the environmental performance of the treatment processes taking place at an integrated urban waste management system. In doing so, the methodological drawbacks of the indicators employed could be overcome by taking advantage of their complementary approach. The use of these evaluation processes can even become an important tool for planning future facilities and waste management strategies to be more efficient and environmental friendly.

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Appendix

Table A.1
Inventory data for the Sorting Plant (LIPOR, 2007–2011).

	2007	2008	2009	2010	2011	Units
Input flows						
Separated recyclable wastes	49,884	55,470	59,966	58,591	55,153	t
Raw materials						
Wire	47.3	70.7	109.3	57.1	69.0	t
Water						
Tap water	514	386	376	376	415	m^3
Energy						
Natural gas	90	92	144	152	117	GJ
Diesel	2905	3452	3590	2877	3157	GJ
Electricity	1713	1957	1924	1986	1870	GJ
Output flows[a]						
Refuse from platform (to ERP)	n.a.	5141	6465	6630	n.a.	t
Paper and cardboard (to ERP)	1211	1095	719	947	119	t
Packages (to ERP)	580	432	489	759	564	t
Fine material (to ERP)	456	581	541	466	851	t
Pre-screening (to ERP)	1049	1137	1292	1543	1478	t
WEEE[b] (to ERP)	n.a.	72.7	58	85.3	n.a.	t
Concentrated particles from the sleeve filters (to be made inert)	640	900	1060	1140	240	t

[a] Note that only the outputs form the SP that are further treated at LIPOR are indicated here. The remaining materials are sent to third-party recycling facilities.
[b] These are small appliances and other small WEEE that arrive to the SP in the packaging or paper containers (wrongly sorted). It's not the ones deposited at the eco-parks (fridges, washing machines, etc.).

Table A.2
Inventory data for the Composting Plant (LIPOR, 2007–2011).

	2007	2008	2009	2010	2011	Units
Input flows						
Separated organic wastes	30,730	37,146	42,215	47,308	46,140	t
Raw materials						
Pallet	50.0	92.8	106.8	64.4	42.6	t
Packaging plastic	11.1	7.0	2.2	20.0	25.7	t
Big bags	0.6	2.9	1.9	2.7	n.a.	t
Water						
Tap water	12,725	18,082	20,596	16,237	18,144	m^3
Water catchments	9718	938	4643	13,898	13,893	m^3
Energy						
Natural gas	996	900	1106	999	1227	GJ
Diesel	2339	2728	3255	3482	3120	GJ
Electricity	11,522	13,269	16,550	16,927	15,230	GJ
Output flows						
Compost produced	5667	7200	9097	10,027	9686	t
Air emissions						
CO_2 equivalent[a]	5001	6575	7472	8374	8167	t
Sub-products						
Ferrous materials (recycling)	19	19	29	25	49	t
Light wastes (recycling)	475	555	646	1170	51	t
Heavy wastes (landfilling)	1041	234	351	2726	n.a.	t

[a] The CO_2 equivalent was extracted from previous carbon footprint estimates of LIPOR. The different greenhouse gases are converted into their CO_2 equivalent by considering their global warming potential. These only include the fossil emissions, not the biogenic CO_2.

Table A.3
Inventory data for the Energy Recovery Plant (LIPOR, 2007–2011).

	2007	2008	2009	2010	2011	Units
Input flows						
Non-differentiated waste	419,389	383,553	398,392	378,693	392,140	t
Chemicals						
Hydrated lime	4331	4001	4337	4581	4268	t
Urea	1531	1540	1808	1685	1299	t
Activated carbon	183	179	193	147	145	t
Caustic soda	n.a.	43	38	30	21	t
Hydrochloric acid	n.a.	45	44	35	26	t
Tripolyphosphate	n.a.	0.6	0.7	0.5	0.6	t
Water						
Tap water	6734	6360	5911	5351	5078	m^3
Water catchments	23,484	26,812	13,368	11,060	15,141	m^3
Energy						
Natural gas	2373	5641	4625	7014	4963	GJ
Diesel	56	90	93	158	55	GJ
Electricity	348	1009	3180	2700	1089	GJ
Output flows						
Energy exported	183,079	165,948	167,072	161,725	168,176	MWh
Air emissions						
HCl	8630	6562	6830	6546	6269	kg
NO_x	286,000	222,898	264,165	273,483	280,348	kg
HF	433	145	325	466	280	kg
SO_2	8570	9398	9482	8831	10,675	kg
Particulates	4140	2532	2563	1778	1551	kg
CO	8559	9736	16,220	15,616	12,364	kg
Dioxins and furans[a]	$9.6\cdot10^{-6}$	$1.2\cdot10^{-5}$	$3.1\cdot10^{-6}$	$1.0\cdot10^{-5}$	$3.7\cdot10^{-6}$	kg
CO_2 equivalent[b]	235,778	202,018	209,829	199,454	206,537	t
Sub-products						
Ash (to landfilling)	32,364	30,037	30,482	29,748	29,790	t
Slag (to landfilling)	76,606	72,798	75,872	73,105	75,055	t
Ferrous scraps (to recycling)	5425	4554	4265	5499	5854	t

[a] Note: unlike the other air emissions released at the ERP that are continuously monitored, dioxins and furans are only determined twice a year because of technical limitations.
[b] The CO_2 equivalent was extracted from previous carbon footprint estimates of LIPOR. The different greenhouse gases are converted into their CO_2 equivalent by considering their global warming potential. These only include the fossil emissions, not the biogenic CO_2.

Table A.4
Inventory data for the sanitary landfill (LIPOR, 2007–2011).

Input flow	2007	2008	2009	2010	2011	Units
Landfilled waste	27,185	63,308	39,339	57,835	21,399	t
Chemicals						
Sulfuric acid	9.1	4.2	9.8	6.0	3.3	t
Acetic acid	4.3	6.5	13.1	22.8	8.6	t
Soda	26.4	57.4	28.3	47.2	74.4	t
Antifoam	508	495	555	293	290	L
Water						
Tap water	5347	4944	3122	1033	2389	m^3
Energy						
Diesel	1126	1957	1298	1760	943	GJ
Electricity	1495	1496	1728	1559	1528	GJ
Air emissions						
CO_2 equivalent[a]	183,404	176,027	167,287	160,566	145,069	t
Biogas	n.a.	n.a.	369,387	194,507	260,711	m^3

[a] The CO_2 equivalent was extracted from previous carbon footprint estimates of LIPOR. The different greenhouse gases are converted into their CO_2 equivalent by considering their global warming potential. These only include the fossil emissions, not the biogenic CO_2.

Table A.5
Inventory data for the general activities taking place at LIPOR (2007–2011).

Input flow	2007	2008	2009	2010	2011	Units
Raw materials						
White paper	1547	4019	2960	529	710	kg
White stationery	0	521	n.a.	307	145	kg
Recycled paper	1197	4032	2948	2025	2220	kg
Recycled stationery	0	7173	1646	788	100	kg
Water						
Tap water	2813	2756	2435	2327	2548	m^3
Water catchments	19,463	17,912	24,702	17,554	13,718	m^3
Energy						
Natural gas	126	181	246	334	421	GJ
Diesel	5260	5383	5144	4977	5942	GJ
Gasoline	n.a.	317	251	214	140	GJ
Electricity	2937	3003	3139	3203	2918	GJ
Wastes (managed by authorized companies)						
Mineral oil	7400	10,200	9300	11,600	12,900	L
Oily water	1000	5500	10,500	12,000	9900	L
Vegetable oil	375	755	1130	1280	1245	kg
Sawdust and rags with oil	41	n.a.	n.a.	n.a.	80	kg
Contaminated packaging	5240	8800	3181	9980	4460	kg
Non-rechargeable batteries	27,260	28,500	31,160	19,740	16,120	kg
Rechargeable batteries	56,000	36,900	34,680	17,060	6400	kg
Syringes	63	93	107	80	78	kg
Other urban or similar	n.a.	n.a.	n.a.	n.a.	94	kg
Cartridges and toners	580	1260	305	500	200	kg
Fluorescent lamps	n.a.	n.a.	19,340	16,540	11,200	kg
Tires	n.a.	3260	6440	2880	3280	kg

Table A.6
Electricity mix for Portugal in 2009 (ERSE, 2009).

Energy source	Contribution (%)
Fossil	
Carbon	17.85
Natural gas	34.40
Fuel oil	1.46
Nuclear	5.95
Cogeneration	8.29
Renewable	
Hydro power	16.44
Wind power	13.75
Other	1.86

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