LCA of MSW Management. The Environmental Impacts of Wrong Choices

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Abstract

The management of municipal solid waste (MSW) is currently one of the most serious and controversial issues faced by the local and regional authorities of a country. The member countries of the European Union (EU) are required to propose waste management systems that comply with the hierarchy of options, based on the following order of priority: prevention (in waste generation), preparing for reuse, recycling, other types of recovery (including energy) and, finally, the disposal of waste. To demonstrate the performance of management alternatives in the decision-making process, authorities, communities, industry and waste management companies should consider environmental aspects in addition to the evaluation of technical and economic aspects. Life Cycle Assessment (LCA) has been demonstrated to be a suitable tool for evaluating waste management systems, although its performance strictly depends on the detailed knowledge of the state of the art and on the "localness" of data used. This paper summarizes the main results of the application of LCA methodology to the MSW management system currently adopted in Naples (Italy), affected in the past years by a waste disposal emergency, not yet completely solved. The main streams of MSW generated in Naples are assessed in terms of their environmental impacts and a general picture of the management system is drawn through a detailed collection of local data concerning all waste streams' routes and destinations. In such a way, LCA allows the identification of criticalities and bottlenecks of the complex issue of waste management, thus highlighting the effects that wrong choices can generate as a starting point for future improvements.

Keywords: *Waste Management, Life Cycle Assessment, Municipal Solid Waste*

1. Introduction

Waste is increasingly generated by anthropogenic activities worldwide, with overwhelming consequences on environmental pollution, climate change, human health and resource depletion. In particular, Municipal Solid Waste (MSW) is expected to double in the next decade due to population growth, increasing urbanization and socio-economic development of low- and middle-income countries (Karak et al., 2012; Hoornweg and Bhada-Tata, 2012). Different solutions aiming at improved sustainability of waste management systems have been proposed, stemming from waste reduction, life style changes, recycling, conversions and, finally, safe disposal technologies. The member countries of the European Union (EU) are required to implement waste management systems that comply with the hierarchy of options, based on the following order of priority: prevention (in waste generation), preparing for reuse, recycling, other types of recovery (including energy) and, finally, the disposal of waste (Directive 2008/98/EC of the European Parliament and of the Council of 19th November 2008, on Waste).

Life Cycle Assessment (LCA) methodology (ISO, 2006a, 2006b) provides an excellent framework for evaluating waste management strategies: through its holistic perspective in quantifying environmental impacts, it has been demonstrated to help in identifying appropriate solutions for managing solid waste (Ekvall et al., 2007; Blengini et al., 2012; Saner et al., 2012; Laurent et al., 2014a; EU Directive 2008/98/EC). Therefore, LCA is a valuable decision-support tool: to demonstrate the performance of management alternatives in the decision-making process, authorities, communities, industry and waste management companies can consider environmental aspects in addition to technical and economic aspects, by means of LCA. LCA is commonly used to evaluate treatment options for specific waste fractions in several European countries, including Italy (e.g. Buttol et al., 2007; Brambilla Pisoni et al., 2009; Scipioni et al., 2009; Cherubini et al., 2009; De Feo and Malvano, 2009), Spain (Bovea and Powell, 2006; Guereca et al., 2006), UK (e.g. Tunesi, 2011), among others, whereas a limited number of LCA studies refer to waste management systems in the developing countries (Laurent et al., 2014b). In particular, applications of LCA to MSW management were reviewed by Cleary (2009). However when applying LCA to waste management, there are some peculiar aspects that must be considered and assumptions to be undertaken that might affect the results to a large extent (Ekvall et al., 2007; Finnveden, 1999; Merrild et al., 2008; Rigamonti et al., 2010). Detailed applications of LCA to integrated waste management systems are complex and the subsequent analysis necessarily reflects this complexity.

In this paper, LCA methodology was applied to assess the management system of MSW generated in Naples (Southern Italy). Naples was investigated as a representative case-study, since in the last decades the city has struggled with waste management policies and the crisis of waste disposal has not been resolved yet. Political and scientific analyses of the waste crisis indicate that the emergency situation was created by inappropriate waste management policy and practice. Therefore, the aim of this study was firstly to overview the present state of the art and illustrate a clear picture of the currently applied waste management (baseline scenario): the environmental impacts generated by each step of the whole waste management chain were investigated, throughout a detailed collection of local data concerning all waste streams' routes and destinations. Secondly, MSW management possibilities, barriers as well as treatment issues were highlighted to address the development of aware and informed waste management policies intended to continuously improve sustainability.

2. Methods

The methodological framework used in this paper was the LCA as defined by ISO and ILCD standards (International Standard Organization, ISO 14040/2006, ISO 14044/2006, ILCD, 2010). The 'zero-burden waste' approach was assumed, not including the generation of waste (the life cycle of the products before they became waste) (Ekvall et al., 2007). An attributional approach was adopted in order to establish the burdens associated with the system under investigation and, consequently, the local waste management chains were analyzed based on site-specific data, also following waste streams that are partially sent outside the administrative territory. A consequential approach was also implemented, including a system expansion, to account for the environmental benefits coming from the recovery of energy, heat and materials from the assessed system; the environmental consequences and market implications generated by the avoided production of virgin materials and energy were taken into account, considering that the produced electricity substitutes the marginal Italian electricity mix on market scale and that the co-generated heat is used for district heating, agricultural greenhouses and industrial uses. The potential advantages of paper, glass, plastic and metals recycling were also accounted for by considering the avoided production of the corresponding primary goods.

2.1 Case Study: waste management in Naples metropolitan area

Naples metropolitan area is a metropolitan area in Campania Region, Southern Italy. The urban area — core of metropolitan area — has a population of about 3 million people being the 10th-most populous urban area in the European Union. Naples metropolitan area consists of 92 different municipalities (Fig.

1) which differ in some organizational functions, such as the type of separate collection: door-to-door or brig-points-collection.

Index	
Population	3,128,701
Area (kmq)	1,171
Population Density (inhs/kmq)	2,671.82
MSW production (2012) (kg/yr)	1.46E9

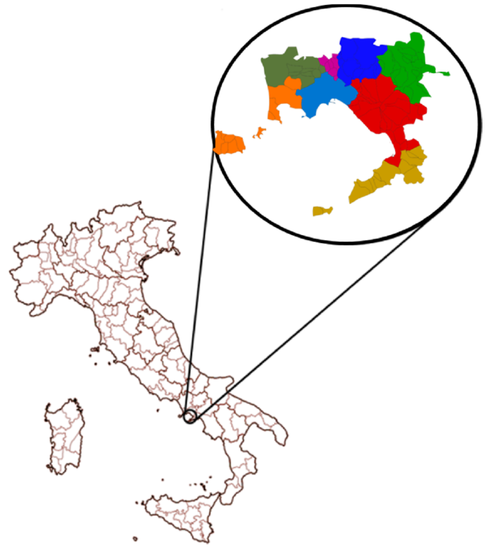

Fig. 1. *Naples location and main characteristics.*

With reference to the total waste production of 1.46E+09 kg/yr, the amounts of different fractions (according to EWC catalogue) collected in Naples metropolitan area in 2012 are reported in Table 1: 9.19E+08 kg of Mixed Municipal Solid Waste (hereinafter referred as MMSW), 4.67E+08 kg of separate collection sent to recycling or organic treatment (including paper and cardboard, glass, plastic, metals and biodegradable fractions), 7.29E+07 kg (representing less than 5% of total waste generation) of 'others' (including batteries, clothes, bulky waste), not accounted for in this analysis due to the lack of reliable data.

Table 1. Waste composition in Naples in 2012.
Source: ARPAC (Regional Environmental Authority), 2012 (Personal Communication)

Waste fraction	Unit	Amount	%
Paper&Cardboard	kg/yr	9.48E+07	6.5%
Glass	kg/yr	4.37E+07	3.0%
Plastic	kg/yr	2.92E+07	2.0%
Metals	kg/yr	1.46E+07	1.0%
Biodegradable	kg/yr	2.84E+08	19.5%
MMSW	kg/yr	9.19E+08	63.0%
Other	kg/yr	7.29E+07	5%

The model of urban waste collection in 2012 was based on a combination of two different methods of source separation, depending on the area and its characteristics. The first is the door-to-door collection, based on partly door-to-door bins (240 L, HDPE) for biodegradable, multimaterial (aluminium, plastic, steel), paper and cardboard, whereas MMSW is collected in kerb-side containers (1100 L, steel) for all households and commercial activities. Glass must be transferred to special bring points where there are green bell shaped bins, textiles must be transferred to special containers, whereas bulk refuse and WEEE are collected on demand. The second method is the bring points collection, based on the collection of waste in street side containers where the public must transfer sorted materials and place them in the correct bins (white containers for paper, yellow containers for multimaterial, green bell shaped bins for glass and grey containers for MMSW). After being collected, the recyclable materials go to recycling and/or sorting platforms in or outside the Region (Fig. 2). In particular, the majority of biodegradable fraction is diverted outside the Region to composting plants (94%) or anaerobic digestion plants (3%). Nevertheless, separate collection fractions are not 100% recyclable and a non-negligible amount of residues is produced, which is disposed of in landfill. MMSW amounts to 63% of total collected waste and only a small percentage (4%) is directly delivered to landfill (Terzigno landfill – Naples), whereas the remaining 96% is initially sent to six Mechanical Biological Treatment (MBT) plants located in Campania Region which generate: (1) a dry fraction (RDF or EWC 191212 according to European Waste Catalogue) which is sent to Waste to Energy (WtE) plants (only partially situated in the Region) for energy recovery or to landfills; (2) a minimal part of metals, that is sent to recycling; (3) a stabilized organic fraction (S.O.F. or EWC 190501), diverted to extra-regional landfills ; (4) wastewater and sewage sludge, sent to waste water treatment (WWT) plant.

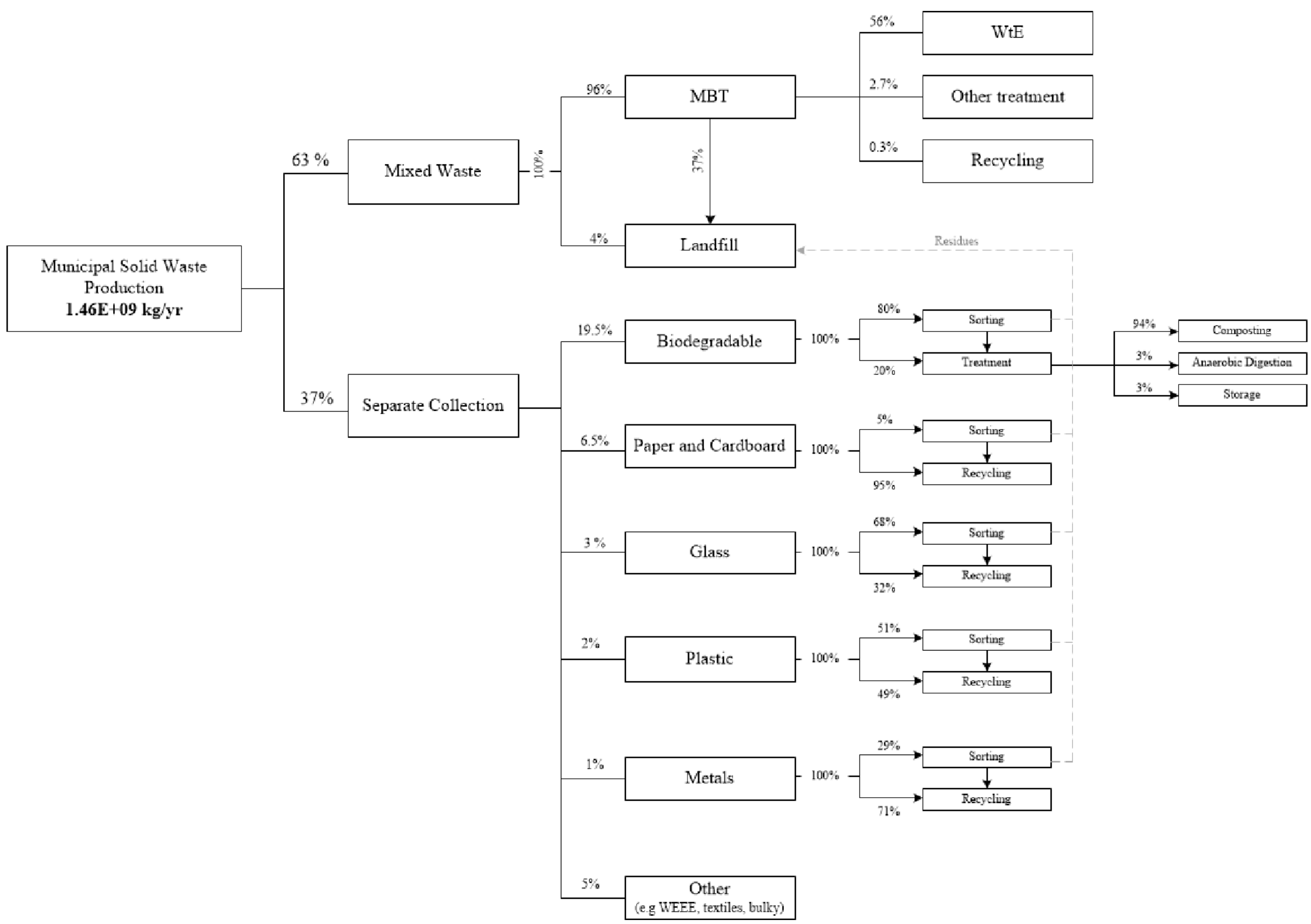

Fig. 2. Schematic flow chart for waste treatment in Naples metropolitan area.

2.1 Goal and scope definition

The aim of this study is to assess the current waste management practices and their associated environmental impacts in Naples using a life-cycle perspective. The functional unit of the study is: collection, transport and treatment of municipal solid waste (hereinafter referred as MSW) produced in Naples metropolitan area in 2012.

2.2 System description and boundaries

It is well known that the choice and the definition of system boundaries is a very important step that can heavily influence LCA results. In this study, an attributional modeling was applied with the aim of taking a picture of the present operating conditions. However, the boundaries of the system are not limited to the physical boundaries of the treatment plants but are extended upstream and downstream to encompass the whole waste chain: from the production of the collection systems (upstream of waste production), to final disposal of residual waste (not further undergo treatment).

In order to identify the bottlenecks, the system was also divided into different "subsystems", intended as a subset of the tasks/processes or a limited sequence of process units (ISO14040) within the full model of the life cycle. The phases of the life cycle considered in this study for each fraction are:

- Collection (including the production of containers/bins);
- Transportation, including all the routes tracked from each single municipality belonging to Naples metropolitan area through all the sorting/treatment steps. This subsystem includes transport from collection points to the respective treatment facilities;
- Processing/treatment of all fractions (including selection/pre-treatment processes, recycling, composting, landfilling, WtE and final disposal of residual flows downstream of waste collection). In particular, based on local data, different types of treatment were modelled:
  - Biodegradable fraction is, directly or indirectly, delivered to composting (94%) or anaerobic digestion (3%). When dealing with the consequential approach, N, P and K fertilizers were assumed as avoided products, since substituted by produced compost (Blengini et al., 2008), whilst electricity and heat were assumed to be recovered in the anaerobic digestion process with efficiencies of 32% and 55% respectively (Ecoinvent, 2014);
  - Paper collected is firstly selected with a loss of about 8% of input amount, then delivered to pulping and deinking process. In the consequential analysis, sulphate pulp was considered as avoided product (Ecoinvent, 2014);
  - Glass is firstly selected with a loss of about 8% of input amount, then delivered to a process of fusion to obtain virgin glass. In the consequential analysis, packaging white glass was considered as avoided product (Ecoinvent, 2014);
  - Mixed plastics are firstly selected with a loss of 25% and then PE and PET are sent to recycling. The production of a mix of virgin plastics was considered to be avoided thanks to the recycling treatment (Ecoinvent, 2014);
  - Metals, assumed mainly as steel and aluminum, are primarily sent to mechanical treatment with a loss of 9% and then delivered to a furnace to obtain secondary metals. In the consequential analysis, pig iron was assumed as avoided product (Ecoinvent, 2014);
  - MMSW is sent, directly or indirectly, to landfill or WtE, the latter allowing the recovery of heat and electricity with conversion efficiencies of 26% and 13%, respectively (Ecoinvent, 2014) and assuming an average Lower Heating Value (LHV) of 10 MJ/kg (Reimann, 2012).

2.3 Life cycle inventory

Input and output data for each stage have been obtained from different sources. Primary local data were provided from ARPAC (Environmental Regional Authority in Campania Region). Raw data concerning waste production and collection, distances, local treatments were collected and further processed and modelled. Collection and transport of waste by compactor truck is based on Ecoinvent Municipal waste collection truck service (where adjustment factors for Stop&Go driving are also included with consequent adjusted emissions). Material recycling processes are modelled with processes from the Ecoinvent database. Residues from source separation and loss during recycling are sent to landfill, according to the precautionary principle. The avoided production of virgin materials (avoided primary production from recycling, fertilizers from composting, etc) is credited to the waste management system in the consequential approach. Emissions from MMSW treatments were modelled with reference to MMSW composition in Naples. Capital goods, infrastructures and related environmental impacts were also included in the analysis. Background data over the supply chain of energy and materials were derived from the databases available within the LCA software SimaPro 8.1, in particular the Ecoinvent Unit Processes library v.3.1, which comprises complete upstream processes (e.g., energy supply and raw materials extraction), including infrastructures (e.g., means of transportation or pipelines). For electricity, the reference was to the Italian production mix of medium voltage electricity (Ecoinvent v.3.1, 2014). All the values were referred to the functional unit.

2.4. Life cycle impact assessment

LCIA was performed by means of the LCA software SimaPro 8.0.3.14. Among the impact assessment methods, the ReCiPe Midpoint (H) v.1.10 (http://www.lcia-recipe.net/) was chosen, considering that it includes both upstream and downstream impact categories, among which fossil depletion (Frischknecht et al, 2007). Moreover, the ReCiPe Midpoint (H) method allowed to assess the environmental impacts on different impact categories of interest in waste management (e.g. global warming, abiotic depletion, acidification, eutrophication). The ReCiPe method provides both characterization factors to quantify the contribution of processes to each impact category and normalization factors to allow a comparison across categories (Europe ReCiPe Midpoint (H), 2000, revised 2010) (Wegener Sleeswijk et al., 2008). Normalization is a life cycle impact assessment tool used to express impact indicator (characterized) data in a way that can be compared among impact categories. This procedure normalizes the indicator results by dividing characterized values by a selected reference value. There are numerous methods of selecting a reference value, including, for example, the total emissions or resource use for a given area that may be global, regional or local. Even if the normalization step is not mandatory in LCA, due to its somehow arbitrary parameterization, it was applied in this study, according to the SimaPro Database Manual (Methods library), in order to compare the relative impacts on the different categories generated by the investigated system.

In this study, the following categories were explored: Global Warming Potential (GWP, in kg CO_2 eq), Terrestrial Acidification Potential (TAP, in kg SO_2 eq), Freshwater Eutrophication Potential (FEP, in kg P eq), Human Toxicity Potential (HTP, in kg 1,4-DB eq), Photochemical Oxidant Formation Potential (POFP, in kg NMVOC), Terrestrial Ecotoxicity Potential (TEP, kg 1,4-DB eq), Water Depletion (WD, in m^3), Metal Depletion (MD, in kg Fe eq), Fossil Depletion (FD, in kg oil eq).

3. Results and Discussion

The system under study was assessed in an attributional mode, in order to model physical flows, resources consumption and emissions to the environment with reference to the total amount of waste generated, collected, transported, treated and disposed of in Naples in 2012, as input and output functional units.

Table 2 summarizes the characterized results obtained by applying the ReCiPe Midpoint (H) method to all the waste streams.

Table 2. Characterized impacts calculated for all the waste fractions produced in Naples metropolitan area in 2012 (attributional approach, referred to a functional unit of 1.39E9 kg of waste treated).

Impact category	Unit	Total impact	MMSW	Biodegradable	Glass	Paper	Plastic	Metals
GWP	kg CO_2 eq	1.10E+09	8.00E+08	1.87E+08	7.31E+07	2.66E+07	9.56E+06	1.63E+06
TAP	kg SO_2 eq	3.36E+06	1.84E+06	8.87E+05	4.62E+05	1.22E+05	3.82E+04	9.60E+03
FEP	kg P eq	5.86E+04	3.52E+04	2.88E+03	8.14E+03	1.03E+04	1.42E+03	7.04E+02
HTP	kg 1,4-DB eq	3.61E+08	3.26E+08	4.64E+06	1.41E+07	1.65E+07	-1.21E+06	1.26E+06
POFP	kg NMVOC	6.51E+06	4.21E+06	1.67E+06	4.87E+05	9.41E+04	3.78E+04	1.20E+04
TEP	kg 1,4-DB eq	4.31E+04	2.19E+04	6.95E+03	1.15E+04	1.65E+03	9.17E+02	1.86E+02
WD	m^3	3.34E+08	9.96E+07	2.51E+07	6.71E+07	9.58E+07	4.28E+07	3.12E+06
MD	kg Fe eq	1.64E+07	6.59E+06	1.68E+06	1.91E+06	5.57E+06	2.29E+05	4.44E+05
FD	kg oil eq	2.04E+08	1.22E+08	5.03E+07	2.28E+07	4.91E+06	3.12E+06	4.65E+05

The total impact on GWP category, corresponding to 1.10E9 kg CO_2 eq, depends on MMSW and biodegradable fractions for 73% and 17%, respectively. MMSW results to be the most impacting fraction on all the analysed categories, ranging from 30% in WD up to 90% in HTP, whereas biodegradable fraction shows the main impacts on TAP, POFP and FD, respectively accounting for 26%, 26% and 25% of total impacts. The impacts of glass and paper fractions reach the highest value on TAP and MD, contributing respectively by 27% and 34%. The impact of plastic and metal fractions never overcomes 3% of total impact for each category, except for WD where plastic accounts for 4.28E+07 m^3, corresponding to 13% of the total amount.

If normalized values of impacts are taken into account (Figure 2), according to Europe ReCiPe Midpoint (H) method normalization factors, a comparison across impact categories becomes possible and human toxicity shows the highest value of 5.74E5 (summing up the impacts from all the fractions). Comparable values are reached by FEP, POFP and FD (1.41E+05, 1.15E+05, 1.31E+05, respectively), whereas the WD category is not detectable at all, due to the normalization factor equal to zero. As already pointed out in the characterization analysis, MMSW is the main contributor to all the categories, ranging from 60% to 90% of the total impact. Nevertheless, biodegradable fraction provides a non-negligible contribution to GWP (1.67E+04), TAP (2.58E+04), POFP (2.94E+04) and FD (3.24E+04).

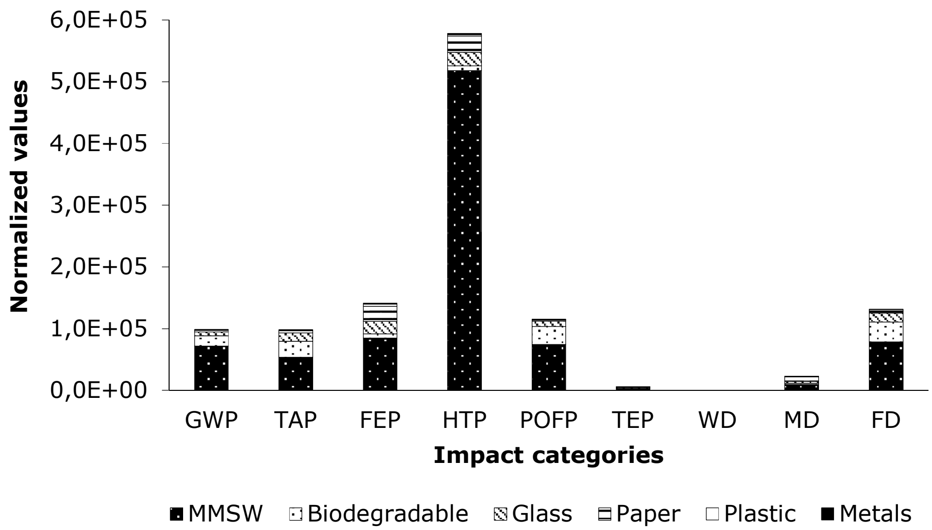

Fig. 2. Normalized impacts calculated for all the waste fractions produced in Naples metropolitan area in 2012 (attributional approach, referred to a functional unit of 1.39E9 waste treated).

Resulting the most impacting waste fraction, a special focus on MMSW is needed and all the phases of its management are shown in deeper detail in Table 3: the impacts associated to collection, metal recycling and WWT stage are negligible in comparison to the impacts of transport and final treatments (landfilling and WtE) on all impact categories. In particular, transportation is the main contributor on GWP, TAP, POFP, TEP, WD, MD and FD, varying between 46% and 95% of the total impact of each single category. Transportation accounts for the 95% of FD total impact, pointing out the critical nature of the MMSW chain. In fact, after a pre-treatment step in Campania Region, MMSW is partially (38%) sent outside the Region (also in Sweden and Netherlands), thus causing high costs in terms of fossil fuel consumption and emissions from fuel combustion. On the other side, final treatments, i.e. landfilling and WtE, mainly affect HT, totaling together to 97% of the whole impact. HT is the most impacted category in absolute terms, also in the case of normalized results (data not shown).

Table 3. Characterized impacts calculated for the MMSW fraction produced in Naples metropolitan area in 2012 (attributional approach, referred to a functional unit of 1.39E9 waste treated).

Impact category	Unit	Total impact	Collection	Transport	Landfill	WtE	Metals recycling	WWT
GWP	kg CO_2 eq	8.00E+08	5.54E+05	3.74E+08	1.89E+08	2.34E+08	3.97E+05	2.16E+06
TAP	kg SO_2 eq	1.84E+06	2.33E+03	1.58E+06	5.93E+04	1.74E+05	2.54E+03	1.80E+04
FEP	kg P eq	3.52E+04	3.62E+02	5.78E+03	5.89E+03	1.93E+04	2.20E+02	3.58E+03
HTP	kg 1,4-DB eq	3.26E+08	4.42E+05	9.55E+06	1.65E+08	1.49E+08	3.97E+05	1.06E+06
POFP	kg NMVOC	4.21E+06	2.57E+03	3.79E+06	1.35E+05	2.69E+05	2.61E+03	1.02E+04
TEP	kg 1,4-DB eq	2.19E+04	2.84E+01	1.22E+04	3.73E+03	5.08E+03	5.58E+01	8.09E+02
WD	m^3	9.96E+07	3.53E+06	4.55E+07	1.79E+07	2.89E+07	9.96E+05	2.77E+06
MD	kg Fe eq	6.59E+06	9.36E+05	3.38E+06	3.39E+05	1.35E+06	1.39E+05	4.44E+05
FD	kg oil eq	1.22E+08	1.28E+05	1.15E+08	2.93E+06	3.04E+06	1.11E+05	4.43E+05

This is in line with the long and short-term direct emissions from landfill as well as to indirect emissions generated via incineration (e.g. residual sludge from leachate treatment). Although energy costs are not the most important impact category in waste management, it is clear that improving the chain system, by promoting 'localness', may require smaller investments and this can be pointed out only by means of a deep knowhow of the state of the art.

In Figure 3, normalized results of the consequential approach are reported. When a consequential approach is adopted, the system boundaries are typically re-defined to include the activities that might benefit from using recovered resources in order to generate different environmental consequences as a follow up of changes of resources used (e.g., use of recovered resources *versus* virgin resources). In the present study, environmental costs of goods and energy (i.e. electricity, heat and materials) produced by the system under investigation are detracted from the accounting of the system's impacts, considering that their production by conventional routes is avoided. A general decrease of impacts can be observed in the consequential perspective: the negative values indicate that the recovery of metals, glass, paper and plastics as well as the production of electricity and heat allow savings in the production of virgin metals, electricity and heat by conventional routes so that impacts become negative and an environmental benefit is attained. Some environmental benefits are observed for FEP, FD, MD and HTP, the latter still remaining highly impacted by the contribution of landfill treatment (from which no useful products are obtained).

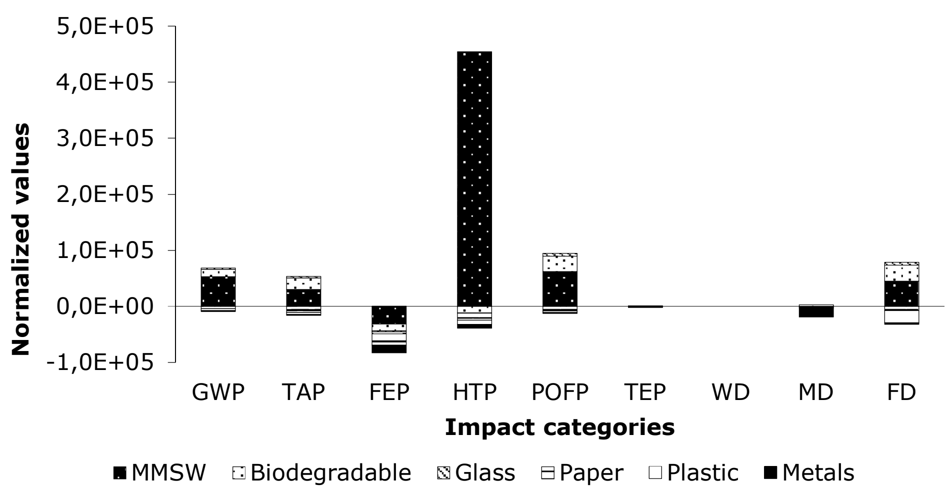

Fig. 3. Normalized impacts calculated for all the waste fractions produced in Naples metropolitan area in 2012 (consequential approach, referred to a functional unit of 1.39E9 waste treated).

4. Conclusions

The results of the LCA carried out in this study, based on full-scale waste management chains and site-specific data, confirmed that there is room for improving the eco-efficiency of the collection-recycling chain, which is not fully optimized (separate collection is still very low and a large part of the waste is diverted far away).This conclusion was drawn after considering the whole sequence of activities in the chain, thus quantifying the eco-balance of collection, transportation, selection, recycling of the main waste flows and landfill/energy recovery from residues. The complexity of MSW management issue is however deeply embraced by the LCA methodology, that confirms to be a suitable tool to identify criticalities, driving factors and improvement potentials. LCAs of complex systems such as WMs necessarily reflect this complexity, which is also influenced by technical site-specific aspects and local socio-economic constrains. Developing waste management strategies is a challenging task which has to start from a deep, complete and detailed overview of the state of the art. To this aim, LCA allows the identification of criticalities and improvement potential, thus providing sufficient information for evaluating the existing bottlenecks and re-directing management efforts.

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