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Factors influencing GWP, AP and EP in assessing waste management systems through a LCA approach

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No problem can be solved from the same level of consciousness that created it.

Albert Einstein

Preface

This thesis stems from a study performed during a six months internship in Lappeenranta, within a collaboration plan between University of Florence and Lappeenranta University of Technology, in particular the department of Environmental Technology, School of Energy Systems.

Acknoledgements

I would like to take the opportunity and express my gratitude to all the people who have supported and inspired me during the University course.

I would particularly like to thank Prof. Lidia Lombardi and Prof. Mika Horttanainen, my supervisors, for the opportunity provided to me to perform the internship in Lappeenranta and for their assistance during the draft of this thesis. The internship experience was really great also thanks to the YMTE group in Lappeenranta University and thanks to all the people I met there.

I especially want to thank my family, all my friends and the people who have been close to me, supporting and helping me during this period.

INDEX

1 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVE OF THE STUDY

Waste can be regarded as a human concept as there appears to be no such thing as waste in nature. The waste products created by a natural process or organism quickly become the raw products used by other processes and organisms. Recycling is predominant, therefore production and decomposition are well balanced and nutrient cycles continuously support the next cycles of production. This is the so-called *circle of life* and is a strategy clearly related to ensuring stability and sustainability in natural systems. On the other hand there are man-made systems.

Nowadays is worldwide recognized that the production of waste is counterproductive to the attainment of a sustainable society.

The focus of the study is on municipal solid waste (MSW) management, particularly on the waste generated by households. This is due to the fact that MSW is known to be as an important contributor to many different environmental problems, such as global warming, air and water acidification and water eutrophication, thus, a good management is necessary in addressing this waste problems.

An important and well known tool for quantifying the environmental impacts of any kind of system is the life cycle assessment (LCA). When LCA methodology is applied to waste management, it focuses only on the disposal stage. Despite the fact that an LCA of waste excludes the processes that come before disposal, it still follows a life cycle thinking (LCT) approach, which is in accordance with Article 2, Paragraph 4 of the EU Waste Framework Directive (European Parliament and The Council, 2008). The life cycle of waste is considered to start at the point where it becomes waste, which can be defined as the point where it is no longer of value to the owner and/or is placed into a waste receptacle.

Many LCA studies have been made by various practitioners with the purpose of investigating the most environmentally friendly waste management system (WMS), which can be different for every country, city or even district. The best way of handling solid waste cannot be unequivocally established, whereas it depends on various factors, such as technological, social or geographical circumstances.

Likewise, it is impossible to establish beforehand a fixed value of emissions for every process, since it must be known how it is carried out, the input waste characteristics and technology parameters. Therefore, it is also impossible to know beforehand how much every process will contribute to the total amount of emissions for the whole management system. Nevertheless, it is interesting to know the lessons learned from previous studies, in order to distinguish between most important process and factors (the ones that must be thoroughly evaluated) and least important factors (the ones that can be disregarded without committing considerable mistakes).

Besides, every LCA study is performed by making some assumptions depending on the background situation of the country, city or even plant that is being analyzed and it should be well considered that all those hypotheses can strongly influence the final LCA results. Therefore, it is interesting to find out whether or not there are some crucial parameters or assumptions that should be made more carefully when studying different system backgrounds.

The mentioned observations lead to the following research questions:

- Is it possible to identify what are the most important and least important processes and factors affecting the LCA results of a WMS, i.e. referring to global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP) impact categories?
- How much are the contribution of those processes influenced by social, political and technological factors of the operating environment and by management strategies with respect to the final LCA result?
- What are the parameters that affect most both the total and single process results in a LCA study with respect to GWP, AP and EP?

1.2 STRUCTURE AND APPROACH

In order to investigate and solve the problem described in the problem formulation, both theoretical and empirical research methods were followed. Theory is generally described as a simplified picture of reality, and is utilized to achieve an understanding of the problem and to see how the investigation will contribute to the reality of the problem, before the identified solutions are tested in practice. Empiricism is the collection of experiences and observations which is then used to build upon the understanding that was created in the process of theory (Andersen, 2005).

In the first part of the work a review of previous LCA studies of waste management was performed, in order to understand if and how these problems are discussed in literature and to figure out which are the lessons to be learned from theory. This topic is described in chapter 2.

A wide share is given to the second part of the work, where two waste management case studies were analyzed and compared. The first one is about Province of Siena (Tuscany, Italy) and the second one is about South Karelia region (Finland). The two case studies were implemented by means of LCA approach, adopting the specific LCA tool *GaBi TS* 6.0.

1.2.1 Data collection

Regarding the first part of the study, the methodological framework, the characteristics of reviewed articles and the selection of significant data are well described in section 2.1, since these features can be considered as an integrated part of the work itself.

Concerning Siena case study, a large amount of data were taken from *Zanchi L., 2011, LCA comparison of MSW management systems in Tuscany and Catalonia,* a master thesis developed in the University of Florence. Specific upgraded data concerning waste generation and plants technical parameters were provided by local waste management authorities. Finally, in cases where no existing primary or secondary data from the case area were found, Italian or European average data were assumed from *GaBi TS* software databases.

Regarding South Karelia case study, it was developed in the Department of Environmental Technology, School of Energy Systems, at Lappeenranta University of Technology. The study was a revision and an upgrading of the previous article *Hupponen, Grönman, & Horttanainen (2015), How should greenhouse gas emissions be taken into account in the decision making of municipal solid waste management procurements? A case study of the South Karelia region, Finland.*

1.2.2 LCA methodology

Life cycle assessment is an environmental assessment tool that can be applied to determine the entire environmental impact of a product or system over its the entire life. The methodological framework of LCA are defined by the international standard series ISO 14040 which are accepted worldwide. An LCA includes a compilation and evaluation of the input and output flows and the potential environmental impacts of a production system during its life cycle (ISO 14040:2006-10). For this purpose, the whole product life cycle, from the supply of raw materials to the disposal or respectively recycling, is investigated in relation to the use of energy and materials (Figure 1.1).

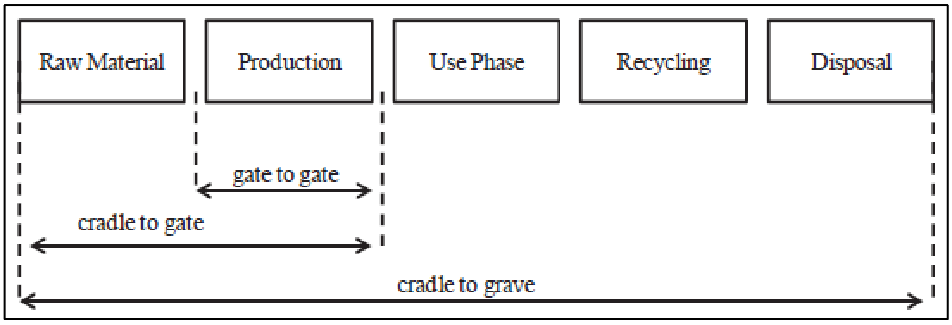

Figure 1.1 Product life cycle phases with system boundaries.

Figure 1.2 shows the four phases that make up an LCA; it also shows that they do not need to be in a successive order. The approach is rather an iterative process.

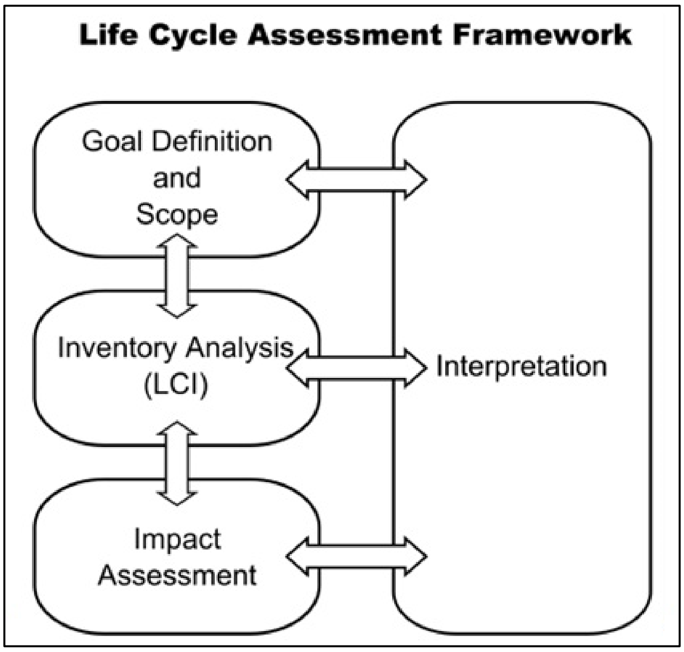

Figure 1.2 Conceptual framework of LCA.

In the following a brief description of each step is given.

Goal and scope definition

In the first phase, all general decisions for setting up the LCA system are made. This phase is called the goal and scope definition and is of central importance to each LCA. In the goal definition, the reasons for the study as well as the overall goals are defined. In addition, the target group for the LCA report is defined. Whether the LCA will be used to make a comparison between systems is also determined at this stage.

In the scope definition, the product or process system is characterized and all assumptions are detailed. The system boundaries (time, geographic and technical), choice of impact categories and data quality requirements as well as the methodology used to set up the product system are also described. To describe the product or process, the function of it has to be defined as well as the demands the product or process is supposed to fulfill. This becomes very important when products or processes with a different range of functionalities are to be compared. For this, a functional unit is defined. The functional unit is the quantified definition of the function of a product or process system with a physical unit (*W. Klopffer, B. Grahl, 1997, Life Cycle Assessment (LCA): A Guide to Best Practice*).

Inventory analysis

The life cycle inventory (LCI) includes data acquisition and calculation methods for the quantification of relevant input and output flows of a production system within the determined boundaries (Herrmann, 2010). All activities that are related to the production of one functional unit need to be analyzed regarding components as raw material extraction, intermediate products, the service or product itself, the use phase and the waste removal at the end. Additional inputs that can be included are energy, transportation or auxiliary products. Typical outputs for an inventory analysis are emissions to air, water and soil, waste heat, coproducts and solid waste (Klöpffer, 1997). The data acquisition in this phase involves collecting quantitative and qualitative data for every process in the system. This can be done by the collection of primary data (from plant visits or by using available databases) or through the collection of secondary data from the literature. It is important that the collected data is related to the functional unit and validated. When necessary, allocations must be modeled and in some cases, the system boundaries potentially may be redefined (More about LCA, 2006). The ISO 14044 standard defines allocation as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems”.

Impact assessment

In the life cycle impact assessment (LCIA) phase, the results from the inventory analysis are used to identify and evaluate the significance of potential environmental impacts of a product or process system as such as the effects on the natural resource use, the natural environment and the human health. According to the ISO 14044 standard, the LCIA involves several steps. The selection of relevant impact categories, classification and characterization belong to the mandatory elements, while normalization, grouping and weighting are included in the optional elements of a study (Herrmann, 2010).

Classification is the process where each resource and emission is assigned to one or more impact categories. Impact categories are scientific definitions linking specific substances (e.g CO2, CH4, etc.) to a specific environmental issue. The issue of global warming for example is represented by the global warming potential (GWP) impact category. Any emission to air that contributes to the global warming potential, such as carbon dioxide or methane, is then classified as contributors. The next step is the characterization of the results. This means that the results of the impact analyses are converted into the reference unit of the impact category. Regarding the impact category GWP for example, CO_2 is the reference substance for it and its reference unit is defined as “kilograms CO2 equivalence”. All emissions that contribute to that same impact category (GWP) are then converted likewise to “kilograms CO2 equivalence” corresponding to their own characterization factor. The determination of these factors is made by different scientific groups and is based on different methodologies and philosophical views on the environmental issues. The two most widely used impact category methodologies are TRACI in the US (developed by the EPA) and CML in Europe (developed by the University of Leiden) (PE International, 2013a).

After characterizing every substance that contributes to the system, all of the characterized quantities can be simply added together. This results in a final number that represents the extent of this environmental impact. Finally, it is done for every impact category of interest, so that these calculated results are collectively referred to as the LCIA results.

The optional elements of the LCIA, i.e. normalization, grouping and weighting are performed to facilitate the interpretation of the LCIA results.

Interpretation

This final phase involves identifying the most significant results of the LCI and LCIA phases. This should also be accompanied by a discussion of the sensitivity and uncertainty of the study and a critical review of the methods that have been employed.

The interpretation also concludes the results of the study and gives recommendations based on the results and conclusions.

As already mentioned, the impact categories considered for the entire work, both for the articles review and for the LCA case studies analyses, are: global warming, air and water acidification and water eutrophication.

1.2.3 Data analysis

Concerning the first part of the work, it consists in a systematic, semi-quantitative review of 34 papers dealing with LCA of municipal solid waste management. After a critical examination, some conclusions are drawn and in the end of the work these results are further compared to the outcomes from case study analysis.

The next phase is the development of Siena case study. The research is going through:

- description of the waste management system;
- data collection about waste flows, plants processes and technological parameters;
- computational modeling of mechanical and biological treatment, waste incineration and waste landfilling;
- performing LCA of the waste management system;
- interpretation of results through scenario comparison, contribution analysis and sensitivity analysis;

As already mentioned, South Karelia case study was not developed inside this work. However, within the collaboration between Department of Environmental Engineering of University of Florence and Department of Environmental Technology of Lappeenranta University of Technology, it was possible to get some data and results from that study.

The original LCA case study about South Karelia waste management is taken from the article Hupponen et al., (2015); the study has been upgraded and reviewed, by including also acidification and eutrophication impact categories, contribution and sensitivity analysis. Within the scope of this work, the following parts were included:

- description of the waste management system;
- data about waste flows and plants processes collected from the article;
- brief description of computational modeling and general inventory description;
- presentation of the results consistent with the purpose of this work and useful for case study comparison.

Further, the results from the case studies are compared and discussed, with reference also to the introductory review.

2 REVIEW OF LCA STUDIES ABOUT MSW MANAGEMENT: PROCESSES, FACTORS AND ASSUMPTIONS AFFECTING GWP, AP, EP IMPACT CATEGORIES

Making a LCA study of an integrated MSW management system means looking into the whole processes involved in every treatment within the system boundary; every process has input and output streams, and it implies produced emissions and avoided emissions.

Many LCA studies have been made all over the world with the purpose to investigate about the most environmentally friendly waste management systems, which can be different for every country and city.

In the following paragraphs, scope, methodology and aim of the review are described, as well as a critical comparison and discussion about the articles analyzed.

2.1 SCOPE AND METHODOLOGY OF THE REVIEW

The overall objective of this study is to identify which are the most important and least important factors, involved in different integrated MSW management systems, affecting GWP, AP and EP impact categories and to examine how much every condition of the operating environments can affect the results concerning these categories. In fact, in the assessment of SWMS, the local context, which determines highly-variant parameters, such as waste composition or energy supply mix, has a strong influence on what the optimal strategy is.

The work is carried out by analyzing previous studies about MSW management in different countries and cities all over Europe. The identification of studies in scientific journals was performed following a two-step procedure. At first, several articles were screened via the Scopus search engine (www.scopus.com) and then briefly checked. To ensure consistency, papers to include in the review were selected based on the following criteria: (i) the study was published in a peer-reviewed scientific journal; (ii) the study focused on municipal solid waste management from a LCA perspective; (iii) an impact assessment was performed and at least one between GWP, AP, EP impact category was included; (iv) the article was dealing with an European country/city and (v) the study was reported in English.

A total of 70 articles were identified. After that, a deeper screen of the studies was performed: only 34 have been discussed in this study, although also the rest of them were satisfying the mentioned selection criteria. This was done because it has been observed that only some authors of the articles perform detailed contribution analyses (also called *hot-spot analyses*), as some of them prefer just showing the net impact values deriving from the whole analysis. Similarly, the investigation about how much the hypothesis affect the results (also called *sensitivity analysis*) is not always assessed.

The articles considered for the discussion are listed in Table 2.1. The table reports: reference; geographical and temporal scope; considered WMS and examined scenarios; investigated impact categories (only referring to GWP, AP and EP); whether or not the authors perform a detailed contribution analysis; whether or not the authors perform a sensitivity analysis and what are the main investigated parameters; whether or not the authors report some Sensitivity Ratios (see paragraph 6.3) or if it is possible to estimate them instead.

Given the wide variance noticed in the way of showing results by various authors, it was not always possible to report numerical outcomes; where possible, some calculations were done for transforming graphical results into numbers and percentages in order to compare them. The percentages regarding the contribution analyses are computed as explained in paragraph 6.2. This is done in order to understand the real relative contribution on the total count, regardless if it is positive (e.g. direct emissions from the incineration stack) or negative (e.g. energy recovery from incineration).

The papers discussion is divided per country of origin, in order to better evaluate the differences between various social/economical/political/geographical situations; as a matter of fact, these differences decisively affect the waste management (e.g. different composition of waste, different treatment technologies).

Table 2.1 List of analyzed articles.

Reference	Geographical scope	Year	Considered WMS	Impact categories	Detailed contribution analysis	Sensitivity analysis, main param.	SR calc. or est.
Arena, U., Mastellone, M. L., & Perugini, F.	Campania, Italy	2003	-Landfilling -Mass burn -RDF prod. and inc.	GWP, AP	Yes	No	
Assefa, G., Eriksson, O., & Frostell, B.	Sweden	2005	-Mass burn -Landfilling -MBT and incineration -Source separation and treatment of residual	GWP, AP, EP	Yes	No	
Eriksson, O., Reich, M. C., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J. O., Thyselius, L.	Uppsala, Stockholm and Alvdalen (Sweden)	2005	-Mass burn -Landfilling	GWP, AP, EP	No	-Displaced energy mix	No
Morselli, L., Bartoli, M., Bertacchini, M., Brighetti, a., Luzi, J., Passarini, F., & Masoni, P.	Rimini, Italy	2005	-Mass burn	GWP, AP, EP	Yes	No	
Bovea, M. D., & Powell, J. C.	Valencia, Spain	2006	-Recycling/landfilling	GWP, AP, EP	Yes	-Excl. Bio-CO2 -Use of transfer station	No
Kirkeby, J. T., Birgisdottir, H., Hansen, T. L., Christensen, T. H., Bhander, G. S., & Hauschild, M.	Aarhus, Denmark	2006	-Mass burn -Pre-treatment and incineration	GWP, AP, EP	No	-LFG generation pot. -Electr. consumpt. for pretreat. -Electricity prod. Eff.	No
Winkler, J., & Bilitewski, B.	Dresden, Germany	2007	-Mass burn -Landfilling	GWP	Yes	No	
Morselli, L., De Robertis, C., Luzi, J., Passarini, F., & Vassura, I.	Emilia Romagna, Italy	2008	- Mass burn	GWP, AP + EP	Yes	No	
Riber, C., Bhander, G. S., & Christensen, T. H.	Aarhus, Denmark	2008	- Mass burn	GWP, AP, EP	Yes	-Displaced energy mix	No
Gentil, E., Clavreul, J., & Christensen, T. H.	DK, FR, DE, GR, PL, UK	2009	According to the country	GWP	Yes	-LFG collection eff. -Heat/electr. Recov.Eff -Recycling efficiencies -Waste characteristics	No

Rigamonti, L., Grosso, M., & Sunseri, M. C.	Italy	2009	-Material recycling and residual treatment	GWP, AP	No	-Substitution ratio -Selection efficiency	Yes
Bovea, M. D., Ibáñez-Forés, V., Gallardo, A., & Colomer-Mendoza, F. J.	Castellón de la Plana, Spain	2010	- Recycling, MBT, lanfilling	GWP, AP, EP	Yes	-Substitution ratio -LCI assumptions	No
Eriksson, O., & Baky A. (follows Assefa, G., Eriksson, O., & Frostell, B., 2005)	Sweden	2010	-Mass burn -Landfilling -MBT and incineration -Source separation and treatment of residual	GWP, AP, EP	No	-Displaced energy mix -Transport distances -Waste characteristics -Recycling efficiencies (no numerical results)	No
Miliute, J., & Kazimieras Staniskis, J.	Lithuania	2010	-Recycling, composting, landfilling -Landfilling -Recycling, MBT, incineration -Recycling, incineration	GWP, AP, EP	Yes	-Displaced energy mix -LFG collection eff. -Electr. recov. eff.	Yes
Manfredi, S., Tonini, D., & Christensen, T. H.	Denmark	2011	-Mass burn -Landfilling -Recycling	GWP, AP, EP	No	-Displaced energy mix -Heat recovery -Waste characteristics	No
Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L., & Astrup, T.	Milan, Italy and Aarhus, Denmark	2011	-Mass burn	GWP, AP, EP	Yes	-Displaced energy mix -Waste characteristics	No
Burnley, S., & Coleman, T.	United Kingdom	2012	-Mass burn	GWP, AP, EP	No	- Displaced energy mix -Metals recovery rate -Electr. recovery eff.	Yes
Clavreul, J., Guyonnet, D., & Christensen, T. H.	Denmark	2012	-Mass burn -Anaerobic digestion	GWP	Yes	-Waste characteristics -Heat/electr. recov. eff. -LFG generation pot.	Yes
Merrild, H., Larsen, A. W., & Christensen, T. H.	Denmark	2012	-Mass burn -Recycling	GWP, AP, EP	No	-Energy recov. eff. -Transport distances	No
Belboom, S., Digneffe, J.-M., Renzoni, R., Germain, A., & Léonard, A.	Liège, Belgium	2013	-Mass burn -Landfilling -Anaerobic digestion	GWP	Yes	-Displaced energy mix	No

Beylot, A., & Villeneuve, J.	France	2013	-Mass burn	GWP, AP, EP	No	-Displaced energy mix	No
Jeswani, H. K., Smith, R. W., & Azapagic, A.	London, United Kingdom	2013	-Mass burn -Landfilling	GWP	Yes	-Waste characteristics -Displaced energy mix -LFG collection eff.	Yes
Sevigné Itoiz, E., Gasol, C. M., Farreny, R., Rieradevall, J., & Gabarrell, X	Spain	2013	-MBT, incineration, landfilling	GWP	Yes	-Waste composition -Landfill parameters -Coll. and transp. param.	Yes
Slagstad, H., & Brattebø, H.	Norway	2013	-Recycling, incineration, landfilling	GWP, AP, EP	No	-Waste characteristics	No
Tonini, D., Martinez-Sanchez, V., & Astrup, T. F.	Denmark	2013	-Mass burn -Landfilling -Source separation -Recycling -MBT and incineration	GWP, AP, EP	Yes	-Waste characteristics -Displaced energy mix -Electr. recov. eff.	No
Al-Salem, S. M., Evangelisti, S., & Lettieri, P.	London, United Kingdom	2014	-Landfilling -MBT and incineration	GWP, AP, EP	No	- Substitution ratio	No
Boesch, M. E., Vadenbo, C., Saner, D., Huter, C., & Hellweg, S.	Switzerland	2014	- Mass burn	GWP	Yes	-Displaced energy mix	No
Evangelisti, S., Lettieri, P., Borello, D., & Clift, R.	London, United Kingdom	2014	-Mass burn -Landfilling -Anaerobic digestion	GWP, AP, EP	Yes	-Displaced energy mix	No
Fernández-Nava, Y., del Río, J., Rodríguez-Iglesias, J., Castrillón, L., & Marañón, E.	Asturias, Spain	2014	-Mass burn -Landfilling -Source separation and treatment of residual	GWP	Yes	No	
Arena, U., Ardolino, F., & Di Gregorio, F.	Italy	2015	-Mass burn -Gasification	GWP	Yes	-Displaced energy mix -Electr. recov. eff	Yes
Bisinella, V., Conradsen, K., Christensen, T. H., & Astrup, T. F.	Denmark	2015	-Recycling, incineration -Recycling, landfilling -Recycling, anaerobic dig.	GWP, AP, EP	Yes	-Heat/Electr. recov. eff -Waste characteristics -Recycling parameters	Yes

Di Maria, F., Micale, C., Morettini, E., Sisani, L., & Damiano, R.	Italy	2015	-MBT, recycling, landfilling	GWP, AP, EP	Yes	-Displaced energy mix -Recycling substitution ratio -LFG collection eff.	
Parkes, O., Lettieri, P., & Bogle, I. D. L.	United Kingdom	2015	-Composting, recycling, landfill -Composting, recycling, incineration -Recycling, landfill -Recycling, incineration	GWP, AP, EP	Yes	-Recycling rate -Waste characteristics	No
Burnley, S., Coleman, T., & Peirce, A.	United Kingdom	2015	-Mass burn	GWP, AP, EP	No	-Displaced energy mix -Electr. recov. eff -Metal recov. from BA	Yes

2.2 RESULTS AND DISCUSSION

Some general data about the reviewed articles are reported in Figure 2.1 and Figure 2.2.

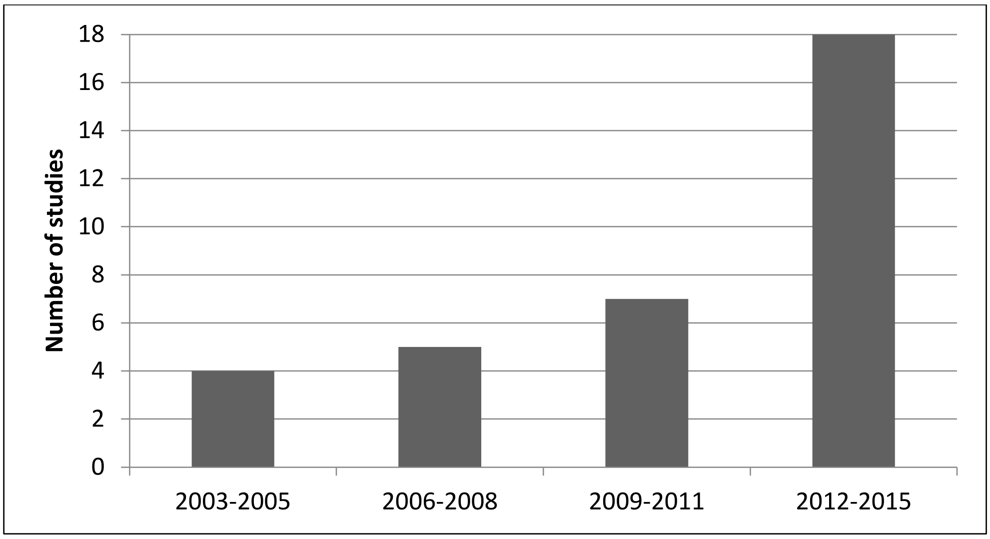

Figure 2.1 Temporal scope of the reviewed articles.

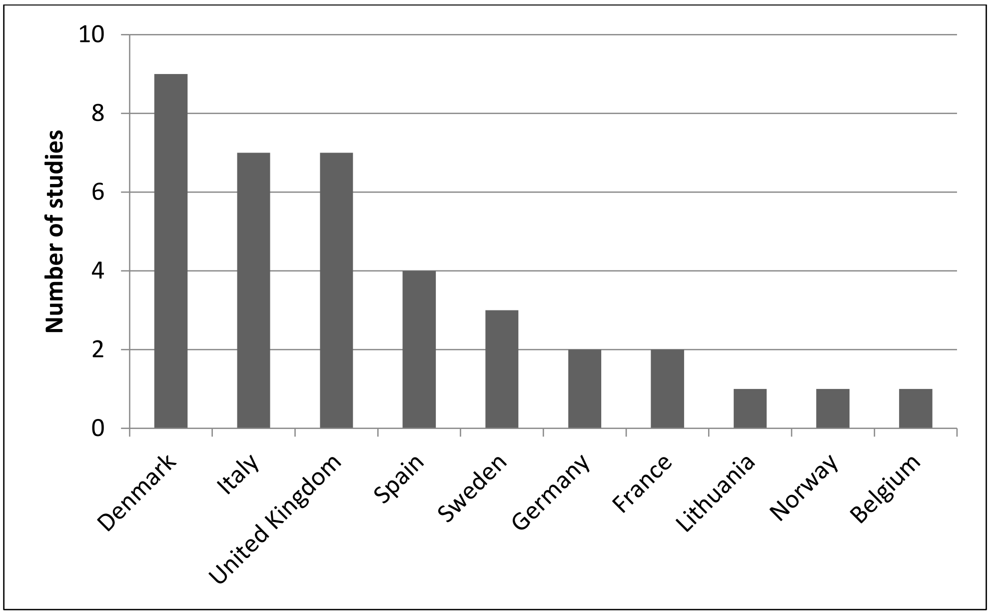

Figure 2.2 Geographical scope of the reviewed articles.

It can be noted that most of the considered studies (more than 50%) have been published in the last three years, and this trend is likely to reflect the importance of LCA as an increasingly accepted approach to analyse the environmental performance of waste management, as already stated by Laurent et al., (2014).

Further, most of the studies are conducted in few European countries such as Denmark, Italy and United Kingdom, which represent the geographical scope of almost two-thirds of the reviewed articles.

The most discussed waste management systems/scenarios are showed in Figure 2.3. The so-called *mass-burn scenario* is one of the most analyzed options to manage MSW and the comparison between this option and the direct landfilling of the waste is often assessed.

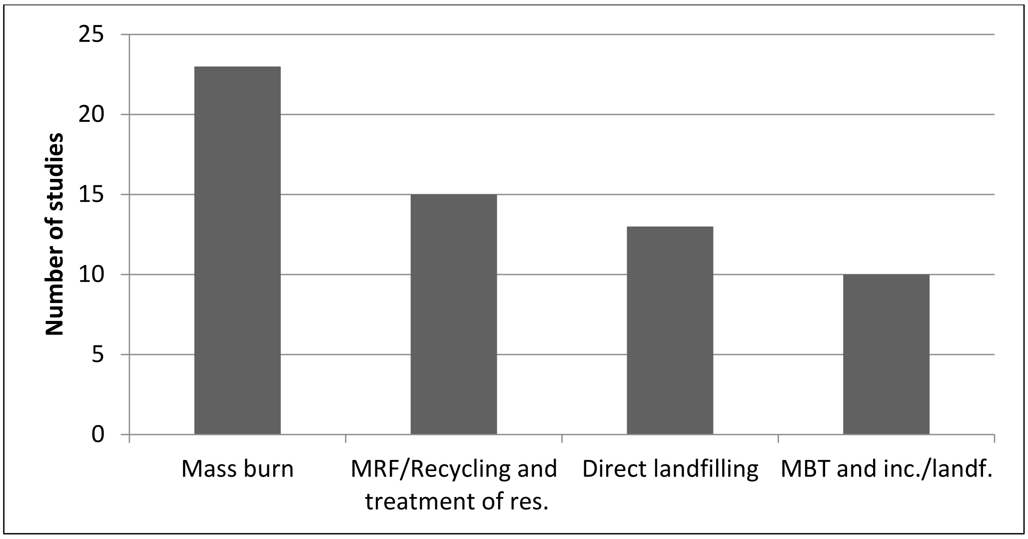

Figure 2.3 Main waste management systems investigated in the considered studies.

Concerning the impact coverage, 22 studies out of 34 include all GWP, AP and EP impact assessment, while 9 of those consider only GWP category and 3 studies include GWP and AP categories.

A detailed contribution analysis is performed in 23 studies while sensitivity analysis is performed in 28 studies (considering at least one investigated parameter/assumption); 17 studies carry out both the analyses. As explained in chapter 6, there is a deep relation between the two analyses and in particular the contribution analysis should be the first step for a general sensitivity analysis.

The histogram in Figure 2.4 shows which are the main investigated parameters and assumptions in the sensitivity analyses. The effect of the country specific displaced energy mix on the final results is the most frequently investigated assumption, assessed in 16 studies. It should be stressed that this analysis is usually carried out by substituting to the specific national energy mix only one primary energy source (e.g. coal, natural gas or oil) and evaluating the effect on the global LCA results. Therefore, the consequent substantial differences in the results are often generated by non-realistic assumptions.

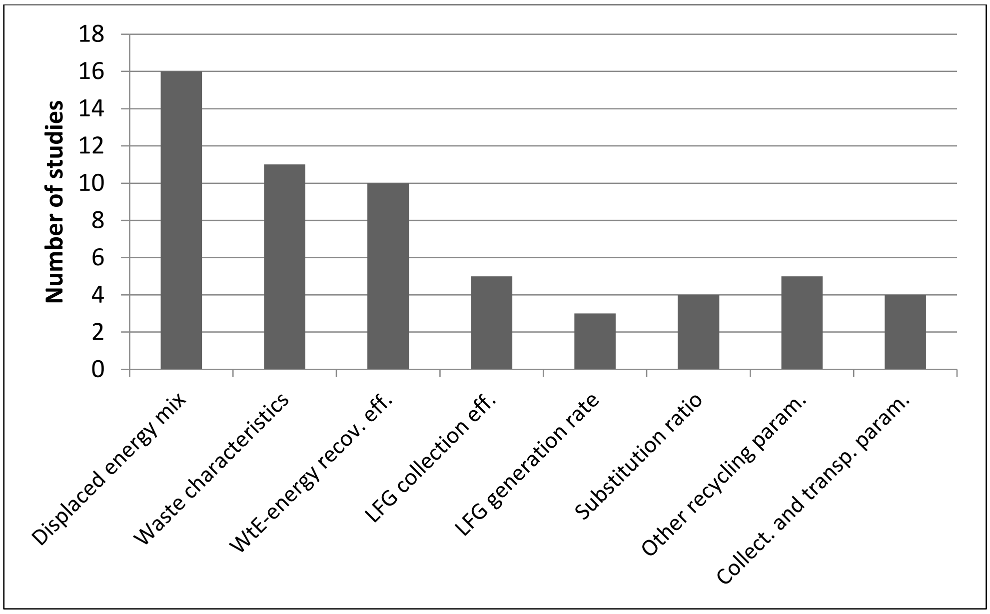

Figure 2.4 Main parameters/assumptions investigated through a sensitivity analysis in the reviewed articles.

Also the assumptions about input waste characteristics (e.g. composition, fraction of biogenic and fossil carbon, water content, LHV,…) and energy recovery from waste incineration (both electricity and heat) are frequently investigated in the reviewed articles. Other parameters and assumptions analyzed in the studies are landfill parameters (e.g. LFG collection efficiency and LFG generation rate), recycling parameters (e.g. substitution ratio, source separation efficiency,…) and parameters related to collection and transportation of waste (e.g. transportation distances, use of transfer stations,…).

In the following paragraphs the most important findings from the reviewed studies are discussed. The studies are grouped per country of origin.

Italian studies

Arena et al. (2003) compare three possible MSWM systems for a southern Italian district: i) waste landfilling with energy recovery, ii) RDF production and combustion with energy recovery, iii) mass burn combustion with energy recovery. Waste transportation process is accounted and its contribution to both GWP and AP is less than 5% of total in every scenario. With respect to GWP emissions, the direct emissions from incineration (including stack emissions, flue gas cleaning, ash treatment) are contributing for more than 30% in scenarios 2 and 3, and the same is for the energy recovery (more than 30%, as a negative value); for the first scenario the direct emission from the landfill represents more than 30% of the total, while the energy recovery (biogas combustion) has a contribution between 5-10%. Referring to AP, it’s been observed that in scenarios 2 and 3 the direct emissions from incineration (including stack emissions, flue gas cleaning, ash treatment) are contributing between 11-30 % of the total emission while energy recovery represents more than 30% of AP, as avoided emissions; in the first scenario, the direct emission from the landfill is contributing between 5-10 % of the total and the same is for energy recovery (as a negative contribution).

Morselli et al., (2005) model a WtE incineration plant in Rimini, Italia. The results are shown just in terms of EP category and it can be seen that the major contributions to the total balance are given by the stack emission (more than 30%) and by the avoided emissions due to energy recovery (between 11-30 %). Flue gas cleaning is contributing between 5-10 %, while ash treatment represents less than 5% of total balance. Also capital goods contribution is considered, but it appears to be completely negligible.

Rigamonti et al. (2009) assess the influence of assumptions about selection and recycling efficiencies in integrated waste management systems, from a LCA perspective. In the hypothetical situation they consider around 50% of waste is recycled and residual waste is routed to a WtE incineration plant. What comes out is that GWP and AP are significantly influenced by the selection efficiency (for both plastics and paper), and the SR is -1.05 for GWP and -1.08 for AP.

Turconi et al. (2011) analyze two different WtE incineration plants, one in Milan, Italy and the other in Aarhus, Denmark. Regarding GWP, direct emissions from incineration (which include in this case: stack emissions, flue gas cleaning and ash treatment) and avoided emissions for energy recovery are the main stages, contributing for more than 30% each one; metal recovery from slags is not significant unit in accounting GWP, since it represents less than 5% of the global balance.
Concerning AP and EP, direct emissions from incineration and avoided emissions for energy recovery are again the main stages,contributing for more than 30% each one, while metal recovery from slags is contributing between 5-10 % on the final balance for both categories.
Results are very sensitive to the variation of displaced energy mix, which has a great influence on all impact categories (no values are reported); also waste composition is investigated, by switching the Italian average waste composition with the Danish one, but it has small influence for GWP result, and no relevance for AC and EP results.

Arena et al. (2015) compare two different WtE technologies by means of LCA methodology. They consider two scenarios: waste incineration with energy recovery and waste gasification with energy recovery. GWP is the only assessed impact category. They find out that for both the incineration and gasification scenarios, the direct emission is the most important unit, contributing for more than 30% of the total emissions; even recovery of energy contributes (as avoided burden) for more than 30% of the total emission for the incineration scenario, and between 11-30 % for the gasification;

ash treatment is between 5-10 % of total emission for the incineration scenario, but is less than 5% for the gasification scenario; metal recovery from slags is negligible for the incineration scenario while it contributes between 5-10 % for the gasification one, as an avoided burden; flue gas cleaning is less than 5% of the emission for the both systems. Displaced energy mix and energy recovery efficiency are the most important factors affecting the system; sensitivity ratios have been estimated from the paper, obtaining following values: $SR_{MIX,INC}$= 1.66, $SR_{MIX,GAS}$= 1.25, $SR_{EFF,INC}$= 1.15, $SR_{EFF,GAS}$= 0.8.

Danish studies

Kirkeby et al. (2006) assess different assumptions in their study about MSW management systems, in order to indicate any changes in scenario ranking. The results of the analysis point out the relevance of energy recovery efficiency from WtE and biogas plants, while a lower importance of energy consumption of pre-treating of waste. They also stress the small relevance of collection and transport of waste and residues, which constitutes only a minor part of the environmental impacts and concluding that collection and transport is controlled more by the economic costs than by environmental issues.

Riber et al. (2008), investigate about the environmental aspects of waste incineration using LCA approach. From their contribution analyses, it can be stated that direct emissions from incineration (including stack emissions, flue gas cleaning, ash treatment) and avoided emissions due to energy recovery are the main stages in terms of contribution to the final balances of GWP, AP and EP.

The importance of evaluation of energy recovery and use in waste management is discussed by Fruergaard et al. (2009). With respect to global warming, they mark how the benefits of energy recovery are highly dependent on the data types: average or marginal. Using average data the benefits of energy recovery will be highly country specific; however, as electricity markets operate across national borders, this approach does not reveal the true consequences in the energy system. Consequently, they conclude that marginal data should be preferred.

Bhander et al. (2010) evaluate the environmental impact of an integrated municipal waste management system in a typical Danish large city. Curbside collection and further separation bring to three waste fractions: organic waste (24%, routed to combined anaerobic-aerobic composting plant with energy recovery), mixed papers and cardboard (17%, routed to a MRF plant for recycling and residue to a WtE incineration plant) and residual waste (59%, routed to a WtE incineration plant). The processes are divided in three groups: processes related to collection of waste, processes related to transportation and processes related to treatment, recovery and disposal of waste, but only net values are reported in the contribution analysis. The relative contributions from different processes are the same in all impact categories: collection and transportation have a small relevance on the total emission; treatment, recovery and disposal of waste represent almost the total amount of emission, which is globally negative.

Manfredi et al. (2011), model different management options for individual waste fractions with LCA approach. They stress the importance of the waste chemical composition and the displaced energy mix, when assessing the most environmentally-friendly treatment option for a given waste fraction, between recycling, incineration and landfilling.

Merrild et al. (2012) have questioned about the relevance of transportation in a recycling scenario, in order to understand if there's a break-even point that can compromise the benefits of waste recycling against waste incineration (as long as the right means of transport are used). They concluded that the environmental impact potentials from collection and transportation of separated materials are comparably small and cannot compromise the benefits of recycling. There is of course a certain long transportation distance which implies bigger impacts (break-even point), but that would not be a realistic situation. Anyway, they underline how much it is important to consider means of transport and transport distances for the different kind of materials when assessing the benefits of recycling.

The importances of waste composition and energy recovery efficiency from waste thermal treatment are investigated by Tonini et al. (2013), in comparing different waste management options. Waste composition and characteristics play a fundamental role in determining the best WM option from a GWP, AP and EP point of view.

Bisinella et al. (2015) perform a detailed sensitivity analysis in their LCA study of waste management systems. They define a hypothetical case study based on three different waste management options: recycling + incineration, recycling + incineration + anaerobic digestion and recycling + landfilling. They find out that, referring to the first scenario, the most relevant parameters for GWP are the electricity recovery (SR=0.59) and the water content of waste (SR=-0.51), while regarding EP category, the main parameters are the heat and electricity recovery (SR=2.7 and SR=1.3 respectively) and the water content of waste (SR=-2.6).

English studies

Evangelisti et al. (2014) consider three different scenarios for the management of the organic fraction of MSW (OFMSW) in London: (i) landfill with gas recovery for electricity generation; (ii) incineration with energy recovery by combined heat and power (CHP) and (iii) anaerobic digestion

with CHP and organic fertilizer production. Also in this case transportation process has a negligible relevance for all Global Warming, Acidification and Eutrophication impact categories in all scenarios.
With respect to GWP, in the first scenario direct emissions from landfill have a great importance on the total emission (more than 30%) while electricity recovery from biogas has a much smaller relevance (between 5-10 % of the total, as a negative value); in the second scenario direct emissions from incineration process are important for more than 30% of total emissions and the same is for the energy recovery by CHP (as a negative value); in the third scenario direct emissions from anaerobic digestion have a great relevance on the total emissions (more than 30%) and the same is for the energy recovery by CHP (as a negative value).
Referring to Acidification impact category, in all scenarios the main stages are direct emissions (from landfill, incineration and anaerobic digestion) and energy recovery.
Concerning Eutrophication impact category, in the first scenario direct emissions from landfill have a great importance on the total emission (more than 30%) while electricity recovery from biogas has very low relevance (less than 5% of the total, as a negative value); in the second and third scenarios direct emissions from incineration (and anaerobic digestion) process are important for more than 30% of total emissions and energy recovery from CHP unit accounts between 11-30 % of the total, as avoided emissions.
In the sensitivity analysis they investigate a different parameter for every scenario: in the first one they evaluate the effect of methane losses on GWP, giving SR=0.4; in the second scenario the CHP unit global efficiency is studied and the effects are relevant for AP, SR=16.3, and GWP SR=1.1, but negligible for EP; however the displaced energy mix is identified as the most important factor affecting AP and GWP results.

Similar outcomes about displaced energy mix and energy recovery efficiency can be taken by Burnley & Coleman (2012), concerning integrated MSW management from a LCA perspective. They also investigate the importance of materials recovery from slags in the incineration system and it is asserted its relative quite important contribution in GWP, AP and EP impact categories as a negative value.

Jeswani et al. (2013) compare a waste incineration and a waste landfilling scenarios, from a GWP point of view, assuming a hypothetical WMS in United Kingdom. Both systems are equipped with heat and energy recovery units. Regarding incineration scenario, stack emissions and avoided emissions due to energy recovery represents the main stages, contributing each one for more than 30% to the final GWP balance, while metal recovery from BA and is around 10% of contribution. Flue gas cleaning system and transportation of waste are both negligible in term of GWP emissions. Regarding landfilling scenario, emissions due to LFG to atmosphere is definitely the main contributor to final GWP balance, while avoided emissions due to energy recovery from LFG is around 5% of contribution. They perform a sensitivity analysis where the influence of the displaced energy mix is investigated by testing different mix options. The relevance of this assumption is stressed, especially for incineration scenario, where a different grid mix can overturn the results. The sensitivity analysis point out also the importance of LFG collection efficiency, giving SR=-1.21 (estimated value), the low relevance of CHP overall efficiency in the landfilling scenario (SR<0.2) and the importance of the assumption about fossil carbon content of waste, which is mainly related to the waste composition.

Rather different conclusions about the relevance of waste transportation in evaluating environmental impacts of MSWMS, can be found in Al-Salem et al. (2014). The study deals with MSW management in Greater London area. Within the different scenarios, transportation process is negligible in accounting GWP and EP categories, but it becomes significant (between 11-30 % of the total contribution) in accounting AP impact category in the landfill scenario.

Parkes et al. (2015) deal with different potential future MSW management options for Queen Elizabeth Olympic Park district in London. Within the thirty potential scenarios presented in the study (3 scenarios and 10 IWMS`s for each scenario), 3 scenarios have been analyzed. Total MSW stream is divided in three groups: (a) source-separated organic fraction of municipal solid waste, (b) recyclable materials and (c) residual unsorted waste and rejected materials. In the first (i) scenario (a) is routed to a composting plant, (b) to MRF and (c) to landfill with energy recovery; the second (ii) scenario differs from the first for (c) is routed to a WtE incineration plant; third (iii) scenario is like the previous except for (a) which is sent to a composting plant. As already observed in other studies, also in this case waste transportation plays a negligible role to the final GWP and AP balance in all scenarios; for all scenarios direct emissions from recycling process are contributing between 5-10 % for GWP and between 11-30 % for AP while avoided emissions due to materials substitution has a higher contribution: between 11-30 % of total emissions for GWP and more than 30% for AP; regarding (ii) and (iii) scenarios, as it could be expected, stack emissions from incinerator have a great relevance for GWP, contributing for more than 30% to the total emissions, and between 5-10 % for AP category, while energy recovery is contributing between 11-30 % for GWP and between 5-10 % for AP; emissions and savings due to composting and anaerobic digestion processes appear to have small relevance for both GWP and AP emissions in all scenarios.

Burnley et al. (2015) assess the environmental impacts of an average English WMS, where all the waste are routed to incineration, comparing different assumptions about metal recovery from BA. The main outcome from the comparison is that, while recovering and recycling ferrous material has negligible benefit for GWP, AP and EP, recovering also non-ferrous metals shows much higher benefits for all impact categories. They also investigate the influence of assumptions about electricity recovery efficiency from WtE and displaced energy mix, on the global results. Concerning the first parameters, it is possible to estimate its relative SR, which gives: SR_{GWP}=-1.68, SR_{AP}=-0.93 and SR_{EP}=-4.73; even the effect of conventional power source displaced deeply affects the global balance in GWP, AP and EP impact categories.

Spanish studies

Bovea et al. (2010) focus on the integrated MSW management system in the city of Castellón de la Plana (Spain). Between a total of 24 analyzed scenarios, two of them were reviewed in this paper. The system boundary is the same for the both of them (waste collection and transportation, recycling of separated collections, composting of the organic fraction and landfilling for residuals), except of the landfilling process: only in the second scenario energy recovery is performed.
Collection and transportation stage contributes between 5-10 % for GWP and EP and between 11-30 % for AP to the final balance for both scenario, which is in contrast with other authors like Winkler & Bilitewski, (2007), Bhander et al., (2010), Merrild et al., (2012) who assessed the irrelevance of this process. Recycling has a small positive relevance for GWP (between 5-10 %), while it represents the main stage for AP and EP (more than 30% as a negative contribution) for both scenarios; also composting stage contributes globally between 5-10 % for GWP and between 11-30 % for AP and EP, referring to the final balances. Landfilling is the most impactful process, with a contribution of more than 30 % for GWP category in both scenarios. In the first scenario, waste landfilling has small relevance for AP (less than 5%), but more for EP (between 5-10 % of total emissions) while in the second one, thanks to energy recovery from biogas, the contribution to AP is negative (between 5-10 %) and net contribution to EP is smaller (less than 5%). They also perform a sensitivity analysis on substitution ratio parameters in recycling process: what it comes out is that result in GWP is not influenced by those assumptions, but they influence quite much AP and EP impact categories.

Sevigné Itoiz et al. (2013) try to understand what are the factors with the greatest effect on GHG emissions, in assessing a Spanish case study of integrated MSW management, from a LCA perspective. Four scenarios are considered, differing on the amount of waste routed to every treatment technology. It comes out that every different treatment affects the final GWP balance depending on the amount of waste that is routed to that specific process. However, it can be noted that direct emissions from landfill and the avoided emission due to material recycling always have a great contribution on GWP balance.

Bovea & Powell (2006) analyze several scenarios for MSW management in Valencian Community (Spain). In the baseline scenario recycled waste are 10.5% of the total, 34% are routed to composting, and 55% are landfilled without energy recovery; in the first scenario, recycled waste are 24%, 47% are routed to composting and 27% of total are landfilled.

Contribution due to collection of waste is the same for both scenarios: negligible for GWP emissions, between 5-10 % for AP and between 11-30 % for EP. In the first scenario, contribution from transportation of waste is negligible for GWP, but it is between 5-10 % of total AP emissions and between 11-30 % for EP, which is inconsistent with outcomes from other studies. As we could expect recycling and landfilling contributions are the most important ones: in base scenario, recycling is contributing between 5-10 % to GWP emission, and more than 30% to AP and EP (as negative values); in the first scenario, this process represents more than 30% of total emissions (negative values) for all GWP, AP and EP categories. Landfilling is the main stage in terms of contribution to GWP for both scenario. Emissions due to composting process is negligible for GWP and it is between 5-10 % for EP; this is contrast with Bovea et al. (2010) and Miliute & Kazimieras Staniskis (2010) who find out a positive and bigger contribution (between 11-30 %) to EP emissions.

Fernández-Nava et al. (2014) investigate five different scenarios for MSW treatment in Asturias city (Spain). The interesting outcome which comes out from the study, is that when landfilling is not the main treatment, the transportation has a rather relevant impact in the total GWP category, contributing for more than 30% to the total emissions.

Bueno et al. (2015) analyze MSW management in Gipuzkoa city (Spain). They compare two alternative MSWM scenarios: in the first one, 25% of waste is separately collected and recycled while the other 75% of mixed residual waste is treated in a WtE plant; in the second one, 75% of waste is separately collected and recycled while the other 25% of mixed residual waste is subjected to mechanical biological pretreatment and subsequent disposal of inert materials to landfill.

Although in the second scenario the final balance is clearly overall better than the first one, results are similar for the two cases in terms of relative contribution for each process, for the considered impact categories (GWP, AP, EP). Collection and transportation are evaluated together and they have no relevance in GWP and AP, while a small relevance in EP. Composting is the most important process affecting EP, contributing for more than 30% to the total emissions and between 11-30 % in the GWP impact category (as a negative value); small contribution results for AP. Avoided emissions due to materials recycling is the most relevant process for every impact category, contributing for more than 30% to the final balance. Incineration and landfilling processes have a very limited influence on all impact categories for the both scenarios, and this can be explained by the fact that only net contribution values are presented.

Swedish studies

Eriksson & Baky (2010) investigate the robustness of results presented in Eriksson et al. (2005) through a numerical sensitivity analysis of several input parameters and assumptions as displaced energy mix, characteristics of incineration plant, waste transport distances, waste characteristics, recycling process parameters. The outcomes point out that in many cases no changes in scenarios ranking order can be observed. For example, waste transport distance is irrelevant in accounting for the final balance and also changing the input waste characteristics generate a very small variation in the results, except for AP which is more sensitive to these parameters. The most unexpected result, as they state, is the small variation when changing compensatory energy: this was supposed to be decisive, as previous studies have shown. However, the sensitivity analysis they perform is just referring to the scenario ranking, without considering the relative differences for each scenario from the base-case.

Norwegian studies

Slagstad & Brattebø (2013) focus on the relevance of assumptions regarding waste composition, in affecting the environmental impacts of a MSW management system, by a LCA point of view. They refer to a hypothetical MSWM system in Norway where 56% of waste is incinerated, around 40% collected for recycling and the rest is landfilled. The reference waste composition is the average between five important Norwegian cities. Transportation has a very little influence on the performance of waste systems as long as the waste is not transported for very long distances. They also found that a ±15% change in selected waste fractions resulted in a greater than 10% change in global warming and eutrophication, hence such LCA impacts are highly sensitive to assumptions regarding waste composition. In particular, changes in paper content have the largest effect on global warming impact, while eutrophication impact category is especially sensitive to changes in food waste.

German studies

Winkler & Bilitewski, 2007 compare three different MSW management options for the city of Dresden, throughout six LCA models. In the first scenario the main waste treatment is landfilling, in the second is incineration and in the third is MRF; collection and transportation are also evaluated, but in nearly every case the contribution of this stage is negligible in terms of emissions, for the total balance. The most important finding of the analysis is that the LCIs calculated through different models are mainly influenced by only one or two major processes of the waste management system. These stages are landfilling, incineration or MRF and the avoided emissions due to energy and material recovery.

Austrian studies

Salhofer et al. (2007) discuss whether material recovery and recycling with longer transport distances is environmentally advantageous or whether waste disposal without recycling is to be preferred, referring to Vienna MSWM current situation. Results are divided per different type of transportation per different waste fraction and it can be observed how, in the majority of cases, transport does not affect or limit the environmental benefit of recycling strategies and this is in agreement with Merrild et al., 2012. Anyway, as they state, it should be borne in mind the “social” relevance of transportation process that can be culturally and politically crucial.

2.3 CONCLUSIONS

More than 30 European LCA studies about MSW management have been analyzed. The objectives of this review were: (i) to investigate the most and least important processes involved in different integrated solid waste management systems affecting Global Warming, Acidifcation and Eutrophication issues; (ii) to detect the most important factors and assumptions related to the operating environment influencing those impact categories and (iii) to provide a general state of the art of LCA studies about MSW management, in order to have a solid background for the following case study development.

It has been observed that not every LCA study includes a detailed contribution analysis, which should be the basis for understanding where the WMS could be improved, and the first step for a general sensitivity analysis.

Moreover, most of the times a sensitivity analysis is carried out with the only purpose of comparing two or more different scenarios. This is done in order to understand if their global ranking is varying when some assumptions are changed and not to figure out the absolute influence of considered parameters on the results.

Given the inconsistency between the findings from those articles, some calculations were necessary for comparing outcomes from different studies.

Collection and transportation processes are often jointly evaluated: their contribution to GWP, AP and EP is usually less than 5 % of total emissions or is considered insignificant while other times its effect can be notable especially for Acidification and Eutrophication related emissions (Bovea et al., 2010, Bovea & Powell, 2006, Miliute & Kazimieras Staniskis, 2010). Nevertheless it is important to evaluate its contribution, mainly when recycling treatment is operated, in order to assess the real benefits of recycling (Merrild et al., 2012, Salhofer et al., 2007, Bovea et al., 2010).

As an average finding, recycling process emissions play an important role on the total balance: direct positive emissions are far lower than avoided emissions deriving from material substitutions, bringing to a net negative contribution of more than 30% on the final balance for AP and EP and between 5-10 % for Global Warming emissions.

Mechanical-Biological plant process emission is observed to have a small influence on the final balance for all impact categories.

As we could expect, in almost all considered studies incineration and landfilling processes are the most important stages in terms of contribution to the final envinronmental balance. In particular, it can be observed that, regarding GWP the most important stage for incineration technology is the stack emission, while flue gas cleaning and ash treatment related emissions are usually smaller or negligible; also the avoided emissions due to energy recovery cover an important role as a negative contribution. Direct emissions from waste landfilling are always important to the final balance, while energy recovery from biogas usually covers a rather small relevance, due to the scarce recovery rate (e.g. compared to energy recovery from incineration).

Results about composting treatment seem to be inconsistent, showing relevant contribution in some cases (especially for AP and EP), but small contribution to the final results in other cases.

The most important assumption that can completely upset the final results has been observed to be the displaced energy mix (Laurent et al., 2014), and this is a consistent conclusion between the studies. It is thereby crucial the way how electricity data must be determined, average or marginal data (Fruergaard et al., 2009). However, it is also crucial the type of hypothesis made when changing the energy mix; for example, changing the energy mix to only coal source can bring completely different results, although this is as predictable as utterly unrealistic.

Even energy recovery efficiency is noticed to have a great relevance affecting mainly GWP and AP (SR>1) and this result is consistent between the studies.

Regarding the importance of assumptions about waste composition, divergent outcomes can be observed in the articles. Some of them mark the crucial relevance of this assumption, mainly affecting GWP emissions (Clavreul et al., 2012; Tonini et al., 2013; Manfredi et al., 2011) while other authors notice its limited influence in their case studies. However, this is strictly related to the way the waste composition is modified.

Substitution ratio and recycling efficiencies seem to be important parameters to evaluate, due to the strong influence that can have on LCA results, mainly GWP (Bovea et al., 2010; Rigamonti et al., 2009).

Anyway it should be kept in mind that these results cannot be generalized for two main reasons:

- the relative contribution of every process on the final balance and the influence of the process related parameters highly depend on the percentage of waste that is routed to that kind of treatment, and this is a consequence of the considered WMS (in a system where 50% of waste are recycled, the recycling processes relative related emissions would be much higher than in a system where only 10% of waste are routed to recycling treatment);
- the relative contribution of every process on the final balance strongly depends on the other processes involved in the WMS, i.e. on the final amount of emissions (e.g. in a system where landfilling is the main waste treatment, landfilling related emissions would represent the greatest part of the total emissions making other unit processes much less significant).

3 MUNICIPAL SOLID WASTE MANAGEMENT SYSTEMS

The following paragraphs will describe the two different municipal waste management systems analyzed.

The description is going through a geographical and demographic explanation as well as a data summary on waste generation. Then a description of the municipal waste management system is performed, starting from the collection, through the treatment, until the final disposal of waste. Finally a short characterization of the plants is carried out, in order to explain which are the processes and technologies involved.

3.1 DISTRICT OF SIENA

The District of Siena belongs to the ATO Toscana Sud (Toscana region, Italy), one of the several authorities in the Italian territory, carrying out the solid waste management system. ATO is Italian acronym of *Ambito Territoriale Ottimale,* a specific area where integrated public services are arranged (e.g. urban water and municipal waste management), according to the national directive. Tuscany region is divided into three different ATO concerned with waste management: Toscana Centro, Toscana Costa and Toscana Sud.
SEI Toscana is at present the sole managing company within ATO Toscana Sud, grouping the previous waste management companies from different areas.

In the following a short description of Siena is given.

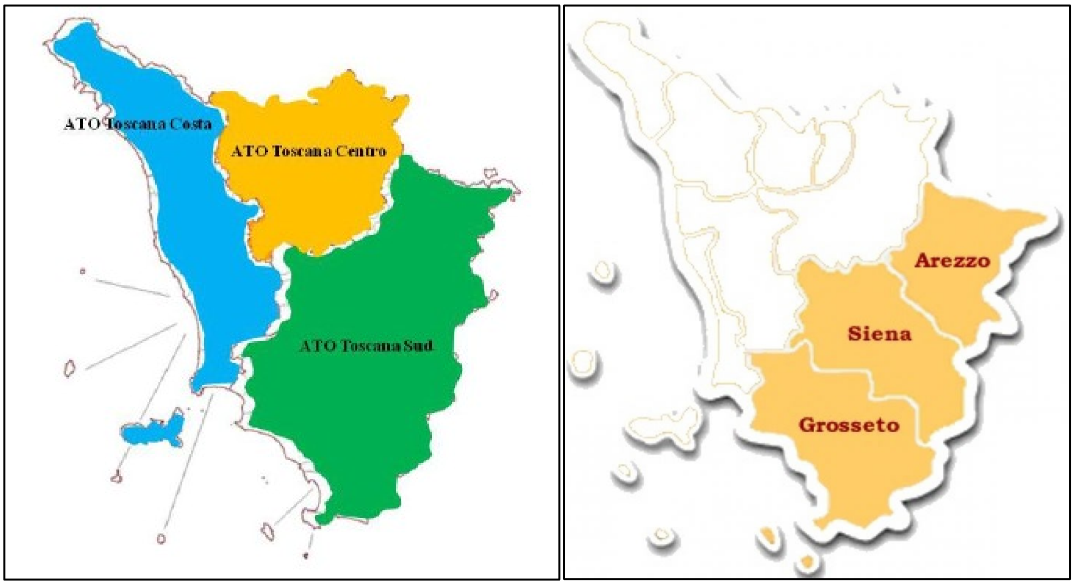

Figure 3.1 Toscana different ATO and ATO Toscana Sud.

3.1.1 Description of the area and waste generation

Province of Siena has an area of 3 762 km^2, divided into 36 municipalities (*comuni*). Referring to 2013 the total population is 270 817 inhabitants, with a density of 72 inhabitants/km^2. Its main city is Siena (54 126 inhabitants).

Regarding waste generation primary data are reported in

Table 3.2, Figure 3.3 and Figure 3.4. The total amount of municipal waste generated in Province of Siena in 2013 was 163 823 t and between them 94 963 t are mixed waste, while the rest are source separated waste (about 45% efficiency). It can be noted how waste production per capita is decreasing in Siena and Italy, probably due to the economic crisis effect, while source separated waste collection is increasing up to 40% all over the country.

The waste total generation is composed by waste from source separation (organic fraction, paper, cardboard, glass, plastics, etc.) and residuals, which are mixed waste.

Mixed waste include food wastes, market wastes, yard wastes, plastic containers and product packaging materials, and other miscellaneous solid wastes from residential, commercial and institutional. Further details about municipal mixed waste composition will be given in the following.

Figure 3.2 Province of Siena divided into municipalities.

Table 3.1 Siena population (Rapporto Rifiuti Siena, 2013-2014).

	Area [km^2]	Population [inhabitants]	Density [inhab./ km^2]
Siena	118	54 126	458
Province of Siena	3 762	270 817	72
ATO Toscana Sud	11 498	846 187	74
Tuscany	22 987	3 745 593	163

Table 3.2 Waste generation in Siena and Tuscany (Rapporto Rifiuti Siena, 2013-2014; ISPRA, Rapporto rifiuti urbani 2014).

	Total amount of waste		Source separated waste		Residual waste	
	[t/year]	[t/(pers*year)]	[t/year]	[t/(pers*year)]	[t/year]	[t/(pers*year)]
Province of Siena	163 823	605	68 860	254	94 963	351
Tuscany	2 252 697	601	901 078	241	1 351 618	360

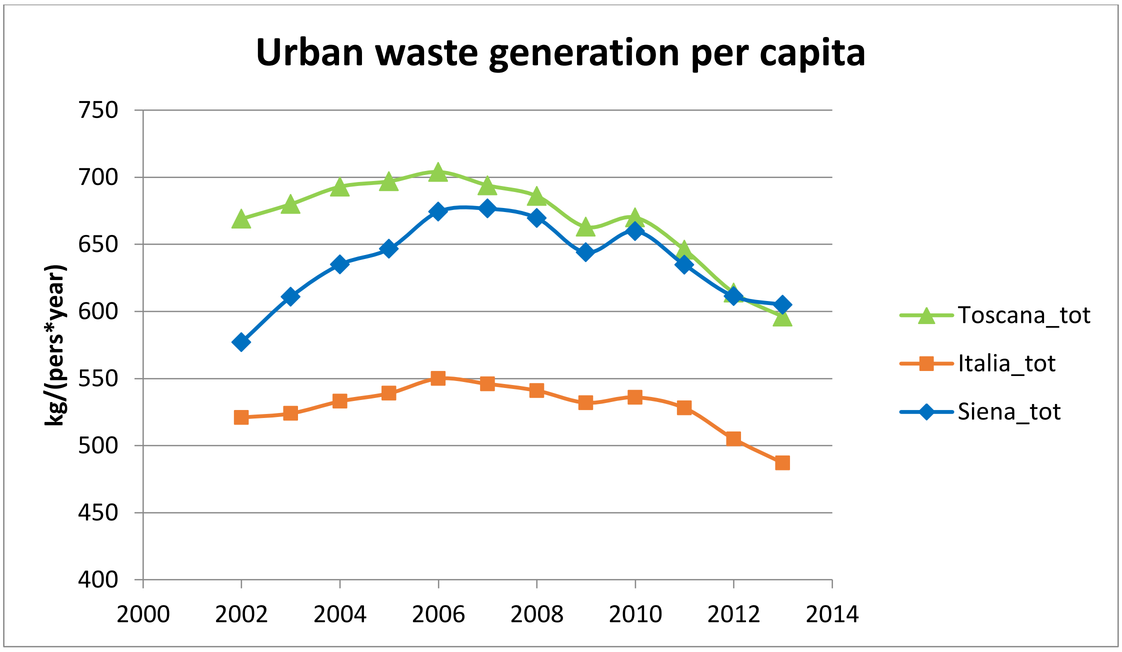

Figure 3.3 Urban waste generation per capita in Siena, Tuscany and Italy (Rapporto Rifiuti Siena, 2013-2014).

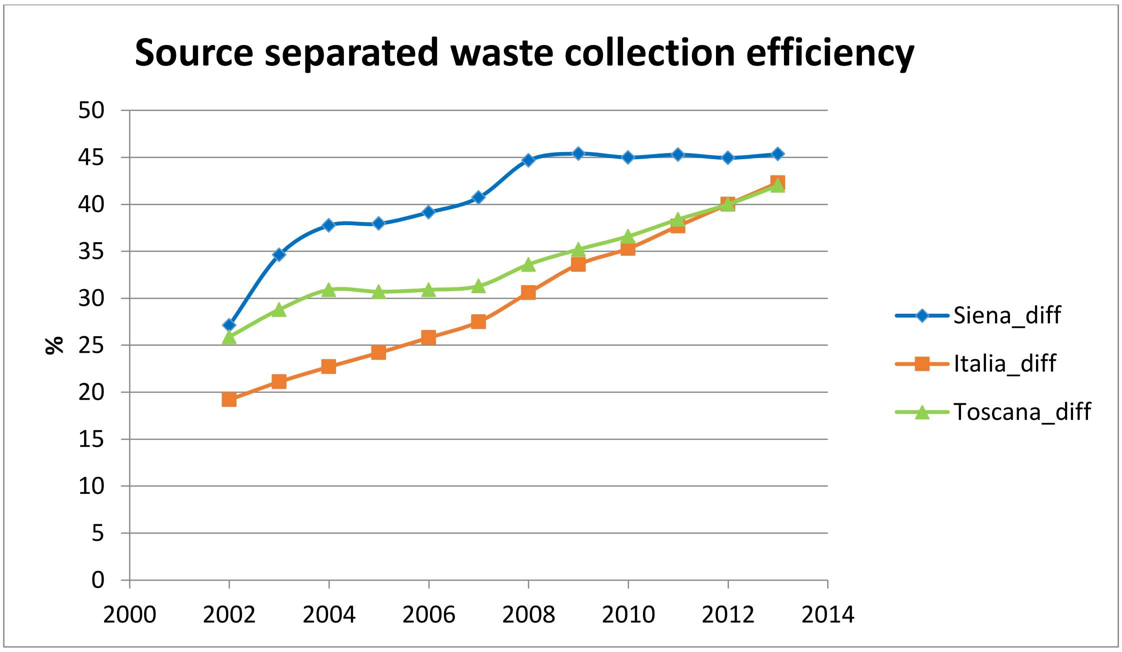

Figure 3.4 Source separation waste collection efficiency in Siena, Tuscany and Italy (Rapporto Rifiuti Siena, 2013-2014).

3.1.2 Waste management system

Different collections of source separated municipal waste are managed individually and could be slightly different in the city centres and in residential areas. Both collection of residuals and source segregated fractions are carried out mostly by public collection point, where large containers (1 300 ÷ 2 000 litres) or small ones (750 ÷ 1 000 litres) are placed and emptied by side-loader truck or medium size rear-loading truck. In the city centre, where the collection trucks cannot drive up to the bins, the door-to-door collection is also activated. In this case sacks or small containers are collected according to a fixed schedule and emptied by means of smaller rear-loading collection trucks. Another opportunity are the collection centres which are collection points where waste can be brought by private car and disposed in different large containers. The collection centres are located in non-residential areas, sometimes near shopping centres, because of their size and the increase in traffic and noise.

From the collection system until the final disposal residuals and source segregated fractions are managed separately; the flow chart in Figure 3.5 shows the waste management system.

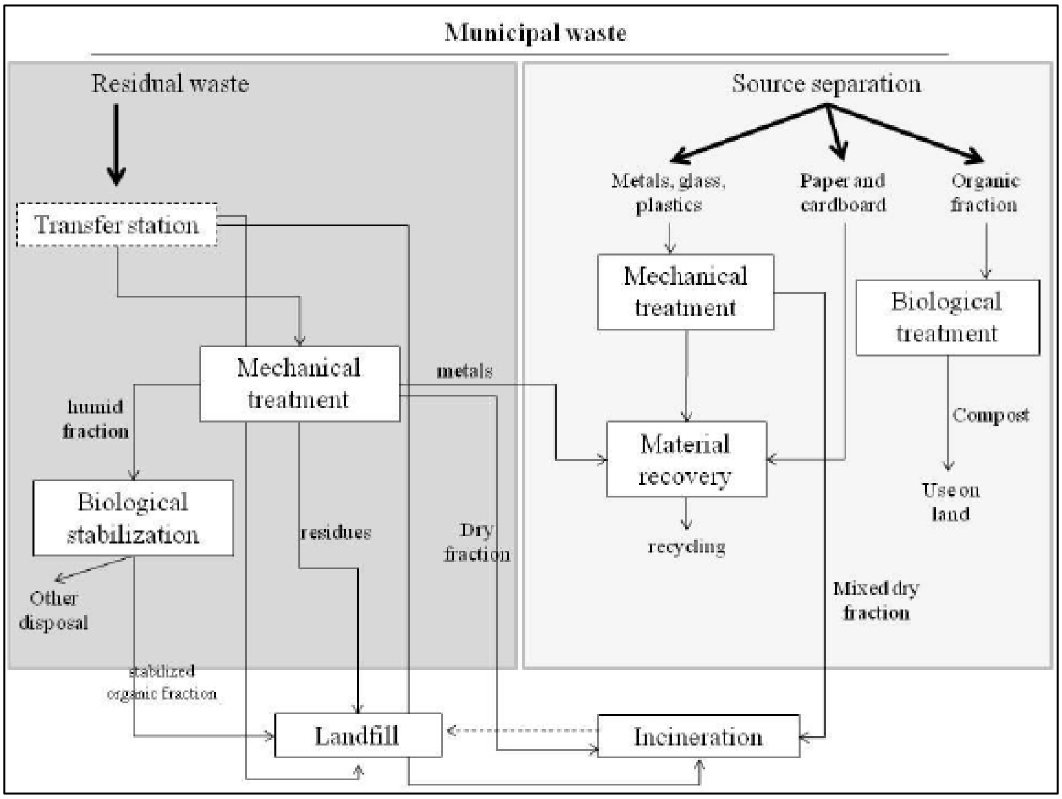

Figure 3.5 Flow chart of the municipal solid waste management system in the District of Siena.

After the collection, residual wastes go to transfer station and then to mechanical and biological treatment. A minor part goes directly to landfill or incinerator. Mechanical treatments are used to separate organic fraction, dry fraction and metals. These flows go respectively to biological stabilization or landfill, incinerator and material recovery.

Wastes from source separation are handled with the aim of material recovery and, concerning organic fraction, with the purpose of production of compost for use on land.

All the residuals from treatment and remanufacturing of materials are routed to landfill or incinerator.

3.1.3 Description of the plants

Several plants are involved in Siena waste management system; all of them are handled by *SienAmbiente SPA,* a public-private joint venture dealing with solid waste, sharing around 25% of *SEI Toscana*.

Figure 3.6 shows where main plants are located within Province of Siena.

Figure 3.6 Plants location in Siena Province (www.sienambiente.it).

- Poggio alla Billa, landfill for non-hazardous waste, Abbadia San Salvatore municipality;
- Torre a Castello, landfill for non-hazardous waste, Asciano municipality;
- Le Cortine, mechanical and biological treatment facility for residual waste, Asciano municipality;
- Pian dei Foci, Waste to Energy incinerator plant, Poggibonsi municipality.

Mechanical and Biological treatment plant, Le Cortine

Built in 2002, it's a multi-function facility which consists of an area dedicated to mechanical and biological treatment for mixed MSW and an area for aerobic stabilization for sorted OF.

Its main functions are:

1. selection of waste with high energy content to send to Poggibonsi incinerator;
2. aerobic stabilization of organic fraction of municipal solid waste before landfilling;
3. cleaning and selection of others fraction material coming from source separated collection in order to recycle them.

The area dedicated to mechanical selection of MSW is composed by:

- waste input area;
- size reduction facility;
- trommel screen with 3 different size output (dry fraction, organic fraction and fine residues);
- two magnetic separators, one for the line of dry fraction and one for the line of organic fraction;
- power press for Refuse-derived fuel (RDF) production from dry fraction.

After magnetic separator the dry fraction (then RDF) is sent to incineration plant, while organic fraction is treated with aerobic stabilization in order to reduce biodegradability before going to landfill. Metals are sent to other specialized facilities for material recovery.

This area is confined and an aspiration system is installed in order to withdraw exhaust air and to treat it with biofilters to remove odorous and volatile organic compounds.

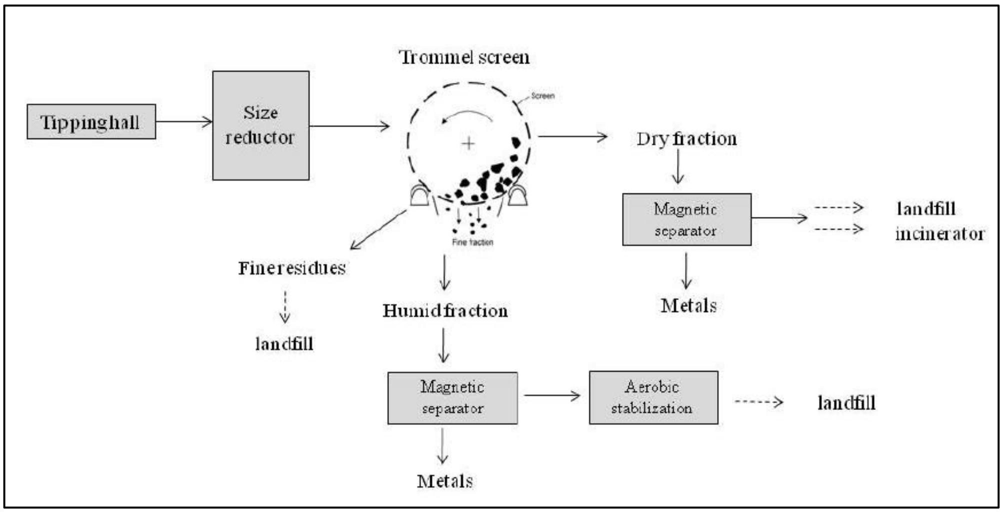

Figure 3.7 Waste flow chart in MBT plant Le Cortine.

Figure 3.8 Mechanical treatment area, MBT Le Cortine (www.sienambiente.it).

Figure 3.9 Areobic stabilization area, MBT Le Cortine (www.sienambiente.it).

Figure 3.10 RDF bales, MBT Le Cortine (www.sienambiente.it).

Waste to Energy incinerator plant, Pian dei Foci

The incinerator located at Le Foci consists on three different lines with different furnace capacity, energy recovery technology and air cleaning system. Built in the second half of 70s, at the beginning the plant had only two lines, the third one has been added in 2008, after a huge renovation.

The furnace capacity is about 1.5 t/h of waste for the first two lines and 8 t/h of waste for the third one, furnishing an incineration capacity of 70 000 tons of waste per year. Main information about incineration capacity and energy recovery system are reported in Table 3.3.

Figure 3.11 shows the sketch of the new third line: tipping hall, waste bunker with grabs system to feed the chute of the furnace, furnace area with moving grate, primary air fan, bottom ash bunker, energy recovery system, flue gas cleaning system and stack.

Table 3.3 Incineration plant Le Foci, operating parameters (www.sienambiente.it).

		First and second lines	Third line
Incineration capacity	t/h	1.5	8
Total thermal power	MW	35	
Operating temperature	°C	950-1050	950-1050
Operating pressure in the combustion chamber	mm H_2O	7	7
Heat capacity of the combustion chamber	Kcal/(m^3*h)	150000	150000
Turbine power	MWel	8.4	
Steam production	t/h	36-42	
Steam pressure (turbine)	bar	40	
Steam temperature (turbine)	°C	360	
Gross electric efficiency	%	22	
Flue gas temperature after boiler	°C	230	

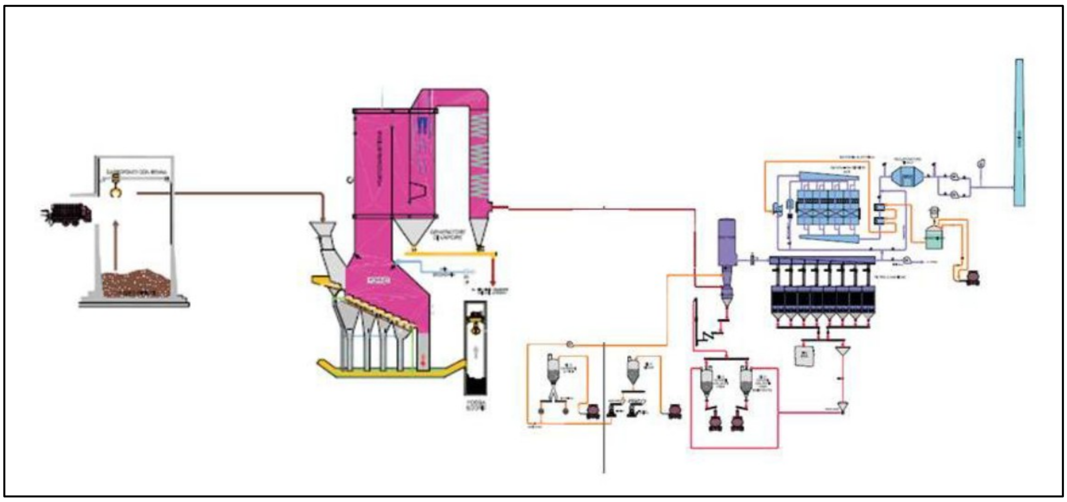

Figure 3.11 Incinerator Le Foci, third line sketch flow (www.sienambiente.it).

The energy recovery system is composed by a boiler which uses heat of flue gases, producing between 4.5 and 34 ton/h of steam which is later expanded in turbines/generators entering at about

40 bar and 360 °C. The excess heat of the low-pressure steam is used to pre-heat air before going to chamber of combustion and to heat water in the steam circuit.

The flue gas cleaning system is different according to the line. The first two lines have a post-combustion chamber where elimination of organic compounds is completed, NOx removal by means of urea injection in the post-combustion chamber, dry system for the acid gases removal by means of sodium bicarbonate injection and activated carbon to eliminate PCDD/PCDF and mercury, and fabric filters to reduce fly ashes. The third line has a cyclone-reactor where dry sodium bicarbonate and activate carbon are used to eliminate acid gases and PCDD/PCDF and mercury respectively. After the cyclone, flue gases go to fabric filters and then to a SCR selective catalytic reduction for NOx removal.

Landfills for non-hazardous waste, Torre a Castello and Poggio alla Billa

The both are landfills for non-hazardous waste, one is located at Torre a Castello, under Asciano municipality, the other one is in Poggio alla Billa, under Abbadia San Salvatore municipality. The main waste input streams are mixed MSW, residues from composting plants, organic fraction of mixed waste and stabilized organic fraction.

Both the landfills are located on a low permeability clayey soil, nevertheless a bottom lining with synthetic material is placed, according to national directive. Leachate collection systems are composed by HDPE pipes of 160-200 mm in diameter, together with drainage systems. Leachate is collected and stored in tanks before going to waste water treatment plant.

Biogas is collected by means of HDPE pipes of 200-280 mm in diameter, then through vertical wells and pump system is extracted and sent partly to gas engine for energy recovery, partly to flare system. Since 2002, Sienambiente is cooperating with another company, called *Marco Polo Engineering S.p.A.*, which manages biogas treatment and energy recovery. Information about biogas collection and combustion for 2013 is reported in Table 3.4.

The upper layers of the landfill consist of soil and vegetation (about 1 m), synthetic drainage layer (0.5 m) and natural clay layer (about 1m).

Table 3.4 Biogas collection and combustion data (www.sienambiente.it).

		Torre a Castello	**Poggio alla Billa**
Starting date		2004	2006
Installed power	kW	836	1 461
Produced electricity	kWh	4 929 132	2 323 186
Combusted biogas	Nm^3	2 895 886	1 527 866

It is important to stress that all the mentioned plants managed by *Sienambiente* have been certified EMAS (Eco-Management and Audit Scheme). EMAS is a voluntary environmental management instrument, which was developed in 1993 by the European Commission. It enables organizations to assess, manage and continuously improve their environmental performance.

In order to register with EMAS an organisation must comply with the following implementation steps (Article 4 of the EMAS-Regulation):

- Environmental review
- Environmental policy
- Environmental programme
- Environmental management system
- Environmental audit
- Environmental statement
- Verification and Registration

Besides, according to latest EMAS guidelines, registered organisations must report key performance indicators in six key environmental areas: energy efficiency, material efficiency, water consumption, waste generation, biodeversity (use of land), emissions to air.

Being registered to EMAS brings environmental, economic and social benefits as well as performance improvements (Vernon, Peacoc, Belin, Ganzleben, & Candell, 2009)

3.2 SOUTH KARELIA REGION

South Karelia is a region in the southern Finland on the border with Russia. The Regional Council of South Karelia is a joint municipal authority of nine member municipalities. The Council operates as the authority for regional development and unit for regional planning.

In the following paragraphs a brief description of the region will be given, together with a sketch of waste generation and management.

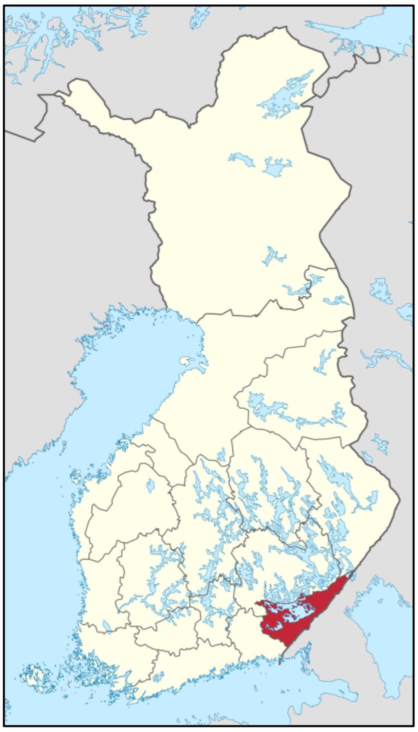

Figure 3.12 Map of Finland, South Karelia region in red (www.wikipedia.it).

3.2.1 Description of the area and waste generation

South Karelia region covers an area of 6 873 km^2 (of which 1 610 km^2 covered by Saimaa lake) divided into nine municipalities: Imatra, Lappeenranta, Lemi, Luumäki, Parikkala, Rautjärvi, Ruokolahti, Savitaipale, Taipalsaari (Figure 3.13).

Population in 2013 was 132 252 inhabitants, with a density of 19 inhabitants/km^2.

Regarding waste generation, in 2013 the total amount of municipal waste from South Karelia was 75 280 tonnes, approximately 569 kg/inhabitant. Among these, nearly 52 780 tonnes are source separated waste, while 22 500 t is the residual dry waste. Separate collection is reserved for recoverable materials as cardboard, glass, metal and paper, as well as for biodegradable waste.

Table 3.5 Waste generation in South Karelia and Finland (www.ekjh.fi; www.jly.fi)

	Total amount of waste		Source separated waste		Residual waste	
	[t/year]	[t/(pers*year)]	[t/year]	[t/(pers*year)]	[t/year]	[t/(pers*year)]
South Karelia	75 280	569	52 780	399	22 500	170
Finland	2 681 547	501	1 372 350	248	1 372 350	253

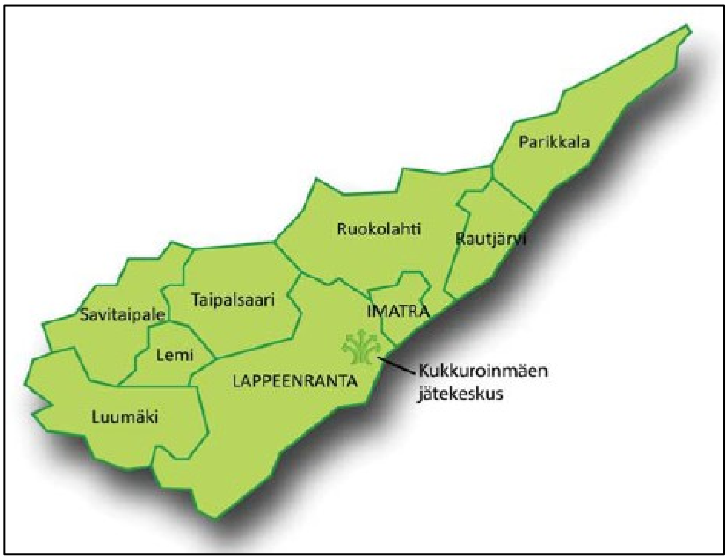

Figure 3.13 South Karelia region divided into nine municipalities (Etelä-Karjalan Jätehuolto Oy. 2013. Vuosikertomus 2013, Annual report 2013).

3.2.2 Waste management system

Etelä-Karjalan Jätehuolto Oy, literally "South Karelia Waste Management" (www.ekjh.fi), is the waste management company that is jointly owned by the nine municipalities in South Karelia region. The company handles and develops the waste management services provided by its owner municipalities. It's a member of *Jätelaitosyhdisty (JLY),* the Finnish Solid Waste Association (FSWA), a national organization that represents Finnish regional and municipal waste management companies all over the country.

Etelä-Karjalan Jätehuolto Oy is responsible for the transportation, reception, and further processing of dry and biowaste, and for recoverable waste management.

Within the operating area of *Etelä-Karjalan Jätehuolto Oy*, all housing properties including holiday homes must be included in organized waste management in some way.

There are three options for organizing waste management of the property:

- Individually owned waste bins;
- A shared waste bin (e.g. between neighbours);
- A local waste collection point.

In densely populated areas, individually owned and shared waste bins are most common while in sparsely populated areas, a local waste collection point is sometimes the only option.

Separate collection is reserved for recoverable materials (cardboard, glass, metal, and paper) as well as for biodegradable waste; separately collected bio-waste is transported for composting and the soil generated is later used. Residual urban waste are called *dry waste* and they can be disposed to landfill or burned into Waste to Energy incinerator plants. According to the Waste Act, disposal of waste at landfills must be reduced significantly, but still in 2012 almost all the amount of mixed MSW from South Karelia (residual dry waste) was landfilled.

There are 141 regional collection points used all year-round and eight collection points are used only in summertime. The mixed MSW is transported from the regional collection points to the waste management company in the city of Lappeenranta, i.e. the Kukkuroinmäen waste management center, showed in Figure 3.14.

Figure 3.14 Kukkuroinmäen waste management center, Lappeenranta (Etelä-Karjalan Jätehuolto Oy. 2013. Vuosikertomus 2013, Annual report 2013).

The landfilling and/or the reloading of the mixed MSW takes place at the company in Lappeenranta.

Dry waste are compressed by the garbage trucks and transported on a temporary transfer station in Kukkuroinmäen plant; dry waste which is not disposed of in Kukkuroinmäen disposal area, is reloaded on trucks and delivered for energy use.

Landfilling has been nearly the only way to treat the mixed MSW in the South Karelia region. In 2012, the waste management company invited tenders for the combustion of the mixed MSW. It was decided that the mixed MSW was to be transported and combusted in the grate furnace in Riihimäki, however, this is not the closest incineration plant. The decision was made based on the total cost of transportation and treatment. Transport of the mixed MSW started in the beginning of 2013 and in the end of the year one third of total dry waste was burned into the plant, producing district heating and electricity for the grid. This change has been made step by step so that all the mixed MSW will be combusted in 2015 (*Etelä-Karjalan Jätehuolto Oy. 2013. Vuosikertomus 2013, Annual report 2013*).

In Figure 3.15 the flow chart of South Karelia MSW management is shown; four different alternatives are pointed out for the residual dry waste: landfilling was the only destination for dry waste up to 2012.

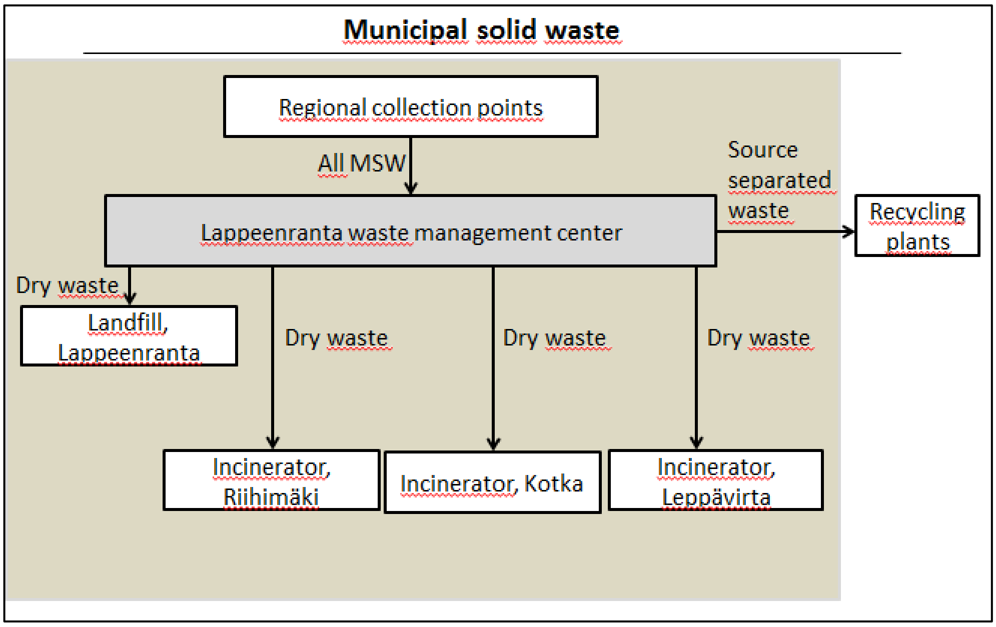

Figure 3.15 Municipal Solid Waste flow chart for South Karelia region.

3.2.3 Description of the plants

The main plants involved in South Karelia waste management are:

- Lappeenranta waste management center;
- Lappeenranta landfill;
- Riihimäki Waste to Energy incinerator plant;
- Kotka Waste to Energy incinerator plant;
- Lappävirta Waste to Energy incinerator plant (still in construction).

Figure 3.16 shows the locations of the different plants involved in South Karelia waste management, while Table 3.6 shows the main characteristics of the WtE incineration plants mentioned above.

Figure 3.16 Map of the plants involved in South Karelia waste management.

Table 3.6 Characteristics of considered WtE plants (www.kotkanenergia.fi, www.ekokem.fi, www.riikinvoima.fi).

		Kotka	Riihimäki	Leppävirta
Starting date		2008	2007	2016
Managing company		*Kotkan Energia*	*Ekokem*	*Riikinvoima*
Type of incinerator		Grate furnace	Grate furnace	Fluidized bed boiler
Capacity	[t/y]	100 000	150 000	145 000
Waste pretreatment		No	No	Yes
APC system		Semidry, AC+lime	Semidry, AC+lime, SNCR	Semidry, AC+ limewater, SNCR
Heat prod.	GWh/y	33	458	180
Electricity prod.	GWh/y	30	24	90
Process steam prod.	GWh/y	106	0	0
Total efficiency [%]	%	64	69	-

The incineration plant in Leppavirtä is still under construction and it will be probably ready in December 2016 (www.riikinvoima.fi).

Lappeenranta waste management center (Kukkuroinmäen waste center) has already been described in paragraph 3.2.2. It's important to note that the sanitary landfill in Lappeenranta has a system for biogas collection and flaring, but it is not provided with a system for energy recovery from biogas combustion.

4 COMPUTATIONAL IMPLEMENTATION

This chapter contains a brief description of *GaBi ThinkStep* software, one of the most known decision support LCA tool for product sustainability; then a description of *GaBi* database is performed, focusing on those ready processes which are used in this work.

There are several LCA softwares currently on the market and each one offers different features, layers of complexity and databases. The main function of the software is to support the user in the inventory phase of LCA and in order to do that it must have two important characteristics:

- volume, quality and relevance of the available data;
- ease of use of the software.

The other important feature of the software is to provide a support for the impact assessment: there are different computing systems in GaBi software, so that the user can choose the impact assessment technique which is more congenial to the study, providing also the possibility to compare different methods.

Within the scope of this study, this LCA software has been utilized as an evaluation tool for different municipal solid waste management options for the province of Siena, therefore only those related processes are investigated. Besides, a large part of the following chapter is committed to the description of other external process models: Mechanical and Biological treatment, Waste to Energy incineration and landfilling.

4.1 GABI THINKSTEP 6.0

GaBi software has been developed by University of Stuttgart together with *PE International* , now *ThinkStep* (a company working in the field of Life Cycle Assessment and Life Cycle Engineering) and it's considered as one of the most known and used LCA software all over the world (www.gabi-software.com).

GaBi (shortened word for *Ganzheitliche Bilanz,* which means Holistic Balance in German) allows user to create life cycle balances for products and services and to interpret results in terms of cost, environmental impacts, social and technical criteria, according to the standards of ISO 14040 series.

The software contains more than 70 impact categories and impact assessment methods (CML, Eco-Indicator, ReCiPe,...) and databases provide information and details about LCA for more than 2000 processes. Software interface is easy to use and from the result window it is allowed data transfer on Excel. Figure 4.1 shows the main page of *GaBi 6.0.*

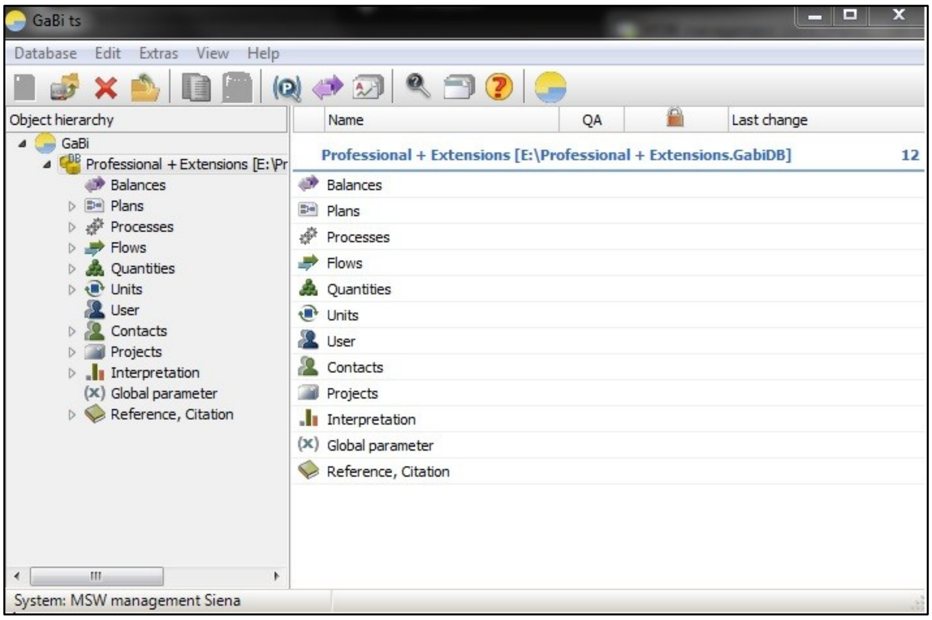

Figure 4.1 GaBi main page.

The creation of a life cycle balance is based on plans, processes and flows; in the following every feature is briefly described, summarizing information taken by GaBi 6.0 Manual (PE International AG, 2012).

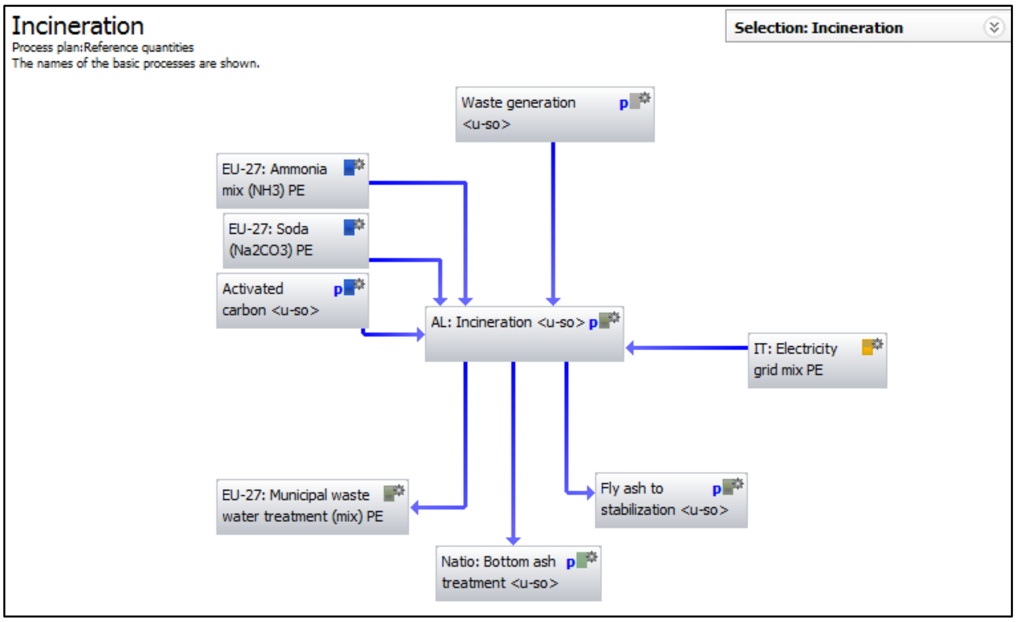

Figure 4.2 Example of plan in GaBi: the plan is called Incineration and it includes the processes (grey boxes) and the flows (blue arrows) that link the processes.

On GaBi plans, individual elements of a product or the product life cycle are combined into an overall model using unit processes. The individual processes are represented by grey boxes. They represent the underlying process and procedural steps. The arrows between the boxes form the material and energy flows that are exchanged between the individual process steps (PE International AG, 2012). The user can therefore build a Sankey diagram describing the product-system life cycle.

Figure 4.2 shows an example of plan as built in GaBi.

FLOW

The basis of modeling using GaBi is the flow object type. A GaBi flow is a representative of an actual material or energy (and in further analysis also money) flow. Flows are used by processes (in ISO nomenclature: "modules“ as in- and outputs) and represent the link between processes within a life cycle. The GaBi database has a comprehensive hierarchical division of flow definitions called the "flow group hierarchy”. The hierarchy provides a pre-defined set of flows categorized by type, however you can create new flows. During the development of a model, energy or material flows are assigned to processes. GaBi distinguishes between two kinds of flows: valuable flows and elementary flows. Valuable material flows, i.e., flows of materials that can be recovered and waste material flows can be designated as “Tracked flows”. Only flows that have been marked as “Tracked flows” in the corresponding processes can connect processes with one another and therefore be sent to another processing step. Elementary flows on the other hand are flows which originate from or go outside of the limits of the technical system (e.g. resources or emissions). Elementary flows do not visually appear on plans. Figure 4.3 shows an example of valuable and elementary flows in input and output from a process; the incineration process is considered in the example. The bolded flows are valuable flows while the red ones are elementary flows (emissions).

Inputs

Parameter	Flow	Quantity
tot_c_AC	**Activated carbon [Organic interi**	**Mass**
tot_c_ami	**Ammonia [Inorganic intermedia**	**Mass**
RDF	**Dry waste [Waste for recovery]**	**Mass**
tot_electri	**Electricity [Electric power]**	**Energy (net ca**
MSW	**MSW to Incinerator [Waste for r**	**Mass**
tot_c_sod	**Sodium bicarbonate [Inorganic i**	**Mass**
	Flow	

Outputs

Parameter	Flow	Quantity
tot_flyash	**Fly ash (unspecified) [Stockpile**	**Mass**
tot_bottoi	**Furnace bottom ash [Waste for i**	**Mass**
tot_waste	**Water (waste water, untreated)**	**Mass**
tot_e_CO2	Carbon dioxide [Inorganic emissions t	Mass
tot_e_HCl	Hydrogen chloride [Inorganic emission	Mass
tot_e_HF	Hydrogen fluoride [Inorganic emission	Mass
tot_e_NOx	Nitrogen oxides [Inorganic emissions t	Mass
tot_e_SO2	Sulphur dioxide [Inorganic emissions t	Mass

Figure 4.3 Example of valuable and elementary flows in input and output from a process.

PROCESS

GaBi processes are representative of actual processes, technical procedures or groups of procedures. They roughly correspond to the term "unit process" in ISO 14044. GaBi processes are lists which consist of input and output flows representing the manufacture of a product, the procurement of a raw material, transport, service etc. Generally more than one process is required to manufacture a product. Like flows, processes in the GaBi system are hierarchically grouped. The process hierarchy enables you to save your own processes and use processes multiple times. In addition, a set of processes is provided with your database to support your modeling. In particular upstream data, such as energy generation, basic material generation, etc., does not have to be specially collected by the user since these are already available in the database.

ALLOCATIONS

If processes have several product outputs (co-products), all other flows assigned to a process can be distributed among the product outputs. In ISO 14044 this is called an "Allocation". GaBi 6 makes it possible to perform allocations easily. It also allows allocations to be performed without changing the process in the database.

PLANS

Plans are used in GaBi to assemble processes in the product system. Essentially, plans are the process maps which visually depict a stage or sub-stage in the system. GaBi plans can be nested in order to display complex balance systems. Thus you can nest a plan within another plan in the same way that you use processes on a plan. For example, you can develop a process plan for a manufacturing system and use it in several places in your model.

BALANCES

The GaBi object type "balances" compares all inputs of one or several balance systems with their outputs. Balances are calculated based on the system model. GaBi balances therefore contain the results of the life cycle inventory. Balances can be viewed multiple ways, using different units, category filters, impact categories, etc. Thus the balance window can be used to perform life cycle inventory analysis, impact analysis and interpretation.

IMPACT ASSESSMENT

According to ISO 14044, the goal of balancing the system is the assessment of the potential environmental impacts. The assessment is divided into two sub-steps which must be performed (according to ISO) as a minimum:

- Assigning life cycle inventory data to life cycle impact categories (classification).

- Modeling the life cycle inventory data within the life cycle impact categories (characterization).

GaBi performs these two sub-steps in the Balances window simultaneously. You can very easily toggle between life cycle inventory variables such as "mass" or "energy" and life cycle impact categories such as "global warming potential – GWP" or "ozone depletion potential – ODP" in the GaBi balance window.

The object oriented structure enables you to view the classification (assignment of material flows to environmental impacts) and equivalency factors (quantification of material flows relative to the environmental impact of a standard material flow) and to make changes at any time using current scientific findings via the database manager. The data supplied in the GaBi database for classification and characterization are published by ISO, SETAC, WMO and IPCC, and the resulting characterization are sets provided by CML, EDIP, EcoIndicator, TRACI, EPFL 2002+, UseTox, ReCiPE. In order to summarize balances to aid decision-making, weighting can be performed from the balance window.

4.2 GaBi TS database

Together with the software a detailed database is included in the license. GaBi databases offer more than 8 000 Life Cycle Inventory datasets based on primary data collection gathered during cooperation work with companies, associations and public bodies. GaBi Databases span most industries including (www.gabi-software.com):

- Agriculture
- Building & construction
- Chemicals & materials
- Consumer goods
- Education
- Electronics & ICT
- Energy & utilities
- Food & beverage
- Healthcare & life sciences
- Industrial products
- Metals & mining
- Plastics
- Retail
- Service sector
- Textiles

The database which is used for this work is the standard *GaBi Professional database 2014;* it includes:

- PE-International dataset;
- ecoinvent v3 database;
- complete European Life Cycle Database (ELCD);

- Plastic Europe – Association of Plastics Manufacturers dataset.

Figure 4.4 shows how the processes are grouped into GaBi Database.

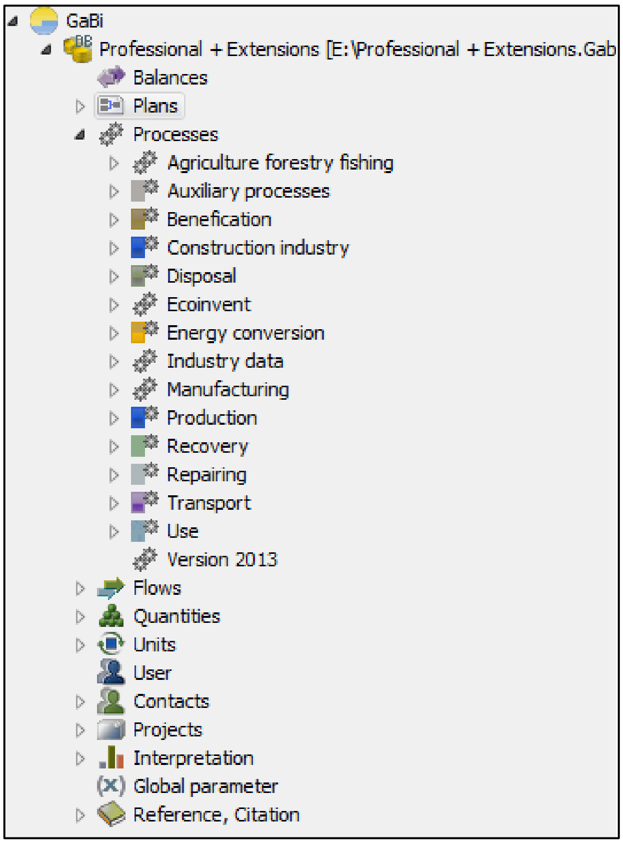

Figure 4.4 Processes grouping in GaBi database.

Some of the processes used for the life cycle assessment of the waste management system were taken as ready processes from *GaBi professional database 2014.* Below a brief description of them.

4.2.1 Transportation: truck and diesel filling

The transportation stage is modeled using two ready processes contained in GaBi Database: *Truck PE,* which contains the inventory for the utilization of trucks for material transportation, and *EU-27 Diesel mix at filling station PE* which contains the inventory for the use of diesel as fuel for trucks.

Trucks

The utilized means of road transportation are cargo trucks, Euro 5 (SCR equipped), diesel driven. The considered gross weight is more than 32 t, with 24.7 t payload capacity.

The data set allows individual settings of the variable parameters. The following parameters are variable: payload, utilisation ratio, distance, sulphur content of fuel and driving share urban/rural/motorway. Default values of the variable parameters have to be checked and adjusted for individual use. The data set does not include the fuel supply route.

The variable parameters are set as described below:

- distance: according to the real distances (Table 5.1);
- payload: 24.7 t;
- ppm sulfur in diesel: 10 ppm;
- share of biogenic C in fuel: 5 %;
- driving share motorway: 70%;
- driving share rural road: 23 %;
- driving share urban road: 7 %;
- share of utilization by mass: 85 %.

The process has as outputs cargo and combustion emissions (ammonia, benzene, carbon dioxide, carbon monoxide, methane, nitrogen monoxide, nitrogen dioxide, nitrous oxide, NMVOC, particulate PM 2.5, sulphur dioxide). NMVOC emissions of the truck result from imperfect combustion and evaporation losses via diffusion through the tank. Truck production, end-of-life treatment of the truck and the fuel supply chain are not included in the data set.

Diesel mix at filling station

The data set covers the entire supply chain of the filling station products. This includes well drilling, crude oil production and processing, transportation of crude oil via pipeline to the refinery as well as transportation from refinery to filling station. Main technologies such as conventional (primary, secondary, tertiary) and unconventional production (oil sands, in-situ), both including parameters like energy consumption, transport distances and crude oil processing technologies are individually considered for each crude oil production country. Also considered are country specific downstream (refining) and filling station technologies, feedstock (crude oil) and product (diesel fuel) properties, like sulphur contents. All fuel delivering countries, including domestic production, contribute by their corresponding shares to the fuel mix. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.

Petroleum refineries are complex plants. The combination and sequence of a large number of processes is usually very specific to the characteristics of the crude oil and the products to be produced. Additional influencing factors are the market demand for the type of products, the available crude oil quality and certain requirements set by authorities the configuration and complexity of a refinery. A simplified flow chart of the refinery operation is shown in Figure 4.5. The arrangement of these processes can vary among refineries.

The data set considers the whole supply chain from crude oil exploration and well installation, production, transport to refining operation, transport to filling station and the re-fuelling operation. The country specific fuel consumption mix, mixes indigenous produced fuel with fuel imports from the corresponding producing countries (Figure 4.6).

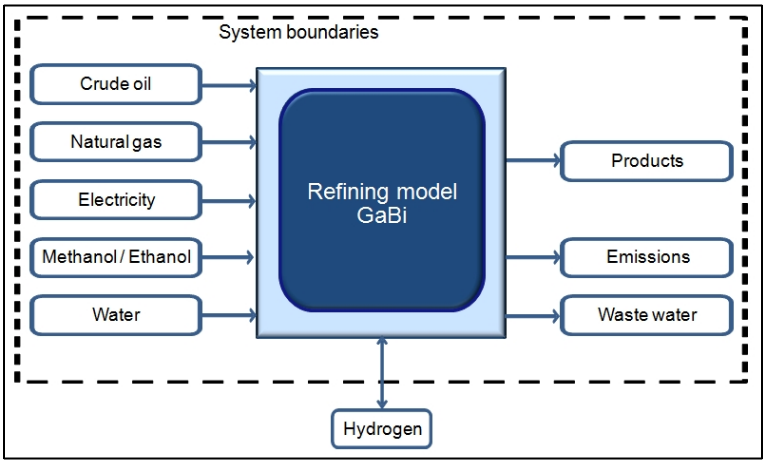

Figure 4.5 GaBi database ready process: diesel refining, system boundaries (GaBi database).

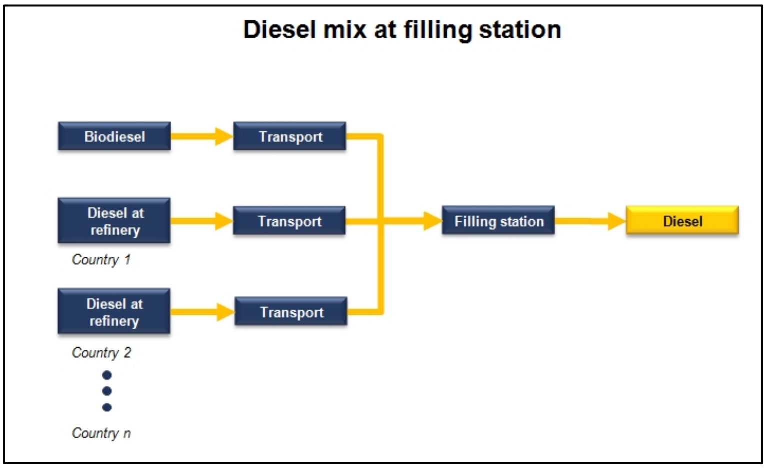

Figure 4.6 GaBi database ready process: diesel production, system boundaries (GaBi database).

4.2.2 Electricity and heat, Italian and European mix

For the supplying of electricity within different stages of the WMS and the production of both electricity and heat included as additional functions in the system expansion (paragraph 5.3.3), two ready processes contained in GaBi Database have been used: *IT: Electricity grid mix PE* and *EU-27: Heat PE*.

Italian electricity grid mix

The data set represents the average Italian specific electricity supply for final consumers, including electricity own consumption, transmission/distribution losses and electricity imports from neighboring countries. The national energy carrier mixes used for electricity production, the power plant efficiency data, shares on direct to combined heat and power generation (CHP), as well as transmission/distribution losses and own consumption values are taken from official statistics (International Energy Agency, and US-EPA eGRID for USA regions) for the corresponding reference year. Detailed power plant models are used, which combine measured (e.g. NOx) with calculated emission values (e.g. heavy metals). The inventory is partly based on primary industry data, partly on secondary literature data.

The electricity is either produced in energy carrier specific power plants and/or combined heat and power plants (CHP). Also considered are the national and regional specific technology standards of the power plants in regard to efficiency, firing technology, flue-gas desulphurisation, NOx removal and de-dusting. The electricity provided by non-combustible renewable energy sources also considers the national or regional situation, such as solar radiation (photovoltaic), annual full load hours (wind power), and share of hydro power stations by type (run-of-river, storage and pumped storage). Figure 4.7 shows the considered system boundaries.

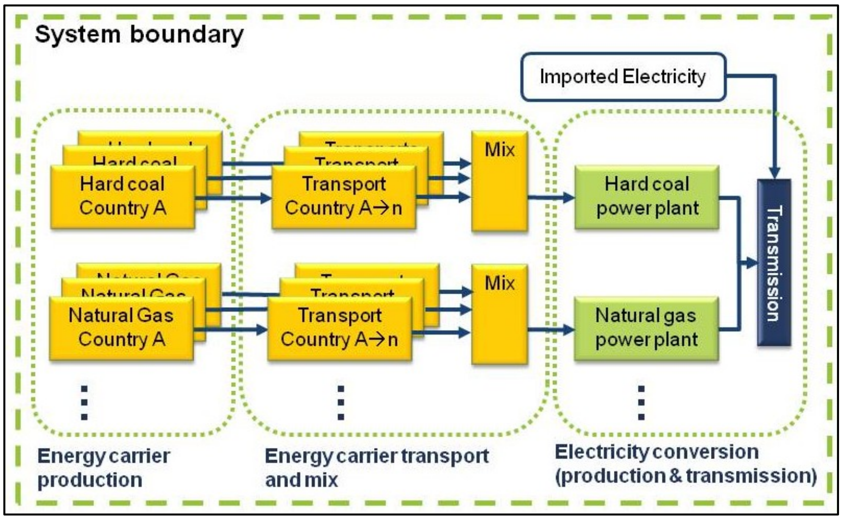

Figure 4.7 GaBi database ready process: electricity production, system boundaries (GaBi database).

The fossil power plant models combine emission data from literature with calculated values for non-measured emissions e.g. organics or heavy metals. For the emissions CO2, SO2, NOx, CO, CH4, N2O, NMVOC and particulate matter (PM) measured/calculated data are used, taken from national inventory reports, emission inventory data bases, utility companies and other sources.

Figure 4.8 shows the considered Italian average electricity mix, referring to 2011.

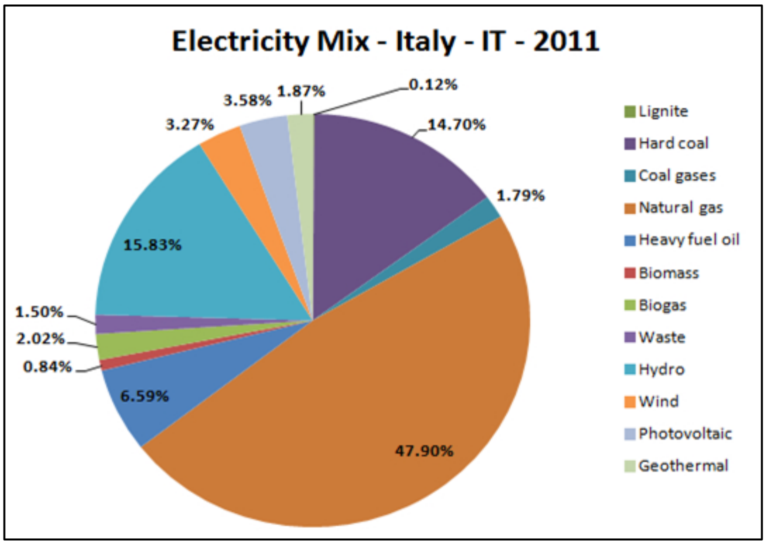

Figure 4.8 Italian average electricity grid mix, 2011 (GaBi database).

Heat

The data set represents the currently used technical standard of newly installed residential heating systems. The functional unit is the supply of 1 MJ heat at a temperature level of 55°C, with the purpose of residential heating. The heat is produced in a light fuel oil (LFO) condensing boiler with a maximum heat output of 14.9 kW. As burner, a blue flame burner is used. A part of the hot exhaust gas is re-circulated and heats the oil mist. The oil droplets are evaporating before the burning process. Thus gaseous oil, exhaust gas and air are mixed and are burning in a blue flame, resulting in lower nitrogen oxide and carbon monoxide emissions in contrast to the formerly used yellow flame burners (which are still existing and used). The data set considers the whole supply chain of light fuel oil, i.e. exploration, production, processing, the long distance transport, the regional distribution and refining of crude oil as well as the distribution of light fuel oil.

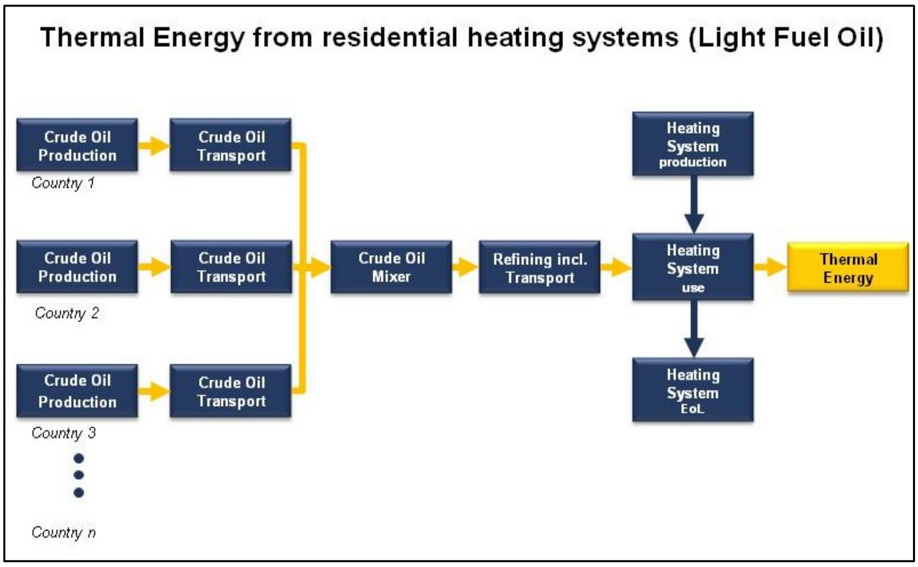

Figure 4.9 GaBi database ready process: heat production, system boundaries (GaBi database).

4.2.3 Steel scrap and aluminum recovery

Another functions included in the system expansion is the credit due to the recycling of recovered metals, i.e. steel scrap and aluminum (see chapter 5). In order to take into account the avoided emissions due to the substitution of these materials, the processes called *EU-27 Aluminum ingot mix PE* and *Credit for recycling of steel scrap* contained in GaBi Database have been used. While the former considers the emissions due to the production of the virgin material, the latter one refers to the credit (avoided emissions) due to the substitution of steel scrap to the virgin material.

Credit for steel scrap recycling

The "value of scrap" is calculated on the basis of the steel product cradle-to-gate LCIs. The datasets include raw material extraction (e.g. coal, iron, ore, etc.) and processing, e.g. coke making, sinter, blast furnace, basic oxygen furnace, hot strip mill, etc. All data and information are taken from the world-steel LCA Methodology Report from 2011. Inputs included in the Life Cycle Inventory relate to all raw material inputs, including steel scrap, energy, water, and transport. Outputs include steel and other co-products, emissions to air, water and land.

Aluminum production

The data set is based on European averages calculated from site-specific data of the European aluminum industry covering bauxite mining, alumina production, primary aluminum production and process scrap remelting. Bauxite mining is a global average. Alumina and primary aluminum production are based on a mixture of local production and imports.

The common raw material for aluminium production, bauxite is composed primarily of one or more aluminium hydroxide compounds, plus silica, iron and titanium oxides as the main impurities. It is used to produce aluminium oxide through the Bayer chemical process and subsequently aluminium through the Hall-Heroult electrolytic process. On a world-wide average 4 to 5 tonnes of bauxite are needed to produce two tonnes of alumina, from which one tonne of aluminium can be produced. In Europe, the average bauxite consumption is 4.1 tonnes per tonne of aluminium.

4.2.4 Ammonia and sodium bicarbonate production

Ammonia and sodium bicarbonate are used in the incinerator APC system. The former one is used for the reduction of nitrogen oxides and the latter is used for acid gases removal. The environmental burdens due to ammonia and sodium bicarbonate production are considered by using the ready processes *EU-27 Ammonia mix (NH3) PE* and *EU-27 Soda (Na2CO3) PE* respectively, contained in GaBi Database.

Ammonia

The GaBi data set represents the European situation, focusing on the main technologies, the region specific characteristics and import statistics.

Ammonia is produced almost exclusively by the well-known HABER-BOSCH process. First, synthesis gas has to be produced. It is a mixture of nitrogen and hydrogen. Nitrogen is gained from air by fractionation, hydrogen from natural gas by steam reforming. The latter process produces CO and CO2, which can be oxidised entirely to CO2 for sale. In this model, the CO2 is not used and calculated as an emission. The final conversion of synthesis gas to ammonia is a carefully trimmed equilibrium reaction which runs at high temperature and pressure. The product then undergoes multiple stages of purification.

Sodium bicarbonate

The data set covers all relevant process steps and technologies over the supply chain of soda cradle to gate inventory. The process of soda production instead of sodium bicarbonate was chosen because it has been assumed that the two processes are most likely the same in terms of emissions. In fact, sodium bicarbonate is one of the final steps in the Solvay process for soda production.

In the Solvay process (ammonia-soda process) for the production of soda ash, ammonia is absorbed and led into a nearly completely saturated solution of common salt (sodium chloride brine). The ammoniated brine is reacted with carbon dioxide (from hydrocarbon products) to form sodium bicarbonate and ammonium chloride.

By calcination the sodium bicarbonate is decomposed into soda (sodium carbonate), water and CO2. The carbon dioxide is again introduced into the carbonation step. Ammonia is re-obtained from the mother liquid by treatment with quick lime (2 NH4Cl + CaO --> 2 NH3 + H2O + CaCl2), and it is then re-introduced into the production process. Further carbon dioxide is produced when the lime is burnt (re-obtaining of ammonia).

4.2.5 Cement production

Cement is used for the stabilization of incineration FA. The environmental burdens arising from the production of cement are considered by using the ready process.

This data is an LCI for steel scrap, calculated using the worldsteel recycling methodology. It should be used to account for the burden of using steel scrap within the steel making process and the credit for the end of life recycling of steel within a product. The net amount of scrap should be used (recycling rate - scrap input).

The main processes in cement production are raw material extraction, production of clinker, and cement grinding. The extraction of the main raw material from the quarry normally takes place in the immediate area of the cement works. Clinker as main ingredient is made up of a mixture of mainly calcium oxide, silica, aluminum oxide, and iron oxide. Limestone, chalk and clay provide these chemical constituents. The raw materials get extracted, homogenised, grinded and afterwards kilned. Result is grinded clinker, the obligatory ingredient of all types of cement.

4.2.6 Waste water treatment

In order to model the waste water flow coming from incinerator plant, it was used the ready process *EU-27 Municipal waste water treatment (mix) PE* contained in GaBi Database.

This data set covers all relevant inputs and outputs from the treatment of incoming waste water from industrial processes. It contains mechanical, biological and chemical treatment steps for the waste water (including precipitation and neutralization), and treatment steps for the sludge (thickening, dewatering, drying, conditioning). The outflow goes directly to the receiving water (natural surface water). The waste water composition to the plant represents an average outflow of a chemical industry commodity to the treatment plant with organic and inorganic substances. The process steps are taking average elimination and transfer coefficients into account.

In this dataset 50% of the sludge is processed via sludge incineration and 50% via an agricultural application (use as fertilizer). The background system is addressed to average European conditions.

4.3 EXTERNAL MODELS

For the processes of Mechanical and Biological Treatment, waste incineration and landfilling, external models were used. This was established in order to set real parameters taken from the plants and to consider the real input waste composition for the calculations. In the following paragraphs each of these models is described.

4.3.1 Mechanical and Biological Treatment

To model the different output flows originating from mechanical separation and biological treatment an Excel spreadsheet was created. The reference system is the *MBT Le Cortine* plant described in paragraph 1.1.3.

The calculations regard only the trommel screen step and the aerobic stabilization of the organic fraction, which are likely to be the core stages of the unit process. Also magnetic separation is considered, just assuming a specific value for metal recovery efficiency. A flow chart is reported in Figure 4.10.

The process is characterized by one input flow (municipal solid waste) and 4 output flows:

- oversize material: mainly composed by dry waste (plastics, paper, cardboard…), therefore characterized by a high calorific value;
- undersize material: mainly composed by humid waste (organic waste and heavy waste), characterized by a high rate of biodegradability;
- fine residues: mainly composed by inert and small material;
- metals: composed by ferrous and non-ferrous material contained in oversize and undersize flows.

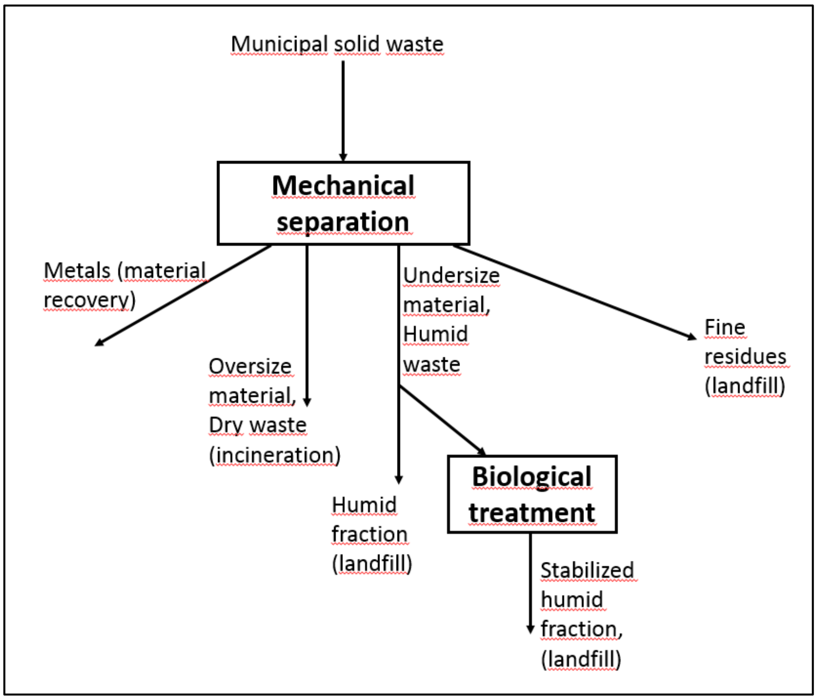

Figure 4.10 MBT flow chart.

Mechanical separation

For the separation efficiency calculations it has been necessary to adopt a size distribution for the different fractions of waste (*Zanchi L., 2011*). Given the size distribution it is possible to determine the separation efficiency for every fraction of waste, once trommel screen parameters are set.

In Figure 4.11 is shown the separation efficiency of the trommel screen in terms of percentage of material in the undersize flow, for different aperture size, for every fraction of waste.

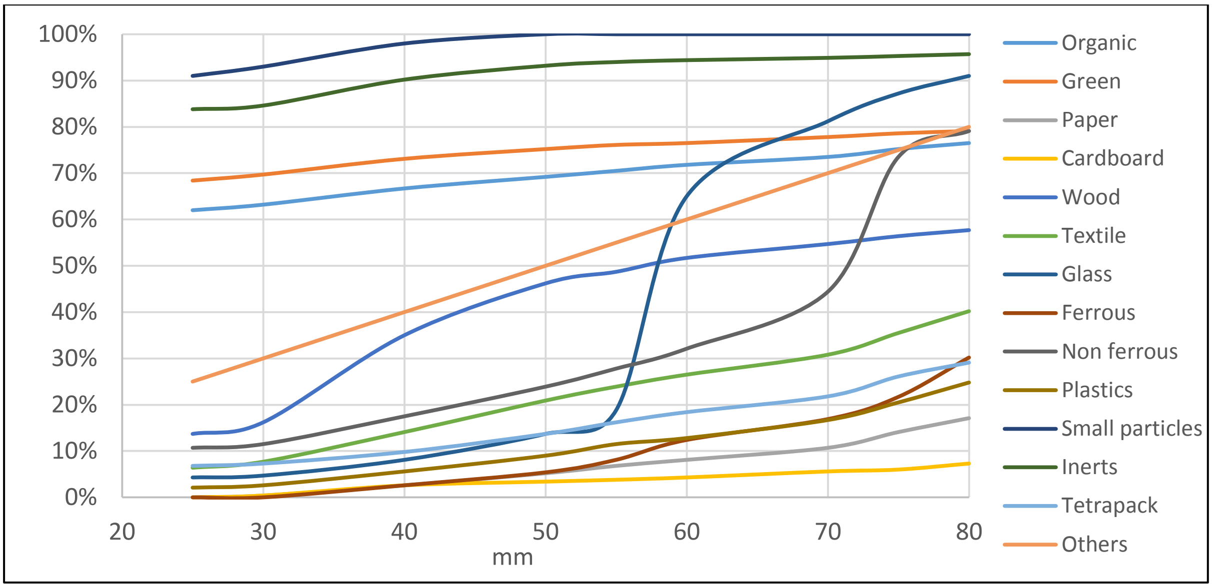

Figure 4.11 Separation efficiency of the trommel screen for different aperture size for every fraction of waste.

The only input data which are needed in this part are the MSW composition, the aperture size of the trommel screen, the magnetic separation efficiency and the percentage of fine residues for every fraction of waste. Defining:

- $f_{i,j}$ = mass of fraction *i* in the undersize flow assuming an aperture size *j* [%];
- m_i = mass of fraction *i* in the input waste composition [%];
- s = magnetic separation efficiency [%];
- r_i = mass of fine residues in fraction *i* [%] (only from undersize flow);

it is thus possible to calculate the material composition of the different output flows.

$$undersize_i\ (\%) = f_{i,j} * (1 - r_i)$$

$$oversize_i\ \ \% \ = m_i * (1 - f_{i,j})$$

$$fine\ residues_i\ \ \% \ = undersize_i * r_i$$

Regarding ferrous metal recovery it can be calculated multiplying the percentage of ferrous metal both in the undersize and oversize flows by the magnetic separation efficiency *s.*

It can be observed how the aperture size of the trommel screen affects the oversize flow (dry waste then refuse derived fuel, RDF) characteristics. The example in Figure 4.12 is calculated considering the Italian average municipal solid waste composition (Ispra, 2013) and the total waste input amount used in this work (provided by *Sienambiente*).

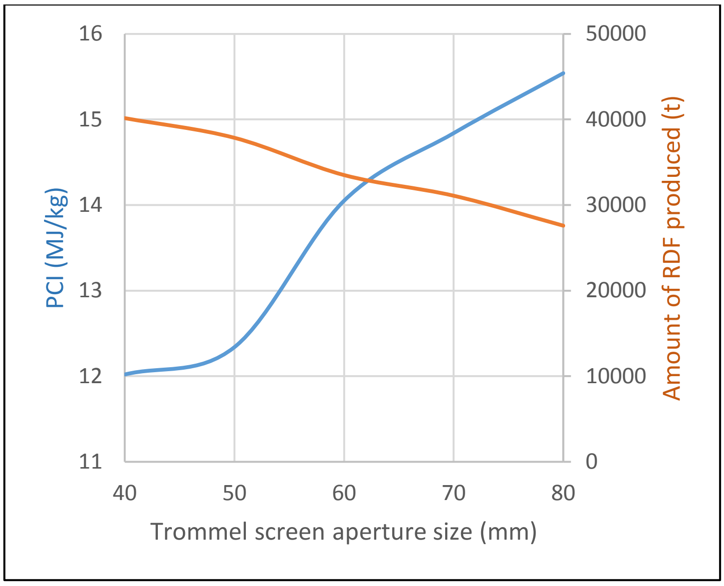

Figure 4.12 Effects of trommel screen aperture size on oversize flow's (RDF) PCI and amount.

There is a trade-off between the amount of RDF produced and its calorific value.

Biological treatment: Aerobic stabilization

As mentioned, part of the organic fraction coming from the trommel screen is routed to an aerobic stabilization in order to reduce its biodegradability. During this treatment there is a mass loss due to biodegradation of the organic fraction of waste. In order to quantify this loss and to determine the composition of the stabilized organic fraction, some assumptions have to be made.

Basing on literature (Zanchi L., 2011), a chemical-physical analysis of the waste has been performed to obtain, for every fraction of waste:

- total solids, TS [% of total weight];
- moisture, U [% of total weight];
- total volatile solids, TVS [% of TS];
- biodegradable volatile solids, BVS [% of TVS];
- chemical composition, dry basis, in terms of Carbon, Hydrogen, Oxygen, Nitrogen, Sulphur, Inerts [% of TS].

Assuming that only a certain percentage α of the BVS is removed and that water losses are negligible (*Zanchi L., 2011*), it is therefore possible to calculate the weight losses for every fraction *i*:

$$removed\ BVS_i = \alpha * BVS_i$$

$$remained\ TS_i = TS_i - removed\ BVS_i$$

The detailed input data and procedure concerning Mechanical separation and Biological treatment calculations can be found in Appendix.

4.3.2 MSW incinerator model

The simulations of the WtE process were generated through a thermodynamic model developed by Department of Industrial Engineering of University of Florence, by means of Engineering Equation Solver (EES), F-Chart Software. The reference plant consists of a conventional WtE system where MSW (or possibly RDF) is fed directly to a moving grate combustor integrated with the steam generator. The combustion temperature and the condenser pressure are assumed respectively 1000 °C and 0.09 bar. The moving grate supports waste throughout the combustion process and makes it travel from the feeding section to the ash discharge section. The oxidizing agent is air, supplied underneath the grate (primary air) and over the flame region (secondary air). Flue gases leave the combustion chamber through a series of radiant channel cooled by evaporator tube walls. The flue gases exiting the boiler (economizer outlet) at 180° C enter a dry flue gas treatment system that includes, along the direction of the gas flow: a reactor with injection of sodium bicarbonate and activated carbon, a fabric filter for residual sodium salts removal and low temperature Selective Catalytic Reduction (SCR) reactor for NOx abatement. Across the treatment line no heat is recovered, so the flue gas temperature at the stack is 180 °C.

The power section comprises a conventional superheated steam cycle with moderate regenerative feed-water preheating. The steam maximum pressure is assumed to be 35 bar, while the steam maximum temperature is assumed to be 380 °C. Further, the turbine isoentropic efficiency is equal to 0.73 (Department of Industrial Engineering, University of Florence).

In Figure 4.13, Figure 4.14 and Figure 4.15 some pictures of the graphical user interface of the software are reported.

Once all the parameters are fixed (i.e. the above mentioned design parameters of the plant and what formula to be used for heating value calculation), the required input data can be set. They are the amount of incinerated waste during the considered time and its chemical composition on wet basis. The model outputs, which are here expressed per ton of combusted waste, are the following:

- ✓ direct emissions at the stack, in terms of carbon dioxide (fossil CO_2), nitrogen oxides (NO_X), sulfur dioxide (SO_2), hydrochloric acid (HCl) and hydrofluoric acid (HF);
- ✓ solid residues in terms of bottom ash and fly ash;
- ✓ chemicals consumption for air pollution control (APC) system, which are sodium bicarbonate ($NaHCO_3$), activated carbon and ammonia (NH_3);
- ✓ net electricity production.

Figure 4.16 shows a simple sketch flow of the EES incineration model.

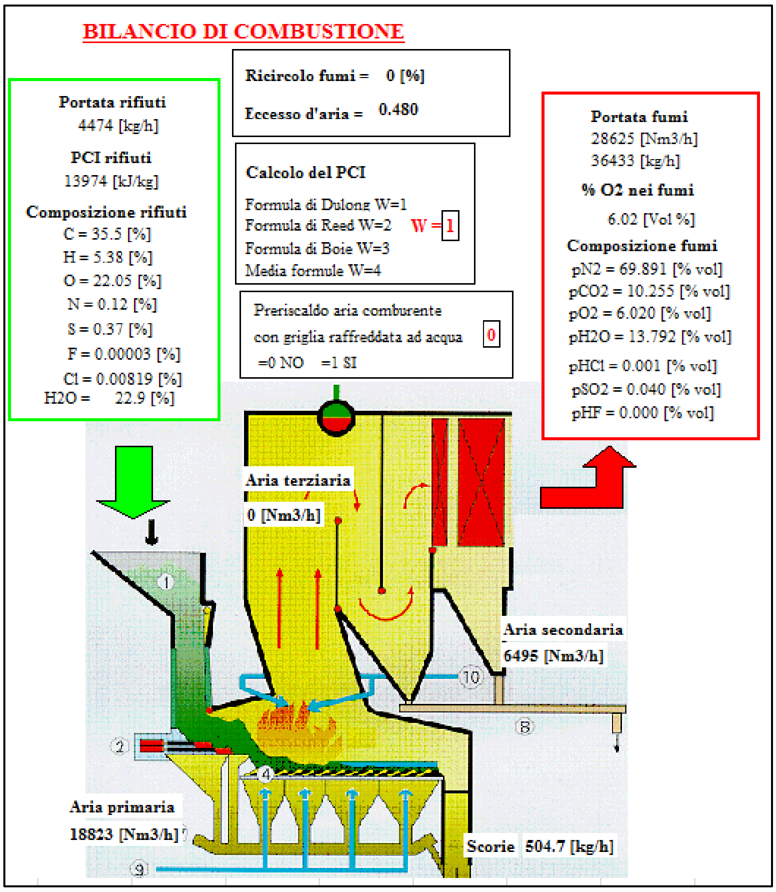

Figure 4.13 EES software interface: balance in combustion chamber.

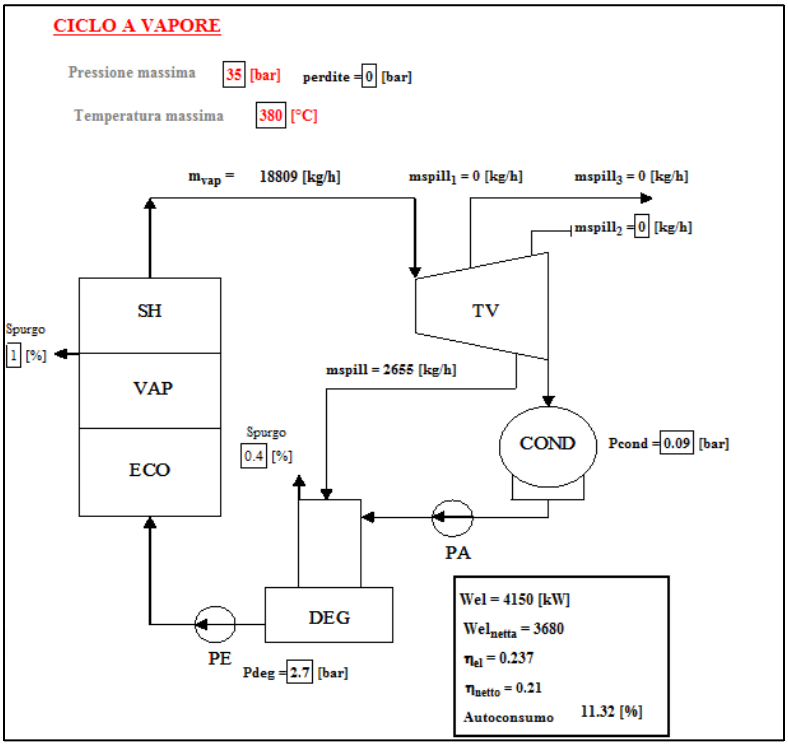

Figure 4.14 EES software interface: steam power cycle.

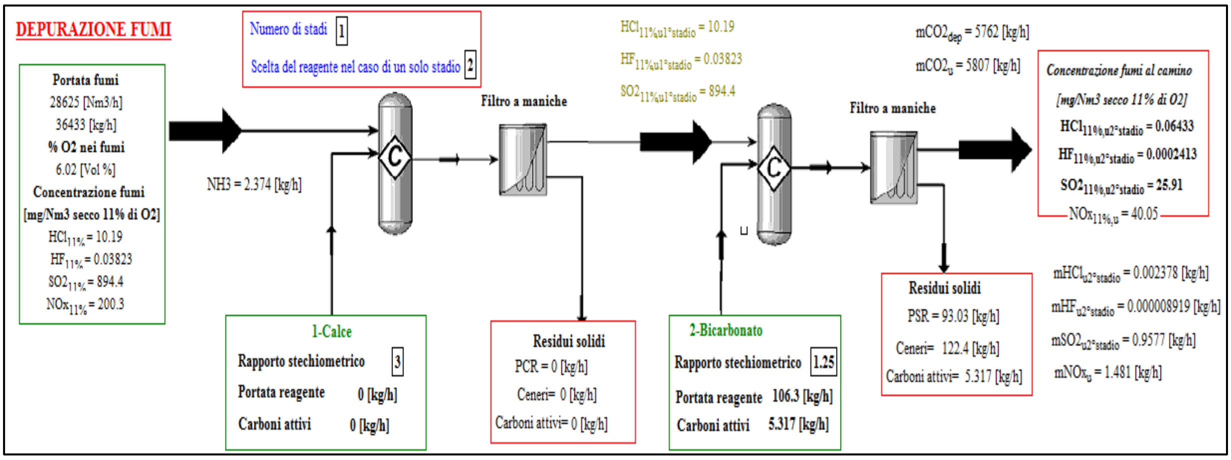

Figure 4.15 EES software interface: APC system.

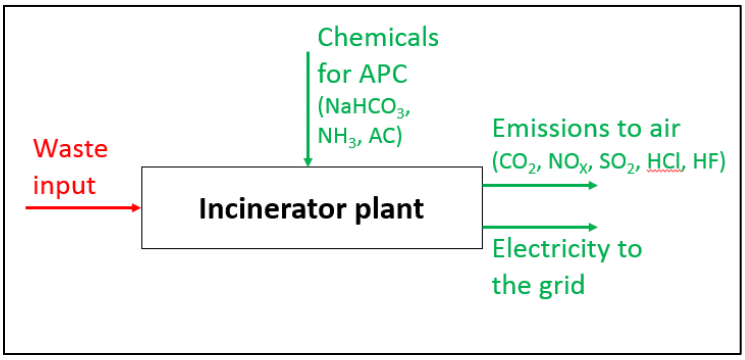

Figure 4.16 Incinerator flow chart; the red line is the input needed by the software, green lines are the output.

4.3.3 MSW landfill model

The model of waste landfilling consists of two different parts:

- a model for evaluating landfill gas (LFG) generation and emission/exploitation;
- a model for evaluating leachate related emissions.

The first one is based on the calculations and assumptions made in Lombardi, Carnevale, & Corti, 2006, *Greenhouse effect reduction and energy recovery from waste landfill;* the second one is taken from ecoinvent database and described in Doka G., 2003, *Life cycle inventories of waste treatment services*. In the following an explanation of the both models is performed.

In the LCA study it was assumed only one landfill where ideally routing all the wastes, without distinction between the two landfills in Siena province, as described in paragraph 3.1.3.

LFG generation model

Municipal solid waste in a landfill undergoes a number of simultaneous and interrelated biological, chemical and physical changes. The most important biological reactions occurring in landfills are those involving the organic material in MSW that lead to the evolution of LFG and, eventually, liquids (Lombardi et al., 2006). The biological decomposition process is usually aerobic in the first phase, due to the initial presence of residual oxygen in the waste mixture. During aerobic decomposition CO_2 is the principal gas produced. Once the available oxygen has been consumed, the decomposition becomes anaerobic and the organic matter is converted to CO2, CH4 and trace amounts of ammonia and hydrogen sulphide (Lombardi et al., 2006). In order to estimate the total volume of potentially produced LFG, it is possible to apply the Buswell Equation (1952), considering the generalized chemical reaction for the anaerobic decomposition of waste:

$$C_aH_bO_cN_dS_e + \frac{4a - b - 2c + 3d + 2e}{4} \; H_2O \;\rightarrow$$

$$\frac{4a + b - 2c - 3d - 2e}{4} \; CH_4 + \frac{4a - b + 2c + 3d + 2e}{4} \; CO_2 + dNH_3 + eH_2S$$

Only the biodegradable part of the organic matter should be included in the first term of the equation. Biodegradability is different for different constituents of solid waste and the reference values are reported in the Appendix.

Further, a sort of process efficiency, depending on the waste temperature and representing the percentage of biodegradable organic matter that is effectively degraded, should be considered according to the following (Lombardi et al., 2006):

$$k_d = 0.014\,T + 0.28$$

where T is the temperature inside the landfill, expressed in °C. For example, assuming mesophilic conditions in the landfill body, i.e. 35°C, brings a process efficiency of 0.77.

This equation was modeled in an Excel spreadsheet which is structured as described below:

- one sheet for input data setting;
- one calculation sheet for each kind of waste input;
- one sheet for summarizing relevant output data.

Input data needed for the calculations regard both waste characteristics and technology parameters, and they are:

- ✓ waste composition and amount for each kind of waste input (MSW flow and the flows coming from MBT process: organic fraction, stabilized organic fraction and fine residues);
- ✓ chemical composition on wet basis and biodegradability coefficients for each waste fraction (organic, paper, cardboard, plastics…);

- ✓ technological parameters of the plant such as: percentage of captured LFG, percentage of flared LFG and percentage of CHP burned LFG (referring to the captured), thermal and electrical efficiencies of CHP system.

Regarding the stabilized organic fraction coming from the aerobic stabilization in the MBT plant, it was assumed a lower biodegradability, since a part of its organic matter has already been degraded. Thus, all the biodegradability coefficients of this fraction were multiplied by 0.5.

Once all the input data are set, the results are shown in the last spreadsheet (expressed per kilogram of landfilled waste). Model's outputs are listed below:

- ✓ direct LFG emissions in terms of methane (kg CH_4)
- ✓ recovered electricity from biogas combustion in terms of electrical energy (kWh);
- ✓ recovered heat from biogas combustion in terms of thermal energy (MJ);
- ✓ methane and nitrous oxide leaks from CHP engine (kg CH_4, kg N_2O).

For the calculation of the methane loss and nitrous oxide emissions from the engine, the values of 323 g/GJ and 0.5 g/GJ were respectively assumed, according to *Denmark ' s National Inventory Report*, 2008.

Leachate related emissions model

In this study the model of municipal solid waste-sanitary landfill (MSWLF) is used, taken from ecoinvent database. The description below is going through:

- system boundaries;
- categorization of landfill emissions;
- necessary waste input data;
- short-term emissions;
- long-term emissions;
- model for leachate treatment.

All the parameters and calculation described below are included in two excel files, linked to each other. The complete description of the model is provided by ecoinvent in the report Life cycle inventories of waste treatment services (Doka, 2003).

In Figure 4.17 is shown the process chain for MSW landfilling with the system boundaries.

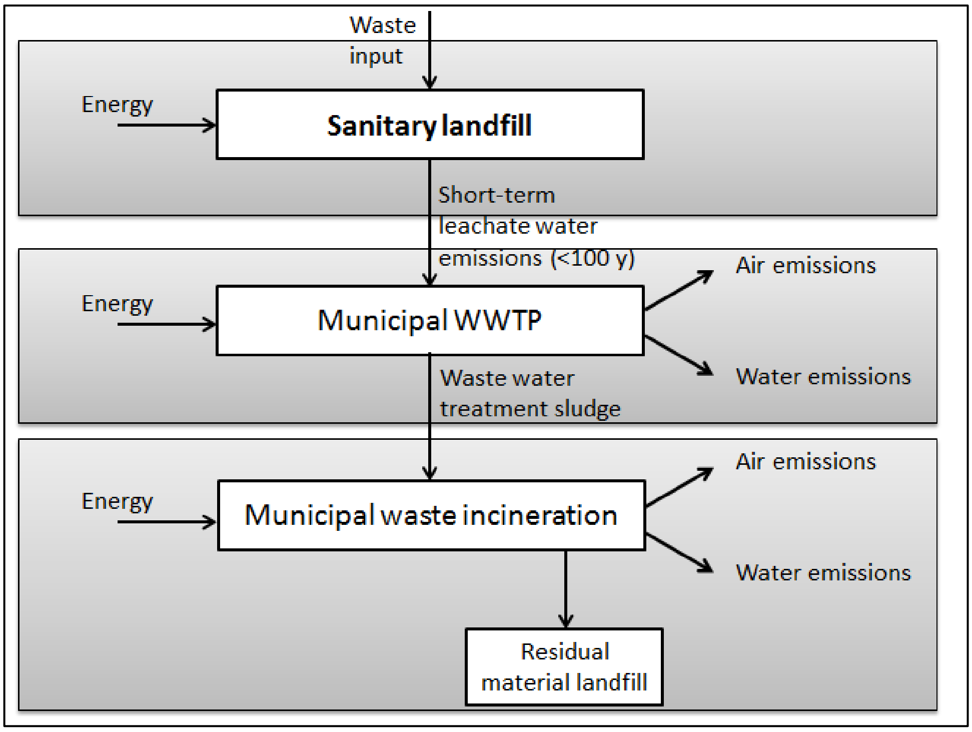

Figure 4.17 MSW sanitary-landfill, system boundaries (Doka, 2003).

The system boundaries are divided into 3 sections:

- the first one contains all the processes involved in the landfill;
- the second one all the processes involved in the wastewater treatment plant;
- the third one all the processes involved in the incineration of sludge.

The model assumes that leachate is completely collected and treated during the first 100 years, it is treated in a wastewater treatment plant and the sludge is incinerated.

As shown in Figure 4.17, the landfilling of waste generates indirect and direct emissions. Indirect emissions are caused by material and fuel used for landfill operations, direct emissions are generated both from landfill operation (transports and waste spreading) and from waste itself. Regarding emissions from waste degradation, an important variable is the time. In fact, the landfill is a deposit where different reactions are activated in different period. The ecoinvent model divides emissions into short-term and long-term emissions. The first ones are originated within the first 100 years, while the long-term emissions occur after 100 years; they are considered to be only leachate emissions which are discharged directly to groundwater. Both short and long-term emissions are waste-specific, so they depend on waste characterization.

The user must specify the waste input composition in the first excel spreadsheet referring to 1 kg of wet waste; for each fraction material a default chemical composition is given, although the user can change it in order to make it more conforming to the waste input characteristics. An important parameter in MSW landfill model is the degradability rate that represents the decomposition of the fraction materials in a waste matrix. Even the degradability factors are provided for each fraction of waste and referring to the first 100 years. When the waste characterization is set, the ecoinvent tools calculate: the degraded fraction of each chemical element of the waste (kilogram of degraded element per kilogram of waste) and the percentage of degraded element (D_e). The percentage of degraded element D_e is used for the calculation of short-term emissions.

The short-term emissions depend on the degradability factors D_e, the concentration of the element in the waste fraction m_e, the average release factor for element r_e and the factor $\%gas_e$ that expresses what share of the element *e* occurs as gas emission.

The degradability factor D_e determines how much of the element is decomposed during the first 100 years, whereas the release factor r_e determines how much of the decomposed element is actually released in the emissions.

The short-term emissions are calculated as follows:

$$E_{leach,e} = m_e \times D_e \times r_e \times \ 1 - \%gas_e$$

The direct emissions could be calculated by means of application of *short-term transfer coefficients* (TK_e) which express how much of each element of the waste is transferred in air and water. In this case the transfer coefficients for every chemical element are expressed as follows:

$$TK_{leach,e} = D_e \times r_e \times \ 1 - \%gas_e$$

$TK_{leach,e}$ is the short-term transfer coefficient of the element *e* to leachate (kilogram of waste per kilogram of element *e*) (Doka G., 2009).

Also the long-term emissions are calculated with the application of *long-term transfer coefficient cumulated* ($LTTK_e$) which express how much of the element is transferred in water in a long period.

$$LTTK_e = STTK_e + \ TK_\infty - STTK_e \ \times \frac{\emptyset LTTK_e - \emptyset STTK_e}{TK_\infty - \emptyset STTK_e}$$

Where:

- $\emptyset STTK_e$ is the short-term transfer coeff. of the element *e* for average waste (sum of gas and leachate contribution);
- $\emptyset LTTK_e$ is the long-term transfer coeff. of the element e for average waste;
- $STTK_e$ is the short-term transfer coeff. of the element e for a specific waste (sum of gas and leachate contribution);

- $LTTK_e$ is the long-term transfer coeff. of the element e for a specific waste (sum of gas and leachate contribution).

The $LTTK_e$ refers to the time of zero to 60 000 year, so it includes also the short-term emissions. To avoid double counting the short-term emissions must be subtracted from the total emissions. So the long-term transfer coefficient ΔLT for the emissions after 100 years is obtained with the difference (Doka G., 2009):

$$\Delta LT = LTTK_e - \ TK_{gas,e} + TK_{leach,e}$$

The leachate emission after 100 years is calculated by the multiplication of ΔLT with m_e.

As already mentioned, the model assumes the leachate emissions of the first 100 years are not emitted directly but are collected, discharged to a sewer and treated in a municipal wastewater treatment plant.

The model of the landfill is linked to a specific model of wastewater treatment plant (WWTP); the WWTP model calculates the inventory of leachate treatment, not only the direct burden from the wastewater treatment process itself, but also the burdens from incineration of sludge. The leachate concentration is assumed to be constant in the first 100 years.

The calculation of the short-term leachate emissions, $E_{leach,e}$, allows to obtain waste-specific burdens calculation. For each pollutant X in the leachate, a list of burdens $B_{i,x}$ is obtained as follows.

$$B_{i,x} = m_x \times \ B^0_{i,x} - B_{i,w}$$

where:

- $B_{i,x}$ is the burden for exchange i from pollutant X in leachate;
- m_x is the mass of pollutant X in leachate during 100 years (in kg);
- $B^0_{i,X}$ is the burden for exchange i from 1 kg pollutant X in 1 m^3 of wastewater (from WWTP model);
- $B_{i,W}$ is the base burden for exchange i from 1 m^3 of unpolluted wastewater (from WWTP model).

The factors ($B^0_{i,x}$ - $B_{i,w}$) represent a matrix (i, X) of 215 rows (burdens) and 216 columns (pollutants). The full matrix is contained in the calculations tools of the landfill model. The factor $B^0_{i,x}$ for each pollutant X is a list of burdens due to emissions, required processes and materials. The factor $B_{i,w}$ is a "base burdens" irrespective of the pollutant content.

The total burden from leachate treatment is obtained as follows:

$$B_i = B_{i,w} \times V \times 100_{years} + \sum_{x} B_{i,x}$$

where:

- B_i is the total burden for exchange *I* from leachate treatment;
- $B_{i,W}$ is the base burden;
- *V* is the mean annual leachate output from landfill per kg of waste.

The average annual leachate output V is calculated from the landfill height *h* (assumed 20m), the waste density *δ* (1000 kg/m^3) and a rainwater infiltration rate *α* assumed equal to 0.5 m^3/(m^2 *year); thus, the total leachate volume treated is:

$$V = \frac{\alpha}{h \times \delta} = 2.5 \times 10^{-5} \frac{m^3}{kg \times year}$$

The model's outputs consist of emissions to air and emissions to water, and energy and fuel consumption. Table 4.1 shows the emissions classification with different subcategories. Water emissions into ground water are classified as long-term emissions and thus they are not taken into account in the *GaBi* process, since the leachate is completely collected in the first 100 years.

Table 4.1 Characterisation of landfill's model outputs.

EMISSIONS	**AIR**	High population density Low population density
	WATER	River Ground, long-term

In particular, Table 4.2 lists the emissions taken from ecoinvent tool and accounted in the *GaBi* model.

Table 4.2 Considered emissions from ecoinvent landfill tool.

Ammonium, ion	water
Nitrite	water
Nitrogen	water
Nitrogen oxides	air
Ammonia	air
Dinitrogen monoxide	air
Phosphorus	air
COD, Chemical Oxygen Demand	water
TOC, Total Organic Carbon	water
Nitrate	water
Phosphate	water
Sulfur dioxide	air
Hydrogen chloride	air
Hydrogen fluoride	air

4.3.4 Activated carbon production

The evaluation of the emissions associated to the production of the activated carbon (which are used in the incinerator APC system) is based on the paper Bayer, Heuer, Karl, & Finkel, 2005, *Economical and ecological comparison of granular activated carbon (GAC) adsorber refill strategies.*

The study focuses on the production of GAC out of hard coal, which is prevalently used in Central Europe. The main processes during the production of this GAC type are: wet grinding of coal, mixing with binding agent, creation of briquettes, oxidation, drying, carbonization, activation, crushing, sieving and packaging. The crucial step is the activation procedure, a selective high-temperature treatment of the carboniferous precursor resulting in a highly porous material. Steaming with water vapor and CO_2 yields partial coal gasification at temperatures between 800 and 1000 °C. During this procedure, 60% of the original weight is lost. The demand of raw material is specified as 3 tons hard coal per 1 ton GAC (Bayer et al., 2005).

A conventional practice to save money, resources and obviate liabilities associated with GAC disposal at offsite facilities is the recycling of used GAC (*reactivation*). The weight losses during reactivation vary between 5% and 15%. A mean value of 10% is assumed here (Bayer et al., 2005). Recycling of GAC particularly means avoiding emissions resulting from mining and processing of raw coal.

Table 4.3 lists the calculated indicator values for the GWP, AP and EP impact categories, given in the respective emission equivalents for GAC production.

Table 4.3 Emission factors for GAC production (Bayer et al., 2005).

		Virgin GAC	Recycled GAC	Assumed
GWP	kg CO_2eq/kg GAC	11	1.17	6.09
AP	kg SO_2eq/kg GAC	0.0058	0.0018	0.0038
EP	kg PO_4^{3-}eq/kg GAC	0.00052	0.0003	0.00041

A striking feature is the high emissions of CO_2 equivalents for virgin GAC, which reaches 11 times the mass of the final product. This especially denotes the high net loss of raw coal during the production process. The CO_2 equivalents spent for recycling reach only a tenth of this, reflecting the minor role of energy consumption during heating (Bayer et al., 2005)

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5 LIFE CYCLE ASSESSMENT OF SIENA MSW MANAGEMENT SYSTEM.

In this chapter the LCA of Siena MSW management system is performed: goal and scope definition are presented in the first part, including system boundaries and scenarios descriptions. Then the life cycle inventory analysis is carried out and finally a short characterization of the *GaBi* model used for the impact assessment is given.

Regarding South Karelia case study a brief description of the inventory is given in the end.

5.1 GOAL DEFINITION

The goal of this study is to assess the environmental impacts through the MSW management in province of Siena. Thus, the LCA heeds the impacts related to the treatment and final disposal of MSW. In addition to the actual scenario, which is the Siena MSW management system referring to 2013, four other scenarios were studied.

The first part of the study focuses on performing the LCA of those five systems in order to compare their results and to analyze which are the main processes and factors affecting the LCA balances. Thus, a perturbation analysis is performed.

Investigating the importance of each process in the waste management system, in terms of contribution to the environmental burden, is also called *contribution analysis*.
Contribution analysis consists in decomposing the LCA result (characterised, normalised or weighted impact) of a system into its individual process contributions, providing a quick overview of the important contributors. Processes that have both positive and negative impacts have to be subdivided into their sub-components, to avoid neglecting important processes. For example an incineration process might have an impact close to zero, but as the net total of high direct impacts (fossil CO2 emission from burning of plastic) and high avoided ones (produced electricity substituting fossil CO2 emissions from a coal-burning power plant) (Clavreul et al., 2012).

The contribution analysis can be as a guide for the authorities, suggesting in which point of the waste management chain, more efforts should be made. Moreover, it can help LCA practitioners to understand what processes are the most relevant to the final LCA balance and what processes are the least important. The former ones should be precisely and carefully analyzed, while the latter ones could be even disregarded without committing significant errors.

The second part aims to a comparison with the South Karelia case study: the comparison is not just focusing on the final LCA results, but most on assessing how much every factor of the operating system is influencing the entire outcomes for each LCA study.

The operating system plays an essential role when assessing the LCA of a waste management system. As a matter of facts, the assumptions made within the study, related to the system background, can thoroughly influence the final LCA results. The point is to determine what are the key factors and how they change when varying the operating system.

5.2 SCOPE DEFINITION

The object of this study is the MSW management system of Province of Siena referring to 2013. The model boundaries cover bin-to-grave, i.e., from the point where products become waste and put into the waste bin at the waste generation source, to the point where the waste either has been converted into a useful material or into energy in a WtE plant or has become part of the environment after final disposal. In particular, the solid waste management system in Province of Siena is responsible for collection, mechanical separation and aerobic stabilization, incineration and landfilling of all mixed MSW produced in the area of expertise.

Functional unit

According to the goal of the study, the functional unit (FU) of the LCA is the management of the total amount of mixed MSW during the 2013 in the Province of Siena: 94 963 tons of mixed MSW generated by 270 817 inhabitants.

Since the results will be compared to South Karelia case study, considering the difference in population and total waste amount of the two areas, the comparison is possible only choosing the same amount of treated MSW. Thus, the results will be compared dividing the total impacts by the total amount of waste, obtaining specific indicators per ton of waste.

System boundaries

As previously said, the system boundaries of this LCA study include the impacts generated during the collection and transportation, treatment and final disposal of the mixed MSW. All the plants involved in the treatment of mixed MSW are included; their impacts related to upstream, direct and downstream activities are considered. The system boundaries include also waste transports among the plants. Capital goods are not included for the huge amount of data needed. Figure 5.1 shows the system boundaries for the LCA study.

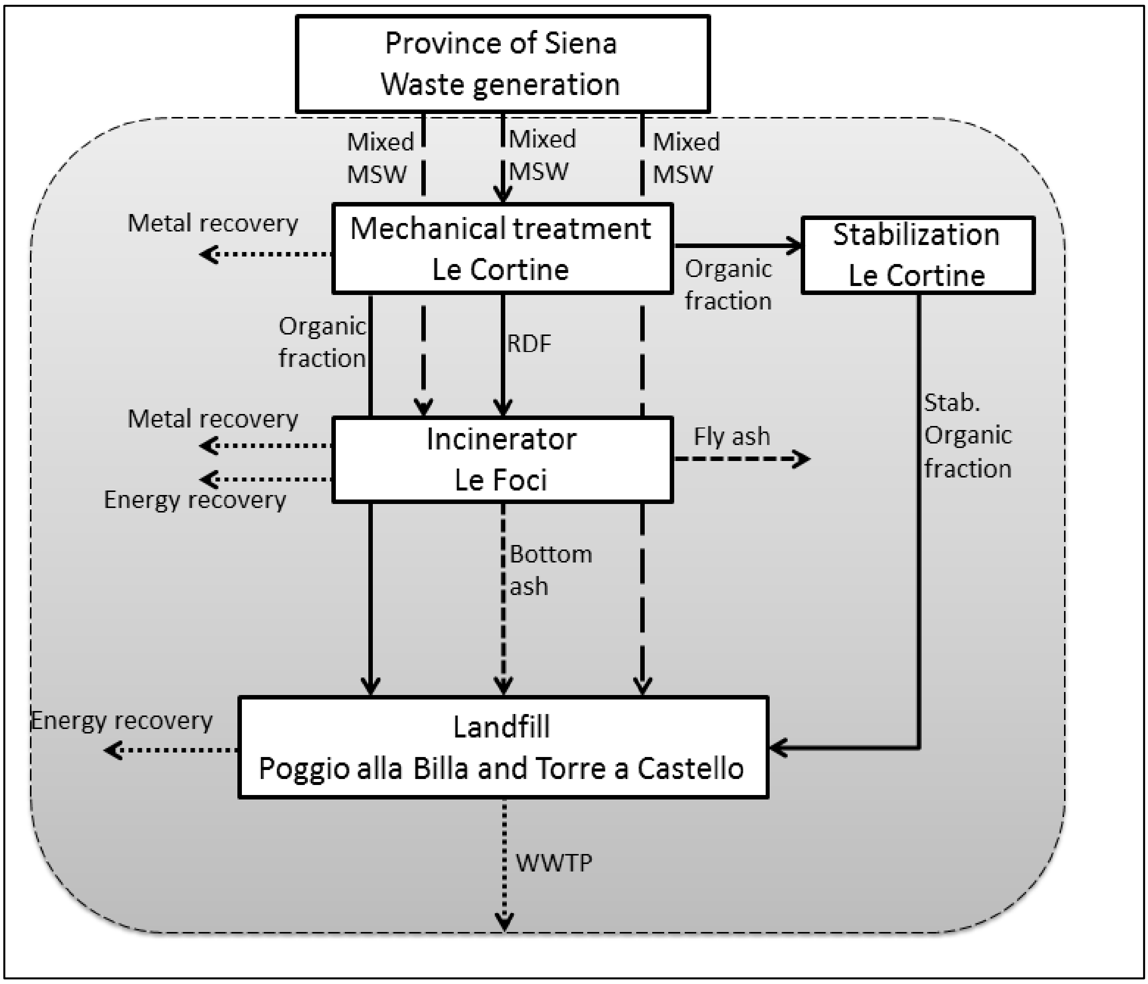


Figure 5.1 Province of Siena waste management, system boundaries for LCA.

This study utilizes a consequential approach to system delimitation, meaning that the system represented in the study actually reflects the physical processes that are affected. Some of the benefits of taking a consequential approach are that it avoids co-product allocation through system expansion, and marginal processes and suppliers are included in comparison to average processes and suppliers with an attributional approach. The ISO 14044 (2006) standard also supports a consequential approach over an attributional approach, stating that "Wherever possible, allocation should be avoided" (ISO 14044, 2006).

The following pictures (Figure 5.2, Figure 5.3 and Figure 5.4) report the detailed descriptions of the system boundaries of the involved plants.

The mechanical and biological treatment plant Le Cortine is modelled considering energy and fuel demand for machineries. It is assumed that direct emissions from MBT are negligible.

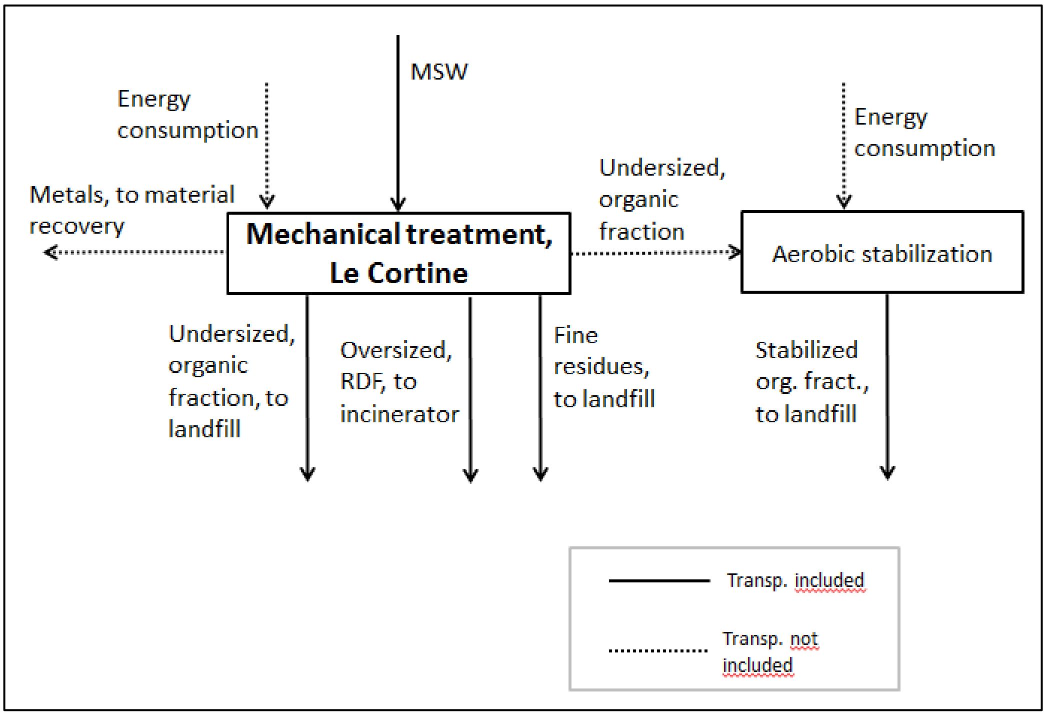


Figure 5.2 MBT plant, system boundaries.

The incinerator plant is modeled considering: direct emissions from the stack, electricity production from waste incineration, supplying of chemicals for APC system, supplying of cement for FA stabilization, waste water flow output and metals recovery from BA.

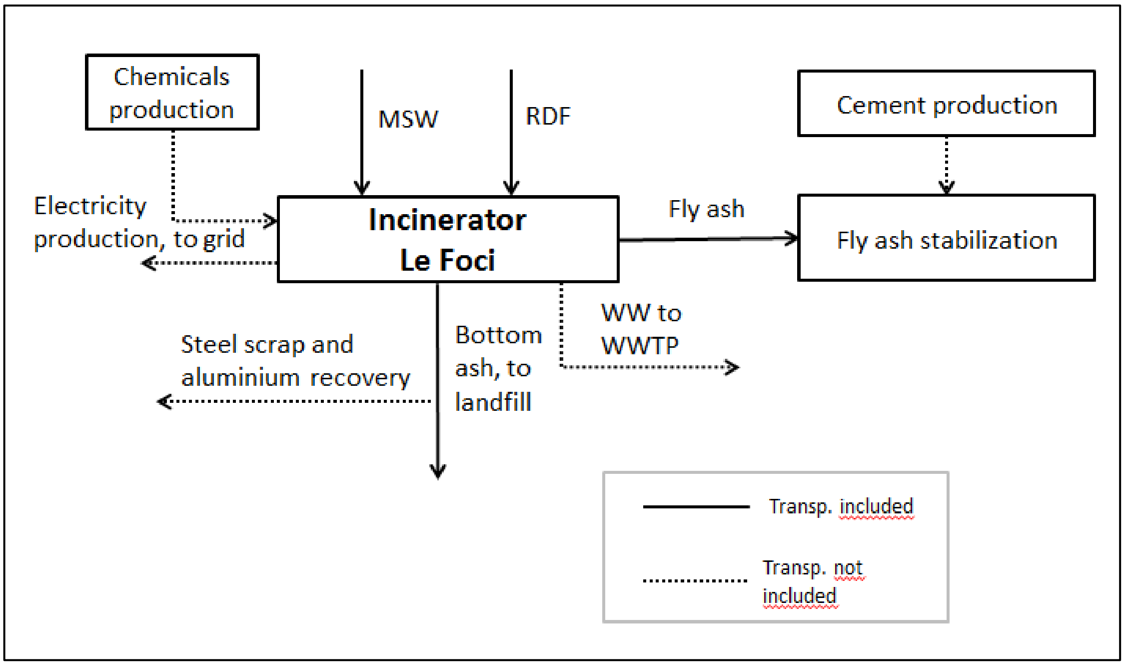


Figure 5.3 WtE incinerator plant, system boundaries.

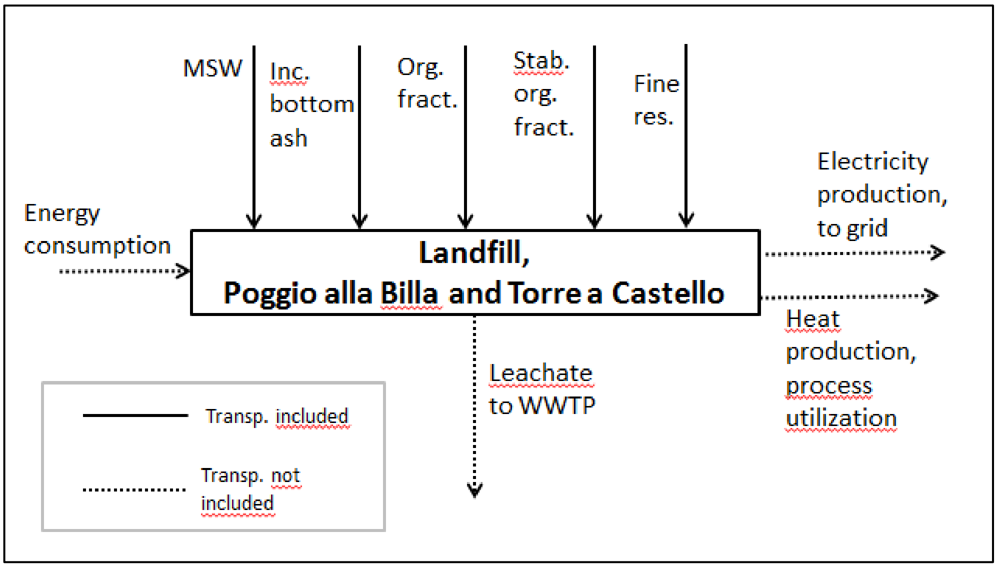


Figure 5.4 Landfill, system boundaries.

The landfill is modeled considering: direct emissions, energy consumption, leachate treatment in a WWTP and electricity and heat production in a biogas CHP unit.

Assessment criteria

In this study the impact assessment CML 2001 – April 2013 method was used. The impact categories considered within this study are:

- climate change (global warming), excluding biogenic carbon (only fossil carbon is accounted for), in kg carbon dioxide equivalent [kg CO_2-eq];
- acidification, in kg sulfur dioxide equivalent [kg SO_2-eq];
- eutrophication, in kg phosphate equivalent [kg PO_4^{3-}eq].

Temporal and geographical scope

This study is referring to Province of Siena residual waste flow in 2013. Therefore, the results are valid for the reference year 2013. However, they could be considered as a good proxy of the situation of the WMS of Siena, until waste generation rate, waste composition, waste collection system, quality of source separation, technologies etc. will remain the same.

Allocation and system expansion

Some of the processes included in the system boundaries are multi-functional processes, which means that they are shared between several product systems. In order to avoid allocation problems, a system expansion is performed whenever possible, according to ISO 14044. This is done by including affected parts of other life cycles in the technological system under study. In particular, the method used within this study is often referred to as the substitution by system expansion or avoided burden method.

The system expansion includes:

- recovered metals from mechanical separation;
- recovered metals from incineration bottom ash;
- electricity produced from waste incineration;
- electricity produced from landfill gas combustion;
- thermal energy produced by landfill gas combustion.

5.3 INVENTORY ANALYSIS

The following paragraph lists the flows of waste, material and energy within the system boundaries. These data were entered into GaBi model in order to calculate the impact results.

5.3.1 Scenario description and waste flows

In addition to the current waste management system, four other scenarios were tested, in order to observe the changes on the final results. The total amount of waste is the same for each scenario (94 963 tons of MSW), but they differ by the amount of waste routed to MBT plant, incinerator plant or landfill.

A detailed description of each scenario is given in the following.

- **S0, base line scenario** (*business as usual*, *BAU*). This is the actual situation in Siena WMS referring to 2013. Around 64% of total MSW are routed to the MBT plant where they are separated into three main flows: 55% are dry waste (RDF) directed to incineration, 29% are wet waste routed to landfill and 13% are wet waste routed to aerobic stabilization and then landfill. 24.5% of initial amount of MSW are incinerated while 11.5% are directly landfilled. Figure 5.6 describes the waste flows.
- **S1, mass burn scenario.** In this scenario 100% of MSW are directly incinerated without any pre-treatment. Figure 5.7 describes the waste flows.
- **S2, *no-MBT* scenario.** The amount of MSW routed to MBT in scenario 0, here is divided between incinerator and landfill. Hence, around 55% of MSW are directly incinerated while 45% of MSW are landfilled. Figure 5.8 describes the waste flows.
- **S3, all-to-MBT.** This scenario and the previous one were created in order to assess the effectiveness of the MBT. Here the total amount of MSW is routed to the MBT and then to the following treatment, according to the MBT separation efficiency, which are the same as in scenario 0. Figure 5.9 describes the waste flows.

- **S4, landfilling scenario.** The all amount of MSW is directly landfilled. Figure 5.10 describes the waste flows.

Figure 5.5 shows the initial waste flows for different scenarios.

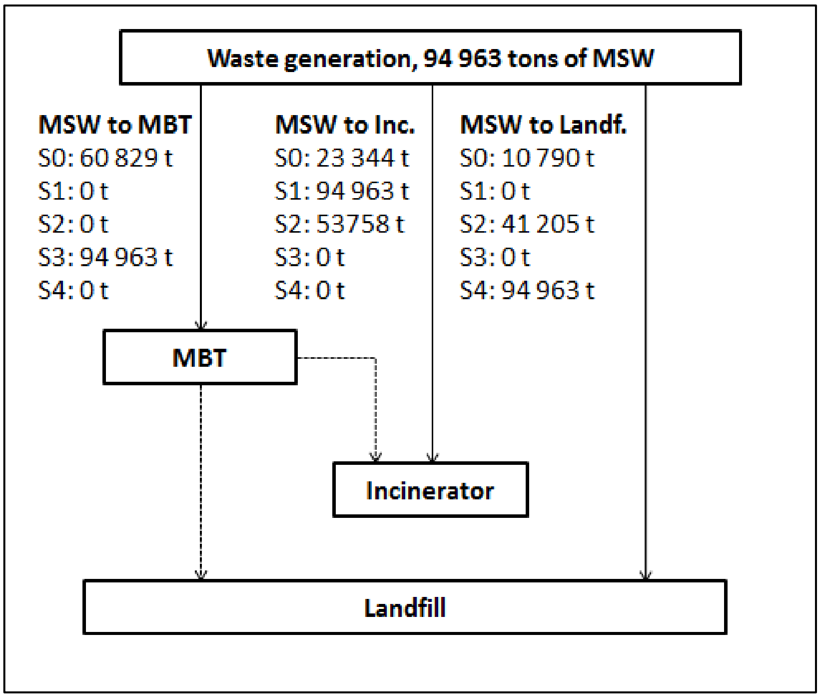


Figure 5.5 Waste flows for different scenarios.

Scenario 0

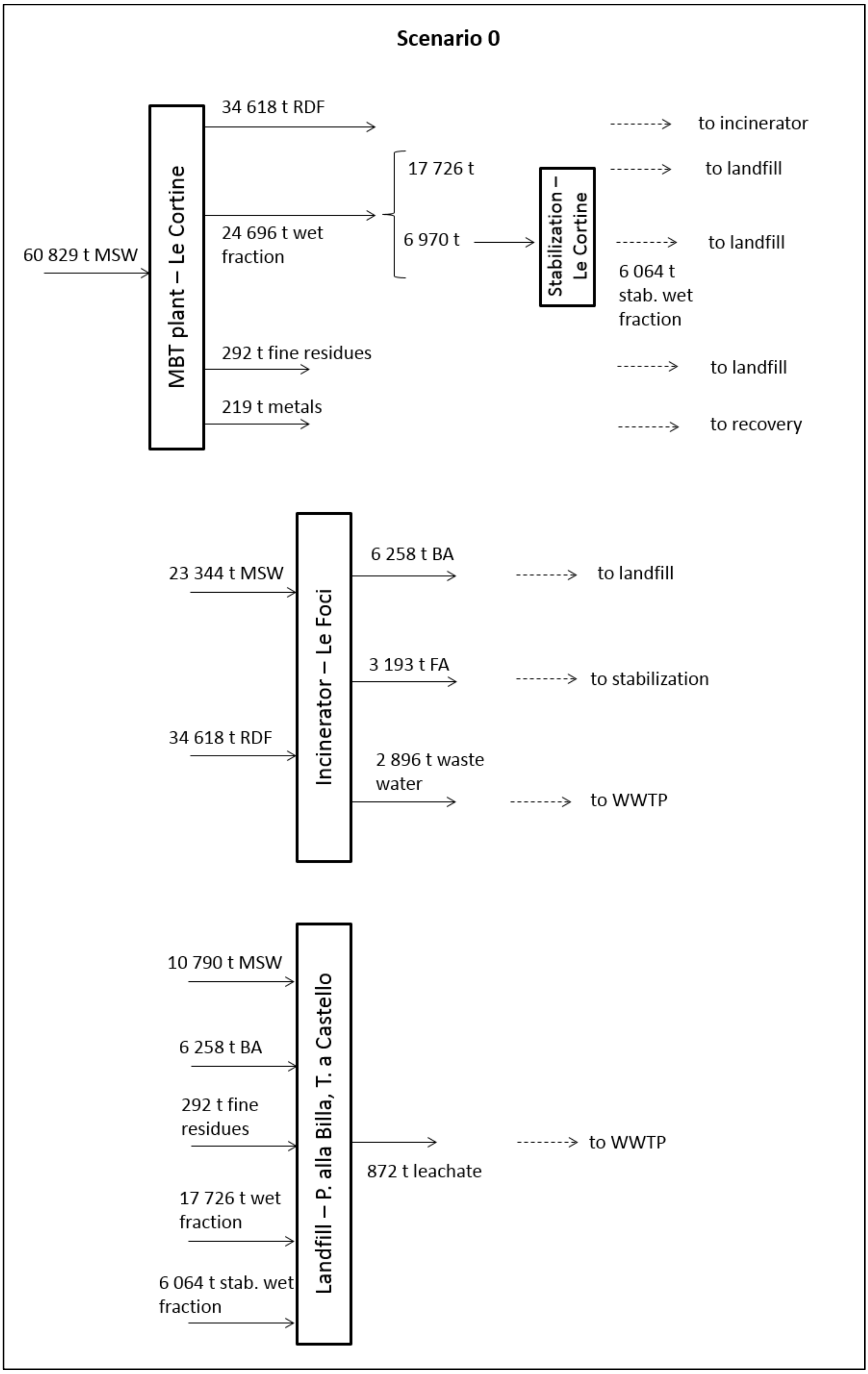


Figure 5.6 Waste flows in scenario 0, Siena WMS.

Scenario 1

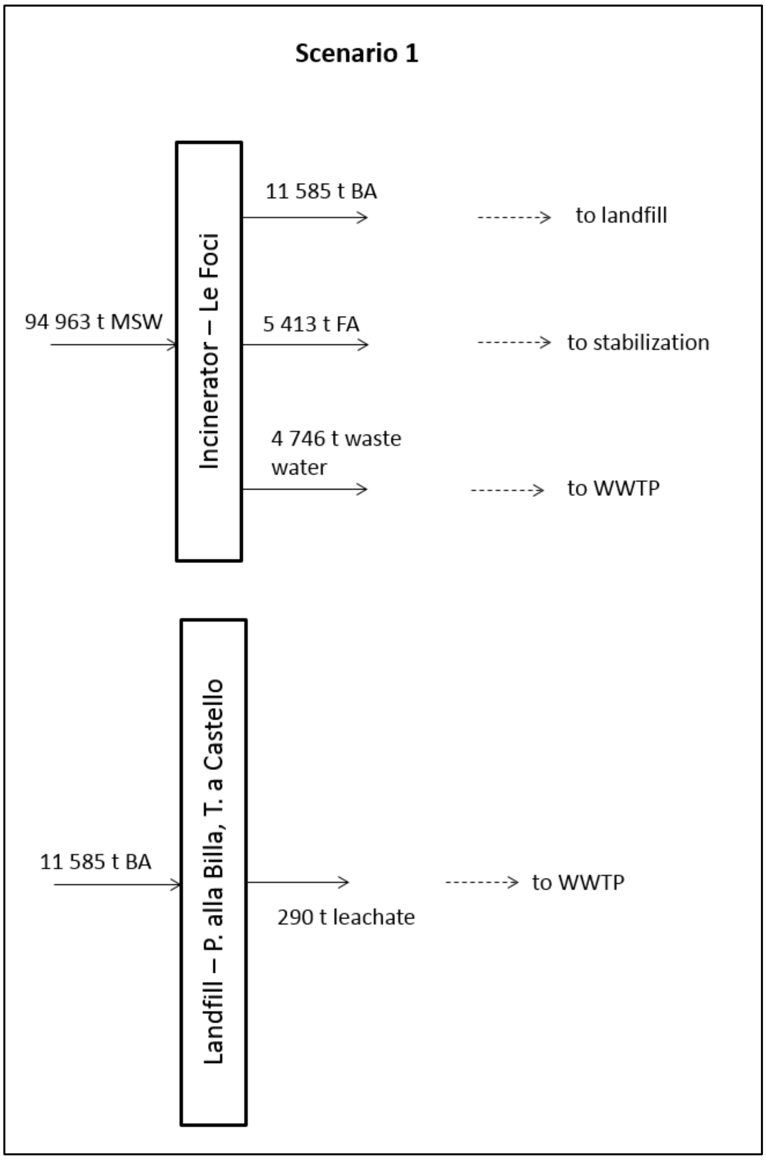


Figure 5.7 Waste flows in scenario 1, Siena WMS.

Scenario 2

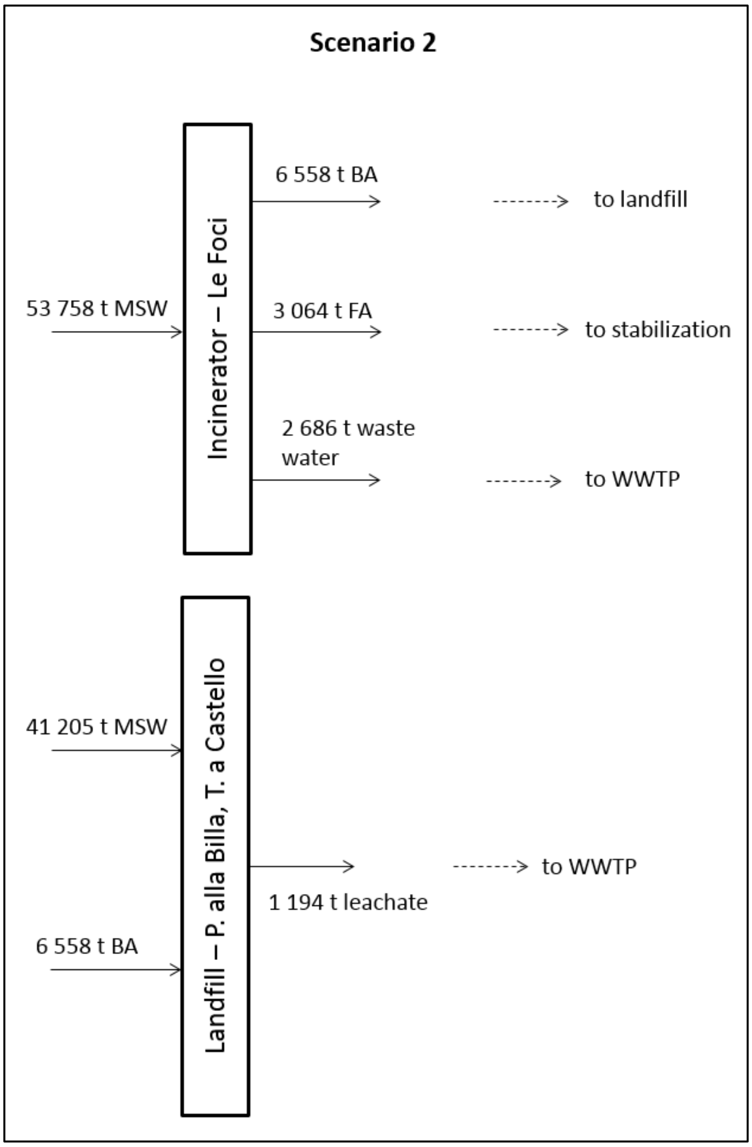


Figure 5.8 Waste flows in scenario 2, Siena WMS.

Scenario 3

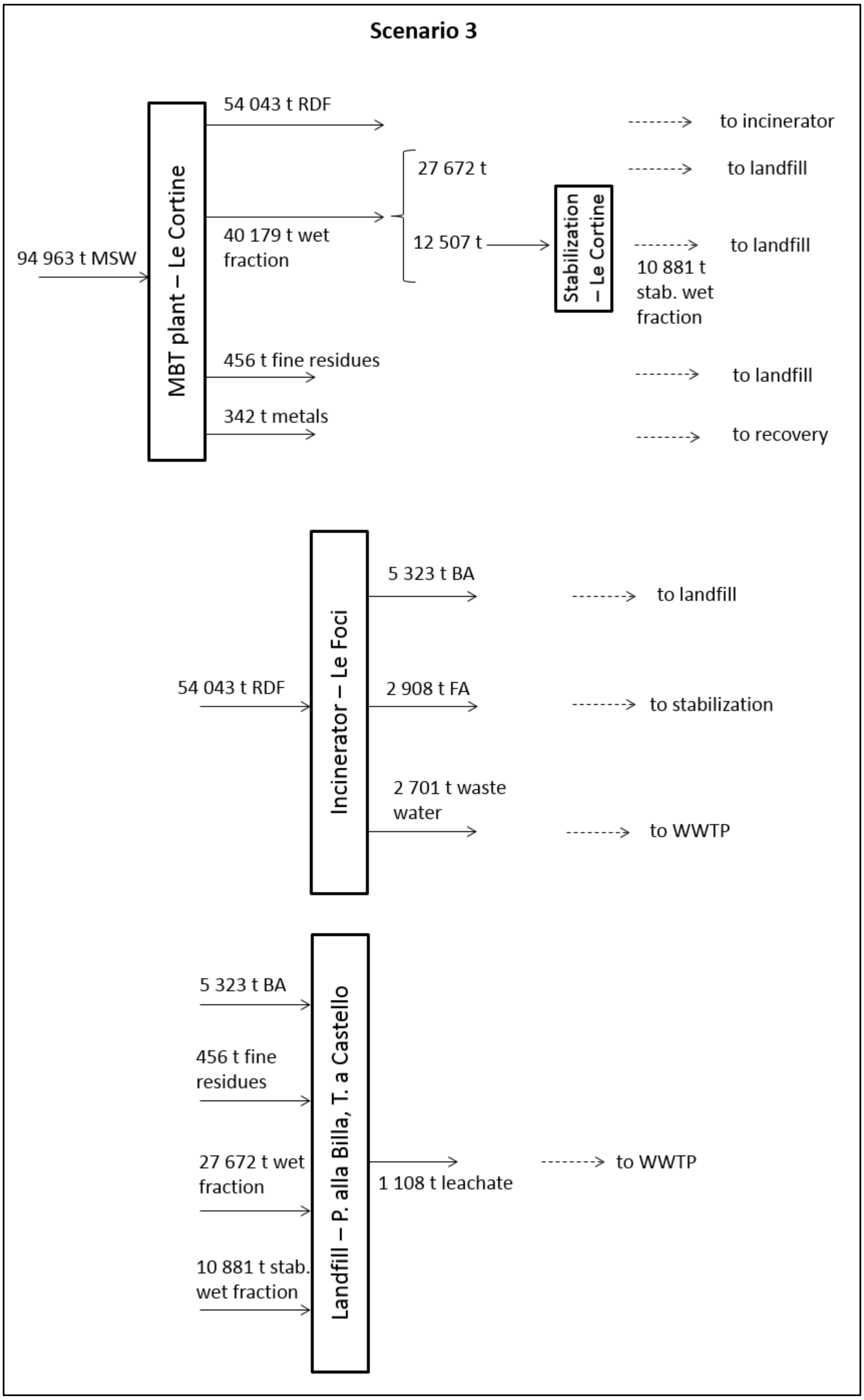


Figure 5.9 Waste flows in scenario 3, Siena WMS.

Scenario 4

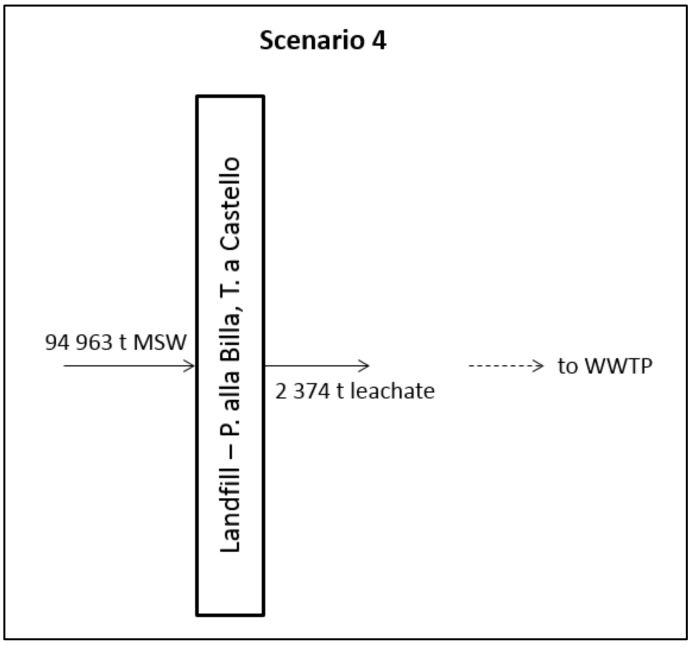


Figure 5.10 Waste flows in scenario 4, Siena WMS.

Table 5.1 Transportation distances and volume of transportation for different scenarios.

From	to	Distance [km]	S0	S1	S2	S3	S4
			Volume of transportation [1 000 tkm]				
Waste generation	MBT	30	1 820	0	0	2 850	0
	Incinerator	30	700	2 850	1 610	0	0
	Landfill	45	490	0	1 850	0	4 270
MBT	Incinerator	70	2 420	0	0	3 780	0
	Landfill	50	1 190	0	0	1 930	0
Incinerator	Landfill	90	560	1 040	590	480	0
	FA stab.	100	320	540	310	290	0
			7 510	**4 430**	**4 360**	**9 330**	**4 270**

5.3.2 Plants data inventory

MBT

The mechanical and biological treatment plant is modeled as showed in Figure 5.2. For a detailed description of mechanical separation and biological treatment efficiencies see paragraph 4.3.1 and Appendix. Table 5.2 reports the input MSW waste composition and the output compositions after the mechanical treatment (oversized RDF and undersized OF).

Table 5.2 MBT main input and output waste compositions.

	MSW	RDF	OF
Organic	20.0 %	9.9 %	33.8 %
Green	3.1 %	1.3 %	5.6 %
Paper	10.1 %	16.3 %	1.9 %
Cardboard	4.7 %	8.0 %	0.5 %
Wood	2.2 %	1.8 %	2.7 %
Textile	7.6 %	9.8 %	4.7 %
Glass	3.2 %	1.9 %	4.8 %
Ferrous metal	3.3 %	4.5 %	0.9 %
Non-ferrous metal	0.8 %	1.0 %	0.6 %
Plastic	22.3 %	34.2 %	6.7 %
Undersized	9.9 %	0.0 %	23.1 %
Inert	2.0 %	0.2 %	4.1 %
Tetrapak	4.7 %	6.8 %	2.1 %
Others	6.1 %	4.3 %	8.6 %

The electricity consumption for mechanical treatment was assumed to be 28 kWh/t_{waste}, while for aerobic stabilization it was assumed 25 kWh/t_{waste} (Zanchi L., 2010). Air emissions from bio-stabilization are neglected because of the use of air cleaning systems (bio-filters). Even leachate emissions are neglected since

Metal recovery was set to 90% of the content of metal in the input waste.

Incinerator

The incinerator is modeled as described in paragraph 4.3.2, with the system boundaries as reported in Figure 5.3.

The input waste chemical compositions (wet basis) are reported in Table 5.3.

Table 5.3 Incinerator input waste chemical composition, wet basis.

	MSW	RDF
C	33.65 %	44.34 %
H	5.28 %	7.18 %
O	20.17 %	17.46 %
N	0.13 %	0.14 %
S	0.44 %	0.48 %
Cl	0.01 %	0.01 %
F	0.00 %	0.00 %
Inert	14.81 %	11.95 %
Moisture	25.52 %	18.44 %
LHV [MJ/kg]	13.5	20.1

Table 5.4 lists output data obtained from EES incinerator model (except from waste water output which is taken from Doka, 2013). These data were then used as input in GaBi model.

Table 5.4 Inventory data, Siena incinerator plant (EES incinerator model).

	MSW	**RDF**
Air emissions		
CO_2 (fossil) [kg/t_{waste}]	704.80	1065.17
NO_X [kg/t_{waste}]	0.346	0.478
SO_2 [kg/t_{waste}]	0.1976	0.2156
HCl [g/t_{waste}]	0.257	0.329
HF [g/t_{waste}]	0.0025	0.0012
Electricity production		
Recovery efficiency [%]	19.8	22.3
Self-consumption [%]	12.4	7.7
Net electricity production [kWh/t_{waste}]	743.5	1250.0
Chemicals consumption		
$NaHCO_3$ [kg/t_{waste}]	14.485	18.20
Activated carbon [kg/t_{waste}]	1.474	1.610
NH_3 [kg/t_{waste}]	0.555	0.767
Solid and liquid outputs		
BA [kg/t_{waste}]	122.12	98.55
FA [kg/t_{waste}]	57.04	53.84
Waste water [kg/t_{waste}]	55	45

It's noteworthy to observe the data about sodium bicarbonate ($NaHCO_3$) consumption for flue gas cleaning system, coming from EES incinerator model. The consumption seems to be high compared to the one suggested by *Solvay*, the main producer, which is 10-13, and this may be due to the high concentration of sulfur dioxide in flue gases, due to large amount of sulfur in the waste. However, it is in line compared to other Italian case studies (Table 5.5).

Table 5.5 Sodium bicarbonate consumption for flue gas cleaning system in different italian incinerator plants.

Consumption (kg_{NaHCO3}/t_{waste})	**Plant**	**Reference**
16.9 avg	Poggibonsi	This study (2016)
10-13	-	Neutrec (2001) - www.solvay.com
15-20	Padova	AcegasApsAmga, Technical Report (2011)
15.9	Milano	Biganzoli, L., Racanella, G., Marras, R., & Rigamonti, L. (2015)
15.4	Valmadre	Biganzoli, L., Racanella, G., Marras, R., & Rigamonti, L. (2015)
20.5	Piacenza	Biganzoli, L., Racanella, G., Marras, R., & Rigamonti, L. (2015)
14.6	Como	Biganzoli, L., Racanella, G., Marras, R., & Rigamonti, L. (2015)
16.8	Milano	Turconi, R., Butera, S., Boldrin, a., Grosso, M., Rigamonti, L., & Astrup, T. (2011)

Metal recovery from bottom ash is included in the system boundaries. Both ferrous (steel scrap) and non-ferrous (aluminum scrap) materials are recovered. The recovery efficiencies were assumed to be 50% and 90% for aluminum scrap and steel scrap respectively, referring the content of those material in the incinerator input waste (Bunge, 2015). The electricity consumption for metal recovery was assumed to be 0.1 kWh/kg recovered metal .

Landfill

The landfill is modeled according to ecoinvent database, as described in paragraph 4.3.3.

Siena landfill receives MSW, wet fraction from mechanical separation (OF), stabilized wet fraction (SOF, i.e. OF after the aerobic stabilization) and fine residues from MBT. The landfill input waste compositions are reported in Table 5.6.

Table 5.6 Landfill input waste compositions.

	MSW	OF	SOF	Fine res.
Organic	20.0 %	33.8 %	31.8 %	14.9 %
Green	3.1 %	5.6 %	4.8 %	2.5 %
Paper	10.1 %	1.9 %	1.4 %	0.9 %
Cardboard	4.7 %	0.5 %	0.4 %	0.0 %
Wood	2.2 %	2.7 %	1.9 %	0.0 %
Textile	7.6 %	4.7 %	3.9 %	2.1 %
Glass	3.2 %	4.8 %	5.5 %	4.3 %
Ferrous metal	3.3 %	0.9 %	1.0 %	0.0 %
Non-ferrous metal	0.8 %	0.6 %	0.7 %	0.0 %
Plastic	22.3 %	6.7 %	7.7 %	3.0 %
Undersized	9.9 %	23.1 %	24.0 %	41.4 %
Inert	2.0 %	4.1 %	4.7 %	31.0 %
Tetrapak	4.7 %	2.1 %	2.4 %	0.0 %
Others	6.1 %	8.6 %	9.9 %	0.0 %

Ecoinvent landfill model uses a different characterization for the waste fractions. In order to enter consistent waste compositions some assumptions and modifications were necessary. More details are explained in Appendix.

Table 5.7 reports the annual emissions values obtained from ecoinvent landfill model, referring to 1 ton of landfilled MSW. Different values come out from the other waste fractions.

Table 5.8 reports other technical parameters and also landfill annual biogas emissions per ton of MSW, obtained from LFG generation model, as described in paragraph 4.3.3. Again, different values come out from the other waste fractions.

Table 5.7 Landfill emissions per ton of landfilled MSW – evoinvent results.

	MSW
Water emissions [g/t_{waste}]	
Leachate generation [kg/t_{waste}]	250
Ammonium, NH_4^+	744
COD	813
TOC	206
Nitrate, NO_3	2712
Nitrite, NO_2^-	16
Nitrogen, N	20
Phosphate, PO_4^{3-}	6
Air emissions [g/t_{waste}]	
Ammonia, NH_3	1.4
Dinitrogen monoxide, N_2O	3.8
Nitrogen oxides, NO_X	13.8
Hydrogen chloride, HCl	19.5
Hydrogen fluoride, HF	6.4
Phosphorus, P	0.004
Sulfur dioxide, SO_2	25.4

Table 5.8 Landfill biogas emissions, energy consumptions and energy recovery.

		MSW
LFG generation – Lombardi et al. (2006)		
Biogas	[kg/t_{waste}]	186.0
	[Nm^3/t_{waste}]	145.8
Methane, CH_4	[kg/t_{waste}]	51.7
	[Nm3/t_{waste}]	73.9
directly emitted	[kg/t_{waste}]	20.7
captured	[kg/t_{waste}]	31.0
flared	[kg/t_{waste}]	10.8
CHP combusted	[kg/t_{waste}]	20.2
Consumptions - ecoinvent		
Electricity	[kWh/t_{waste}]	8.8
Diesel	[kg/t_{waste}]	1.3
Energy recovery		
CHP electricity efficiency	%	35
CHP thermal efficiency	%	30
Recovered electricity	[kWh/t_{waste}]	98.1
Recovered heat	[MJ/t_{waste}]	302.7

5.3.3 System expansion

As already mentioned, system expansion was performed to avoid allocations problems for multi-functional processes.

Table 5.9 summarizes the additional functions included in the system expansion for each multi-functional process.

Table 5.9 Siena system expansion summary.

Additional function	Subst. Material	Multi-functional process			
		MBT	Incinerator	BA treatment	Landfill
Electricity recovery	IT electr. mix	-	✓	-	✓
Heat recovery	IT heat mix	-	-	-	✓
Steel scrap recov.	Virgin steel	✓	-	✓	-
Aluminum scrap recov.	Virgin aluminum	-	-	✓	-

5.4 GaBi model

GaBi 6.0 was used to perform the impact assessment phase. The *plan* called "MSW management Siena" was created, in order to build the model and define the system boundaries. Specific processes were created for: waste generation, MBT plant (mechanical separation and aerobic stabilization), incinerator, BA treatment, FA stabilization, activated carbon production and landfill. For each process were set valuable flows and elementary flows, according to the values obtained by the external models described before (see 4.3). Table 5.10 describes these processes. All the other processes were taken from GaBi Professional database (see 4.2).

Table 5.10 Description of processes created in GaBi model.

Valuable input flows	Valuable output flows	Elementary output flows
Waste generation		
	MSW to landfill MSW to incinerator MSW to MBT	
Mechanical and Biological treatment		
MSW to MBT Electricity	RDF Organic waste Organic waste to stab Metals Fine residues	
Aerobic stabilization		
Organic waste to stab Electricity	Stabilized organic fraction	
Activated carbon production		
	Activated carbon	Table 4.4
Incinerator		
RDF MSW to incinerator Ammonia Sodium bicarbonate Activated carbon	Electricity Bottom ash Fly ash Waste water	Table 5.5
Bottom ash treatment		
Bottom ash Electricity	Steel scrap Aluminum Bottom ash	
Fly ash stabilization		
Fly ash Cement		
Landfill		
Electricity	MSW to landfill	Tab 5.7 and 5.8

Diesel	Organic waste Stabilized organic waste Fine residues Bottom ash Electricity Heat	

5.5 LCA OF SOUTH KARELIA WASTE MANAGEMENT

As already mentioned, the LCA study of South Karelia WMS was developed inside the Environmental Technology department of Lappeenranta University of Technology, by upgrading the previous study by Hupponen et al. (2015). Figure 5.11 shows the considered system boundaries.

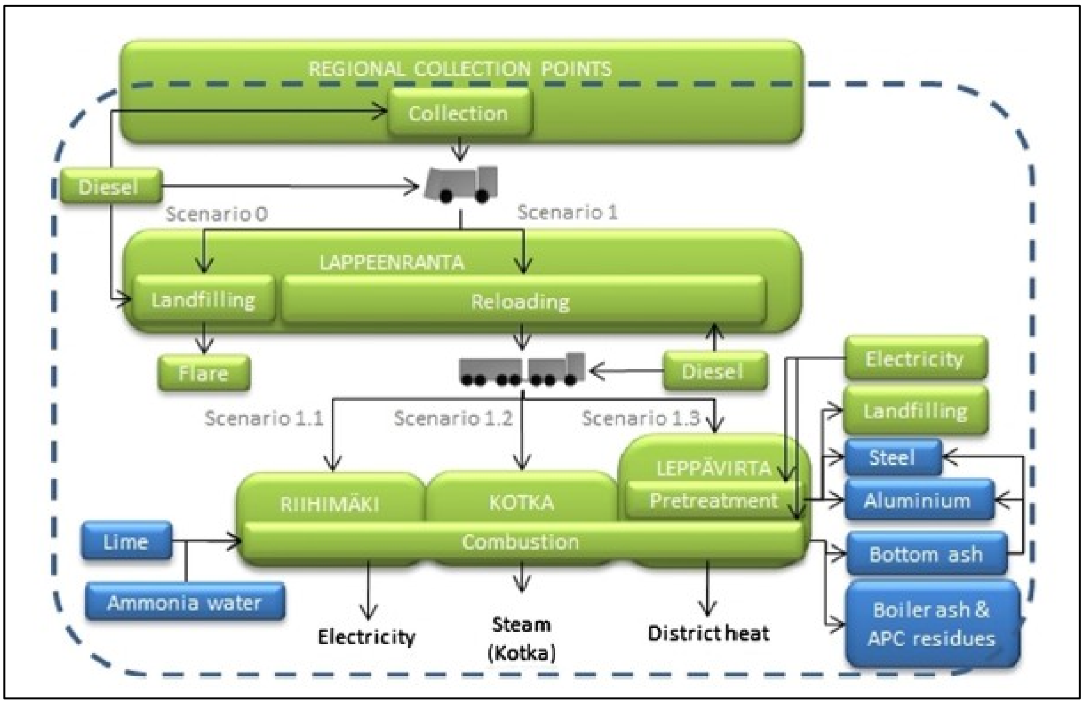


Figure 5.11 South Karelia WMS, system boundaries (Hupponen et al., 2015).

Two main scenarios were selected for the study:

– **Scenario 0**: The mixed MSW are collected and transported to the landfill in Lappeenranta. This was still the situation in 2012.

– **Scenario 1**: The mixed MSW are collected and transported to Lappeenranta where the waste are reloaded. Scenario 1 was divided into three sub-scenarios in which the reloaded mixed MSW are:

1.1 transported to Riihimäki (220 km) and combusted in the grate furnace;

1.2 transported to the nearest waste incineration plant in Kotka (120 km) and combusted in the grate furnace;

1.3 transported to a waste incineration plant in Leppävirta (210 km) that is now under construction, and pretreated and combusted in the fluidized bed boiler.

The considered waste composition is reported in Table 5.11. The LHV of the waste is 15.2 MJ/kg_{MSW}.

Table 5.11 South Karelia mixed MSW composition (Hupponen et al., 2015).

	Mixed MSW
Biowaste	27.1%
Landfill waste	11.7%
Recyclable carton and paperboard	6.0%
Recyclable paper	4.5%
Glass	2.4%
Metals	4.0%
Recyclable plastics	0.2%
Non-recyclable plastics	21.5%
Non-recyclable combustible waste, renewable	6.2%
Non-recyclable combustible waste, non-renewable	8.3%
Other combustible waste	4.9%
Dangerous waste	0.7%
Electric and electronic waste	2.4%

In order to calculate the methane emissions from landfill, the following formula was used:

$$L_0 = DOC \cdot DOC_f \cdot MCF \cdot F \cdot \frac{16}{12}$$

where L_0 is the methane generation potential (kg_{CH4}/kg_{MSW}), DOC is the fraction of degradable organic carbon in the waste assumed equal to 15.1 kg_C/kg_{MSW}, DOC_f is the fraction of DOC that decomposes (assumed 50% wt), MCF is the methane correction factor (assumed 1), F is the fraction of CH_4 in generated landfill gas (assumed 50%) and 16/12 is the molecular weight ratio CH_4/C.

A default value for landfill gas collection of 75% was applied, while the treatment efficiency of CH_4 flaring was assumed to be 99%. No energy recovery from biogas combustion is performed in Lappeenranta landfill. In addition to emissions calculated and presented in Hupponen et al. (2015), also the leachate generation and SO_2 and NO_X emissions (from landfilling and machines) have been taken into account in the LCA model.

Regarding waste incineration, all the emissions were provided by local waste management authorities, together with chemicals consumption and energy efficiencies of the plants. Table 5.12 reports some of these data, taken from the study. It is important to mark that the energy recovery efficiencies of these plants are rather high because the energy content of the waste is recovered also in the form of process steam (for nearby industries supplies) and district heat, and not just electricity as in Siena plant.

Table 5.12 Inventory data, South Karelia incinerator plants (Hupponen et al., 2015).

	Unit	Scenario 1.1	Scenario 1.2	Scenario 1.3
CaO-Ca(OH)$_2$ consumption	kg/t$_{MSW}$	5.1	5.3	5 (4-18)
Ammonia water consumption	kg/t$_{MSW}$	4	4.2	4.7
Plant, total annual energy eff.	%	64	68	66
Plant, annual electricity eff.	%	12	10	26
Plant, own need of electricity	MJ/kg	0.29	0.29	0.34
Share of bottom ash	% of MSW	16	17	1
Share of boiler ash	%of MSW	1	1	4
Share of APC residues	%of MSW	2	2	9

In addition to the GHG emissions calculated and presented in Hupponen et al. (2015), also SO_2, NO_X, HCl and HF emissions from incineration as well as SO_2 and NO_X emissions from working machines have been taken into account in the LCA.

6 EVALUATION AND INTERPRETATION OF RESULTS

In this chapter all the results from this study are presented and discussed.

The first part concerns the results from the LCA of Siena WMS, where different scenarios are investigated and compared in terms of GWP, AP and EP.

Then a contribution analysis of Siena and South Karelia LCAs is performed, and the results are discussed and compared even with the literature review (chapter 2).

Finally, the results interpretation is going through a sensitivity analysis based on parameters perturbation and assumptions alteration. Several parameters are tested and compared between the two case studies and with the literature review; furthermore, others assumptions regarding Siena system are modified and tested in order to better understand which are the most important factors affecting the global outcomes.

6.1 SIENA SYSTEM IMPACT ASSESSMENT

The LCIA phase is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results. The GWP, AP and EP in the CML 2001-April 2013 characterization database in GaBi has been selected for the result analysis.

The classification procedure involves sorting the inventory results in accordance with the selected impact categories, in this case the GWP, AP and EP categories. This sorting takes place in GaBi, where the LCI data is automatically converted to common units and the results are combined. The LCI data is multiplied with the relevant characterization factors in order to obtain LCIA results for the selected impact categories. The factors are conveyed as:

- GWP (100), excluding biogenic carbon, in kg carbon dioxide equivalent: kg CO_2-eq;
- AP, in kg sulfur dioxide equivalent: kg SO_2-eq;
- EP, in kg phosphate equivalent: kg PO_4^{3-}-eq.

This process is automated in GaBi. The software allows analysis of the entire system as well as sub models and individual processes.

In the following paragraphs the results for different scenarios analyses are presented in terms of GWP, AP and EP.

Scenario analysis consists in testing different options individually and observing the effect of these changes on the final result. The new results obtained for each scenario can easily be compared with the baseline results to identify the uncertainties that change some scenario result significantly or the ranking between alternatives.

6.1.1 Global warming potential

Figure 6.1 and Table 6.1 show the results for GWP impact category in different scenarios.

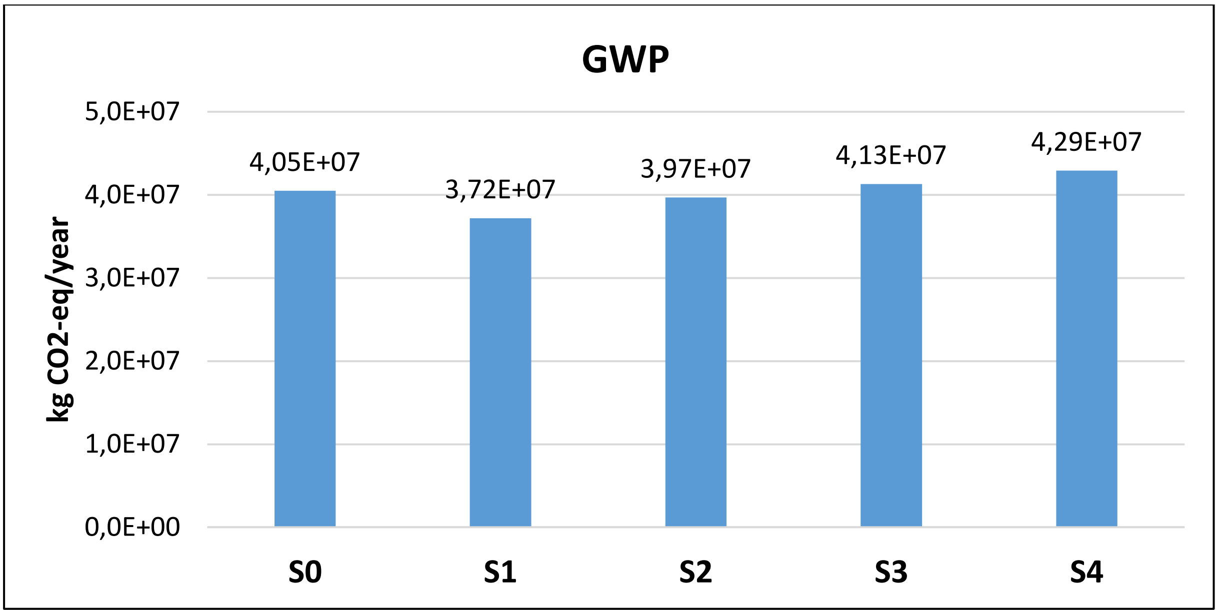


Figure 6.1 Total results for GWP impact category in different scenarios.

Table 6.1 GWP results for different scenarios.

	GWP		
	Annual emiss.	**Annual emiss. per ton of waste**	**Difference from S0**
	kg CO_2-eq/year	kg CO_2-eq/year/t_{waste}	kg CO_2-eq/year
S0	40 494 000	426	
S1	37 201 000	392	-3 293000
S2	39 686 000	418	-808 000
S3	41 327 000	435	+833 000
S4	42 928 000	452	+2 434 000

The best scenario from a GWP point of view is the mass-burn scenario. The scenario ranking is: 1, 2, 0, 3 and 4. However, as can be observed, there are no relevant differences between the different scenarios.

These results are unexpected, comparing to the outcomes from literature review. Above all, the comparison between mass-burn and landfilling scenarios (S1 and S4 respectively) should be likely to bring a much greater difference than the one illustrated in Figure 6.1. A comparison of landfilling and incineration of MSW from the point of view of GHG emissions has been done in many studies (e.g. Eriksson et al., 2005; Manfredi, Tonini, & Christensen, 2011; Sevigné Itoiz, Gasol, Farreny, Rieradevall, & Gabarrell, 2013; Hupponen et al., 2015; Arena, Mastellone, & Perugini, 2003; Miliute & Kazimieras Staniskis, 2010) and all of those are in favour of incineration, showing a considerable difference, in terms of emissions, with the landfilling scenario.

The differences between the two opposing scenarios, taken from several studies, are reported in

Table 6.2. The percentage values are calculated by:

$$\%\,diff = \frac{GWP_{INC.\ SCEN} - GWP_{LANDF.\ SCEN}}{GWP_{LANDF.\ SCEN}}\,100$$

Table 6.2 Difference between landfilling and incineration scenarios reported by several studies (* average value for different incineration scenarios).

Reference	Country	GWP Δ%
Arena et al., 2003	Italy	**-84**
Eriksson et al., 2005	Sweden	**-33**
Miliute & Kazimieras Staniskis, 2010	Lithuania	**-77**
Sevigné Itoiz et al., 2013	Spain	**-57**
Parkes, Lettieri, & Bogle, 2015	UK	**-78**
Hupponen et al., 2015	Finland	**-96 ***
This study	Italy	**-13**

While the difference between incineration scenario and landfilling scenario is over 50% in almost all the studies, in this case the difference is only 13%. This is due to the fact that the incineration of 1 ton of MSW is generating 705 kg CO_2-eq and saving -380 kg CO_2-eq for electricity recovery, while the landfilling of 1 ton of MSW is generating 524 kg CO_2-eq and saving -79 kg CO_2-eq for both heat and electricity recovery. Further, when we take in account the supplying of chemicals for the APC system in the incineration scenario the difference between the two waste management systems is even lower.

The direct emissions from MSW incineration are rather high compared to the avoided emissions due to energy recovery, bringing a positive and considerable net contribution to the final GWP balance. And this is partly due to the medium/low energy recovery efficiency in the incineration process (i.e. there is no heat recovery) and partly, as tested in the following paragraphs, due to the high plastic content of the waste in Siena MSW specific composition (around 22%), that is the main contributor to CO_2 fossil emissions.

Produced and avoided emissions from different processes are presented in detail in Figure 6.3 and the grouping scheme for LCA results is shown in Table 6.3.

Table 6.3 Grouping of emissions for LCA results analysis.

MBT	**MBT_Energy cons.**	Electricity consumption for mechanical separation and aerobic stabilization.
	MBT_Metal recov.	Credit for recycling of steel scrap from MSW.
INCINERATION	**INC_Direct emissions**	Stack emissions.
	INC_APC and WW treat.	Supplying of chemicals for APC, treatment of FA and WW
	INC_Energy recov.	Credit for electricity recovery.
	INC_Metal recovery BA	Credit for steel scrap and alumium recovery from BA.
LANDFILL	**LAND_Direct emissions**	Direct emissions and energy consumption (fuel+electricity).
	LAND_Energy rec.	Credit for electricity and heat recovery from biogas combustion.

In scenarios 0, 1, 2 and 3 the main impacts are generated by direct emissions and energy recovery from incineration process, with positive and negative impacts respectively; in scenarios 0, 2 and 3 another relevant contribution is provoked from landfill direct emissions. Even the supplying of chemicals and the treatment of FA and waste water from the incineration has a considerable contribution on the final balance. In Figure 6.2 is presented the contribution from each process to the *INC_APC and WW treat.* stage. The supplying of soda and cement are the most relevant burdens in terms of GHG emissions, while supplying of ammonia and GHG emissions from treatment of waste water are fairly minor.

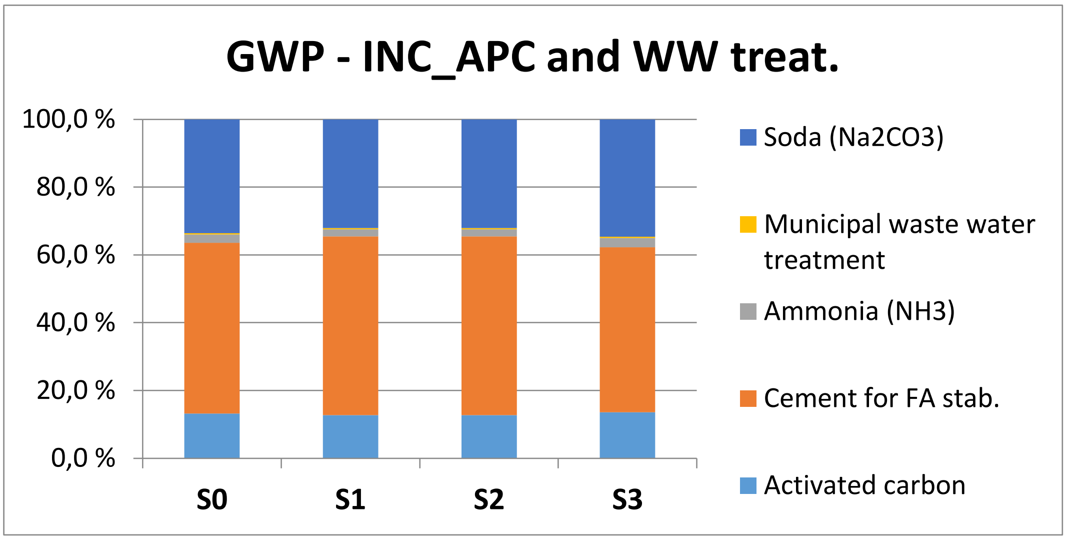
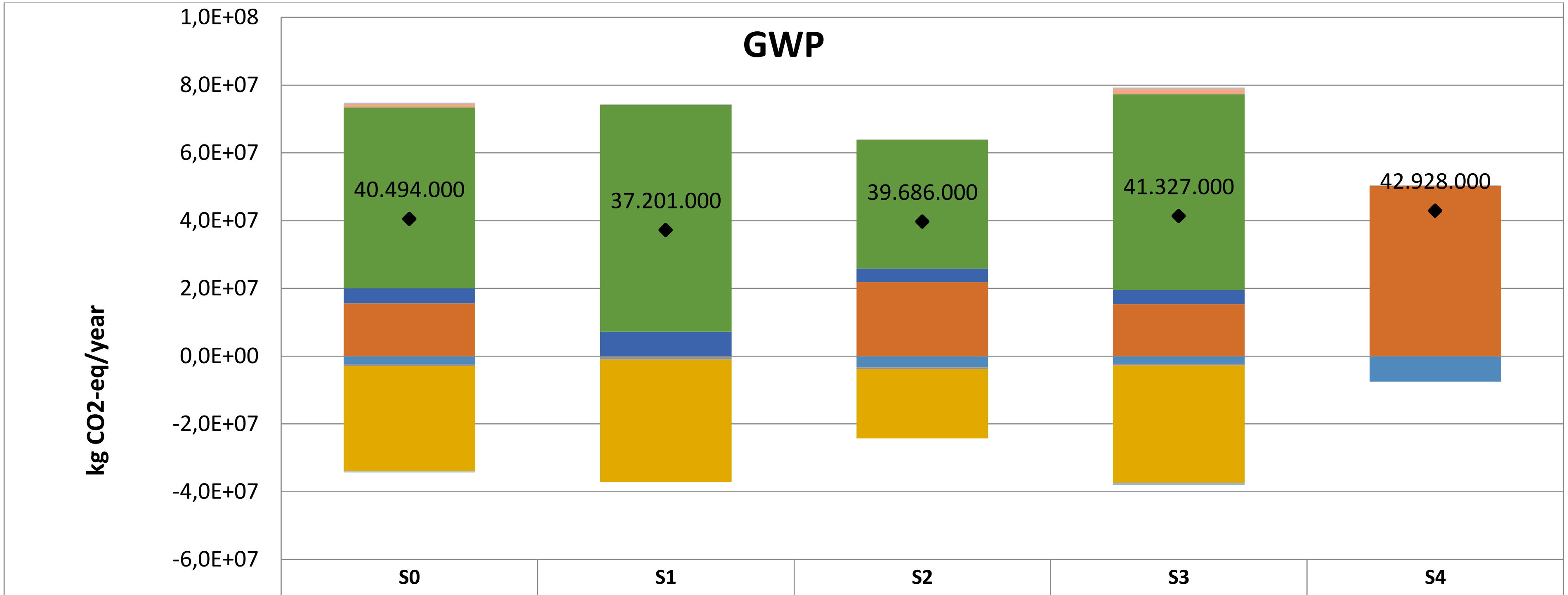


Figure 6.2 Hotspot analysis for the process of INC_APC and WW treat, GWP impact category.



	S0	S1	S2	S3	S4
Transp.	383.000	224.000	220.000	473.000	216.000
MBT_Energy cons.	983.000	0	0	1.534.000	0
MBT_Metal recov.	-332.000	0	0	-519.000	0
INC_Direct emissions	53.437.000	66.930.000	37.889.000	57.738.000	0
INC_APC and WW treat.	4.437.000	7.157.000	4.052.000	4.181.000	0
INC_Energy recov.	-31.103.000	-36.143.000	-20.461.000	-34.686.000	0
INC_Metal recovery BA	-543.000	-1.004.000	-568.000	-462.000	0
LAND_Direct emissions	15.557.000	38.000	21.819.000	15.361.000	50.237.000
LAND_Energy rec.	-2.324.000	0	-3.265.000	-2.294.000	-7.524.000
◆ LCA net result	40.494.000	37.201.000	39.686.000	41.327.000	42.928.000

Figure 6.3 GWP related produced emissions and avoided emissions from specific processes for different scenarios.

Figure 6.4 shows the differences between incineration and landfilling of waste in terms of net impact per ton of treated waste. The net impact for a ton of incinerated waste is calculated adding all the contributions from incineration stage (direct emissions, energy recovery, APC supplying and metal recovery from BA) and dividing by the total amount of waste routed to incineration. The net impact for a ton of landfilled waste is calculated adding all the contributions from landfilling stage (direct emissions and energy recovery from LFG combustion) and dividing by the total amount of waste routed to landfill.

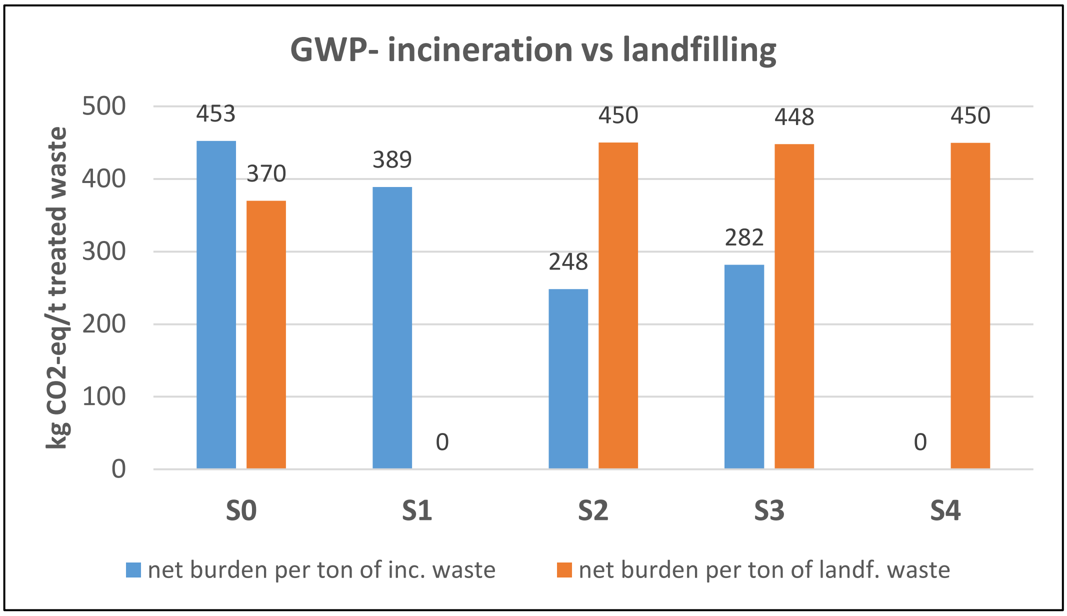


Figure 6.4 Comparison between incineration and landfilling of waste for each scenario.

Further, the credit due to the energy recovery from landfill gas combustion is not as relevant as it might be expected. This is due to the assumptions regarding the LFG collection efficiency, the percentage of burned LFG (with energy recovery, instead of flaring without energy recovery) and the CHP overall efficiency, which are 60%, 65% and 65% respectively. These assumptions bring as result that only 182 kWh (electricity + heat) are recovered per ton of landfilled MSW (different outcomes originate from landfilling of organic fraction and stabilized organic fraction of MSW). As it can be observed, transportation processes as well as the impacts generated by MBT, have a very low contribution for GWP emissions, in every scenarios. The same conclusion can be drawn for the credit due to the metal recovery from incineration bottom ash, which appears to be negligible even in the mass-burn scenario.

6.1.2 Acidification potential

Figure 6.5 and Table 6.4 show the results for AP impact category in different scenarios.

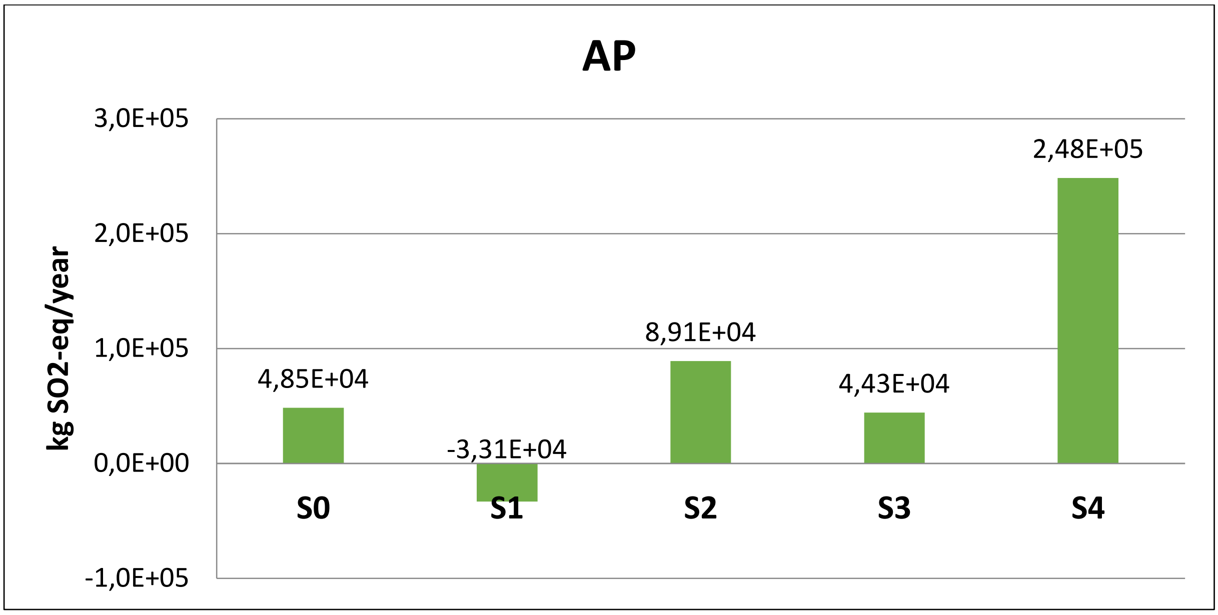
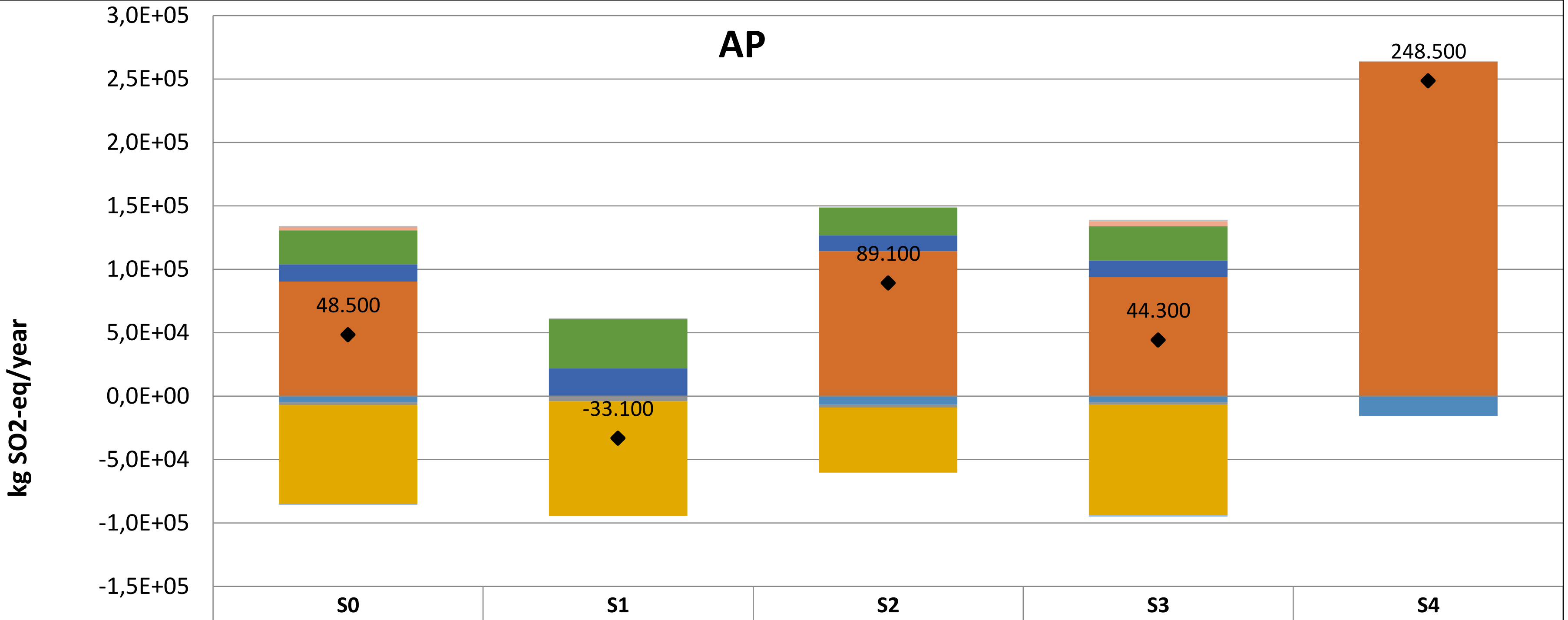


Figure 6.5 Total results for AP impact category in different scenarios.

Table 6.4 AP results for different scenarios.

	AP		
	Annual emiss. kg SO_2-eq/year	**Annual emiss. per ton of waste** kg SO_2-eq/year/t_{waste}	**Difference from S0** kg SO_2-eq/year
S0	48 500	0.51	
S1	-33 100	-0.35	-81 600
S2	89 100	0.94	+40 600
S3	44 300	0.47	-4 200
S4	248 500	2.62	+200 000

It can be observed that there are considerable differences between different scenarios in terms of AP related emissions. The best scenario is S1 (mass-burn scenario) with a global negative impact, which means avoided emissions, while all the others have positive impacts. This is due to the amount of electricity production from the combustion of all MSW. The worst scenario is number 4 (landfilling scenario). The scenario ranking is: 1, 3, 0, 2 and 4. Produced and avoided emissions from different processes are presented in detail in Figure 6.6.



	S0	S1	S2	S3	S4
Transp.	1.000	600	600	1.200	500
MBT_Energy cons.	2.500	0	0	3.800	0
MBT_Metal recov.	-800	0	0	-1.200	0
INC_Direct emissions	26.900	39.000	22.100	27.000	0
INC_APC and WW treat.	13.600	21.800	12.300	12.900	0
INC_Energy recov.	-78.000	-90.600	-51.300	-87.000	0
INC_Metal recovery BA	-2.100	-3.900	-2.200	-1.800	0
LAND_Direct emissions	90.300	100	114.400	94.100	263.500
LAND_Energy rec.	-4.800	0	-6.800	-4.800	-15.600
◆ LCA net result	48.500	-33.100	89.100	44.300	248.500

Figure 6.6 AP related produced emissions and avoided emissions from specific processes for different scenarios.

In scenarios 0, 2 and 3 the main impacts are generated by direct emissions from landfill and by energy recovery from waste incineration; the contribution of direct emissions from incinerator and the contribution of the supplying of chemicals for APC are also rather relevant with respect to the final balances. In Figure 6.7 is presented the contribution from each process to the *INC_APC and WW treat.* stage, concerning AP impact category. In scenario 1 the most important factor is the energy recovery from the incineration, as avoided emissions, while the main produced burdens are the direct emissions from incinerator and the supplying of chemicals for APC and for FA stabilization. Concerning scenario 4, the only relevant contribution is given by direct emissions from the landfill, while energy recovery plays a fairly lower role.

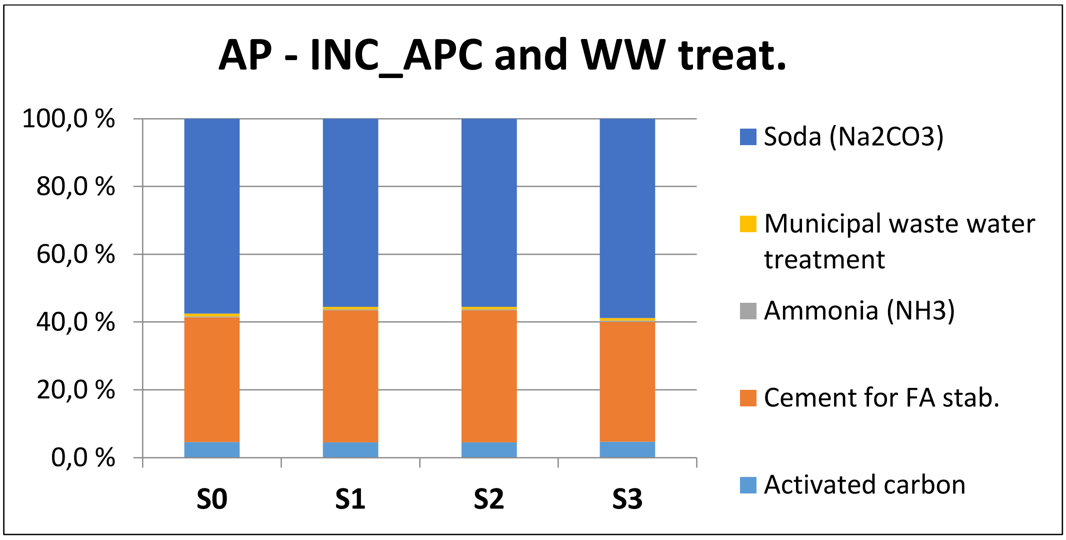


Figure 6.7 Hotspot analysis for the process of INC_APC and WW treat, AP impact category.

Transportation, MBT and metal recovery from BA have nearly negligible contributions in each scenario in terms of AP related emissions.

6.1.3 Eutrophication potential

Figure 6.8 and show the results for EP impact category in different scenarios.

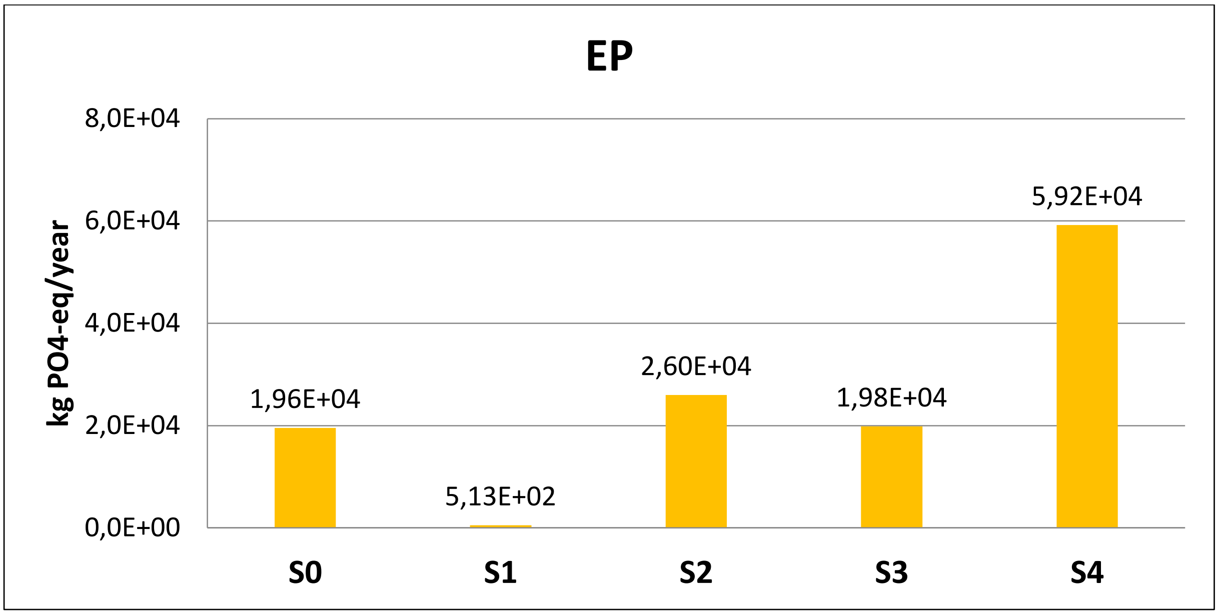


Figure 6.8 Total results for EP impact category in different scenarios.

Table 6.5 EP results for different scenarios.

	EP		
	Annual emiss.	**Annual emiss. per ton of waste**	**Difference from S0**
	kg PO_4-eq/year	kg PO_4-eq/year/t_{waste}	kg PO_4-eq/year
S0	19 600	0.21	
S1	500	0.01	-19 100
S2	26 000	0.27	+6 400
S3	19 800	0.21	+200
S4	59 200	0.62	+39 600

The same remarks made for AP are valid also for the eutrophication impact category. The best scenario is scenario 1, while the worst is number 4. The differences between scenarios are considerable, but in this case the ranking changes among scenario 0 and scenario 3. Produced and avoided emissions from different processes are presented in Figure 6.10. The relative contributions of the single processes are similar to the acidification (Figure 6.6).

For scenarios 0, 2, 3 and 4 the main impact is generated by the landfill direct emission, and in scenario 0, 2, 3 the avoided emissions due to energy recovery from incineration are much less relevant compared to that. The direct emissions from incineration and the supplying for chemicals for APC have almost the same contribution in terms of EP related emissions, which becomes more important in scenario 1, than in scenarios 0, 2 and 3. In Figure 6.9 is presented the contribution from each process to the *INC_APC and WW treat.* stage, concerning EP impact category.

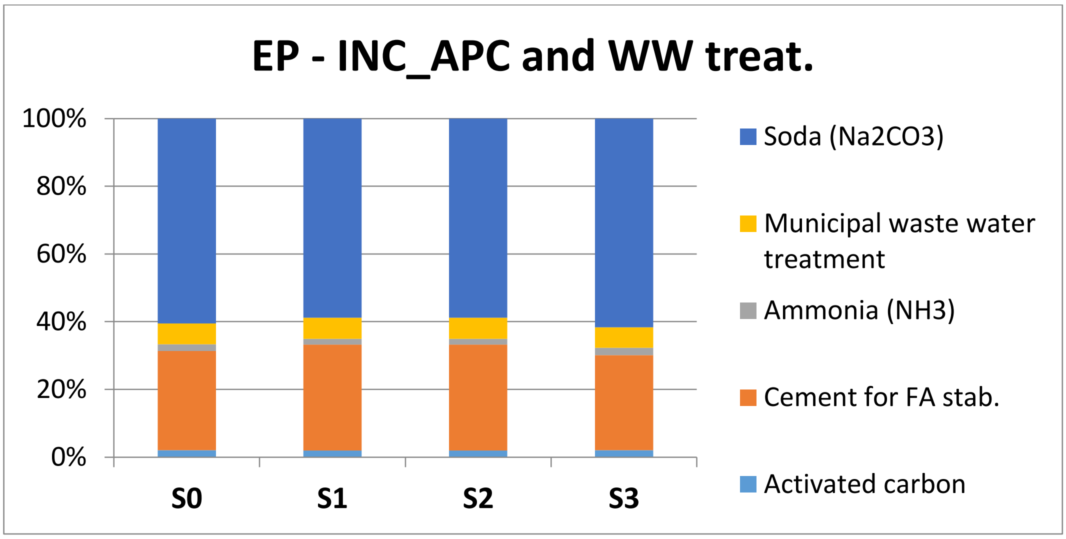
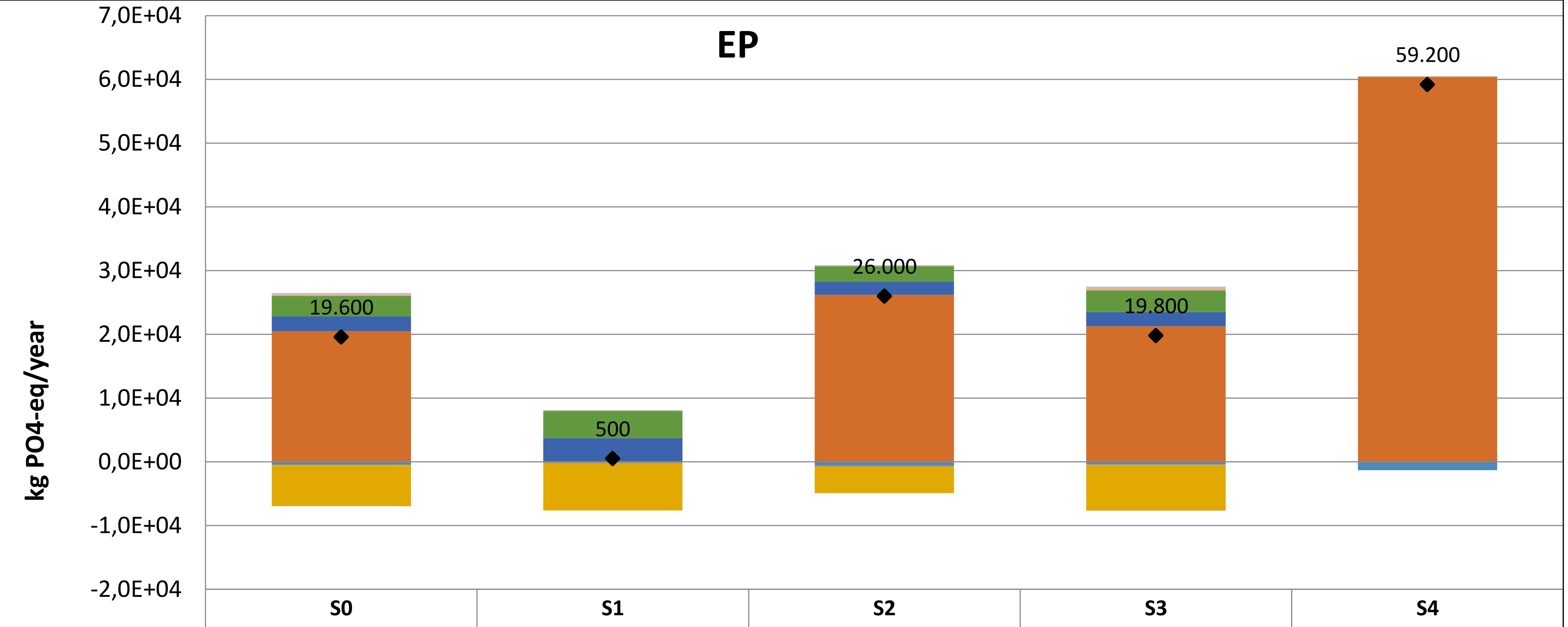


Figure 6.9 Hotspot analysis for the process of INC_APC and WW treat, EP impact category.

Transportation, MBT, metal recovery from BA and energy recovery from landfill have nearly negligible contributions in each scenario in terms of EP related emissions.



	S0	S1	S2	S3	S4
Transp.	240	140	140	300	130
MBT_Energy cons.	200	0	0	310	0
MBT_Metal recov.	-20	0	0	-30	0
INC_Direct emissions	3.210	4.270	2.420	3.370	0
INC_APC and WW treat.	2.340	3.710	2.100	2.230	0
INC_Energy recov.	-6.380	-7.410	-4.200	-7.110	0
INC_Metal recovery BA	-110	-210	-120	-100	0
LAND_Direct emissions	20.500	20	26.210	21.280	60.380
LAND_Energy rec.	-410	0	-570	-400	-1.320
◆ LCA net result	19.600	500	26.000	19.800	59.200

Figure 6.10 EP related produced emissions and avoided emissions from specific processes for different scenarios.

6.2 CONTRIBUTION ANALYSIS: COMPARISON WITH SOUTH KARELIA CASE STUDY AND LITERATURE REVIEW

This analysis is aiming at evaluating how much the contribution of each step in the entire waste management chain is relevant, and what are the main factors in the operating systems which affect this feature. In order to do this, the case study results are compared with the results from South Karelia case study and also with the outcomes from the literature review.

For this analysis the results are compared in terms of percentage of contribution on the final LCA balance: this means that the contribution from each process is divided by the sum of the absolute values of all the individual burdens to that impact category.

$$\%C_i = \frac{C_i}{{}_i\ C_i}\ 100$$

Since the impact from each process can be either a positive or a negative value (produced emissions and avoided emissions respectively), the division by the sum of the absolute values provides a better understanding of the individual percentage contribution, than the division by the sum of the relative values. The example shows what could be the misunderstanding due to the different assumption.

Example:

1. direct emissions from incineration: 100 000 kg CO2-eq
2. avoided emissions for energy production: -80 000 kgCO2-eq
3. emissions for collection and transportation of waste: 5 000 kg CO2-eq

Transportation process, percentage contribution (first method, sum of absolute values):

$$\%C_3 = \frac{5\,000}{100\,000\ +\ -80\,000\ +\ 5\,000}\ 100 = 2.7\ \%$$

Transportation process, percentage contribution (second method, sum of relative values):

$$\%C_3 = \frac{5\,000}{100\,000 - 80\,000 + 5\,000}\ 100 = 20\ \%$$

6.2.1 Global warming potential

Figure 6.11 shows the comparison, in terms of contribution analysis for GWP, between the mass-burn scenario in Siena case study (scenario 1) and the three mass-burn scenarios concerning South Karelia case study.

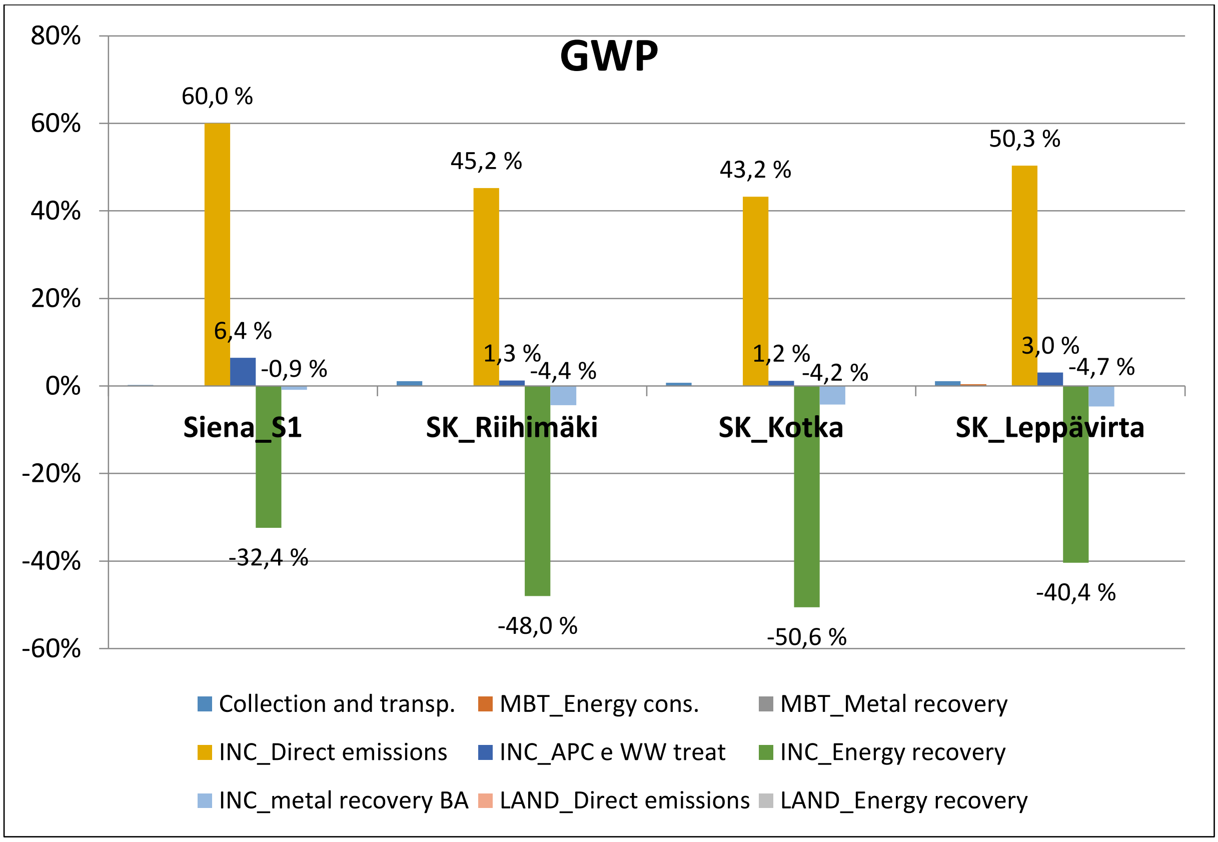


Figure 6.11 GWP contribution analysis, comparison between mass-burn scenarios in both Siena (scenario 1) and South Karelia (scenarios 1, 2 and 3) case studies.

It can be noted the similarity between the two case studies in the contributions to GWP. The main processes are the direct emissions and the energy recovery from incinerator, as it also arises from literature review. However, in Siena case study the contribution due to the direct emissions from incinerator is higher compared to South Karelia case study, and at the same time the negative impact due to the energy recovery is rather lower. As a matter of facts, the energy recovery efficiency in Finnish WtE plants is higher than in Siena case, since the former includes heat and process steam recovery and subsequent exploitation; this can be observed in Figure 6.12. However, the difference in the benefits from energy substitution is also influenced by the type of energy mix which is substituted, and this is highly country specific, as discussed by Fruergaard, Astrup, & Ekvall, (2009).

Further, the supplying of chemicals for APC has a considerable relevance in Siena case study (greater than 5%), while it could be neglected in the first two scenarios of South Karelia case study (around 1%). This is partly due to the fairly high GWP impact for the production of sodium bicarbonate needed in Siena incinerator, instead of lime and ammonia needed in Finnish WtE plants. As already observed, what it comes out from literature review is that this process can be negligible for the final LCA balance (Umberto Arena et al., 2015), but sometimes it can assume a relevance role in terms of contribution (Morselli et al., 2005). However, in most of the cases the processes related to incineration are evaluated together and accordingly it becomes hard to understand the individual contributions.

The same can be said regarding metal recovery from BA. It provides a negligible contribution in Siena case, while a contribution around 5% in South Karelia scenarios. However, other authors recognize the scarce importance of this process for the final GWP balance (Turconi et al., 2011). A detailed analysis regarding the accounting of metal recovery from incineration BA is performed by Allegrini, Vadenbo, Boldrin, & Astrup, (2015). They state that benefits to the GWP category increase proportionally in line with increasing metal recovery, which includes also the metal content in the input waste to incinerator and the virgin material substitution ratio.

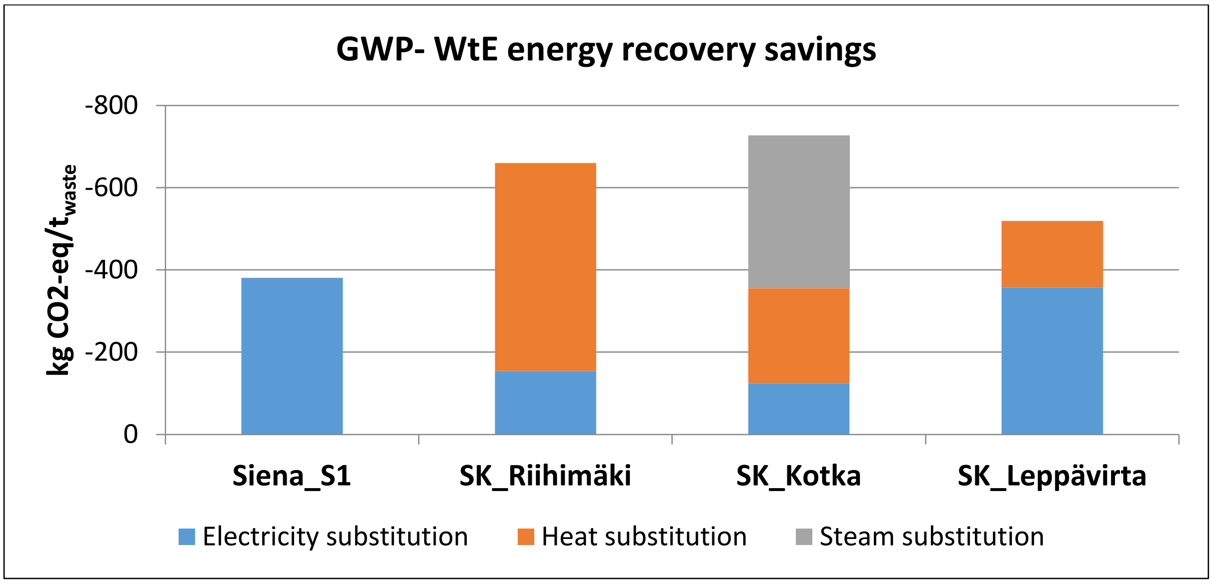


Figure 6.12 Avoided GHG emissions due to energy recovery from WtE plants, comparison between Siena and South Karelia.

Collection and transportation stage has a negligible relevance for GWP accounting in both cases, and this is consistent with the outcomes from literature review.

Table 6.6 shows a comparison between the landfilling scenarios in the two case studies. Collection and transportation stage has a higher contribution in South Karelia case and this is probably due to geographical reasons: waste are transported for longer distances since the area is larger and the population is much more widespread. However, this also due to the fact that the total GHG emissions from Siena landfill are much higher than the emissions from South Karelia landfill, therefore this brings a lower percentage contribution of transportation stage.

Table 6.6 Comparison between landfilling scenarios, GWP impact category.

	Siena_S4	SK_Lapp. landf.
Collection and transp.	0.4%	1.8%
LAND_Direct emissions	86.6%	98.2%
LAND_Energy recovery	-13.0%	0.0%

6.2.2 Acidification potential

Figure 6.13 shows the comparison, in terms of contribution analysis for AP, between the mass-burn scenario in Siena case study (scenario 1) and the three mass-burn scenarios concerning South Karelia case study.

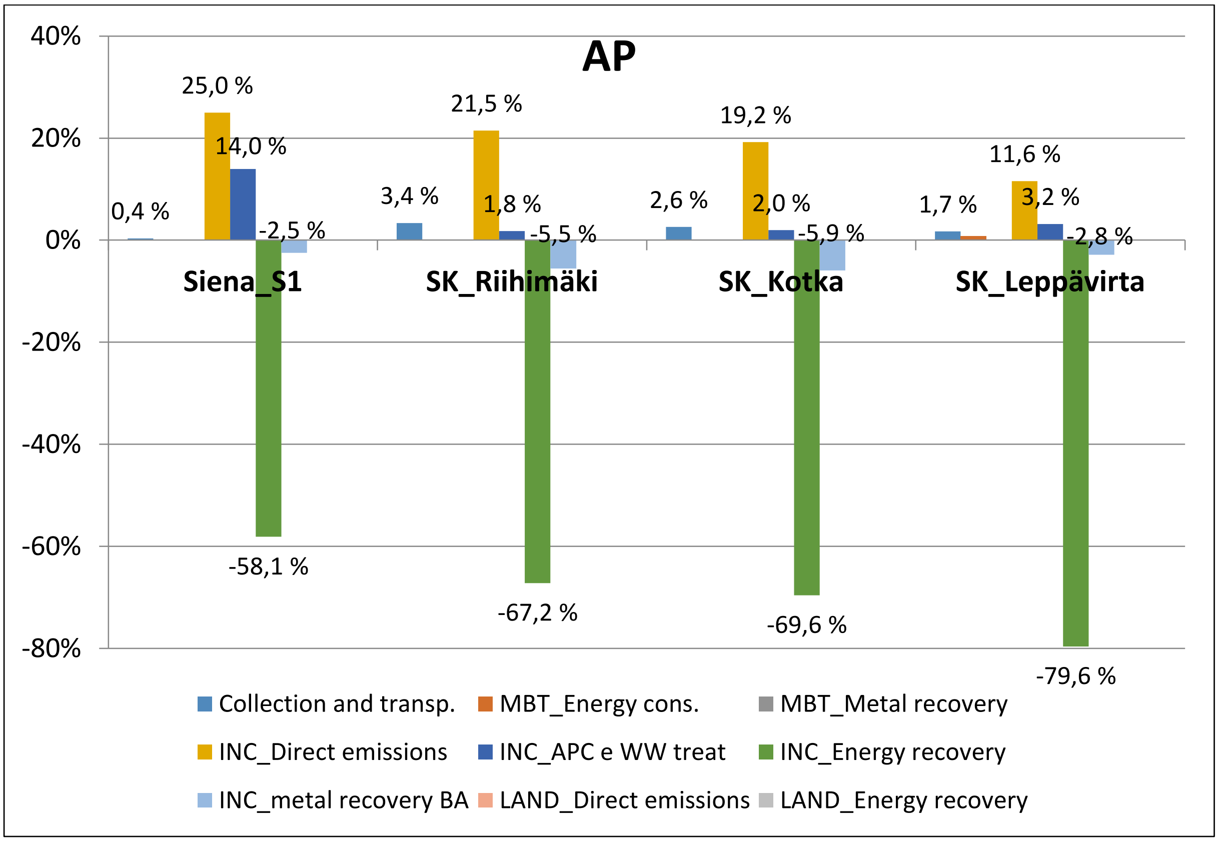


Figure 6.13 AP contribution analysis, comparison between mass-burn scenarios in both Siena (scenario 1) and South Karelia (scenarios 1, 2 and 3) case studies.

The main processes are again the direct emissions and the energy recovery from the incinerator, with positive and negative contribution respectively, and this is in agreement with literature review. The differences in the contributions of these process are mainly due to the different performances of the plants, as shown in Figure 6.12, but the observations made for GWP impact category about energy mix are still effective.

Regarding the impacts due to the supplying of chemicals for APC and FA stabilization, Siena case shows a rather high contribution of this process, which is comparable to the direct emissions from the incinerator (around 14%); while in South Karelia cases this stage is not as relevant (2-3%). The main contributor in this process is the supplying of sodium bicarbonate, as shown in Figure 6.7.

Metals recovery from BA provides negative contribution to the final AP balance; the percentage contributions are higher in South Karelia cases than in Siena case.

Collection and transportation stage is still negligible (< 3% contribution) in each scenario, even though its relevance in AP related emissions is stressed by several LCA performers (Bovea, Ibáñez-Forés, Gallardo, & Colomer-Mendoza, 2010; Al-Salem, Evangelisti, & Lettieri, 2014).

Table 6.7 shows a comparison between the landfilling scenarios in the two case studies. The situation is the same than in GWP impact category, and the transportation brings even higher contribution in South Karelia case.

Table 6.7 Comparison between landfilling scenarios, AP impact category.

	Siena_S4	SK_Lapp. landf.
Collection and transp.	0.2%	4.4%
LAND_Direct emissions	94.2%	95.6%
LAND_Energy recovery	-5.6%	0.0%

6.2.3 Eutrophication potential

Figure 6.14 shows the comparison, in terms of contribution analysis for EP, between the mass-burn scenario in Siena case study (scenario 1) and the three mass-burn scenarios concerning South Karelia case study.

The main processes are still the direct emissions and the energy recovery from the incinerator, and this is consistent with the literature review. However, here the differences between the two case studies are more evident.

In effect, the emissions related to the supplying of chemicals for APC and FA stabilization are much more relevant in Siena than in South Karelia case (31 % and 2-4 % respectively); even Morselli et al., (2005) found the relevance of incinerator APC related emissions in accounting eutrophication potential. Further, in the Finnish case the emissions for transportation contribute up to 5% (5.5% in Riihimäki scenario) of the total EP LCA impact, while they can still be neglected for Siena LCA final balance. The main difference between the two case studies is that in the Italian mass-burn scenario the final EP impact is a positive one, while in all South Karelian mass-burn scenarios the final LCA balance for EP is negative, which means avoided emissions.

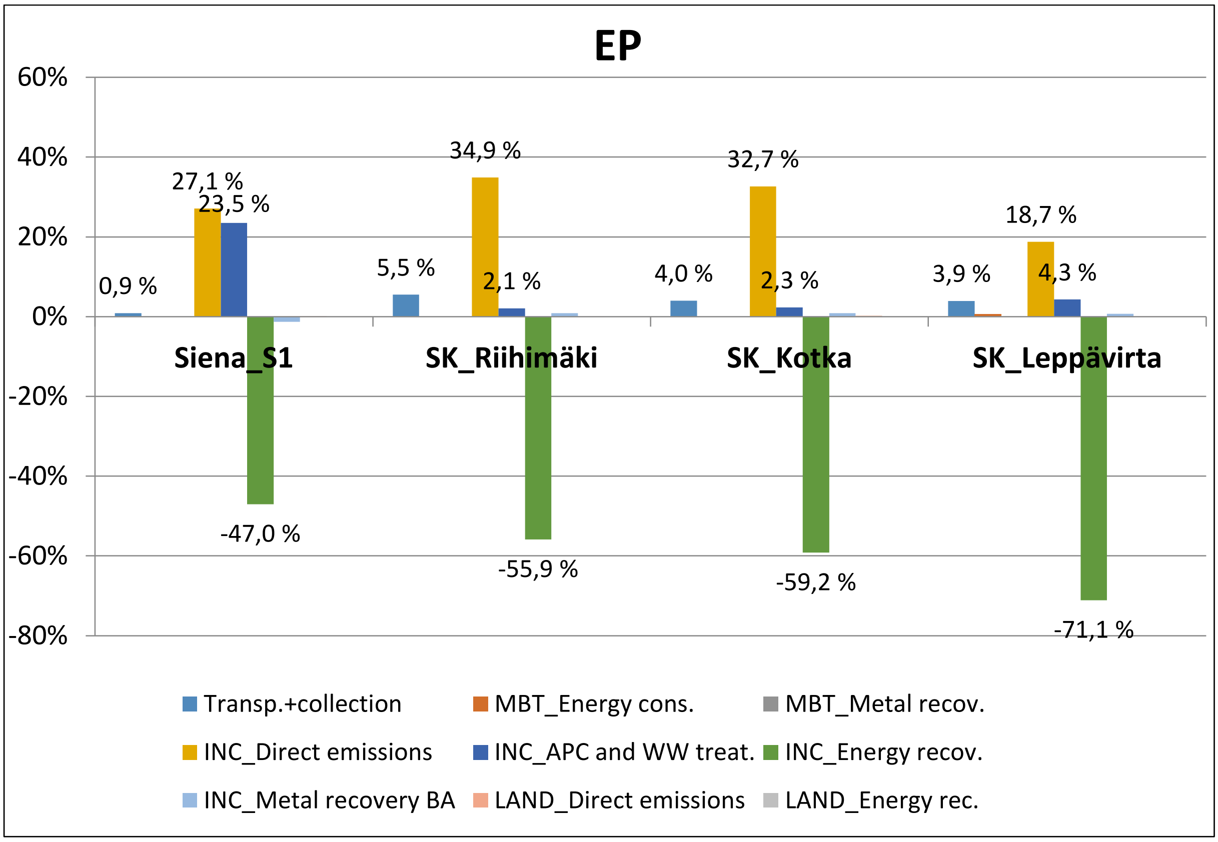


Figure 6.14 EP contribution analysis, comparison between mass-burn scenarios in both Siena (scenario 1) and South Karelia (scenarios 1, 2 and 3) case studies.

Table 6.8 shows a comparison between the landfilling scenarios in the two case studies. The situation is the same than in AP impact category, and the transportation brings even higher contribution in South Karelia case. It can be noted how the relevance of energy recovery (only for Siena case) is fairly minor, giving an almost negligible contribution to the final LCA balance in this impact category.

Table 6.8 Comparison between landfilling scenarios, EP impact category.

	Siena_S4	**SK_Lapp. landf.**
Collection and transp.	0.2%	6.4%
LAND_Direct emissions	97.7%	93.6%
LAND_Energy recovery	-2.1%	0.0%

Table 6.9, Table 6.10 and Table 6.11 show the summaries of contribution analysis for GWP, AP and EP impact categories for the discussed scenarios, while Figure 6.15, Figure 6.16 and Figure 6.17 show the contribution analysis for other Siena scenarios.

Table 6.9 Summary of % contribution from different process to GWP balance, for all scenarios.

	GWP - % contribution					
	Mass-burn scenarios				Landfilling scenarios	
	Siena_S1	SK_Riihimäki	SK_Kotka	SK_Leppävirta	Siena_S4	SK_Landfill
Transp.+collection	0.2%	1.1%	0.7%	1.1%	0.4%	1.8%
MBT_Energy cons.	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%
MBT_Metal recov.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
INC_Direct emissions	60.0%	45.2%	43.2%	50.3%	0.0%	0.0%
INC_APC and WW treat.	6.4%	1.3%	1.2%	3.0%	0.0%	0.0%
INC_Energy recov.	-32.4%	-48.0%	-50.6%	-40.4%	0.0%	0.0%
INC_Metal recovery BA	-0.9%	-4.4%	-4.2%	-4.7%	0.0%	0.0%
LAND_Direct emissions	0.0%	0.0%	0.0%	0.0%	86.6%	98.2%
LAND_Energy rec.	0.0%	0.0%	0.0%	0.0%	-13.0%	0.0%

Table 6.10 Summary of % contribution from different process to AP balance, for all scenarios.

	AP - % contribution					
	Mass-burn scenarios				Landfilling scenarios	
	Siena_S1	SK_Riihimäki	SK_Kotka	SK_Leppävirta	Siena_S4	SK_Landfill
Transp.+collection	0.4%	3.4%	2.6%	1.7%	0.2%	4.4%
MBT_Energy cons.	0.0%	0.0%	0.0%	0.8%	0.0%	0.0%
MBT_Metal recov.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
INC_Direct emissions	25.0%	21.6%	19.3%	11.6%	0.0%	0.0%
INC_APC and WW treat.	14.0%	1.8%	2.0%	3.2%	0.0%	0.0%
INC_Energy recov.	-58.1%	-67.6%	-70.1%	-79.9%	0.0%	0.0%
INC_Metal recovery BA	-2.5%	-5.6%	-5.9%	-2.9%	0.0%	0.0%
LAND_Direct emissions	0.1%	0.0%	0.1%	0.0%	94.2%	95.6%
LAND_Energy rec.	0.0%	0.0%	0.0%	0.0%	-5.6%	0.0%

Table 6.11 Summary of % contribution from different process to EP balance, for all scenarios.

	EP - % contribution					
	Mass-burn scenarios				Landfilling scenarios	
	Siena_S1	SK_Riihimäki	SK_Kotka	SK_Leppävirta	Siena_S4	SK_Landfill
Transp.+collection	0.9%	5.5%	4.0%	4.0%	0.2%	6.4%
MBT_Energy cons.	0.0%	0.0%	0.0%	0.7%	0.0%	0.0%
MBT_Metal recov.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
INC_Direct emissions	27.1%	35.1%	32.9%	18.8%	0.0%	0.0%
INC_APC and WW treat.	23.5%	2.1%	2.3%	4.3%	0.0%	0.0%
INC_Energy recov.	-47.0%	-56.3%	-59.6%	-71.5%	0.0%	0.0%
INC_Metal recovery BA	-1.3%	0.9%	0.9%	0.7%	0.0%	0.0%
LAND_Direct emissions	0.1%	0.1%	0.2%	0.0%	97.7%	93.6%
LAND_Energy rec.	0.0%	0.0%	0.0%	0.0%	-2.1%	0.0%

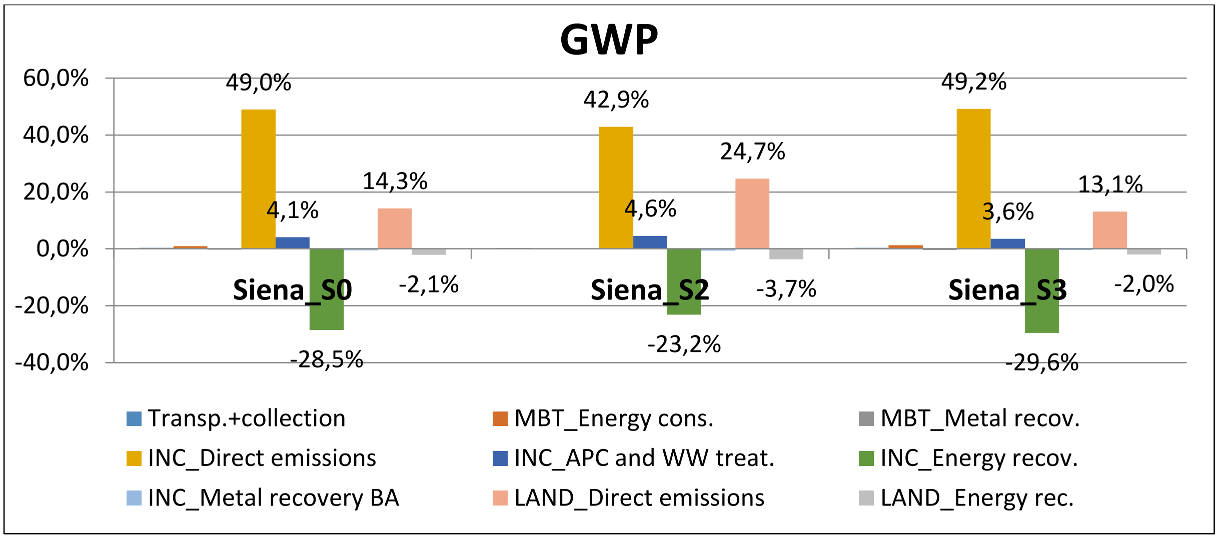


Figure 6.15 GWP contribution analysis, comparison between Siena scenarios.

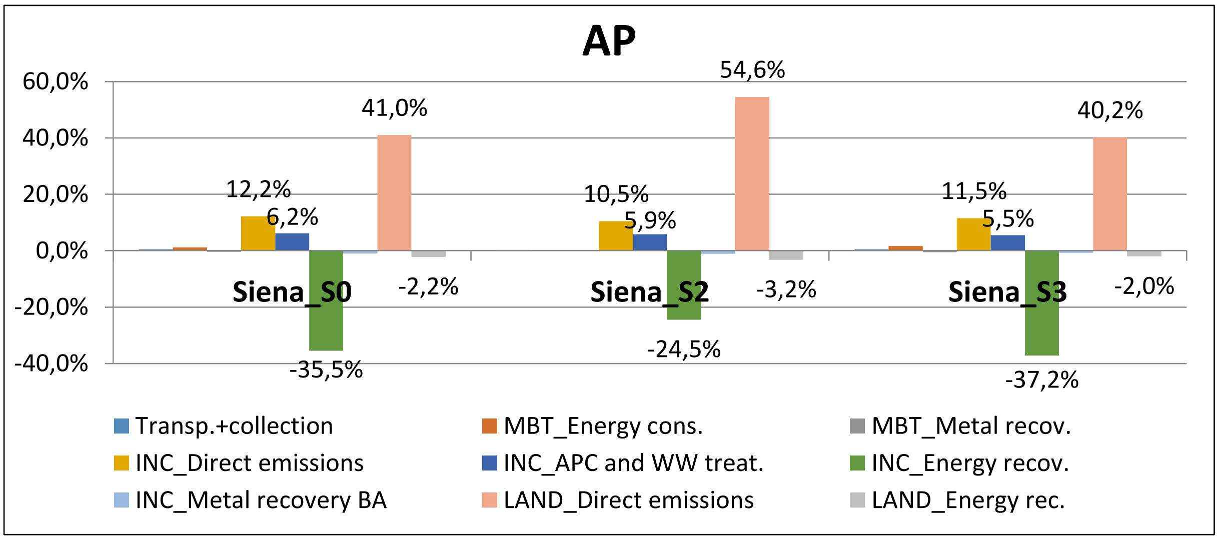


Figure 6.16 AP contribution analysis, comparison between Siena scenarios.

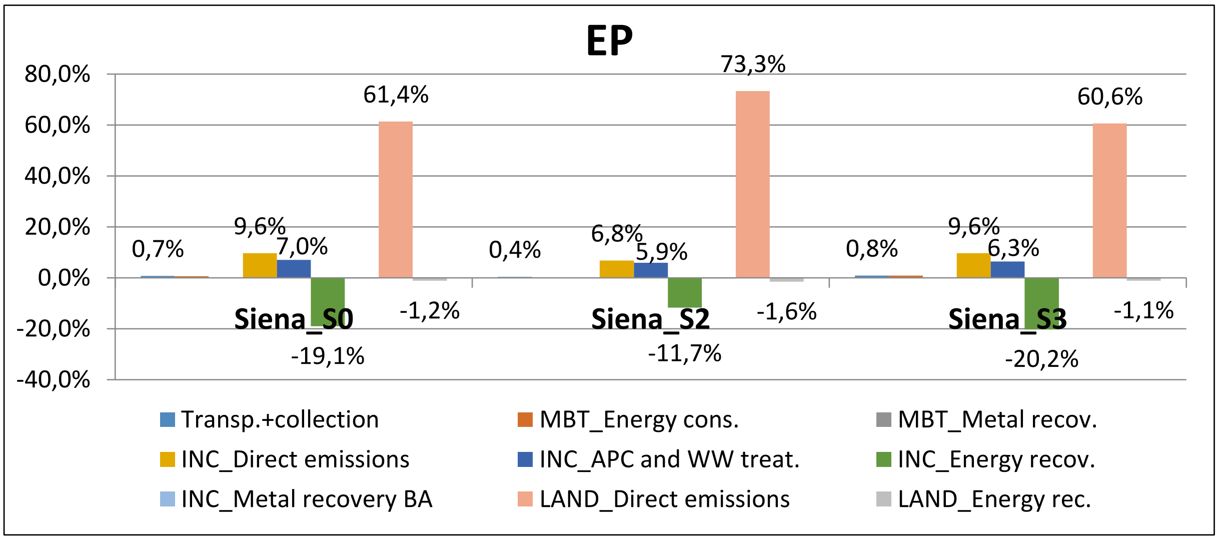


Figure 6.17 EP contribution analysis, comparison between Siena scenarios.

6.3 SENSITIVITY ANALYSIS

Sensitivity analysis consists in computing the effect of changes in input on model results. One of the most known method for sensitivity analysis is the perturbation analysis, which is used to assess the influence of parameter uncertainties. The aim is to determine the effect of an arbitrary change of single parameter values on the model's result. Each parameter value is individually varied, accordingly, the variation of the result is calculated. Thus, in order to evaluate the sensitivity of that parameter on the global system, it is possible to calculate the *sensitivity ratio,* which is the ratio between the two relative changes. If a parameter has a SR of +2 (-2), it implies that when increasing its value by 10%, the final result is increased (decreased) by 20% (Clavreul et al., 2012b).

$$SR = \frac{\frac{\Delta result}{initial\ result}}{\frac{\Delta parameter}{initial\ parameter}}$$

Where:

$$\Delta result = \begin{matrix} result2 - result1 & \quad if\ result1 > 0 \\ result1 - result2 & \quad if\ result1 < 0 \end{matrix}$$

The sensitivity ratio automatically calculates how strongly the results are affected by a fixed change across all key parameters. SR applies to any size of fixed change since the modeled impacts are linear with all parameters contributing (Bhander et al., 2010). This means that regardless of how much is the variation of a parameter, the SR of that parameter is constant.

As a rule of thumb, one can say that SR of which the absolute value is higher than 0.8 and especially larger than 1 are noteworthy, while SR of which the absolute value is lower than 0.2 are insignificant (Heijungs & Kleijn, 2001).

Further, it is important to remind that the differences in SR values are also due to the fact that the delta between results generated in the perturbation analysis is divided by the original result score, as shown in previous SR equation. Therefore, impact categories with small magnitude scores are likely to have higher SR values, even though they have the same delta between results. For this reason, the choice of the most sensitive parameters should not be based on comparisons between SRs of different impact categories, and the effect of parameter variations should be carefully evaluated within the individual impact categories and scenarios.

Where possible, the analyses are described in terms of sensitivity ratios. However, for some parameters or assumptions, is not possible to calculate a unique value for the SR (e.g. waste composition, MBT trommel screen aperture size, displaced energy mix); therefore, in these cases the respective percentage of variations are shown.

$$\Delta\,\% = \frac{result_{mod} - result_{orig}}{result_{orig}} \;\; 100$$

where $result_{orig}$ and $result_{mod}$ are the results before the parameters variations and after the parameters variations respectively.

The following parameters and assumptions have been analyzed:

- transportation distances;
- energy recovery from incineration process;
- amount of chemicals needed for APC;
- metal recovery efficiency from BA;
- biogas collection efficiency from landfill;
- biogas generation efficiency;
- MBT-trommel screen aperture size (80 mm and 40 mm);
- amount of organic waste to stabilization;
- energy recovery from LFG combustion;
- waste composition;
- displaced energy mix.

6.3.1 Transportation distances

In many waste management LCA studies, included these ones, the collection and transportation stage is considered to be as a minor contributor to the final results. From the literature review, it has been observed that its contribution to GWP, AP and EP related emissions is usually less than 5 % or it is not even accounted for. However, as already stated, sometimes it can considerably affects AP and EP impact categories.

In order to have a further confirmation of the low relevance of this process, the both systems have been tested doubling all the distances covered by trucks (Δ% = 100%).

The obtained results are shown in Table 6.12 in terms of SR for each impact categories, for every scenarios in the both case studies.

Table 6.12 Sensitivity ratios for transportation distances.

	GWP	AP	EP
S0	0.01	0.02	0.01
S1	0.01	0.02	0.06
S2	0.01	0.01	0.01
S3	0.01	0.02	0.01
S4	0.01	0.00	0.00
SK_Landfill	0.02	0.00	0.06
SK_Riihimäki	0.20	0.06	0.37
SK_Kotka	0.06	0.04	0.17
SK_Leppävirta	0.10	0.02	0.08

It can be noted that the SR related to this parameter are rather low (<0.1 for Siena case), for each impact category, in every scenarios. Regarding South Karelia case, SR values are higher for EP impact category, but still not noteworthy.

It can be concluded that changings in this parameter nearly don't affect GWP, AP and EP emissions in these WMSs.

6.3.2 Electricity recovery from waste incineration

The avoided emissions due to energy substitution from a WtE plant are responsible for a large part to the contribution of the final LCA balance, and this is widely recognized in literature. Therefore, the assumption regarding the recovery efficiency should be investigated in order to take into account the related uncertainty and to examine how this parameter can affect the final LCA results.

The electricity recovery efficiency was modified and results for each impact category, for every scenarios, are shown in Table 6.13, in terms of SR.

Table 6.13 Sensitivity ratios for electricity recovery from incineration.

	GWP	AP	EP
S0	-0.77	-1.61	-0.33
S1	-0.97	-2.74	-14.46
S2	-0.52	-0.58	-0.16
S3	-0.84	-1.96	-0.36
S4	-	-	-
SK_Landfill	-	-	-
SK_Riihimäki	-2.73	-0.99	-2.10
SK_Kotka	-1.11	-0.79	-1.17
SK_Leppävirta	-3.08	-0.77	-0.96

As expected, all SRs are negative, which means that an increasing of the parameter causes a decreasing in the LCA result, i.e. a “better performance”. Concerning Siena case, the most sensitive scenario to this parameter is the mass-burn scenario S1 (all SR are higher than in the other scenarios). Scenario 4 is not affected since no waste are routed to incineration. AP is the most affected impact category by the variation of energy recovery efficiency from incinerator. EP shows a large SR in the mass burn scenario (when increasing the efficiency by 20% the result is changed from positive to negative value), while fairly minor values in the others. Concerning GWP, all SR are lower than one, with respect to their absolute values; however, the values are around or higher than 0.8, which means they can be considered significant in terms of influence on the final GWP balance.

Different results come out from South Karelia case: GWP is the most affected impact category and all SR are higher than 1 (as absolute values), while AP is the least affected impact category and all SR are lower than 1. Electricity recovery efficiency has the strongest effect on Riihimäki scenario, in terms of AP and EP. Landfill scenario is obviously not affected.

Comparing Siena mass-burn scenario with the three burning scenarios in South Karelia, it can be noted that, while in Siena case the most affected categories are AP and EP (SR higher than 3), regarding South Karelia GWP is the most influenced one by this parameter.

The result obtained in Siena mass-burn scenario for the SR value related to GWP is consistent with the outcomes estimated by Clavreul et al., (2012) (SR=1.15) and by Umberto Arena et al., (2015) (SR=0.9).

In Siena case, the electricity recovery efficiency was calculated by the analytical model used for waste incineration, depending on some characteristics of the steam cycle and on the waste input composition. The parameter in input to GaBi model is the amount of electricity recovered per ton of waste routed to incineration (different for MSW and RDF). Thus, in order to analyze the recovery efficiency parameter, the amount of produced electricity has been increased by 20%, which means from an average efficiency around 21% to a value of 25%.

In order to observe the numerical differences depending on the two assumptions, the LCA results and their percentage variations are shown in Table 6.14, referring to Siena case.

Table 6.14 Effects on GWP,AP and EP of the variation of energy recovery efficiency from waste incineration; best scenario is highlighted for each impact category.

		Base case eff= 21%	eff=25%	Δ %
GWP [kg CO2-eq]	S0	40 494 000	34 274 000	-15%
	S1	37 201 000	29 973 000	-19%
	S2	39 686 000	35 594 000	-10%
	S3	41 327 000	34 390 000	-17%
	S4	42 928 000	42 928 000	-
AP [kg SO2-eq]	S0	48 500	32 900	-32%
	S1	-33 100	-51 200	-55%
	S2	89 100	78 800	-12%
	S3	44 300	26 900	-39%
	S4	248 500	248 500	-
EP [kg PO4-eq]	S0	19 600	18 300	-7%
	S1	510	-970	-290%
	S2	26 000	25 100	-3%
	S3	19 800	18 400	-7%
	S4	59 200	59 200	-

6.3.3 Amount of chemicals needed in APC

As observed from contribution analysis, the supplying of chemicals for APC can play an important role in the final balance of emissions related to GWP, AP and EP. Therefore, it is worth to investigate the influence of the APC system efficiency, in terms of amount of chemicals needed.

The two WMS were tested by increasing the necessary amount of products for the cleaning system, respectively ammonia, sodium bicarbonate and activated carbon for Siena plant, while ammonia and lime for South Karelia plants.

Table 6.15 shows the results in terms of SR of the two systems, within different scenarios.

Table 6.15 Sensitivity ratios for APC system efficiency.

	GWP	AP	EP
S0	0.05	0.18	0.08
S1	0.09	0.40	4.51
S2	0.05	0.08	0.05
S3	0.05	0.19	0.07
S4	-	-	-
SK_Landfill	-	-	-
SK_Riihimäki	0.13	0.07	0.06
SK_Kotka	0.01	0.01	0
SK_Leppävirta	0.06	0.05	0.01

All SR are certainly positive but far lower than 1, except the ones referred to AP and EP for Siena mass burn scenario. In fact, in this case AP and EP are fairly influenced by this parameter, and this is due to the high contribution of the APC-chemicals supplying process, with respect to the final AP and EP LCA balance. Regarding South Karelia case study, no relevant influence of this parameter can be detected on the final results.

6.3.4 Metal recovery from BA

In order to evaluate the influence of the metal recovery from incinerator bottom ash, the recovery efficiency of ferrous and non-ferrous metals was investigated. Concerning Siena case study, the analysis was made by increasing those efficiencies, while concerning South Karelia case study, it was made by increasing the share of metals (steel and aluminum) in BA, except for Leppävirta plant, which is not provided with metal recovery.

Table 6.16 shows the results in terms of SR of the two systems, within different scenarios.

Again, all SR are negative and much lower than one as absolute values. Only Riihimäki mass-burn scenario shows a rather high SR for GWP impact category.

Table 6.16 Sensitivity ratios for metal recovery efficiency from incineration BA.

	GWP	AP	EP
S0	-0.01	-0.04	-0.01
S1	-0.03	-0.16	-0.09
S2	-0.01	-0.02	0.00
S3	-0.01	-0.04	0.00
S4	-	-	-
SK_Landfill	-	-	-
SK_Riihimäki	-0.90	-0.13	-0.13
SK_Kotka	-0.44	-0.13	-0.09
SK_Leppävirta	-	-	-

6.3.5 Landfill biogas collection efficiency

Given the high GWP of methane content in biogas, the landfill gas losses are one of the most important emissions which contribute to climate change, within a waste management system. The main parameter affecting this feature is the LFG collection efficiency, which has been decided during the inventory phase, according to the national average data. Concerning Siena case, the collection efficiency is assumed to be 60%, while in South Karelia case it is assumed to be 75%.

In order to investigate the influence of this parameter to the final results, the SR values were calculated for different scenarios in Siena and South Karelia WMSs. The results are described in Table 6.17.

Table 6.17 SR for biogas collection efficiency from landfill.

	GWP	AP	EP
S0	-0.62	-0.10	-0.02
S1	-	-	-
S2	-0.89	-0.08	-0.02
S3	-0.60	-0.11	-0.02
S4	-1.89	-0.06	-0.02
SK_Landfill	-2.73	0	0
SK_Riihimäki	-	-	-
SK_Kotka	-	-	-
SK_Leppävirta	-	-	-

As expected, GWP is the most affected impact category, while SR for AP and EP are close to 0. In fact, the increasing of LFG collection efficiency has a double effect on GWP: it reduces methane emissions to atmosphere and it increases the substituted energy production from the biogas CHP unit. In the landfilling scenarios SR are -1.89 and -2.73 respectively for Siena and South Karelia.

Table 6.18 Effects on GWP, AP and EP of the variation of LFG collection efficiency from landfill; best scenario is highlighted for each impact category.

		Base case eff= 60%	eff=75%	Δ %
GWP [kg CO2-eq]	S0	40 494 000	34 225 000	-15%
	S1	37 201 000	37 201 000	-
	S2	39 686 000	30 875 000	-22%
	S3	41 327 000	35 142 000	-15%
	S4	42 928 000	22 622 000	-47%
AP [kg SO2-eq]	S0	48 500	47 300	-2%
	S1	-33 100	-33 100	-
	S2	89 100	87 400	-2%
	S3	44 300	43 100	-3%
	S4	248 500	244 600	-2%
EP [kg PO4-eq]	S0	19 600	19 500	-1%
	S1	510	510	-
	S2	26 000	25 800	-1%
	S3	19 800	19 700	-1%
	S4	59 200	58 900	-1%

In order to observe the numerical differences depending on the LFG recovery efficiency assumption, the LCA results and their percentage variations are shown in Table 6.18 , referring to Siena scenarios. It is clear that this parameter is affecting only GWP impact category. Further, it is interesting to notice that under this assumption, landfilling scenario (S4) becomes the best one from a GWP point of view.

6.3.6 Biogas generation efficiency

For the same reasons illustrated above, another parameter thought to be important for the final LCA result is the LFG generation efficiency from waste. This feature can be described in many different ways throughout the LCA models: it is affected by the content of biodegradable organic matter in the waste fractions, by the biodegradability characteristics of the waste and by environmental characteristics of the landfill.

Regarding Siena landfill model, the tested parameter is the process efficiency depending on the temperature inside the landfill, as described by the following equation (Tabasaran, 1982):

$$k_d = 0.014\,T + 0.28$$

In the base case it was assumed T=35 °C, which brings a process efficiency k_d=0.77; for the sensitivity analysis a landfill body temperature T=50 °C was assumed, obtaining a process efficiency k_d=0.98. Internal landfill temperatures are relatively independent of outside temperatures and typically range from approximately 30 to 60°C (EPA - Environmental Protection Agency, 2005).

Regarding South Karelia landfill model, the tested parameter is the methane production potential L_0 referred to some waste fractions. L_0 describes the total amount of methane gas potentially produced by a metric ton of waste as it decays. (EPA, 2005).

Although the tested parameters are different between the two systems, they represent the same efficiency. Results from sensitivity analysis are reported in Table 6.19. Again, it can be noted that this parameter is influencing only GWP category, since all the SR related to AP and EP are close to 0. Further, the assumption about LFG generation efficiency affects the two Siena and South Karelia landfilling scenarios in the same way, as they provide the same SR value.

Table 6.19 Sensitivity ratios for landfill gas generation efficiency.

	GWP	AP	EP
S0	0.32	-0.10	-0.02
S1	-	-	-
S2	0.45	-0.08	-0.02
S3	0.31	-0.11	-0.02
S4	0.97	-0.06	-0.02
SK_Landfill	0.97	0	0
SK_Riihimäki	-	-	-
SK_Kotka	-	-	-
SK_Leppävirta	-	-	-

In order to observe the results differences depending on the LFG generation efficiency assumption, the LCA results and their percentage variations are shown in Table 6.21, referring to Siena scenarios.

Table 6.20 Specific methane generation per ton of waste, comparison between different temperature conditions, referring to Siena case study.

		T=35 °C	T=50 °C
MSW	$kgCH4/t_{MSW}$	20.7	26.3
Organic fraction	$kgCH4/t_{OF}$	19.0	24.1
Stabilized_OF	$kgCH4/t_{S\_OF}$	6.8	8.6
Fine residues	$kgCH4/t_{F\_RES}$	9.0	11.4
Average	$kgCH4/t_{waste}$	17.0	21.7

The increasing of this parameter produces effects in both directions referring to GWP: it increases the methane directly emitted to atmosphere, but also the collected biogas routed to energy recovery system. The final GWP balance shows that the former effect prevails on the latter one. The small improvement in AP and EP impact categories is due to the increasing of substituted energy from biogas CHP unit.

Table 6.21 Effects on GWP, AP and EP of the variation of LFG generation efficiency; best scenario is highlighted for each impact category.

		Base case eff= 0,77 (T=35 °C)	eff=0,98 (T=50 °C)	Δ %
GWP [kg CO2-eq]	S0	40 494 000	43 997 000	8%
	S1	37 201 000	37 201 000	-
	S2	39 686 000	44 610 000	12%
	S3	41 327 000	44 782 000	8%
	S4	42 928 000	54 276 000	26%
AP [kg SO2-eq]	S0	48 500	47 200	-2%
	S1	-33 100	-33 100	-
	S2	89 100	87 300	-2%
	S3	44 300	43 000	-3%
	S4	248 500	244 200	-2%
EP [kg PO4-eq]	S0	19 600	19 500	-1%
	S1	510	510	-
	S2	26 000	25 800	-1%
	S3	19 800	19 700	-1%
	S4	59 200	58 800	-1%

6.3.7 MBT separation efficiency

During the mechanical treatment, the MSW are separated in two main streams, according to the particle size distribution of their waste fractions. The undersized material is mainly composed by the organic fraction of the waste, while the oversized material is mainly composed by plastics, paper, cardboard, i.e. material with high energy content.

One of the most important design parameter within this process is the trommel-screen aperture size, which determines how much waste is going in each stream. The effect of this parameter on the RDF characteristics is described in paragraph 4.3.1.

In Siena base case the aperture size was a=60mm; for the sensitivity analysis two other alternatives were tested: a=40mm and a=80mm. Table 6.22 shows how the flow streams change according to the aperture size variations.

The results are presented also in terms of percentage variation, in Table 6.23. Results from scenarios 1, 2 and 4 are not reported, since no MBT is included in their waste management chains.

Table 6.22 Waste streams characteristics according to trommel-screen aperture size.

		a=60mm	a=40mm	a=80mm
Undersized	%	42.3	33.7	51.4
Oversized	%	56.9	65.5	47.5
Overs. LHV	MJ/kg	20.2	18.7	21.3

Table 6.23 Effects on GWP, AP and EP of the variation of trommel-screen aperture size; best scenario is highlighted for each impact category.

		a=60mm	a=40mm	Δ %	a=80mm	Δ %
GWP [kg CO2-eq]	S0	40 494 000	41 641 000	3%	39 187 000	-3%
	S1	37 201 000	37 201 000	-	37 201 000	-
	S2	39 686 000	39 686 000	-	39 686 000	-
	S3	41 327 000	43 121 000	4%	39 289 000	-5%
	S4	42 928 000	42 928 000	-	42 928 000	-
AP [kg SO2-eq]	S0	48 500	40 200	-17%	65 000	34%
	S1	-33 100	-33 100	-	-33 100	-
	S2	89 100	89 100	-	89 100	-
	S3	44 300	35 700	-19%	74 300	68%
	S4	248 500	248 500	-	248 500	-
EP [kg PO4-eq]	S0	19 600	17 000	-13%	22 300	14%
	S1	510	510	-	510	-
	S2	26 000	26 000	-	26 000	-
	S3	19 800	16 800	-15%	25 100	27%
	S4	59 200	59 200	-	59 200	-

As it can be observed, this parameter significantly affects the final results, especially concerning AP and EP. Decreasing the aperture size brings a small worsening in GWP, but a significant improving in AP and EP: this is due to the fact that a larger amount of waste is routed to incineration instead of landfilling. For the just mentioned reason, the increasing of the aperture size brings the opposite effects, but with a greater power on AP (up to 68% worsening in scenario 3) and EP.

6.3.8 Amount of organic fraction to stabilization

In Siena WMS, the organic fraction leaving the mechanical separation is partly routed to landfill and partly routed to aerobic stabilization. The amount of organic fraction routed to the aerobic stabilization is set according to the real treatment capacity of the biological reactor, and it is described in the LCI.

In order to evaluate the effectiveness of the treatment and the influence of this process on the final results, it has been decided to change the amount of waste to stabilization, by setting the percentage to 100% of organic fraction. Table 6.24 shows the obtained results.

Table 6.24 Effects on GWP, AP and EP of the variation of the amount of waste to aerobic stabilization; best scenario is highlighted for each impact category.

		Base line (30% to stab.)	100% to stab	Δ %
GWP [kg CO2-eq]	S0	40 494 000	35 750 000	-11%
	S1	37 201 000	37 201 000	-
	S2	39 686 000	39 686 000	-
	S3	41 327 000	33 921 000	-17%
	S4	42 928 000	42 928 000	-
AP [kg SO2-eq]	S0	48 500	40 500	-15%
	S1	-33 100	-33 100	-
	S2	89 100	89 100	-
	S3	44 300	31 900	-25%
	S4	248 500	248 500	-
EP [kg PO4-eq]	S0	19 600	17 400	-10%
	S1	510	510	-
	S2	26 000	26 000	-
	S3	19 800	16 500	-16%
	S4	59 200	59 200	-

It is possible to observe that the variations in GWP, AP and EP results are rather significant. The improvements are proportional to the amount of organic waste leaving the mechanical treatment, which is higher in S3 than in S0.

This variation affects even the scenario ranking: when the amount of waste routed to stabilization is 100% of organic waste, then S3 is the best scenario from a GWP point of view. This is due to the fact that the stabilized organic fraction undergoes to a rather slight degradation in the landfill, since it has been already aerobically degraded; LFG generation is therefore decreased.

Variations in AP and EP are also significant, but they do not affect the scenario rankings.

6.3.9 Energy recovery efficiency from biogas combustion

For the CHP unit installed in the landfill for LFG energy utilization, it was assumed 30% thermal recovery efficiency and 35% electricity recovery efficiency. In order to evaluate the influence of these assumptions on the final results, a perturbation analysis was performed. This analysis was carried out only for Siena case study, since no energy recovery from LFG is applied in South Karelia landfill. Table 6.25 shows the results in terms of sensitivity ratio.

Table 6.25 Sensitivity ratios for energy recovery efficiency from biogas CHP unit.

	GWP	AP	EP
S0	-0.06	-0.10	-0.02
S1	-	-	-
S2	-0.08	-0.08	-0.02
S3	-0.06	-0.11	-0.02
S4	-0.18	-0.06	-0.02

Examining the table it can be concluded that this parameter has no influence on the final results for GWP, AP and EP impact categories, since all SR are lower than 0.2.

6.3.10 Waste composition

The composition data set used for this research is taken from Zanchi L., 2011, *LCA comparison of MSW management systems in Tuscany and Catalonia*, and it refers to Siena MSW average composition in 2010. The waste composition presents a high level of variability since it depends on the place and time of collection for a specific municipality or area.

In order to assess the influence of this assumption on the final LCA results, another waste composition was tested within Siena WMS. For this test, the Italian average MSW composition in 2013 was assumed as reference (Ispra, 2013).

Table 6.26 shows a comparison between the two waste compositions. The differences are rather significant, especially concerning plastic content, which is almost half in the Italian average waste composition. The results obtained using the Italian waste composition are shown in Table 6.27 and Figure 6.18, Figure 6.19 and Figure 6.20.

Table 6.26 Comparison between the two waste compositions.

	Siena av. 2010	Italian av. 2012
Organic	20.0%	24.3%
Green waste	3.1%	5.1%
Paper	10.1%	15.5%
Cardboard	4.7%	7.3%
Wood	2.2%	3.8%
Textile	7.6%	5.1%
Glass	3.2%	7.6%
Ferrous metal	3.3%	3.1%
Non-ferrous metal	0.8%	0.7%
Plastic	22.3%	11.8%
Undersized	9.9%	4.3%
Inert	2.0%	2.4%
Tetrapak	4.7%	1.5%
Others	6.1%	7.5%

Table 6.27 LCA results comparison: Siena waste composition and average Italian waste composition; best scenario is highlighted for each impact category.

		Siena w.	Avg. Italian w.	Δ %
GWP [kg CO2-eq]	S0	40 494 000	33 017 000	-18%
	S1	37 201 000	20 698 000	-44%
	S2	39 686 000	33 217 000	-16%
	S3	41 327 000	34 812 000	-16%
	S4	42 928 000	49 548 000	15%
AP [kg SO2-eq]	S0	48 500	73 700	52%
	S1	-33 100	-3 200	90%
	S2	89 100	91 900	3%
	S3	44 300	78 000	76%
	S4	248 500	215 900	-13%
EP [kg PO4-eq]	S0	19 600	21 200	8%
	S1	510	1 650	224%
	S2	26 000	23 700	-9%
	S3	19 800	23 100	17%
	S4	59 200	52 500	-11%

Significant differences can be observed in the results, especially concerning GWP and in general for the mass-burn scenario. Even scenario ranking is different for GWP and AP, when using the other waste composition.

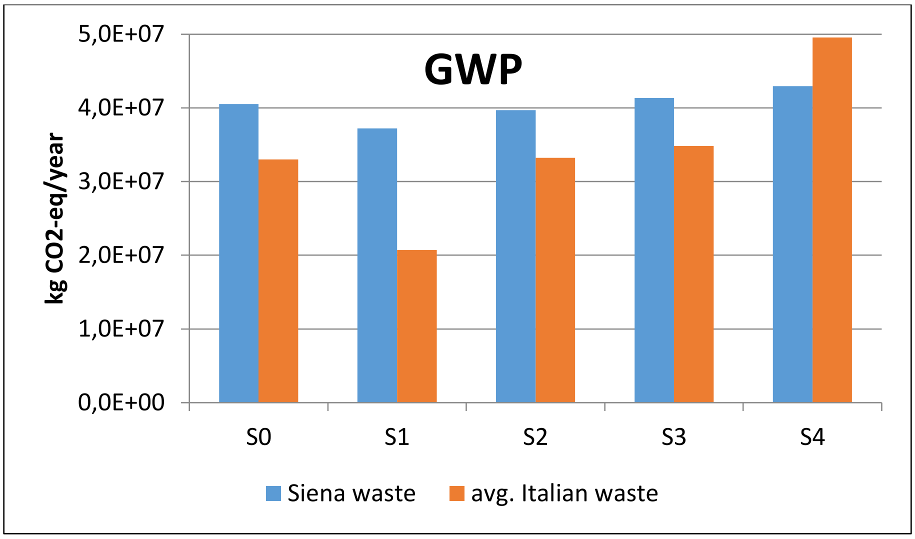


Figure 6.18 GWP comparison: Siena waste composition and average Italian waste composition.

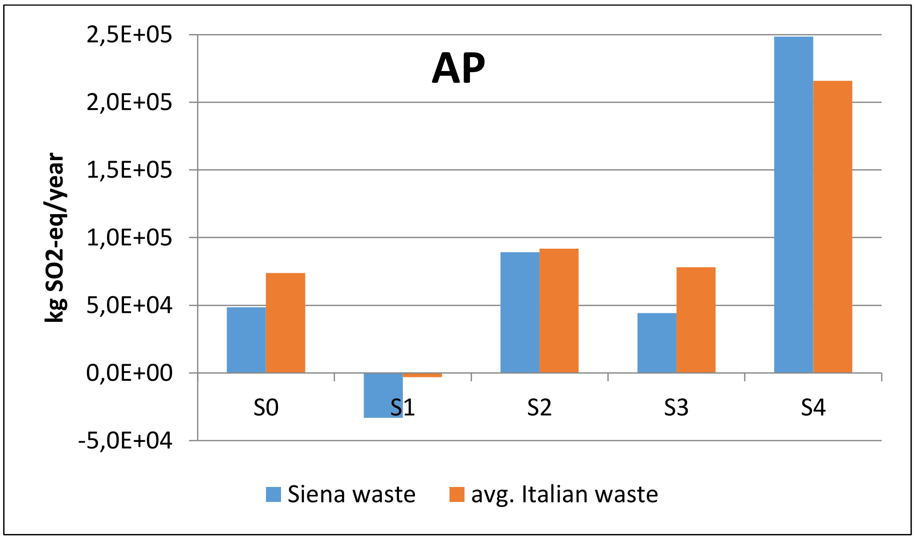


Figure 6.19 AP comparison: Siena waste composition and average Italian waste composition

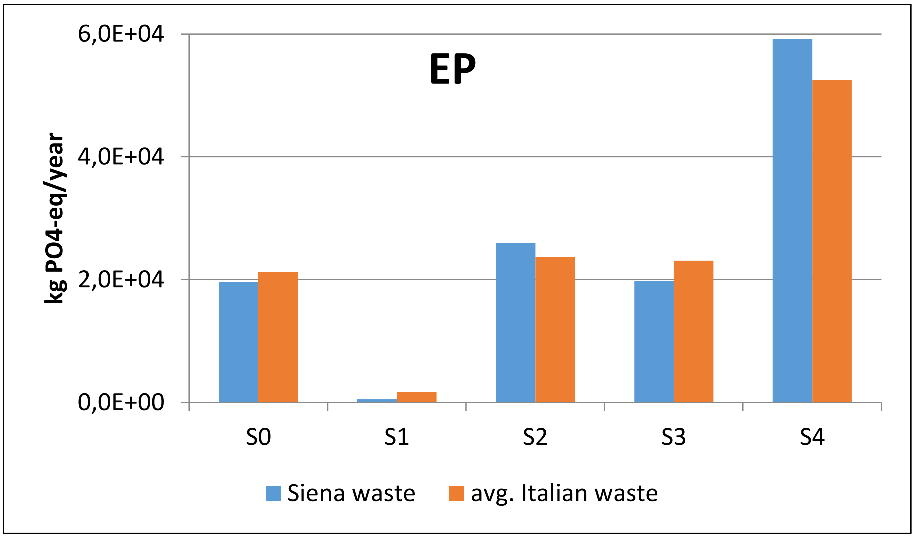


Figure 6.20 EP comparison: Siena waste composition and average Italian waste composition

Regarding GWP, it can be noted that the differences between the scenarios are more significant than in the base case. In particular, the waste incineration seems to be much more efficient in terms of GHG emissions, while the situation is reversed for waste landfilling (scenario 4).

Concerning AP, the average Italian waste composition brings higher emissions in scenarios 0, 1 2 and 3, while the landfilling scenario is improved; same situation is for EP category.

This is probably due to the much lower percentage of plastic content and to the higher content of organic and green waste, which means: less fossil carbon dioxide emissions from the incinerator but a higher biogas generation from the landfill.

The considerable influence of the assumption about waste composition on the final LCA results was found also in literature review. Clavreul, Guyonnet, & Christensen (2012) stress the crucial effect of the waste composition assumption in a mass burn scenario; also Manfredi et al. (2011) and Tonini, Martinez-Sanchez, & Astrup (2013) mark the influence of this assumption in LCA studies, especially for GWP impact category.

Given the crucial influence of the waste composition on the final results, and given the high variability of residual MSW composition itself, which is due to technological, social and geographical factors, it has been decided to perform another sensitivity analysis, using as baseline the results obtained with average Italian reference waste composition. Table 6.28 shows the results obtained analyzing the energy recovery efficiency from waste incineration, the energy recovery efficiency from biogas CHP unit, the biogas generation efficiency, the biogas collection efficiency and the amount of organic fraction routed to stabilization.

Table 6.28 Sensitivity analysis on Siena WMS, using Italian average waste composition.

	SR						Δ%		
	GWP	AP	EP	GWP	AP	EP	GWP	AP	EP
	INC. energy rec. eff.			LANDF. energy rec. eff.			All organic fract. to stab.		
S0	-0.58	-0.65	-0.19	-0.08	-0.08	-0.02	-17%	-10%	-10%
S1	-1.00	-16.41	-2.56	-	-	-	-	-	-
S2	-0.35	-0.32	-0.10	-0.11	-0.09	-0.03	-	-	-
S3	-0.63	-0.71	-0.20	-0.08	-0.07	-0.02	-24%	-15%	-14%
S4	-	-	-	-0.18	-0.08	-0.03	-	-	-
	LFG generation eff.			LANDF. LFG collection eff					
S0	0.45	-0.08	-0.02	-0.88	-0.08	-0.02			
S1	-	-	-	-	-	-			
S2	0.63	-0.09	-0.03	-1.23	-0.09	-0.03			
S3	0.42	-0.07	-0.02	-0.82	-0.07	-0.02			
S4	0.97	-0.08	-0.03	-1.90	-0.08	-0.03			

Regarding the energy recovery efficiency from incineration, SR are lower compared to the base case with Siena waste composition, except for the mass burn scenario, that is very influenced by this parameter with respect to AP. Energy recovery efficiency from landfill doesn't affect significantly the final LCA results. Regarding the efficiency of LFG collection and the efficiency of LFG generation, they seem to have more influence on the final GWP results (higher SR) than in the base case. And this is most likely due to the higher content of biodegradable matter in the waste, which is responsible of the increasing of LFG generation. The assumption about the amount of organic fraction routed to stabilization has a greater effect on GWP, while a lower effect on AP and EP, compared to the base case. By way of example, the results obtained using different assumptions are reported in Table 6.29.

Table 6.29 Global results: comparison between the base case and the modified cases; best scenario is highlighted for each impact category.

		Base case (IT waste comp.)	**+20% Inc.rec.eff**	**+20% Landf.rec.eff**	**0.98 LFG gener.**	**75% LFG collect.**	**Org. to stab.**
GWP [kg CO2-eq]	S0	33 017 000	29 178 000	32 478 000	37 081 000	25 745 000	27 568 000
	S1	20 698 000	16 562 000	20 698 000	20 698 000	20 698 000	20 698 000
	S2	33 217 000	30 875 000	32 459 000	38 926 000	23 000 000	33 217 000
	S3	34 812 000	30 408 000	34 280 000	38 822 000	27 636 000	26 306 000
	S4	49 548 000	49 548 000	47 803 000	62 706 000	26 003 000	49 548 000
AP [kg SO2-eq]	S0	73 700	64 100	72 600	72 200	72 300	66 100
	S1	-3 200	-13 500	-3 200	-3 200	-3 200	-3 200
	S2	91 900	86 000	90 300	89 700	89 900	91 900
	S3	78 000	67 000	76 900	76 500	76 700	66 200
	S4	215 900	215 900	212 300	210 900	211 300	215 900
EP [kg PO4-eq]	S0	21 200	20 400	21 100	21 100	21 100	19 100
	S1	1 700	800	1 700	1 700	1 700	1 700
	S2	23 700	23 300	23 600	23 600	23 600	23 700
	S3	23 100	22 200	23 000	23 000	23 000	19 800
	S4	52 500	52 500	52 200	52 100	52 200	52 500

6.3.11 Displaced electricity mix

The last assumption which has been modified is the Italian electricity grid mix. As observed in the literature review, this is surely one of the most investigated and apparently one of the most influencing assumption in LCA studies about MSW management. In fact, in many cases it completely upsets the final results (e.g. Evangelisti et al., 2014, Burnley et al., 2015 and Arena et al., 2015).

Within this study, the assumption about the electricity grid mix has been modified trying to adopt a realistic scenario. In particular, it was decided to investigate about a possible near future scenario, where the electricity production mix is projected to 2030, according to the European policy to promote the use of renewable energy sources.

The projection data regarding the Italian electricity mix in 2030 were taken from a report published by ENEA, the national agency which deals with new technologies, energy and economic development in Italy (ENEA, *Una mappa delle emissioni specifiche e del costo medio di generazione di diversi mix elettrici,* 2013). In the report, the authors assume that in 2030 50% of the Italian electricity mix will be produced from renewable energy sources and that the total electricity production will be 400 GWh. However, they do not specify the detailed electricity mix for 2030, so some calculations and assumptions were necessary in order to obtain the percentage values. As explained in Table 6.30, the values for hydro and geothermal production were assumed to be constant compared to 2011 values (the percentages on the total are therefore decreased since the total amount of electricity produced in 2030 is increased). The percentage values for wind, photovoltaic and biomass systems are assumed within this study, according to the reading of the authors while the percentage values for coal and lignite, natural gas and others are taken as they are in the report.

Table 6.30 Primary sources for electricity production in 2030, as described in ENEA report.

Primary energy source	%	Data source
Hydro	13.2	Estimated (congruent to 2011)
Geothermal	1.5	Estimated (congruent to 2011)
Wind	**12.5**	**Assumed**
PV	**14.3**	**Assumed**
Biomass (Solid+Biogas+WtE)	**8.5**	**Assumed**
Coal and lignite	10.0	Taken from the report
Natural gas	34.0	Taken from the report
Others (HFO+Coal gases)	6.0	Taken from the report

The comparison between the electricity mix considered in this LCA study (from GaBi database) and the one taken from ENEA report, after the above mentioned adjustments, is presented in Table 6.31.

Table 6.31 Differences between Italian electricity grid mix in 2011 and the one supposed for 2030.

%	2011_GaBi	2030_ENEA	Difference
Biogas	2.0	3.9	1.9
Biomass solid	0.8	1.6	0.8
Coal gases	1.8	1.3	-0.5
Geo-thermal	1.9	1.5	-0.4
Hard coal	14.7	9.9	**-4.8**
HeavyFuelOil	6.6	4.7	-1.9
Hydro	15.8	13.2	-2.6
Lignite	0.1	0.1	0.0
Natural gas	47.9	34.0	**-13.9**
Photovoltaics	3.6	14.3	**10.7**
Wind	3.3	12.5	**9.2**
WtE	1.5	2.9	1.4
Total RENEW.	**28.9**	**50**	**21.1**

It can be noted that the main differences in 2030 scenario are the reduction of natural gas and hard coal utilization, and the increasing of photovoltaic and wind power turbine systems for energy production. In fact, the authors of the research state that hydroelectric and geo-thermal energy systems have already reached their maximum level of exploitation and therefore they are not expecting further developments in the near future.

The LCA results obtained when using the electricity grid mix projected to 2030 are reported in Table 6.33.

The calculation of the environmental impacts generated by the production of 1 kWh of electricity, with a specific energy source mix, is performed by using the data from GaBi database. However, the GWP value obtained with that calculation method (*2030_ENEA_calc.* in Table 6.32) is completely different from the one given in the ENEA research (*2030_ENEA* in Table 6.32), when assuming the same electricity grid mix. This 50% discrepancy is probably due to different assumptions about specific environmental impacts and different calculation procedures (which are not reported in ENEA research).

Table 6.32 Environmental impacts generated by the production of 1 kWh of electricity in Italy; comparison between GaBi 2011 grid mix and 2030 grid mix, as expected by ENEA research.

Production of 1 kWh of electricity in Italy				
		2011_GaBi	**2030_ENEA_calc.**	**2030_ENEA**
GWP	kg CO_2 eq /kWh	0.559	0.425	0.21
AP	kg SO_2 eq /kWh	0.0014	0.0011	-
EP	Kg PO_4 eq /kWh	0.000113	0.000106	-

Table 6.33 LCA results comparison: different electricity grid mixes; best scenario is highlighted for each impact category.

		Base case	2030_ENEA_calc	Δ %	2030_ENEA	Δ %
GWP **[kg CO2-eq / t_{waste}]**	S0	426	482	13%	621	46%
	S1	390	454	16%	614	57%
	S2	417	456	10%	555	33%
	S3	435	497	14%	649	49%
	S4	451	459	2%	478	6%
AP **[kg SO2-eq / t_{waste}]**	S0	0.51	0.62	21%	-	
	S1	-0.36	-0.24	+34%	-	
	S2	0.93	1.00	8%	-	
	S3	0.47	0.59	25%	-	
	S4	2.61	2.63	1%	-	
EP **[kg PO4-eq / t_{waste}]**	S0	0.21	0.20	0%	-	
	S1	0.00	0.00	0%	-	
	S2	0.27	0.27	0%	-	
	S3	0.21	0.21	0%	-	
	S4	0.62	0.62	0%	-	

The comparison in Table 6.33 shows the great differences in the LCA final results: when the electricity grid mix changes toward a *cleaner* energy sources utilization, the environmental impacts of the MSW management system increase, especially for GWP category. This is due to the lower benefit coming from the energy recovery systems. As expected, the influence is higher in scenario 1, where all the waste are routed to incineration. The differences are even greater when assuming the GWP value for electricity production in 2030 from ENEA study: in this case the scenario ranking is completely upset and landfilling scenario (number 4) becomes by far the best one from a GWP perspective.

6.3.12 Summary of sensitivity analyses

Table 6.34 summarizes the results discussed in previous paragraphs, reporting the absolute values of SR, sorted in descending order, for different Siena scenarios, with respect to GWP, AP and EP impact categories.

Table 6.35 is referred to South Karelia case study.

The parameters abbreviations are described below:

- Inc-EnRecEf: energy recovery efficiency from WtE incinerator;
- LFG-ColEf: landfill gas collection efficiency;
- LFG-GenEf: landfill gas process generation efficiency;
- APC: amount of chemicals needed for air pollution control (ammonia, sodium bicarbonate and activated carbon for Siena case; lime and ammonia for South Karelia case);
- Landf-EnRecEf: energy recovery efficiency from biogas CHP unit;
- MetRecEf: metal recovery efficiency from incineration bottom ash;
- TranspDist: transportation distances.

Table 6.34 Absolute values of SR sorted in descending order, for different scenario, , for GWP, AP and EP. Siena case study.

Siena |SR|					
GWP		**AP**		**EP**	
Scenario 0					
Inc-EnRecEf	0.77	Inc-EnRecEf	1.61	Inc-EnRecEf	0.33
LFG-ColEf	0.62	APC	0.18	APC	0.08
LFG-GenEf	0.32	LFG-ColEf	0.10	Landf-EnRecEf	0.02
Landf-EnRecEf	0.06	LFG-GenEf	0.10	LFG-ColEf	0.02
APC	0.05	Landf-EnRecEf	0.10	LFG-GenEf	0.02
MetRecEf	0.01	MetRecEf	0.04	TranspDist	0.01
TranspDist	0.01	TranspDist	0.02	MetRecEf	0.01
Scenario 1					
Inc-EnRecEf	0.97	Inc-EnRecEf	2.74	Inc-EnRecEf	14.46
APC	0.09	APC	0.40	APC	4.51
MetRecEf	0.03	MetRecEf	0.16	MetRecEf	0.09
TranspDist	0.01	TranspDist	0.02	TranspDist	0.06
Scenario 2					
LFG-ColEf	0.89	Inc-EnRecEf	0.58	Inc-EnRecEf	0.16
Inc-EnRecEf	0.52	APC	0.08	APC	0.05
LFG-GenEf	0.45	Landf-EnRecEf	0.08	Landf-EnRecEf	0.02
Landf-EnRecEf	0.08	LFG-ColEf	0.08	LFG-ColEf	0.02
APC	0.05	LFG-GenEf	0.08	LFG-GenEf	0.02
MetRecEf	0.01	MetRecEf	0.02	TranspDist	0.01
TranspDist	0.01	TranspDist	0.01	MetRecEf	0.00
Scenario 3					
Inc-EnRecEf	0.84	Inc-EnRecEf	1.96	Inc-EnRecEf	0.36
LFG-ColEf	0.60	APC	0.19	APC	0.07
LFG-GenEf	0.31	LFG-GenEf	0.11	LFG-GenEf	0.02
Landf-EnRecEf	0.06	LFG-ColEf	0.11	LFG-ColEf	0.02
APC	0.05	Landf-EnRecEf	0.11	Landf-EnRecEf	0.02
MetRecEf	0.01	MetRecEf	0.04	TranspDist	0.01

TranspDist	0.01	TranspDist	0.02	MetRecEf	0.00
Scenario 4					
LFG-ColEf	1.89	LFG-ColEf	0.06	LFG-GenEf	0.02
LFG-GenEf	0.97	LFG-GenEf	0.06	LFG-ColEf	0.02
Landf-EnRecEf	0.18	Landf-EnRecEf	0.06	Landf-EnRecEf	0.02
TranspDist	0.01	TranspDist	0.00	TranspDist	0.00

Table 6.35 Absolute values of SR sorted in descending order, for different scenario, , for GWP, AP and EP. South Karelia case.

South Karelia |SR|					
GWP		**AP**		**EP**	
Landfilling scenario					
LFG-ColEf	2.73	-	-	TranspDist	0.06
LFG-GenEf	0.97	-	-	-	-
TranspDist	0.02	-	-	-	-
Riihimäki scenario					
Inc-EnRecEf	2.73	Inc-EnRecEf	0.99	Inc-EnRecEf	2.10
MetRecEf	0.90	MetRecEf	0.13	TranspDist	0.37
TranspDist	0.20	APC	0.07	MetRecEf	0.13
APC	0.13	TranspDist	0.06	APC	0.06
Kotka scenario					
Inc-EnRecEf	1.11	Inc-EnRecEf	0.79	Inc-EnRecEf	1.17
MetRecEf	0.44	MetRecEf	0.13	TranspDist	0.17
TranspDist	0.06	TranspDist	0.04	MetRecEf	0.09
APC	0.01	APC	0.01	APC	0.00
Leppävirta scenario					
Inc-EnRecEf	3.08	Inc-EnRecEf	0.77	Inc-EnRecEf	0.96
TranspDist	0.10	APC	0.05	TranspDist	0.08
APC	0.06	TranspDist	0.02	APC	0.01

7 CONCLUSIONS

Waste management is one of the greatest challenges that man is called to face today. The problem of waste disposal is actually only one aspect of the challenge. The amount of waste we produce is the result of our unsustainable lifestyle. Our current modes of production and consumption must be changed in order to minimize the pressure on non-renewable sources of the Earth. In essence, waste production is one of the most considerable indicators of our progress towards a sustainable development.

Until the mid 2000s the production of municipal waste in Europe has been growing, but since ten years this trend is reversed, thanks to EU's waste management policy that fostered a strong increase of waste prevention, but also of source separated waste collection and recycling. In addition to this, the interest in finding the best waste management strategies is continuously growing, especially in European developed countries. However, today the two main technologies for municipal solid waste (MSW) management are waste landfilling and waste incineration. None of these solutions is perfect as both of them are potentially harmful to the environment and to human health.

The present research is an analysis of the main factors and features that must be considered when assessing integrated waste management systems through a Life Cycle Assessment (LCA) approach. In particular, the objectives of the study were: (i) to find out what are the most important and least important processes and factors affecting the LCA results of a waste management system (WMS), i.e. referring to Global Warming potential (GWP), Acidification potential (AP) and Eutrophication potential (EP) impact categories; (ii) to evaluate the influence of social, political and technological factors of the operating environment on those processes and their contribution and (iii) to assess how much the parameters and assumptions made in LCA studies affect the final results, with respect to GWP, AP and EP.

The first part of the study was a review of other LCA studies of MSW management in European contries. This was done in order to understand if and how these problems are discussed in literature and to figure out what are the lessons to be learned from theory. The second part of the work is a case study analysis: the waste management system of Province of Siena is analyzed and assessed through a LCA approach. In addition, the South Karelia WMS case study was considered, as described by Hupponen et al. (2015) and updated within the cooperation with Environmental Technology department of Lappeenranta University of Technology. After that, a large part of the present work is devoted to the analyses and interpretation of the results.

Concerning Siena case study, it was observed that the best scenario, from a GWP, AP and EP perspective, is the mass-burn scenario (S1), i.e. the one where all the MSW are directly routed to incineration. The worst one is the landfilling scenario (S4), i.e. the one where all the MSW are directly routed to the landfill without any pre-treatment. However, regarding GWP emissions, there are small differences between the five scenarios, and this is probably due to the high-plastic content of the waste.

The contribution analysis revealed that, for every different scenario, there are usually one or two main processes which represent around 90% of total emissions for GWP, AP and EP categories. For instance, in the mass-burn scenarios, those processes are the direct emissions from the stack and the avoided emissions due to energy recovery; differently, in the landfilling scenario, the most important contribution is given by the direct emissions from the landfill, while avoided emissions due to energy recovery have a scarce relevance on the global balance.
The stage of waste collection and transportation has usually a negligible influence on the final GWP and AP results, but is more relevant for EP category, especially for South Karelia case study, where distances are much longer. It is anyway important to evaluate its contribution mainly when recycling treatment is operated, in order to assess the real benefits of recycling. However, in terms of social acceptance, transport of waste will continue to play a fundamental role.
Further, in Siena case study, a relevant contribution to AP and EP categories is due to the emissions from APC chemicals supply and treatment of the residues, and this is not consistent with the outcomes from South Karelia case study and from literature review. Metal recovery from incineration BA may have a significant influence on AP category, but it is negligible for GWP and EP. All the other processes involved in the analyzed WMSs generate small contributions to GWP, AP and EP global balances.

However, the results from contribution analysis cannot be generalized since they are strictly related to the characteristics of the considered WMS, e.g. in a system where 50% of waste are routed to a MRF plant, the recycling processes relative related emissions would be much higher than in a system where only 10% of waste are routed to material recovery treatment. Further, the relative contribution of every process on the final LCA balance strongly depends on the other processes involved in the WMS, i.e. on the final amount of emissions; for instance, in a system where landfilling is the main waste treatment, landfilling related emissions would represent the greatest part of the total emissions making the other unit processes much less significant.

Several parameters and assumptions were investigated in the sensitivity analysis for Siena case study, and compared with South Karelia case study and with the outcomes from literature review.

For some of them it was possible to identify a certain level of influence on the results, by calculating their SR, while for some others it was not possible and therefore it was decided to show the percentage difference from the base case.

The analyses of Siena and South Karelia case studies showed that the most important parameters affecting GWP results, between the ones considered within this study, are the energy recovery efficiency from WtE incineration and the LFG collection efficiency in the landfill; same conclusions are reported by several authors in the literature. Even the LFG generation rate in the landfill has been recognized to have quite large effect on GWP results, when landfilling is one of the main waste treatment in the WMS. Other assumptions that can largely influence the choice of the best WMS, from a GWP perspective, are the specific waste composition, the displaced electricity mix (the sources utilized for electricity production) and the amount of organic fraction to stabilization after mechanical separation. The least important parameters for GWP category are the transportation parameters (e.g. distances), the amount of chemicals needed for air pollution control (APC) system, the amount of metals recovered from bottom ash (BA) and the energy recovery efficiency from CHP biogas unit.

Regarding AP category, the most important parameter is the energy recovery efficiency from waste incineration, while all the others have no significant influence on the final results. Further, the assumptions about mechanical separation efficiency, amount of organic fraction to stabilization, waste composition and displaced energy mix have a crucial role in identifying the best scenario from a AP point of view.

Concerning EP category, the most important parameter is again the energy recovery efficiency from waste incineration, but it has a relevant influence only in the mass burn scenario (S1 for Siena case study). The assumptions about mechanical separation efficiency, waste composition and amount of organic fraction to stabilization have a significant impact on the results, while changing the displaced energy mix has negligible effect on EP results.

It is important to remind that the differences in sensitivity ratio (SR) values may be also due to the fact that the delta between results generated in the perturbation analysis is divided by the original result score. Therefore, impact categories with small magnitude scores are likely to have higher SR values, even though they have the same delta between results. Moreover, different results in the sensitivity analyses may also depend on the inherent diversities of the LCA models and not only on different geographical contexts.

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APPENDIX

Mechanical treatment – Siena waste composition (2010) and Italian average waste composition (2012).

A 1 Siena waste composition and MBT separation efficiencies, screen mesh diameter 60 mm.

Waste fraction	Waste input [%]	Undersized (organic fraction) [%]	Oversized (dry fraction) [%]	Fine residues [%]
Organic	20.0	33.8	9.9	14.9
Green waste	3.1	5.6	1.3	2.5
Paper	10.1	1.9	16.3	0.9
Cardboard	4.7	0.5	8.0	0.0
Wood	2.2	2.7	1.8	0.0
Textile	7.6	4.7	9.8	2.1
Glass	3.2	4.8	1.9	4.3
Ferrous metal	3.3	0.9	4.5	0.0
Non-ferrous metal	0.8	0.6	1.0	0.0
Plastic	22.3	6.7	34.2	3.0
Undersized	9.9	23.1	0.0	41.4
Inert	2.0	4.1	0.2	31.0
Tetrapak	4.7	2.1	6.8	0.0
Others	6.1	8.6	4.3	0.0

A 2 Italian average waste composition and MBT separation efficiencies, screen mesh diameter 60 mm..

Waste fraction	Waste input [%]	Undersized (organic fraction) [%]	Oversized (dry fraction) [%]	Fine residues [%]
Organic	24.3	39.3	12.4	19.6
Green waste	5.1	8.8	2.2	4.4
Paper	15.5	2.8	25.9	1.4
Cardboard	7.3	0.7	12.6	0.0
Wood	3.8	4.4	3.3	0.0
Textile	5.1	3.0	6.8	1.5
Glass	7.6	11.1	4.8	11.1
Ferrous metal	3.1	0.8	4.4	0.0
Non-ferrous metal	0.7	0.5	0.9	0.0
Plastic	11.8	3.4	18.7	1.7
Undersized	4.3	9.5	0.0	19.4
Inert	2.4	4.7	0.2	40.8
Tetrapak	1.5	0.6	2.2	0.0
Others	7.5	10.2	5.4	0.0

A 3 Siena waste composition and MBT separation efficiencies, screen mesh diameter 40 and 80 mm.

Waste fraction	Waste input [%]	Undersized (organic fraction) [%]		Oversized (dry fraction) [%]		Fine residues [%]	
		40 mm	80 mm	40 mm	80 mm	40 mm	80 mm
Organic	20	39.3	29.5	10.2	9.9	15.3	15.8
Green waste	3.1	6.7	4.8	1.3	1.4	2.6	2.6
Paper	10.1	0.8	3.3	15.0	17.7	0.3	1.8
Cardboard	4.7	0.4	0.7	7.1	9.3	0.0	0.0
Wood	2.2	2.3	2.4	2.2	1.9	0.0	0.5
Textile	7.6	3.2	5.9	9.9	9.5	1.2	3.2
Glass	3.2	0.8	5.5	4.4	0.6	0.6	7.5
Ferrous metal	3.3	0.2	1.7	4.3	4.3	0.0	0.0
Non-ferrous metal	0.8	0.4	1.3	1.0	0.4	0.0	0.0
Plastic	22.3	3.7	10.7	32.2	35.3	1.4	5.7
Undersized	9.9	28.9	18.8	0.0	0.0	45.8	38.6
Inert	2	4.9	3.3	0.3	0.2	32.7	24.4
Tetrapak	4.7	1.4	2.7	6.5	7.1	0.0	0.0
Others	6.1	7.2	9.5	5.6	2.6	0.0	0.0

A 4 Undersize percentage for different waste fraction for different diameters.

Waste fraction	25mm	30mm	40mm	50mm	55 mm	60mm	70mm	75mm	80mm
Organic	62%	63%	67%	69%	71%	72%	74%	75%	77%
Green waste	68%	70%	73%	75%	76%	77%	78%	79%	79%
Paper	0%	0%	3%	5%	7%	8%	11%	14%	17%
Cardboard	0%	0%	3%	3%	4%	4%	6%	6%	7%
Wood	14%	16%	35%	46%	49%	52%	55%	56%	58%
Textile	6%	8%	14%	21%	24%	27%	31%	36%	40%
Glass	4%	5%	8%	14%	19%	65%	81%	87%	91%
Ferrous metal	0%	0%	3%	5%	8%	12%	15%	22%	30%
Non-ferrous metal	11%	12%	18%	24%	28%	32%	44%	74%	79%
Plastic	2%	3%	6%	9%	12%	13%	17%	21%	25%
Undersized	100%	100%	100%	100%	100%	100%	100%	100%	100%
Inert	84%	85%	90%	93%	94%	94%	95%	95%	96%
Tetrapak	7%	7%	10%	14%	16%	18%	22%	26%	29%
Others	25%	30%	40%	50%	55%	60%	70%	75%	80%

Biological treatment - Siena waste composition (2010) and Italian average waste composition (2012).

A 5 Waste physical characterization.

Waste fraction	Total solid TS [%]	Moisture [%]	Total Volatile Solid TVS [%]	Biodegradable Volatile Solid BIO-TVS [%]
Organic	40.0	60.0	80.0	81.0
Green waste	60.9	39.1	85.0	72.0
Paper	94.3	5.8	67.3	81.0
Cardboard	79.0	21.0	67.3	81.0
Wood	82.6	17.4	80.9	81.0
Textile	75.0	25.0	66.0	83.0
Glass	100	0.0	0.0	0.0
Ferrous metal	100	0.0	0.0	0.0
Non-ferrous metal	100	0.0	0.0	0.0
Plastic	84.7	15.3	0.0	0.0
Undersized	85.0	15.0	20.0	80.0
Inert	100	0.0	0.0	0.0
Tetrapak	91.1	8.9	0.0	0.0
Others	19.9	80.2	0.0	0.0

A 6 Waste chemical characterization, wet basis.

Waste fraction	Ash [%]	Carbon [%]	Hydrogen [%]	Oxygen [%]	Nitrogen [%]	Sulfur [%]	Moisture [%]	Tot. Dry [%]
Organic	8.6	16.2	2.0	12.6	0.4	0.2	60.0	40.0
Green waste	7.3	25.8	3.1	23.9	0.8	0.2	39.1	60.9
Paper	4.5	38.6	4.9	46.1	0.1	0.1	5.8	94.3
Cardboard	2.3	45.0	5.5	26.0	0.2	0.1	21.0	79.0
Wood	0.1	40.2	5.0	37.2	0.1	0.0	17.4	82.6
Textile	0.3	37.2	5.0	29.1	3.1	0.3	25.0	75.0
Glass	97.4	0.0	0.0	0.2	0.0	2.4	0.0	100
Ferrous metal	99.9	0.0	0.0	0.0	0.0	0.1	0.0	100
Non-ferrous metal	100	0.0	0.0	0.0	0.0	0.0	0.0	100
Plastic	2.6	63.4	10.6	7.4	0.6	0.1	15.3	84.7
Undersized	47.2	17.2	1.9	17.3	1.1	0.3	15.0	85.0
Inert	83.9	0.0	0.0	16.1	0.0	0.0	0.0	100
Tetrapak	5.7	48.2	6.7	30.2	0.2	0.1	8.9	91.1
Others	1.6	9.1	1.2	7.9	0.0	0.0	80.2	19.9

A 7 Waste chemical characterization, dry basis.

Waste fraction	Ash [%]	Carbon [%]	Hydrogen [%]	Oxygen [%]	Nitrogen [%]	Sulfur [%]
Organic	21.4	40.6	5.0	31.6	1.0	0.4
Green waste	11.9	42.3	5.0	39.2	1.3	0.3
Paper	4.7	41.0	5.2	48.9	0.1	0.1
Cardboard	2.8	57.0	6.9	32.9	0.3	0.1
Wood	0.1	48.6	6.1	45.1	0.1	0.0
Textile	0.4	49.6	6.7	38.8	4.1	0.4
Glass	97.4	0.0	0.0	0.2	0.0	2.4
Ferrous metal	99.9	0.0	0.0	0.0	0.0	0.1
Non-ferrous metal	100	0.0	0.0	0.0	0.0	0.0
Plastic	3.1	74.8	12.5	8.7	0.7	0.2
Undersized	55.5	20.2	2.2	20.4	1.3	0.4
Inert	83.9	0.0	0.0	16.1	0.0	0.0
Tetrapak	6.3	52.9	7.3	33.1	0.2	0.2
Others	8.3	45.6	6.2	39.6	0.2	0.1

A 8 Waste physical characterization after biostabilization.

Waste fraction	TS [kg/kg]	Moisture [kg/kg]	TVS [kg/kg]	Inert [kg/kg]	BIO-TVS [kg/kg]	Removed BIO-TVS [kg/kg]	Not removed BIO-TVS [kg/kg]	Remained TS [kg/kg]
Organic	0.400	0.600	0.320	0.086	0.259	0.181	0.078	0.133
Green waste	0.609	0.391	0.518	0.073	0.373	0.261	0.112	0.276
Paper	0.943	0.058	0.635	0.045	0.514	0.360	0.154	0.538
Cardboard	0.790	0.210	0.532	0.023	0.431	0.302	0.129	0.466
Wood	0.826	0.174	0.668	0.001	0.541	0.379	0.162	0.446
Textile	0.750	0.250	0.495	0.003	0.411	0.288	0.123	0.460
Glass	1.000	0.000	0.000	0.974	0.000	0.000	0.000	0.026
Ferrous metal	1.000	0.000	0.000	0.999	0.000	0.000	0.000	0.001
Non-ferrous metal	1.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
Plastic	0.847	0.153	0.000	0.026	0.000	0.000	0.000	0.821
Undersized	0.850	0.150	0.170	0.472	0.136	0.095	0.041	0.283
Inert	1.000	0.000	0.000	0.839	0.000	0.000	0.000	0.161
Tetrapak	0.911	0.089	0.000	0.057	0.000	0.000	0.000	0.854
Others	0.199	0.802	0.000	0.016	0.000	0.000	0.000	0.182

A 9 Waste chemical characterization after biostabilization.

Waste fraction	Ash [kg/kg]	Carbon [kg/kg]	Hydrogen [kg/kg]	Oxygen [kg/kg]	Nitrogen [kg/kg]	Sulfur [kg/kg]	Moisture [kg/kg]	Weight [kg/kg]
Organic	0.086	0.069	0.008	0.053	0.002	0.001	0.600	0.819
Green waste	0.073	0.132	0.016	0.123	0.004	0.001	0.391	0.739
Paper	0.045	0.231	0.029	0.276	0.001	0.000	0.058	0.640
Cardboard	0.023	0.273	0.033	0.158	0.001	0.001	0.210	0.698
Wood	0.001	0.217	0.027	0.201	0.001	0.000	0.174	0.621
Textile	0.003	0.229	0.031	0.179	0.019	0.002	0.250	0.712
Glass	0.974	0.000	0.000	0.002	0.000	0.024	0.000	1.000
Ferrous metal	0.999	0.000	0.000	0.000	0.000	0.001	0.000	1.000
Non-ferrous metal	1.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
Plastic	0.026	0.634	0.106	0.074	0.006	0.001	0.153	1.000
Undersized	0.472	0.128	0.014	0.130	0.008	0.003	0.150	0.905
Inert	0.839	0.000	0.000	0.161	0.000	0.000	0.000	1.000
Tetrapak	0.057	0.482	0.067	0.302	0.002	0.001	0.089	1.000
Others	0.016	0.091	0.012	0.079	0.000	0.000	0.802	1.000

A 10 Organic fraction (undersize) composition after biostabilization – Siena 2010 waste composition.

Waste fraction	Input OF composition kg/100kg_in	Mass losses kg/100kg_in	Output stab_OF composition kg/100kg_in	Output stab_OF composition kg/100kg_out
Organic	33.76	6.13	27.64	31.77
Green waste	5.62	1.47	4.15	4.77
Paper	1.93	0.69	1.23	1.42
Cardboard	0.48	0.15	0.34	0.39
Wood	2.66	1.01	1.65	1.90
Textile	4.72	1.36	3.36	3.87
Glass	4.82	0.00	4.82	5.54
Ferrous metal	0.85	0.00	0.85	0.98
Non-ferrous metal	0.63	0.00	0.63	0.72
Plastic	6.73	0.00	6.73	7.73
Undersized	23.05	2.19	20.86	23.97
Inert	4.05	0.00	4.05	4.65
Tetrapak	2.07	0.00	2.07	2.37
Others	8.62	0.00	8.62	9.91
TOT	100.00	13.00	87.00	100.00

A 11 Organic fraction (undersize) composition after biostabilization – Italian 2012 average waste composition.

Waste fraction	Input OF composition kg/100kg_in	Mass losses kg/100kg	Output stab_OF composition kg/100kg_in	Output stab_OF composition kg/100kg_out
Organic	39.32	7.13	32.19	37.48
Green waste	8.79	2.30	6.50	7.57
Paper	2.83	1.02	1.81	2.11
Cardboard	0.71	0.21	0.49	0.58
Wood	4.45	1.69	2.76	3.22
Textile	3.05	0.88	2.17	2.53
Glass	11.08	0.00	11.08	12.90
Ferrous metal	0.78	0.00	0.78	0.90
Non-ferrous metal	0.51	0.00	0.51	0.59
Plastic	3.40	0.00	3.40	3.96
Undersized	9.54	0.91	8.64	10.06
Inert	4.72	0.00	4.72	5.50
Tetrapak	0.63	0.00	0.63	0.73
Others	10.19	0.00	10.19	11.87
TOT	100.00	14.13	85.87	100.00

Landfilling – ecoinvent and biogas generation

A 12 Waste fractions as described in ecoinvent model.

Average residual materials from MSWI	average paper	Bitumen sheet	FR hard coal ash	sludge from pig iron production to landfill	Ethylene oxide catalyst carrier	glass
PE	cardboard	inert material	HR hard coal ash	dust from electric chromium steel production to landfill	polluted rail ballast residue	textiles
PP	soiled textiles	bitumen	IT hard coal ash	Sludge from Steelrolling	Al in ASR burnable	minerals
PS	chrome-preserved wood electricity pole	wiring copper	NL hard coal ash	redmud from bauxite digestion	Al in ASR inert	natural products
PVC	chrome-preserved building wood	wiring plastic	PL hard coal ash	spent pot liner, carbon fraction	Fe in ASR burnable	compostable material

PET	natural wood	asphalt	PT hard coal ash	spent pot liner, refractory fraction	Fe in ASR inert	inert metals
PU	Alkyd paint	bilge oil	SK hard coal ash	filter dust, aluminium electrolysis	Zn in ASR burnable	electronic goods
Mixed various plastics	cement hydrated	separator sludge	hard coal ash small scale	dross, aluminium electrolysis	Zn in ASR inert	volatile metals
Rubber	cement-fibre slab	refinery sludge	lignite ash small scale	reduced residues dichromate prod	Cu in ASR burnable	batteries
Plastics from electronic consumer goods	Gypsum natural	hazardous waste avg.	drilling waste	residue from TiO2 production (sulfate process)	Cu in ASR inert	electronic goods
Plastics from electronic industrial goods	organics in plastic plaster	waste oil	inorganic Waste Si wafer production	residue from TiO2 production (chloride process)	Pb in ASR burnable	
PVF	Emulsion paint (remains)	Anti-Freeze liquid	wood ash pure	salt tailings potash mining	Pb in ASR inert	
tin sheet inert	paint (remains)	waste solvents mixture	sludge from pulp and paper production	Brine filtration sludge without mercury cells	sulfidic tailings nickel mine	
tin volatile	durable plastic	cooling tower residue	composition of paper sludge ash	Brine filtration sludge with mercury cells	avg wastewater treatement sludge	
MSWI iron scrap	PVC sealing sheet	hard coal tailings	Green liquor dregs from pulp production, to landfill	residue from H3PO4 purification	paper	
Alu in MSW	EPS insulation	AT hard coal ash	Ash, from Incineration of Deinking Sludge, to landfill	decarbonising waste	Mixed cardbord	
Glass	PE sealing sheet	BE hard coal ash	Nickel smelting slag	cation exchange resin f. water	plastics	

inert material (as cement)	Vapour barrier, flame-retarded	CZ hard coal ash	dust from unalloyed electric steel production to landfill	anion exchange resin f. water	laminated materials
newspaper	Filler (lime)	DE hard coal ash	slag from electric steel production to landfill	EDC Oxychlor catalyst	laminated packaging, e.g. tetra bricks
packaging paper	plastiziser	ES hard coal ash	BOF waste mix	Formox catalyst carrier	combined goods e.g. dipers

A 13 Landfill emissions per ton of landfilled waste – evoinvent results.

	Organic fract.	Stab_OF	Fine residues
Water emissions [g/t_{waste}]			
Leachate generation [kg/t_{waste}]	250	250	250
Ammonium, NH_4^+	763	672	325
COD	488	446	178
TOC	123	113	45
Nitrate, NO_3	2782	2449	1186
Nitrite, NO_2^-	16	14	7
Nitrogen, N	21	18	9
Phosphate, PO_4^{3-}	7	7	3
Air emissions [g/t_{waste}]			
Ammonia, NH_3	1.4	1.2	0.6
Dinitrogen monoxide, N_2O	3.9	3.4	1.7
Nitrogen oxides, NO_X	14.2	12.5	6.0
Hydrogen chloride, HCl	22.5	21.7	7.4
Hydrogen fluoride, HF	8.5	7.7	3.8
Phosphorus, P	0.004	0.004	0.002
Sulfur dioxide, SO_2	24.8	22.4	10.4

A 14 Landfill biogas emissions, energy consumptions and energy recovery for different kind of waste.

		Organic fract.	Stab_OF	Fine residues
LFG generation – Lombardi et al. (2006)				
Biogas	[kg/t_{waste}]	172	60	87
	[Nm^3/t_{waste}]	132	46	66
Methane, CH_4	[kg/t_{waste}]	47.4	16.9	22.4
	[Nm^3/t_{waste}]	67.7	24.1	32.0
directly emitted CH_4	[kg/t_{waste}]	19.0	6.8	9.0
captured CH_4	[kg/t_{waste}]	28.4	10.1	13.4
flared	[kg/t_{waste}]	10.0	3.5	4.7
CHP combusted	[kg/t_{waste}]	18.5	6.6	8.7
Consumptions - ecoinvent				
Electricity	[kWh/t_{waste}]	8.1	7.1	3.5
Diesel	[kg/t_{waste}]	1.3	1.3	1.3
Energy recovery				
CHP electricity efficiency	%	35	35	35
CHP thermal efficiency	%	30	30	30
Recovered electricity	[kWh/t_{waste}]	89.9	32.0	42.5
Recovered heat	[MJ/t_{waste}]	277.4	98.8	131.2

A 15 Waste biodegradability coefficient for landfill emissions.

Waste fraction	Biodegradability %	Biodegradability Stab_OF %
Organic	82	41
Green waste	60	30
Paper	52	26
Cardboard	47	24
Wood	72	36
Textile	54	27
Glass	0	0
Ferrous metal	0	0
Non-ferrous metal	0	0
Plastic	0	0
Undersized	20	10
Inert	0	0
Tetrapak	40	20
Others	20	10

Incineration – Supplying of chemicals for APC system

A 16 Emissions due to the production of APC chemicals and cement, used in South Karelia and Siena incinerator plants.

		Lime	Sodium bicarbonate	Ammonia	Cement	Activated carbon
GWP	kg CO2/kg	1.22	1.67	2.76	0.70	6.50
AP	g SO2/kg	0.37	8.78	1.17	1.56	7.00
EP	g PO4/kg	0.05	1.58	1.18	0.21	0.50

Production of electricity from different primary sources.

A 17 Emissions due to the production of 1 kWh of electricity from different sources (GaBi database).

	GWP	AP	EP
	kg CO2-eq/kWh	g SO2-eq/kWh	g PO4 eq/kWh
Biogas	0.450	3.145	0.664
Biomass solid	0.072	2.630	0.500
Coal gases	1.156	2.352	0.505
Geo-thermal	0.068	9.420	0.001
Hard coal	1.146	3.343	0.282
HeavyFuelOil	1.132	5.291	0.233
Hydro	0.007	0.006	0.001
Lignite	1.342	1.558	0.182
Natural gas	0.570	0.410	0.055
Photovoltaics	0.038	0.175	0.014
Wind	0.013	0.039	0.004
WtE	0.700	0.830	0.156