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ENVIRONMENTAL IMPACT ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT

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Abstract

The continuously expanding amounts of waste produced in the EU constitute a major concern at a European level. Municipal waste management represents one of the most critical problems that need to be addressed in Greece, despite the lack of available funds due to the financial crisis. Nowadays, Waste Framework Directive is poorly implemented and many illegal landfills still pollute the environment, with Greece being penalized by the European Court of Justice for several cases. On this basis, the development of an optimal waste management strategy, exploiting all available technologies and taking into account all waste streams is more than critical at a national level.

This thesis focuses on the Life Cycle Assessment (LCA) of different scenarios of Municipal Solid Waste (MSW) management practices in an effort to estimate quantitatively their environmental impacts and identify the alternative that provides the best environmental output for municipal waste management plans. An LCA study is conducted for municipal solid waste in the Region of Central Macedonia, Greece. In the LCA the current waste management plan is compared both with the future management plan for the study area, and a scenario in compliance with the past practices in the area.

Key findings of the study are summarized below. The most environmental friendly scenario is the one where high rates of sorting of the waste at the source take place. In this scenario, great quantities of MSW are recycled and most of the organic fraction is composted, thus results in significant environmental benefits due to material recovery. The scenario that examined the landfill of municipal waste as the main treatment method is the most undesirable from an environmental point of view. Overall, the implementation of an integrated waste management system with high rates of separately collection of the waste streams is necessary in the area.

Keywords: waste management; municipal solid waste; life cycle analysis; Central Macedonia.

Preface

This dissertation was written as part of the MSc in *Environmental Management and Sustainable Development* at the International Hellenic University. It is the culmination of my studies in the International Hellenic University's MSc in environmental Management and Sustainable Development, through which I gained valuable knowledge and experiences that expanded my horizons and helped me become a better professional but more importantly a better person.

To that end, I would like to express my gratitude to my supervisor Dr Georgios Baniias, for the opportunity to work on this interesting project and thank him for our excellent cooperation. His valuable advice and continuous support, guidance, and trust were really helpful in order to bring this project to completion.

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Maria Batsioulia

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CHAPTER 1

INTRODUCTION

It is common knowledge that the world is changing. The population is constantly growing and lifestyles and trends are changing rapidly. Greater levels of consumption are observed, following by the need to dispose more and more food waste, paper, packages and many other components from the various waste streams, thus leading to an increase in municipal solid waste and further environmental degradation. At the same time, the growing realization of the consequences on the environment, human health and climate change has as a result waste management to become an issue of increasing global concern.

Increasing quantities of municipal waste is a key issue in modern cities worldwide, and one of the major challenges for municipalities is the collection, recycling, treatment and disposal of solid waste (Cherubini, Bargigli and Ulgiati, 2009). In this context and in accordance with the idea of Sustainable Development, a strategy for integrated waste management has been developed. In European Union, Waste Framework Directive (2008/98/EC) and Landfill Directive (1999/31/EC) set the regulatory framework within which member states should minimize the amount of waste sent to landfills. Instead,

more environmental options are adopted, based on the “Waste Hierarchy” concept, which includes the ideas of reduce, reuse, recycling/compost and energy recovery from waste thereby aiming at waste prevention.

Consequently, there has been a growing interest in sustainable management of MSW, which covers generation, collection, transfer, sorting, treatment, recovery and disposal of waste has become increasingly required. On this basis, much research on integrated solid waste management systems, which include various options like materials recycling, biological treatment of biodegradable fractions, composting or thermal treatments with energy recovery, has been done. Several publications have appeared evaluating several MSW management strategies at local, regional and national level. Different practices on waste management have been reviewed for countries such as: Germany, Denmark, Greece and other European countries (Bassi et al., 2017; Gentil et al., 2009), for regions: Lombardia, Italy (Rigamonti et al., 2013), for cities: Niš, Serbia (Milutinović et al., 2017), Porto, Portugal (Herva, Neto and Roca, 2014), Naples, Italy (Hornsby et al., 2017).

However, very few publications can be found in the literature that discuss the issue of municipal waste management in Greece, despite the fact that Waste Framework Directive is poorly implemented, with the country being penalized by the European Court of Justice since 2005. Trends and patterns of solid waste generation and waste composition (Papachristou et al., 2009), challenges of waste management (Erkut et al., 2008), dynamics, comparison and evaluation of waste policies and treatment methods (Koroneos and Nanaki, 2012; Karagiannidis et al., 2013; Minoglou and Komilis, 2013; Koufodimos and Samaras, 2002) have been reviewed for the city of Thessaloniki. Nevertheless, most of the previous studies do not take into account the revised Regional Waste Management Plans (PWMP) for the Region of Central Macedonia.

1.1. AIMS AND OBJECTIVES

As mentioned above, in Greece, waste management is one of the most pressing issues facing municipalities. Previous attempts, such as the study of Koroneos and Nanaki, (2012) concerned the status in Greece, in Region of Central Macedonia and in Municipality of Thessaloniki before the new National Waste Management Plan

(NWMP) and the revised Regional Waste Management Plan (RWMP). Therefore, the aim of this study is: *to develop the methodological framework for the selection of the most suitable integrated system for the management of municipal waste in Region of Central Macedonia, based on the up-to-date RWMP and taking into account environmental considerations.*

In order to achieve this aim, this study fulfills the following objectives:

- To conduct a review of all existing waste management practices and waste treatment methods.
- To compare the different management practices and to select the optimal and most sustainable integrated system from an environmental point of view.

The applicability of the methodological framework is controlled by assessing the environmental impact of the alternative management of the MSW. For this reason, Life Cycle Analysis is adopted to benchmark these practices on the basis of specific environmental indicators that were considered important for the environment and human health. On this basis, the main purpose of this dissertation is to review the final stage of the municipal waste's life cycle based on the requirements of each waste treatment and disposal method selected for study.

1.2. METHODOLOGY

The basic methodological framework of the study is established upon Life Cycle Assessment (LCA) methodology, also accompanied by an extensive literature review focusing on Waste Management, its regulatory framework and its various practices.

Initially, a bibliographic review was carried out on the various waste management practices applied to MSW at the end of their useful life. The next step is to review the product life cycle assessment as a tool for the sustainability assessment, providing quantitative and overall information on environmental impacts of the systems investigated. Then, the presentation of the SimaPro software as a tool for the implementation of life cycle assessment follows.

After that, using SimaPro, the final stage of the life cycle of the municipal waste generated in the Region of Central Macedonia was conducted, taking into account

RWMP's requirements. In addition, the alternative waste management practices that resulted from the MSW management in the Region were evaluated, in relation to specific environmental indicators. Finally, the comparative evaluation of the results was carried out in order to highlight the best practice of management of municipal waste in the studied area, from the environmental point of view.

1.3. SECTION SUMMARY

In this section an outline of the basic structure of the project is being enunciated. Having defined the thesis's scope and methodological framework, in the *second chapter*, a literature overview regarding Waste management follows. The overview covers the drives for the development of waste management as well as the various waste treatment methods which are implemented worldwide. Besides that, the relevant European and Greek regulatory framework is presented in detail. Also, the generation and treatment of MSW in EU are analyzed, including the current waste management practices in Greece, which is the main subject of research in this dissertation.

In *chapter three*, the methodological approach for the selection of the optimal waste management practice is discussed. As mentioned earlier, first is the presentation of LCA as an environmental impact assessment tool and its application in MSW Management. Then, the description of the specialized LCA software (SimaPro), which was used as a tool for assessing the life cycle of the municipal waste under study, follows. In addition, this chapter illustrates the assessment of alternative waste management practices with the help of the SimaPro 7 software, and describes the structure and characteristics of the case study as well as the choice of environmental indicators for impact assessment.

In *chapter four*, the results from the implementation of the LCA approach are presented. First the results are presented by tables and charts, followed by their interpretation according to the respective environmental indicator. Moreover, chapter four contains a discussion on the results as well as some recommendations for further improvement. Lastly, *chapter five* summarizes the results of this study and draws conclusions.

CHAPTER 2**WASTE MANAGEMENT**

Waste management is possible the strongest common threat that face all countries worldwide. Despite the context, directly or not, waste is one of the greatest challenges of the urban world (UN-HABITAT, 2010). Although until recently, urban solid waste was not considered to be a problem, nowadays, more and more countries around the world develop waste management strategies, studies and projects (Kayakutlu et al., 2017).

2.1. BACKGROUND

The world population increases continuously. In 2014, 54% of the total population was referred to live in urban areas, and this rate could reach 66% by 2050 (Chifari et al., 2016). This excessive population resulting also in higher levels of consumption and consequently greater disposal of waste, including food waste, packages, paper and other components that make up the different waste streams (Filho et al., 2016). Thus, waste management is a key issue to all countries, both in an urban and in a rural context.

Indeed, Municipal Solid Waste (MSW) has turned into a problem of global concern. As indicated by recent studies, the estimated amount of MSW created worldwide is

between 1.3 and 1.9 billion tons for each year (Filho et al. et al., 2016). Also, EU member states produced more than 1800 kg of waste per capital of which 27% was a Municipal Solid Waste (Tomić and Schneider, 2017). Under these circumstances wastes have been more hard and perilous than ever regarding collection, setting and withdrawing (Kayakutlu et al., 2017). This is expecting to worsen issues of municipal solid waste management, which is already inefficient in the majority of cities over the world. As a result, awareness of waste disposal is grown up in both local and global levels and within this context Waste Management concept has been developed.

2.1.1. Municipal Solid Waste (MSW) Definition

Waste Management is described as the activities of “collection, transport, processing, recycling, disposal and monitoring” of the waste in such a way that limits the harm to the Earth. These actions vary according to the area and demographics and even into the same country, big cities, small cities, surroundings, villages and rural areas use different waste management practices (Kayakutlu et al., 2017).

Ordinary types of wastes are agricultural, commercial, institutional, industrial and household waste (Kayakutlu et al., 2017). Municipal Solid Waste (MSW) is defined as *“waste generated by households, and wastes of a similar nature generated by commercial and industrial premises, by institutions such as schools, hospitals, care homes and prisons, and from public spaces such as streets, markets, slaughter houses, public toilets, bus stops, parks, and gardens”* (UN-HABITAT, 2010). Due to the vast variety of waste management practices, the MSW definition differs over the countries, for instance contingent upon which sector does the collection (UN-HABITAT, 2010).

Municipal Solid Waste is waste collected by or on behalf of municipalities. It incorporates packaging waste, waste electrical and electronic equipment of domestic origin, and in many cases small quantities of “household hazardous wastes”, including, among others, waste portable batteries and accumulators, fluorescent lamps, withdrawals, ink cartridges and various detergents (together with their packaging) used for cleaning, disinfecting and maintenance of households, paints and coatings, pesticides meds (RWMP, 2016). Comparative hazardous waste may come from small companies. Municipals in developed countries usually have systems that aim to gather

and handle these independently and decrease their harmfulness. However there are not many cities in which this works totally and consequently, most MSW streams incorporate some of these perilous components when they reach disposal (UN-HABITAT, 2010). For this reason, the development of an effective waste management system is required.

2.1.2. Development of urban waste management

As mentioned earlier, waste amounts have been increased constantly in all cities despite their income level and the implementation of a waste management system is urgent. Together with industrialization and urbanization, particular drivers have been associated with the growth of waste management.

2.1.2.1. Development drivers for waste management practices

Waste Management is not a new idea. As Wilson (2007) state in his study, since the Middle Ages, many times cities appeared to be dirty, as their streets were covered with foul-smelling mud – made out of soil residual waste, human and animal excrement and stagnant water. Many endeavors were made throughout of years to clean up, driven both by the need to have streets free of any obstacles, and by the nauseous odour (Wilson, 2007). Under these poor sanitation conditions over the centuries, contagious diseases such as cholera were developed and spread to the European and American cities (UN-HABITAT, 2010). Consequently, public health became the main driver for the collection of the municipal waste. In the middle of the 19th Century, in order to deal with the poor sanitation conditions, a Public Health Act was progressively developed and it required residents to collect their waste in a kind of bin and set municipal authorities to remove solid waste and keep streets litter free (UN-HABITAT, 2010; Wilson, 2007). However, as Wilson (2007) states, nowadays the driver of public health is “taken for granted” in most European cities.

In the 19th Century there were additional drivers, such as technological development and source scarcity driving recycling during the two World Wars (Wilson, 2007). In pre-industrial times, resources were moderately scarce, so people repair and reuse any product in their house. As cities developed with industrialization, many people found a

financial specialty as ‘rag-pickers’ or ‘street-buyers’, gathering and utilizing or offering materials recovered from waste and this activity proceeds with today in many developing countries (UN-HABITAT, 2010). Also, the resource value of waste was a crucial factor for economies such as those of Soviet Union and Eastern Europe, where the municipal recycled raw materials were the basic driver for industry (Wilson, 2007). Besides that, as Wilson (2007) states in his study, the driver of “resource value of waste” is linked with the “Waste Hierarchy” which was presented in 1977 in the EU's Second Environment Action Program (CEC 1977) and required to change the current “take-make-use” system into a more sustainable one.

Another major driver for the development of the waste management is the environmental protection and because of it, it was in the late 1960s and 1970s, when the uncontrolled waste disposal at last went onto the political agenda (UN-HABITAT, 2010; Wilson, 2007). New laws were presented, in the first place, on water contamination, and from the 1970s on solid waste management, due to emergencies of pollution of water, air and soil and their effects upon the well-being of those living near hazardous waste dumps (UN-HABITAT, 2010). The first “control” stage concentrated on eliminating uncontrolled disposal, both on landfilling and by burning. Following regulations began in the 1980s and continue up to date, focusing on technical standards, for instance, to limit leachate and gas from landfills, minimize dioxin and other gas levels from incineration, and control smell for anaerobic digestion (Wilson, 2007). A later environmental driver has been climate change, driving both to a move far from landfill of biodegradable waste and to new ways of energy recovery from waste (UN-HABITAT, 2010; Wilson, 2007).

Finally, public awareness is likewise a vital driver. In most of the countries ecological issues including climate change, resources and waste management are in major concern of the political agenda. As Wilson (2007) states, the recent practices of higher levels of recycling, repair and reuse, or more home-composting that are recommended in order to move towards better waste management, all demand lifestyle change, public education and awareness.

There is no, one single driver for improvement in waste management and the balance between all of them has differed through the years, and will change between countries. However, the understanding of the mechanisms that have contributed to the development of waste management is significant in understanding the various waste management systems worldwide.

2.1.2.2. MSW Treatment Methods

Waste management systems vary between different regions and countries, but despite the differences, all of them integrate waste streams, waste collection, treatment and disposal methods (Filho et al., 2016). For instance, in over the European Union MSW collection practices are different and incorporate: door-to-door collection of mixed waste (frequently once a week or once every two weeks, and daily in inner cities), collection of separate waste such as glass, paper, metal or packaging and collection opportunities under special standards for bulky waste like large appliances, machines and furniture (European Parliament, 2015). In any case, as Filho et al. (2016) indicates, technological innovations and development are in progress and the existing principle activities are continuously upgraded to meet municipal needs and regulatory and ecological demands, based always on the concept of “waste hierarchy”.

The Waste Hierarchy states that the best waste management option is to stop generate waste and it prioritizes the waste management methods in a preferred order (Figure 2.1.). Several publications have appeared in recent years in accordance with the waste hierarchy principle documenting basic waste treatment and disposal methods including:

- Prevention options,
- Preparing for re-use options,
- Recycling options,
- Other recovery (e.g. energy recovery) options,
- Disposal options.

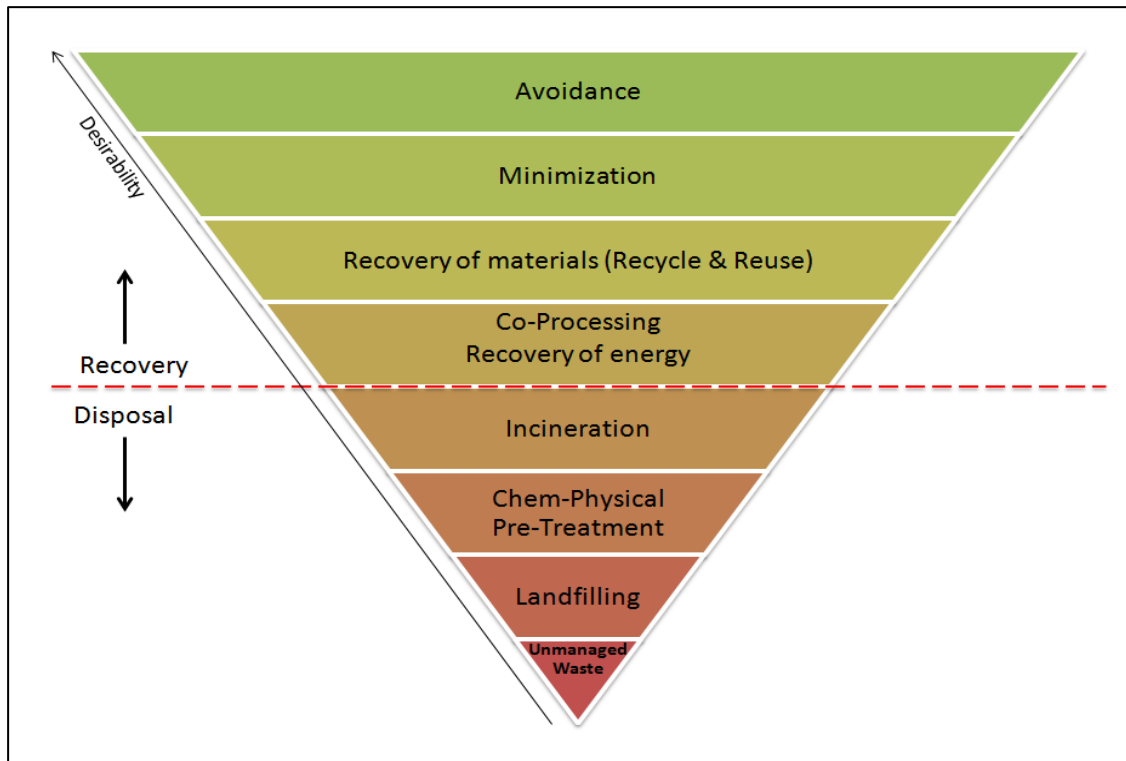


Figure 2.1.: Waste Hierarchy

According to these categories, the most widely used MSW treatment methods are landfilling, recycling and incineration (usually with energy recovery). Besides that, other methods are composting and anaerobic digestion, which are mostly used to treat organic waste, mechanical biological treatment, pyrolysis and gasification (European Parliament, 2015).

2.1.2.2.1. Disposal options

At the bottom of the waste hierarchy is the waste disposal either by landfilling or by incineration methods. Both of these methods may have high costs and significant environmental impacts if they are unregulated and not follow specific standards.

2.1.2.2.1.1. Landfilling

Historically landfilling has been the mostly used form of municipal solid waste disposal. Nowadays, municipalities are obliged to replace it with more sustainable disposal solution, since it is considered to be the worst disposal practice due to its important ecological impacts as well as an absence of land accessibility caused by a quickly developing population and a higher rate of waste creation (Dubois et al., 2004). Even though, there are cases like some C&D waste, in which waste disposal at landfills is

unavoidable, does not have significant ecological impacts and supposed to be the best environmental solution (European Commission, 2011).

Landfilling is a lasting disposal process by which we spread, compact, and cover (seal) waste with either ash or soil. It is as yet the most well-known type of transfer in by far most of cases (Dubois et al., 2004). Landfilling usually progresses from open-dumping, controlled dumping, controlled landfilling, to sanitary landfilling. Common (sanitary) landfilling depends on anaerobic degradation of waste, thus it has to be well designed in order environmental pollution to be prevented. For this reason, typical technical measures applied are bottom and side liners, top soil cover, gas and leachate collection and treatment systems, which are active for at least 30 to 40 years (European Commission, 2011).

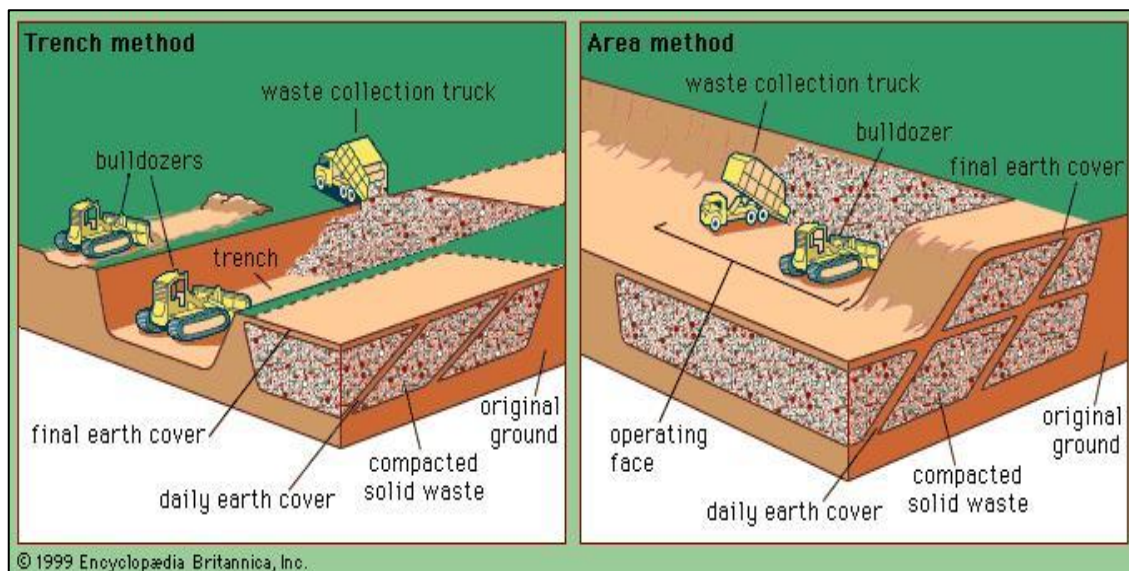


Figure 2.2.: Types of sanitary landfilling (Encyclopedia Britannica, 2017).

Accordingly to the site topography, there are three types of sanitary landfilling: the area, the ramp and the trench method (Figure 2.2.). In the area method waste is spread into different layers on the ground, then be compacted to 2 meters and finally be covered by soil or a synthetic material. The ramp method is similar to area method and is used in sloping land. Finally, the trench method is the most common method and used for flat or gently sloping land. In the trench configuration trenches are dug twice as wide as the tractors and then the waste, in which wet waste should be separated from dry waste, is put in and covered by soil (Dubois et al., 2004).

Another type of landfilling is a bioreactor landfill, which is a sanitary landfill that uses moisture (usually leachate) and through microbiological procedures change and settle the decomposable organic waste inside 5 to 10 years of usage, contrasted with 30 to 100 years for dry landfills, without any landfill gas to be produced. There are three distinct types of bioreactor landfilling: aerobic, in which leachate is re-flowed into the landfill and air is introduced, anaerobic, in which leachate is re-circulated as well into the landfill but biodegradation happens without oxygen, hybrid, a combination of aerobic and anaerobic treatment to debase organics in the upper piece of the landfill and gather gas from bring down part (Dubois et al., 2004).

The disposal of waste to landfills is the last sustainable disposal option as it has many disadvantages. The most important one is the emission of greenhouse gases, especially methane, from the biodegradable waste. Besides that, a major concern is the pollution of both surface and underground water due to the release of leachates. Finally, fire and explosions risks exist, noise, litter and dust occur, as well as occupation of huge land areas that could be used in a different and more efficient way is observed (Dubois et al, 2004; European Commission, 2011). However, landfill sites have some advantages as well. This disposal method appear to be the most appropriate one for the disposal of a wide variety of wastes, and at the same it has relatively low costs. Furthermore, it is suitable for the restoration of land for leisure uses, agriculture or wildlife. Finally, landfill gas is a very good fuel for heat and power (Dubois et al., 2004).

2.1.2.2.1.2. Mechanical Biological Treatment

Mechanical-Biological Treatment (MBT) is a mechanical pre-treatment in which the non-degradable parts of the waste are isolated and then a biological treatment of the remaining waste is following before the landfilling (Figure 2.3.) (European Commission, 2011). Such pre-treatment can have as a result the material to be landfilled being relatively more environmental friendly and consequently, it can help the compliance with the Landfill Directive (1999/31/EC) focuses on minimization of landfilling of biodegradable waste.

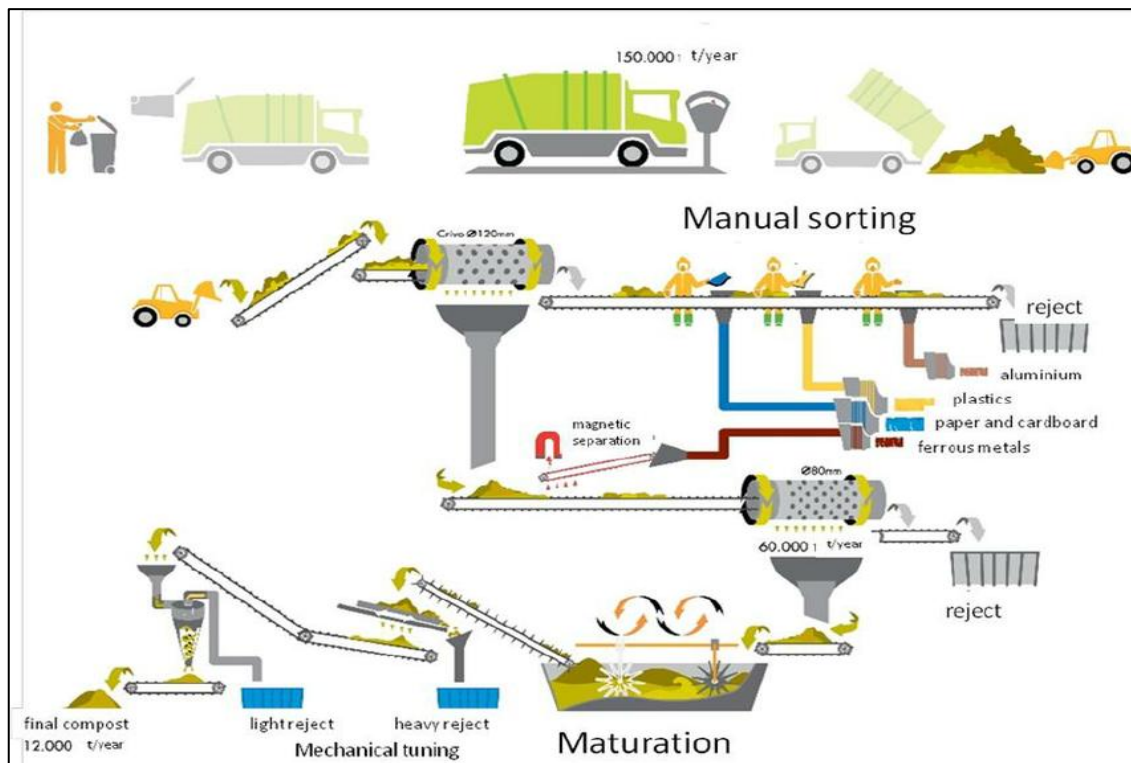


Figure 2.3.: Typical flowsheet of one MBT plant (Dias and Teresa Carvalho, 2011).

There are four phases of this procedure: waste input and control, mechanical conditioning, biological treatment and emplacement of treated waste at a landfill. The mechanical stage is to separate the non-biodegradables and any recyclables. After that, the remaining waste is getting ready for biological treatment by comminution, blending and, if essential, moistening. The biological process, which impacts vast biological stabilization of the waste, follows. The waste is either composted due to its exposition to atmospheric oxygen, or anaerobically digested by separating it without atmospheric oxygen (Dubois et al., 2004). The natural procedure in the aerobic MBT is like a conventional composting procedure, whereas in the anaerobic MBT, the biological procedure comprises of an anaerobic digestion phase creating biogas (European Commission, 2011). In the last stage, the biodegradable fraction is either disposed at landfill sites or, more rarely, valorized (Dubois et al., 2004).

Mechanical Biological Treatment has a few advantages: decrease the volume of waste, extend the landfill's lifespan, and at the same time, minimize the leachate load, diminish the rate of landfill gas production and subsequently decrease the risk of landfill fires (Dubois et al., 2004).

2.1.2.2.1.3. Incineration

Incineration is a controlled burning procedure. More specifically, it is the oxidation of the ignitable parts of the waste. During incineration, flue-gases are produced which include most of the accessible fuel energy as heat. Especially, in the case that the thermal value of the waste is adequate, which is a common case in Europe for municipal solid waste, this results in no requirement for more adding fuels under ordinary operating conditions due to the self-self-supporting combustion occurred by the warm chain reaction (European Commission, 2011). The most well-known sorts are: mass burn and Fluidised Bed Combustion (FBC) (Dubois et al., 2004).

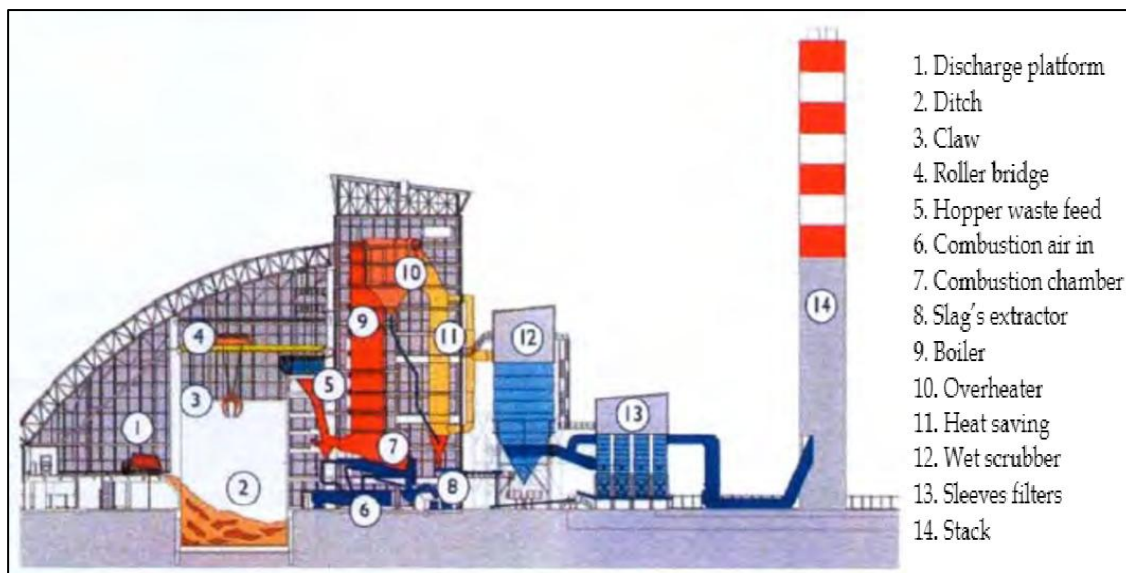


Figure 2.4.: Municipal solid waste Incineration plant (Puna and Santos, 2010).

Mass burn is the easiest and the most widely recognized type of incineration (Figure 2.4.). In order to begin the burning process, the incineration's temperature has to be around 740°C. Waste arrives into a holding area, where it is grabbed by the snatchers, dropped into the feed hoppers and then is mechanically pushed onto the incinerator for two and a half hours. Air from the holding chamber is gone to the combustion chamber in order the release of odour to the surrounding area to be prevented. The ash is extinguished and its reusing can be completed by separating the metal substance utilizing an electromagnet. The bottom ash is either disposed at landfill sites, or used as a substitute raw material in road construction and buildings. The fly ash, due to its hazardous properties, should be sent to particular landfill sites. At the same time, the heat from the burning chamber is used in a multi-pass boiler. The flue

gas should be cleaned before emitted to the air. For this reason, an air pollution control system removes pollutants from the combustion gas including dry urea infusion into the combustion chamber for the minimization of nitrous oxides, lime milk spray into the scrubber reactor for the treatment of acid pollutants and introduction of active carbon to abstract the organic compounds, and finally, filter in order to remove heavy metals. After this processes, the remaining gases, which are mostly compiled by carbon dioxide and water vapour, can be emitted to the atmosphere (Dubois et al., 2004).

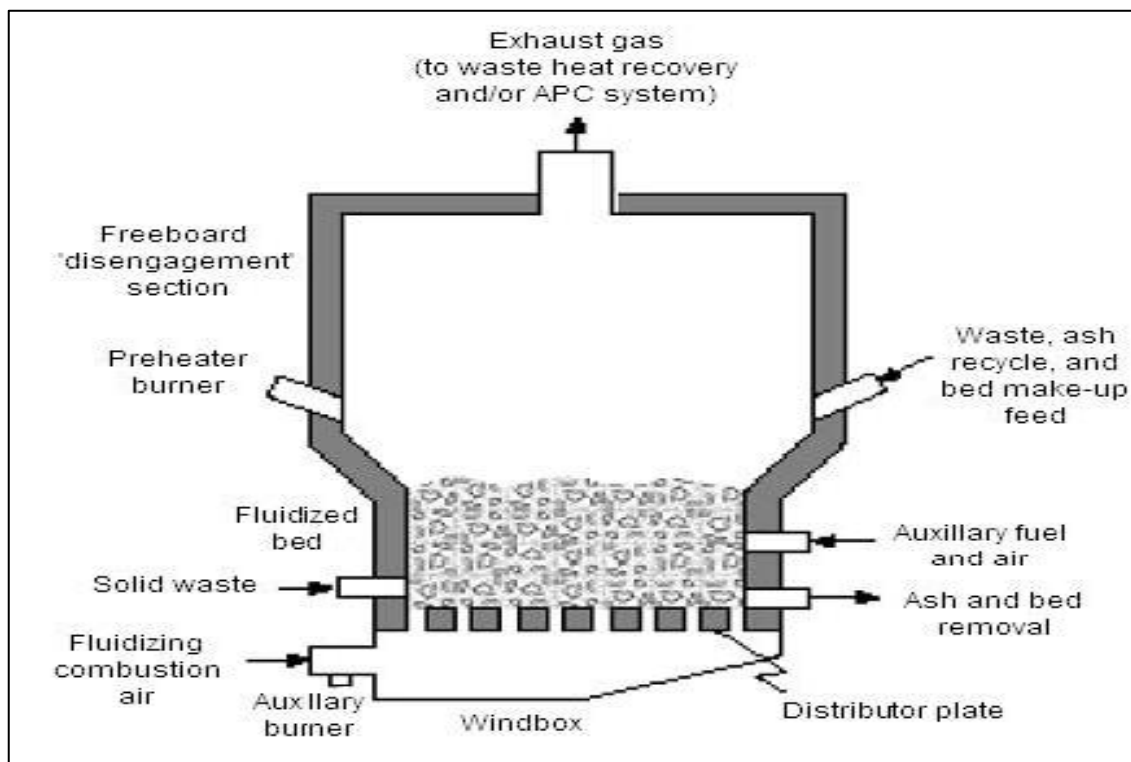


Figure 2.5.: Fluidised bed combustion system (Waste To Energy International, 2017).

The second type of incineration is the Fluidised bed combustion (Figure 2.5.). In this method fluidized bed incinerators, which work with a bed of hot sand, is used. Initially, the non-combustible components of the waste are expelled, the wastes are cut in order coarse Refuse Derive Fuel (cRDF) to be created and then, cRDF is introduced into a bed of sand and dolomite. In the following procedure small parts of waste and sand bed materials are fluidised by infusion of air underneath, which blend the materials keeping them in a constant turbulent movement. Also, air is infused over the bed in the freeboard, where burning of volatile compounds happens at a temperature around 1000°C. There are two types of fluidised beds: bubbling fluidised beds and circulating

fluidised beds. In a bubbling fluidised bed the combustion air speed is set so that extended bed configuration is stable and most of the reactions and heat exchange occurring either in the bed or above it. With circulating fluidized beds, higher speeds are developed so the solid particles are removed with the flue gasses (Dubois et al., 2004).

Incineration has been a solution to the area availability problems, which the municipalities are facing, since it minimizes both the volume and the weight of the waste in landfill sites. In spite of these advantages Incineration has many environmental and health impacts which must be controlled in case that burning process is selected as the basic waste management option for municipalities. Emissions include persistent pollutants of high toxicity which can be spread over a vast area. Besides that, the remaining ash and especially the fly ash contain toxins and consequently it demands very careful disposal. Furthermore, other disadvantages related to incineration practices are: incomplete burning of some materials, insufficient pollution control equipment and monitoring in the incineration plans, higher operational costs than those in landfilling and the difficulty to find incineration sites (Dubois et al., 2004).

2.1.2.2.2. Energy Recovery options

An alternative option and more sustainable than disposal, is waste management options with energy recovery. This can result to considerable environmental benefits as it can be the solution to two problems: treating non-recyclable and non-reusable waste, and recovering the energy inherent within them which can be used in the energy sector (World Energy Council, 2016). Waste-to-energy is a term which includes different waste treatment options generating different forms of energy, such as electricity, heat or waste-derive fuel (European Commission, 2017). Energy recovery from waste can be acquired by using various solutions, each of which has particular characteristics (Figure 2.6.).

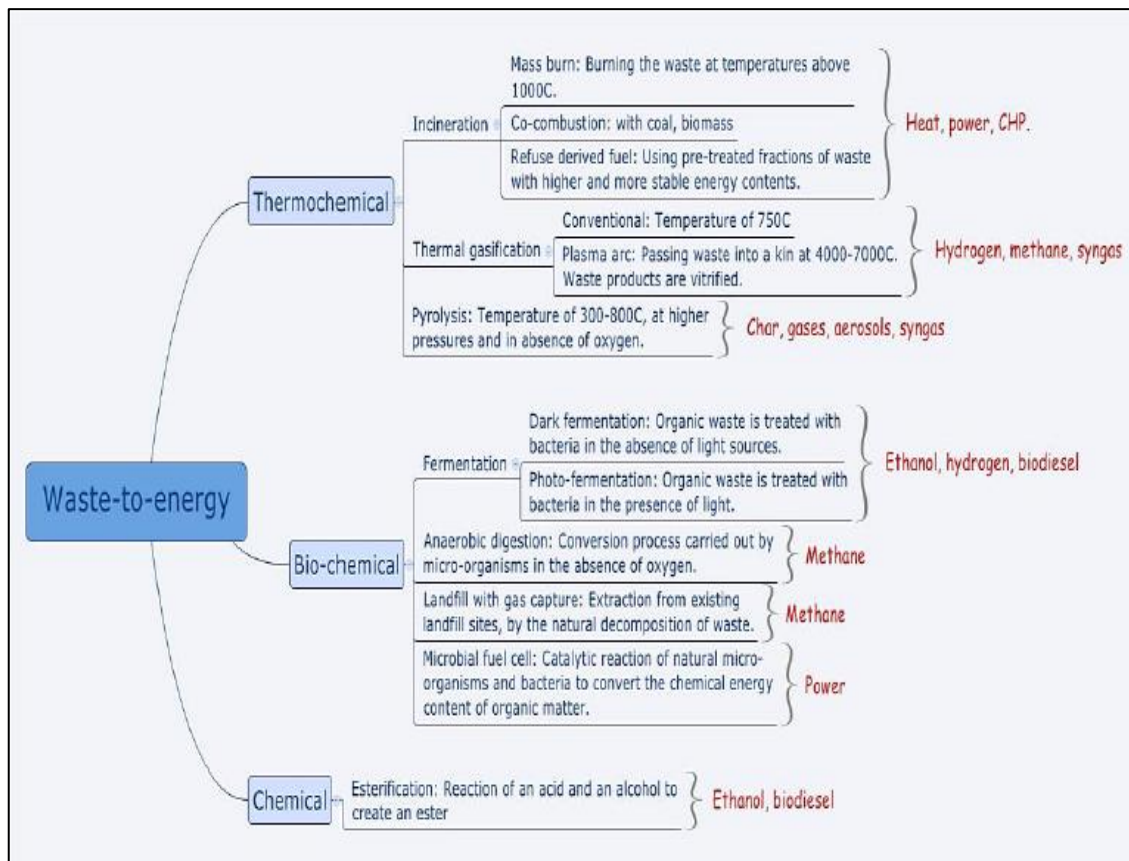


Figure 2.6.: Current Waste-to-energy technologies (World Energy Council, 2016)

2.1.2.2.2.1. Landfilling with biogas/electricity recovery

As mentioned earlier, landfilling is considered to be the least preferred waste management solution, since the emissions of landfill gas lead to many environmental issues due to their odours, toxic compounds and especially the presence of methane. However, the use of new technologies can limit those impacts and transform landfills for municipal waste into a source of energy. Decomposition of organic waste due to anaerobic bacteria living in landfills release landfill gas, called biogas, which is contain a high volume of methane (World Energy Council, 2016). The biogas can be collected, treated and burn, in order to generate electricity or heat (European Commission, 2011; Evangelisti et al., 2015).

The biogas collection process includes covering a part of landfilling and installation collection systems with either horizontal or vertical trenches, depending on the site-specific conditions (Figure 2.7.). As gas goes through this system, the condensate (water) shaped must be gathered and treated. The gas is pulled from the gathering

wells into the accumulation header and sent to downstream treatment with the support of a blower. The extra gas is burned in open or enclosed conditions to control landfill gas emissions at the beginning or the end of the energy recovery system. The biogas treatment of moisture, particulates and other dirt is essential, yet the sort and the degree depend of the kind of energy recovery utilized and the site characteristics, and may include more complex procedures with absorption beds and biological scrubbers (World Energy Council, 2016).

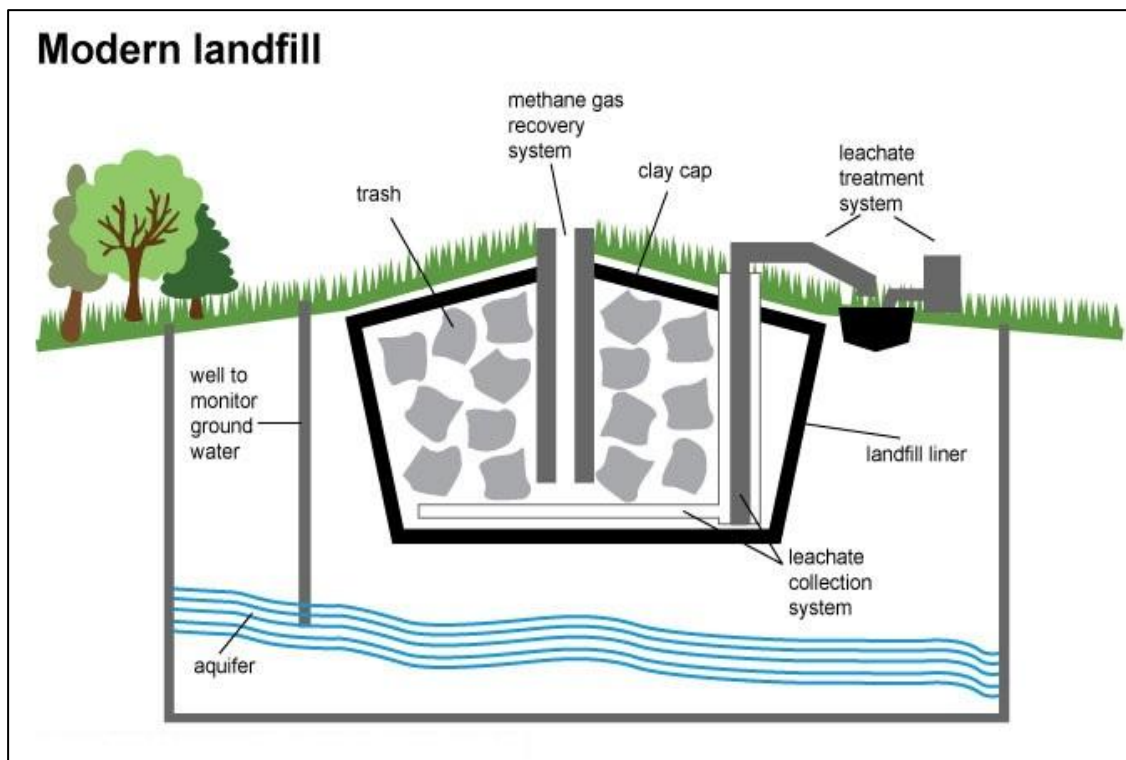


Figure 2.7.: Landfill with biogas recovery (Eia.gov, 2017).

Collecting biogas from landfills is not only beneficial methane has benefits not only for the environment as it helps to minimize methane emissions and thus moderate climate change, but also for the production and energy sector by recovering gas for electricity, heat and fuel generation (European Commission, 2011; World Energy Council, 2016).

2.1.2.2.2. Incineration with energy recovery

As it is already mentioned, MSW incineration is an exothermic complex procedure resulting in the total oxidation of the combustible materials contained in solid waste. With the use of various technologies, large quantities of heat produced during the

solid waste burning process can be recovered and used for district heating or for the production of electricity (Dubois et al., 2004).

During incineration process, after the moisture contained in the waste has been vaporized into the combustion chamber, the actual combustion procedure begins and finally the wastes are transformed into flue gas, ash and heat (Figure 2.8.). The heat which is produced turns water into steam in a boiler. Finally, this high-pressure superheated steam is sent either to the steam turbine, turning the blades of a generator to produce electricity, or is used to give process steam (World Energy Council, 2016).

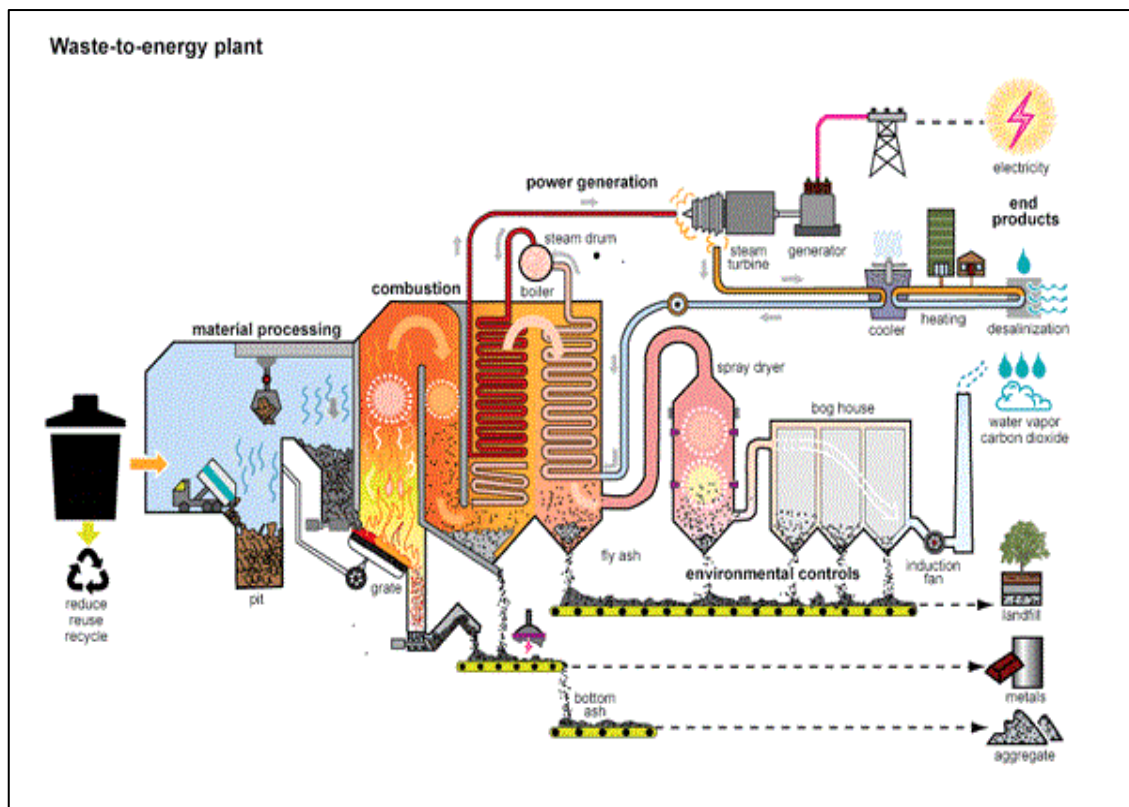


Figure 2.8.: Waste-to-Energy process diagram. Waste incineration plant with energy recovery (Eia.gov, 2017).

Incineration with energy recovery is considered to be more preferable solution, assuming pollution control requirements and costs are adequately addressed. And this is because, this waste management option is more sustainable as the energy production minimizes the use of fossil fuels like oil and coal and at the same time, it is more efficient because the energy generated is 5 times more effective than from landfilling (Dubois et al., 2004).

2.1.2.2.3. Alternative thermal treatments

Apart from incineration there are other alternative emerging thermal methods for the treatment of municipal waste. Two of them, pyrolysis and gasification are quite new and thus remain generally unproven in Europe in contrast with traditional and more applied options of incineration or composting. Regardless of their extent use as industrial processes for energy recovery, their development as treatment method for municipal waste is at an early stage (Dubois et al., 2004; European Commission, 2011). Both pyrolysis and gasification transform waste into energy rich fuels. Contrary to incineration, which completely changes over the waste into energy and ash, these procedures purposely restrain the transformation in order the burning not happen immediately. Rather, they change over the waste into important intermediates, such as syngas, oils and char, which can be used for energy production or materials recycling (Dubois et al., 2004).

More specifically, the major object of these processes is to increase thermal decay of solid waste to gasses and concentrated stages (World Energy Council, 2016). Pyrolysis of solid waste is a thermal procedure where the waste is decomposed at temperatures between 500°C and 800°C, under pressure and without oxygen, and covered into gas (syngas), liquid (tar) and solid products (char) (European Commission, 2011; World Energy Council, 2016) (Figure 2.9.).

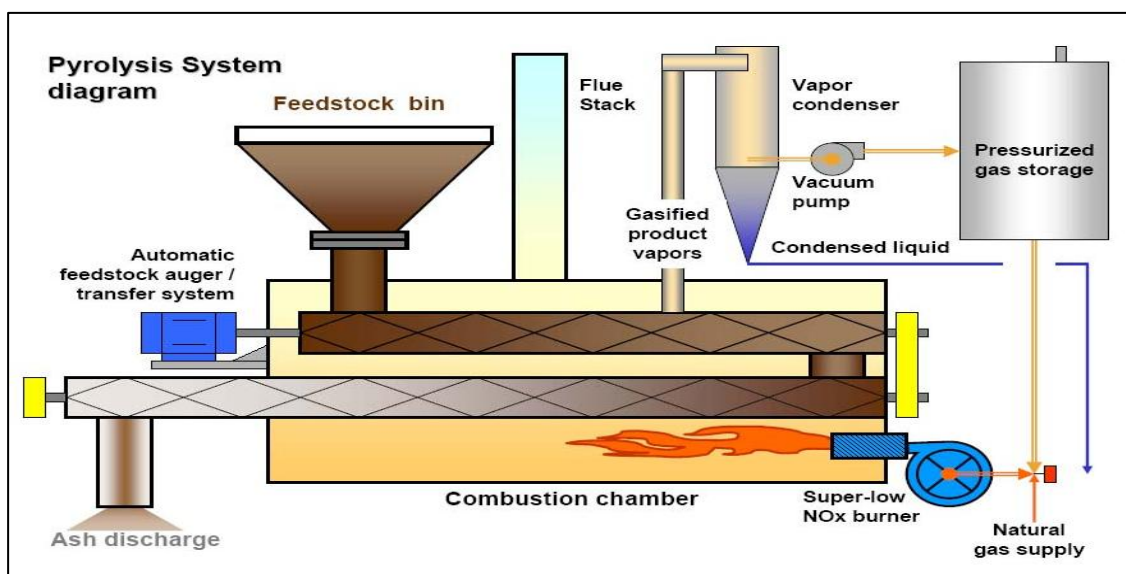


Figure 2.9.: Pyrolysis system (Waste To Energy International, 2017).

Like for the other thermal methods, the most of non-organic waste components should be removed and the waste is homogeneous. The gaseous output from the pyrolysis process can be combusted in order to generate electricity. Finally, the solid char which is created may be either disposed, for example landfilling, or need further processing, such as gasification (European Commission, 2011). The volume of useful products, such as CO , H_2 , CH_4 and other hydrocarbons produced from this procedure and their extent depends totally on the pyrolysis temperature and the rate of heating (World Energy Council, 2016).

Gasification is a similar method for reducing the solid waste volume and for recovering energy (Figure 2.10.). It generates 500-600 kWh useable energy per ton of waste (Dubois et al., 2004). Particularly, solid waste gasification is the incomplete oxidation of waste within the existence of an oxidant of lower amount than that needed for the combustion (World Energy Council, 2016), and also, it requires higher temperatures than pyrolysis (European Commission, 2011). That reaction is autothermic and does not need extra heat to be provided from somewhere else in the procedure (Dubois et al., 2004). Gasification procedure includes several stages. Initially, carbonaceous material is dried to remove moisture. Then, contingent on the procedure, pyrolysis happens in a primary chamber under controlled, low air conditions, at around 450°C , transforming the feedstock into gas, vapourised liquids and a solid char residue. Finally, gasification takes place, in a secondary chamber at between $700\text{--}1000^\circ\text{C}$. Here the pyrolysis gases, liquids and char undergo partial oxidation into a vaporous fuel, including an assortment of gases such as hydrogen, carbon monoxide, carbon dioxide, methane and higher hydrocarbons. This reaction resulting in the formation of contaminants like oils, powder tars and little scorch particles (ECOTEC, 2002). Superheated steam can be infused to encourage the transformation into vaporous fuel (ECOTEC, 2002) and be burned in a gas turbine to generate electricity (Dubois et al., 2004). The produced gas, which is called syngas, can be used for various applications after it has been cleaned, for instance to create high quality fuels, chemicals or synthetic natural gas, electricity (World Energy Council, 2016). Besides that, the char generated by gasification of organic waste can be used as secondary construction material (European Commission, 2011).

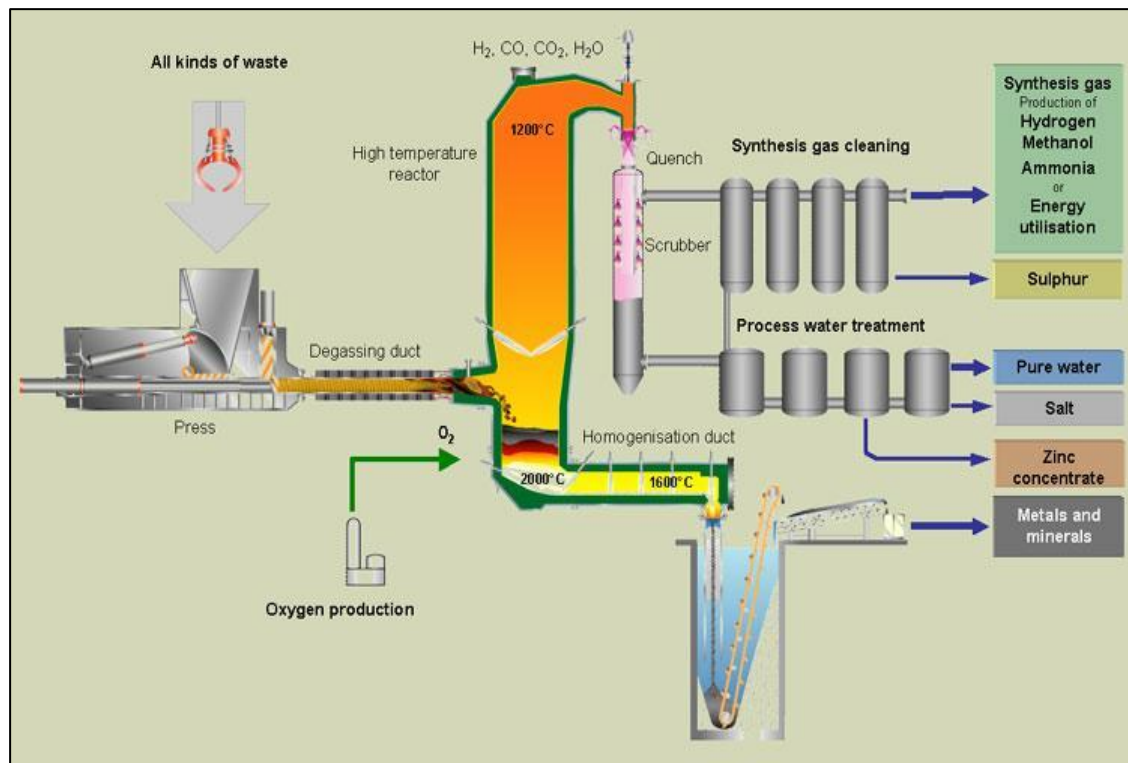


Figure 2.10.: Gasification process (Waste To Energy International, 2017).

Both methods have both advantages and disadvantages. As far as pyrolysis method is concerned, one of its benefits is that some fluid fuel can be created, which is flexible, easy to be transported and could be utilized, for instance, as a vehicle fuel in a worldwide burning motor. However, since a significant part of the fuel created in the pyrolysis procedure is used inside the operation, pyrolysis tends not to be such efficient. On the other hand, gasification is a more common due to its more efficient procedure which creates only one gaseous product. Also, gasification technology does not face any problem with heat transfer (Dubois et al., 2004). Nevertheless, due to limited development of both methods in waste management sector their environmental performance cannot be evaluated in a great extent (European Commission, 2011).

2.1.2.2.4. Anaerobic Digestion

Anaerobic digestion (AD) is an alternative treatment procedure which leads to energy recovery. AD is the bacterial disintegration of organic waste in the relative lack of oxygen (ECOTEC, 2002). Biogas, which mainly contains carbon dioxide and methane, is the major product of this process and it is used as an energy source for electricity

generation. In addition, another by-product of anaerobic digestion is a semi-solid residue, called digestate, which after further treatment, generally through composting, can be used for agricultural activities as a fertiliser and source of nutrients (ECOTEC, 2002; European Commission, 2011; World Energy Council, 2016). There are various AD systems, such as mesophilic or thermophilic, wet or dry, continuous flow or batch flow, single or multiple digestors, vertical tank or horizontal plug flow, the final choice of which depends on different factors, like the type of feedstock, the space, infrastructure and financing availability, the desired output for instance, more biogas for energy production, waste mitigation, bedding, digestate (World Energy Council, 2016).

Anaerobic digestion process last usually 15 to 30 days (World Energy Council, 2016) and has three stages: pre treatment, anaerobic digestion and post-treatment (ECOTEC, 2002) (Figure 2.11.). In the pre-treatment stage the MSW is separated in order to be handled more easily. Even MSW that comes from already separated sources needs to be further divided in order not to include wrongly sorted materials, for example, plastics, metals and larger components. This stage can be done under either wet or dry conditions. Then, a procedure aiming at reducing the waste size follows, so that a homogenous material which will help fermentation and facilitate processing to be created. Next stage is digestion. There are various technologies of anaerobic digestion, which include: *wet single-step*, in which MSW is slurried with process water to give a diluted feedstock as a supply to a blend tank digester, *wet multi-step*, in which MSW is as well slurried and undergone by hydrolytic and fermentative bacteria to let free volatile fatty acids which are then changed over to biogas in a high-rate industrial wastewater anaerobic digester, *dry continues*, in which digestion vessel is always full of a material with 20% - 40% dry matter, *dry batch*, in which a quantity is inoculated with digestate from another reactor and left to process while leachate is moving around to keep the moisture and methane bacteria at a certain level in the vessel, and finally, *sequencing batch*, a process similar to the dry batch procedure, in which leachate is moved from old bunches to new ones to help start up, inoculation and removal of volatile materials from the active reactor (ECOTEC, 2002). At last, after digestion, post-treatment stage follows. In this step, if the feedstock is wet, the material which is

considered as “sludge” can be spread to land without further treatment. Otherwise, solid and liquid components can be isolated and after 2 to 4 weeks they will have been transformed into stabilized compost. At the same time, the liquid part may either be recycled for dilution of fresh waste, spread to land as a liquid fertiliser, or sent to a wastewater treatment plant (ECOTEC, 2002).

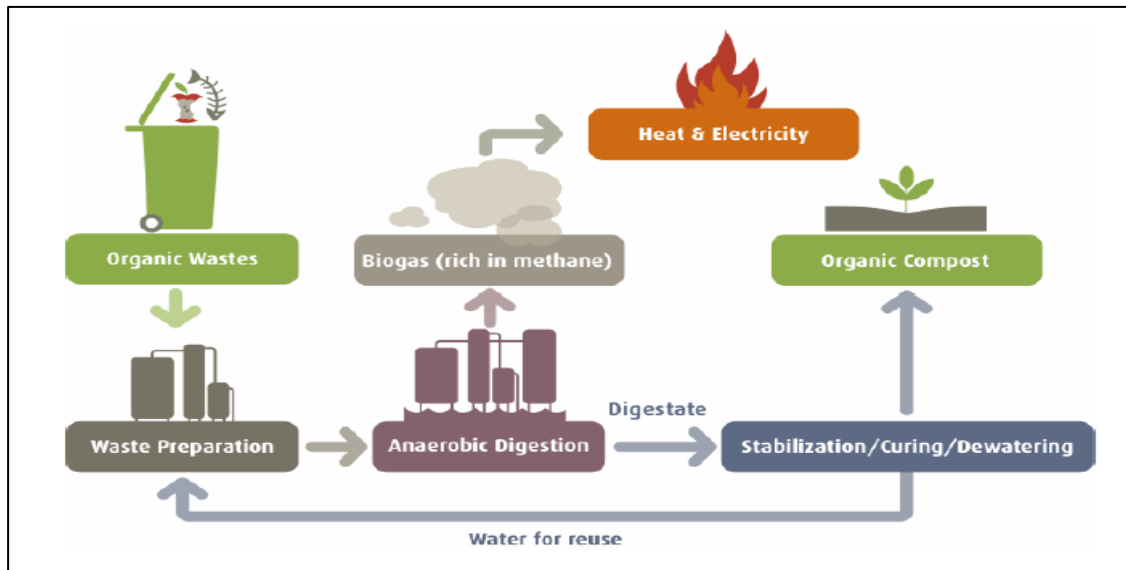


Figure 2.11.: Illustration of ad process treating biodegradable MSW (World Energy Council, 2016).

Anaerobic digestion is considered to be better waste treatment method than conventional composting, especially in case that is combined with a digestate composting facility. From an environmental point of view, the major advantage is the production of methane, which is an important energy source and the supply of biogas, which helps to minimization of emissions since fossil fuels are not used for the energy generation (European Commission, 2011). Besides that, the total volume of the sludge produced is less and the final product can be used as a soil fertilizer. Also, the AD process effectively leads to removal of diseases as it inactivates pathogens. Despite these benefits of AD method, there are several disadvantages. To begin with, AD process has many restrictions concerning waste composition as it is not suitable for all kind of waste, such as low concentrated wastewaters, as well as operating conditions like the need of high temperatures. At the same time, the growth rate of anaerobic organisms is very slow and production of odour and corrosive gases is increased. Moreover, the quality of the sidestream which is created is poor and the final digestate

sometimes needs further aerobic treatment in order to fulfill discharge requirements. Finally, it is a waste treatment method with high investment and operating cost (Hung, Wang and Shammass, 2013).

2.1.2.2.2.5. Co-processing of waste in industrial processes

Co-processing is the replacement of natural resources and fossil fuels, such as coal, petroleum and gas, by waste that is used as raw materials and a source of energy. This method can be applied in industrial sector for the production processes of cement, brick, steel or aluminum. The literature on co-processing MSW as raw materials focuses on the burn of MSW in cement kilns for cement clinker production. However, the method is applied in a similar way also to other resource-intensive industries (European Commission, 2011).

More specifically, the co-processing of MSW in clinker kilns is affected by the pre-treatment that is needed in order to separate recyclable materials and organic components with high conciseness of wet (Meystre and Silva, 2013). Some waste streams, such as waste tyres and foundry sand, are suitable for co-processing without any pre-treatment operation, whereas other waste streams, such as unsorted municipal solid waste need a pre-treatment operation before they can be put into the kiln system (European Commission, 2011). The remaining waste is called Refuse Derived Fuel (RDF) and can be utilized as secondary fuel in the clinker kiln. Besides that, the ash created by burning of RDF can be included in the clinker consequently diminishing the needed amount of raw material. During the co-processing process for the clinker production alkaline conditions are developed and together with the intensive blending help the retention of flying components from the gas phase. The clinker reacts at 1450°C and ash and particularly the chemical binding of metals are incorporated into the clinker (Meystre and Silva, 2013).

Co-processing is a proven sustainable waste management concept. Its main advantages are the complete demolition of MSW and its transformation into a product with economic value and the financial growth of the industrial plans. Besides that, the reduction on demands on natural resources and the replacement of fossil fuels with

alternatives contribute to minimize pollution and reduce of landfill sites (Meystre and Silva, 2013).

2.1.2.2.3. Recycling options

Recycling is the third component of the "Reduce, Reuse, and Recycle" waste hierarchy. The term "Recycling" includes any action by which waste is converted into new products, materials or substances either for the original or different use. In contrast with other recovering methods, it incorporates only the reprocessing of organic material and excludes energy recovery and its use for the creation of fuels and raw materials (European Commission, 2011). It is a major and extremely environmentally beneficial method of waste management.

2.1.2.2.3.1. Recycling

Recycling transforms materials that would in any other way become waste into useful resources. After collection, materials, like glass, aluminum, steel, plastics, and paper are isolated and sent to facilities that can procedure them into new materials or products.

This waste treatment method leads to many ecological, financial, and social advantages. Initially, recycling limit environmental pollution since it helps lower emission of different greenhouse gas emissions, as well as the air pollution from incineration practices and water and pollution from landfilling. Also, it minimizes the demand and consumption of fresh raw materials that release toxic materials during their process and consequently pollute air, soil and water. Besides that, it can reduce energy usage for the production of new materials and at the same time provides raw materials for new industries. Nevertheless, recycling requires higher costs as well as energy used for collecting, transporting and reproducing recyclables (Dubois et al., 2004).

2.1.2.2.3.2. Composting

Composting is an alternative natural type of recycling and a treatment method for MSW and especially biological degradable waste. More specifically, it is the

biodegradation of organic materials through a self-heating, solid phase, aerobic procedure (ECOTEC, 2002).

The proper conditions for an efficient composting process are: temperature around 65°C, air supply at least one or twice a month, moisture content at 40% up to 60%, porosity of the material approximately 5cm and carbon to nitrogen ratio by weight to be 30 parts carbon to 1 part nitrogen (Dubois et al., 2004). Under these circumstances, waste and microorganisms within it interact and transform organic components into a stable, granular material (Dubois et al., 2004). The microorganisms that complete this procedure fall into three categories: bacteria, fungi and actinomycetes. The composting process includes three stages: initially, bacteria consume easily accessible sugars, thus results in a quick increase of temperature. Then, bacteria and actinomycetes break down the cellulose and finally, in the last stage, while the compost cools down, fungi break down the tougher lignins included (ECOTEC, 2002; Dubois et al., 2004).

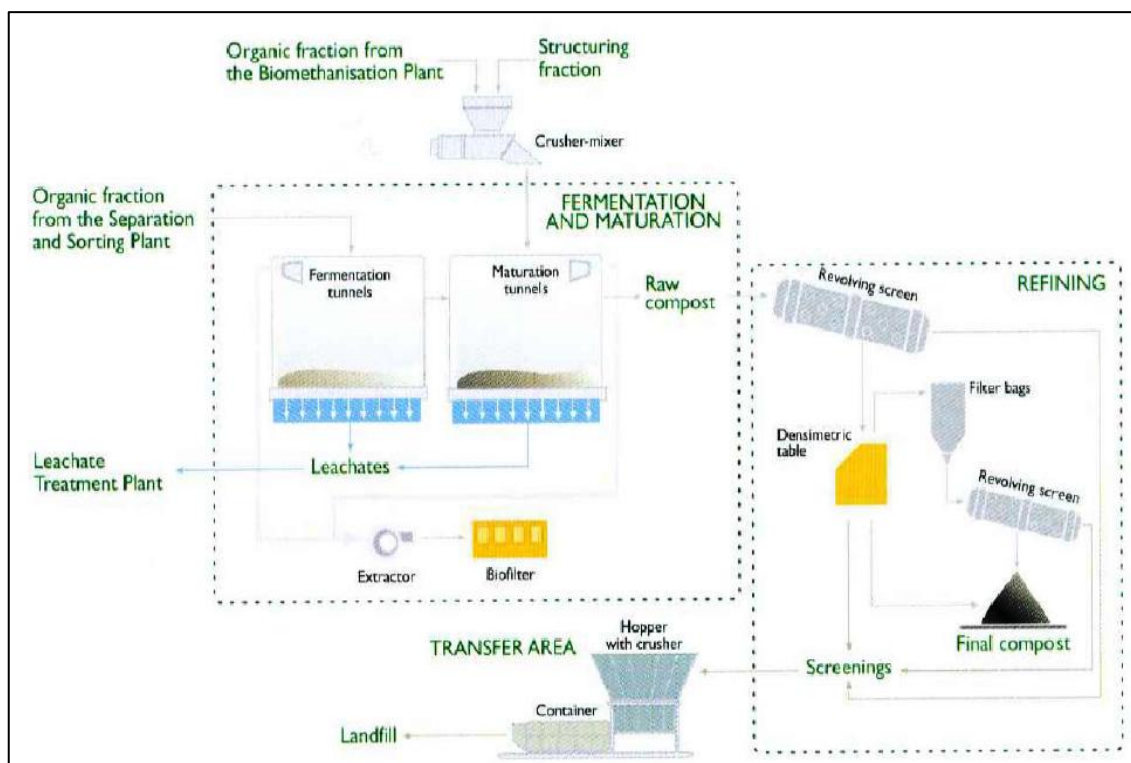


Figure 2.12.: Composting plant display diagram (European Commission, 2011).

There are various methods for the composting process. It can take place in private gardens (home composting), on field (agriculture residues left in/on the soil) as well as

in advanced industrial plants (Figure 2.12.), which can be either open or closed. In open composting the biological activity may last from 3 to 6 months and may have some disadvantages, for instance, odour emissions and high area availability. In closed composting plants the procedure is quicker due to automatic oxygen and moisture control, the odour emissions are minimized and the gas which is emitted can be collected and cleaned through a biofilter (European Commission, 2011).

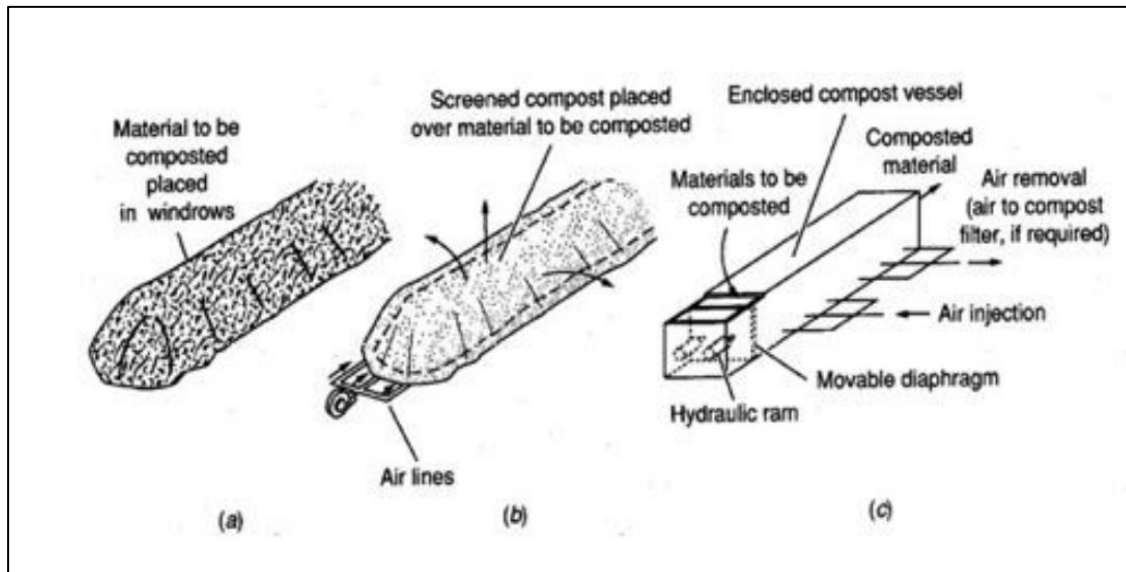


Figure 2.13.: The three basic composting technologies: a) windrows system, b) aerated piles and c) enclosed vessels (Papadimitriou, 2014).

There is a wide range of composting technologies (Figure 2.13.), such as windrows systems, aerated piles and enclosed vessels (in-vessels) (Dubois et al., 2004). Windrows system is a low technology system which does not demand high investment in terms of both equipment and finance. They are a conventional type of composting in which during the active composting phase the waste materials are piled into long low piles or rows (windrows), more often between 2-3m high and 3-4m wide. Oxygen supply of the windrow is succeeded by turning the material. Compost in windrow is generally prepared inside 10 months. After this period, it is set aside to curing and storage piles in order to mature for an additional 40 days (Dubois et al., 2004; ECOTEC, 2002). Aerated piles are a technology which enhance the air circulation and keep the ideal conditions within a de-composting system. They are used to move air through the pile when temperature in the material gets higher than the optimum. In this case, a

thermostatically controlled blower pushes or pulls air through the pile for air circulation and cooling the pile temperature and providing oxygen. Since there is no system for remixing during the composting procedure aerated piles are mainly used for homogeneous materials, for example, sludges (Dubois et al., 2004). Enclosed vessels is a composting system in which composting process takes place rapidly (lasts only few days) in a container, such as a silo, using forced air circulation, similar to an aerated pile. Inside these systems it is possible to collect and treat odours from MSW. There are various types of such systems, for instance silo-type systems which depend on gravity to move material in the vessel, as well as agitated bed systems which incorporates inside blending that physically moves the contained materials, joining the benefits of both the windrow and aerated pile methods (Dubois et al., 2004).

Composting as a waste treatment method has both advantages and disadvantages. On the one hand, composting removes organic materials from waste in landfill sites, thus minimizing methane emissions. Also, it enhances soil properties with organic materials, humus and nutrients. Besides that, gives a compost which can be used in agricultural sector and it replaces other soil improvers, protects against erosion, rebuilds and maintain the soil for sustainable production. On the other hand, during composting process odour, spores and fungi and polluted liquid may be developed and released to the environment, especially in case that specific operational standard are not implied. Besides that, in large scale composition separation costs may be high whereas issues related to infection of the final product can appear (Dubois et al., 2004).

2.1.2.2.4. Prevention options

Good waste management starts with reducing, or avoiding generation of waste, since what is not produced does not have to be disposed of. Therefore, waste prevention and minimization should be a priority in any waste management plan (European Commission, 2013).

2.1.2.2.4.1. Reduction

Prevention, or source reduction as it is also called, refers to avoiding or minimizing waste generation. Furthermore, as it is defined in the Waste Framework Directive

(2008/98/EC) prevention includes, apart from the reduction of waste volume, the actions taken in order to minimize dangerous component wastes of materials and products and limit their environmental and human health impacts (European Commission, 2011).

Waste prevention includes efficient product design, optimal manufacturing process, less and reusable packaging, different buying behavior, purchase and use of the products so that to minimize the amount and toxicity of waste generated through the whole life cycle. Besides that, other ways of reducing waste are the replacement of hazardous sources with non-hazardous, recyclable and recoverable ones, the extension of product's life span, the maintenance of durable equipment and re-use of supplies and products, without pre-processing operations (Dubois et al., 2004; European Commission, 2011).

The benefits of this waste management option are obvious. Reducing the volume of the waste created is a commonsense approach to decrease disposal and production costs (Dubois et al., 2004). In addition, it minimizes ecological and human health effects. Especially, as far as the greenhouse emissions are concerned, waste prevention leads to the avoidance of emissions related with material and product manufacturing process, as well as it eliminates the emissions released from the avoided waste management methods (Bhada-Tata and Hoornweg, 2012).

2.1.2.2.4.2. Re-use

An alternative solution to reduce waste is reusing. The Waste Framework Directive (2008/98/EC) defines re-use as any activity which leads to the ability to use again products that are not waste in the same way as did the first time of their use.

Re-use permits expanding the lifespan of a product with regards to the end of its useful lifetime. After its use from its first owner, the object's lifetime can be extended by a few operations, although its way of use remains the same. Re-use exclude reusable objects instead of disposables, as this is more like a prevention option (European Commission, 2011).

The advantages that re-use has are clear, since the re-use option leads to lower need to manufacture new products, thus resulting to less energy and material demands, less emissions and less waste disposal. Nevertheless, the re-use method as a way to prevent waste also requires a separate collection system and pre-processing operations such as washing or reconditioning stage. In addition, in the case that the re-conditioning infrastructure is limited, the re-usable products should be transported long distances and consequently more transport emissions will be emitted. Finally, re-usable products may need higher energy consumption in order to be use than the new and more efficient ones (European Commission, 2011).

2.1.2.2.4.1. Preparing for re-use options

Preparing for re-use should not be confused with “re-use”. The last one, as mentioned in the previous sub-chapter, is a type of waste prevention, thus is higher in the waste hierarchy. According to the Waste Framework Directive (2008/98/EC), preparing for re-use is defined as *“checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing”*. The main difference between “re-use” and “preparing for re-use” is that in the first case the product has not turned into a waste, though in the last it has (European Commission, 2011).

2.2. REGULATORY FRAMEWORK

Waste hierarchy, which includes Prevention, Materials and Energy Recovery and Disposal options, ranks all the possible waste treatment methods described in the previous sub-chapter according to sustainability directions and basis. However, the waste management method which is finally chosen must comply not only with the hierarchy’s prioritization, but also with the universal and national regulatory frameworks.

In the case study Greece, waste management systems which are implemented must comply with both the European Union (EU) and Greek legislation.

2.2.1. EU policy and waste legislation

The importance of waste issue was recognized by the international community, thus set it in the Agenda 21 and a framework for integrated waste management evolved (Columbus and Themelis, 2006). At the same time, at 1970's, EU environment policy has developed and up to now is one of the most supported policy areas (European Commission, 2005).

2.2.1.1. History of EU waste policy

Waste policy has been the starting point of EU environmental policy. In the 1970's and 1980's, various waste treatment scandals were identified, policy-makers warned of the dangerous environmental and human health impacts of such practices and waste control measures began to be developed. These led to the Waste Framework Directive and the Hazardous Waste Directive, both adopted in 1975, and later to the Waste Shipment Regulation, all of which put the basis and defined the key concepts of the waste regulation (European Commission, 2005) and in the Fifth Action Program for the Environment (1993 – 2000) EU espoused the concept of integrated waste management (Columbus and Themelis, 2006). However, there were many gaps regarding emission parameters for the different waste management methods such as landfill, incineration and recycling. These issues were addressed by the Landfill Directive of 1999 and the Waste Incineration Directive of 2000. In addition, the 1996 Directive on Integrated Pollution Prevention and Control (IPPC) represented a permit system in order to prevent pollution from industrial and agricultural facilities (European Commission, 2005). In 2005, Thematic Strategy on waste established the general policy framework based on waste life cycles and the “Reduce-reuse- recycle” concept. Then, in 2008, Waste Framework Directive (2008/98/EC) was developed and set the general regulatory framework. Also, the 2011 Roadmap to a resource-efficient Europe aims to “manage waste as a resource” by 2020. Nowadays, The Seventh Environment Action Program, called “Living well, within the limits of our planet” also deals with waste management issues, aiming “to turn the Union into a resource efficient, green and competitive low-carbon economy” (European Parliament, 2015).

2.2.1.2. EU Legislation

In contrast with many countries, European Union has a highly developed waste regulatory framework, which set the same targets to all Member States, although the legislation of each particular country differs depending on country's specific culture, economic development and administrative structures (Filho et al., 2016). Nevertheless, every waste management system implemented in European countries must follow EU waste regulation, particularly: Waste Framework Directive (2008/98/EC), Directive (99/31/EC) on the landfill of waste, Directive (2000/76/EC) on incineration of waste, Regulation 2037/2000 on substances that deplete the ozone layer and Directive 2008/1/EC concerning integrated pollution prevention and control (Milutinović et al., 2017).

Waste Framework Directive (2008/98/EC) establishes the general regulatory framework. More specifically, it defines the major concepts of waste management and sets principles, such as “polluter pays principle”, the “waste hierarchy” and the “end-of-waste status”. *Directive (99/31/EC) on the landfill of waste* refers to prevention and minimization of landfill's environmental impacts, by defining the various waste categories and setting a system of operating permits for every landfill site. Also, sets targets for the reduction of landfilling of biodegradable waste (European Parliament, 2015). *Directive (2000/76/EC) on incineration of waste* establishes the technical and operational standards for both waste incineration and waste co-incineration plants, in order to reduce environmental pollution caused by the incineration process.

Based on the general waste legislative framework, the waste policy is accompanied by a number of more specific Directives. These are related either to specific operational standards of treatment facilities, such as the Directive of Hazardous waste, or to Directives on specific waste streams (EEA, 1999). The specific waste stream Directives are (European Parliament, 2015):

- Directive on packaging and packaging waste;
- Directive on waste electrical and electronic equipment (WEEE);
- Directive on batteries and accumulators and waste batteries and accumulators;

- Directive on end-of-life vehicles;
- Regulation on ship recycling;
- Directive on waste from extractive industries;
- Directive on the disposal of PCB and PCT;
- Directive on sewage sludge in agriculture;
- Directive on radioactive waste.

2.2.2. Greek Legislation

The Greek regulatory framework that defines the waste management is in accordance with the development of the European waste framework and the relative Directives. Until recently, all corresponding EU Directives have been transposed to Greek laws, with the latest case being the transposition of the Waste Framework Directive (2008/98/EC) in the *Law 4042/2012* of 2012 (European Environment Agency, 2013).

The Ministerial Decision EIB/301/64 «on collection and disposal of waste» was the first Greek legislation in which technical requirements about waste collection and disposal were set. A few years later with the Legislative Regulation 703/1970, Law 25/1975, Law 429/1976 and Law 1080/1980 sanitary fees were imposed in relation to the household surface in sq. meters, and this has not changed until today. In 1986, the EU Waste framework Directive was transposed into Greek law, through the Joint Ministerial Decision 49541/1424/86 (“solid waste in conformity with Directive 75/442/EEC...”). A few years later, the Law 2939/2001 defines the guidelines for recycling of waste and the Directive 94/62/EEC is transposed into national Law. Also, Presidential Decrees were issued which set objectives for every waste stream. So far the P.D.’s 82/2004, 109/2004, 115/2004, 116/2004, 117/2004 and 15/2006 for used oils, tires, batteries, end of life vehicles and waste electrical and electronic equipment have been issued. In 2002, the J.M.D. 29407/3508/2002 transposes Directive 1999/31/EC which is referred on measures for the landfilling and one year later, the J.M.D. 50910/2727/2003 «on measures and terms for solid waste management - national and regional planning management», in complete compliance with the European Waste Framework Directive 91/156/EEC is issued and it addresses major principles and objectives related to solid waste management as well as it set the

specifications for national and regional planning. In 2005, the J.M.D. 22912/1117/2005 incorporates Directive 2000/76/EC regarding the incineration of waste and finally, in 2012 EU Waste framework directive was adopted and transposed into the Law 4042/2012 (eedsa.gr, 2017; Ministry of Environment, Energy and Climate Change, 2017).

More specifically, Law 4042/2012 on waste management indicates the development of a new National Waste Management Plan (NWMP) in which the policy, strategy, principles and targets for the waste management in Greece are defined and the suitable measures and action for the achievement of these objectives are suggested. In addition, based on the NWMP's guidelines, local waste management plans should be prepared for the management of all waste generated at regional level (Watson Farley & Williams, 2015).

2.2.3. Implementation issues

Poor implementation of waste regulation is a regular phenomenon and there are many reasons why this happens. First of all, waste has not been a political priority until recently and the rule of "out of sight, out of mind" was usually applied. Furthermore, in some areas, implementation is poor despite there is the proper transposition of EU regulatory framework into national laws, there are not effective actions with an important environmental benefit. However, the most important problems regarding these implementation gaps are the uncontrolled landfilling and the shipments of hazardous waste disregarding worldwide traditions. Since these two issues have the most significant environmental and human health impacts, the implementation efforts should be focus on them (European Commission, 2005).

A typical example of poor implementation is Greece. Despite the fact that the EU Landfill Directive (1999/31/EC) has been transposed into Greek legislation, little has been done to either satisfactorily implement the Directive, or achieve any of its targets, since dumping sites still operate. Besides that, none of these dumps could meet the prerequisites of a controlled or sterile landfill site under the EU Landfill Directive (1999/31/EC) as these sites do not accomplish the demands of the Groundwater Directive and Environmental Impact Assessment of an Integrated

Pollution Prevention and Control (IPPC) (Ezeah and Byrne, 2014). Consequently, Greece has been penalized by the European Court of Justice for several cases since 2005 (Bosdogianni, 2007; Ezeah and Byrne, 2014; Watson Farley & Williams, 2015). More recently, in December 2014, the Hellenic Republic was bound to pay to the Commission a fine of 10 million Euros and an extra fine every six months in case that the 70 operating illegal landfills are still open and the 223 sites which have already been closed are not satisfactorily reestablished (Watson Farley & Williams, 2015).

2.3. WASTE MANAGEMENT PRACTICES

Over the last two decades, political emphasis on municipal waste is very high in all European countries, in spite of the fact that municipal waste represents only 10% of total waste generated in EU. The different waste policies set various targets at the EU level concerning management of certain types of waste. For instance, in 2015, the European Commission recommended new objectives for municipal waste of 60% recycling and preparing for reuse by 2025 and 65% by 2030. Besides that, it proposed new targets about packaging waste, as well as about reduction of MSW disposed of in landfill. Nevertheless, in countries that the municipal waste management systems are efficiently developed, a general better performing is observed in relation to overall waste management (EEA, 2016).

2.3.1. Generation and treatment of municipal waste in EU

Waste generation, as well as waste management options are different for each European country, and are depended on various factors such as economic growth, population density, consumer behavior or existing waste management facilities (EEA, 2007). Data on municipal waste have been collected by Eurostat since 1995 are widely used for comparing and getting information for municipal waste generation and treatment across EU countries.

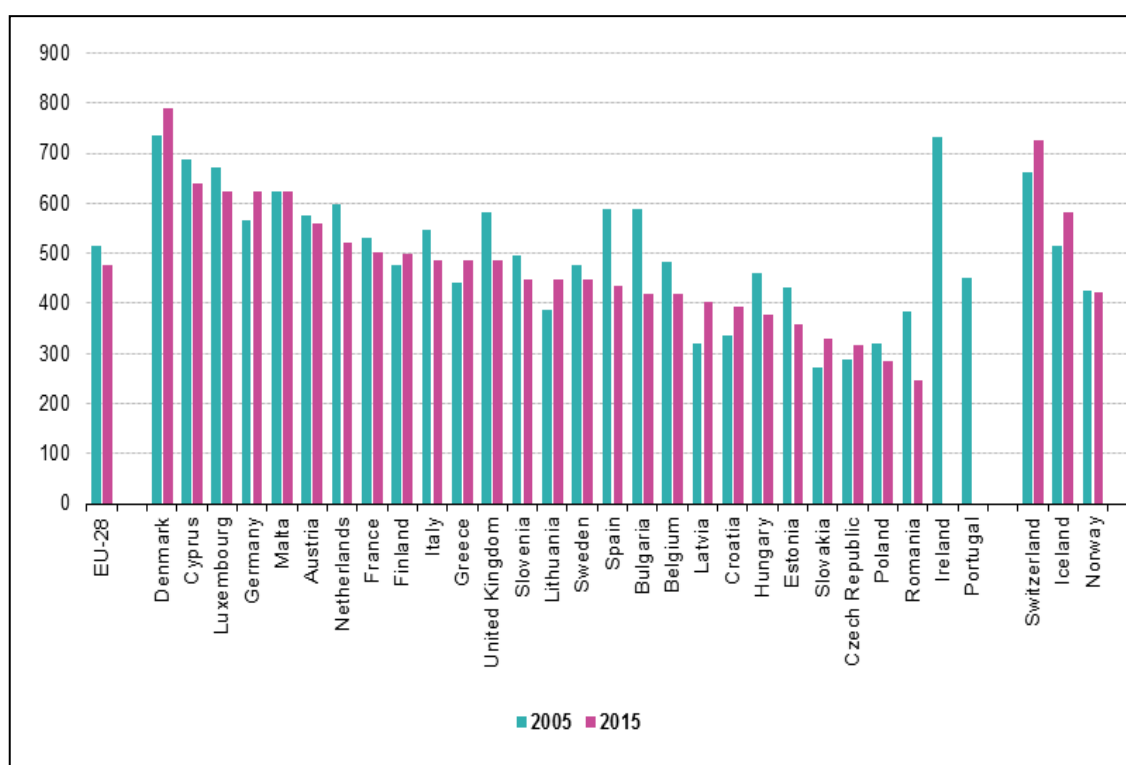


Figure 2.14.: Municipal waste generated by country in 2005 and 2015, sorted by 2015 level (kg per capita) (Eurostat, 2017).

According to these data, total municipal waste generation in EU countries declined approximately 8% from 2005 to 2015 (Figure 2.14.). However, **Table 2.1.** summarizes that in 16 of the 31 countries (Member States and EFTA), the volume of municipal waste generated per capita increased from 1995 to 2015. Based on 1995 and 2015 data the highest average annual growth rates were recorded for Malta and Greece (both 2.4%), as well as Latvia and Denmark (both 2.1%). On the other hand, Bulgaria has the largest reduction, with an annual average decrease of -2.5%, followed by Romania (-1.6%) and Slovenia (-1.4%) (Eurostat, 2017).

As far as management of municipal waste and specific treatment strategies are concerned, Table 2.2. presents the amount of municipal waste treated in the European Union (EU-27) for the period 1995 to 2015 by treatment method (landfilling, incineration, recycling, and composting) and in Figure 2.15. the total amount of waste generated and the amount of waste by treatment category are depicted. Although more waste is being produced in the EU-27 since 1995 (Table 2.1.), the total amount of municipal waste landfilled has reduced (**Table 2.2.**) (Eurostat, 2017).

Table 2.1.: Municipal waste generated by country in selected years (kg per capita), 1995-2015 (Eurostat, 2017).

	1995	2000	2005	2010	2015	change (%) 1995-2015
EU-28	-	521	515	504	476	-
EU-27	473	523	517	505	476	1
Belgium	455	471	482	456	418	-8
Bulgaria	694	612	588	554	419	-40
Czech Republic	302	335	289	318	316	5
Denmark	521	664	736	-	789	52
Germany	623	642	565	602	625	0
Estonia	371	453	433	305	359	-3
Ireland	512	599	731	624	-	-
Greece	303	412	442	532	485	60
Spain	505	653	588	510	434	-14
France	475	514	530	533	501	5
Croatia	-	262	336	379	393	-
Italy	454	509	546	547	486	7
Cyprus	595	628	688	689	638	7
Latvia	264	271	320	324	404	53
Lithuania	426	365	387	404	448	5
Luxembourg	587	654	672	679	625	6
Hungary	460	446	461	403	377	-18
Malta	387	533	623	601	624	61
Netherlands	539	598	599	571	523	-3
Austria	437	580	575	562	560	28
Poland	285	320	319	316	286	0
Portugal	352	457	452	516	-	-
Romania	342	355	383	313	247	-28
Slovenia	596	513	494	490	449	-25
Slovakia	295	254	273	319	329	12
Finland	413	502	478	470	500	21
Sweden	386	428	477	439	447	16
United Kingdom	498	577	581	509	485	-3
Iceland	426	462	516	484	583	37
Norway	624	613	426	469	421	-33
Switzerland	600	656	661	708	725	21
Montenegro	-	-	-	-	533	-
The former Yugoslav Republic of Macedonia	-	-	-	351	-	-
Serbia	-	-	-	363	259	-
Turkey	441	465	458	407	400	-9
Bosnia and Herzegovina	-	-	-	332	-	-
Kosovo*	-	-	-	-	178	-
(:) not available						
(*) This designation is without prejudice to positions on status, and is in line with UNSCR 1244 and the ICJ Opinion on the Kosovo Declaration of Independence.						

Table 2.2.: Municipal waste landfilled, incinerated, recycled and composted in the EU-27, 1995 to 2015 (Eurostat, 2017).

Municipal waste landfilled, incinerated, recycled and composted in the EU-27																				
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	change (%) 1995-2015
million tonnes																				
Landfill	144	142	143	140	139	139	135	131	124	117	109	108	106	99	96	92	84	76	70	-58
Incineration	32	32	35	35	36	39	40	41	41	44	48	51	52	55	56	57	60	59	62	99
Recycling	25	28	32	35	40	40	42	46	47	49	52	54	59	60	61	62	64	65	65	176
Composting	14	16	17	18	19	24	24	26	26	28	29	31	32	35	35	35	35	36	37	184
Other	10	14	12	12	12	11	12	12	12	13	16	13	11	10	7	6	6	6	6	-35
kg per capita																				
Landfill	302	296	299	290	288	288	278	269	255	239	221	220	214	200	193	184	168	152	140	-60
Incineration	67	68	72	73	75	80	82	85	85	90	98	104	105	110	112	115	121	119	123	89
Recycling	52	59	66	72	82	83	88	95	97	99	105	109	119	120	123	125	129	131	129	161
Composting	30	34	36	37	40	49	50	53	54	57	59	62	64	71	70	69	69	72	74	166
Other	22	29	26	24	25	24	24	24	24	27	33	27	22	20	15	12	12	13	13	-38

More specifically, during the last 20 years, the total municipal waste landfilled in the EU-27 minimized by 58 %, from 144 million tons in 1995 to 61 million tons in 2015. In the period between 2005 and 2015, landfilling has diminished by as much as 5.6% per year on average, thus the landfilling rate compared with municipal waste generation, dropped from 64% in 1995 to 25% in 2015. Besides that, the amount of waste recycled increased from 25.0 million tons in 1995 to 69 million tons in 2015 at an average annual rate of 5.4% and the recovery of organic material by composting has also raised with an average annual rate of 5.4% for the same period. Waste incineration has also increased. Since 1995, the amount of municipal waste incinerated in the EU-27 has raised by 32 million tons and accounted for 64 million tons in 2015. Nevertheless, mechanical biological treatment (MBT) and sorting of waste are not covered directly as categories in the relative reporting of municipal waste treatment (Eurostat, 2017).

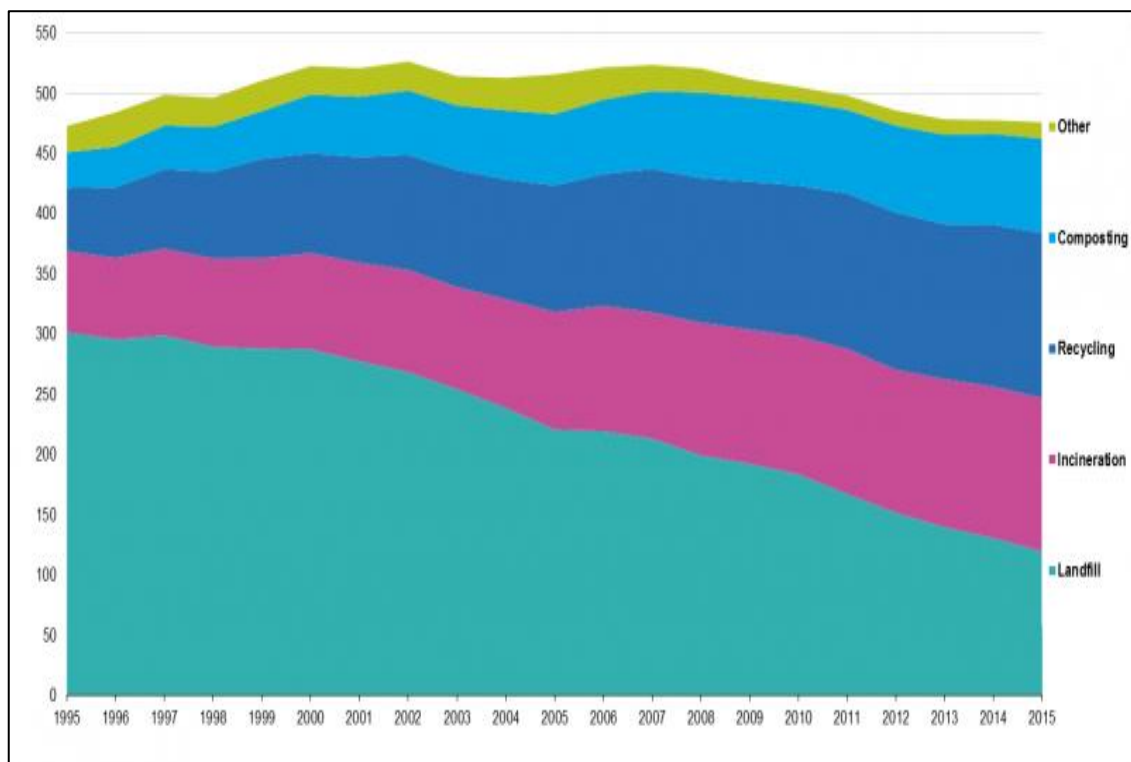


Figure 2.15.: Municipal waste treatment by type of treatment, EU-27, (kg per capita), 1995 – 2015 (Eurostat, 2017).

2.3.2. Waste management practices in Europe

However, waste management systems differ significantly between EU countries, as they are depicted in Figure 2.16., which outlines the volume of municipal waste

landfilled, incinerated, recycled and composted in 2015 as a percentage of the total waste treated. Some countries have highly developed their waste management system, thus their landfill rates are very low, sometimes below 5%. For instance, Switzerland, Germany and Sweden have landfill rates almost zero, whereas the same rate for Belgium, Denmark, Netherlands, Austria and Norway is below 5%. In contrast, as can be seen from Figure 2.16., there are many countries where landfilling is used as a basic treatment method for more than 50% of the total municipal waste treated. For example, Malta (93%) and Greece (84%) have the highest landfill rates in EU, and Romania, Croatia and Cyprus follow with the same bad performance regarding landfill of waste (landfill rate more than 80%) (Eurostat, 2017).

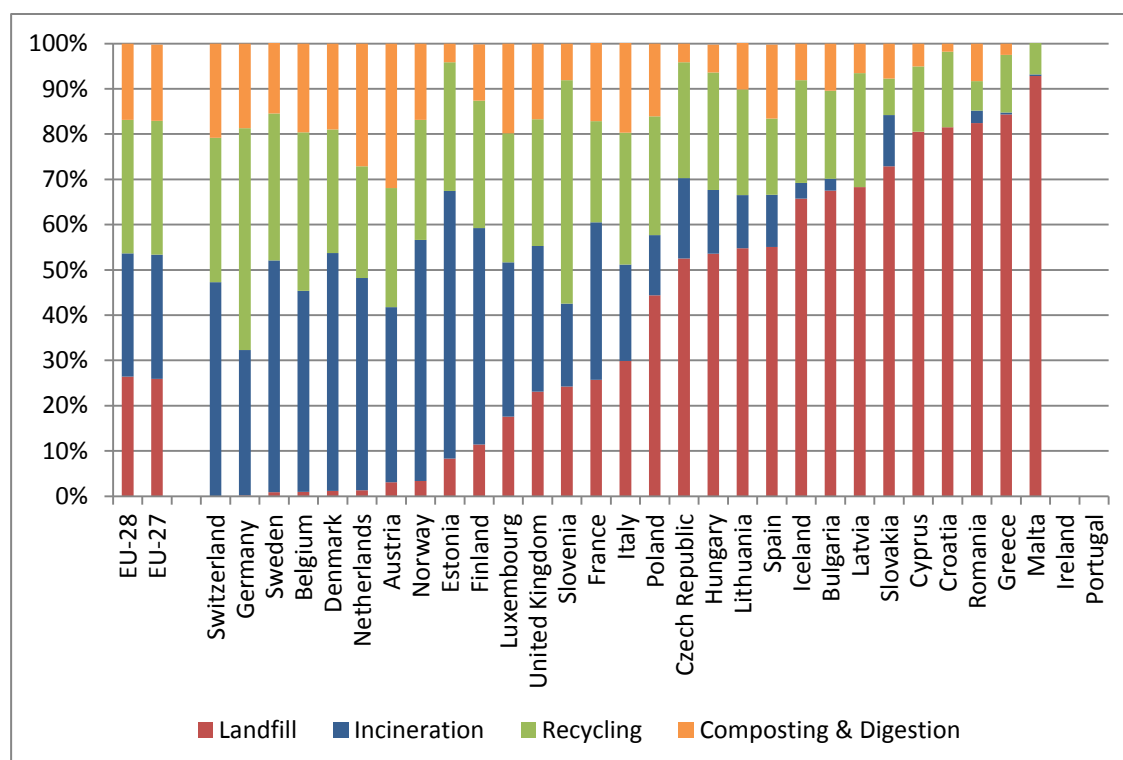


Figure 2.16.: Municipal waste treated in 2015 by country and treatment category, sorted by percentage of landfilling, (% of municipal waste treated), (Eurostat data, 2017).

The literature on municipal waste management shows a variety of examples on the approaches used by EU countries. To begin with, Bassi et al. (2017) and Gentil et al. (2009) indicate that *Germany* has minimal landfilling and its waste treatment is significantly based on recycling, whereas, it presents high levels of incineration and mechanical-biological treatment as well. Another example of low volumes of waste

disposed presented is *Sweden*. In Sweden, a ban on disposal combustible waste through landfilling has been implemented since 2002 (Eriksson et al., 2005), thus incineration method is widely used (Eriksson et al., 2005; Klavenieks and Blumberga, 2017). In 2005, 22 incineration plans were in use and another 20 were designed (Eriksson et al., 2005), however, an incineration tax was introduced in order the amount of waste recycling to grow (Klavenieks and Blumberga, 2017).

Together with Sweden, *Denmark* is another country where waste is managed mainly by incineration methods with energy recovery (Bassi et al., 2017; Gentil et al., 2009). As Kirkeby et al. (2006) observe, in municipality of Aarhus, municipal solid waste was separated with an optical sorting facility which uses green bags for organic waste and black ones for inorganic, whereas glass and paper are separately collected. As a result, for the major volume of waste incineration and anaerobic digestion are used, as well as paper and glass are brought to Material Recovery Facilities (MRF).

Moreover, landfill rate is below 5% in *Netherlands*. This results from the country's two major waste policies: landfill tax and landfill ban. In 1996, landfill tax was implemented and until 2011 it was increased to 108 EUR/t for waste suitable for incineration and 16 EUR/t for waste that is not suitable for incineration (Klavenieks and Blumberga, 2017). Besides that, a landfill ban put into practice and as Klavenieks and Blumberga (2017) indicate in 2014 the ban policy was applied for 64 waste categories. Similarly, *Norway* reported very low volumes of landfill waste. As mentioned by Slagstad and Brattebø (2012), landfill of organic waste was banned in 2009, although the country's waste police has been based on waste hierarchy since 1990's. An example presented by Slagstad and Brattebø (2012) is Trondheim, where incineration with heat recovery is the main waste management system. More specifically, approximately 200.000 tons of waste are treated every year in the incineration plans, and at the same time, paper, plastic, glass and metal are taken to MRF. Furthermore, another country with relatively low landfill rate (11%) and one of the highest incineration rates (53%) is *Finland*. An example of waste incineration in Finland is demonstrated by Liikanen et al. (2017). They describe municipal waste treatment in South Karelia, a region in South-East Finland, where all mixed municipal waste is incinerated, despite the fact that

incineration in the region started only in 2013 and until then all waste generated was landfilled.

Nevertheless, there are many other countries in EU which do not achieve Landfill Directive's target to reduce landfill to maximum of 10% of total municipal waste by 2030, even though their landfill rate does not exceed 50%. Such examples are UK (23%), France (26%) and Italy (30%). More specifically, as Gentil et al. (2009) observed, in 2009 *France* used almost equally landfilling, incineration, recycling and composting methods, and it continues to follow the same waste policy in 2015 (Eurostat, 2017). In *UK* case, Jeswani and Azapagic (2016) indicates that the landfill tax which was imposed and increased to £82.6 in 2015, helped UK to limit the volume of MSW disposed of by landfill. Incineration is the waste treatment methods that is more used thus, in the country there are 25 MSW incinerators with energy recovery, most of which generate electricity (Jeswani and Azapagic, 2016). In *Italy* approximately 30% of the total municipal waste is disposed of by landfill, although many studies (Bassi et al., 2017; Guerrini et al., 2017) are documenting that landfilling is the basic waste treatment method thus resulting many waste mismanagement issues (Chifari et al., 2017). A particular example is the case of Naples in Campania Region in the Southern Italy, where illegal waste activities led to a waste crisis in the area in 2008 (Hornsby et al., 2017). Waste facilities in Campania Region generally involve: 7 MBT plants, a Waste-to-Energy plant, two operational landfill sites, many storage and sorting platforms and recycling plants (Ripa et al., 2017) and the major MSW management technology used in Naples is Mechanical Biological Treatment (Hornsby et al., 2017). Hornsby et al. (2017) have found that MSW collected is processed in MBT plants, and around 40% of them transfer in landfills, whereas 38% follow incineration process.

Unfortunately, there are 13 countries within EU where landfilling is the dominant waste management option for more than 50% of the total municipal waste. Among them are: Lithuania (55%), Spain (55%), Latvia (68%), Romania (82%). In case of Baltic countries - *Estonia, Latvia and Lithuania*- there are many differences in waste management practices. In the literature, there are references (Filho et al., 2016; Klavenieks and Blumberga, 2017) on waste management systems developed after 2004, when Baltic countries became members of the European Union. Since 1990's

waste management in these countries changed a lot, due to the implementation of the EU Directive. In contrast to the countries of Scandinavia and Central Europe, none of the three countries have initially chosen the most developed practices, such as incineration (Filho et al., 2016; Klavenieks and Blumberga, 2017). Instead, they started from closing all the old dumpsites until 2009 and replaced them with new sanitary landfill sites according to the European standards. However, waste management differs between the three countries, for instance in Lithuania and Latvia regional principals are responsible for waste management, whereas in Estonia it depends on the private sector (Filho et al., 2016). As reported by Filho et al. (2016), Estonia is an example of good practice, since it achieved within 3 years to minimize waste landfilling less than 10%, mainly due to high landfill tax as well as a landfill ban of unsorted municipal waste. On the contrary, Lithuania has not introduced the landfill tax and consequently, it has low landfill fees thus making recycling actions more difficult (Filho et al., 2016). All in all, according to Filho et al. (2016), the main processes that are used in those countries are the mechanical biological treatment and mass-burn waste incineration.

Despite the fact that Eurostat data for waste treatment in *Portugal* in 2015 is not available, Herva, Neto and Roca (2014) studied Portugal's case and show that landfilling is the most preferred option as well, with the landfill rate be 58% in 2011. Although landfill appeared to be the predominant alternative at national level, in cities like Porto and Lisbon most of the municipal waste is thermal-treated (Herva, Neto and Roca, 2014). Nevertheless, Portugal has not achieved Waste Framework Directive and its targets yet. Finally, one of the countries with the worst performance is *Romania*, where more than 82% of waste is disposed of in landfills. In a recent paper by Căilean and Teodosiu (2016), landfill seems to be the main waste treatment process, while none Waste-to-Energy facilities exist for MSW.

2.3.3. Waste management practices in Greece

As it is already mentioned, municipal waste management in Greece is not as developed as in other European countries. Thus the landfill rate is equal to 84% and one of the highest in EU, whereas only 13% of the total volume of municipal waste generated is

recycled (Figure 2.16.). Besides that, not much concern is given to landfill options combined with energy recovery (Koufodimos and Samaras, 2002). Papachristou et al. (2009) showed in their study that 52% of the disposed waste is transported to sanitary landfills, while the remaining is disposed in non-engineered dumpsites. Also, in the same study they indicate that the majority of household waste is organized collected and disposed, and only in mountainous and island areas these activities are not performed in a proper way.

Nevertheless, many waste reduction programs, as well as recycling and energy recovery ones have been put into practice, in order an integrated solid waste management policy to be developed (Erkut et al., 2008). In the literature there are references in the case study of Thessaloniki, the second largest city in Greece, where landfill treatment is a predominant option as well. Koroneos and Nanaki (2012) indicate that all of the municipal waste generated is disposed to Tagarathes landfill site, an area located in the surroundings of the city. Also, Papachristou et al. (2009) studied the composition of those amounts of MSW and showed that they include a significant amount of packaging and other recyclable materials, thus even more recycling programs for recovering of materials such as paper, plastic, glass and metals should be implemented.

2.4. LITERATURE REVIEW

As mentioned above, previous studies indicates that municipal waste management is a major concern for European countries and one of the most challenging issues facing Greek authorities. Until recently, there were many unlawful landfills in breach of the Waste Framework Directive, for which Greece has been found guilty by the European Court of Justice since 2005. Moreover, from 5.575.00 tons of MSW generated in 2011, 78.2% sent to sanitary landfills, 4.8% to uncontrolled landfills disposal, 14.9% was recycled, 2.8% composting, and only 0.3% used for energy recovery. Similarly, in the Region of Central Macedonia, in 2012, 859.100 tons of waste was produced and more than 50% were disposed either in Sanitary Landfills (667.563 tons) or in uncontrolled landfills (23.365 tons). At the same time, the recycling rate in the Region was 15.98%, whereas in the Region of Attica the same rate was 38.4%.

Therefore, the current NWMP focuses on minimizing significantly the generated waste and reusing and recycling more than 50% of the total MSW. Also, the implementation of waste treatment methods with energy recovery is recommended, while landfill should be limited to less than 30% of total waste and considered only as a final treatment option. On this basis, the existing RWMP of Region of Central Macedonia was revised and an optimal waste management plan developed in the area.

CHAPTER 3

**AN INTEGRATED METHOD FOR THE OPTIMAL WASTE MANAGEMENT:
THE CASE STUDY OF REGION OF CENTRAL MACEDONIA**

During the last decades, Life Cycle Assessment (LCA) methodologies are more and more used in the MSW management, as they offer a useful tool which helps the decision-making of a waste management policy by evaluating and comparing the environmental impacts of the various waste management systems. In the case study of the Region of Central Macedonia an LCA assessment is applied to significant municipal waste stream and focuses on all possible alternatives of MSW management strategies, according to the up-to-date RWMP.

3.1. METHODOLOGICAL FRAMEWORK**3.1.1. Data Collection**

All the necessary data utilized in this study is compiled from the Regional Waste Management Plan of the Region of Central Macedonia (RWMP). The RWMP is an integrated waste management plan which establishes the general guidelines for the waste management in a Region, based on the National Waste Management Plan and the National Waste Prevention Plan, and suggests appropriate measures to promote

solutions in accordance with waste hierarchy concept. According to Regional Waste Management Plan of Central Macedonia, the data on waste generation that used originate from the following sources (RWMP, 2016):

- Measurements of the Regional landfills in operation,
- Questionnaires sent to the Local Authorities of the Region,
- Existing studies related to waste management projects in the study area,
- Various waste competent authorities.

3.1.2. Life Cycle Assessment

As it was mentioned in the previous chapter, municipal waste management is an issue of great concern due to its significant environmental and human health impacts. Consequently, waste policies have been developed and improved waste regulatory frameworks have been implemented. However, as Ripa et al. (2016) indicate new waste facilities are not established since public acceptance is very low, especially due to worries on adverse impacts. Within this context, it is necessary a suitable environmental assessment method to be applied to the whole life cycle of waste, from waste generation until the final treatment and disposal (Milutinović et al., 2017), thus leading to MSW management policies that follow the waste hierarchy as well as the general sustainability concept (Ripa et al., 2016).

This approach, known as Life Cycle Thinking, has been recommended by the Commission of the European Communities: "All phases in a resource's life cycle need to be taken into account as there can be trade-offs between different phases and measures adopted to reduce environmental impact in one phase can increase the impact in another. Clearly, environmental policy needs to ensure that negative environmental impact is minimized throughout the entire life cycle of resources. By applying the life-cycle approach, priorities can be identified more easily and policies can be targeted more effectively so that the maximum benefit for the environment is achieved relative to the effort expended." (Milutinović et al., 2017). Therefore, Life Cycle Assessment (LCA) method should be implemented according to European Commission (Milutinović et al., 2017), since it provides a tool within whose framework various municipal waste treatment approaches can be evaluated by quantifying all

their impacts, thus resulting to the selection of the best policy for controlling municipal waste (Ripa et al., 2016).

LCA is an assessment method, which can be applied to determine the entire environmental impact of a product or system over its entire life. Since 1995, LCA has been used for evaluation of waste management practices, and the implementation of the ISO 14044 standards for LCA methodology globally, as well as the introduction of EU Waste Framework Directive (EU Directive 2008/98/EC) led to an increase in LCA applications in municipal waste management sector after 2008 (Laurent et al., 2014). Moreover, previous research on the evaluation methods, which are used on waste management sector, has demonstrated that around 40% of reviewed articles are life cycle assessment-based (Milutinović et al., 2017).

Consequently, in recent years, the use of LCA method has become very popular, as several publications have been appeared documenting LCA use for the evaluation of various scenarios of municipal waste management practices in a wide range of countries across Europe. For instance, they include: Serbia (Milutinović et al., 2017), Spain (Bovea et al., 2010; Fernández-González et al., 2017; Fernández-Nava et al., 2014), Portugal (Herva et al., 2014), Italy (Cherubini et al., 2009; Hornsby et al., 2017; Ripa et al. 2016), UK (Evangelisti et al., 2015; Jeswani and Azapagic, 2016), Norway (Slagstad and Brattebø, 2012), Sweden (Eriksson et al., 2005), Denmark (Kirkeby et al., 2006; Bassi et al., 2017).

3.1.2.1. LCA methodology

The LCA methodology started in 1970s, when the first “net energy analysis” studies were published. As reported by Koroneos and Nanaki (2012), initially the researchers took into account only energy use over the life cycle of a product or a process and later, wastes and emissions were included as well. In order a reliable and complete framework to be developed, the Society of Environmental Toxicology and Chemistry and the International Organization for Standardization (ISO) created in the 1990s a LCA methodology (Standard ISO 14040), which was revised in 2006 and a new standard ISO 14044 was finally presented (Koroneos and Nanaki, 2012).

According to this ISO Standard, LCA methodology is an internationally standardized process, which helps to assess the environmental burdens of a product or procedure. It is defined as an objective method, which identifies and quantifies energy and material used as well as waste released to the environment over the entire life cycle of a product, process, or activity and evaluates and implements opportunities for achieving environmental improvements (Cherubini, Bargigli and Ulgiati, 2009; Ec.europa.eu, 2017).

In particular, LCA is a rapidly developed systems analysis tool (Finnveden, 1999), which takes into account significant environmental and human health impacts occurred from raw material acquisition to production, use and disposal and focuses not only to material products, but also to services such as waste management systems (Milutinović et al., 2017). Many relevant guidelines have been developed, with ISO 14040 Standard be the most popular among them (Finnveden, 1999). According to this, the most important impact categories, which should be taken into account, are: resource use, human health, and ecological considerations (Milutinović et al., 2017). A typical LCA study, as it is described by the ISO 14040 series, is implemented in 4 phases: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA), interpretation of the results (Figure 3.1.).

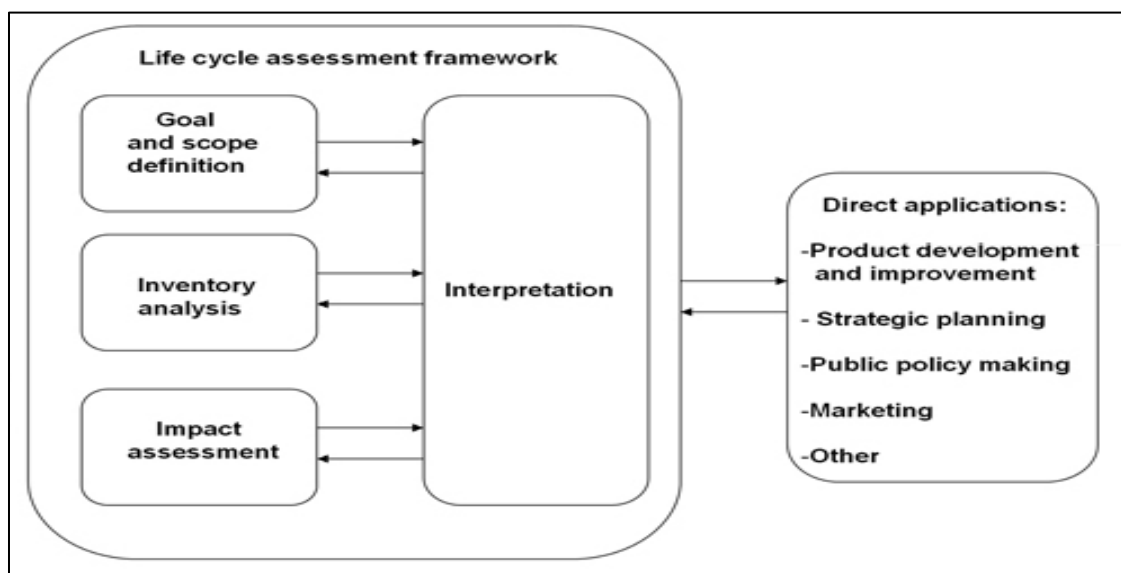


Figure 3.1.: The four stages of a Life Cycle Assessment, as defined by ISO 14040 (ISO 14040:2006).

3.1.2.1.1. Goal and scope definition

At the beginning, in the “Goal and scope definition” phase, the aim of the study is established. It is a guide referred to throughout process ensuring that it remains consistent to the defined aim. More specifically, the purpose and the extent of the LCA study should be formulated. This requires definition of intended applications and audience, reasons for carrying out the study, critical review and other procedural aspects. Besides that, the functional unit, reference flows, system boundaries and impacts of interest are also established (ISO 14040, 2006; Milutinović et al., 2017).

The functional unit is a unit, which describes the performance characteristics of the products and enables the comparison of LCA results on the basis of an equivalent function. Also, the system boundaries define which processes are included or excluded from the system which is studied (ISO 14040, 2006). More specifically, the boundaries of the assessed system should make sure that all the relevant processes and their environmental effects are included, in order to minimize the risk of wrongly burden one part of the life cycle (Laurent et al., 2014).

3.1.2.1.2. Life Cycle inventory Analysis (LCI)

The second phase is life cycle inventory analysis, which is considered to be the most time-consuming and resource-demanding part of a LCA assessment (Laurent et al., 2014). In this step, all components that fall within the defined system boundaries are identified. It also involves the compilation and quantification of inputs and outputs flows for the given system. Data that is collected referred to raw materials, manufacturing processes, transports, use and waste management and includes material inputs, products, by-products, waste, air and water emissions. Then, the analysed system is modeled and the amount of each requirement is calculated in relation to the functional units. The resulting LCI provides a breakdown of all the energy and materials involved to the processes and operations making up the life cycle (ISO 14040:2006; Milutinović et al., 2017; Laurent et al., 2014). Together with manufacturing processes, transportation must be included as well as manufacture and disposal of plant and equipment (Milutinović et al., 2017).

3.1.2.1.3. Life Cycle Impact Assessment (LCIA)

Once a detailed inventory analysis is developed, environmental impacts are assigned to each component of the product system. These included in the phase of Life Cycle Impact Assessment, which aims at understanding and evaluating the significance and magnitude of the potential impacts of the system (ISO 14040:2006; Milutinović et al., 2017). According to the ISO 14040 Standard, LCIA process involves the following steps:

- Selection and definition of impact categories, category indicators and characterization models,
- Classification, which includes assigning specific environmental impacts to each component of the LCI, and
- Characterization, which entail the conversion of the LCI results into directly comparable impact indicators with the aid of characterization factors.

There are also two voluntary steps to the LCIA process: normalization and weighting. Normalization refers to normalizing the impact assessment by scaling the data by a reference factor, thus enabling the comparison between different impact categories. Weighting evaluates the importance of the various impact categories by converting and possibly aggregating indicator results across impact categories using numerical factors (ISO 14040, 2006).

3.1.2.1.4. Interpretation

Finally, interpretation phase occurs. In this step, all the information used by, and resulted from the LCI and LCIA phases is clarified, quantified, checked and evaluated and then combined with the goal and scope of the study in order to reach conclusions and recommendations (ISO 14040:2006; Milutinović et al., 2017).

3.1.2.2. SimaPro Software

Nowadays, there is a vast variety of software tools that can be used for modeling and analyzing MSW systems and their environmental performance. Laurent et al. (2014) reviewed 222 LCA studies of solid waste management systems. The distribution of the software used in the reviewed studies (Figure 3.2.) showed that SimaPro is one of the most popular LCA software used in waste management studies (Laurent et al., 2014).

The SimaPro software is an LCA tool, which has been developed in accordance with ISO 14040 series standards. It is used by industries, consultancies, and educational institutes in more than 80 countries in order to collect, analyze and monitor the sustainability performance of products, processes and services. Also, it enables the measurement and evaluation of environmental impacts throughout the life cycle, from extraction of raw materials to manufacturing process, use, and final disposal. SimaPro software can be used for various applications, such as: sustainability reporting, carbon as well as water footprint calculation, products' eco-design, Environmental Product Declarations (EPD), Determination of key performance indicators (KPIs) (SimaPro, 2017).

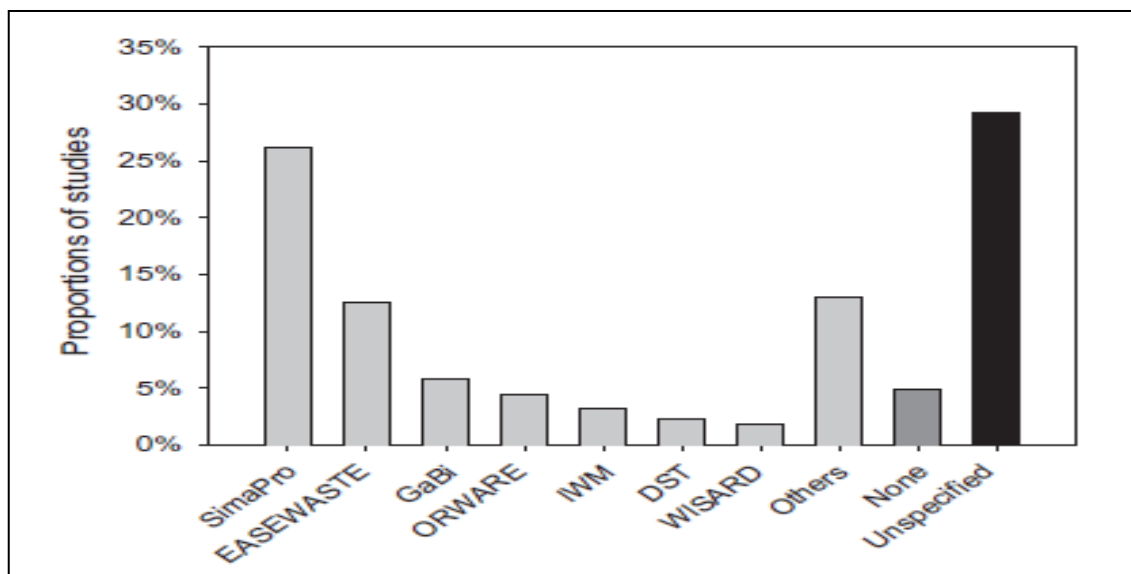


Figure 3.2.: LCIA methods used in total of 222 reviewed studies related to solid waste management (Laurent et al., 2014).

3.1.2.3. LCA implementation in MSW

The complete life cycle of municipal solid waste is depicted in Figure 3.3. More specifically, the stages of MSW management that fall into the life cycle are (Abeliotis, K., 2011; Eedsa.gr, 2017; Papadimitriou, 2014):

- Waste generation,
- Waste collection, either via mixed-bags or separate collection at source, using special collection vehicles,
- Transportation initially to a transfer station in order waste to be storage temporarily until transferred to a permanent disposal site, and then

another transportation stage follows in which mixed waste goes to the landfill site, whereas source-separated waste goes to a material reclamation facility in order the different types of materials to be sorted,

- Separation, treatment and physical, chemical or biological conversion of solid waste with the use of the appropriate equipment and processes,
- Final disposal.

Even though the life cycle of MSW does not seem to be too complicated, the implementation of a LCA analysis is considered to be demanding. Literature on application of LCA indicates that there are more challenges when LCA deals with MSW management systems than applied to traditional products. And that is because, results are based on few waste treatment procedures whose impacts are significantly affected by the local conditions (Laurent et al., 2014). Some of these challenges are analyzed in the following.

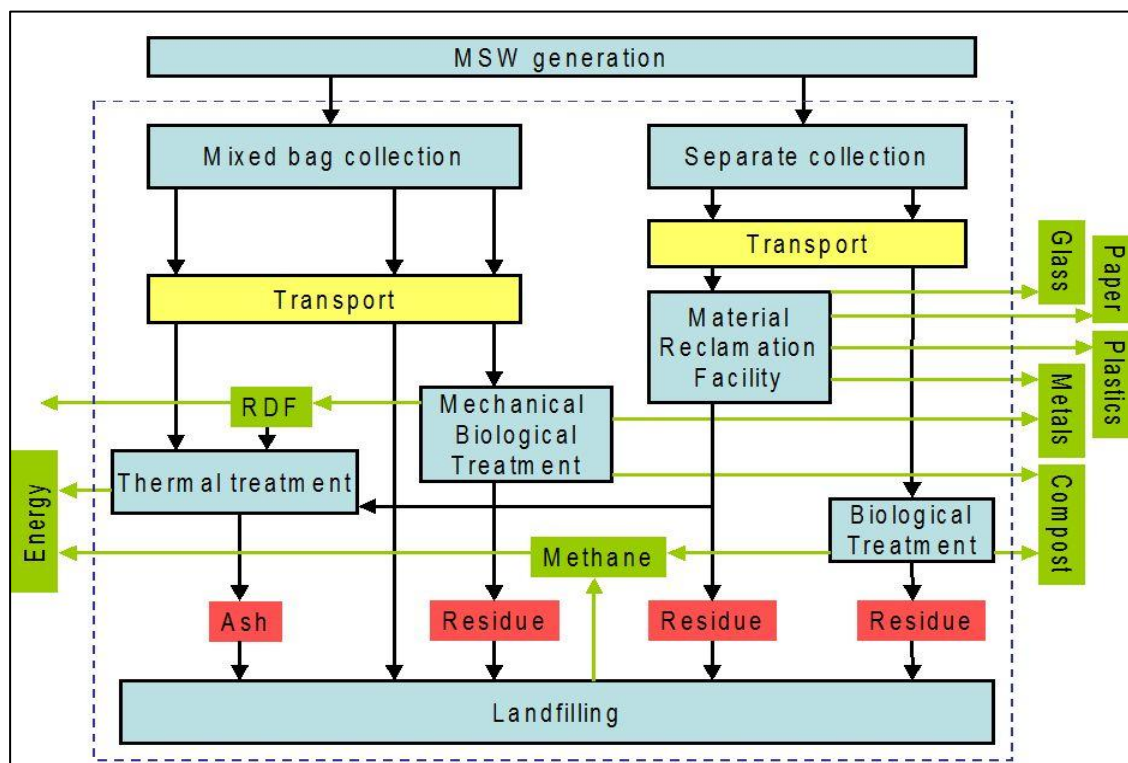


Figure 3.3.: The life cycle of municipal solid waste (Abeliotis K., 2011).

Initially, one major challenge is the definition of the system boundaries that may results a very large and complicated system. In contrast with the common LCA systems, in LCA of waste management systems neither the inputs do not originate from the environment without prior human change, not the outputs are disposed of to

the environment without further human transformations. Instead, the inputs are usually waste as being generated, for instance from municipal waste or households, and the outputs, such as materials or energy are recycled and transformed into new products, which are usually not disposed but reused (Finnveden, 1999). Besides that, as Abeliotis (2011) indicates, although solid waste management facilities “produce” some useful products, for example sorts of paper or glass, fertilizer substitutes, solid fuels, electricity and heat, they are not considered to be environmentally friendly like any other single waste management system as they require non-renewable natural resources in order to operate and release various air pollutants and leachates.

Furthermore, time aspects lead to many uncertainties related to the time frame of the impacts. More specifically, in the case of landfilling, which is the most popular waste treatment method, emissions are considered to be long-lasting and affect the environment for thousands of years or more (Abeliotis, 2011; Laurent et al., 2014; Finnveden, 1999). Thus, a certain time period, either a limited (100 years) or an infinite time horizon (Laurent et al., 2014), must be defined in order to enable a comparison between potential emissions from landfilling and other emissions throughout the life cycle (Laurent et al., 2014; Finnveden, 1999).

Moreover, there are allocation issues in case of the mix of different waste materials. As Finnveden (1999) demonstrates when only one of the fractions of solid waste and its emissions need to be analyzed, there is a difficulty to allocate the emissions between the various waste materials that have already been treated. Also, in an LCA, it is not possible to know the exact time and place that the emissions take place, and consequently, only potential impacts can be predicted (Finnveden, 1999). Finally, the high quality of data related to the waste composition is another challenging factor, since the lack of it may lead to significant uncertainties in the final results (Abeliotis, 2011; Laurent et al., 2014). Consequently, LCA of solid waste management systems must be accurately modeled.

3.2. THE CASE STUDY OF THE REGION OF CENTRAL MACEDONIA

As it is already mentioned, municipal solid waste management represents one of the most critical issues that need to be addressed by Greek authorities. On this basis, the

development of an optimal waste management strategy is more than urgent in the area. Thus, an integrated waste management framework has been established and the existing Regional Waste Management Plan (RWMP) for the Region of Central Macedonia has been revised in accordance with the waste legislation. The current study focuses on the environmental impacts caused by the existing waste management system in the Region of Central Macedonia and the comparison of alternative scenarios regarding MSW management in the area.

3.2.1. Description of the geographic area under study

Greece consists of 13 administrative regions, which are further subdivided into 54 prefectures. This dissertation is focused on the management of municipal waste in the Region of Central Macedonia, which is located in North Greece and consists of the central part of the geographical region of Macedonia (Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε..). The region has the largest surface area (18.811km²) among all regions, and it is divided into seven prefectures: Thessaloniki, Imathia, Pella, Kilikis, Pieria, Serres and Chalkidiki, as shown in Figure 3.4. These are further subdivided into 38 municipalities.



Figure 3.4.:
Administrative
Region of Central
Macedonia in North
Greece and its
seven prefectures:
Pieria (1), Imathia
(2), Pella (3), Kilkis
(4), Thessaloniki (5),
Chalkidiki (6), and
Serres (7).

Also, it is the second most populous region (1.882.108 habitants) after Attica, with intense urbanization and a high density of inhabitation, especially in Thessaloniki and its metropolitan area, which is the capital of the region. Thessaloniki' population is about 59.01 % of the total region's population. The second most populous city is Serres, with Katerini, Veria and Giannitsa following. The population of each regional unit is illustrated in Table 3.1.

Table 3.1.: The distribution of population in Region of Central Macedonia.
[Source: RWMP, 2016]

Prefecture	Population (2011)	% of the population of RCM
Thessaloniki	1.110.551	59,01
Imathia	140.611	7,47
Pella	139.680	7,42
Pieria	126.698	6,73
Kilkis	80.419	4,27
Serres	176.430	9,37
Chalkidiki	107.719	5,72
Region of Central Macedonia	1.882.108	100,00

With regards to the economic activity of the area, people in the RCM are employed in the primary sector at 12%, in the secondary (manufacturing) sector at 20% and in services sector at 68% (RWMP, 2016). Particularly, the primary sector remains quite significant for the local economy, as a high proportion of arable and irrigated areas is noticed. In Central Macedonia basic products of Greek agriculture are produced, including peach, cotton, tobacco, asparagus, as well as cereals, industrial and aromatic plants, peach and tomato products. Additionally, it is observed a relatively high degree of mechanization and organization of animal farming. Regarding the manufacturing sector, it is dominated by food industry, textiles, non-metallic mineral products and furniture, as well as tobacco industry. Finally, relatively to the service sector, financial services, transport, communications and tourism, education and research are highly developed.

Concerning the environmental characteristics of the region, the natural environment of Central Macedonia displays a significant number of ecosystems and isolated

elements, of environmental and ecological value. More specifically, the Region of Central Macedonia is located in one of the most eco-sensitive zones of the Mediterranean basin. It includes cross-border mountain ranges, ecosystems of great importance and rivers, as well as wetlands and extensive coastal areas that are under protection.

3.2.2. MSW Management in the study area

In the Region of Central Macedonia 842.490 tons/year of waste was generated in 2014, according to up-to-date RWMP (2016), from which 82% ended up to Sanitary Landfills. In general, the composition of MSW depends on the socioeconomic conditions and the various consumption patterns in the area. However, in the specific study, a typical average composition of the waste is used, in accordance with the data available in RWMP. The fractions of MSW included in the study are: the total amount of household organics, paper, plastic, metals, glass, wood, other recoverable such as batteries and household appliances, as well as other unclassified materials including also hazardous waste like textiles, inks, medicine. The composition of total municipal waste in the Region of Central Macedonia is depicted in Figure 3.5., whereas, Table 3.2. illustrates the allocation of each fraction in the different prefectures.

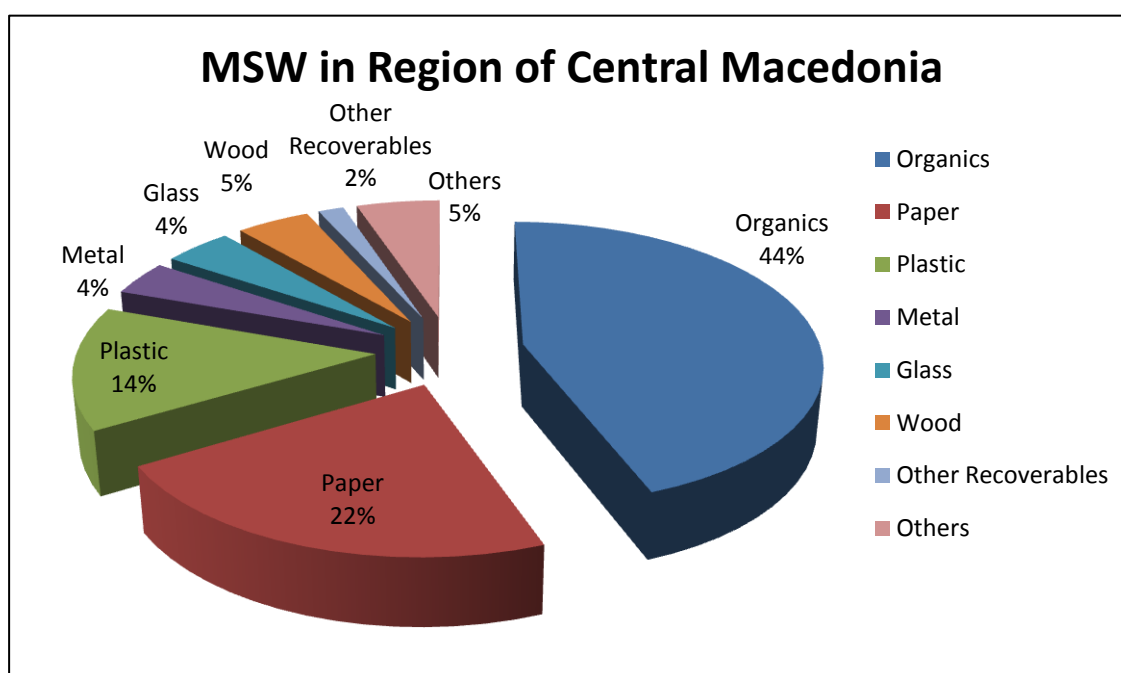


Figure 3.5.: Typical composition of total MSW in Region of Central Macedonia (RWMP, 2016).

Table 3.2.: Allocation of different fractions of MSW for the seven prefectures of the Region of Central Macedonia for the year 2014 (tons) (RWMP, 2016).

MSW Fraction	Thessaloniki	Imathia	Kilkis	Pella	Pieria	Serres	Chalkidiki	RCM
Organics	219.913	23.720	16.412	23.849	26.919	30.299	32.112	373.224
Paper	110.205	11.887	8.224	11.951	13.490	15.184	16.092	187.033
Plastic	69.002	7.443	5.150	7.483	8.446	9.507	10.076	117.107
Metal	19.360	2.088	1.445	2.100	2.370	2.667	2.827	32.857
Glass	21.346	2.302	1.593	2.315	2.613	2.941	3.117	36.227
Wood	22.835	2.463	1.704	2.476	2.795	3.146	3.334	38.753
Other Recoverables	7.943	857	593	861	972	1.094	1.160	13.480
Others	25.814	2.784	1.926	2.799	3.160	3.557	3.769	43.809
Total	496.418	53.544	37.047	53.834	60.765	68.395	72.487	842.490

According to current Regional Waste Management Plan, except for sorting at the source of packaging waste and some other streams such as batteries and WEEE, all municipal waste of the Region of Central Macedonia is sent to landfills. More specifically, 82% of MSW are disposed directly to landfills, whereas only 12% are sorted at the source.

Region of Central Macedonia still has not implement a MSW system which includes advanced waste treatment methods. At present, the region's waste management involves mainly the collection and disposal of waste in the landfill. The current situation in the prefectures of the region is such that initially, municipal waste, that is temporarily storage into bins or containers, is collected by a public company using waste collection vehicles and then transported in Waste Transfer Stations (WTSs). Collection of waste can be either in mixed bags, which is the most widely applied technique, or in separate bins, which help the successful material recovery and recycling. At WTSs the waste is loaded up in larger, special vehicles, suitable for long-distance traffic, which transport the waste to a landfill. At the same time, waste streams such as paper, glass and packaging waste, are separately collected in special bins and collection vehicles transport them in Material Recycling Facilities (MRFs).

As far as bio-waste is concerned, in the RCM no separate collection program is implemented, with the exception of diversion in rural areas for the purpose of animal feeding and on-site composting, as well as pilot composting programs and programs for the collection of cooking oil and grease waste in some schools of the region, that send it in a recycling company that converts it into an alternative fuel, biodiesel. Also, WEEE in almost all municipalities, are collected by private companies and led to processing plants. More specifically, in the Region of Central Macedonia, two WEEE plants and one facility for the temporary storage of lamps and other appliances operate. Besides that, the collection and recycling of batteries is taken place by the company AFIS, whereas the processing of portable batteries is mainly done at 2 recycling and processing plants abroad, Belgium and Romania (RWMP, 2016).

Moreover, bulky waste is collected by the Municipalities' Cleanup Department. In the majority of the municipalities of RCM, after the collection, it is sent mainly direct or after shredding disposal in landfills or dispatch to private companies. In some cases, the collected waste is sent to a construction site where manual sorting is carried out. If something useful is found, it is promoted for re-use, with the rest being driven for burial in the landfill. Similarly, management of garden waste includes segregation and disposal in landfills, since in most of the municipalities of RCM there is not organized system for collection and management of green waste (RWMP, 2016).

3.2.3. Scenarios' description

With the intention to examine and outline the benefits and drawbacks of the techniques used on municipal solid waste management, diverse MSW strategies have been analyzed. The differentiation of those strategies are based on the variations of the waste flows in comparison to the different waste control methods, such as landfill, recycling, anaerobic digestion and others. Brief descriptions concerning the study system follow. For every strategy, a base scenario has been described, in order to specify the parameters and effects of each method.

The alternative practices were developed based on the targets set by the Regional Waste Management Plan and the EU Directive, as well as the various waste treatment methods and represents the various possible MSW strategies that can follow the

municipal waste generation. With the core of conventional waste treatment methods and the final disposal in landfills, the different strategies focuses on reuse and recycling most of MSW, as well as on energy recovery. More specifically:

- *Scenario 0*: the main treatment of this scenario is landfilling without energy recovery,
- *Scenario I*: the main treatment of this scenario is landfill with energy recovery. This scenario corresponds to the current situation in the Region of Central Macedonia, and apart from landfilling includes small percentages of recycling of some MSW fractions,
- *Scenario II*: the main waste treatment of this scenario is recycling and material recovery. This scenario involves the future regional waste management plan and incorporates the future targets that must be completed according to the European Directive.

3.2.3.1. Scenario 0: Landfilling

Scenario 0 represents the most popular until recently waste treatment method in Greece, landfilling. It assumes that the all the municipal waste generated is collected and transferred to Waste Transfer Stations (WTS). Then, without a process of separation of the produced waste, MSW is sent to regional landfill sites, where it is disposed without energy recovery to take place (Figure 3.6.).

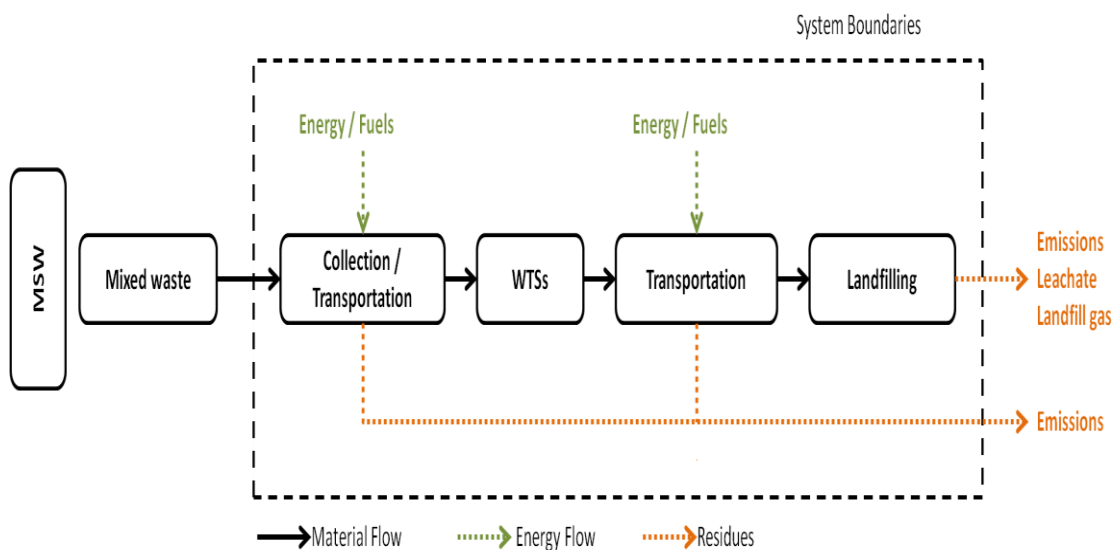


Figure 3.6.: System boundaries for Scenario 0.

3.2.3.2. Scenario I: Landfilling and Recycling

Scenario I models the basic scenario that corresponds to the present situation in the Region of Central Macedonia. 694.873 tons (82%) of municipal waste are sent to landfills, whereas only 147.617 tons (18%) of waste are separated collected as shown in Table 3.3. According to RWMP and the existing recycling facilities in the Region, recyclable waste fractions in the amount of 103.213 tons are recycled, which represents only 12% of the total waste amount, as illustrated in

Table 3.4. At the same time, around 5% of the waste sorted at the source is composted at home facilities, and 1% is sent for reuse.

Table 3.3.: Current waste management system in Region of Central Macedonia (Scenario I) (RWMP, 2016).

MSW Fraction	Total Amount Generated	Mixed Collection (tons / % of the total)		Sorting at the source (tons / % of the total)	
Organics	373.224	338.481	91%	34.743	9%
Paper	187.033	270.011	72%	103.213	28%
Plastic	117.107				
Metal	32.857				
Glass	36.227				
Wood	38.753	36.760	95%	1.993	5%
Other Recoverable	13.480	5.811	43%	7.669	57%
Others	43.809	43.809	100%	0	0%
Total MSW	842.490	694.872	82%	147.618	18%

Table 3.4.: Allocation of the amounts of MSW per waste treatment method in Scenario I.

Scenario I		
Waste treatment Method	MSW (tons / % of the total MSW amount)	
Landfilling	694.872	82%
Recycling	103.213	12%
Composting	36.736	5%
Reuse	7.669	1%
TOTAL	842.490	100%

In this scenario (Figure 3.7.), a typical dry MRF process is taken into account. The waste streams that are assumed to represent the recycling streams at MRF are: glass, metals, mixed papers and mixed plastics. After separation, a part of those materials sent to the MRF will be rejected and disposed to a landfill site. In this scenario the reject rate for all streams is 35,50% (Table 3.5.).

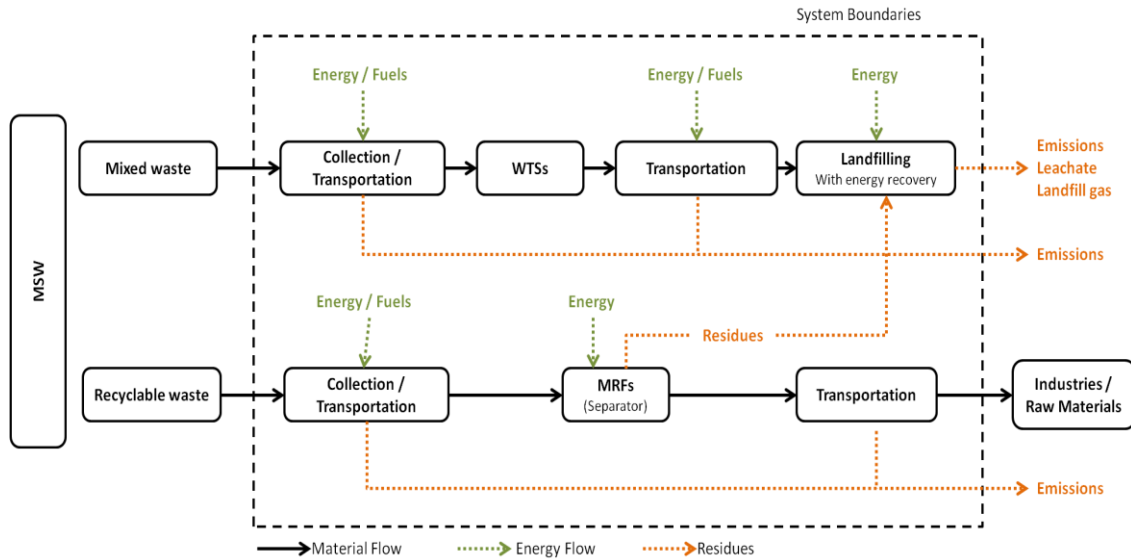


Figure 3.7.: System boundaries for Scenario I.

Table 3.5.: Qualitative composition of recyclable waste according to the existing recycling facilities in the Region of Central Macedonia (RWMP, 2016).

Qualitative composition of recyclable waste	
Waste Fraction	% in Recyclable waste
Paper	45,00 %
Plastic	12,00 %
Aluminum	0,50 %
Iron	2,00 %
Glass	5,00 %
Residuals to landfills	35,50 %

Waste collected by mixed collection system, of 694.872 tons, is landfilled. The landfill gas which is produced is collected and used in order to generate electricity. Its typical composition is: 50% CH₄, 45% CO₂, 5% N₂, <1% O₂, 21 ppmv H₂S, 2,700 ppmv non-methane organic compounds (NMOC) and usually 1-10% water vapor (H₂O), and thus, in the current study the landfill gas produced contains: 53% of CH₄ and 47% of CO₂ (Latsios et al., 2009). Every year, a methane production of 4,5m³/t of landfilled waste is estimated (Xatzidimoulas, n.d.). A fraction of 35% of landfill gas is thought to be

collected through pipes for electricity production (Latsios et al., 2009), and the average energy content of the gas is approximately 5-6kWh/Nm³ (Xatzidimoulas, n.d.). The remaining 65% is directly released to the atmosphere.

3.2.3.3. Scenario II: Future Scenario

Scenario II describes the future waste management plan for 2020 as it is defined by the reviewed RWMP (2016). This scenario emphasizes on reuse and recycling of all fractions of waste generated in RCM, while minimizing the amounts of waste that are sent directly to landfill sites. Particularly, according to the RWMP (2016) 74% of the total municipal waste must be recovered whereas only 26% of the aggregate MSW quantities should be disposed in the regional landfill sites.

More specifically, as Table 3.6. outlines, in this scenario 50% of the total MSW should be collected separately in networks for recyclable materials, such as paper, plastic, glass and metal, bio-waste and other recoverable waste, like wood, WEEE, batteries. The remaining amount of the produced waste, as well as the residuals of the processes from the material recycling facilities and the pre-treated organic waste treatment plants, should be further recovered in a Waste Treatment Plants (WTP) before the final residuals are disposed in a landfill place. The final allocation of the waste amounts per waste treatment method is depicted in Table 3.7.

Table 3.6.: Future waste management system in Region of Central Macedonia (Scenario II) (RWMP, 2016).

MSW Fraction	MSW Generated	Sorting at Source (tons / % of the total)		Mixed Collection			
				Recovery at WTP (tons / % of the total)		Landfilling (tons / % of the total)	
Organics	373.224	149.290	40%	149.290	40%	74.644	20%
Paper	187.033	110.323	59%	18.729	10%	57.981	31%
Plastic	117.107	79.617	68%	11.727	10%	25.763	22%
Metal	32.857	25.293	77%	4.935	15%	2.629	8%
Glass	36.227	27.362	76%	1.983	5%	6.883	19%
Wood	38.753	19.377	50%	11.626	30%	7.751	20%
Other Recoverable	13.480	9.436	70%	674	5%	3.370	25%
Others	43.809	0	0%	0	0%	43.809	100%
Total MSW	842.490	420697	50%	198963	24%	222.830	26%

Table 3.7.: Allocation of the amounts of MSW per waste treatment method in Scenario II.

Scenario II		
Waste treatment Method	MSW (tons / % of the total MSW amount)	
Landfilling	222.830	26%
Recycling	310.971	37%
Composting	298.580	35%
Reuse	10.110	1%
TOTAL	842.490	100%

According to RWMP, in this scenario 65% of the produced recyclable fractions of MSW (paper, glass, metal and plastic) should be separately collected, and together with those amounts that would be recovered from WTPs, their recycling should reach 75% by weight. Similarly, 40% of bio-waste should be diverted from landfill either by home composting or by separately collection. Consequently, additional waste management infrastructures are required. More specifically, Scenario II (Figure 3.8.) takes into account three Waste Treatment Plans, where the residual mixed MSW as well as the residuals from the recycling materials collection centers and facilities (MRFs) and Biological Waste Treatment plants (MBT) should be further recovered before the final disposal. Furthermore, the separate collection of bio-waste is established and the collected waste is led to Biological Waste Treatment plants, where the technology of open composting systems, when is available, or alternative closed-type composting or anaerobic digestion with energy production will be used in order to produce compost that could be further used. The residuals from the BWT plans are assumed to be 10% by weight.

Moreover, as far as the recyclables are concerned, the Separation at the Source initiative is implemented, with the separate collection of four fractions (paper, metal, plastic and glass) to take place. Besides that, a new network of Green Points and Recycling Centers is established. The MRFs that are used require incorporate hand-held cabinets for the management of recyclable materials that will be derived from the Separation at the Source system. The residuals from the processes at MRFs are assumed to be 15%, instead of 35,5% that currently are.

Finally, the residual waste is sent to landfill sites, where energy recovery is taken place. Power plants have been established on the landfill site, which use the landfill gas which is produced for electricity generation. Its composition is 53% of CH₄ and 47% of CO₂ (Latsios et al., 2009), and its yearly production rate assumed to be of 4,5m³/t of landfilled waste (Xatzidimoulas, n.d.). A fraction of 70% of landfill gas is thought to be collected through pipes for electricity production (Latsios et al., 2009), and the average energy content of the gas is approximately 5-6kWh/Nm³ (Xatzidimoulas, n.d.). The remaining 30% is directly released to the atmosphere.

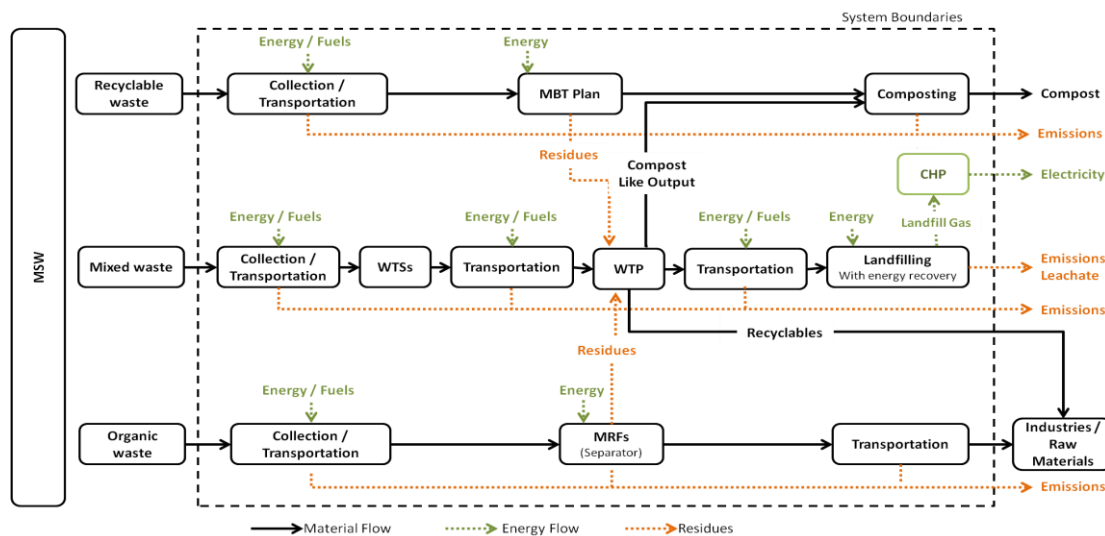


Figure 3.8.: System boundaries for Scenario II.

3.2.4. Application of the LCA methodology to the case study

Nowadays, the management of municipal waste is one of the most serious issues faced by the local and regional authorities, since regardless of significant technological progress, improved legal and regulatory framework and systems, public acceptance of the location and operation of new waste disposal and treatment facilities remains very low (Fernández-Nava et al., 2014). While the concern about environmental impact as well as human health consequences increases, the research interest is concentrated on how waste should be managed and which integrated waste management system is more appropriate to be implemented by the regional authorities.

In recent years, it has been understood that even environmentally friendly waste treatment methods can have an environmental impact. Consequently, the selection of

suitable technology in the design of MSW management systems depends on the environmental impacts that are resulted from the construction and operation of those systems throughout their life cycle. Therefore, a well-structured and comprehensive methodology for systematically assessing all available alternative technologies is required. Within this context, LCA has rapidly expanded over the last years in the field of waste management and it is frequently used as a tool for the design and evaluation of integrated waste management systems (Fernández-Nava et al., 2014).

3.2.4.1. Goal and scope definition

The goal of this study is to analyze and compare different MSW management strategies that can be implemented in the Region of Central Macedonia from an environmental point of view. Therefore, different treatment methods were investigated and alternative MSW management systems were compared. More specifically, four alternative scenarios have been compared regarding the management of MSW generated in the RCM, each of which includes the storage and collection of MSW in bins, both mixed bins and those for separately sorting of recyclable fractions at the source, the gathering of municipal waste and their transport by collection vehicles to the Waste Transfer Stations, the main treatment available in each scenario such as the mechanical separation of the waste, recycling or composting or landfilling, and the final disposal of the residues of those processes in a landfill site.

The LCA methodology was used in order to choose the optimal MSW management system. The application of LCA was carried out using the SimaPro software, which enables the evaluation of environmental impacts for all alternatives for the waste management by using specific environmental impact indicators that will be further analyzed in the following sections.

3.2.4.2. Functional unit

The functional unit is essential to the better understanding of the outcomes of an LCA, as it offers a common basis for the comparison of the results, since it enables the normalization of input and output data under a reference factor (Georgiopoulou and Lyberatos, 2017). Especially, in case of LCAs for municipal waste, as Cleary (2009)

mentions, the functional unit guarantees that all of the environmental impacts are primarily based on equal inputs to every MSW management system.

Thus, the functional unit, in this study, is defined equal to the reference flow. More specifically, this is the whole amount of municipal solid waste generated in the Region of Central Macedonia over a period of one year (842.490 ton), as it was illustrated in

Table 3.4. Although the choice to use the entire amount of waste produced as a functional unit may limit the ability to draw general conclusions for regions and municipalities, it was considered more relevant than to select a standard unit like 1 ton of waste, since the current study tries to define the situation as it is in the RCM.

3.2.4.3. System boundaries

The system under study is defined as an integrated waste management system for 842.490 tons of municipal waste. Its boundaries involve the final stage of the life cycle of the waste generated in the RCM. More specifically, as Figure 3.9. outlines, the system boundaries include all processes from the moment the waste is collected until it leaves the system either as an emission or as a secondary raw material, biogas or energy.

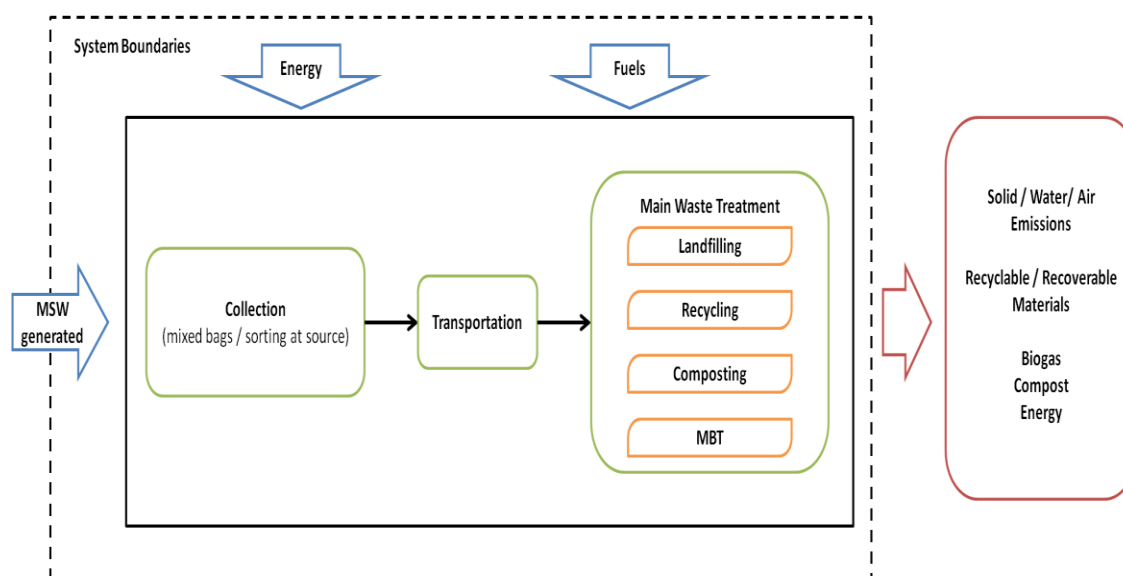


Figure 3.9.: Schematic Flowchart of System's Boundaries.

Municipal waste enters the system after been discarded either as mixed waste or as source-segregated streams which are separately collected. The system covers waste

collection from bins, transport, mechanical separation, when is available, recycling or other waste treatment, and finally disposal in a landfill. Also, within the system boundaries, besides the main treatment of MSW, the required fuels for the transport, as well as energy for both the operation and construction of all required facilities are included.

3.2.4.4. Life Cycle Inventory (LCI)

This study aims at offering a transparent and complete environmental assessment of various waste management methods for handling mixed municipal waste of a Region. In the LCA, a specific inventory was created for every one of the alternative scenarios. In general, the inventory that selected was based on those available in the Ecoinvent database v2.2, whereas, particular changes and modifications were introduced only in the case that real data regarding the implemented processes were available.

3.2.4.4.1. Assumptions

Due to the complexity that an integrated MSW management system has, several reasonable assumptions are required in order to simplify complex calculations and overcome the problem of lack of data, to comply with the requirements of the SimaPro software and result in a proper comparison between the different scenarios.

The summary of the main assumptions, as well as the major data used in the modeling of the alternatives follows:

- In order to export valid results, and given the incomplete compatibility of management practices, identification with the techniques included in the SimaPro software was performed.
- The term “generated MSW” includes: household and commercial solid wastes, like food waste, paper, glass, plastic, aluminum, tin cans, ferrous metals, other metals, as well as WEEE, textiles, rubber, leather, wood and yard waste. Its composition is based on the data of MSW in the Region of Central Macedonia.
- According to the design, waste category “Other Recoverables” assumed that include household electrical appliances, batteries, lamps and the percentage of the various fractions in its composition are taken by literature (Ylä-Mella,

2012). Similarly, waste category “Others” assumed to include textiles, leather and rubber, based on the literature (Zhou et al., 2014).

- In Scenario I, the composition of total recyclable materials (paper, glass, metal and plastic) that are sent to MRFs (Table 3.5.), as well as the residue fraction (35.5% of the recyclable stream) from the MRFs processes which is disposed to landfill sites, is assumed to be the same as the average composition of the recyclable fractions that is sent to each of the MRFs in the RCM according to RWMP (2016). In Scenario II, the residue fraction is equal to 15% based on the target set in RWMP (2016).
- The collection type is assumed curb collection and consists of the gathering of municipal waste in bins from various locations in the municipalities of the RCM. Besides that, closed-body vehicles also are considered as part of the collection system. The type of the collection vehicles depends on the quantity of waste to be gathered every day. In this study, the type of vehicle that is assumed to be used is “*Transport, municipal waste collection, lorry 21t*”, as appeared in Ecoinvent database. Nevertheless, only the environmental impacts from waste transportation with collection vehicles and not those of raw material and manufacture of bins are taken into consideration.
- Due to software restrictions, the environmental impacts of the energy (biogas collection, as well as electricity generation and consumption during the operation phase for mechanical separation and energy recovery when is available) are not taken into consideration. Similarly, the construction of new facilities, in Scenario II, is not taken into consideration as well.
- Since the quantities of WEEE that are separately collected and sent for reuse are small in comparison with the other waste streams, and because of lack of information regarding their treatment, it is assumed that those amounts of waste are sent for recycling.
- Transport to the various waste management facilities was entered on the software according to the following assumptions (Table 3.8.):

Table 3.8.: Assumption regarding transport processes.

Transportation Assumptions	Distances for transportation processes are calculated using Google Maps.
	The required total distance for waste collection is comprised of the distance between the capital city of each prefecture and the final management point.
	Regarding the new waste facilities that are established in Scenario II, the required distance for transportation are calculated based on data provided by RWMP.
	The distance calculations are made on the basis of the assumption that empty-collection vehicles returns are also included.
	Vehicles of the EURO 5 type were imported as a means of transport, depending on the waste amount required to carry.
	Pollutants and emissions from transport are available as ready processes in SimaPro libraries.

3.2.4.5. Life Cycle Impact Assessment (LCIA)

Life Cycle Assessment data was mainly compiled from the SimaPro (Ecoinvent) databases, from the bibliography, as well as from the inventory of current waste management system in RCM as described in the latest RWMP. For the Life Cycle Impact Assessment, which based on the outcomes of the inventory, both Eco-indicator 99 and CML 2001 methods were utilized.

According to CML 2001 Method, the emissions from the alternative scenarios studied are classified to the following impact categories:

- *Abiotic Depletion Potential (ADP, kg Sb eq)*: refers to the protection of human well-being and health, as well as the ecosystems's health. This factor is derived for every extraction of element and fossil fuels and is a relative measure, with the depletion of the element antimony as a reference (kg of antimony equivalents/ kg of used materials). It measures the positive prospects of the recovery of waste, both in form of energy and recycling recovery, as it calculates the non-renewable nature of the materials contained in the waste (Milutinović et al., 2017; Roidi, 2014).
- *Global Warming Potential (GWP, kg CO₂ eq)*: is related to emissions of greenhouse gases. In particular, "it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, in respect to

the emissions of 1 ton of carbon dioxide (CO₂)” (US EPA, 2018), and it is expressed usually over a 100-year horizon in kg CO₂ / kg of emissions (Roidi, 2014). In waste management, typical emissions with a considerable effect to GWP are fossil CO₂, N₂O and CH₄ (Milutinović et al., 2017).

- *Human Toxicity Potential (HTP, kg 1,4-DCB eq)*: accounts the negative effects of toxic substances on the human health. HTP describes fate, exposure and effects of toxic substances for an infinite time horizon, and is expressed as 1.4-dichlorobenzene equivalents/ kg emission (Ministry of the environment, 2018). Emissions from waste management which contribute significantly to this category include: heavy metals (Cr(VI), Hg, Ni, Cu), dioxins, Ba and Sb (Milutinović et al., 2017).
- *Acidification Potential (AP, kg SO₂ eq)*: is defined by OECD as “ the aggregate measure of the acidifying potential of some substances, calculated through the conversion factor of sulphur oxides and nitrogen and ammonia into acidification equivalents (H⁺ ion)” (Directorate, 2018). In waste management, NH₃ from biological processes, SO₂ emissions from electricity production and NO_x emissions from thermal processes are the major contributors to this impact category (Milutinović et al., 2017).
- *Eutrophication Potential (EP, kg PO₄ eq)*: refers to the emissions that have over nourishment results in the ecosystem and shows the potential effects of a substance on biomass formation, by comparing it to the effect of PO₄ (PE INTERNATIONAL AG, 2010; AgroParisTech, 2010). As far as waste management is concerned, impacts within this category mainly arise from atmospheric emissions of NO_x and NH₃, P and N to water from biological methods (Milutinović et al., 2017).
- *Ozone Layer Depletion Potential (OLD, kg CFC-11 eq)*: measures the effects of different ozone-depleting compounds on the ozone layer.
- *Photochemical Ozone Creation Potential (POCP, kg C₂H₄)*: categorizes compounds based on their ability to form ozone and describes the change that is observed in the quantity of ozone formed because of a change of those particular compounds (Andersson-Sköld, Grennfelt and Pleijel, 1992). NMVOC and CH₄ from landfills, as well as emissions of NO_x and CO that are released

during thermal processes are the major emissions that contribute to this impact category in the waste management field (Milutinović et al., 2017).

On the other side, Eco-indicator 99 is a damage-oriented method which classifies the various impact categories and the damages caused into three damage categories (SimaPro, 2016):

- *Damage to Human Health*: expresses the number of years lost.
- *Damage Ecosystem Quality*: measures the loss of species over an area.
- *Damage to Resources*: refers to the extra energy that is needed for future extractions of fossil fuels and minerals.

CHAPTER 4**RESULTS AND DISCUSSION**

Based on the developed alternative scenarios and described quantities and waste streams, the environmental impacts of the various Waste Management Systems were calculated using the SimaPro 7.3 software and the environmental burdens are grouped according to the environmental impact categories included by the methodology chosen (CML 2001, Eco-indicator 99). The results are presented in the following sub-chapters. Overall, landfilling, as a predominant waste treatment method, has much more impacts than others and as it is already mentioned in the literature it should be the least preferable treatment option for municipal waste.

4.1. NETWORK RESULTS

After building the alternative scenarios using the processes that obtained from the SimaPro libraries and databases, the graph of the applied network is generated. With focus on the final stage of the waste life-cycle, the network's performance was graphically displayed by a flow chart for all disposal scenarios and depicts the main processes of each scenario that cause environmental burdens and gives a visual representation of each process's contribution to the overall impact. It is noted that the

red line shows environmental burdens, while green line is used for the environmental benefits.

Transport, as well as the processes used in the various waste treatment methods, which are already included in the software's libraries, gives environmental load to the system. In addition, the large amount of waste that is sent to a specific waste treatment method, such as waste disposed to municipal landfill site, can result higher environmental cost than smaller quantities of waste.

The network chart flows of the three waste disposal plans follow. For all alternatives, the single score that results from Eco-indicator 99 method was selected, since it represents the entire environmental impact of the waste management system at one indicator. Nevertheless, network flow charts are available for every single impact category included in both Eco-indicator 99 and CML 2001 methods, and are included in Appendix I.

4.1.1. Scenario 0

In Scenario 0, all waste generated in the Region of Central Macedonia is disposed in regional landfill sites. As Figure 4.1. illustrates, the Scenario 0 network results that the disposal of municipal waste contributes approximately 92,4% of the total environmental impact. The fuel consumption for the collection and the transport of solid waste to the transfer, treatment and disposal stations has a significantly lower contribution (2 – 5%) to the total burden.

As far as the single indicators, such as ecosystem quality, human health and resources, of Eco-indicator 99 Method are concerned, the results are similar with those of the single score. In case of the damage to resources, the impacts from the fuel consumption are greater (20 – 40%) in comparison to the other indicators (0,5 – 2,5%).

Regarding the CML 2001 Method, all impact categories result that the disposal of waste in municipal landfill sites has the greater contribution to the total environmental impacts caused by Scenario 0, while transport of waste and fuel consumption contribute significantly to Acidification (21%), Abiotic depletion (37%) and Ozone layer depletion (37%).

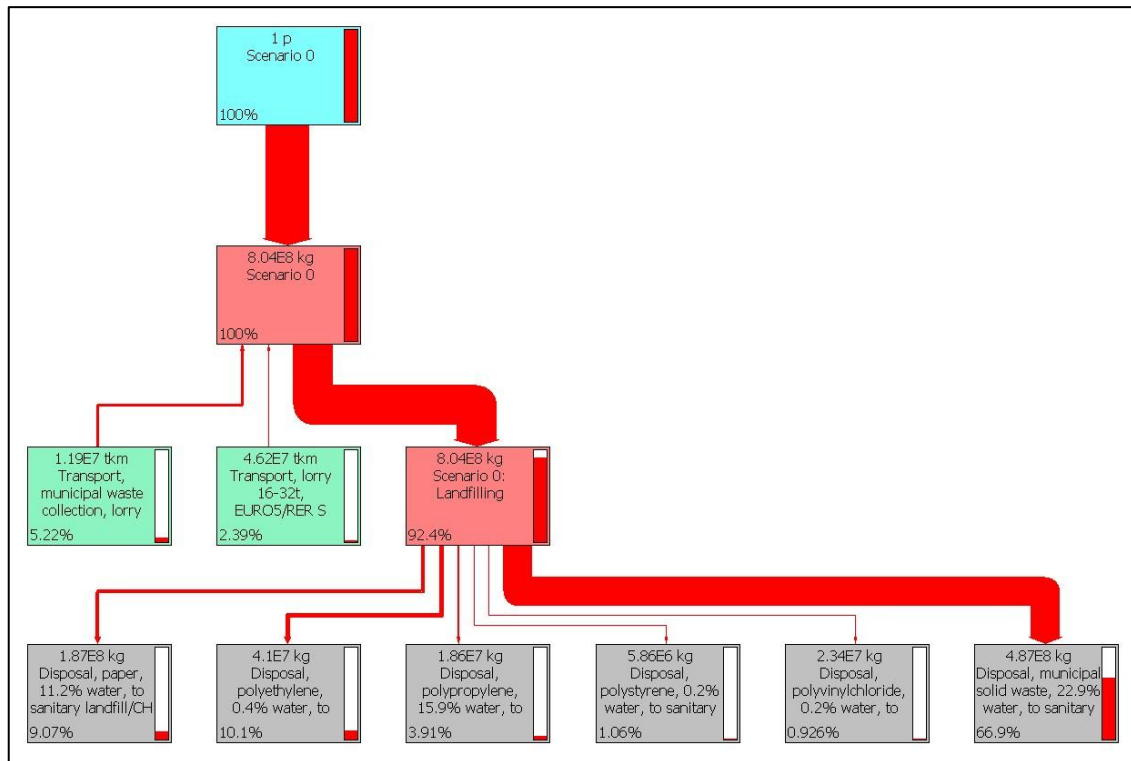


Figure 4.1.: Network chart flow for Scenario 0, which refers to single score as resulted from Eco-indicator 99 method (SimaPro software).

4.1.2. Scenario 1

In Scenario 1, 82% of the total municipal waste is landfilled, whereas only 13% is recycled and 4% is composted. Figure 4.2. depicts that, similarly to Scenario 0, disposal to municipal landfill has the greater environmental impact. In this Scenario, recycling has a positive contribution as well as composting. Nevertheless, their contribution is not considered significant since the waste amounts that are sent to these waste treatments are quite small.

Regarding Human Health and Ecosystem quality indicators, the results are similar to those already presented. However, in Resource damage category, Recycling and Composting have significant environmental benefits since they help to the protection of natural resources through the avoided products that are replace the raw materials during the various production processes.

Results from CML 2001 Method shows that the environmental burden caused by landfilling is greater, but in cases of Acidification and Abiotic Depletion the benefits mainly from the recycling methods are more.

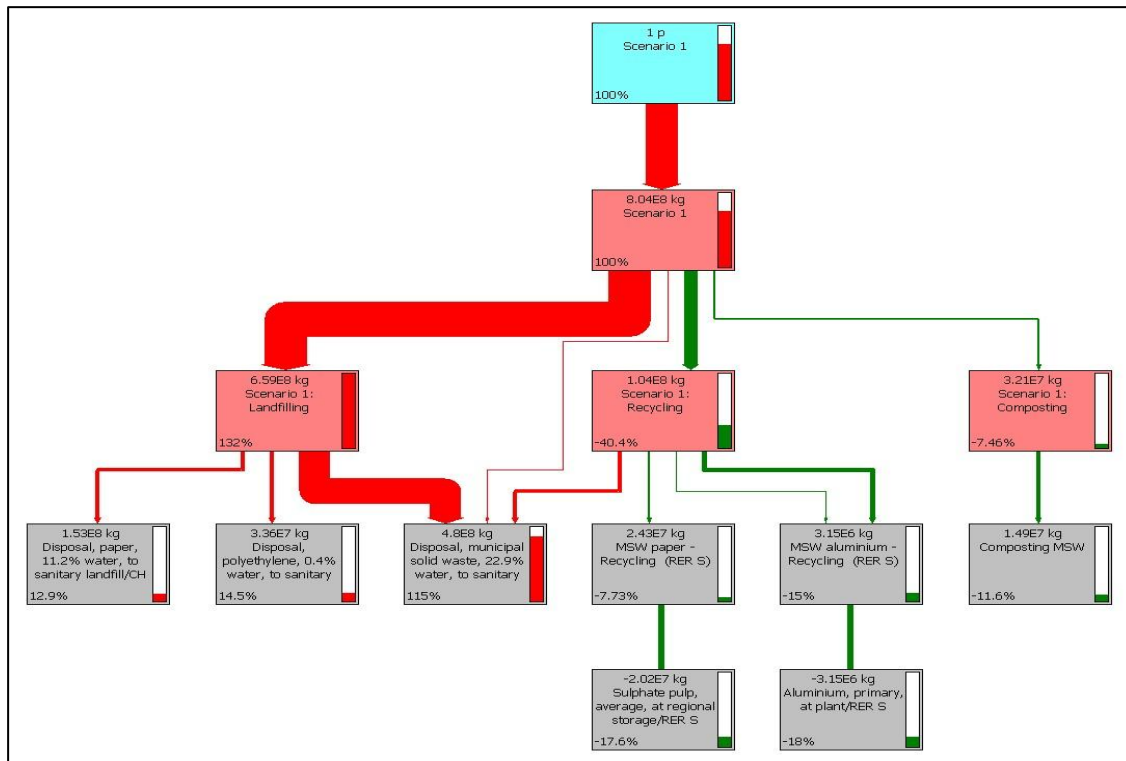


Figure 4.2.: Network chart flow for Scenario 1, which refers to single score as resulted from Eco-indicator 99 method (SimaPro software).

4.1.3. Scenario 2

In Scenario 2, waste generated in RCM is sorting at source, thus 38% is recycled, 35% is sent for composting and only 26% is disposed in sanitary landfills. Consequently, as Figure 4.3. outlines, in Scenario 2 the environmental benefits are much more than the negative impacts caused by landfilling of waste. Even though there are impacts of disposal of waste, they are considerably less than the previous Scenarios due to fewer quantities sent to landfills.

The Eco-indicator 99 model presents similar results for the Resource damage category, whereas the environmental impacts of this MSW management system are more in case of Ecosystem quality. Similar results has the CML 2001 Method for the categories of Eutrophication and Global Warming, in which the environmental burden caused by landfilling is greater than the benefits derived from the quantities that are either recycled or composted. In all the other impacts categories the environmental benefits of these waste treatment methods are obvious and more than the negative impacts of landfilling.

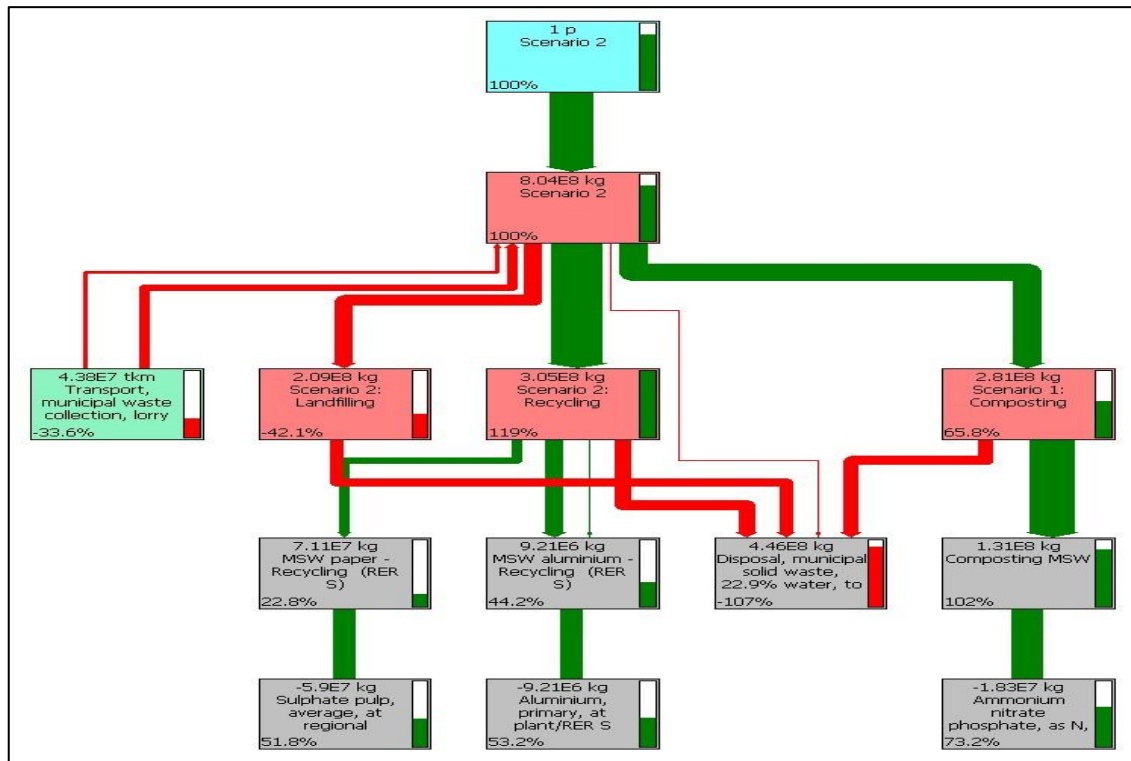


Figure 4.3.: Network chart flow for Scenario 2, which refers to single score as resulted from Eco-indicator 99 method (SimaPro software).

4.2. Impact Assessment

By comparing the three disposal scenarios, the environmental burdens of each practice were calculated with both selected Methods (CML 2001, Eco-indicator 99) and are presented below. According to the ordinary practice in LCA studies, positive values imply a burden for the environment, therefore negative impacts, whereas, negative ones indicate savings, and so environmental benefits (Rigamonti, Falbo and Grosso, 2013).

4.2.1. Results of impact indicators according to CML 2001 Method

Results of inventory data were categorized to the main impact categories: Abiotic depletion (ADP), Acidification (AP), Eutrophication (EP), Global warming (GWP₁₀₀), Ozone layer depletion (ODP), Human toxicity (HTP) and Photochemical oxidation (POCP). The normalization of the characterized results enables the comparison of the magnitude of the impacts in the various categories, since they are associated with the overall environmental burden in a certain region for a certain year (Milutinović et al., 2017). Normalization values, as resulted by CML 2001 methodology are given in **Table**

4.1., and environmental impacts of the three alternatives in terms of relative contribution to the selected impact categories are presented in Figure 4.4.

Table 4.1.: Normalized values of impact categories, according to CML 2001 method.

Impact Categories	Scenario 0	Scenario 1	Scenario 2
Abiotic depletion (ADP)	1,724 E-06	-3,364 E-06	-1,596 E-05
Acidification (AP)	9,834 E-07	-5,332 E-07	-4,600 E-06
Eutrophication (EP)	1,674 E-05	1,385 E-05	3,203 E-06
Global warming (GWP ₁₀₀)	9,964 E-06	7,325 E-06	7,427 E-07
Ozone layer depletion (ODP)	1,206 E-08	5,271 E-09	-1,488 E-08
Human toxicity (HTP)	6,006 E-06	1,690 E-06	-8,630 E-06
Photochemical oxidation (POCP)	1,235 E-06	8,218 E-07	-2,208 E-07

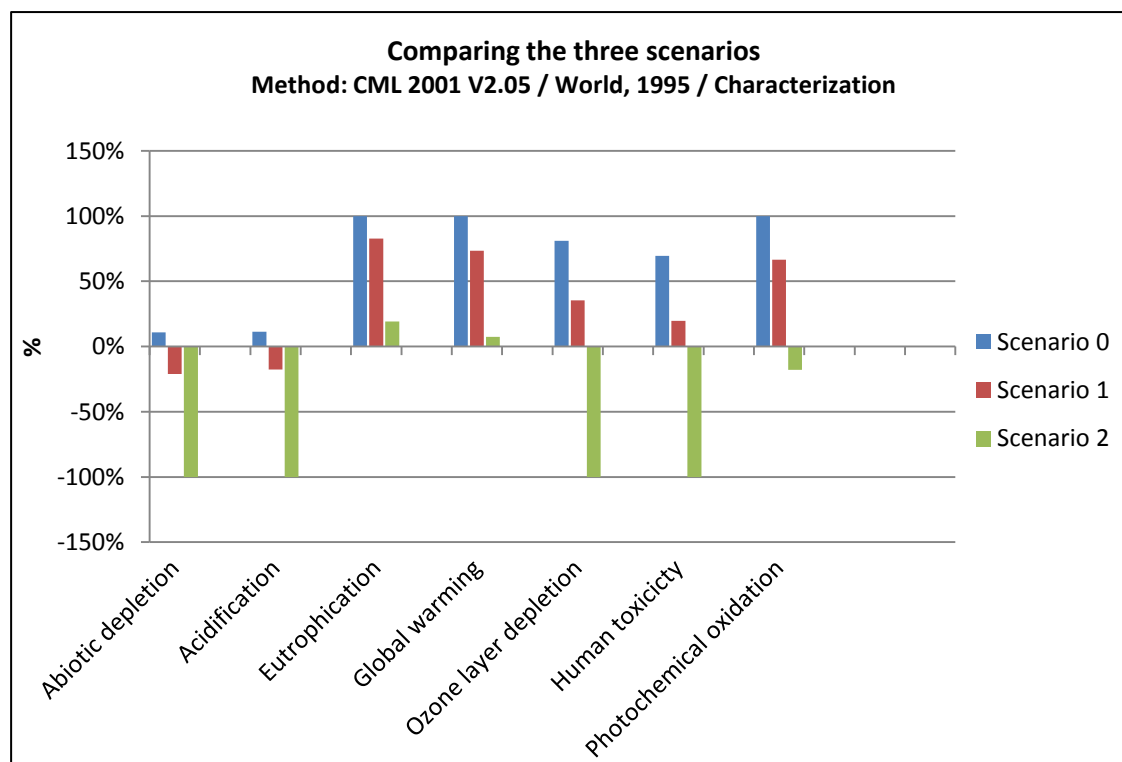


Figure 4.4.: Comparison of the nine management practices for the seven categories of impact of the CML 2001 method.

Taking into consideration results from Figure 4.4., it is obvious that an integrated waste management system can minimize significantly the environmental impacts caused by municipal waste generated. Application of sustainable practices and treatment methods such as sorting at the source, recycling and composting lead to the reduction of waste disposal.

In accordance to the results of life cycle impact assessment, the Scenario 0, and its main waste treatment method, landfilling, results the worst performance for all the indicators analyzed. This high level of environmental burdens in all of the impact categories, compared with the other management systems, is due to the lack of reuse and the disposal of all waste generated in sanitary landfills. Besides that, findings in both Figure 4.4. and Table 4.1. shows that the Scenario 2 contributes to savings in many impact indicators. The replacement of primary products with products which come from the waste treatment recompenses the impacts caused by the actual process of the treatment, thus Scenario 2 which corporate high rates of recycling and composting is advantageous to most of the impact categories.

However, the situation is different in cases of global warming and eutrophication indicators. Global warming potential shows positive values for all Scenarios (Figure 4.5.). Scenario 0 has the higher contribution for global warming because of the very low level of separate collection. As a result all waste sent to landfills and many CO₂ and CH₄ emissions are released. On the other hand, Scenarios 1 and 2 results positive values for GWP₁₀₀ indicator, which are associated with the CO₂ and CH₄ emissions emitted in the landfill and are not captured by the landfill gas control system. Since the amount of waste that is disposed directly to landfill site is grater in Scenario 1, it contributes more for global warming than Scenario 2.

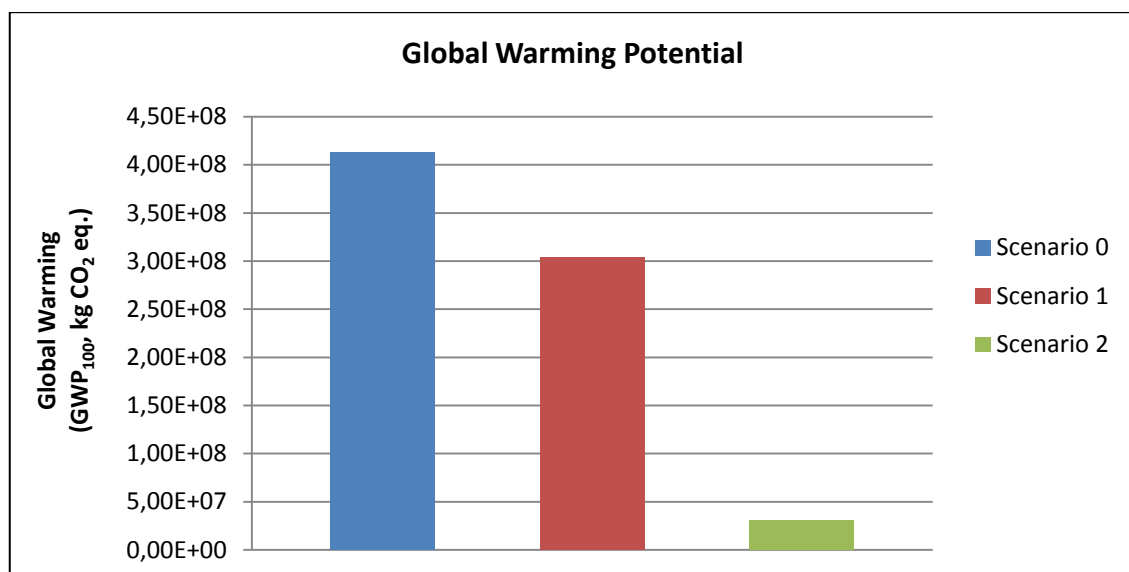


Figure 4.5.: Contribution of all alternative scenarios to the impact category Global Warming Pontential (kg CO₂ eq), Characterization results.

Moreover, all alternatives have positive sign of Eutrophication indicator (Figure 4.6.). In all Scenarios, leachate from landfill, although is treated in wastewater facilities, releases NO_3^- and NH_3 . Thus, in all three alternative management systems, those emissions represent the biggest contribution to eutrophication. Even in Scenario 2, which has generally the most beneficial performance, this indicator shows positive value.

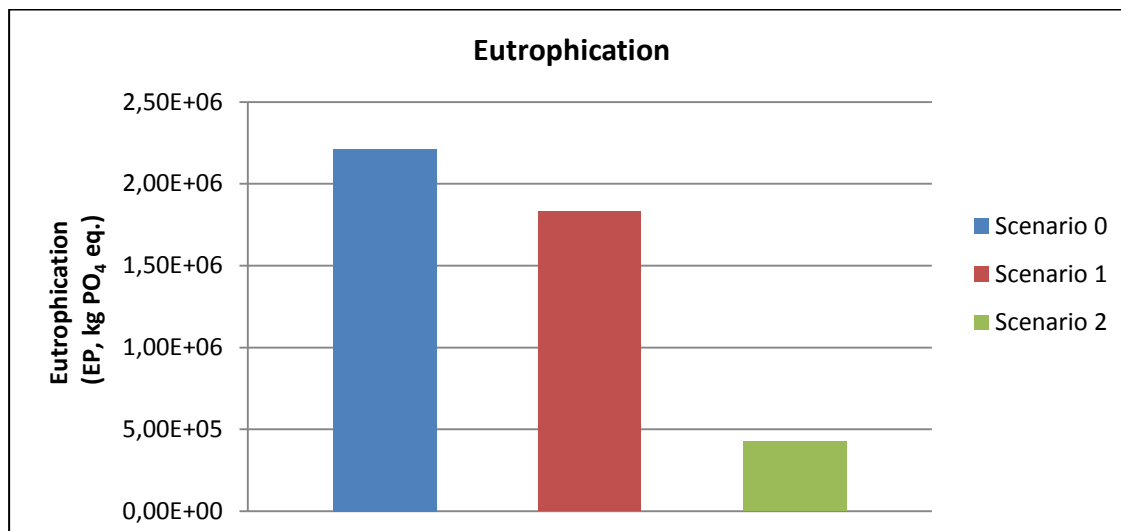


Figure 4.6.: Contribution of all alternative Scenarios to the impact category Eutrophication Potential (kg PO₄ eq), Characterization results.

The evaluation of toxicity categories indicates that the main contribution of emissions comes from Scenario 1, in which the main waste treatment method is landfilling without energy recovery (Figure 4.7.).

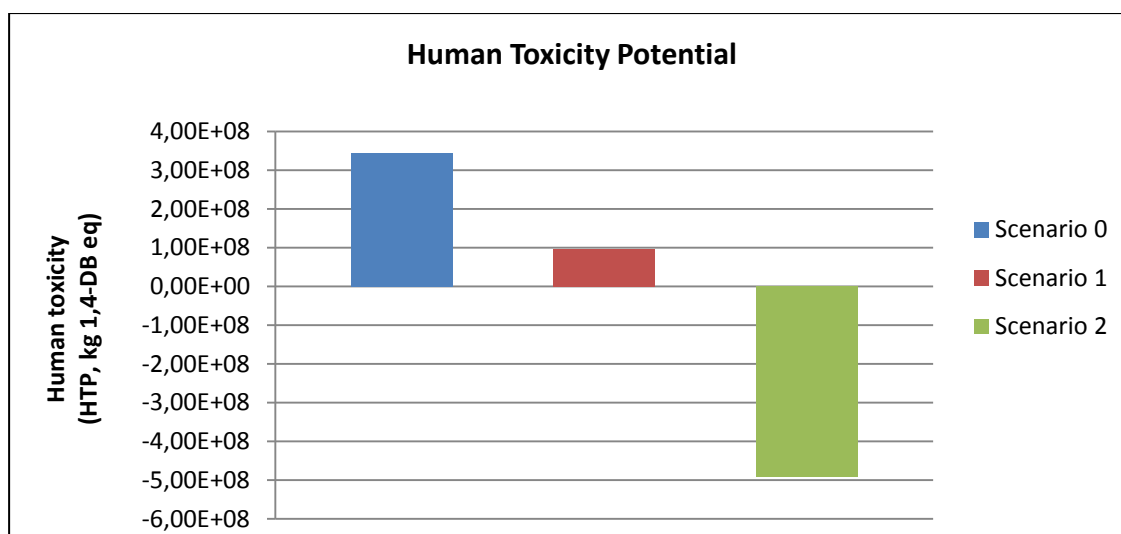


Figure 4.7.: Contribution of all alternative Scenarios to the impact category Human Toxicity Potential (kg 1.4-DB eq), Characterization results.

In contrast, the best scenario is Scenario 2, due to the low amount of municipal waste that is finally sent for landfilling. Also, regarding photochemical oxidation, Scenarios 0 and 1 results positive values due to the high levels of landfill activity, and especially because of CH₄ and NMVOC emissions (Figure 4.8.).

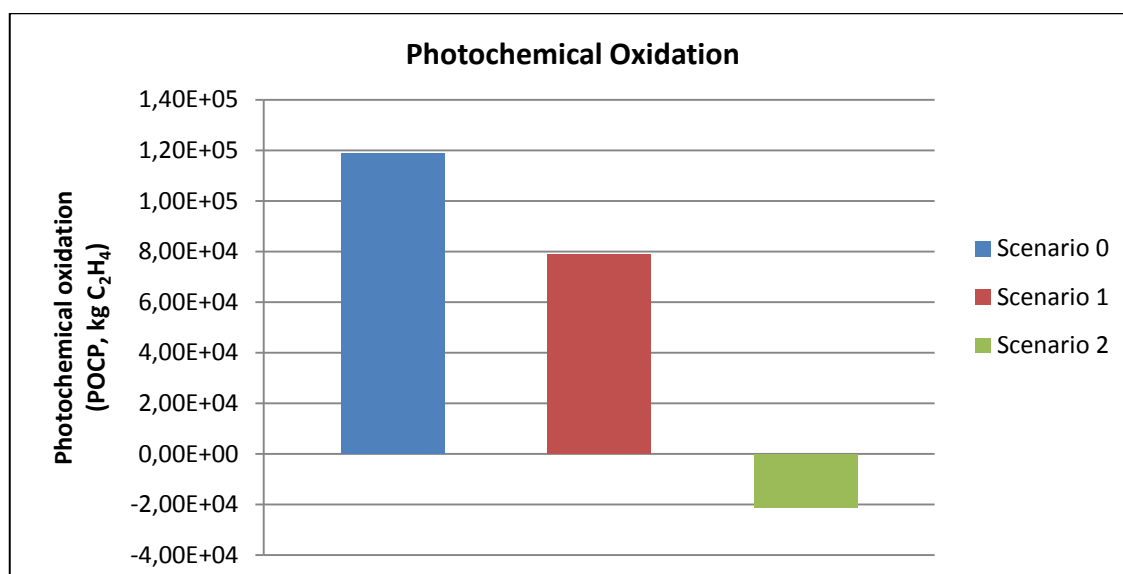


Figure 4.8.: Contribution of all alternative Scenarios to the impact category Photochemical Oxidation Potential (kg C₂H₄), Characterization results.

4.2.2. Results according to Eco-indicator 99 methodology

According to Eco-indicator methodology, results from the inventory data was classified into three general damage categories (Human Health, Ecosystem quality and Resources), which include various impact categories such as: Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/ Eutrophication, Land use, Minerals and Fossil fuels. Based on the life cycle, the normalized damages on the environment of the different scenarios are presented in Table 4.2. Moreover, a comparison of the scenarios' relative contribution to the various impact categories of Eco-indicator 99 method is depicted in Figure 4.9.

Table 4.2.: Normalized values of impact categories, according to Eco-indicator 99 method.

Damage category	Scenario 0	Scenario 1	Scenario 2
Human Health	86348,77	65282,28	-394,696
Ecosystem quality	20243,34	15246,54	3786,134
Resources	10280,87	-14534	-75112,9

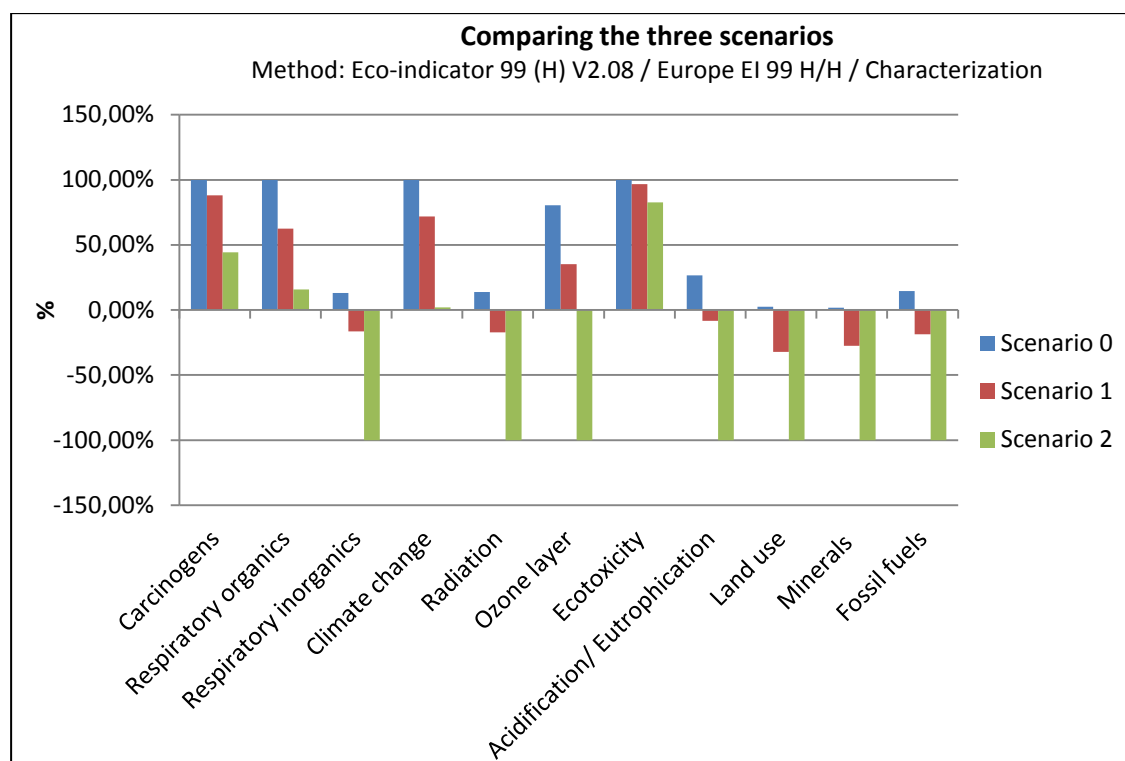


Figure 4.9.: Comparison of the nine management practices for the seven categories of impact of the CML 2001 method.

Taking into consideration the results from Figure 4.9., Table 4.2., as well as the single score that is illustrated in Figure 4.10., it is obvious that Scenario 0 is the worst waste management system that can be implemented in the RCM. Its environmental burden is presented to be significant, according to both methodologies used. In contrast, Eco-indicator 99 method results high environmental benefits for Scenario 2, as well as the previous one. Based on the single score of Eco-indicator method, total environmental impacts caused by Scenarios 0 and 1 are equal to $3,71\text{E}+07$ Pt and $2,13\text{E}+07$ Pt respectively, whereas Scenario 2 has environmental benefits equal to $-2,11\text{E}+07$ Pt.

Similarly with CML 2001, results for Eco-indicator 99 methodology indicates that the main impacts caused by landfilling treatment process and the huge amount of waste that is disposed (Scenarios 0 and 1). Furthermore, the environmental benefits that derive from the replacement of primary products with recycled ones are significant (Scenario 2). As Figure 4.10. outlines, savings of the resources are more advantageous when high rates of sorting collection, recycling and composting are implemented.

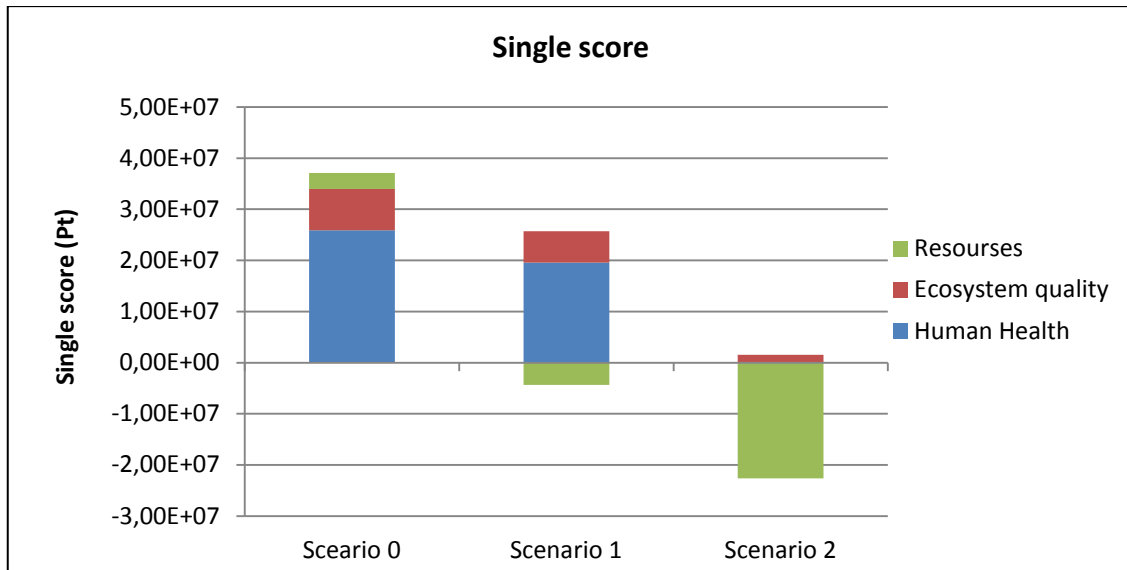


Figure 4.10.: Comparison of the three alternatives scenarios, based on the Single score of Eco-indicator 99 methodology.

4.2.3. Final Scenarios' classification based on SimaPro results

Overall, taking into consideration the final results of the two methods (**Table 4.3.**), it is obvious that Scenario 2 is the best waste management practice, due to high environmental benefits derived from the recycling of waste streams, as well as the small environmental burden from waste disposal, because of the comparatively less amounts of waste sent to landfill sites. On the other hand, landfilling of municipal waste, as it has already been mentioned in the literature, is thought to be the worst method from the treatment of waste generated. And that is because of the significant impacts this process has both to the environment and human health.

Table 4.3.: Final normalized results of CML 2001 and Eco-indicator 99 methodologies for the three alternative scenarios.

CML 2001							
	ADP	AP	EP	GWP ₁₀₀	ODP	HTP	POCP
Scenario 0	1,72E-06	9,83E-07	1,67E-05	9,96E-06	1,21E-08	6,01E-06	1,24E-06
Scenario 1	-3,4E-06	-5,3E-07	1,39E-05	7,32E-06	5,27E-09	1,69E-06	8,22E-07
Scenario 2	-1,6E-05	-4,6E-06	3,2E-06	7,43E-07	-1,5E-08	-8,6E-06	-2,2E-07
Eco-indicator 99							
	Human Health		Ecosystem Quality		Resources		
Scenario 0	8,63E+04		2,02E+04		1,03E+04		
Scenario 1	6,53E+04		1,52E+04		-1,45E+04		
Scenario 2	-3,95E+02		3,79E+03		-7,51E+04		

4.3. UNCERTAINTY ANALYSIS

The previous presentation of the results obtained from SimaPro software helps the identification of the improvements that are required, taking into account the environmental burden throughout the life cycle of municipal solid waste. As a final consideration on the results, the uncertainty of such studies is a significant factor that should be taken under consideration. However, due to lack of time, the analysis of uncertainty does not included in the scope of this dissertation, and thus will not be presented. At least, it should be mentioned that the most important parameters are based on primary data, like the material flows of the various waste fractions in the municipal waste. In case that the energy consumption and recovery was not excluded of the study system, the results would be more accurate. They may present more environmental burdens for some scenarios, due to the large use of electricity, but at the same time, some processes would have more savings because of the energy recovery.

CHAPTER 5

CONCLUSION

The expanding amounts of waste generated nowadays due to changing lifestyles and urbanization have become an issue of high priority for all municipalities. At the same time, the growing realization of the negative effects of municipal waste on the environment and human health results in the development of evaluation methods that enable the design and implementation of optimum integrated waste management systems.

An integrated MSW management system reflects an approach to sustainable waste management. Such an approach is environmentally effective and includes an optimized waste collection system, efficient sorting accompanied by one or more processes like recycling or composting of organic fractions, and finally landfilling of the residual waste. Towards this direction, Waste Framework Directive establishes the concept of “waste hierarchy” and sets the principles for the protection of the environment through the implementation of more efficient MSW management systems. Accordingly, the European Union member states are gradually incorporate the waste regulation into their national regulatory framework and adopt waste treatment methods that lead to energy and material recovery from the various MSW streams. However, in Greece, Waste Framework Directive is poorly implemented,

waste management still represents one of the most critical problems that need to be addressed and the developed of an optimal waste management strategy is more than critical.

In this thesis, the MSW streams were initially defined, as well as the drives for the development of waste management and the different waste treatment methods which are implemented worldwide. Next, a description of the European and Greek regulatory framework is presented and the current situation of MSW generation and treatment in EU are analyzed. Also, a reference has been made in the current waste management practices in Greece. The aim of this study was the development and application of a life cycle methodological framework in order to compare the different management practices and select the optimal and most sustainable integrated waste management system from an environmental point of view.

Within this context, a Life Cycle Assessment study of different MSW management scenarios in the Region of Central Macedonia was conducted using the SimaPro software. The alternative waste management practices were evaluated in relation to specific environmental indicators and through a comparative evaluation of the results the best waste management practice was selected.

According to all indicators, practices that involve either wholly or partial disposal in landfill sites have the worst performance. The parameters that contribute to these negative results are the large quantities of untreated municipal waste that are disposed in landfills and the low rates of landfill gas collection. On the other hand, the alternative management practice of municipal waste, which combines the recycling of metals, glass, plastics and paper, with the composting of organic fractions of MSW, after the separately collection at source is the best solution. And that is because, in this scenario the rate of untreated waste which is sent to landfill sites is significantly low, and at the same time the material recovery offers many environmental benefits. However, it should not be forgotten that alternative waste treatment methods such as recycling do have negative environmental impacts, although these loads do not overshadow the environmental benefits of material recovery.

Taking under consideration the results of the LCA analysis, it has been found that the implementation of an integrated waste management system is important the sustainable management of municipal waste. Nevertheless, this system may not be effective if there is no efficient sorting of waste streams at the source. Overall, a significant percentage of municipal waste can be treated in various ways, recycled or reused before disposed in a landfill site, thus minimizing environmental impacts of the continuously expanding amounts of waste produced nowadays.

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APPENDIX I

*Network Results of Eco-indicator 99 & CML 2001 methodologies
displaying the remaining indicators for the three waste management Scenarios*

1. Eco-indicator 99

Scenario 0

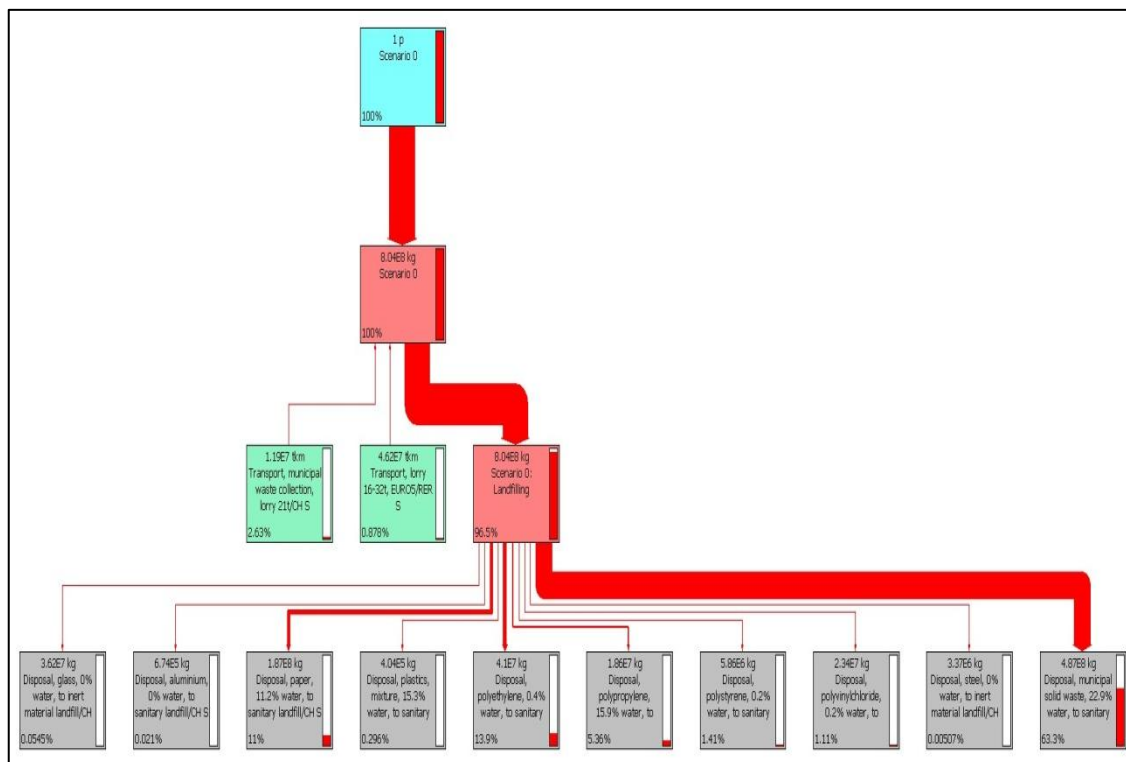


Figure I.1.: Network chart flow for Scenario 0, which refers to human health as resulted from Eco-indicator 99 method (SimaPro software).

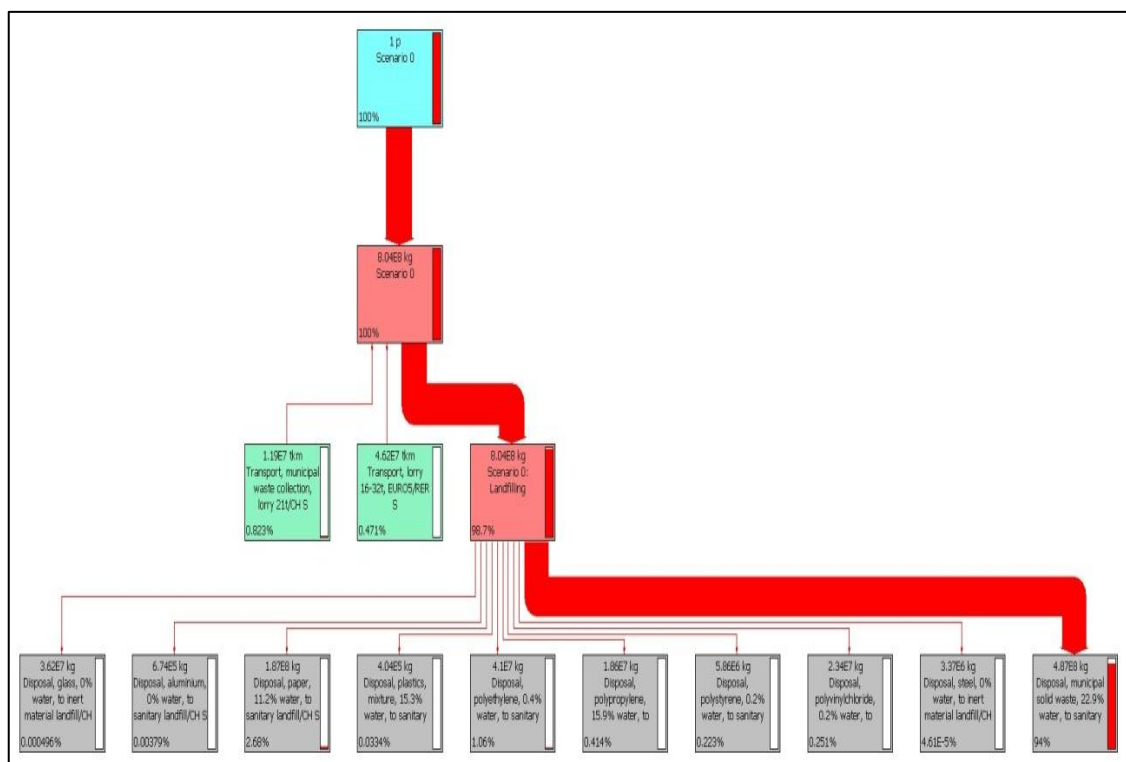


Figure I.2.: Network chart flow for Scenario 0, which refers to ecosystem quality as resulted from Eco-indicator 99 method (SimaPro software).

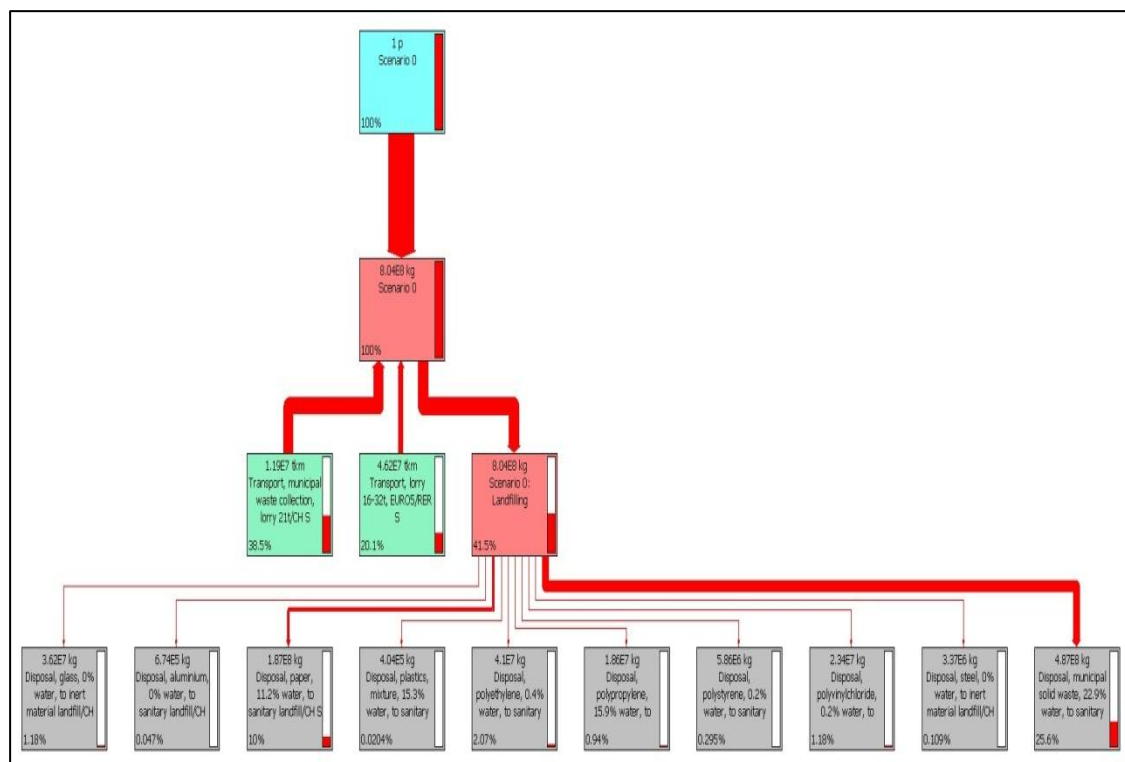


Figure I.3.: Network chart flow for Scenario 0, which refers to resources as resulted from Eco-indicator 99 method (SimaPro software).

Scenario 1

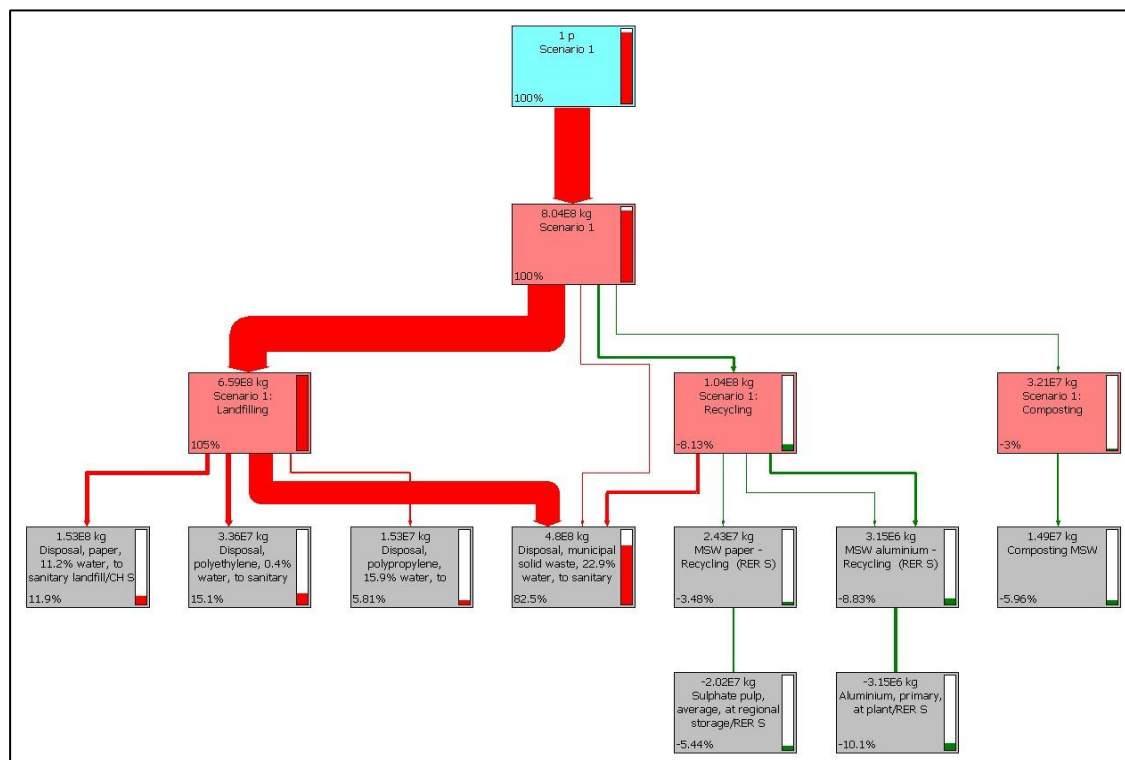


Figure I.4.: Network chart flow for Scenario 1, which refers to human health as resulted from Eco-indicator 99 method (SimaPro software).

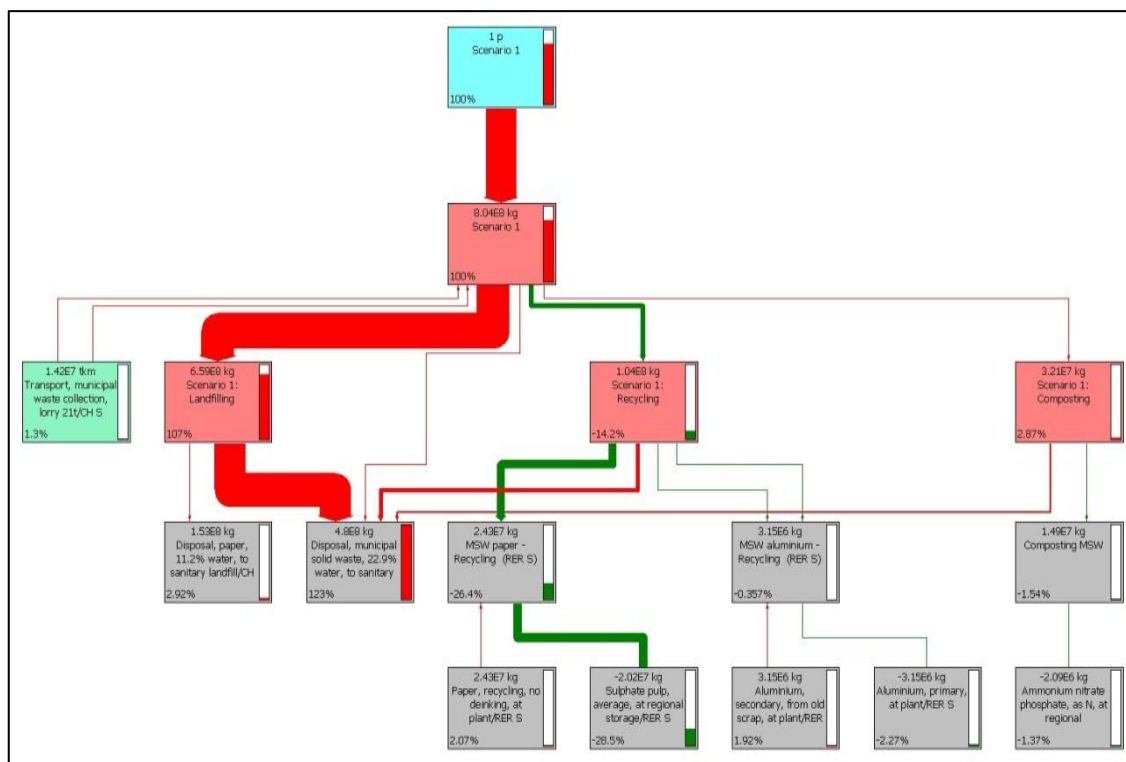


Figure I.5.: Network chart flow for Scenario 1, which refers to ecosystem quality as resulted from Eco-indicator 99 method (SimaPro software).

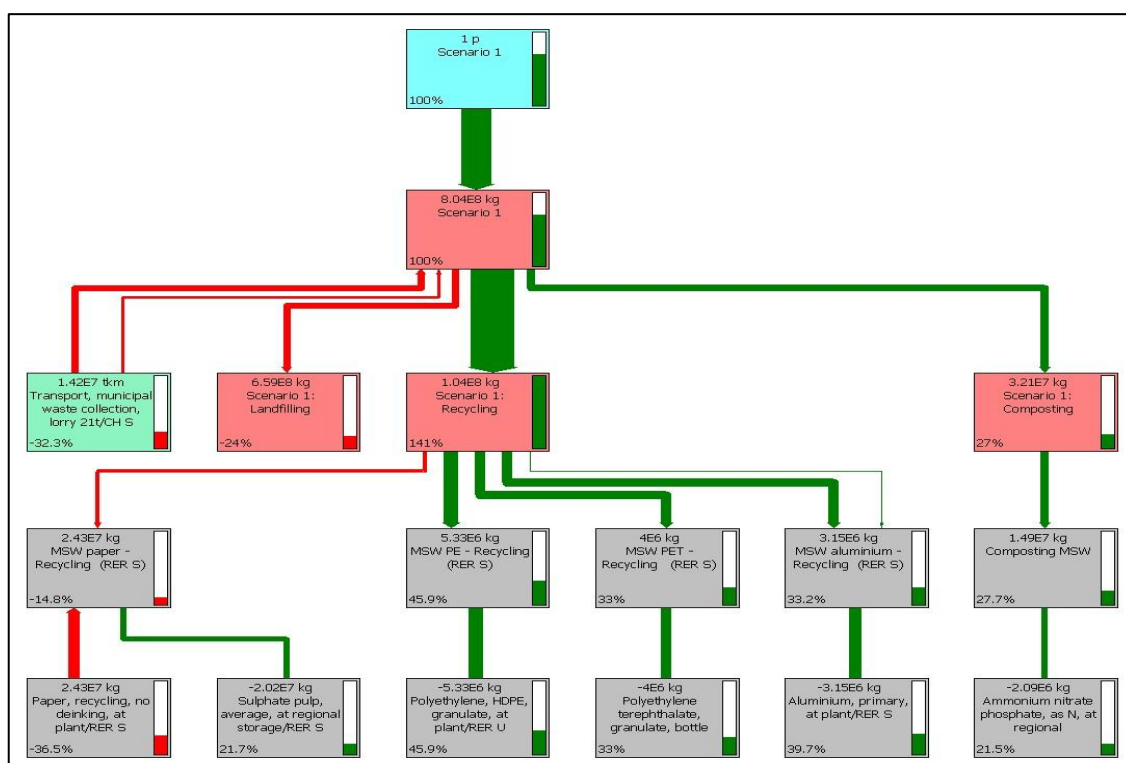


Figure I.6.: Network chart flow for Scenario 1, which refers to resources as resulted from Eco-indicator 99 method (SimaPro software).

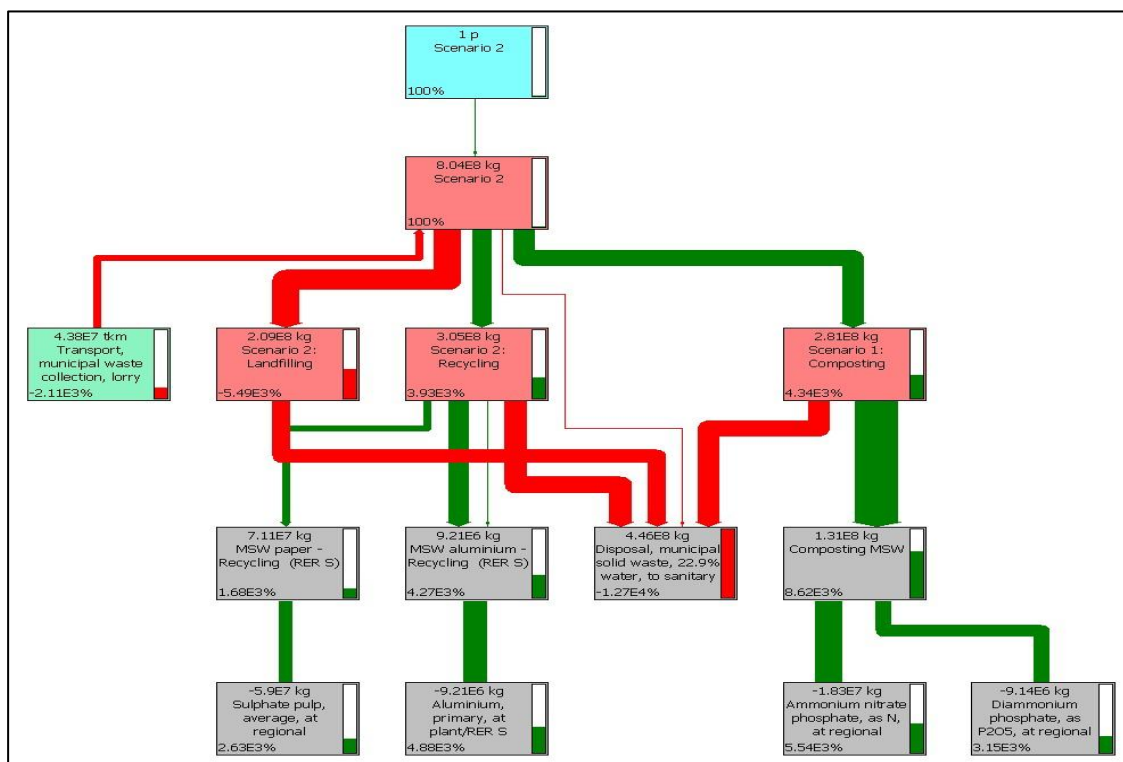
Scenario 2

Figure I.7.: Network chart flow for Scenario 2, which refers to human health as resulted from Eco-indicator 99 method (SimaPro software).

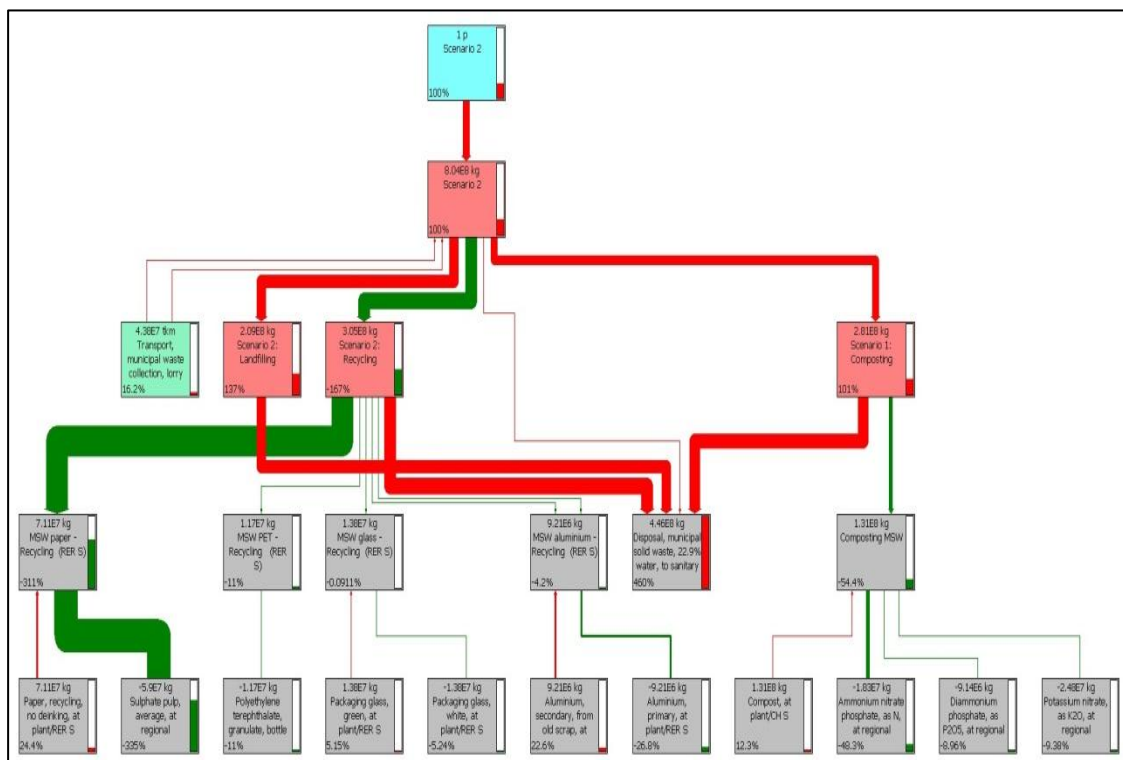


Figure I.8.: Network chart flow for Scenario 2, which refers to ecosystem quality as resulted from Eco-indicator 99 method (SimaPro software).

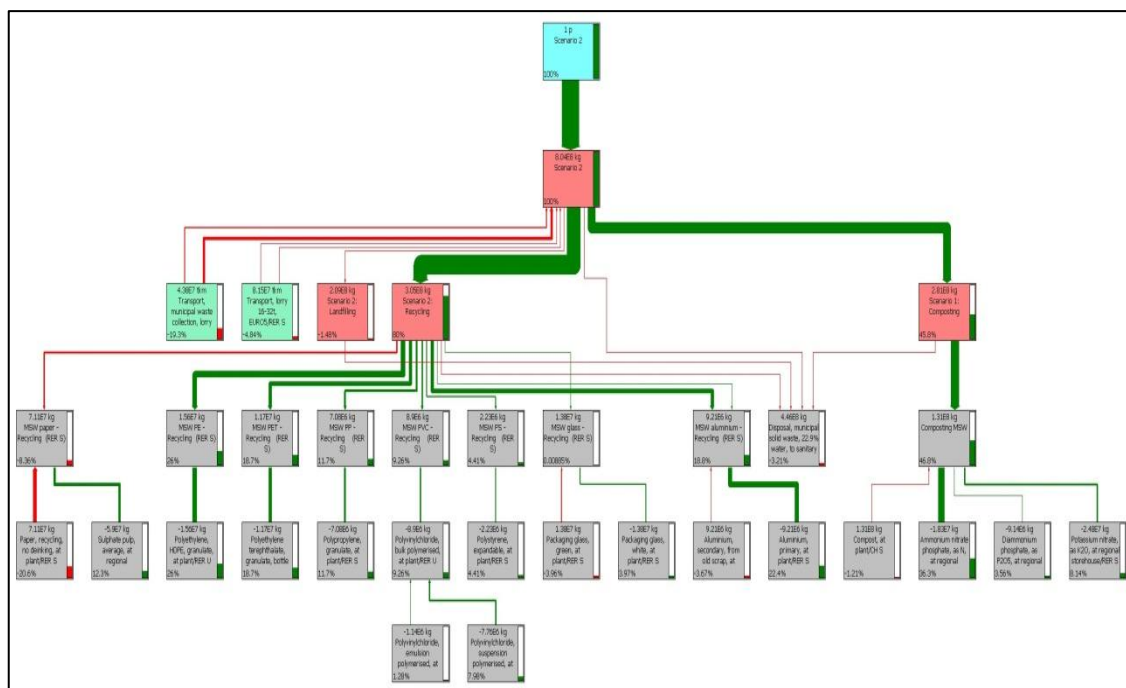


Figure I.9.: Network chart flow for Scenario 2, which refers to resources as resulted from Eco-indicator 99 method (SimaPro software).

2. CML 2001

Scenario 0

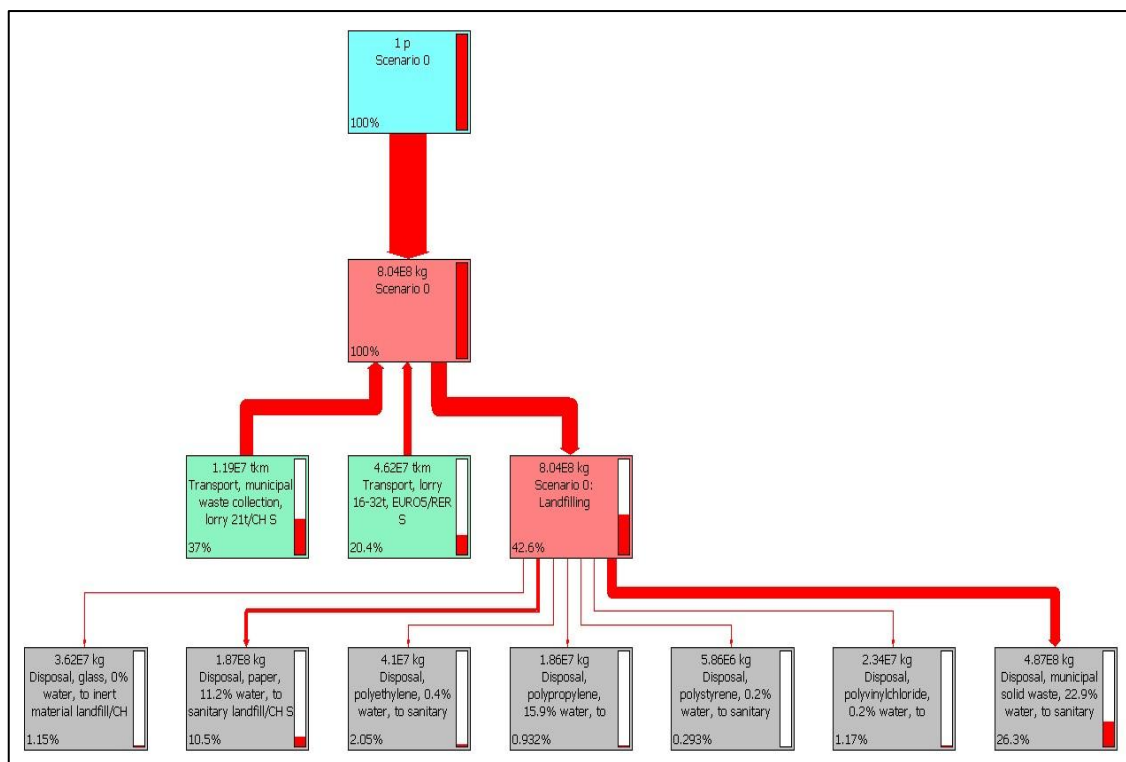


Figure I.10.: Network chart flow for Scenario 0, which refers to abiotic depletion as resulted from CML 2001 method (SimaPro software).

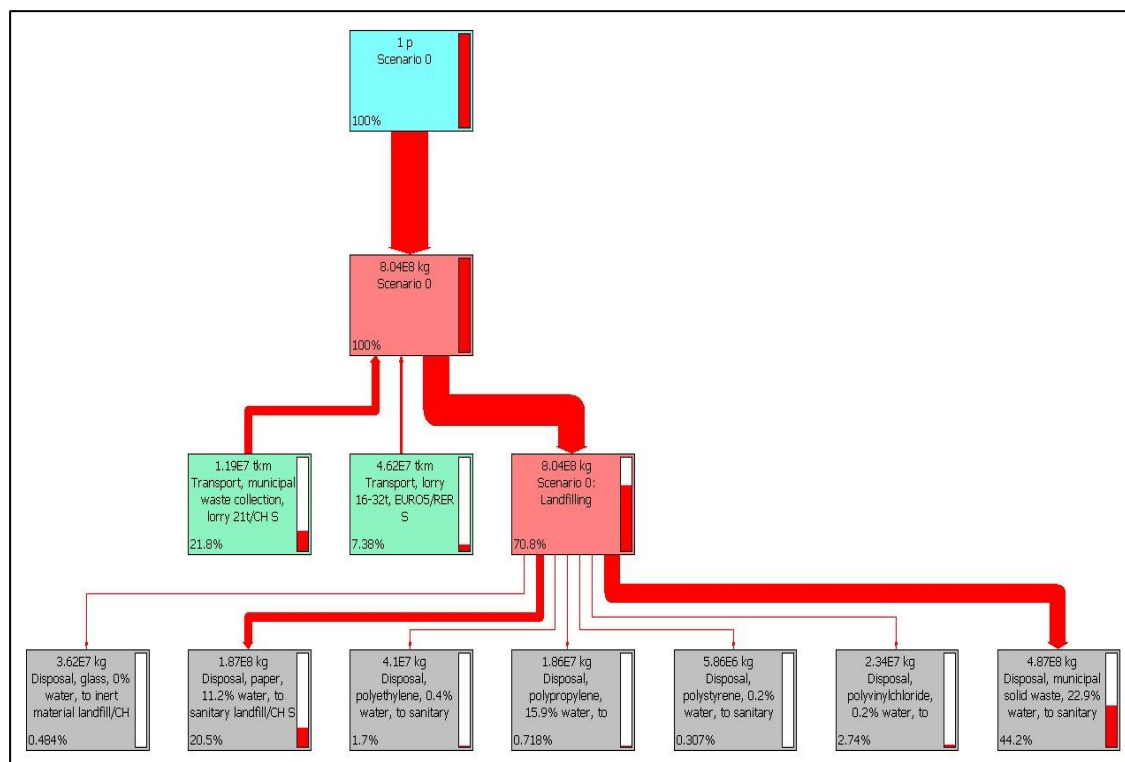


Figure I.11.: Network chart flow for Scenario 0, which refers to acidification as resulted from CML 2001 method (SimaPro software).

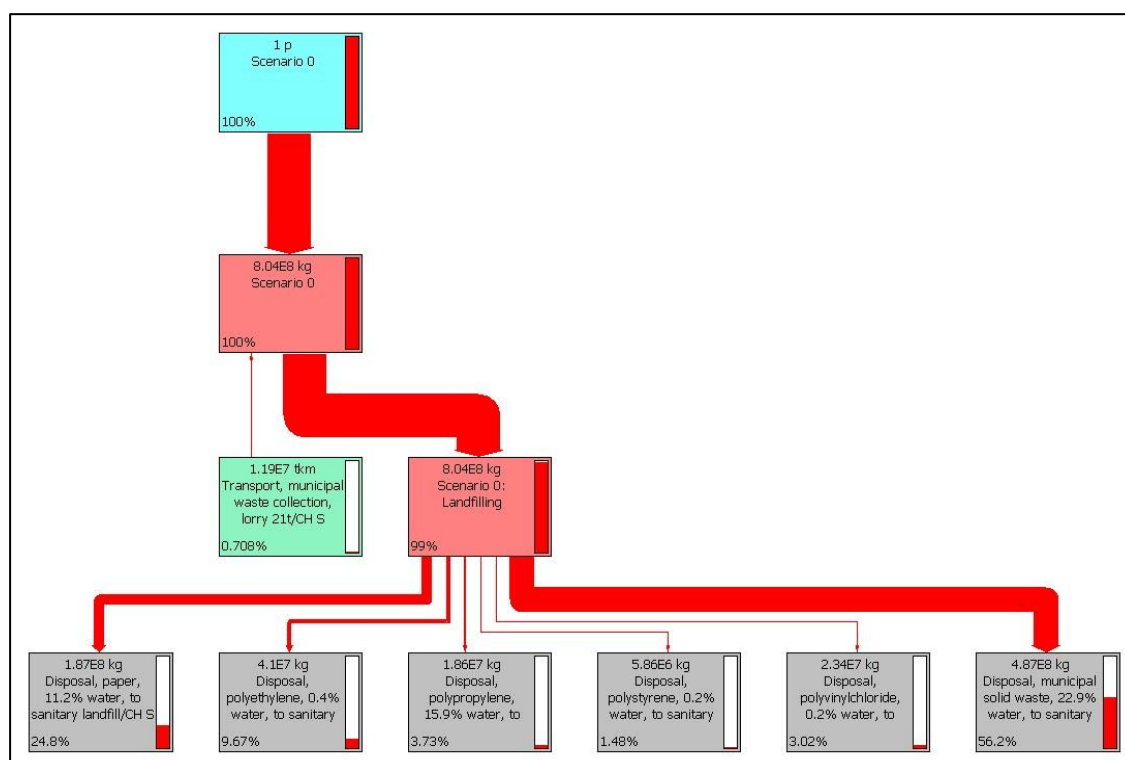


Figure I.12.: Network chart flow for Scenario 0, which refers to eutrophication as resulted from CML 2001 method (SimaPro software).

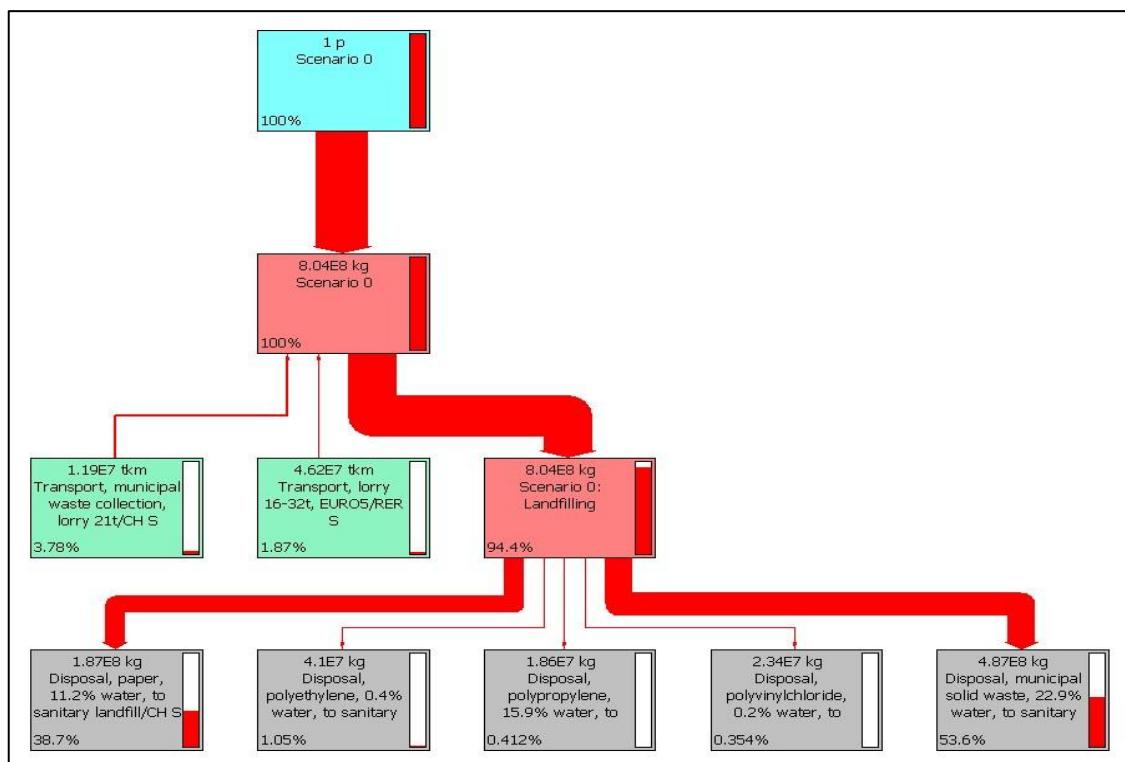


Figure I.13.: Network chart flow for Scenario 0, which refers to global warming as resulted from CML 2001 method (SimaPro software).

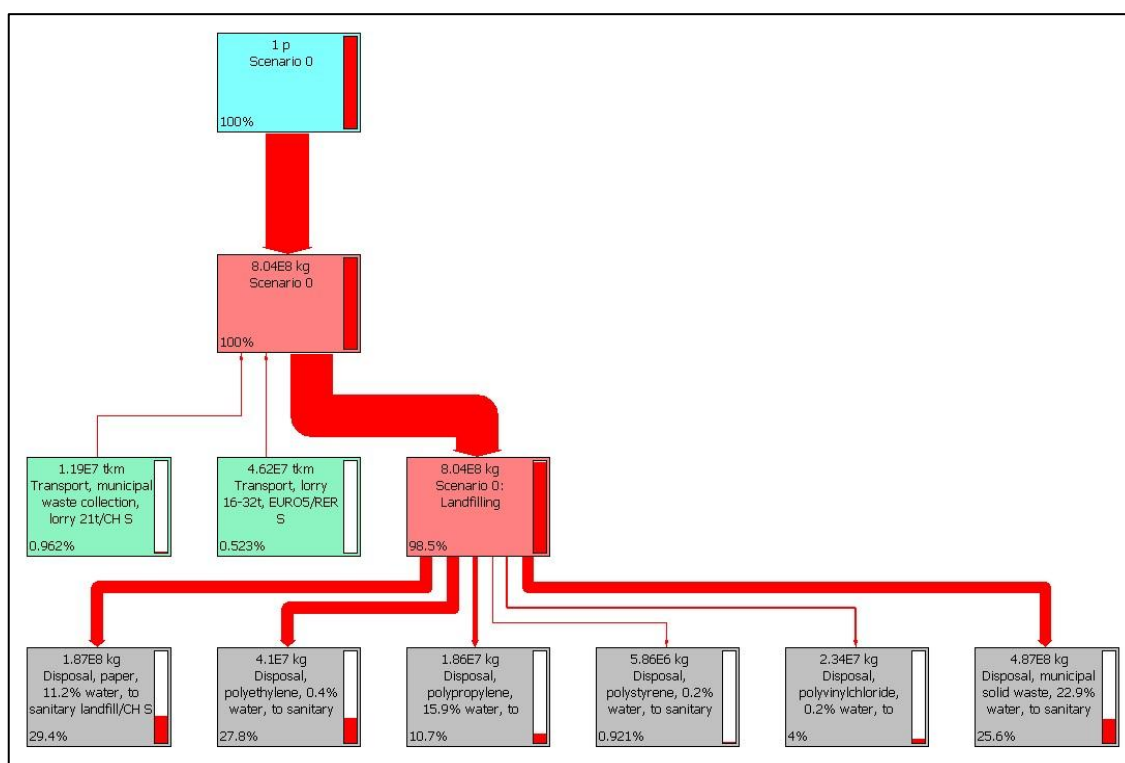


Figure I.14.: Network chart flow for Scenario 0, which refers to human toxicity as resulted from CML 2001 method (SimaPro software).

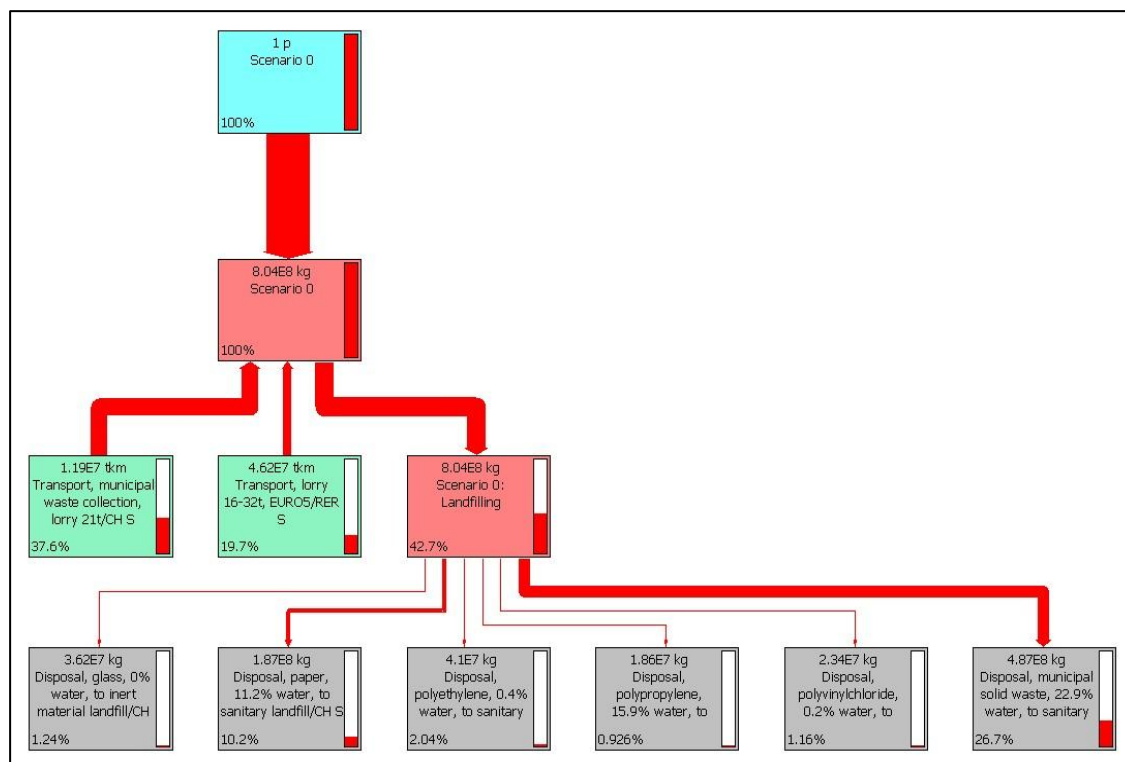


Figure I.15.: Network chart flow for Scenario 0, which refers to ozone layer depletion as resulted from CML 2001 method (SimaPro software).

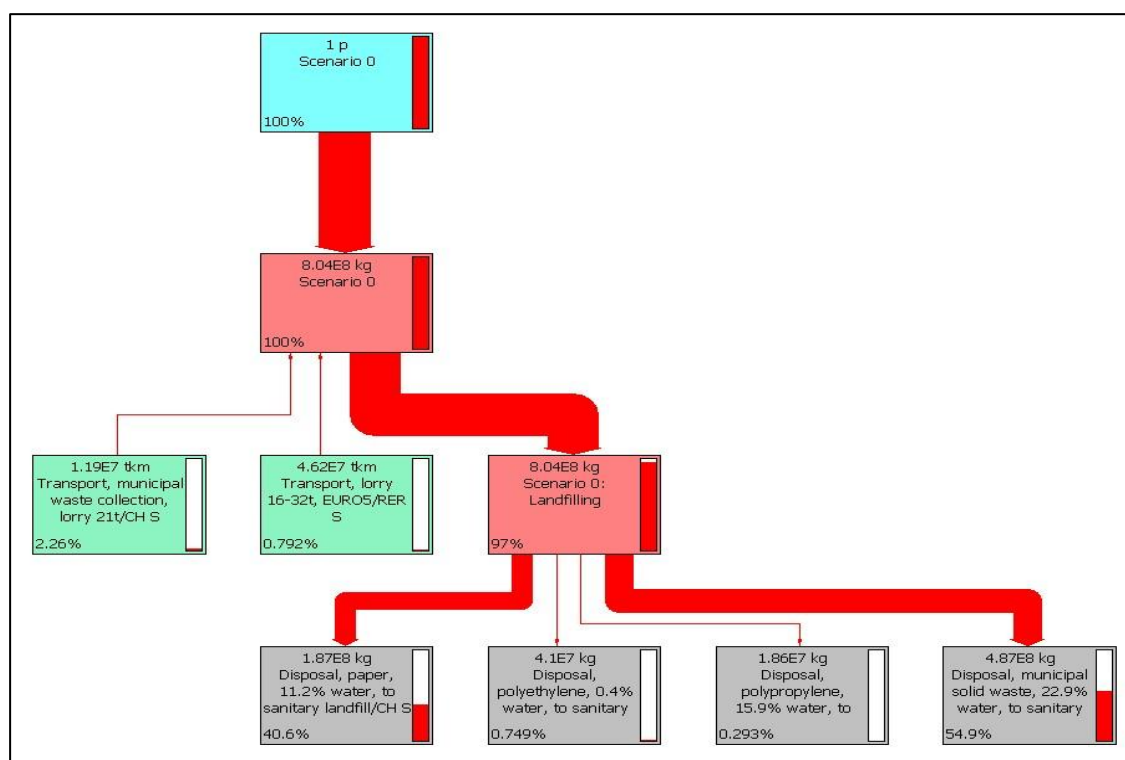


Figure I.16.: Network chart flow for Scenario 0, which refers to photochemical oxidation as resulted from CML 2001 method (SimaPro software).

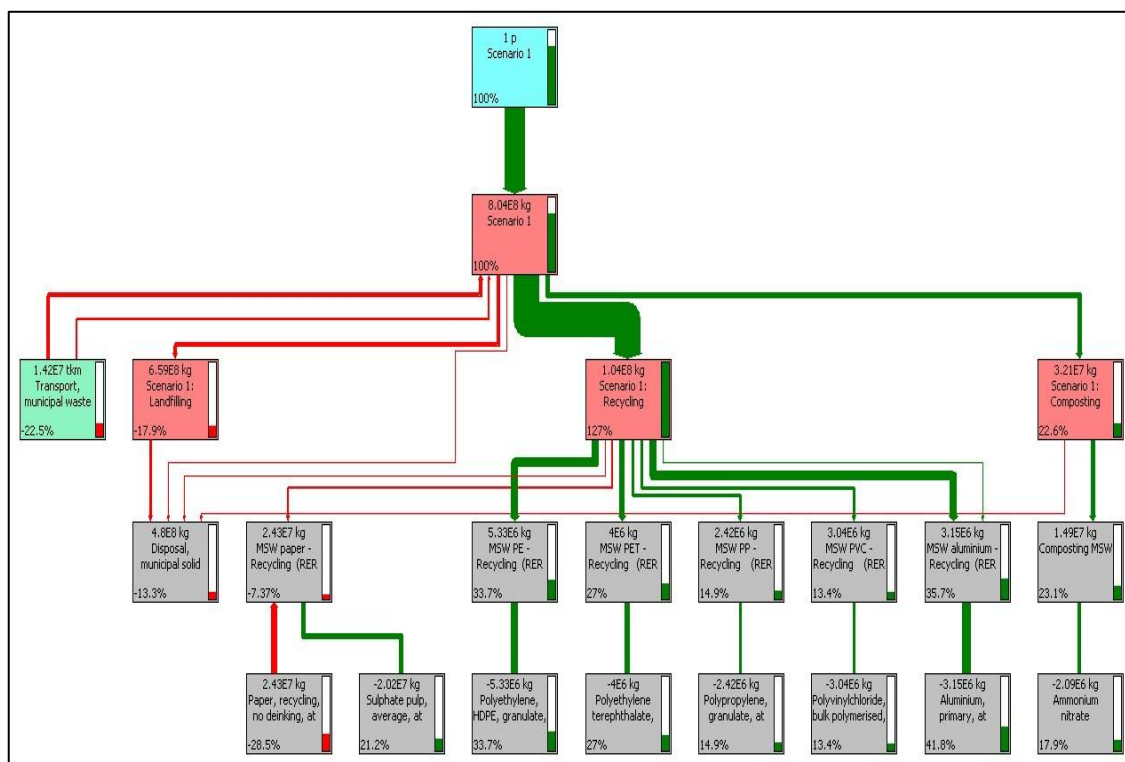
Scenario 1

Figure I.17.: Network chart flow for Scenario 1, which refers to abiotic depletion as resulted from CML 2001 method (SimaPro software).

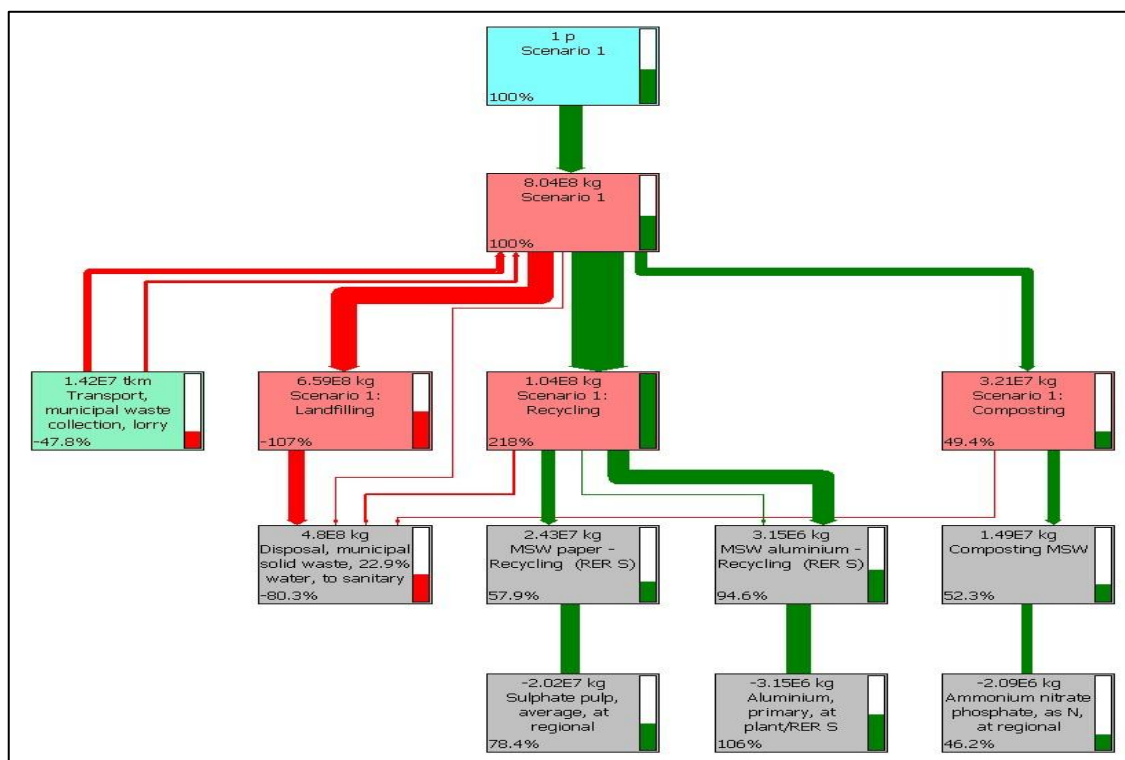


Figure I.18.: Network chart flow for Scenario 1, which refers to acidification as resulted from CML 2001 method (SimaPro software).

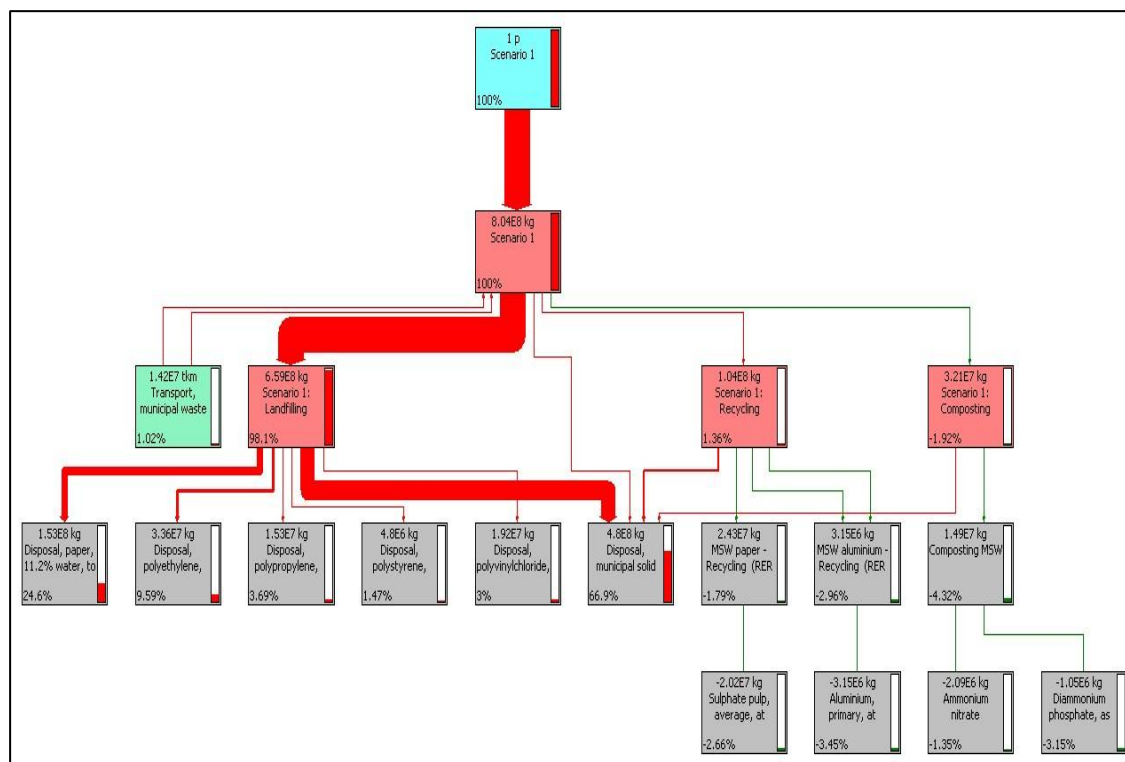


Figure I.19.: Network chart flow for Scenario 1, which refers to eutrophication as resulted from CML 2001 method (SimaPro software).

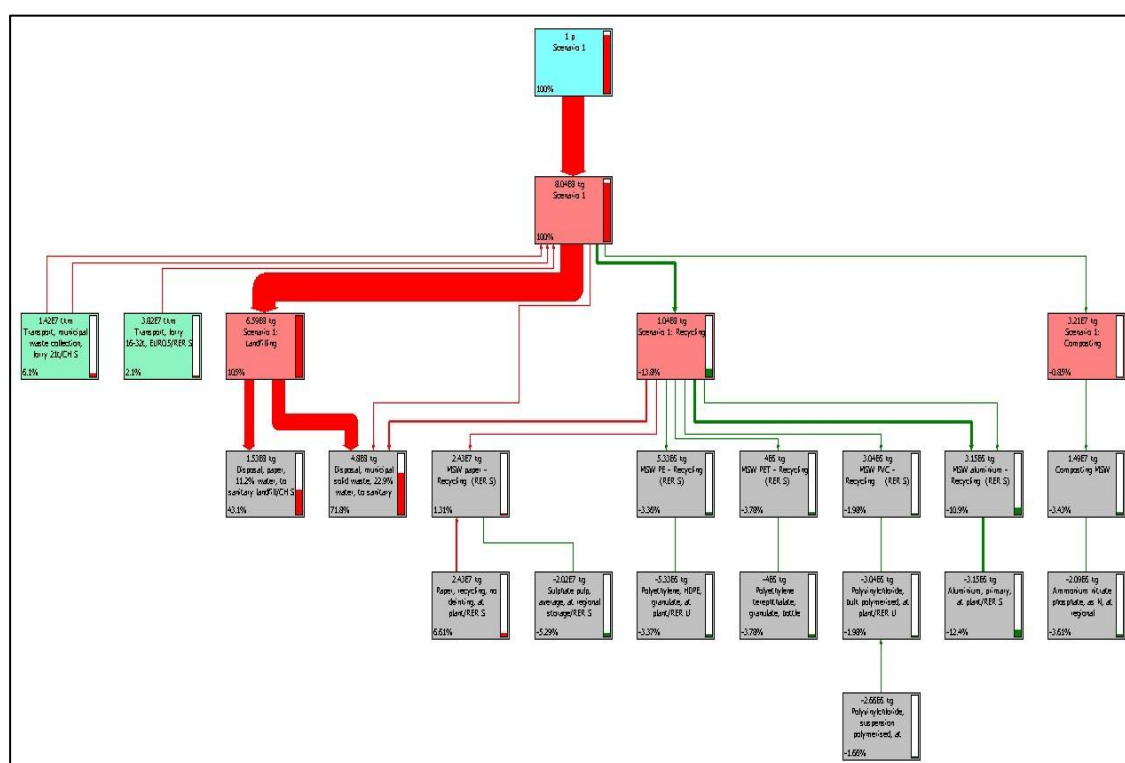


Figure I.20.: Network chart flow for Scenario 1, which refers to global warming as resulted from CML 2001 method (SimaPro software).

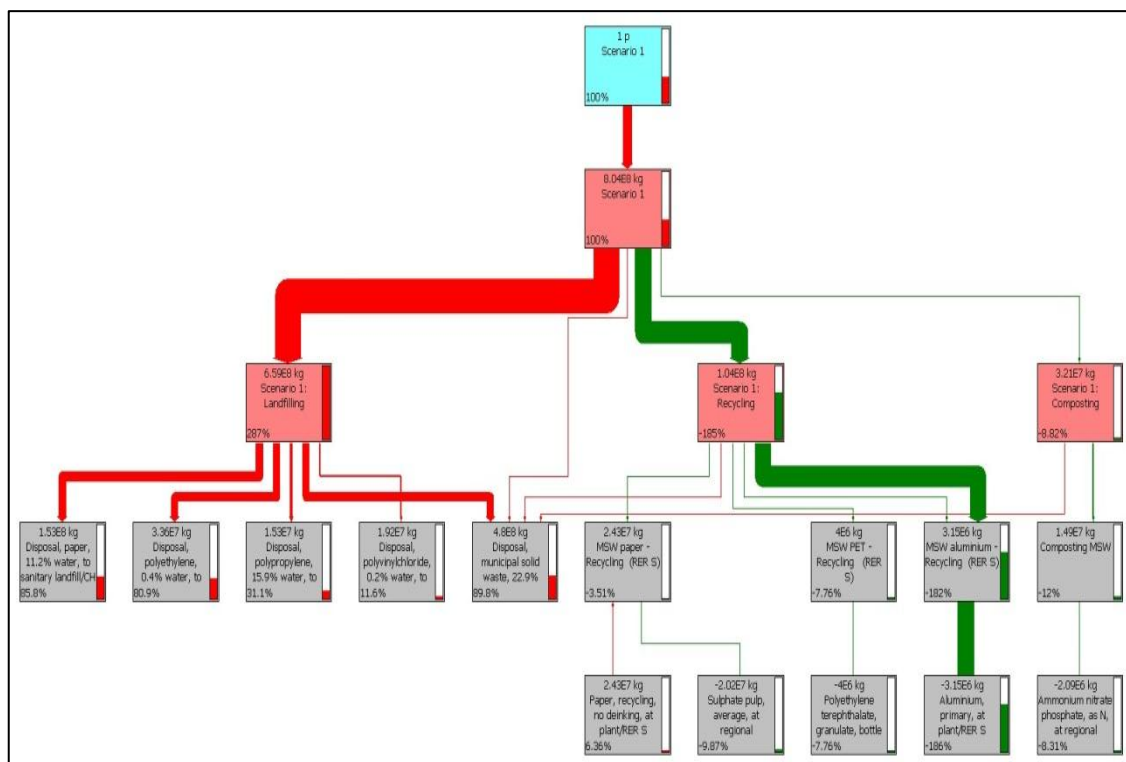


Figure I.21.: Network chart flow for Scenario 1, which refers to human toxicity as resulted from CML 2001 method (SimaPro software).

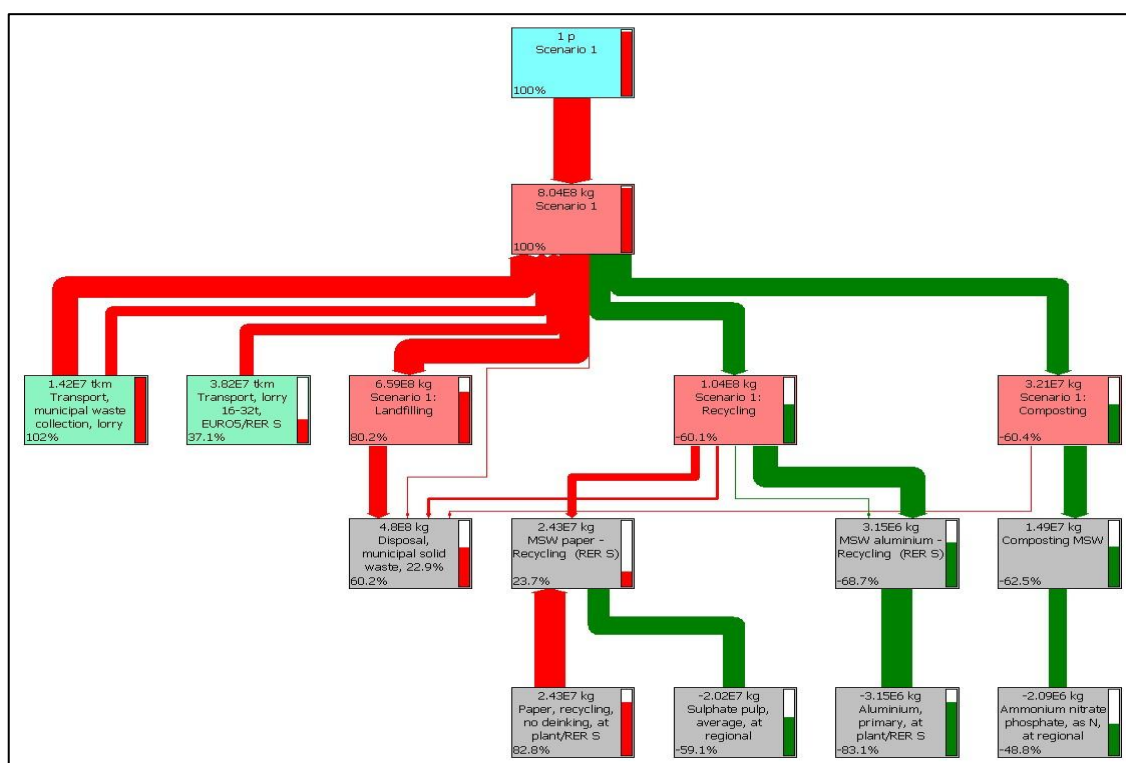


Figure I.22.: Network chart flow for Scenario 1, which refers to ozone layer depletion as resulted from CML 2001 method (SimaPro software).

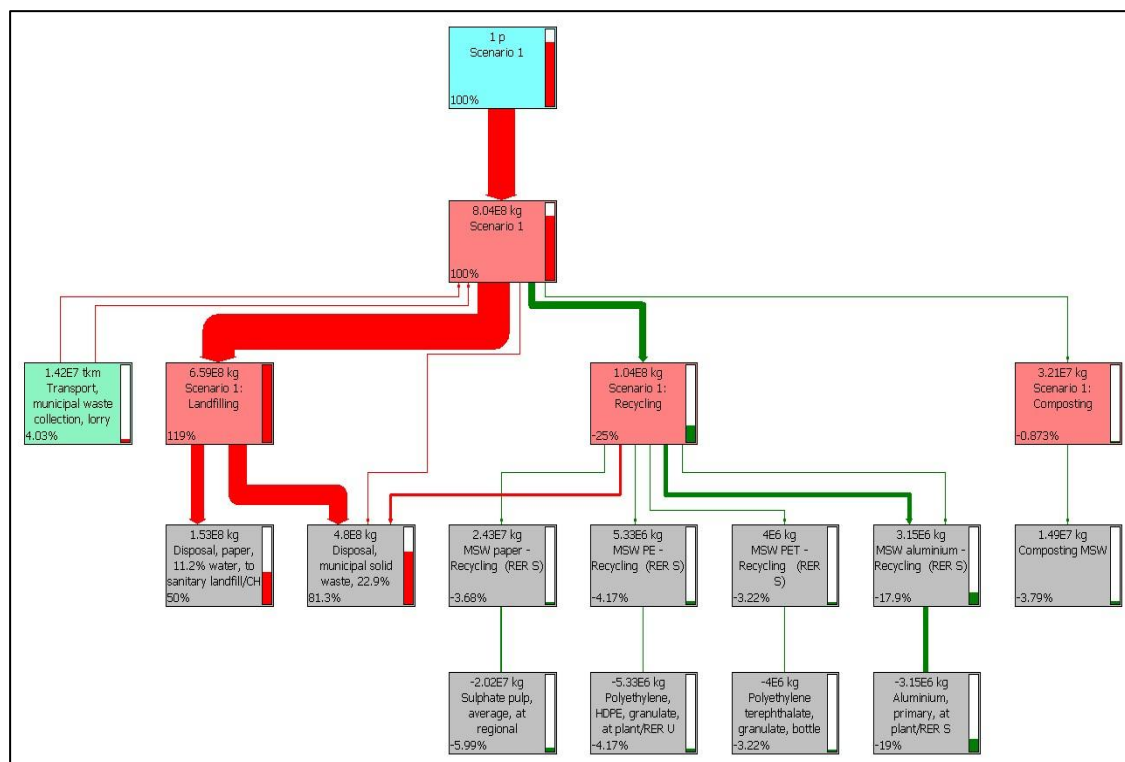


Figure I.23.: Network chart flow for Scenario 1, which refers to photochemical oxidation as resulted from CML 2001 method (SimaPro software).

Scenario 2

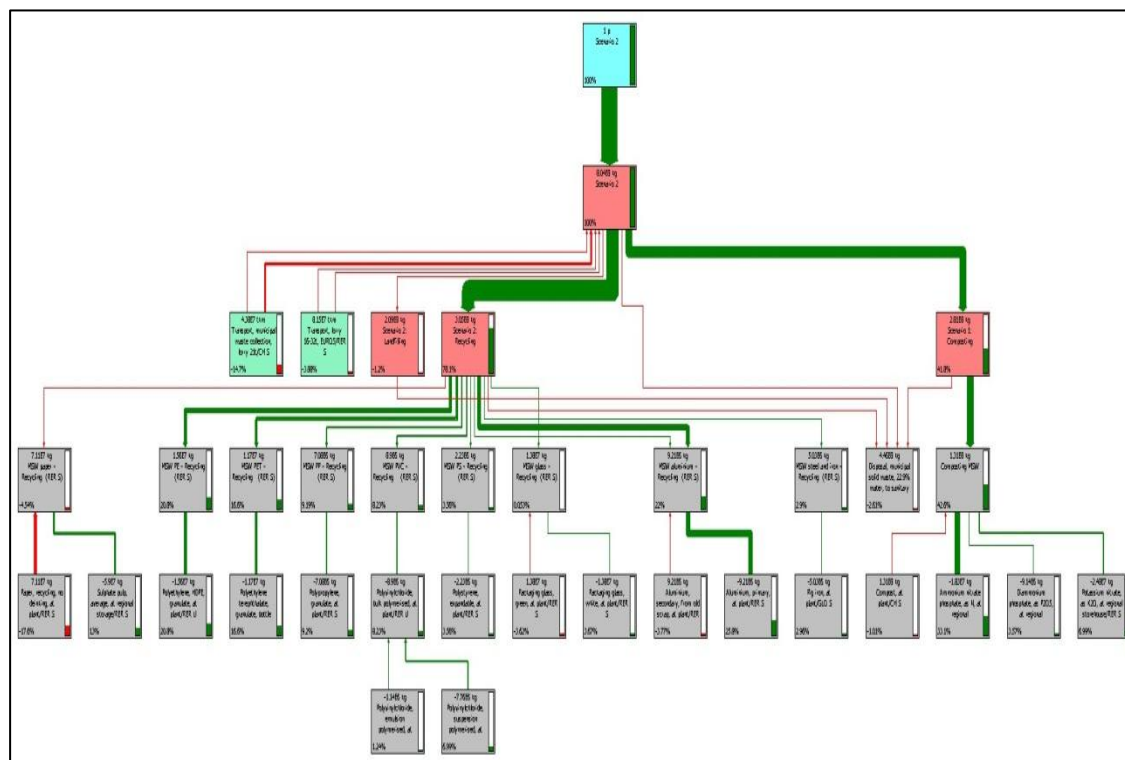


Figure I.24.: Network chart flow for Scenario 2, which refers to abiotic depletion as resulted from CML 2001 method (SimaPro software).

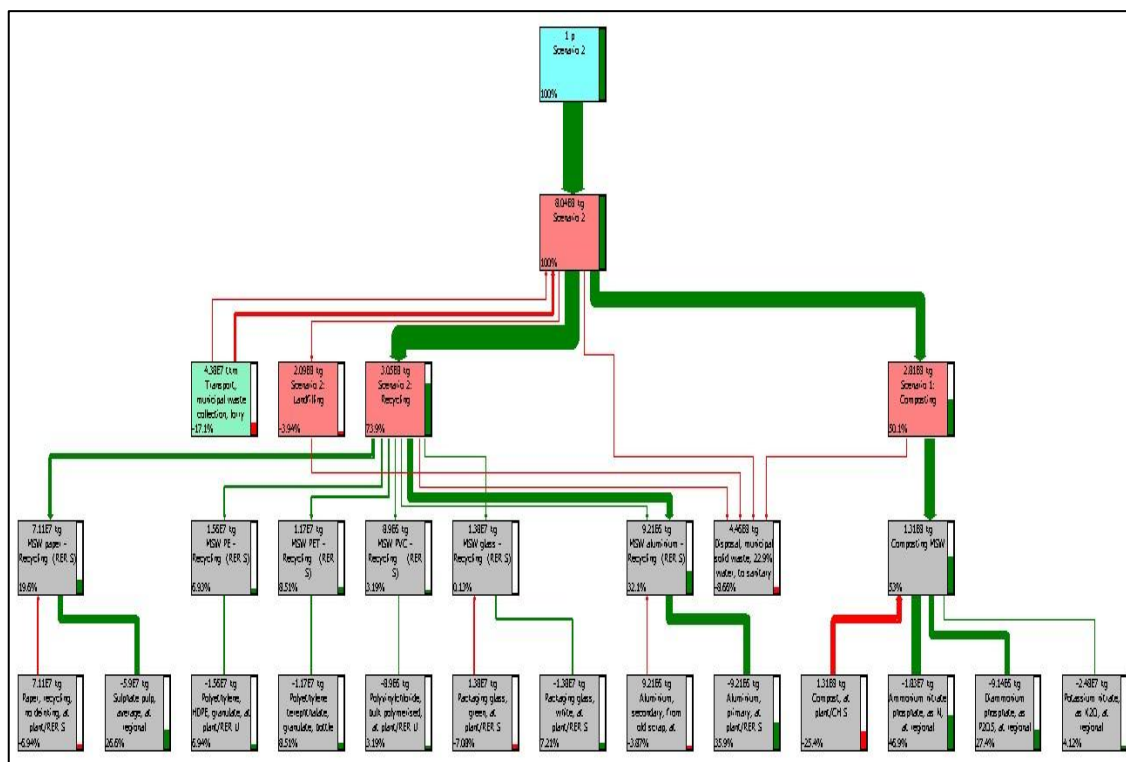


Figure I.25.: Network chart flow for Scenario 2, which refers to acidification as resulted from CML 2001 method (SimaPro software).

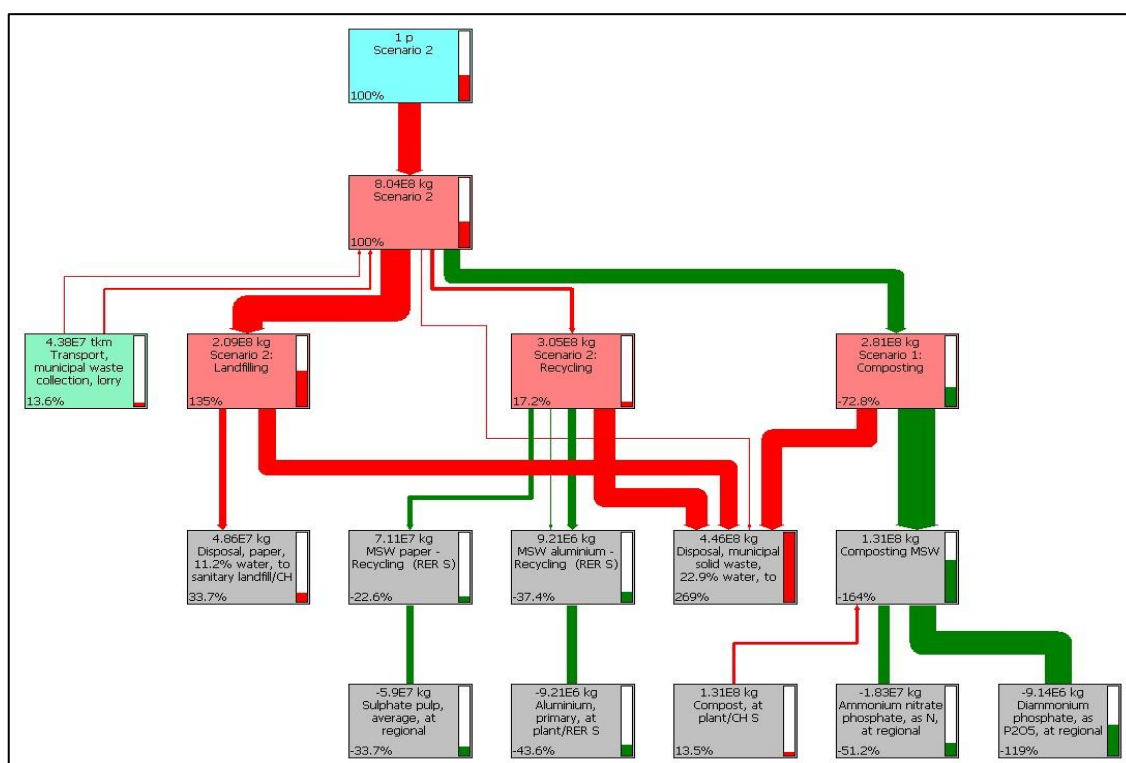


Figure I.26.: Network chart flow for Scenario 2, which refers to eutrophication as resulted from CML 2001 method (SimaPro software).

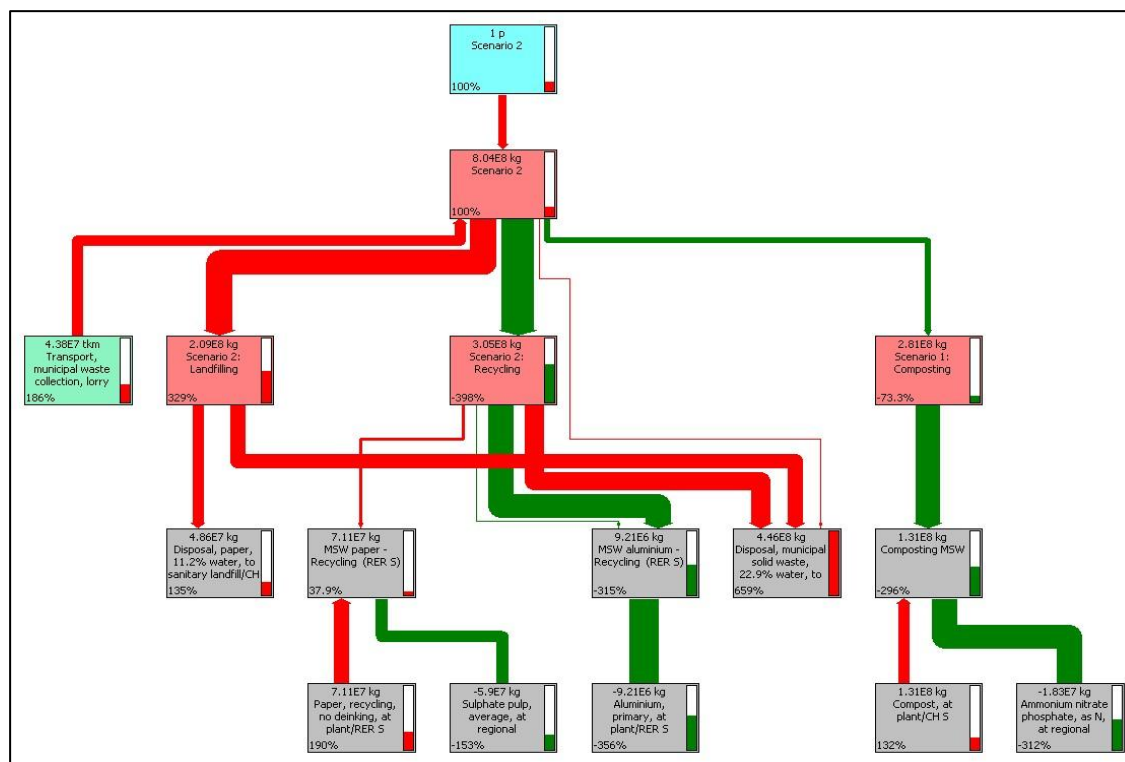


Figure I.27.: Network chart flow for Scenario 2, which refers to global warming as resulted from CML 2001 method (SimaPro software).

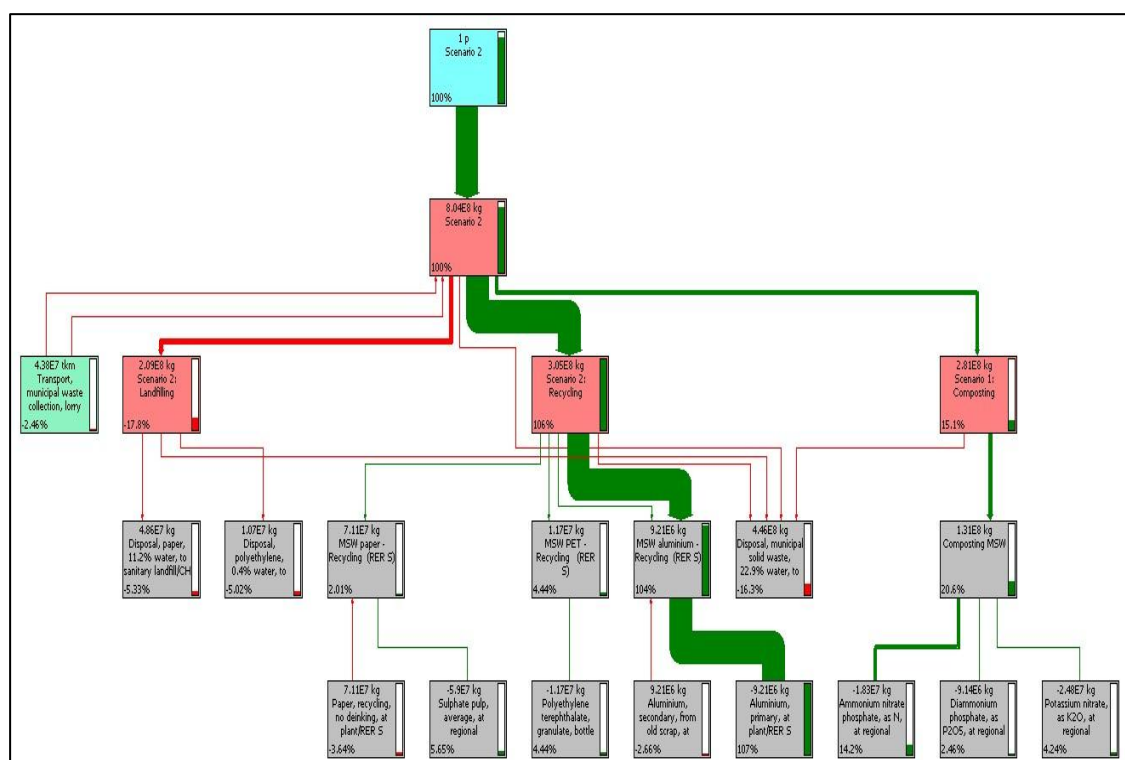


Figure I.28.: Network chart flow for Scenario 2, which refers to human toxicity as resulted from CML 2001 method (SimaPro software).

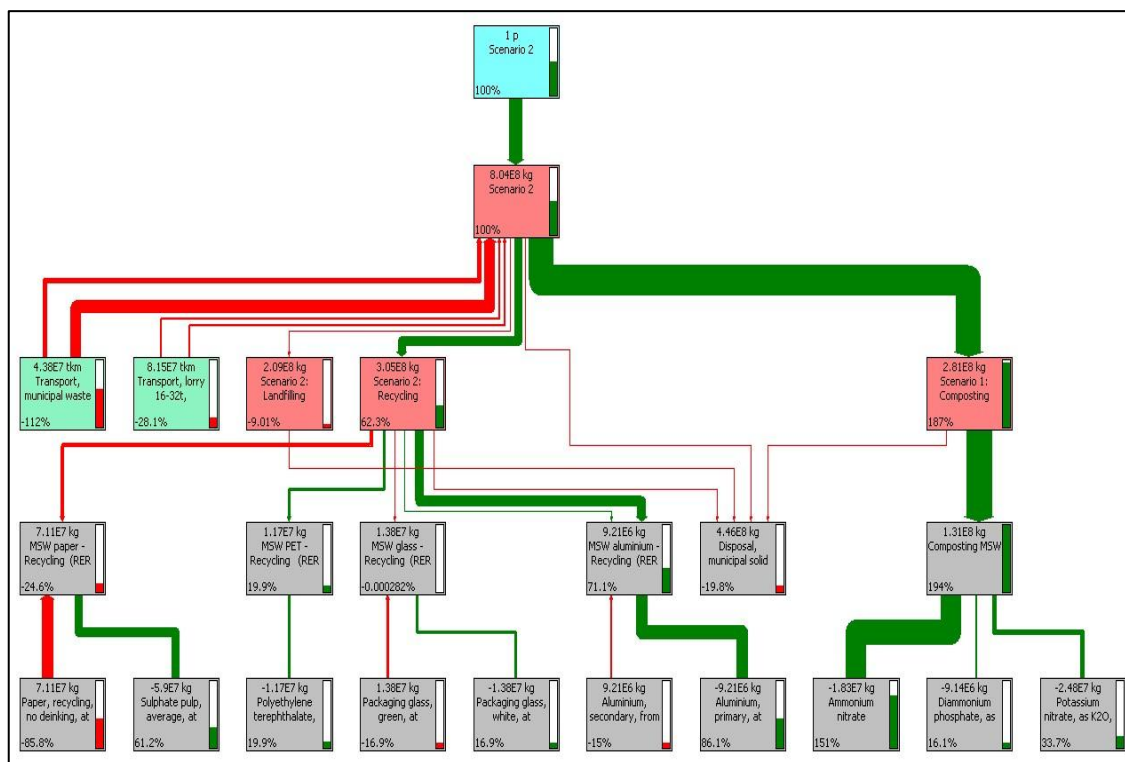


Figure I.29.: Network chart flow for Scenario 2, which refers to ozone layer depletion as resulted from CML 2001 method (SimaPro software).

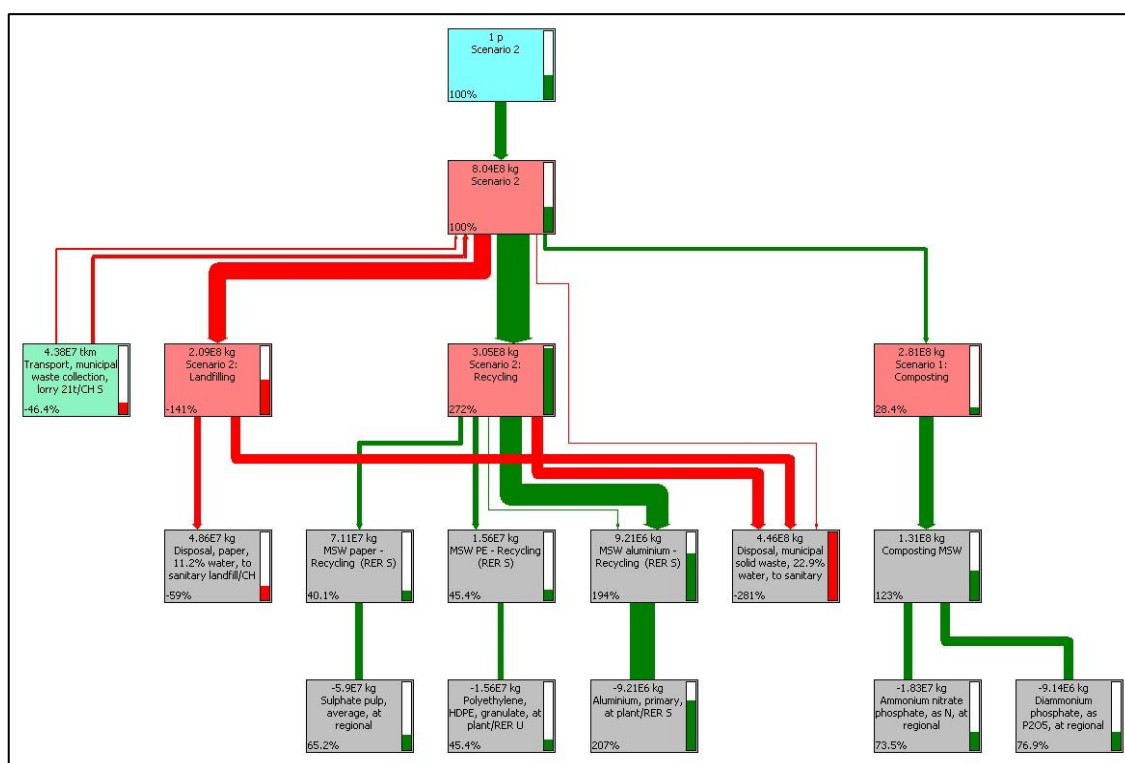


Figure I.30.: Network chart flow for Scenario 2, which refers to photochemical oxidation as resulted from CML 2001 method (SimaPro software).

