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# Waste management in Forlì-Cesena province: Life Cycle Assessment (LCA) of Forlì incinerator

Tesi di laurea in: Sistemi di Gestione Ambientale, di Politica ed Economia Ambientale

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# ABBREVIATIONS

$AlO_3$ - Aluminum oxide

APC - Air Pollution Control

BMW - Biodegradable Municipal Waste

$CaCO_3$ - Calcium carbonate

CaO - Quicklime

CHP - Combined Heat and Power

DCB - Dichlorobenzene

EC - European Community

EEA - European Environmental Agency

EIA - Environmental Integrated Authorization

$Fe_2O_3$ - Iron(III) oxide

$FeSO_4x7H_2O$ - Hydrated iron sulphate

$H_2S$ - Hydrogen sulphide

LHV - Lower Heating Value

MTB - Mechanical Biological Treatment

MSW - Municipal Solid Waste

MSWI - Municipal Solid Waste Incinerator

$Na_2CO_3$ - Sodium carbonate

$NaHCO_3$ - Sodium bicarbonate

NaOH - Sodium hydroxide

$NH_3$ - Ammonia

$NO_x$ - Nitrogen oxides

PCDD - Polychlorinated dibenzodioxins

PCDF - Polychlorinated dibenzofurans

PM - Particulate matter

$PO_4^{3-}$ - Phosphate

RCP - Residual Calcium Product

RDF - Refuse Derived Fuel

RSP - Residual Sodic Product

SCR - Selective Catalytic Reduction

SCW - Separate Collection Waste

$SiO_2$ - Silica

SNCR - Selective Non Catalytic Reduction

SOF - Stabilized Organic Fraction

$SO_x$ - Sulphide oxides

$TiO_2$ - Titanium dioxide

TOC - Total Organic Carbon

UW - Unsorted Waste

WEEE - Waste Electrical and Electronic Equipment

WTE - Waste To Energy

# ABSTRACT

This work assesses the environmental impact of a municipal solid waste incinerator with energy recovery in Forlì-Cesena province (Emilia-Romagna region, Italy). The methodology used is Life Cycle Assessment (LCA). As the plant already applies the best technologies available in waste treatment, this study focuses on the fate of the residues (bottom and fly ash) produced during combustion. Nine scenarios are made, based on different ash treatment disposing/recycling techniques. The functional unit is the amount of waste incinerated in 2011. Boundaries are set from waste arrival in the plant to the disposal/recovery of the residues produced, with energy recovery. Only the operative period is considered. Software used is GaBi 4 and the LCIA method used is CML2001. The impact categories analyzed are: abiotic depletion, acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, ozone layer depletion, photochemical oxidant formation, terrestrial ecotoxicity and primary energy demand. Most of the data are taken from Herambiente. When primary data are not available, data from Ecoinvent and GaBi databases or literature data are used. The whole incineration process is sustainable, due to the relevant avoided impact given by co-generator. As far as regards bottom ash treatment, the most influential process is the impact savings from iron recovery. Bottom ash recycling in road construction or as building material are both valid alternatives, even if the first option faces legislative limits in Italy. Regarding fly ash inertization, the adding of cement and Ferrox treatment results the most feasible alternatives. However, this inertized fly ash can maintain its hazardous nature. The only method to ensure the stability of an inertized fly ash is to couple two different stabilization treatments. Ash stabilization technologies shall improve with the same rate of the flexibility of the national legislation about incineration residues recycling.

# 1 INTRODUCTION

## 1.1 Overview on waste management in Europe

According to Waste Framework Directive 2008/98/EC, waste management consists in *collection, transport, recovery and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker*. MSW management is a widely discussed issue in European countries, because of its fundamental importance. Currently, waste production is strictly correlated to the wealth of a country: the aim of the European strategy is to decouple these two parameters, in order to demonstrate that economical growth is possible without producing more and more waste.

Many European directives expressed about waste management, and influenced its application. One of the fundamental is **Directive 1994/62/EC on packaging and packaging waste** (Packaging Directive). It states that an amount of packaging waste between 50% and 65% had to be recovered, i.e. recycled or incinerated with energy recovery, within 2001. This percentage had to become at least 60% from 2008. Within the end of 2008, the following recycling percentages had to be reached for the packaging materials: 60% for glass, paper and paperboard; 50% for metals; 22.5% for plastic; 15% for wood.

Another essential normative is **Landfill Directive 1999/31/EC**, that sets up targets for Member States in order to reduce the amount of BMW going to landfill, as it is the most inexpensive and simple method to manage non- recyclable MSW (Karagiannidis et al., 2013). This directive states that BMW going to landfill had to be reduced to 75% within 2006; to 50% within 2009 and then to 35% within 2016. Percentages relate to the amount of biodegradable waste produced in Europe in 1995. It also states that waste can be landfilled only if it is submitted to a **pretreatment**. This term includes all the processes that change the characteristics of waste, in order to reduce its volume or its hazardous nature, to facilitate is handling or enhance recovery (Art 1 Landfill Directive). This directive had a great impact in locations where the process of shifting away from landfill was not already under way, such as in Italy (EEA, 2009).

**Incineration Directive 2000/76/EC** sets emission limits for waste incineration and co-incineration plants. Opportune measures must guarantee that: the plant is designed, equipped and is operated in such a manner that the heat generated during the incineration process is recovered as far as practicable. In addition to this, the residues have to be minimized in their amount and harmfulness and recycled where appropriate, or disposed if recycling is not possible. The permit for an incineration plant shall include the total waste incinerating capacity of the plant; in addition to this, the sampling and measurement procedures used to satisfy the obligations imposed for periodic measurements of air and water pollutants has to be specified.

**Waste Framework Directive 2008/98/EC** introduces **waste hierarchy** (Figure 1.1), a priority order in management legislation and policy. The first option to apply when a substance/object becomes waste is the **prevention**: it means to let the substance not become waste. Member States have to encourage the design of products with low environmental impact: technically durable, suitable for multiple uses, with essential packaging and with materials safe to dispose. When preventing the creation of waste is not possible, **preparing for re-use** has to be applied. It consists in all the operations to make the waste re-usable with the same purpose it used to have before becoming waste. Therefore, this phase does not consider chemical/physical transformations. When these are unavoidable, waste is submitted to **recycling**, that performs a new product, that can be either the same or different from the object it was before becoming waste. When even recycling it is not possible, **energy recovery** has to be made. If any of the options above are not viable, the residual option for waste is **disposal** in landfills.

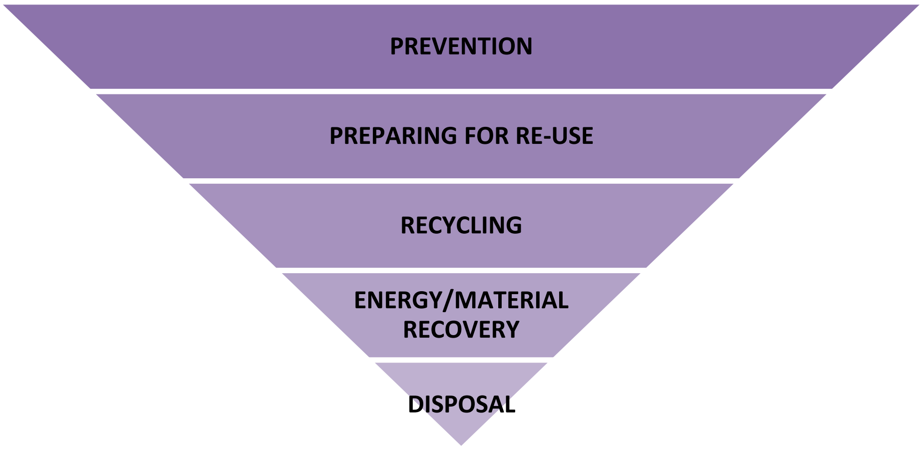


**Figure 1.1 Waste hierarchy as explained in Waste Framework Directive**

According to Waste Framework Directive, the European Commission proposes measures to support waste prevention activities: by 2020, at least 50% of waste materials such as paper, glass, metals and plastic must be prepared for re‑use or recycled. The minimum target set for construction and demolition waste is 70% within 2020 (EEA, 2009). This directive also states that incineration is considered a recovery operation only if plant efficiency is equal or above 0.60 for installations in operation and permitted in accordance with applicable Community legislation before 1 January 2009, 0.65 for installations permitted after 31 December 2008. As the facility analyzed is permitted with EIA n°237 of 29 April 2008, its efficiency must be equal or above 0.6. This value is calculated through this formula:

**$(E_p - (E_f + E_i))/(0.97 \times (E_w + E_f))$**, where:

$E_p$: annual energy produced as heat or electricity. It is calculated with energy in the form of electricity being multiplied by 2.6 and heat produced for commercial use multiplied by 1.1 (GJ/year);

$E_f$: annual energy input to the system from fuels contributing to the production of steam (GJ/year);

$E_w$: annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year);

$E_i$: annual energy imported excluding $E_w$ and $E_f$ (GJ/year);

0.97 is a factor accounting for energy losses due to bottom ash and radiation.

These directives and other waste legislation with similar goals influenced widely waste management in the last decade. Figure 1.2 shows the development of municipal solid waste management in Europe in the last ten years. It is possible to observe that has been a shift in waste hierarchy between 2001 and 2010. Landfilling decreased by almost 40 Mt, due to the closure of dumpsites. Incineration increased significantly by 15 Mt because governments have tightened emissions standards, although the rate of growth has varied widely in the areas studied. Last but not least, recycling increased by 39 Mt. It is notable that the amount of waste recycled has been steady from 2008, as the amount of waste produced, because of the application of the principle of waste prevention (EEA, 2013).

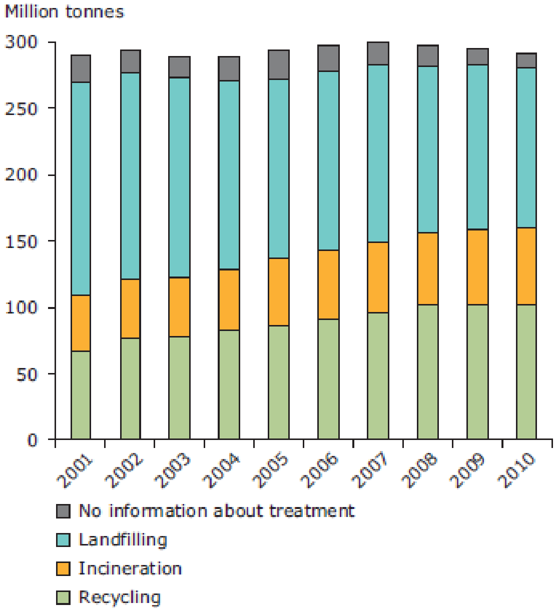


**Figure 1.2 Development of municipal solid waste management in 32 European countries, 2001-2010 (EEA, 2013)**

Focusing on single Member States, they can be distinguished among three waste management "groupings". The first grouping is characterized by high levels of both material recovery and incineration, and with relatively low landfill levels. Countries in this group (Scandinavian and Central Europe countries) generally introduced several policy instruments before the adoption of the directives exposed above. The second grouping brings together countries with high material recovery rates and medium levels of incineration, and with a medium dependence on landfill (Italy, Spain, Great Britain): they introduced policy instruments only after adopting the waste directives above. The third grouping contains countries with low recovery and incineration levels and with high dependence on landfill. This group comprises the majority of the EU‑13 Member States in the process of implementing EU regulations.

## 1.2 Waste legislation in Italy

Italy is characterized by an high material recovery rate and medium levels of incineration, with a medium dependence on landfill. Every "optimal area for the management of waste" (*Ambito Territoriale Ottimale*, ATO, in Italian) has to meet a set of national targets imposed by European directives. ATOs represent a geographical entity where waste management is economically feasible and generally correspond to province boundaries. Italy provinces have an average extension of about 2750 km$^2$. In every Italy province, waste management is applied following the prescriptions of the Provincial Waste Management Plan (*Piano Provinciale della Gestione dei Rifiuti*, PPGR, in Italian). It identifies goals, instruments and actions in order to put into effect waste policies. The plan is oriented to the application of actions and measures able to conform to waste hierarchy, to support reduction of waste hazard and to improve recycling levels. As a result, Italy has continuously decreased municipal waste landfilling; however, there is a considerable difference between the performance of the northern regions and the southern and central regions (EEA, 2009).

Italy put into effect the Landfill Directive with **decree law 36/03**. Instead of transposing the percentage‑based targets, Italy used the amount of BMW produced per capita. That decision was taken due to the lack of reliable data on the amount of biodegradable municipal waste landfilled in 1995 (EEA, 2009). Targets were defined for 2008 (BMW going to landfill lower than 173 kg/(y*inhabitant)), 2011 (lower than 115 kg/(y*inhabitant)), and 2018 (lower than 81 kg/(y*inhabitant)). Also, this decree states that waste with a calorific value higher than

13,000 kJ/kg cannot be landfilled from 2007. Actually, meeting of Landfill Directive targets seems difficult, because BMW generation increased by 20% until 2005. A lot of Italy regions are still far from achieving the 2008 target, particularly in southern and central Italy. On the other hand, there has been a slow but steady increase in separate collection of biodegradable fractions of municipal waste since 2000. Even in this case, the difference between the northern part and the rest of Italy is remarkable. Separate collection was 40% in the northern in 2006, against 10% in the southern and 20% in central Italy. Moreover, it seems that growth in separate collection has leveled off in the south and centre since 2003.

In 2006, Italy incorporated in **decree law 152/06** the old Ronchi decree law (n° 22/97), the Packaging Directive and many other directives about air and water pollution. This new decree law sets targets for separate collection of municipal waste. Targets aimed at 35% of separate collection by 2003, 40% within the end of 2007, 50% within the end of 2009 and 65% within the end of 2012. Italy has not been able to reach any of the targets, even if in northern Italy some local policy makers set more ambitious targets, that only them could realistically achieve due to a well organized waste management system.

Incinerators spreading has been improved by **Provision 6/1992** of Interministerial Price Committee n°6 (*Comitato Interministeriale Prezzi*, CIP6, in Italian), that states that plants fed by incinerated waste can be assimilated to plants working with renewable sources. This is in contrast with European legislation, that states that only fuels made from biodegradable fraction of waste can be considerate renewable sources. This measure was applied to improve the construction of WTE plants, even if in some Italian realities these incentives have been applied without respecting the prescriptions of the directives above. Although in some regions these investments have been planned in the correct way, they have the opposition of local people because of the hazard and the toxicity of incineration process. In northern regions, public acceptance increased the adoption of national guidelines on best available techniques for waste incineration. Instead, in southern regions efforts have been channeled into RDF production by shredding and dehydrating solid waste with a waste converter technology, in order to overcome dependency on landfill.

### 1.2.1 Waste management in Forlì-Cesena province

Forlì-Cesena province is characterized by a well organized waste management system. 2009 Report from Waste Observatory of Forlì-Cesena province shows that in 2009 separated collection rose from 42.8% to 45.7%: this is a relevant improvement, even if 50% target of separated collection stated in decree law 152/06 was not reached. Nevertheless, some local realities in the province have overcame this target, because of the complete implementation of the door-to-door waste collection system. From 2008 to 2009 waste production has increased only by 1%, mainly due to economical crisis: this demonstrates that this value is not correlated with recycling improvement. Per-capita waste production is very high (751 kg/inhabitant): this is due to the touristic fluxes in some cities of the province, and due to the presence of a lot of activities that produce waste similar in its nature and composition to household one. Figure 1.3 shows the MSW management in Forlì-Cesena province. It is possible to observe that the system tries to recover as much waste as possible, although in 2009 landfilled waste was still relevant. Nowadays the amount of waste sent to incinerator than in landfill is even higher, although waste fluxes are similar.

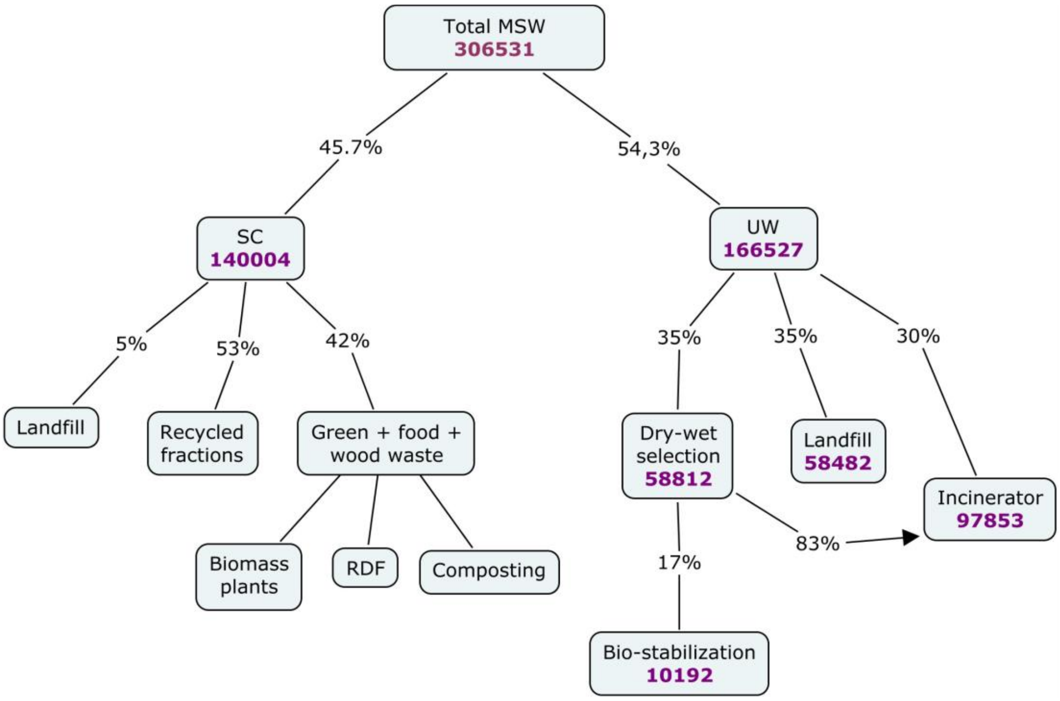


**Figure 1.3 MSW fluxes in Forlì-Cesena province. Data are taken from 2009 Report from provincial Waste Observatory; amounts are expressed in tons**

## 1.3 Forlì WTE plant

WTE plant analyzed is situated in the industrial zone of Forlì city. The plant opened in 1976: at that time, it was composed by two incineration lines treating globally 60,000 t/y of waste. It operated until January 2009, when it was closed down because of the previous opening of the newer incinerator line 3 (happened in July 2008), able to submit 120,000 t/y of waste. This new line includes a co-generator plant (CHP), i.e. it simultaneously generates heat and power by a heat engine. The plant site was awarded quality certification (ISO 9001) in 2004, whilst the new WTE treatment line was awarded ISO 14001 certification in 2009 and has EMAS registration n° IT - 001398 from 2011. Nowadays, lines 1 and 2 have been demolished, while line 3, after a running in phase, is the only one operative (the red building in Figure 1.4):

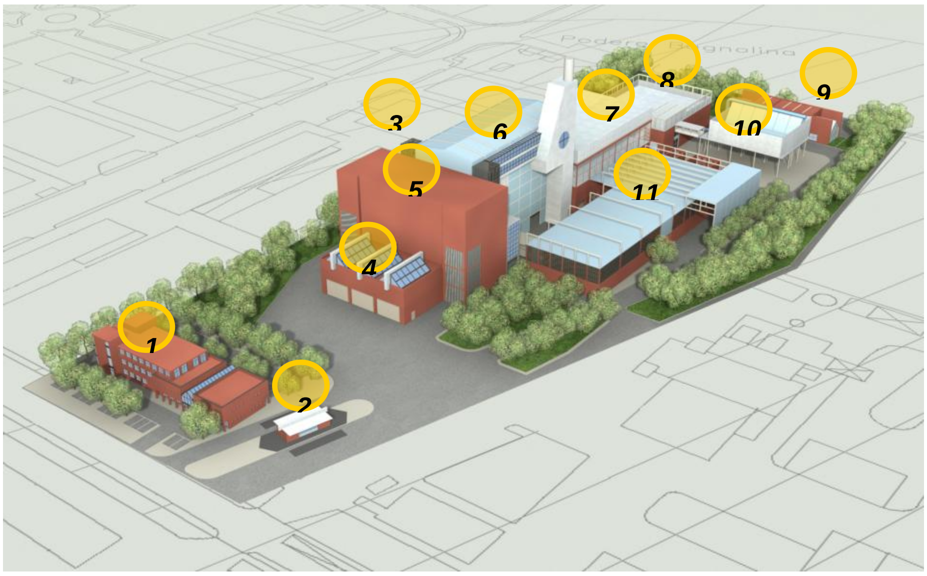


**Figure 1.4 View of the WTE plant (Herambiente, 2012 Environmental Declaration): it is composed by the following parts: 1) office + changing rooms (not realized yet); 2) reception + weigh station; 3) WTE plant, it includes the following: 4) foredeep discharge; 5) loading tank; 6) grid steam generator room; 7) flue gas cleaning room; 8) thermal cycle + auxiliary services room; 9) high-tension station; 10) steam condensation system; 11) bottom ash stocking room**

At the arrival at the site, all the waste coming from sorted and unsorted collection in Forlì-Cesena province is temporally stored in the **ecological platform.** It contains a weigh station and tanks to store solid and liquid waste. Tanks can contain: paper, paperboard, plastic, cans; wood; glass and inert waste; WEEE; and waste find abandoned on public land. Most of this waste is sent to recycling; only 1.1% of waste is disposed in landfills. The waste that cannot be recycled but from which energy can be recovered, goes to incineration. Almost 70,000 t/y of waste are sent to the **preselector** to be submitted to MBT. In his review, Valerio (2010) lists the advantages of MBTs: minimization of landfilled gas and volume, inactivation of biological processes, safer and easier separation of recyclable fractions. Cherubini and collaborators (2009) add the following advantages: higher heating value, more homogeneous chemical composition, easier storage, less emission factors. Also, preselector allows the removing of the bulky waste mistakenly put in the municipal collection, and stores the waste of a couple of days, so that it loses part of its moisture content. As in the tipping hall the air pressure is maintained slightly negative by taking in air for the combustion process, greenhouse gases emissions are unlikely to happen (Astrup et al., 2009). From October 2011 to the end of 2012, structural modifications of the preselector facility (not in activity in that period) have been made in order to increase the minimum amount of waste submitted to MBT from 60,000 to 70,000 t/y. The waste fractions going to the preselector are not different from the ones submitted directly to incineration. The second ones are directly sent to the loading tank, having a volume of 4,000 $m^3$, ready to be burned. In the preselector the waste is being **shredded**, to break down the bulky waste into 10 cm x 10 cm pieces, so that combustion has higher efficiency; then it is **sieved** trough a rotary vacuum-drum filter with 50 mm diameter holes, that splits the dry fraction from the wet one. The last one is collected, piled up and then sent to a facility to be transformed in SOF. The dry fraction goes, together with the amount of unsorted waste not submitted to preselector, to the loading tank trough the foredeep discharge, showed in Figure 1.5.

**Figure 1.5 Foredeep discharge (Herambiente, 2012 Environmental Declaration)**

An overhead crane mixes the waste: it helps to maintain a steady combustion process. Then, trough a furnace hopper, it feeds the waste to the **combustion grate**, that shakes and transports the waste through the combustion chamber. The grate is cooled by primary air blown from the loading tank zone after it is heated up to 220°C by three heat exchangers, in order to increase waste LHV. Then, the combustion takes place in 3 steps:

- **drying**: waste temperature rises fast to 80-100°C and then to 100-200°C. In these conditions, volatile chemicals contained in waste separate from the mass and rise towards the hottest zone of the camera, where their combustion happens;
- **injection and combustion**, aided by waste turbulence made up by secondary air blown from the loading tank zone. The furnace is designed to mix well these components, allowing the exposure of a larger waste surface area to air and high temperatures. Nevertheless, near the walls of the furnace the combustion does often not complete and the incombustible particulate matter is being left: it is known as fly ash, entrained in the flue gas.

- **complete combustion**: oxidation of the flammable residues of waste. These substances, stuck to the already burned particles, enter in contact with the necessary amount of air to let them burn. Combustion camera can incinerate until 16 t/h of waste. The incombustible residue of the combustion is called bottom ash, a stable product which is ejected at the bottom of the combustion chamber. The bottom ash corresponds to 23% by weight of the original waste. Incineration Directive 76/2000 impose the bottom ash TOC not to be above 3% by weight: in Forlì WTE plant, unburned waste is never above 3% of the amount of waste incinerated.

Gases emitted in the combustion phase go to **post-combustion camera**, in which they stay at least for 2 seconds at above 850°C (natural gas burners power on if the temperature goes below 850°C), with a concentration of 6% of $O_2$. This treatment is imposed in Incineration Directive. This stage is necessary to destroy PCDD/DF. Then, $NO_x$ are destroyed in part (50-70%), through **SNCR** system, occurring at 850°-1000°C:

- $NH_3$ 23-24% solution is sprayed into furnace;
- $H_2O$ used to dilute $NH_3$ evaporates;
- the dilution of reagents causes the decomposition of $NO_x$, with the formation of $N_2$, $CO_2$, $H_2O$.

The gases, having a temperature between 850°-1100°C, pass through an **irradiance chamber**. It is composed by channels separated by vertical walls, that impose the fumes to move inverting continuously their movement. This track promotes the falling of the fly ash: this also occurs in the following convective chamber, in which steam tubes are transversal to flue gas flow. Then, fly ash is gathered in a hopper and stocked in silos of 80 $m^3$. After the irradiance chamber, there is the **convective chamber**, that can be seen in Figure 1.6. In this room, flue gases exchange their heat with steam. First of all, flue gases pass through the EVA3131 evaporator bank, in which cool water flows in order to cool down fumes up to 500°C. This initial cooling is necessary, because temperatures above 500°C can promote ash incrustations on the tubes. Meanwhile, in the opposite part cool water enters the convective chamber, passing through a series of three economizers banks: fumes enter ECO3133 at 122°C, steam temperature rises until 186°C in ECO3131 economizer, therefore steam goes in the cylinder body CCV3131 above the convective chamber. Such tubes disposition is necessary to improve the cycle performance and to recovery most of flue gas heat through the economizers. In this way, flue gas coming out of the convective chamber has an adequate temperature for the following cleaning process (150°-180°C). CCV3131 cylinder steam is saturated because water in liquid state is present, too. From this cylinder, steam comes out with a temperature of 250°C, and goes into the heater banks (SH3131, SH3132 e SH3133), with which flue gases exchange heat until the steam into the tubes reaches a temperature of 380°C and 45 bar pressure. After the heater banks there is another evaporator (EVA3132), connected with the cylinder body CCV3131 as the first evaporator does. When waste combustion is not sufficient to keep these temperatures, natural gas is used as auxiliary fuel.

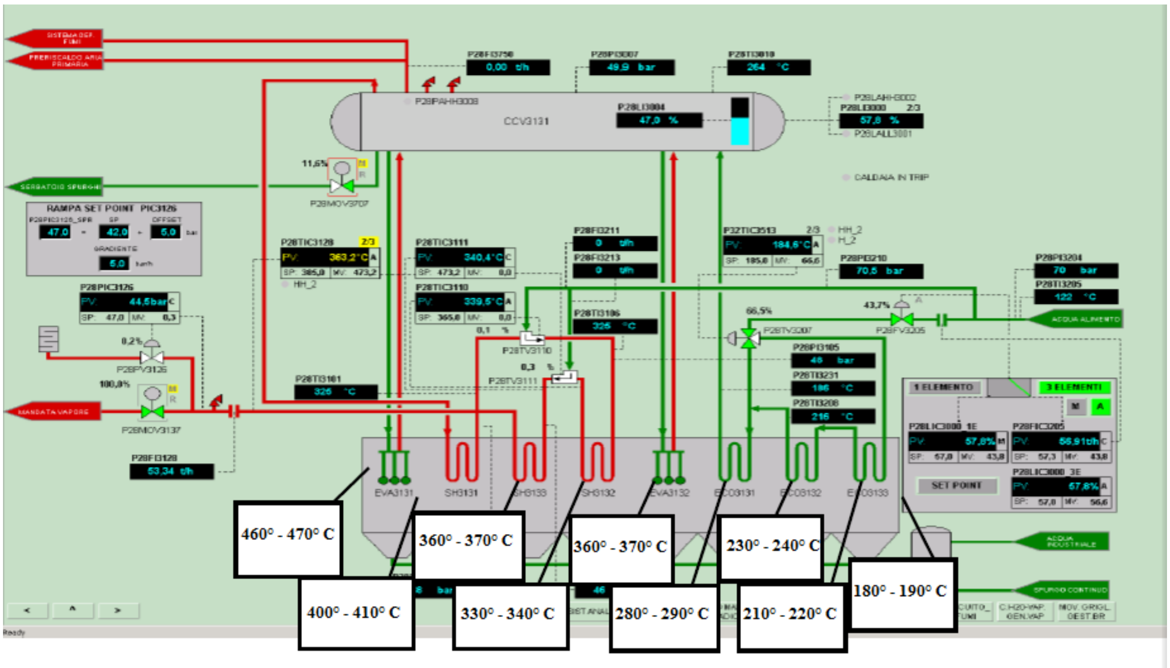


**Figure 1.6 Steam generator circuit. In squares the flue gases temperatures into the tubes are pointed out (Bozzi, 2011)**

Overheated steam goes into a **turbine** where it is expanded, therefore it is possible to convert thermal energy into mechanic energy. Exhausted steam escapes from turbine drain and reaches the condenser, in which air tubes are in contact with ambient air: the steam condenses, therefore it cools down to 50°C. Then, the condensed water is sent into a thermal degasifier, that removes the uncondensed gases, in order to re-introduce the water in the boiler system. The turbine drives an electric generator, that converts mechanic energy into electricity. About 20% of the electricity is used on site and the remainder is fed into the national grid. The heat remaining after the electricity production can be used to heat water, which can be directly piped to people's homes in a **district heating** system.

The highest energetic efficiency is obtained when energy is recovered totally in thermal form: in this case, steam generator performance can achieve values above 70%. Instead, when only electricity is produced from steam, performance is between 15% and 25%. When co-generator works, an average efficiency between the two cases is reached (40%-60%) (Bozzi, 2011).

At this point, fumes are submitted to two series of **flue gas cleaning systems**:

- **first dry reactor**: the spray dryer injects hydrated lime and activated carbon as the alkaline reagents, in order to: adsorb heavy metals, volatile compounds, neutralize partially acid substances, dioxins, organic substances. The water in the atomized solution evaporates, cooling the gas, and the alkali particles react with the acid-gas constituents to form dry salts. Activated carbon has a large surface-area-to-volume ratio, and is extremely effective at adsorbing a wide range of vapor-phase organic-carbon substances, like mercury compounds, dioxins and furans (PCDD/PCDF);
- **first fabric filter**: captures the salts and the unreacted alkals through suspended filter bags; the particles are periodically removed and fed to a collection hopper. The performance of fabric filters is relatively insensitive to particle loading, or to the size distribution, or to physical and chemical characteristics of the particles. The solid residue of this stage is the RCP. It is sent in two storage silos, together with the fly ash generated during combustion and during this stage.
- **second dry reactor**: the spray dryer injects activated carbon and $NaHCO_3$ to complete the neutralization of acid pollutants and residues created in the previous stage, through Neutrec® process. It is based on the immediate thermal decomposition of $NaHCO_3$ in $Na_2CO_3$, at temperatures above 130°C. This reaction leads to the formation of $H_2O$ and $CO_2$. The high-porosity carbonate molecule is highly reactant in presence of acids. The following are examples of acid neutralization:

$$2HCl + Na_2CO_3 \Rightarrow 2NaCl + CO_2 + H_2O$$

$$SO_2 + Na_2CO_3 + {}^1\!/_2\, O_2 \Rightarrow Na_2SO_4 + CO_2$$

- **second fabric filter**: catches the salts used in the previous stage. The solid residue of this stage is the RSP, that is stored in another silos.
- **SCR**: $NH_3$ solution at 23-24% is injected into the flue gases flow, and the mixture is passed through a catalyst with a $TiO_2$ and metals substrate. This stage lowers $NO_x$ below 100 mg/(N*m$^3$). Combustion gas must be reheated at 180°C (through a heat exchanger), after cooling below this level to remove particulate matter;
- **chimney stack**: high 60 m and wide 1.70 m.

### 1.3.1 Air emissions

Emissions collected in Table 1.1 are taken from the Emissions Monitoring System situated in the chimney stack, after all flue gas cleaning phase. *Moniter* is the agency that is involved in investigations about the sanitary and environmental effects of the incinerators situated in Emilia-Romagna region. The measurements are taken twice an hour, and the samples are made periodically. Two are the limits below which incinerators emissions values have to stay: the ones prescribed by decree law 133/05 (the Italian adoption of Incineration Directive 2000/76/EC), and the ones determined by EIA permits (even stricter than the limits prescribed in the decree law). All the emissions are significantly below than the limit values stated by EIA permit. This is why determining how these emissions affect the air pollution conditions of the site (situated in an industrial area, next to a sanitary waste incinerator and to the highway) is very difficult. It can be observed that all the chemicals listed in Table 1.1 are emitted with a concentration of a least an order of magnitude below the prescribed limits. In particular, PAH are the chemicals emitted with the farthest concentration value compared to prescribed limits. This is due to the efficient flue gas cleaning equipment, characterized by a dry filtration system followed by a $NO_x$ abatement facility.

| **AIR EMISSIONS** | | | | | **MASS FLUXES (kg/y)** |
|---|---|---|---|---|---|
| **PARAMETER** | **MEASURE UNIT** | **D.Lgs 133/05 DAILY LIMIT** | **EIA PERMIT DAILY LIMIT** | **$mg/Nm^3$ 2012** | **kg/y 2012** |
| **Total dust** | $mg/Nm^3$ | 1.00E+01 | 3.00E+00 | 6.50E-01 | 5.09E+02 |
| **$NO_x$** | $mg/Nm^3$ | 200E+02 | 7.00E+01 | 3.76E+01 | 2.58E+04 |
| **HCl** | $mg/Nm^3$ | 1.00E+01 | 8.00E+00 | 6.30E-01 | 2.96E+02 |
| **HF** | $mg/Nm^3$ | 1.00E+00 | 5.00E-01 | 6.00E-02 | 4.60E+01 |
| **$SO_x$** | $mg/Nm^3$ | 5.00E+01 | 1.00E+01 | 5.60E-01 | 7.40E+01 |
| **TOC** | $mg/Nm^3$ | 1.00E+01 | 5.00E+00 | 5.80E-01 | 2.73E+02 |
| **CO** | $mg/Nm^3$ | 5.00E+01 | 3.00E+01 | 4.57E+00 | 4.39E+03 |
| **$CO_2$** | % vol | / | / | 9.31E+00 | 1.42E+08 |
| **Metals (As + Cu + Co + Cr + Mn** | $mg/Nm^3$ | 5.00E-01 | 4.00E-01 | 6.80E-03 | 5.80E+00 |

| | | | | | |
|---|---|---|---|---|---|
| **+ Ni + Pb + Sb + V)** | | | | | |
| **PCDD/DF** | ng/Nm$^3$ (I-TEQ) | 1.00E-01 | 5.00E-02 | 1.00E-03 | 8.00E-07 |
| **PAH** | mg/Nm$^3$ | 1.00E-02 | 5.00E-03 | 9.00E-06 | 6.00E-03 |
| **Hg** | mg/Nm$^3$ | 5.00E-02 | 2.00E-02 | 7.70E-04 | 3.80E-01 |
| **Cd + Tl** | mg/Nm$^3$ | 5.00E-02 | 3.00E-02 | 3.54E-04 | 2.80E-01 |
| **$N_2O$** | mg/Nm$^3$ | / | / | 3.31E+00 | 2.42E+03 |
| **$NH_3$** | mg/Nm$^3$ | / | / | 3.40E-01 | 2.66E+02 |
| **$O_2$** | % vol | / | / | 1.11E+01 | / |
| **Zn** | mg/Nm$^3$ | / | / | 8.80E-03 | 6.60E+00 |
| **Benzene** | mg/Nm$^3$ | / | / | 1.00E-01 | 7.80E+01 |
| **PCB** | ng/Nm$^3$ (I-TEQ) | / | / | 3.00E-04 | 2.50E-01 |

**Table 1.1 Concentrations and mass fluxes of the air emissions coming out from the chimney stack (Herambiente, 2012 Environmental declaration)**

As far as concerns particulate emissions, it can be observed that the emission source reference is the total dust instead of being split in $PM_{2.5}$ and $PM_{10}$, as it occurs in the air quality measurement. The total dust concentration listed in Table 1.1 is about one tenth of the emission limit prescribed by the EIA permit. The 85% of the dust is composed by $PM_{2.5}$ (Moniter, 2011). It has to be specified that, despite the concentrations are below the limits, the rate of dust emissions is very variable during the day. Instead, the behavior of PCDD/DF is different: they are emitted continually, without any significant variation in time (Moniter, 2011). Dioxins and furans emissions, below than the limits of an order of magnitude, are determined by various factors. Their production is due to the phenomena occurring in the coldest sections of the combustion chamber, with the contribution of minimal amounts of precursors like chlorine, organic carbon, iron, copper (Consonni et al., 2005). Cherubini and collaborators (2009) agree with Consonni and coauthors about the fact that burning high amounts of organic waste leads to higher dioxins emissions, especially if burned with a waste rich in plastics. Therefore, the prior organic separation is a crucial factor in the PCDD/DF production, but not the only one to determine it.

## 1.4 Incineration residues and their recovery

In the same order as they are showed in Paragraph 1.3, the destinations and the treatments of the main residues created throughout the incineration process are described.

- The wet fraction coming out from the preselector, as soon as it is generated it is collected, piled up and then sent to a plant that submits this material to bio-stabilization. This process consists in the reduction of the organic load and of the fermentation rate, through bio-oxidation and maturation. The product obtained is a low-quality compost (SOF) that is used as landfill cover. It is supposed that the wet fraction is sent to Voltana composting plant, managed by Herambiente, far about 30 km from the WTE plant.
- In combustion phase, bottom ash is produced, collected at the base of the combustion chamber. It is composed primarily of coarse non-combustible materials, unburned organic matter and grate siftings (Karagiannidis et al., 2013). The density of the bottom ash coming out from the plant is 0.80 kg/dm$^3$, and it is primarily composed by an amorphous matrix of silicon (400.000 mg/kg), calcium (127,000 mg/kg), aluminum (23,000 mg/kg) and iron (11,800 mg/kg), that is, the less volatile and less harmful elements. As bottom ash is not classified as hazardous waste (EWC 19.01.12), it can directly disposed to landfill sites without any prior treatment. Currently, 50% by weight of the bottom ash produced by Forlì WTE plant is directly discharged in a suitable landfill. Before the landfilling, iron scrapes are extracted from it through magnetic separation. The remaining half is sent *to Officina dell'Ambiente* plant (Figure 1.7). This structure is authorized to treat hazardous and not hazardous waste, primarily made up by bottom ash produced downstream of the process of incineration of MSW. The treatment the bottom ash is submitted to allows the production of a family of raw materials called *Matrix*$^{®}$ that can be used as aggregates in several branches of the construction industry (cement, concrete, clay bricks, etc.). The plant was awarded ISO 14001 certification, and has EMAS registration n° IT 000555 from 2006.

**Figure 1.7 Overwiew of the *Officina dell'Ambiente* plant (*Officina dell'Ambiente*, Environmental Declaration 2012)**

As soon as the bottom ash arrives at *Officina dell'Ambiente* plant, it is stocked in piles protected from rain, in order to let the moisture content diminish through evaporation. In fact, the bottom ash is delivered from the WTE plant after being quenched with water in order to decrease its temperature. Then, excess water is drained:, but still it consists in 20% of the total weight of the bottom ash. During the stocking period, air and humidity promote the oxidation and carbonation of the substances which bottom ash is composed by, forming new chemical and mineralogical phases.

The next process is the mill grinding, in which the bottom ash is split in different grain sizes. During the stabilization process, ferrous and non ferrous scraps are magnetically separated from bottom ash. As the sum of the metal scraps, the unburned waste and the lost moisture makes up about the 20% by weight of the initial amount of bottom ash, the actual quantity recovered is about 80% of the initial weight. It is called *Matrix*®, a silicon-based matrix with chemical-physical characteristics suitable for the partial substitution of marl, gravel and sand in different sectors of the construction industry (Barberio et al., 2010).

- Fly ash, collected from the flue gas exiting the combustion chamber via the air pollution control devices, presents high concentrations of soluble salts, sulphates and chlorides (such as dioxins) due to the volatilization and subsequent condensation. In fact, dioxins are difficult to destroy or stabilize, since alkali chlorides hinder cement hydration (Park and Heo, 2002). Moreover, fly ash contains relevant amounts of heavy metals such as Pb, Cr, Cu, Zn. For these reasons, this incineration residue is classified as hazardous (EWC 19.01.13*) and its treatment prior to final disposal is imposed

(Karagiannidis et al., 2013). Fly ash coming out from Forlì WTE plant has a specific gravity of 2.2 kg/dm$^3$ (it is actually a dusty material), and it is composed primarily by: calcium (294,000 mg/kg), chlorides (139,000 mg/kg), sulphates (92,100 mg/kg) and sodium (25,900 mg/kg). Fly ash actual destination is Disidrat plant, managed by Herambiente, situated 30 km far from the WTE plant. It works with different types of industrial residues, in order to let them suitable to be recovered in the safest way. Fly ashes, together with sludge coming from urban and industrial water depuration, is one of the matrices that are treated in the plant. In particular, fly ash is unloaded in a silos as soon as it arrives at Disidrat. After being sieved and crushed, fly ash is inertized through the blending of lime and concrete in variable percentages. After this, the material obtained is stored in a closed room for the following 24 hours. All the operations in the plant are conducted in slightly negative air pressures. Then, inertized fly ash is stocked, waiting to be sent to *Systema Ambiente* facility, situated near Brescia (Figure 1.8). In this plant, industrial waste, either hazardous or not, is disposed in landfill, with leachate treatment. The plant was awarded ISO 14001 certification, and has EMAS registration n° IT 00326 from 2005.

**Figure 1.8 Overview of the *Systema Ambiente* disposal site (*Systema Ambiente* Srl, 2010 Environmental Declaration)**

- RSP is taken away at Rosignano Solvay plant once a month to be recycled. In this case is used Neutrec® process. The brine produced by the reaction is used to produce $Na_2CO_3$.

## 1.5 An overview on LCA

ISO 14040 defines Life Cycle Assessment (LCA) as a technical tool able to address the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment and disposal (Figure 1.9), in order to improve the environmental performance of products.

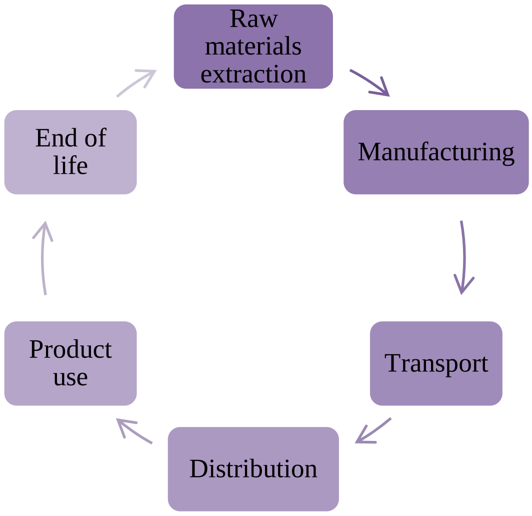


**Figure 1.9 Life cycle of a product, from raw material processing to disposal**

Standard ISO 14040 defines the four basic steps of the assessment:

- **Goal and scope definition**;
- **Life Cycle Inventory** (LCI);
- **Life Cycle Impact Assessment** (LCIA);
- **Life Cycle Interpretation**.

### 1.5.1 Goal and scope definition

The **goal** states: the intended application; the reasons for carrying out the study; the intended audience, i.e. to whom the results of the study are intended to be communicated; and whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

The **scope** includes the following items:

- **functions of the product system**, depending on the goal and scope of the LCA;
- **functional unit**: the quantification of the identified functions of the product, to provide a reference to which the inputs and outputs are related;
- **reference flow**: the amount of products needed to fulfill the function;

- **system boundary**: model that describe the key elements of the physical system, defining the unit processes to be included. The choice of elements of the physical system to be modelled is dependent on the assumptions made from the goal and scope criteria above.

#### 1.5.1.1 Data quality requirements

ISO 14044 defines the following quality requirements:

- **time-related coverage**: age of data and the minimum length of time over which data should be collected;
- **geographical coverage**: area from which data for unit processes should be collected to satisfy the goal of the study;
- **technology coverage**: specific technology or technology mix;
- **precision**: measure of the variability of the data values;
- **completeness**: percentage of flow that is measured or estimated;
- **representativeness**: degree to which the data set reflects the true;
- **consistency**: whether the study methodology is applied uniformly to the various components of the analysis;
- **reproducibility**: extent to which information about the methodology and data values would allow an independent reproduction of the results reported in the study;
- **sources** of the data;
- **uncertainty** of the information.

### 1.5.2 Life Cycle Inventory

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. This process is iterative: as data are collected and more is learned about the system, new data requirements or limitations may be identified so that the goals of the study will still be met. Some processes and elementary flows are quantitatively irrelevant because they are insignificant to the outcome of the LCI/LCA study: they can be entirely cut-off, because of their inconsistence in view of the intended application of the results (ILCD Handbook, 2010). In Figure 1.10 the stages involved in creation of an LCA inventory are shown:

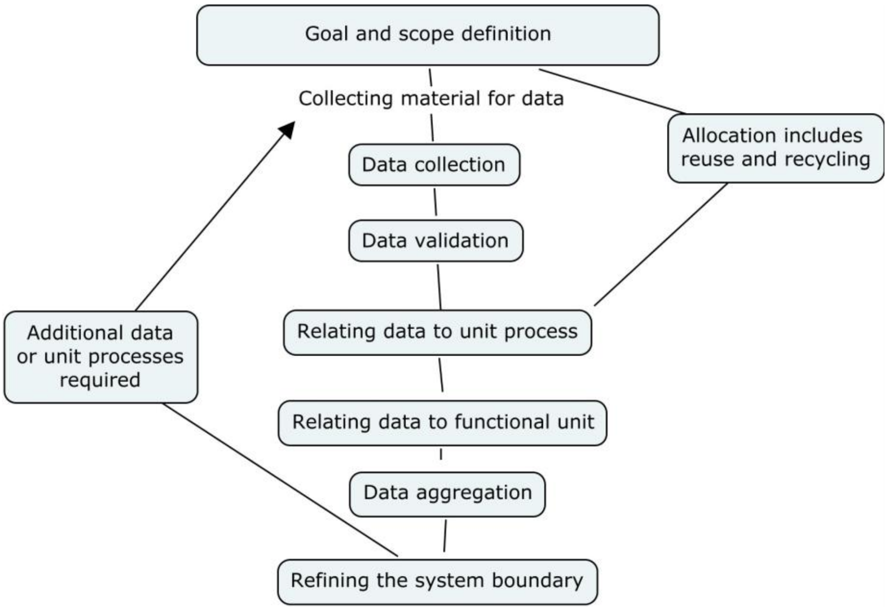


**Figure 1.10 LCI stages (ISO 14044)**

### 1.5.2.1 Allocation

Allocation consists in the partitioning of the flows of a process contained in systems involving multiple products and recycling systems (ISO 14040). Wherever possible, ISO 14044 suggest to avoid allocation by **system expansion**, i.e. the adding of another, not provided function or subtracting a function non required substituting it by the one that is superseded/ replaced, in order to make two systems comparable (ILCD Handbook, 2010). An example is substituting the not required function with an alternative way of providing it, as Figure 1.11 shows:

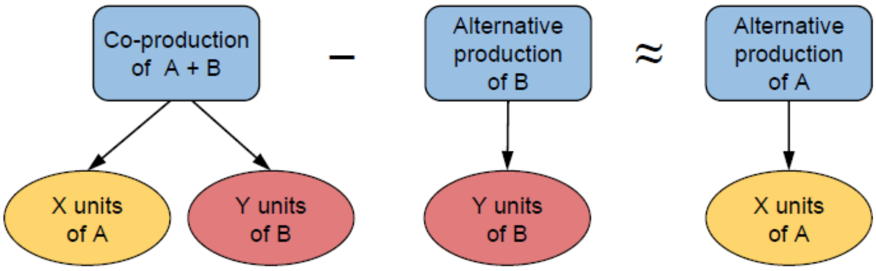


**Figure 1.11 Examples of system expansion (ILCD Handbook, 2010)**

Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them. Where physical relationship alone cannot be established, the inputs should be allocated between the products and functions in a way that reflects other relationships between them (for example, economic value of the products).

In case of allocation in recycling/recovery systems, the inputs and the outputs associated with the processing of raw materials and/or with final disposal of products may be shared by more than one product system. Figure 1.12 illustrates how these constraints can be overcame:

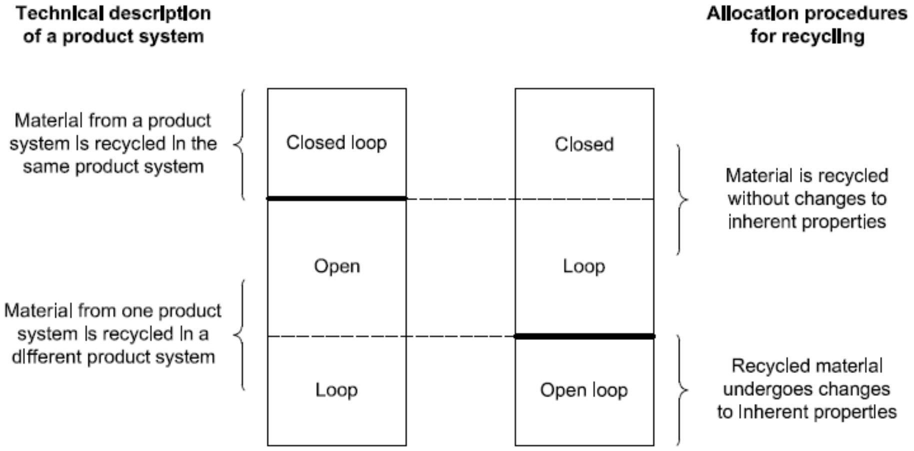


**Figure 1.12 Open and closed loop systems (ISO 14044)**

A closed-loop allocation procedure is applied where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. Instead, an open-loop allocation procedure is applied when the material is recycled into other product systems and the material undergoes a change to its inherent properties. In his review, Finnveden (1999) states that the primary material production used in both products can be allocated (the initial (1) and the recycled (2)), considering the disposal of material used in both products to product 1 (2) and the recycling process to product 2 (1). An alternative method consists in allocating primary material production used in both products to product 1, disposal of material used in both products to product 2, and the recycling process to either produce 2 or as a refinement use or gross sales values for the allocation of the recycling process.

### 1.5.3 Life Cycle Impact Assessment

This phase aims at evaluating the significance of potential environmental impacts, connecting inventory data with specific environmental impact categories, and thereby attempting to understand the relevance of these impacts. The LCIA addresses only the environmental issues that are specified in the goal and scope, therefore it does not consider all environmental issues that actually affect the product system under study.

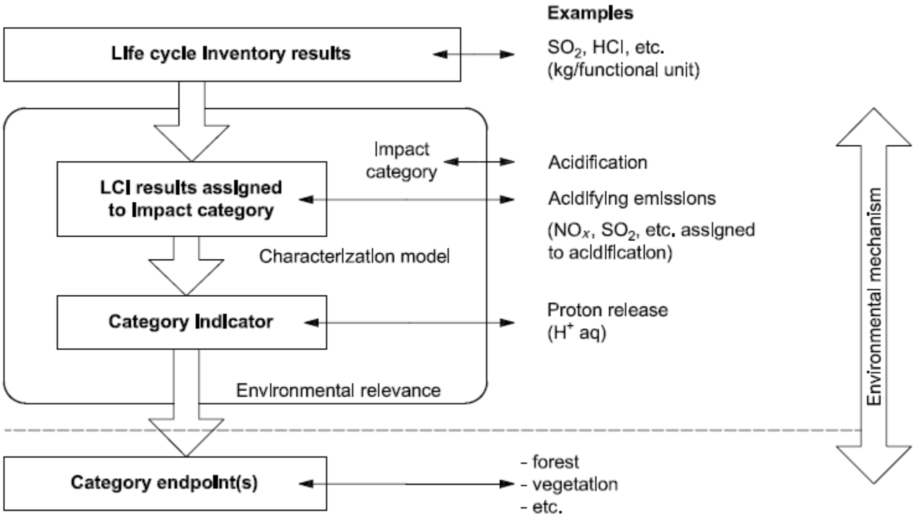


**Figure 1.13 LCIA steps (ISO 14044)**

Figure 1.13 outlines the concept of impact, based on the whole environmental processes involved. ILCD Handbook lists the steps involved in LCIA phase:

- **classification**: all elementary flows of the inventory shall be assigned to those one or more impact categories (environmental issues of concern) to which they contribute;
- **characterization**: assigning a quantitative characterization factor for each category to which the flow contributes;
- **calculation**: for each impact category separately, the amount of each contributing (i.e. classified) elementary flow of the inventory is multiplied with its characterization factor:

$$\sum_i cf_i * m_i$$

where *cf* is the characterization factor related to how much the flow in exam *i* contributes to the impact calculated, *m* is the mass of the flow.

In addition to the elements of LCIA listed above, there are optional stages:

- **normalization**: calculating the magnitude of category indicator results relative to a reference value; its aim is to understand better the relative magnitude for each indicator result;
- **grouping**: sorting and ranking of the impact categories;

- **weighting**: converting and possibly aggregating indicator results of different impact categories using numerical factors based on value-choices.

### 1.5.4 Life Cycle Interpretation

In interpretation phase, the findings and results from the inventory analysis and the impact assessment are displayed in an understandable and complete description, explaining limitations and providing recommendations to decision makers. The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal.

The final evaluation of the process can contain the following procedures: **completeness check** (to ensure that all relevant information and data needed for the interpretation are available and complete); **sensitivity check** (to assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data); **consistency check** (to determine whether the assumptions, methods and data are consistent with the goal and scope).

### 1.5.5 LCA in waste management

Article 4 of Directive 98/2008 specifies that life cycle thinking is necessary to understand the best option to apply to waste management, assessing overall impacts of every option. Integrated waste management involves the application of the most efficient combination of waste treatment, in order to minimize resources use and to maximize waste recovery. In some waste management scenarios the most efficient order of treatments is found to be different from the hierarchy described in Waste Framework Directive, because the environmental impact of a waste management system depends on a number of geographic, economic, social and technological factors (Buttol et al., 2007). If planned in the right way, LCA allows the evaluation of all the combined effects of these factors, revealing the most efficient processing conditions.

When setting an LCA based on waste management systems' analysis, boundaries are set with **zero burden** approach. It means that solid waste life cycle runs from the moment the material becomes waste, until the material ceases to be waste and becomes an emission into air or water, an inert material, or a recycled product. Therefore, all life cycle stages prior to the product becoming waste can be omitted, because it is assumed that all the stages that contribute to generate the waste are common to all management systems (Buttol et al., 2007).

## 1.6 Waste management LCA state of the art

The bibliography consulted analyzes the **whole management system**, with the aim of evaluating the total impact of possible changes in the collection system and/or in the treatment of specific fractions. In Table 1.2 all the focal points of the LCAs carried out by the authors taken in consideration are outlined.

| Authors | Title | Journal | Functional Unit | System Boundaries | Impact categories | Methodology |
|---|---|---|---|---|---|---|
| Consonni, S., Giugliano, M., Grosso, M., 2005 | Alternative strategies for energy recovery from municipal solid waste | Waste Management 25, 123-148 | NA | From waste pre-treatmentto electicity production and solid residues disposal, including plant construction | $GWP_{100}$, AP, POCP, HTTP, Landfill Volume | CML 2001 |
| Finnveden, G., Johansson, J., Lind, P., Moberg, A., 2005 | Life cycle assessment of energy from solid waste—part 1: general methodology and results | Journal of Cleaner Production 13, 213–230 | t/yr of the waste fractions collected in Sweden | From waste treatment to electricity and recycled materials production; not included plants construction and chemicals' synthesis | GWP, Total energy use, non renewable energy | EDIP, USES |
| Buttol, P., Masoni, P., Bonoli, A., Goldoni, S., Belladonna, V., Cavazzuti, C., 2007 | LCA of integrated MSW management systems: Case study of the Bologna District | Waste Management 27, 1059–1070 | 566000 t of MSW produced in Bologna district in 2006 | From waste collection to residues treatment and energy and material recovery; included also construction, operation and end of life of plants | $GWP_{100}$, AP, EP, Aquatic ecotoxicity, VOC, Sediment ecotoxicity, Terrestrial ecotoxicity, HTP, Depletion of non-renewable resources, Total primary energy consumption | USES 2.0, CML, IPCC |
| Chaya, W., Gheewala, S.H., 2007 | Life cycle assessment of MSW-to-energy schemes in Thailand | Journal of Cleaner Production 15, 1463-1468 | 1 t MSW | From MSW arrival to plantd to energy recovery and fertilizer production | GWP, AP, EP, POCP, ODP, Heavy metals, Consumption of energy resources, generation of solid waste to landfill | Ecoindicator 95 |
| Morselli, L., Luzi, J., De Robertis, C., Vassura, I., Carrillo, I., Passarini, F., 2007 | Assessment and comparison of the environmental performances of a regional incinerator network | Waste Management 27, S85-S91 | 1 t of waste input | From waste input into the plant to ash, sludge and gas treatment | GWP, AP/EP, POCP, Ecotoxicity, Fossil fuels, Carcinogens, Respiratory organics, Respiratory inorganics, Radiation, Land use, Minerals | Ecoindicator 99 |
| Cherubini, F., Bargigli, S., Ulgiati, S. | Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration | Energy 34, 2116–2123 | 1460000 t of unsorted waste produced in Rome in 2003 | From MSW collection to material and energy recovery and residues treatment | GWP, AP, EP | NA |
| Rigamonti, L., Grosso, M., Giugliano, M., 2009 | Life cycle assessment for optimising the level of separated collection in integrated MSW management systems | Waste Management 29, 934–944 | t/yr of waste fractions collected in Italy (average) | From waste collection to residues treatment and energy and material recovery, considering also construction of plants | GWP, AP, POCP, HTP | CED, CML 2 |
| Khoo, H.H., Lim, T.Z., Tan, R.B.H., 2010 | Food waste conversion options in Singapore: Environmental impacts based on an LCA perspective | Science of the Total Environment 408, 1367–1373 | 570,000 t/yr (potential future amont of food waste in Singapore) | Gate to grave (from pre-processing to electricity and bio-compost production; not included plants construction and chemicals' synthesis impacts) | GWP, AP, EP, POCP, Energy use | EDIP 2007 |
| Giugliano, M., Cernuschi, S., Grosso, M., Rigamonti, L., 2011 | Material and energy recovery in integrated waste management systems. An evaluation based on life cycle assessment | Waste Management 31, 2092 - 2101 | amount of MSW to be managed (750000 t/yr and 150000 t/yr) | Cradle to grave (from domestic waste collection to energy recovery and recycling/composting) | $GWP_{100}$, AP, HTTP, POCP | CED, CML 2001 |
| Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L., Astrup, T., 2011 | Life cycle assessment of waste incineration in Denmark and Italy using two LCA models | Waste Management & Research 29, 78-90 | treatment of 1 Mg wet waste | Gate to grave (disposal of solid residues, recovery of energy + materials) | GWP, AP, EP, POCP, Eco-toxicity to water, HT via air, HT via water, HT via soil | EDIP97, IPCC (2007) |
| Assamoi, B., Lawryshyn, Y., 2012 | The environmental comparison of landfilling vs incineration of MSW accounting for waste diversion | Waste Management 32, 1019-1030 | t of MSW from the City of Toronto between 2011 and 2040 | Gate to grave (from residual waste transport to incinerator/landfill to energy recovery) | $GWP_{100}$, AP, EP | IPCC (2006) |
| Jeswani, H. K., Smith, R. W., Azapagic, A., 2013 | Energy from waste: carbon footprint of incineration and landfill biogas in the UK | International Journal of Life Cycle Assessment 18, 218-229 | disposal of 1 t MSW | Transport to plants, plants construction, electricity/heat generation, metals recycling, leachate management | GWP | NA |
| Slagstad, H., Brattebø, H., 2013 | Influence of assumptions about household waste composition in waste management LCAs | Waste Management 33, 212-219 | treatment of 1 t of household waste | Transport to plants, recycling | GWP, AP, EP, resource depletion, ecotoxicity in water (chronic) human toxicity via water | EDIP |

**Table 1.2 List of the main LCA features of the studies taken in consideration**

**Consonni and coauthors (2005)** aim to understand whether submitting residual waste to MTB before combustion in WTE plants can either increase efficiency or reduce environmental impact or costs. 35% of separate collection is chosen; the remaining 65% of waste goes to incineration. Four scenarios are set: in the first, no preselector before incineration is made. In the second scenario, sieving is made as preselector: the dry fraction (RDF) is incinerated, while the wet is transformed into SOF, sent to landfill. In the third scenario, a shredding preselector is made, followed by aerobic bio-stabilization: RDF and SOF obtained are incinerated together, while metals and non-metal scraps are divided in order to be recycled. Fourth scenario is similar to the second, but there is also metal separation and recycling. Scale effects are also tested, considering that steam cycles are sensible to them: 65,000 t/y of waste treated (small province) against 390,000 t/y (large city). Conclusions show the efficiency gain due to the higher LHV of pre-treated waste does not offset the energy required to produce it, considering also that preselector provokes the loss of combustible material. Regarding plant scale, large plants provide improvements of LHV efficiency varying from 30 to 60% compared to small plants. Plant scale affects also air emissions: in large plants, $SO_x$, $NO_x$, $CO_2$, $PM_{10}$ net balance is negative, so it is totally compensated by energy production.

**Finnveden and coauthors (2005)** test the **waste hierarchy** in **Sweden** comparing five different systems, to identify critical factors in each of them: landfilling (with landfill gas extraction), incineration (of all fractions, with heat recovery), recycling (not of food waste), digestion of food waste, composting of food waste. Nine scenarios are built, in which distance of plants, energy recovery systems, energy source and landfill time period are varying. Impact category "Non renewable fuels" is sensitive to avoided heat production: if it comes from natural gas instead of wood (feedstock used widely in Sweden), incineration saves more non-renewable energy than recycling. Regarding GWP, the order of preference for incineration and landfilling is sensitive to time modeling, i.e. when a short period of time is considered for the total degradation and emission of materials, landfill results are significantly improved.

**Buttol and collaborators (2007)** want to detect the environmental impacts of different waste management strategies in Bologna (Italy) province. This territory is divided in 5 homogeneous areas, each with its own waste production: 1 (city), 2 (hinterland belt), 3 (western plain), 4 (eastern plain), 5 (mountain area). Three scenarios are set: T (trend) does not imply any improvement in SCW percentage, that is equal to the value measured in the province in 2003 (28%). Similarly, UW remains at 30%. In scenario NIA2 (New Incinerator in Area 2), UW sent to incinerator rises to 50%, SCW to 31%. To catch up with these improvements, the scaling up of the incinerator in Area 2 is considered. In scenario NIA5

(New Incinerator in Area 5), UW sent to incinerator is 37%, while SC remains 31%. To catch up with these improvements, the construction of a new incinerator in Area 5 is considered. In addition, it is assumed that landfill emissions continue for about 100 years. Results show that NIA2 scenario gives the lowest impact, especially for AP category. NIA5 is not the best scenario, because the incinerator in mountain area is too far from the city zone, in which the highest amount of waste is produced.

**Chaya and collaborators (2007)** set their study in Thailand, where MSW has increased steadily during the last decade and landfills are not well engineered. The aim of their study is to compare incinerator and anaerobic digestor. The two systems are comparable because both produce electricity (the incinerator from a steam generator, the digestor from biogas; it also produces fertilizer), and treat the same quantity and composition of waste: it is composed of 69% by organic fraction in both cases. Incinerator handles indiscriminately the whole waste (including humid fraction), without preselector. Instead, anaerobic digestor only works with paper, food and yard waste; the remaining fractions are sent to landfill. It is assumed that organic humus from anaerobic digestion has the same features of chemical fertilizers, and that all waste burns completely in incinerator. Results show that anaerobic digestion is preferable: this result is influenced strictly by composition of waste treated, rich in organic fraction, therefore suitable for anaerobic digestion, but with low LHV for incineration. So, in this case preselector before incineration would be fundamental. Focusing on single impact categories, it is found that electricity production does not offset GWP impact from combustion in incinerator (maybe because diesel is the auxiliary fuel). $CO_2$ emissions from organic fractions combustion are not assumed to contribute to GWP. AP impact is worse for incinerator too, because fertilizer production allows acid gases emissions to be avoided, due to chemical fertilizer production. It is interesting to see that lime (used in incinerator) is highly impacting for categories Consumption of energy Resources and Heavy Metals.

**Morselli and collaborators (2007)** goal is to identify the most relevant environmental impacts due to incineration, in seven WTE plants situated in Emilia-Romagna Region, in northern Italy. They, labeled from A (the newest) to G (the oldest), have similar combustion processes, but differ considerably in age, capacity, energy recovery devices, and pollutant abatement technologies. Waste LHV is almost constant for each plant. The main results relate to the categories Carcinogens and Respiratory Disease. The carcinogenic impact is mainly due to Cd and As in water, released from the leachate of landfill, in which sludge, bottom ash and fly ash are disposed. The respiratory disease impact, instead, is mainly due to $NO_x$ in case of oldest plants, not equipped with SCR/SNCR system. Regarding GWP, the worst impacts are related to the oldest plants, that do not have a great combustion efficiency therefore produce high fractions of bottom ash, and consume relevant amounts of auxiliary fuels.

**Cherubini and coauthors (2009)** want to evaluate different waste management strategies in the municipality of Rome, that produced 1,460,000 t of unsorted waste in 2003 (this is the functional unit). Four waste management scenarios are considered. The first two (0 and 1) put all waste in landfill with biogas recovery: scenario 0 releases directly in atmosphere 50% of biogas, 50% is burnt in flares in order to emit in air the less impacting $CO_2$ instead of $CH_4$. In scenario 1 only 25% of the biogas is released in atmosphere, and 25% is burnt in flares; the remaining 50% is collected and burnt to produce electricity. Emissions from biogas burning are not accounted in GWP; because they do not have a fossil origin. Scenario 2 is quite different: waste is collected and submitted to a MBT. It is sorted in the following parts: inorganic fraction (transformed in RDF to be incinerated); organic fraction (50% of which is taken to an anaerobic digestor to produce compost and upgraded biogas, the remaining 50% is landfilled); ferrous metals (recycled); heavy fractions (sent to landfill). Scenario 3 considers the incineration of the whole waste. Results show that scenarios 0 and 1 are strongly affected by landfill gas emissions ($CH_4$, $H_2S$, HCl). Waste management system 2 is the best option, since avoided impacts are reached for GWP, AP and dioxins; instead, scenario 3 is worse because of high dioxins emission, caused by the co-firing of inorganic materials with organic fraction. Most of these impacts are caused by landfilling of waste treatment residues: none of the investigated scenarios is able to avoid the landfill.

**Rigamonti and collaborators (2009)** analyze the correlation between recovery of source-separated materials and efficiency of energy recovery from residual waste. The functional unit is gross MSW composition in average t/y of waste fractions (t). Three different percentages of waste separation are set: 35% (Italy target for 2003); 50% (average value in Northern Italy); 60% (value in some virtuous Italian provinces); the remaining amounts are incinerated. Also, three energy sources for energy recovery are set: Italian mix (20% coal, 20% fuel oil, 20% natural gas, 40% natural gas in a combined cycle), coal, and natural gas in a combined cycle. Results show that 60% of separated collection of organic fraction is less advantageous than 50%, because an higher collection percentage includes an higher fraction of contaminated waste, more difficult to be recycled. Regarding energy source, incineration is environmentally convenient when replaced electricity is produced from coal or from Italian mix; it is not convenient anymore when replaced electricity is produced from natural gas in a combined cycle plant.

**Khoo and coauthors (2010)** compare incinerator and anaerobic digestion coupled to composting, in order to find how to manage food waste in the most efficient way. Study is set in Singapore, that has limited territory for landfills, and it is unlikely to accept food waste. Four scenarios are considered, each having an incinerator process that burns a fraction of the food waste, while the rest is submitted to different types of AD (anaerobic digestion) facilities coupled with composting. Only production of compost suitable for mineral fertilizers replace in the country is considered. The functional unit chosen is the potential amount of food waste generated in Singapore (570,000 t/y), therefore the study has a future perspective. Results show that AP impact is mainly due to $CO_2$ and $NO_x$ emissions, which production depends on: aerobic composting process parameters, on the types of organic matter treated, and on their C/N ratios. About Energy use, Scenario 4 does not show the best results: even if it contains another recycling process (anaerobic digestion of waste fraction incinerated), the production of low quality compost does not offset the energy spent.

**Giugliano (2011) and collaborators** analyze an integrated MSW management system in Italy through 4 scenarios, in which the fraction of MSW separated to be sent to recycling/composting is being varied, while the residual fraction goes to a WTE plant. As Rigamonti et al. (2009) do, their aim is to understand which percentage of separation is better. Waste composition before collection is representative of Italian average, and it is the same in all scenarios. Scenarios are: D35 (35% of separate collection, drop-off system; food is not collected separately); D50 (50% of separate collection, but without food); K50 (kerbside collection at 50%, including food waste); D65 (kerbside collection at 50%, including food waste). For every scenario, not only the percentage of separation changes, but also the percentage of efficiency collection for every waste material (ex. paper, aluminum, etc). It is also assumed that the secondary materials produced by recycling replace the corresponding primary materials. Results show that scenario D50 allows the optimal level of recycling of packaging materials, although they are the main contributor for GWP. Composting shows environmental benefits in GWP, but only when it is applied to green waste alone, and not to food waste (D-scenarios). Energy recovery category impact depends on the content of fossil carbon in the combustible residues.

**Turconi and collaborators (2011)** compare environmental impacts of two incinerators from two different parts of Europe: Milan2 (south) and Aarhus (north). The study is based on the importance of considering local conditions, because they do not want an LCA to be dependent on model features, otherwise it is not possible to gain reliable and consistent results. This is why two different modeling tools are used (SIMAPRO and EASEWASTE). The two plants are similar in various recycling processes. Both use fly ash for mines backfilling, and both recycle metals from bottom ash, and then use it for road construction (in case of Milan2, 12% of bottom ash is landfilled). They differ in energy recovery (Aarhus recovers also heat), APC residues treatment (Milan2 recycles APC redisues through Neutrec® process, Aarhus landfills it), flue gas cleaning (more advanced for Milan2). Regarding waste composition, Milan2 waste contains over 50% of paper and plastic, that make up an high LHV, but it causes worse emissions. Instead, Aarhus waste composition has a great percentage of organic waste (over 70%, together with paper), lowing the LHV. It is also notable that, as energetic input, the most representative fuels in the countries' electricity mixes are chosen (natural gas for Milan2 and coal for Aarhus). Results are presented as normalized potential impacts – expressed as person equivalents (PE) calculated on EU-15 basis. Hotspot analysis shows that the most impacting stages are: stack emissions, upstream processes (i.e. all materials and resources needed to let the plant work) and energy recovery (as avoided impact). Instead, treatment of solid residues and metal recycling are not significant phases, due to the fact that the percentage of solid residues produced by the plant is relatively low (11,8%). This relatively little environmental load is also a consequence of the utilization of bottom ash in road construction, as well as the recycling of fly ashes in exhausted mines. Generally, Aarhus plant has environmentally better results than Milan2, due to recovery of both electricity and heat. In both models, toxic impacts are worse than non-toxic ones, except for GWP, in which the caused impacts, coming mainly from stack emissions, are counterbalanced by energy recovery. About AP, Milan plant has less impacts generated than Aarhus one because of the efficient SCR system, that makes $NO_x$ emissions irrelevant. Human toxicity via soil and air are regarded as avoided impact due to energy recovery, despite a fraction of the impact is caused by the preselection of the bottom ashes before disposal. Also, it is the category most influenced by metal recycling stage, that makes the impact of this category avoided. On the other hand, steel recycling improves impact in water ecotoxicity (mainly in Milan2 plant). Human toxicity via water impact is caused by Hg release.

**Assamoi and collaborators (2012)** compare the environmental performance of incineration and landfilling of residual MSW, after recyclable/compostable fractions are extracted from it. Two scenarios are considered. In the first, all the residual waste is sent to landfill: 75% of landfill gas is collected, with electricity recovery. In the second, 1,000 t/day are sent to incineration, the rest is landfilled with the same mechanism of the first scenario. System boundaries consider only transport to landfilling/incinerator facilities, waste treatment and electricity recovery; auxiliary chemicals and fuels, construction of facilities, residues disposal, landfill emissions after its closure are not part of the system. This analysis is time-integrated: it is assumed that within 2040 diversion rate will increase from 46% to 70%: this means that less waste will be expected to be sent in landfill, therefore landfill lifetime expectancy will stretch to 28 years. Total waste generated is expected to rise by 0.02%. In time, residual waste composition will vary, too; instead, all initial compositions are assumed to remain steady throughout the life time of the study. Results shows that, without considering electricity recovery, GWP impact is strongly affected by plastic incineration and by partial methane combustion of the gas emitted from landfill. Regarding AP, $SO_x$, $NO_x$, HCl are emitted in higher concentration in incineration, because of the sulphur and chloride content of the waste. If electricity recovery in the two systems is considered, incinerator outperforms landfill in every impact category, mainly in AP.

**Jeswani and coauthors (2013)** compare energy recovered from MSW incineration with that from biogas recovered from landfilled waste. In both cases energy savings are accounted: in the case of the incinerator, they come from heat, electricity and recycling of ferrous materials. In the case of landfill, they come from electricity and heat generation from recovered biogas. The disposal process of combustion residues is taken in account, as the leachate and the electricity produced from the landfilling. Results show that incinerator gives better $CO_2$ savings than landfilling; GHG saving could be better if bottom ash is used as a construction material instead of being landfilled. An hotspot analysis shows that the most impacting stage are stack emissions for the incinerator, the venting of biogas into the atmosphere for the landfill. The incineration emissions give worse impacts than the landfilling of combustion residues (even if they make up a huge quantity), because in their landfilling electricity production from the collection and burning of biogas is taken in account. Also, a sensitivity analysis is made, varying waste composition and energy credits. In the first case the rate of recycled paper increases from 40% to 80%, so that all the other fractions increase proportionally to the amount of paper taken out of the waste for being recycled. GWP increases from 9 to 20%, due to the higher contribution of plastics in waste (from 7 to 8,5%). Also, energy source are varied: if heavy fuel oil is considered, the greatest energy savings are reached. If low-carbon electricity mixes are taken into account, such as the French one, the process isn’t convenient anymore because GWP impact score improves.

**Slagstad and collaborators (2013)** investigate how changes in assumptions regarding waste composition affect the modelled environmental impact of a waste management system. Starting from five macro-fractions (mixed waste, paper & cardboard, plastic, glass, metals, food waste), a variation of ± 15% from their average percentages of recycling/incineration is considered. System boundaries include waste transportation to plants; waste separation and treatment of solid residues are not included. Resource depletion reaches the best results when small amounts of paper or high amounts of plastic and metals are recycled/incinerated. As far as regards GWP, the more plastic is incinerated, the more fossil-$CO_2$ is emitted in atmosphere. With paper the same thing occurs, but $CO_2$ emitted has biological origin, so it is not accounted. Human toxicity via water results show impacts in almost all fractions, mainly due to the avoided virgin aluminum production.

From all the studies analyzed, many issues can be discussed. An aspect that affects significantly LCIA results is the type of energy used to feed the plant. It often depends on geographical contest. For example, in their analysis set in Sweden Finnveden and coauthors (2005) find out that if avoided heat comes from natural gas instead of wood (feedstock used widely there), incineration saves more non-renewable energy than recycling. Auxiliary fuel used in plant is also fundamental: Chaya and collaborators (2007) obtain an high GWP impact because diesel is the auxiliary fuel in the WTE plant. Rigamonti and coauthors (2009) find out that incineration is environmentally convenient only when replaced electricity is produced from coal or from Italian mix; it is not convenient anymore is produced from natural gas in a combined cycle plant. Therefore, it can be said that low-carbon energy used for incinerator feeding and upstream/downstream activities does often not offset the energy produced from combustion.

One aspect linked to energy consumption is plant size. Larger plants provide improvements of LHV efficiency varying from 30 to 60% compared to small plants (Consonni et al, 2005); in addition to this, greater $SO_x$, $NO_x$, $CO_2$, $PM_{10}$ amounts are emitted in small plants.

Another fundamental aspect correlated to incinerators is the discussed usefulness of MTB. Consonni and collaborators (2005) prove that all pre-treating systems analyzed consume more energy than the amount produced from combustion of high LHV waste. On the other hand, waste has often features that make necessary to pretreat it before incineration. It happens in Chaya and coauthors (2007) analysis, in which waste treated is rich in organic fraction, therefore with low LHV. Cherubini al collaborators (2009) show a positive opinion about MBT, too: they demonstrate that RDF is advantageous because it emits less dioxins from its combustion, due to the absence of organic matter.

Proceeding in incineration processes, combustion assumptions are find. Many authors, in order to simplify the system modeling, assume that the whole waste is burned in combustion camera, so that there is not any fraction unburned. In addition to this, in three studies (Chaya et al, 2007; Cherubini et al, 2009; Slagstad et al, 2013) emissions from biomass burning are not accounted in GWP; because of its renewable origin.

Another issue widely discussed is the production and disposal of hazardous bottom and fly ash, that generate high impacts if landfilled. Morselli and collaborators (2007) show that the plants that do not have a great combustion efficiency are characterized by worse GWP impacts. This is due to the higher amounts of auxiliary fuels used, and leads to a production of an higher fraction of bottom ash. In Turconi and coauthors (2011) study, impacts in Human toxicity via soil and in air are affected by preselector of bottom ashes before disposal. This problem affect chemicals used in incineration process, too: Chaya and collaborators (2007) find out that lime consumption is highly impacting for categories Consumption of energy Resources and Heavy Metals. These results lead to the conclusion that finding a concrete way to reduce/recover bottom and fly ash is fundamental to reduce incinerators' impacts, improving combustion efficiency and flue gas treatment.

A lot of authors agree about the advantages in metal recycling, as it avoids a lot of toxic impacts.

In composting efficiency many assumptions are made, in order to simplify the system analyzed. Chaya and collaborators (2007) assume that compost produced in anaerobic digestion has the same features of chemical fertilizers replaced, even if in reality it often does not verify. To avoid this simplification, Khoo and coauthors consider only production of compost suitable for mineral fertilizers replacement. This is because they find out that production of bio-compost of low quality (obtained by processing organic bottom ash from incineration) does not offset the energy required to produce it. Therefore, there is an efficiency limit in waste treatment: this is why many authors investigate the correlation between waste separation percentage and recycling/recovery efficiency. Rigamonti and collaborators (2009) and Giugliano and coauthors (2011) verify that an high percentage of separation is less advantageous: both studies demonstrate that 50% of separation allows the optimal recycling level.

There is one issue about which all authors are in agreement: the impacts derived from transport do not affect results in a significant way, nor influence the order or the relevance of the impacts analyzed. This is verified even when different collection transport systems are considered (ex kerbside or drop-off) or when distance to treatment/disposal plant is varied among scenarios.

Focusing on LCA structure, many differences can be found. About half of the authors insert in system boundaries auxiliary impacts such as the ones derived from plant construction, waste, collection, synthesis of chemicals.

Another difference among the studies is the functional unit chosen. Buttol and coauthors (2007) and Cherubini and collaborators (2009) use the waste produced in one year in the geographical unit considered as the functional input. Finnveden and collaborators (2005) consider separately the fraction collected as functional unit. Instead, Chaya and coauthors (2007) and Morselli and collaborators (2007) use 1 t of waste submitted to treatment.

## 1.7 Incineration residues state of the art

As incineration residues are produced in a relevant amount and cause pollution problems, they are inserted in system boundaries. The main residues created by the WTE facility are: bottom ash, fly ash and wet fraction from preselector. The analytical part of the thesis is focused in particular on the first two products. In fact, bottom and fly ash disposal/recycling arise problems due to their potential hazardous nature. More specifically, Ministerial Decree 27/09/2010 sets the limit values of emission of chemical substances from industrial wastes. Three different thresholds are set in order to choose the correct type of landfill disposal: for inert, non hazardous or hazardous wastes.

As bottom ash does not arise relevant problems about its disposal, in most cases it is sufficient to submit it to a mechanical treatment (i.e. crushing). Actually, some analyses, such as the ones conducted by Cioffi and coauthors (2011), show that the quantities of heavy metals released by untreated bottom ash are slightly higher than those imposed by Italian regulations for inert landfills. It means that, without treatment, bottom ash shall be disposed only in landfills for non-hazardous wastes. Another problem is that bottom ash is produced in a huge amount: it consists in the fourth of the waste incinerated, by weight. Various authors are consulted, about the most common and known ash stabilization technologies.

**Shen and Forssberg (2003)** analyze metals' recovery from bottom ash The method shown is the process carried out by Schmeizer (1995), that consist in bottom ash crushing, screening and wet magnetic separation. The products obtained are fine scrap with 90-95% Fe and iron concentrated with 50-50% Fe.

**Birgisdóttir and coauthors (2006)** LCA compares the use of two different materials for road construction: gravel and bottom ash. In this study, bottom ash is used to substitute gravel in sub-base layer. This avoids both gravel extraction and bottom ash landfilling. The functional unit is 1 km of asphalted road, usable for 100 years; the boundaries are set from road design to its demolition and maintenance. The results show that environmental impact of road construction with gravel and with bottom ash are similar. Moreover, the most important avoided impact contribution comes from the avoided bottom ash landfilling. Therefore, road construction with bottom ash is viable only because it avoids bottom ash landfilling, and all its consequences, such as leaching. Considering that the construction and maintenance fluxes are similar in both cases, from this study it can be deduced that environmental impacts of gravel extraction and processing are similar to the ones derived by bottom ash preselector.

**Barberio and coauthors (2010)** analyze the use of bottom ash for frit production. It is used, together with plastic components, for glaze production, i.e. the layer of coating of a vitreous substance that is fired to use with a ceramic object to color, decorate, strengthen or waterproof it (Barberio et al., 2010). For frit production, 3-months aging bottom ash is sent to *Officina dell'Ambiente* plant, in order to be submitted the physical treatments described in Paragraph 1.4.. The Matrix® obtained is sent to a facility in which is vitrificated, i.e. it is abruptly cooled after its heating at 1,500°C. This process allows a suitable base material to be obtained, to be used for glaze production: the chemically stable amorphous structure fixes metals by chemical bonds. This use of bottom ash is compared to its disposal in a landfill, through a LCA. System boundaries include: bottom ash transport to the facilities and its treatment, production and transport of the reagents and the materials occurring, treatment of the residues coming out from the frit production process. Plants construction are included, but incineration activity is taken out from the boundaries because it is the same in both scenarios. The functional unit is the treatment of 1 kg of bottom ash. Methodologies used are CML2000 and IMPACT 2002+. A sensitivity test is carried out to evaluate how much the metals leaching from frit affects the LCA results. The results show that, for all selected categories, the use of Matrix for frit production leads to a drastic reduction of the impacts. The sensitivity test demonstrates that meals emission contributes less than 0.1% of the impacts of the innovative scenario.

**Cuijie and collaborators (2010)** make an LCA based on bottom ash use in road construction, too. In their study, bottom ash is sorted, crushed and sieved; metals are separated magnetically, with a 7% iron recovery. Results show that, even if bottom ash use prevents the use of resources such as gravel and lime, (eco)toxicity impact categories show worse result if bottom ash is used. This is due to the fact that bottom ash contains heavy metals that can be leached out during the service life of the road, causing a remarkable impact on water. More pretreatment techniques should be applied to bottom ash to make the metals contained in it more stable, or to extract them before its re-use.

**Cioffi and collaborators (2011)** deal with the production of an artificial aggregate using bottom ash. After iron extraction, bottom ash is submitted to dry milling and to a rotary plate granulation equipment. In this last phase, hydraulic binders are added, with a percentage of 10-40% respect to the amount of bottom ash, based on: cement, lime and coal fly ash. This process allows the production of granules classified as lightweight aggregate. Results prove that lightweight concrete blocks containing these granules are able to satisfy the technical requirements in force in Italy for structural use. However, currently this type of artificial aggregate is not allowed for the manufacture of the above blocks in Italy (Cioffi et al., 2010).

From these studies, it comes out that bottom ash recovery methods are various and economically feasible, as mechanical treatment is often sufficient to make bottom ash suitable for many useful purposes. Also, it is necessary to submit bottom ash to metal separation, in order to prevent heavy metals leaching problems and to obtain earnings from metal recovery. The problem consists in the fact that, such as in the study conducted by Cioffi and coauthors (2011), often national regulations do not allow many uses of the treated incineration residues.

The scenario is quite different for fly ashes: these residues are considered hazardous waste, therefore they have to be disposed exclusively in hazardous waste landfills: they cannot be admitted in inert waste landfill neither be recovered (Colangelo et al., 2012). About fly ash treatment, the following studies are discussed.

**Lundtorp and collaborators (2002)** analyze the Ferrox stabilization, a process tested at semi-industrial scale. It consists in adding hydrated iron sulphate ($FeSO_4x7H_2O$) to fly ash, mixed with water. This process helps to bind chemically the heavy metals contained in fly ash. The mixing conditions promote the Fe(II) oxidation in atmospheric air; after this, pH variation is adjusted. The residues consist in wastewater and stabilized fly ash, which volume is reduced at about 80% (Fruergaaard et al., 2010).

As the addition of cementitious materials, even if it is a cheap technique, creates a huge amount of final product to be disposed (Karagiannidis et al., 2013), **Park and Heo (2002)** experiment fly ash vitrification as a stabilization method, with the addition of silica ($SiO_2$). This additive is required because it prevents fly ash leaching; in addition to this, hazardous compounds and metals bound into the Si-Al matrix (Karagiannidis et al., 2013). 30% of silica added to 70% of fly ash is verified to be the combination with the least leaching rate. The high temperature helps to volatize chlorine compounds, to destroy furans, dioxins and other toxic organic contaminants (Karagiannidis et al., 2013). This causes a significant fly ash weight loss, up to 65% by weight. The problem is that these volatized chlorine compounds have to be treated using air pollution prevention facilities. Another problem arising is that it is a costly method due to the high energy consumption (Karagiannidis et al., 2013).

**Shen and Forssberg (2003)** report a metal separation technique for fly ash, too. It is carried out by Sakai and Hiraoka (2000) and consists in the mixing of fly ash with acid solution. This wet method allows the dissolution of Zn and Cu in the fly ash into the solution. Then, Zn and Cu in the solution have to be changed into hydroxides through neutralization and sulphured.

As far as concerns authors' opinion, this analysis is incomplete because every metal separation method regarding fly ash should be coupled with an inertization method.

**Colangelo and collaborators (2012)** make a study about fly ash stabilization through soluble salt removal, followed by inert material addition. The study is carried out by an acidic washing pre-treatment, that makes soluble salts move from the solid phase to the liquid one. This gives a better immobilization efficiency of some heavy metals. After this, fly ash is stabilized though the addition of concrete, in order to be recycled as a construction material. Colangelo and coauthors find out that coupling a washing preselector to a following inertization phase is necessary to ensure that the stabilized fly ash does not exceed the limits indicated by the ministerial decree 27/09/2010. Inertization through cementitious materials alone does not ensure to obtain a non-hazardous product because cements, pozzolanes, blast furnace slag and lime are not often suitable to reduce the high mobility of chlorides and sulphates down to the imposed regulations limits (Ferone et al., 2013). Despite these considerations, washing technologies arise problems such as the treatment of the wastewater coming from the process. Moreover, the amount of water needed to carry out this process is very high (up to 20 $m^3$ per ton of fly ash treated). It should be necessary to improve the efficiency of water use, focusing on the effect of the liquid to solid ratio in salt extraction.

**Ferone and collaborators (2013)** study take as a reference the work done by Colangelo and coauthors, using the same preselector washing technologies for fly ash. The difference with the previous study is that inertization is conducted by the adding alkali-activated aluminosilicate materials. The high pH of the alkaline solution allows the dissolution of the raw materials, and the precipitation of the inorganic polymers. The product obtained is a geopolymer, a material with excellent mechanical properties, that can be suitable for many non-structural applications (backfilling of abandoned quarries, decorative materials in construction sector, etc). This technology allows, in particular, an high immobilization level of cadmium (in form of $Cd(OH)_2$) due to its high solubility in high-alkaline solutions.

From these studies it can be deduced that fly ash treatment arises various pollution issues: for example, if chemical treatment is used (it is necessary even to separate metals), there is a significant amount of hazardous wastewater to purify. Instead, if thermal treatments are chosen, a huge amount of electricity has to be used. In addition to this, after these stabilization treatments fly ash can often keep resulting hazardous. Therefore, it is often necessary to couple different treatment technologies to ensure that the stabilized fly ash is sure to be disposed. Currently, fly ash stabilization is in every case a costly and difficult choice.

# 2 MATERIALS AND METHODS

## 2.1 Goal and scope definition

### 2.1.1 Goal

One of the most important targets is to find out the most impacting phases of the whole incineration process, through an hotspot analysis. Scenarios are made, based on the most impacting phases, in order to find out which alternative is the most environmentally viable. Considering that the plant catches up with new technologies and instruments to improve its efficiency, my study focuses on the fate of the solid residues produced during incineration. As each of the incineration residues (bottom and fly ash) has three treatment alternatives, their combination gives nine scenarios: The three destinations of the bottom ash are based both on what happens actually to it, and on hypothetical scenarios, taken from bibliography. Actually, it occurs that 50% of the bottom ash is sent to landfill, and the other half is sent to *Officina dell'Ambiente*. Two of the scenarios are based on these destinations: in the Base scenario, bottom ash is sent in an inert waste landfill, without any preselector necessary. In the other scenario, the bottom ash is sent to Officina dell'Ambiente, in order to produce an aggregate that substitutes natural gravel in construction sector. The third scenario is taken from the ROAD-RES study conducted by Birgisdóttir and coauthors (2006) and developed by Cuijie and collaborators (2010). It consists in the mechanical treatment (sorting, crushing and sieving) of the bottom ash, in order to produce a gravel suitable to substitute natural gravel in the sub-base layer of a road being constructed. From these considerations, seems that they are two similar bottom ash alternatives: in both of them bottom ash is submitted to mechanical-physical treatments. Moreover, the aim of both Road and OdA is to obtain a stable product with the gravel granulometric scale, in order to be used as aggregate in construction sector. In addition to this, they use the same order of magnitude of electricity, and produce similar amounts of gravel. The only difference consist in the fact that in Road gravel is the base to form bitumen used to set up a layer in road construction, in OdA gravel is used to be melted with cement to make concrete to be used in building sector. But, as the subsequent gravel use in construction phase is not taken in account in the model boundaries, this does not consist in a difference. Actually, different environmental burdens can be generated by the construction phase. In fact, the construction made with aggregate of natural origin may require different resources and material compared to the construction made with the aggregate derived from incineration residues. Nevertheless, due to the lack of data, in this study it cannot be possible to find out the impact derived from construction phase.

As far as concerns fly ash fate, the actual alternative is the inertization with cement and subsequent landfilling in a sanitary landfill. It is compared to the chemical stabilization through Ferrox technology (Lundtorp et al., 2002), that consist in adding an iron (III) sulphate solution; and to thermal stabilization through vitrification method (Park and Heo, 2002) vitrificated, i.e. it is abruptly cooled after its heating at 1,500°C, in order to obtain a safe and stabilized material. The combination of these ash recovery technologies gives the nine following scenarios:

- **Base**: both bottom and fly ash disposed in an inert waste landfill; fly ash is inertized with concrete before the disposal in *Systema ambiente* landfill site;
- **BA Road**: bottom ash is physically treated in order to be suitable to substitute gravel in road construction; fly ash is inertized with concrete and therefore disposed in in *Systema ambiente* landfill site;
- **BA OdA**: bottom ash is sent to *Officina dell'Ambiente* plant to be submitted to mechanical treatments that make it suitable to substitute gravel in construction sector; fly ash is inertized with concrete and therefore disposed in *Systema ambiente* landfill site;
- **FA Ferrox**: bottom ash is inertized with concrete and therefore disposed in an inert waste landfill; fly ash is submitted to Ferrox stabilization treatment and then disposed in *Systema ambiente* landfill site;
- **FA Vitrification**: bottom ash is inertized with concrete and therefore disposed in an inert waste landfill; fly ash is submitted to vitrification treatment and then disposed in in *Systema ambiente* landfill site;
- **BA Road + FA Ferrox**: bottom ash is physically treated in order to be suitable to substitute gravel in road construction; fly ash is submitted to Ferrox stabilization treatment and then disposed in *Systema ambiente* landfill site;
- **BA Road + FA Vitrification**: bottom ash is physically treated in order to be suitable to substitute gravel in road construction; fly ash is submitted to vitrification treatment and then disposed in in *Systema ambiente* landfill site;
- **BA OdA + FA Ferrox**: bottom ash is sent to *Officina dell'Ambiente* to be submitted to mechanical treatments that make it suitable to substitute gravel in construction sector; fly ash is submitted to Ferrox stabilization treatment and then disposed in *Systema ambiente* landfill site;

- **BA OdA + FA Vitrification**: bottom ash is sent to *Officina dell'Ambiente* to be submitted to mechanical treatments that make it suitable to substitute gravel in construction sector; fly ash is submitted to vitrification treatment and then disposed in *Systema ambiente* landfill site.

It is noteworthy that in this thesis two actual alternatives (Base and OdA), supported by reliable data coming directly from companies, are compared with a treatment (Road) which information are taken from a bibliography study. As its data are not based on plants actually operating at an industrial level, the following comparison between these bottom ash treatment alternatives will take in consideration the different data origin. In addition to this, it has to be considered that, actually, it is impossible to use bottom ash in Italy in road construction. In fact, if waste recovery method includes the contact with earth like in this recycling treatment, the recycled waste has to be in compliance with Ministerial Decree 186/06. Usually, even if the bottom ash is treated and metals are extracted from it, it does not result to be in compliance with Ministerial Decree 186/06. Therefore, further treatments shall be applied to bottom ash to be used for this purpose, but the recycling process would become environmentally and economical unfeasible.

### 2.1.2 System boundaries

Boundaries are set upstream from waste arrival in pre-selector/loading tank. Waste collection, its transport to the facility, and its unloading in the ecological platform are not considered, because waste that is not going to be submitted to the incineration process takes part of these phases, too. Resources involved in plant construction and upgrading are not considered, too: only operative period is considered. All the fluxes of the activities supported in the plant but not linked directly to incineration are not considered (e.g. energy and resources consumed in office). Transport is taken in consideration, even if it is not evaluated as a process characterized by a relevant impact by the studies consulted. Downstream, boundaries contain: all reagents consumed in the flue gas cleaning phase; the production and disposal/recovery of all the solid and liquid residues produced by the process; energy and thermal recovery (Figure 2.1).

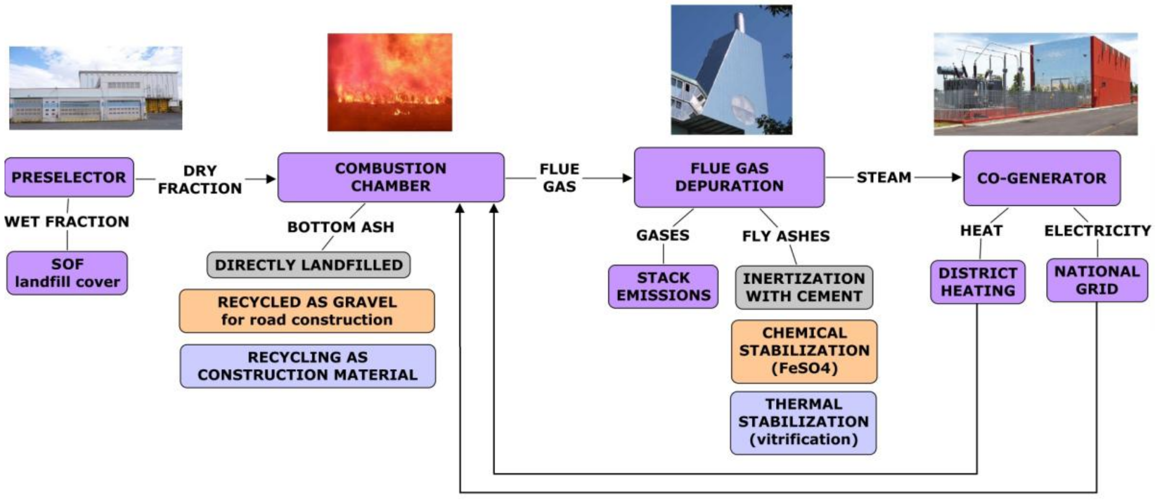


**Figure 2.1 Processes and fluxes included in system boundaries (Herambiente, 2012 Environmental Declaration)**

### 2.1.3 Functional unit

Functional unit is the amount of waste incinerated in 2011 (115,735.095 t). 2012 value is not used, because that year pre-selector did not work, as explained above. Actually, data about waste composition and production is not significantly changed from 2011.

### 2.1.4 Allocation

System expansion is applied through the subtraction of a function non required or avoided. It allows the avoided impacts obtained by particular processes to be taken into account. Therefore, it means that the net impact scores includes not only the impact generated by a process, but also the impact that this process is able to avoid. As the model include energy and material recovery, it often appeals to system expansion. It is applied in the following cases:

- the avoided use of organic, inert material used as landfill cover because of SOF production. This process can be used as an example to understand how system expansion is applied. The biostabilization of $1.3*10^7$ kg of humid waste allows the production of $1.4*10^6$ kg of SOF. This stable material is used to cover landfills daily. This means that $1.3*10^7$ kg of humid waste do not have to be disposed in landfill; moreover, $1.4*10^6$ kg of organic coat do not have to be produced from raw materials, because SOF replaces its function. The impacts that would be generated by these two last fluxes are the avoided impacts taken in consideration in system expansion;

- the avoided extraction and processing of raw iron from minerals due to the iron magnetically separated from bottom ash in deironization;
- the avoided extraction and crushing of gravel in road construction and in *Officina dell'Ambiente* plant, because of physical treatments that make bottom ash suitable to replace natural gravel function, used as an aggregate in construction sector.
- the avoided electricity and heat production due to co-generator process. In Figure 2.2 the way in which electricity and heat recovery are accounted in GaBi co-generator plan is shown:

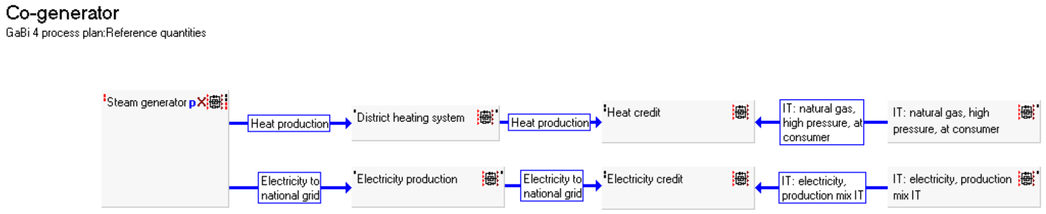


**Figure 2.2 Structure of the plan *Co-generator* in GaBi**

Mass allocation is done when there is no information about the splits in the process fluxes. In case of ammonia, the amount of solution used either in SCR or SNCR process is not known. As the literature does not offer any information about it, half of the ammonia is assumed to be used in SNCR process and the other half is used in SCR. The same occurs in fly ash production: as the amount produced after flue gas cleaning is stocked together with the quantity emitted by the steam generator facility, the amounts related on the single processes are not know. To simplify the model all the fly ash is assumed to be produced in the flue gas cleaning stage.

## 2.2 Life Cycle Inventory

### 2.2.1 Data source

Most of the data are taken from Herambiente. Forlì WTE plant set of data is taken from its 2011 and 2012 Environmental Declarations, together with the 2011 and 2012 Annual Relations. Data referred to Voltana composting facility (managed by Herambiente, too) is taken from its 2012 Environmental Declaration. Therefore, with some exceptions, such as the amount of the waste incinerated shoved in Paragraph 2.1.3, the whole set of data coming from Herambiente plants is taken from 2012. Data about Matrix® production in *Officina* *dell'Ambiente* is taken from its 2012 Environmental Declaration. When the fates of wastes produced in plant are not known, secondary data from, primarily, Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2004) is used and, when Ecoinvent database is not complete about a certain issue, GaBi database (PE International) is used. The geographical origin of database data is preferably Italian. When Italian source data are not found, European or Swiss processes are used. When specific recovery/disposal processes are not found in the database, literature data are used. Literature data origin is wide: it comes mainly from studies made in Italy or in Northern Europe, but few data are taken from Asian analyses.

### 2.2.2 Assumptions

- Considering energetic expenditures and savings, if it is not alternatively specified, electricity is assumed to be taken from/sent to national grid. About heat recovery, it is supposed to substitute natural gas.
- As concerns reagents' consumes, only the ones that are used above 5 t/y are included in the system boundaries. The substances with a consume below 5 t/y are assumed to have a negligible impact on the process. HCl and NaOH use, above 5 t/y each, is not considered because they are already included in demineralization process found in Ecoinvent database. Also, waste produced by side activities of the plant (e.g. office) is not taken in consideration.
- About transport process, various assumptions are made. 100 km is the distance used when the position of a plant whose fluxes are sent to is not known. It is also assumed that at distances identical to or higher than 100 km, the return travel is made at full payload.
- As far as concerns biostabilization process, it is assumed that humid fraction is sent to Voltana composting plant, the facility that is nearest to the WTE plant and that has a consultable Environmental Declaration, from which primary data are taken. It is also hypothesized that he whole humid fraction obtained in preselector is submitted to a process making exclusively Stabilized Organic Fraction.
- As far as regards bottom ash treatment, only two of the three alternatives are based on primary data and processes actual occurring. These are the bottom ash landfilling and the bottom ash sent to *Officina dell'Ambiente* facility. The bottom ash used in road construction is an alternative which data are taken almost by literature.

- Focusing on bottom ash treatment alternatives, it has to be specified that the energy and material required from the production of the construction material from Matrix® (BA OdA alternative) and the production of a sub-base layer in road construction (BA Road alternative) are not included in boundaries, because they are the same regardless the origin of the raw material used.
- Similarly, the impacts associated to the production of iron from the iron scraps extracted by bottom ash has not been considered, due to the lack of data and because it would be an off-topic process.
- In addition to this, some changes are applied to BA OdA data, in order to make an equilibrated mass balance. As the plant stores for a long time bottom ash before making it suitable to transform it in Matrix®, the sum of the fluxes of Matrix® and iron scraps exiting the plant is higher than the amount of bottom ash entering the plant during an year. In fact, the long storage makes possible the treatment of bottom ash accepted in the plant at the end of the previous year. Therefore, some calculations are made, in order to balance the mass fluxes entering and exiting the model, but making sure that the proportions of Matrix® and fine scraps produced are the same.
- Concerning fly ash treatment, only the first of the three alternatives (i.e. the inertization with cement and its subsequent landfilling in a sanitary landfill) is based on the actual process. The other two alternatives (chemical and thermal stabilization) are based on literature projects and data. Despite this differences, the landfill site in which stabilized fly ash is supposed to be sent in all of the three alternatives is the actual one (*Systema Ambiente*).
- In particular, as regards fly ash inertization with cement, as the actual cement used (Soliroc cement) has not been found in the Ecoinvent database, an average cement made up by the mix of different cements is used.

### 2.2.3 Waste inputs

This plant has been built to treat only non-hazardous waste, that can be split in: unsorted waste coming from municipal collection in the whole Forlì-Cesena province, and industrial waste collected from some local activities, composed mainly by treated and natural wood and tires, although the last makes up a minimal percentage on the total amount of waste. These types of waste globally make up above 75% of the total amount of waste incinerated in the plant. The rest is composed by waste produced by other waste treatment plants, sewage sludge and packaging. Table 2.1 shows the average composition of the waste coming at the plant. From data, it is possible to observe that in 2011 most of the waste was composed by biological fractions (cellulosic and organic waste), that together made up about 70% of the total incinerated waste. The subsequent year, most of the waste treated was equally split among plastic, organic fractions and cellulose materials, each contributing with a 30% percentage. Waste composed by cellulose (e.g. wood, paper, paperboard) is diminished, despite the increase of plastic waste and of organic fraction. Both inert and metals diminished steadily between the two years, perhaps due to a better separated collection of these fractions from local activities. The humid fraction amount split from the dry one during the sorting in preselector is steady. It is necessary to take into account that this is the average composition of the waste coming both to preselector and to the loading tank of the combustion chamber, therefore if the waste is not preselected, a significant amount of organic waste is incinerated.

| | **WASTE ENTERING INCINERATOR (%)** | |
|---|---|---|
| | **2011** | **2012** |
| **Plastic** | 19.95 | 30.18 |
| **Cellulose materials** | 42.80 | 27.89 |
| **Organic** | 26.95 | 33.82 |
| **Inerts** | 2.45 | 1.31 |
| **Metals** | 2.60 | 0.78 |
| **Humid fraction from preselector (< 2mm)** | 4.20 | 3.66 |
| **Pick residues** | 1.05 | 1.28 |

**Table 2.1 Waste fractions entering the incineration plant in 2011 and in 2012. Each value is the average of two yearly analyses (Herambiente, 2012 Environmental Declaration)**

## 2.2.4 Reagents

Table 2.2 shows the reagents used in waster demineralization, in flue gas cleaning and in steam generator process. Form data, in can be deduced that 2012 reagents' consume rates did not vary significantly from 2011, except for $NaHCO_3$, which use efficiency doubled from 2011 to 2012, and for hydrated lime, even if it does not show a relevant decline. In 2011 a broader list of reagents was used.

| **REAGENTS** | **T 2012** | **KG/T INCINERATED WASTE 2011** | **KG/T INCINERATED WASTE 2012** | **USE** |
|---|---|---|---|---|
| **Hydrated, ventilated lime** | 1393.75 | 12.65 | **12.41** | **Flue gas cleaning** |

| | | | | |
|---|---|---|---|---|
| **$NH_3$ solution 25% for DeNOx** | 323.56 | 2.69 | 2.63 | **Flue gas cleaning** |
| **$NaHCO_3$-** | 239.55 | 3.05 | **1.87** | **Flue gas cleaning** |
| **Activated carbon** | 128.71 | 1.26 | 1.25 | **Flue gas cleaning** |
| **Sodium hydroxide 30%** | 8.34 | / | / | **Water demineralization** |
| **HCl 32%** | 8.08 | / | 0.067 | **Water demineralization**: removes ions like $Na^+$ or $Ca^{2+}$ through cationic exchange |
| **Micropan** | 3.50 | / | / | **Wastewater**: improves the formation of useful bacterial colonies that degrade the organic substratum |
| **Propylene glycol** | 1.20 | / | 0.01 | **De-icing** |
| **Amersite CHZ** | 1 | / | 0.070 | **Steam generating system**: oxygen-induced corrosion inhibitor |
| **Amercor 8780** | 0.77 | / | 0.0064 | **Boiled water treatment**: neutralizes carbonic acid to raise system pH |
| **AmeroyalC800** | 0.20 | / | 0.0016 | **Water demineralization**: prevents scaling of the membranes in reverse osmosis systems |

**Table 2.2 List of the chemicals used in the plant (Herambiente, 2012 Environmental Declaration)**

### 2.2.5 Water

The **water** used and re-circulating in the process is taken from the municipal main. Part of it is demineralized in the plant. This process is made by a facility that carries out the following reactions: water chlorination (HCl removes ions like $Na^+$ or $Ca^{2+}$ through cationic exchange), sand filtration; then, sodium bisulfite and anti-encrusting are added. Then, de-mineralization is made through reverse osmosis; finally, regeneration reagents are diluted in the water. As shown in Table 2.3, water used for washing operation is not demineralized, whilst water used in steam generator system is necessarily demineralized because water with salts can damage generator tubes.

| **WATER TYPE** | **DEMINERALIZED** | **2011 ($m^3$)** | **2012 ($m^3$)** |
|---|---|---|---|
| Used in incinerator (Line 3) | YES | 25,340 | 29,220 |
| Used in washing operations (load tanks+ bottom ash stock area) + used for human services (NaClO is added) | NO | 2,370 | 1,470 |

| | | | |
|---|---|---|---|
| Main water preselector | NO | 8,360 | 10,410 |

**Table 2.3 Cubic meters of water used in plant (Herambiente, 2012 Environmental Declaration)**

### 2.2.6 Energy

Table 2.4 shows the electricity fluxes involved in the incineration plant. From data, it is possible to conduct that electricity produced in the plant through waste combustion is much higher than the one imported from the national grid to let it work. About a fifth of the electricity produced is re-used for the incineration process, the remainder is sent into the national grid. Heat sent into the district heating contributes to heat a mall situated about 1 km far from the facility. It is notable that part of the steam heated by flue gases is used to heat the combustion chamber itself, reaching the highest exploiting level of the energy coming from waste combustion.

| **ENERGY TYPE** | **MWh** | **PHASE** |
|---|---|---|
| Natural gas to start and keep incineration T° (with steam production) | 4,040 | Combustion chamber |
| Natural gas for combustion gas heating for SCR process + for starts/stops (without steam production) | 3,180 | SCR process |
| Imported electricity | 5,280 | / |
| Electricity produced and used in the plant for incineration | 12,900 | Combustion chamber |
| Electricity sent in the national grid | 51,690 | National grid |
| Heat sent in the district heating with condensate return | 10,010 | CHP |
| Steam for combustion gas heating with condensate return | 3,720 | CHP |
| Electricity preselector | 142.41 | Preselector |

**Table 2.4 Energetic fluxes of the plant (Herambiente, 2012 Environmental Declaration)**

### 2.2.7 Waste outputs

According to Table 2.5, showing the tons of waste produced by the plant, waste production in incineration process is almost steady between 2011 and 2012: there is a slight increase of fly ash production, whilst the production of sludge from bottom ash cooling is increased significantly. No wet fraction from preselector was produced in 2012 because the preselector did not work. This is why 2011 value is used in the model.

| **EWC** | **t** | **t** | **FATE** |
|---|---|---|---|

| | | 2011 | 2012 | |
|---|---|---|---|---|
| 16.10.02* | Washing operations in load tanks | 2,343 | 1,266 | Disposal (sewer) |
| 19.01.05* | Fly ash | 4,694 | 4,803 | Disposal |
| 19.01.06* | Liquid waste coming from bottom ash cooling water and condensation water | 21 | 203 | Disposal |
| 19.01.07 | Sodic residue from $2_{nd}$ flue gas cleaning stage (RSP) | 197 | 191 | Recovery |
| 19.01.12 | Bottom ash from solid waste combustion | 26,828 | 30,371 | Recovery |
| 19.12.12 | Wet fraction from preselector | 12,596 | 0 | Recovery |

**Table 2.5 Types of waste produced in the incineration plant, listed by their EWC. The asterisk (*) characterizes hazardous wastes (Herambiente, 2012 Environmental Declaration)**

Table 2.6 shows the types of waste produced in all the side activities of the plant (office, maintenance, etc.). It can be observed that in 2012 their production decreased significantly from 2011. These amounts of waste are not inserted in the model because their production is negligible compared to the waste fluxes in Table 2.5.

| WASTE WTE PRODUCTION (kg) | | | | |
|---|---|---|---|---|
| EWC | | 2011 | 2012 | FATE |
| 13.02.08* | lubrificant mineral oil | 2,060 | 370 | Recovery |
| 15.02.02* | seeping material contaminated by harmful compounds | 260 | 60 | Disposal |
| 16.02.13* | WEEE with hazardous compounds different from 160209(condensators with PCB) & 160212(eternit in fibers) | NA | 30 | NA |
| 16.06.01* | Pb batteries | 2,590 | NA | Recovery |
| 20.01.21* | Fluorescent lamps | 260 | 29 | Recovery |
| 20.01.27* | Paints | 1,910 | NA | Disposal |
| 20.01.35* | Hazardous WEEE (different from 20.01.21* & 20.01.23(equipment containing CFCs)) | 85,650 | 61 | Recovery |
| 20.01.36 | WEEE broken (not small electric equipment: 20.01.21*, 20.01.23* e 20.01.35*) | 79,800 | NA | Recovery |
| 17.04.05 | Iron and steel | 43,390 | 1,080 | Recovery |

**Table 2.6 Types of waste produced in the side activities of the incineration plant, listed by their EWC (Herambiente, 2012 Environmental Declaration)**

### 2.2.8 Incinerator residues data

Regarding the recovery of the wet fraction produced in preselector, data from Herambiente related to Voltana composting plant are taken. In this facility, wet fraction is submitted to biostabilization, in order to produce SOF. Residues are composed by: leachate and methane produced during bio-stabilization process. Data used are listed in Table 2.7.

| | **2011 DATA/t ORGANIC FRACTION** | **2011 DATA*t ORGANIC FRACTION** | **M.U.** |
|---|---|---|---|
| **Organic fraction** | 1.00E+00 | 1.26E+04 | t |
| **Electricity** | 3.99E-02 | 5.03E+02 | kWh |
| **Water** | 7.23E-02 | 9.10E+02 | $m^3$ |
| **SOF** | 1.11E-01 | 1.40E+03 | t |
| **Leachate** | 1.14E-01 | 1.43E+03 | t |
| **$CH_4$ emissions** | 8.41E-04 | 1.06E+01 | t |

**Table 2.7 Voltana composting plant data (Herambiente, 2012 Environmental Declaration))**

Data related to energy spent in bottom ash treatment in road construction scenario are shown from Table 2.8. The consumes related to the extraction and production of the substituted natural material are taken from Ecoinvent database.

| **ENERGY CONSUMPTION FOR PREPARING MSWI BOTTOM ASH FOR GRAVEL PRODUCTION IN ROAD CONSTRUCTION (kJ/t) (Cuijie et al., 2010)** | |
|---|---|
| Sorting | 900 |
| Crushing | 5,400 |
| Sieving | 1,260 |

| **MATERIALS SUBSTITUTION IN USING BOTTOM ASH IN ROAD CONSTRUCTION (t/t BOTTOM ASH PRODUCED) (Birgisdóttir et al., 2012)** | | |
|---|---|---|
| | **BA not used in road construction** | **BA used in road construction** |
| Gravel pit | 3.7 | 2.7 |
| Bottom ash | 0 | 1 |

**Table 2.8 Electricity and materials spent for bottom ash treatments in road construction scenarios**

It has to be considered that magnetic separation is assumed to occur in all of the three scenarios, as the bottom ashes of Forlì WTE plant are actually submitted to this process: in particular, in Base and BA Road scenarios the data used to make deironization plan are taken from literature (Cuijie et al., 2010), as it can be seen in Table 2.9. Instead, in *Officina dell'Ambiente* scenario data about deironization are included in the total energetic expenditures of the plant, therefore another data are used.

| **BOTTOM ASH DE-IRONIZATION** | | | |
|---|---|---|---|
| Magnetic Separation | 50 | kJ/t | **Cuijie et al., 2010** |
| Iron recovered from slags | 7.37% | % | **Herambiente** |

**Table 2.9 List of the data used for deironization process in bottom ash base and road construction scenarios**

Regarding fly ash fate, in the light of what is said in Paragraph 1.6, fly ash fate is assumed to be the landfill, and no recovery methods are considered. The scenarios compared are three: inertization with cement and subsequent landfilling in a sanitary landfill; chemical stabilization through Ferrox technology; thermal stabilization through vitrification method. Data used are shown in Table 2.10:

| **FLY ASH SCENARIOS (PER TON OF FLY ASH PRODUCED)** | | |
|---|---|---|
| **FERROX STABILIZATION (Lundtorp et al., 2002)** | | |
| **Value** | **M.U.** | **Type** |
| 34 | kWh | Electricity |
| 0.29 | t | Iron sulphide |
| 2.7 | $m^3$ | Water |
| **VITRIFICATION FOLLOWED BY LANDFILLING (Fruergaard, 2010 and Park and Heo, 2002)** | | |
| 700 | kWh | Electricity for melting |
| 0.43 | t | Silica |

**Table 2.10 Energy and materials fluxes used in Ferrox and Vitrification scenarios**

### 2.2.9 Software

The LCA software used to make this analysis is GaBi 4 (PE International, 2006). This software is a modular system composed by plans, processes and flows. The flow object type is the basis of the model: it is representative of an actual material or energy flow. Flows allow the connection between different processes within a life cycle. Processes are model objects representative of the actual mechanisms of the system studied, and contain flows. Plans are the maps in which the processes that are part of the same life cycle phase are connected. GaBi plans can be nested in order to design complex balance systems. This modular structure allows individual life cycle phases (manufacturing, use or disposal phases) to be grouped together, so that they can be processed separately from each other. Another essential feature is that the software and the database are independent from each other. All information related to a product (eco-profiles, material properties, etc.) is stored in the database, whereas the software supplies the user interface and the ability to construct the model and analyze the databases. Once the model of the system is built, the object type “Balance” compares all inputs of the whole system (or only of a selected plan) with its outputs. According to ISO 14044, Balance function submits system data and flows to classification and characterization. The LCIA results are shown in one table, as these two steps are performed simultaneously by the software. Therefore, Balance results are processed in Microsoft Excel 2007 in order to make graphs and tables. In Figure 2.3 the structure of the whole plan is shown, together with the connection between sub-plans.

#### 2.2.9.1 Model overview

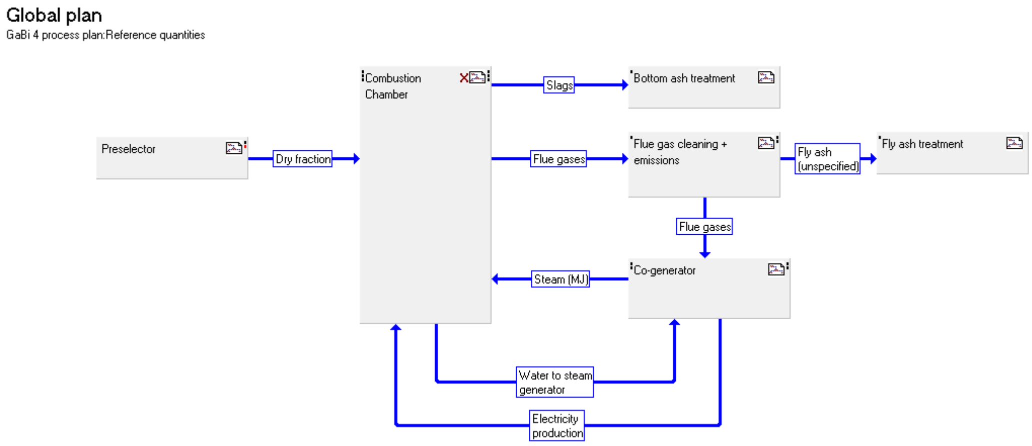


**Figure 2.3 GaBi screenshot of the structure of the global plan**

Starting from the preselector sub-plan, it can be said that electricity and water are used, and that its only outputs are the wastewater (that goes to depuration) and the humid fraction, going to SOF production. The structure of the process used to produce it is shown in Figure 2.4. It can be observed that SOF production produces only leachate as a residue, and that allows two important functions to be recycled: landfill covering and the production of suitable inert materials.

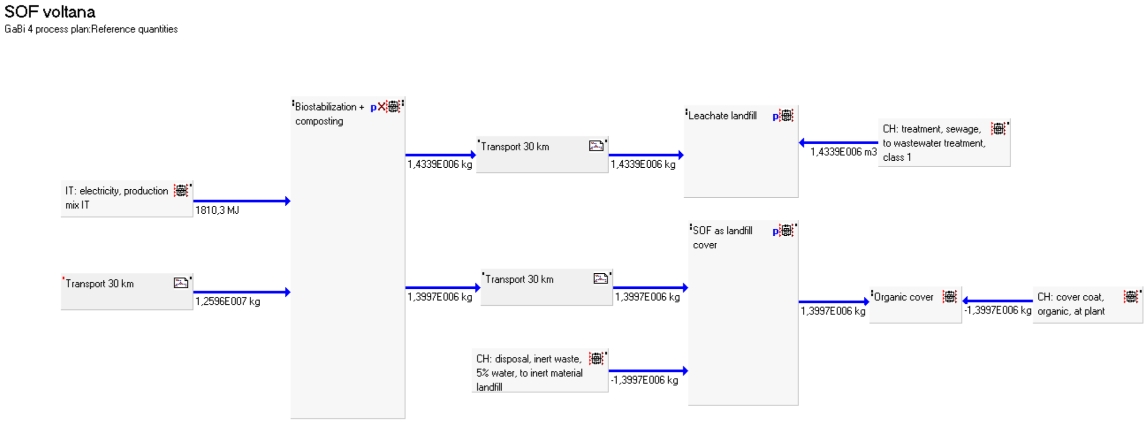


**Figure 2.4 GaBi screenshot of the structure of the SOF production sub-plan**

The central sub-plan is *Combustion Chamber*, that contains all the fluxes related to reagents' synthesis and consumption, and the amounts of methane and electricity used to run the plant. This sub-plan is linked with these two stages in output: *Bottom ash treatment* and *Flue gas* *cleaning and emissions*. The first of these sub-plans is structured as shown in Figure 2.5. From Figure 2.5, it can be seen that bottom ash going out of the WTE facility is submitted to de-ironization: this prevents the extraction of virgin iron from the environment. After iron separation, bottom ash is either landfilled after inertization or treated to be used a construction material. Through choice parameters, only one of these three treatment alternatives can be chosen at time (in Figure 2.5, *Bottom ash inertization* is chosen).

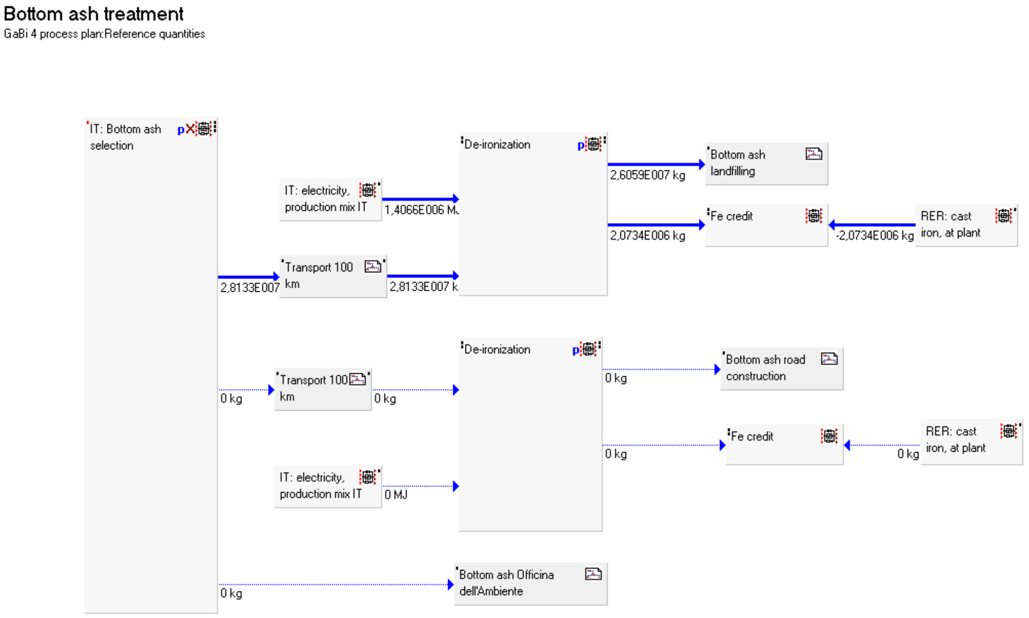


**Figure 2.5 Structure of the sub-plan *Bottom ash treatment* in GaBi 4**

In sub-plan *Flue gas cleaning and emissions*, all the synthesis processes of the reagents necessary to clean the flue gas going out the combustion chamber are found. The outputs of this plan are the air emissions and the fly ash, that is sent to sub-plan *Fly ash treatment*. Also, in this plan it is possible to choose the three alternative fly ash treatment scenarios (inertization with concrete, Ferrox stabilization or vitrification) switching appropriate parameters. Finally, the heat contained in flue gas goes to *Co-generator*, the sub-plan in which there are the electricity and the heat produced by the incinerator itself as outputs. They are partially sent to, respectively, national grid and district heating system. The remaining are sent to the sub process *Combustion Chamber*, where they make up part of the energy necessary to run the plant.

In Table 2.11 all the input and output processes taken by Ecoinvent and GaBi databases, related to the main fluxes used in the model.

| **INPUTS** | **FLUX** | **OUTPUTS** |
|---|---|---|
| **REAGENTS** | | |
| RER: ammonia, steam reforming liquid, at plant | AMMONIA | |
| RER: soda, powder, at plant | SODA | |
| CH: lime, hydrated, packed, at plant | LIME | |
| RER: sodium silicate, spray powder 80%, at plant | SODIUM SILICATE | |
| RER: iron sulphate, at plant | IRON SULPHATE | |
| CH: portland calcareous cement, at plant | CONCRETE (for fly ash inertization) | |
| **TRANSPORT** | | |
| GLO: Truck-trailer > 34 - 40 t total cap./ 27 t payload / Euro 3 | TRANSPORT | |
| **WATER** | | |
| RER: tap water, at user, or: CH: water, deionised, at plant | WATER | CH: treatment, sewage, to wastewater treatment, class I |
| **WASTE** | | |
| | SLUDGE/LEACHATE | CH: disposal, municipal solid waste, 22,9% water, to sanitary landfill |
| | STABILIZED FLY ASH, VITRIFICATION RESIDUES | CH: disposal, inert material, 0% water, to sanitary landfill |
| | INERT WASTE (i.e. bottom ash if landfilled, SOF used as landfill cover) | CH: disposal, inert waste, 5% water, to inert material landfill |
| **ENERGY** | | |

| | | |
|---|---|---|
| IT: electricity, production, mix IT; CH: electricity, PV, at 3kWp flat roof installation, multi-Si; IT: electricity, hydropower, at power plant | ELECTRICITY | |
| IT: natural gas, high pressure, at consumer | NATURAL GAS | |
| **MATERIALS REPLACED** | | |
| RER: cast iron, at plant | IRON (from bottom ash deironization) | |
| CH: gravel, crushed, at mine | GRAVEL (replaced by bottom ash in road construction and in *Officina dell'Ambiente* scenarios) | |
| CH: cover coat, organic, at plant | ORGANIC COVER substituted by SOF | |

**Table 2.11 List of the input/output database processes linked to the main model fluxes**

The pie chart in Figure 2.6 shows how the energetic sources are split in Italy. It is taken from the process: "IT: electricity, production, mix IT" from GaBi database.

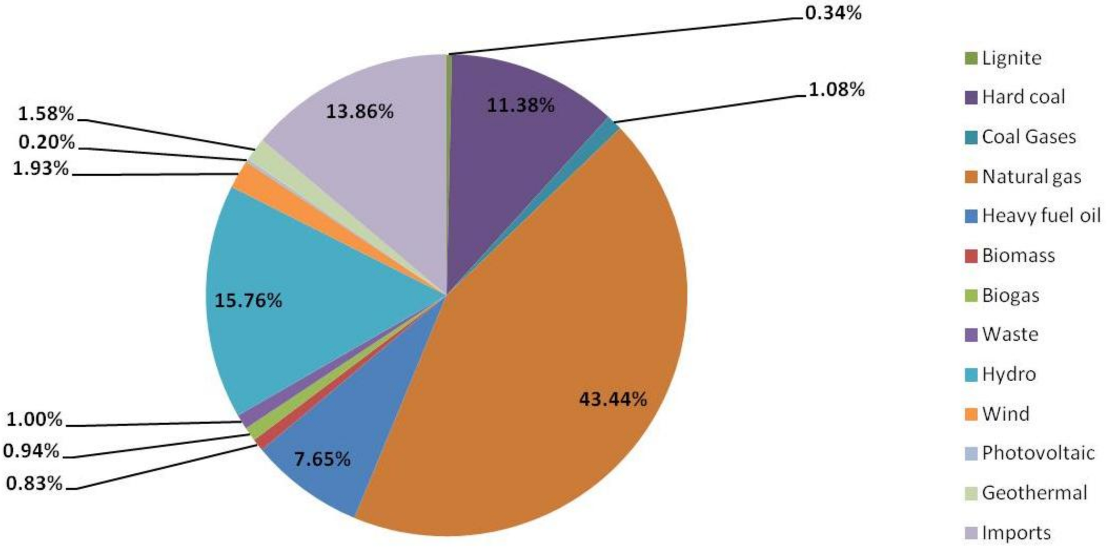
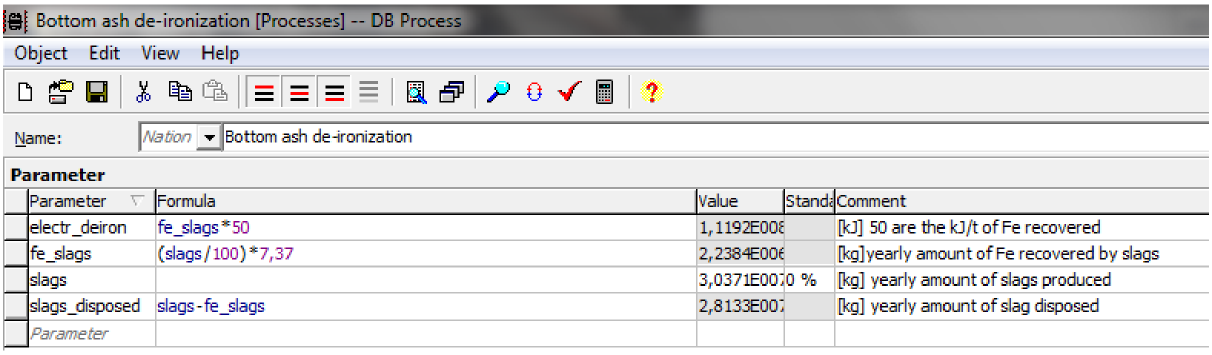


**Figure 2.6 Energetic sources in Italy (PE INTERNATIONAL, 2006)**

#### 2.2.9.2 Parametrization

The use of parameters in GaBi 6 allows users to change the values of flow quantities. An example can be made with a transport process. It can be made up a formula which calculates the required fuel, dependent by distance and load parameters: if distance and/or load varies, they will automatically adjust the amount of fuel required. Some examples can be seen in Figure 2.7, in which some of the parameters of the process "Bottom ash de-ironization" are listed. The independent parameter in this list is *slags* (the one which value is in white), because it is a fixed value. The parameter *fe_slags*, which defines the amount of the iron actually extracted from bottom ash (7.37%) through a formula, is dependent on the value of the above parameter. *Electr_deiron*, consists in the kJ of electricity needed to carry out the de-ironization, based on the fact that 50 kJ are necessary to separate iron from 1 t of bottom ash.



Name: Bottom ash de-ironization

| Parameter | Formula | Value | Standa | Comment |
|---|---|---|---|---|
| electr_deiron | fe_slags*50 | 1,1192E008 | | [kJ] 50 are the kJ/t of Fe recovered |
| fe_slags | (slags/100)*7,37 | 2,2384E006 | | [kg]yearly amount of Fe recovered by slags |
| slags | | 3,0371E007 | 0 % | [kg] yearly amount of slags produced |
| slags_disposed | slags-fe_slags | 2,8133E007 | | [kg] yearly amount of slag disposed |
| Parameter | | | | |

**Figure 2.7 Parameterized values in a Bottom ash treatment plan**

Obviously, if the amount of bottom ash produced changes, i.e. the value of the free parameter *slags* changes, the values of the dependent parameters will change automatically. As fluxes values are connected to these parameters, it is not necessary to modify manually them if a change occurs.

## 2.3 Impact categories

For the classification, characterization and calculation, the LCIA method used is CML2001 (Guinée et al., 2001), developed by the Center of Environmental Science in Leiden University, in Netherlands. It is one of the most chosen in the literature consulted.

The impact categories analyzed are: abiotic depletion (ADP), acidification (AP), eutrophication (EP), freshwater aquatic ecotoxicity (FAETP), global warming (GWP), human toxicity (HTP), ozone layer depletion (ODP), photochemical oxidant formation (POCP), terrestrial ecotoxicity (TETP) and primary energy demand, net value (PED).

### 2.3.1 Abiotic Depletion (ADP)

The characterization factor of this category is the ratio use/stock, standardized respect to a reference substance (antimony):

$$ADP_i = (DR_i / R_i^2) * (R_{ref} / DR_{ref}^2)$$

where $DR_i$ is the extraction rate of the resource *i* (kg/year), $R_i$ is the resource stock (kg); $DR_{ref}$ is the extraction rate of the antimony and $R_{ref}$ is the antimony stock. Therefore, ADP is obtained through the following equation, expressed in kg of equivalent antimony:

$$ADP = \sum_i ADP_i * m_i$$

### 2.3.2 Acidification (AP)

Acidification potential is expressed through potential $H^+$ equivalent, and it is defined as the ratio between the moles of $H^+$ ions produced per kg of a substance and the same for $SO_2$ (the reference substance):

$$AP_i = h_i / h_{SO2}$$

where $h_i$ (mol/kg) are the moles of $H^+$ produced per kg of the substance *i*, $h_{SO2}$ are the moles of $H^+$ produced per kg of $SO_2$. Total acidification value is given by:

$$AP = \sum_i AP_i * m_i$$

which result is expressed in kg of equivalent $SO_2^-$

### 2.3.3 Eutrophication (EP)

Eutrophication potential expresses the potential contribution of biomass formation:

$$EP_i = \frac{\nu_i / M_i}{\nu_{ref} / M_{ref}}$$

where $\nu_i$ and $\nu_{ref}$ are the potential contributions to eutrophication of one mole of substance *i* and ref (i.e. $PO_4^{3-}$), respectively, and $M_i$ and $M_{ref}$ (kg/mol) are the respective masses. Therefore, EP value is obtained through the following equation:

$$EP = \sum_{i} EP_i * m_i$$

which result is expressed in kg of equivalent $PO_4^{3-}$.

### 2.3.4 Freshwater Aquatic Ecotoxicity (FAETP) and Terrestrial Ecotoxicity (TETP)

Ecotoxicity potentials are based on EUSES, the EU's toxicity model, that provides a method for describing fate, exposure and the effects of toxic substances on the environment. Characterization factors are expressed using the reference unit, kg 1,4-dichlorobenzene equivalent (1,4-DCB), and are respectively measured for impacts on fresh-water aquatic ecosystems and terrestrial ecosystems.

### 2.3.5 Global Warming (GWP)

Global warming potential has been defined as the ratio of time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1kg of a reference gas (IPCC):

$$GWP_i = \frac{\int_0^{TH} a_i * [x_i(t)]dt}{\int_0^{TH} a_r * [r(t)]dt}$$

where TH is the time horizon over which the calculation is considered, $a_i$ is the radiative efficiency due to a unit increase in atmospheric abundance of the substance in question (i.e. $W/(m^2*kg)$), [x(t)] is the time-dependent decay in abundance of the instantaneous release of the substance, and the corresponding quantities for the reference gas are in the denominator. GWP is used to assess and aggregate the interventions for the impact category climate change:

$$GWP = \sum_{i} GWP_i * m_i$$

### 2.3.6 Ozone Depletion (ODP)

The ozone reduction potential is the characterization factor of the category "stratospheric ozone depletion". The ODP relative to the gas *i* is defined as:

$$ODP_i = \frac{\delta[O_3]_i}{\delta[O_3]_{CFC-11}}$$

where $\delta[O_3]_i$ is the amount of stratospheric ozone depleted by the emission of the gas $i$ (kg/year) during its whole lifetime (i.e. at stationary phase), $\delta[O_3]_{CFC-11}$ is the amount of stratospheric ozone depleted by CFC-11 flux (the reference substance) in its lifetime. The total amount of reduction of stratospheric ozone is:

$$ODP = \sum_i ODP_i * m_i$$

### 2.3.7 Photochemical Ozone Creation Potential (POCP)

Photochemical smog is a phenomenon caused by the reaction between ozone, nitrogen oxides and organic volatile compounds (VOC), catalyzed by solar radiation in troposphere. The reaction gives the toxic ozone and other photo-oxidants as products. $POCP_i$ of a substance $i$ is calculated as the ratio between the variation of the amount of ozone produced by an emission change in the substance I and the respective relation calculated for the reference gas (ethene).

### 2.3.8 Human Toxicity (HTP)

Human toxicity characterization factors are calculated with a specified method (USES-LCA), that describes transport, exposition and the effects of the toxic substances for an infinite temporal horizon. The toxic substances emissions are expressed in kg of 1,4-DCB.

### 2.3.9 Primary Energy Demand, net value (PED)

Primary energy demand is calculated in MJ and consists in an energy form found in nature that has not been subjected to any conversion or transformation process (e.g. raw fuels).

# 3 LIFE CYCLE IMPACT ASSESSMENT RESULTS AND DISCUSSION

LCIA phase is conducted to the data set listed in Paragraph 2.2; the model is composed by the incinerator system and by the alternative treatments of incineration residues (three for bottom ash and other three for fly ash). The combination of these ash recovery technologies gives the nine scenarios **Base**, **BA Road**, **BA OdA**, **FA Ferrox**; **FA Vitrification**, **Road + Ferrox**, **Road + Vitrification**, **OdA + Ferrox, OdA + Vitrification**. Through the utilization of suitable parameters, the alternative treatments which bottom and fly ash are submitted are chosen alternatively. The only part of the model that does not change throughout the scenarios is the incineration plant. GaBi 4 provides for the classification into environmental groups of the resources and emissions fluxes that are into the system boundaries. Also, through the "Balance" function, GaBi is able to characterize and calculate the impacts generated by these fluxes.

Results are showed and discussed in the following order. First of all, only the incineration plant is analyzed, i.e. the treatment of bottom and fly ash are temporarily excluded. The relative contributions are studied, in order to find out which processes are the most impacting and why. Secondly, bottom and fly ash treatment are introduced. All the net impact scores varying among the nine scenarios are analyzed, for each impact category chosen, in order to understand which scenarios affect most each impact category. Then, the net impact scores of each impact category are analyzed separately.

## 3.1 Hotspot analysis on incineration

The analysis is firstly conducted on the incineration plant itself (i.e. excluding bottom and fly ash treatment). In Table 3.1 the incinerator global impact scores are placed next to the impact scores of each phase which incinerator is composed by. This is made for each impact category taken in consideration. At a first glance, the impact contribution of the co-generator phase is able to compensate the impacts caused of the incineration process: its avoided impact contribution is, in absolute value, one order of magnitude higher than the impacts caused of combustion chamber, flue gas cleaning and emissions and preselector phases. The only exceptions are represented by EP, FAETP and GWP. As far as concerns FAETP and EP, the preselector impact scores are of the same order of magnitude of the avoided impact contribution made by the co-generator. Regarding GWP, the impact score relative to flue gas cleaning and emissions is, in absolute value, one order of magnitude higher than the avoided co-generator impact.

| | GLOBAL SCORE | Preselector | Combustion Chamber | Flue gas cleaning and emissions | Co-generator |
|---|---|---|---|---|---|
| Abiotic Depletion [kg Sb-Equiv.] | -1,86E+05 | -2,74E+02 | 3,30E+04 | 1,89E+04 | -2,38E+05 |
| Acidification [kg $SO_2$-Equiv.] | -1,06E+05 | 3,86E+03 | 1,65E+04 | 2,21E+04 | -1,49E+05 |
| Eutrophication [kg $PO_4^{3-}$-Equiv.] | 1,39E+04 | 1,99E+04 | 3,03E+03 | 3,81E+03 | -1,28E+04 |
| Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.] | 2,78E+05 | 2,46E+05 | 4,61E+05 | 3,09E+04 | -4,60E+05 |
| Global Warming [kg $CO_2$-Equiv.] | 1,16E+08 | 9,19E+05 | 4,01E+06 | 1,44E+08 | -3,32E+07 |
| Human Toxicity [kg DCB-Equiv.] | -1,91E+06 | 4,81E+05 | 5,02E+05 | 4,64E+05 | -3,35E+06 |
| Ozone Depletion [kg R11-Equiv.] | -2,08E+00 | 4,53E-02 | 4,40E-01 | 3,15E-01 | -2,88E+00 |
| Photochemical Ozone Creation [kg Ethene-Equiv.] | -8,62E+03 | 1,54E+02 | 1,49E+03 | 1,64E+03 | -1,19E+04 |
| Terrestrial Ecotoxicity [kg DCB-Equiv.] | -2,11E+04 | 3,59E+04 | 1,32E+04 | 1,55E+04 | -8,57E+04 |
| Primary energy demand [MJ] | -4,19E+08 | 1,72E+06 | 7,30E+07 | 4,05E+07 | -5,34E+08 |

**Table 3.1 Global impact scores related to the incineration plant for each category, and how they are split among the processes that make up incineration**

Figure 3.1 is the graph made from Table 3.1 set of data, in which the four phases are represented as relative contributions for each impact category. In general, it can be observed that co-generator allows a relevant impact contribution to be avoided. This is valid in particular for the following categories: ADP, AP, HTP, ODP, POCP, TETP,PED. Otherwise, this is not valid for EP, FAETP and GWP. Regarding EP, its impact is mainly caused by the preselector phase. FAETP impact score is most affected by the combustion chamber phase. Regarding GWP, flue gas cleaning and emissions is the most impacting phase. Apart from these three categories, the combustion chamber and the flue gas cleaning and emissions phases affect the other impact categories in the same way, with relative contributions of about 10% each. HTP and TETP are affected by preselector phase too, with relative contributions respectively of 5% and 12%. The relative contribution of preselector is irrelevant in the other categories.

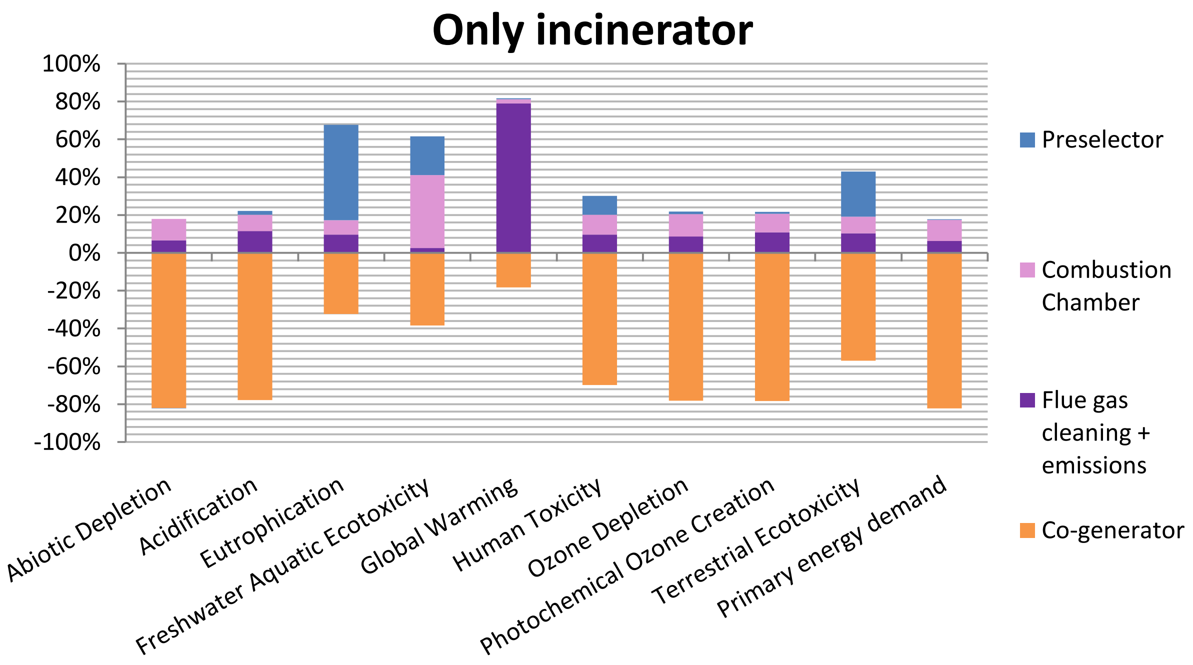


**Figure 3.1 Relative impact contributions from the phases of the incineration plant itself (waste preselector, combustion chamber, flue gas cleaning and emissions and co-generator)**

### 3.1.1 Processes contributions

In the following tables, the impact scores related to the process contributions in each incineration plan are showed in graphs.

#### 3.1.1.1 Preselector

Figure 3.2 shows the relative impact contributions given by the processes conducted in preselector phase: the electricity used in waste sorting and sieving; the tap water used for washing operations in the preselector room and its depuration; the transport of the humid fraction to the composting plant and then to the disposal site; the emissions generated from biostabilization process; the treatment of the wastewater leaching from the humid waste in course of biostabilization. System boundaries are expanded in order to include the avoided production of a landfill cover from virgin materials and the avoided landfilling of humid fraction as waste. From Figure 3.2 it can be observed that the wastewater treatment of the leachate generated from biostabilization and of the water coming from the washing operations in preselector room is the most affecting process (the green contribution in Figure 3.2). In particular, this is valid for almost all the categories: EP (which wastewater treatment relative contribution is of 99%), TETP (94%),FAETP (91%), HTP (85%), AP (68%), ODP (57%), GWP (52%), PED (41%), POCP (40%). The wastewater treatment process chosen from Ecoinvent (CH: treatment, sewage, to wastewater treatment, class I) refers to a plant with a average capacity size (233,000 per capita-equivalents). It includes mechanical, biological and chemical treatments, and also includes sludge fermentation. This last flux may be the cause of the high influence of wastewater process. A different handling of the sludge separated from the purified water could decrease the influence of this process. Another alternative proposal to lower the impact of the wastewater treatment could consist in the incineration of part of the humid waste actually sent to incineration. It has to be accounted that, if this humid fraction was incinerated too, the leaching problems would be prevented, but the LHV of the waste combusted would decrease. The avoided production of an inert material to be used as landfill cover gives a relevant avoided impact contribution, first of all for ADP (-50%). The process of the prevented landfill cover production (the orange contribution in Figure 3.2) represents a significant avoided contribution for categories PED (-43%), POCP (-36%), ODP (-24%), GWP and AP (-18%), HTP (-13%), too. As far as concerns the other categories, this contribution is irrelevant. The impact given by biostabilization and composting (the purple contribution in Figure 3.2) affects only GWP, due to $CH_4$ emissions, and POCP (10%), due to the $NO_x$ and VOC emissions. The electricity use in sieving and shredding processes represents a relative contribution of about 5-10%. This is valid for all the categories. The production of tap water used in the process and the avoided impact given by the avoided disposal of the stabilized humid fraction are irrelevant.

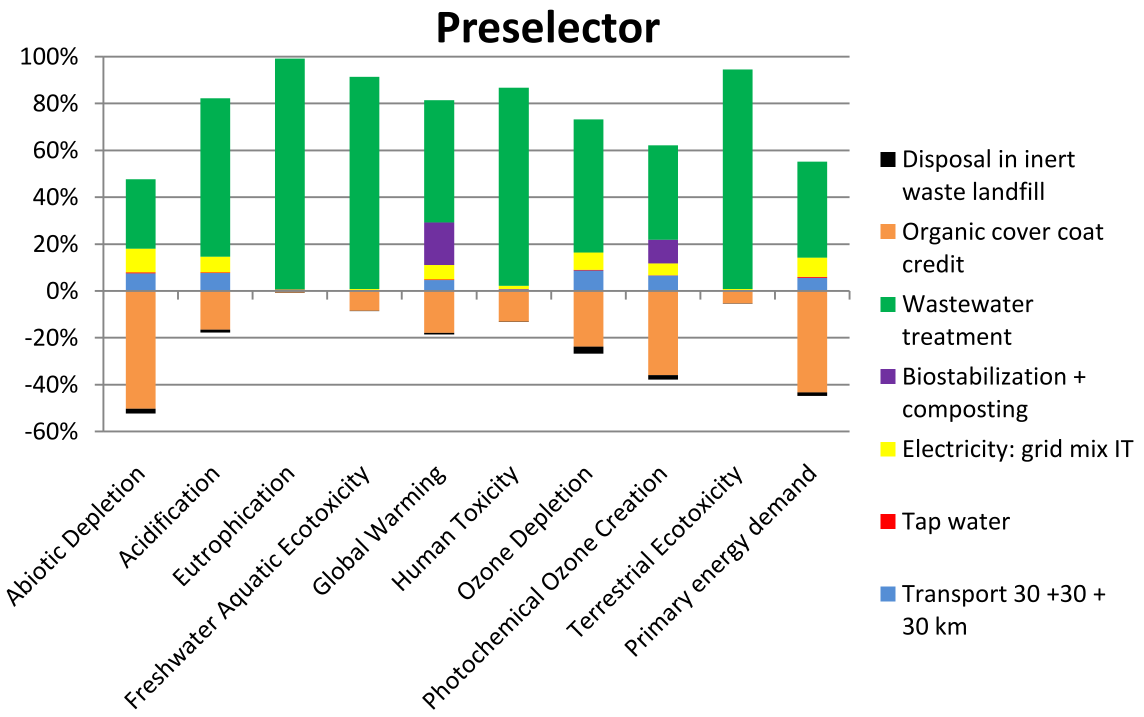


**Figure 3.2 Relative impact contributions from the processes included in the preselector plan**

In Table 3.2 the EP impact score of the preselector plan and the processes it is composed are listed. From data, it is possible to conduct that the depuration of the leachate generated from the stabilization of the humid fraction affects strongly the net EP impact score. In comparison, the impacts generated from the other processes are irrelevant. The avoided production of a suitable organic cover for landfill sites compensates only the most irrelevant processes (e.g. transport, electricity).

| | **PRESELECTOR** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **PLAN SCORE** | **Electricity: grid mix IT** | **Tap water** | **Transport 30 +30 + 30 km** | **Cover coat credit** | **Credit for avoided inert material disposal** | **Waste-water treatment** |
| Eutrophication [kg $PO_4^{3-}$-Equiv.] | 1,99E+04 | 3,50E+01 | 1,23E+00 | 9,93E+01 | -1,53E+02 | -1,49E+01 | **1,99E+04** |

**Table 3.2 Impact score of the preselector plan, and how it is partitioned among its processes**

#### 3.1.1.2 Combustion chamber

Figure 3.3 shows the relative impact contributions given by the processes conducted in combustion chamber phase: the electricity and the natural gas used to support waste incineration, the deionized water used in incineration process and its purification; the tap water used to wash and cool bottom ash, and its disposal; ammonia production and use in post-combustion chamber. From the graph, it is possible to conduct that electricity consumption process (i.e. the energy used only in case the waste combustion does not reach the minimum efficiency) is the most impacting (the light blue contribution in Figure 3.3). This is valid for almost all the categories: AP (relative electricity contribution of 91%), GWP (83%), POCP (78%), PED (69%), HTP and ADP (68%), TETP (66%) ODP (60%). The high impact caused by electricity consumption may be due to the fact that the cases during the year in which the minimum efficiency is not reached are abundant. Otherwise, it could be because the other processes that make up this phase are not noticeable. EP (43% of electricity relative contribution) and FAETP (10%) are the only categories for which the relative impact of the electricity production is below 50%. For them, the main impact contribution is represented by the disposal of the sludge generated from the washing of the bottom ash as soon as it produced, in order to be cooled (the lilac contribution in Figure 3.3). It is a necessary treatment to stock and transport it in a safe way. Analyzing the Ecoinvent process used to modelize the sludge disposal process (CH: disposal, municipal solid waste, 22,9% water, to sanitary landfill), it turns out that landfill gas emissions are collected and burned, without heat recovery. This process, together with the huge amounts of sludge generated from bottom ash washing, can be the main cause of the high impact. Among the other processes analyzed, natural gas affects mainly ODP (25%), ADP (23%), PED (22%), POCP (13%). As electricity, natural gas is used to maintain high temperatures in the combustion chamber in case of low combustion efficiency, too. For the other categories, natural gas relative contribution (the red contribution in Figure 3.3). is below 10%. As far as concerns the ammonia, i.e. the only reagent considered in this phase, it reaches impact contributions of respectively 21% and 26% in HTP and TETP, 11% for ODP. For the other categories, its relevant impact is below 10%. The other processes considered (transport, water supply, wastewater treatment) are irrelevant.

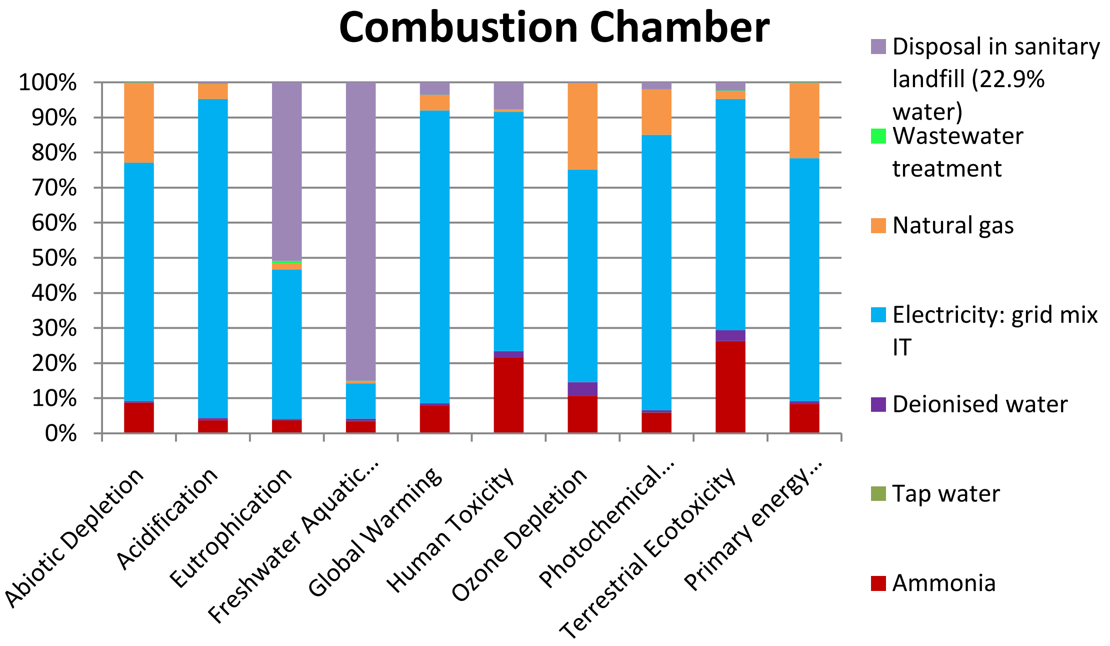


**Figure 3.3 Relative impact contributions from the processes included in the combustion chamber plan**

### 3.1.1.3 Flue gas cleaning and emissions

Figure 3.4 shows the relative impact contributions given by the processes conducted in flue gas cleaning and emissions phase: the reagents used (hydrated lime, soda, ammonia), the natural gas to maintain the necessary heat level to conduct the fumes depuration and, finally, the stack emissions. From the graph, it is possible to conduct that the air emission phase (the light blue contribution in Figure 3.4) makes up almost the whole relative impact for the categories GWP (99%), EP (90%), AP (86%), TETP (70%), HTP (68%), POCP (52%). The main cause affecting GWP impact score is the emission of greenhouse gases like $CO_2$, $CH_4$ and $N_2O$. Instead, the high influence of air emission process on AP is due to the stack emissions of $NO_x$ and $SO_x$. It is noteworthy that, considering that 70% of the incinerated waste is organic or made with cellulosic material, a relevant part of the $CO_2$ emissions are biogenic. In 2007 Chaya and collaborators analysis and in 2013 Slagstad and coauthors study, $CO_2$ emissions from the combustion of organic fractions are not accounted because they are not assumed to contribute to GWP. Therefore, on the basis of their considerations, the impact obtained by $CO_2$ emissions on GWP category would be overrated. For the other categories, the impact caused by the air emissions is irrelevant. The second most significant process is the use of natural gas (the orange contribution in Figure 3.4), mainly for categories ADP (71%), PED (69%), ODP (62%), POCP (21%) and FAETP (16%). For the other categories, the relative contribution of natural gas consumption is below 6%. Among the impact related to the production of reagents used in flue gas cleaning, ammonia (the red contribution in Figure 3.4) represents a relevant impact for FAETP (53%), HTP (23%), TETP (22%), ADP, ODP and PED (15%). Among the other categories, the relevant impact given by the use of this chemical is below 10%. Even hydrated lime production (the green contribution in Figure 3.4) is characterized by similar relative impacts: it consist in a relative contribution of 23% for ODP, 22% for FAETP, 21% for POCP, 15% for PED, 13% for ADP. For the other categories, this percentage results less than 4%. Impacts given by soda production are irrelevant, except for FAETP, for which soda production represent an 8% relevant contribution.

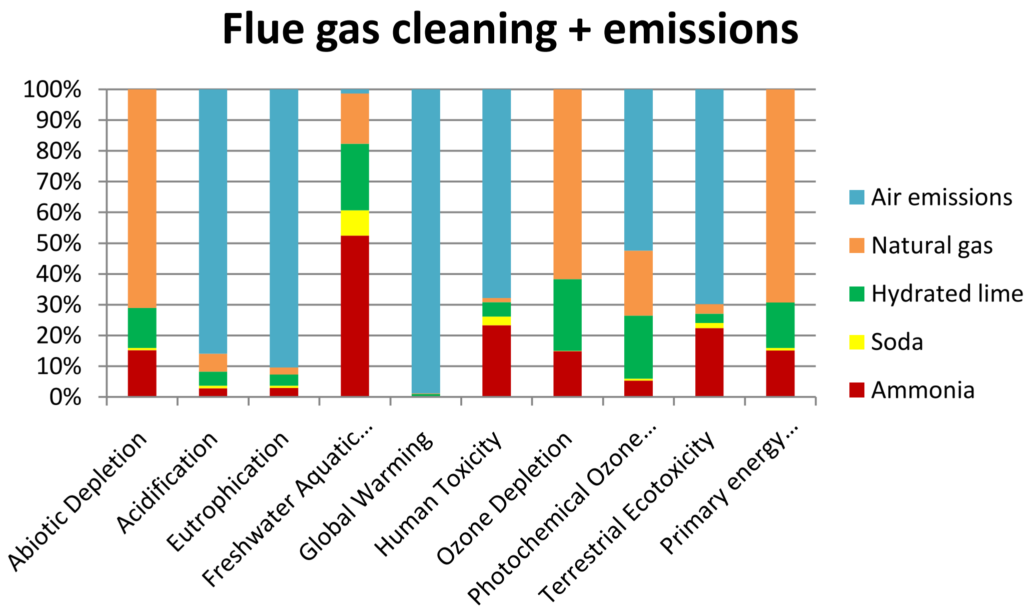


**Figure 3.4 Relative impact contributions from the processes included in the Flue gas cleaning and emissions plan**

### 3.1.1.4 Co-generator

As far as concerns co-generator phase, the relative impacts associated to the recovered electricity and heat are shown in Figure 3.5, for each impact category. In this graph the whole amount of energy produced by incineration process is not shown, but only the electricity fraction sent to national grid and the amount of heat sent to the district heating. In general, the generation of electricity contributes most to the whole energy recovery. This is valid for all the categories except for ADP, ODP, POCP and PED, for which heat and electricity savings contribute to the impact reduction in the same way.

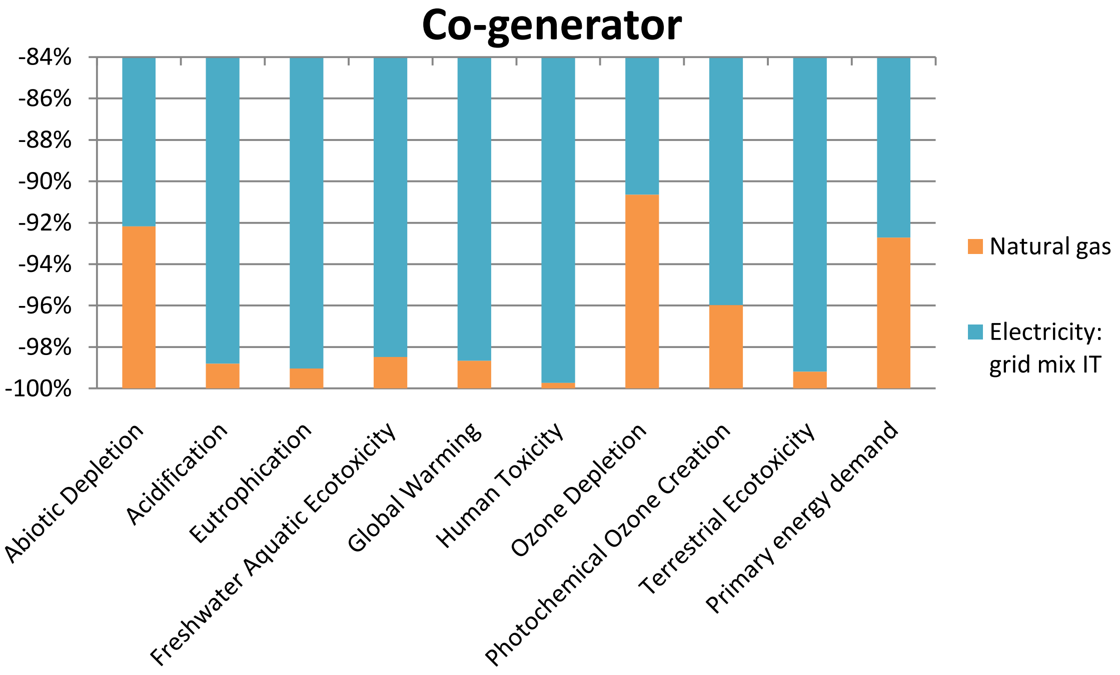


**Figure 3.5 Relative impact contributions from the processes included in the co-generator plan**

To sum up, from the data analyzed it is apparent that co-generator contribution is remarkable. This is caused by an efficient thermal energy recovery process, but it depends on the design of the co-generator plan, too. In fact, in GaBi co-generator plan the source of recovered electricity is established to be the Italian electricity grid mix (shown in Figure 2.6). As this is an electricity mix that includes mainly natural gas and other not-renewable energy sources, the good environmental results shown by the avoided use of this type of electricity can be influenced by the substitution of not-renewable energy. It would be interesting to analyze what happens if the source of recovered electricity changed. The alternative electricity source to be replaced is assumed to be a complete renewable mix: 50% of the recovered electricity is assumed to come from hydropower; the other half is assumed to be generated by a photovoltaic plant. Table 3.3 shows the comparison between the original impact scores and the ones obtained if the electricity replaced by co-generator phase is totally obtained by renewable sources. From data, it is possible to observe that impact scores are increased for all scenarios. In particular, EP, FAETP, GWP total impact scores do not increase excessively as they remain of the same order of magnitude. Otherwise, ADP, AP, ODP POCP and TETP are highly influenced by the electricity source change, as they increase of various orders of magnitude, becoming caused impacts.

| | **GLOBAL SCORE** | **Global Score with renewable energy replaced** |
|---|---|---|
| Abiotic Depletion [kg Sb-Equiv.] | -1,86E+05 | 2,09E+04 |
| Acidification [kg $SO_2$-Equiv.] | -1,06E+05 | 3,22E+04 |
| Eutrophication [kg $PO_4^{3-}$-Equiv.] | 1,39E+04 | 2,52E+04 |
| Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.] | 2,78E+05 | 3,26E+05 |
| Global Warming [kg $CO_2$-Equiv.] | 1,16E+08 | 1,47E+08 |
| Human Toxicity [kg DCB-Equiv.] | -1,91E+06 | -2,78E+05 |
| Ozone Depletion [kg R11-Equiv.] | -2,08E+00 | 1,80E-01 |
| Photochemical Ozone Creation [kg Ethene-Equiv.] | -8,62E+03 | 1,38E+03 |
| Terrestrial Ecotoxicity [kg DCB-Equiv.] | -2,11E+04 | 4,37E+04 |
| Primary energy demand [MJ] | -4,19E+08 | -5,52E+07 |

**Table 3.3 Comparison between the global impact scores of the original incineration plant and the scores obtained if electricity replaced by co-generator is obtained totally from renewable sources**

The results are also shown in Figure 3.6, in which the relative contributions of the incinerator plant are shown (as made in Figure 3.1), considering that the co-generator electricity recovered source changed. At a first glance, it can be observed that the co-generator phase keeps affecting net impact incinerator scores. Nevertheless, the relative contributions associated to caused impacts are higher: if in the original scenario caused impacts reach relative contributions of 20-40% (with the exceptions of EP, FAETP and GWP, for which are of 60-80%), in Figure 3.6 it can be observed that the percentages of the caused impacts are never below 40%. Moreover, the co-generator environmental benefit becomes irrelevant for EP and GWP. Nevertheless, the changed process is still able to overcompensate the generated impacts in HTP and PED categories. In conclusion, it can be deduced that the electricity source replaced by co-generator is crucial, as it influences the whole impact of the incinerator plant. This results prove the considerations made by Rigamonti and coauthors (2009), which find out that incineration is environmentally convenient only with replaced electricity produced totally or partially from fossil fuels.

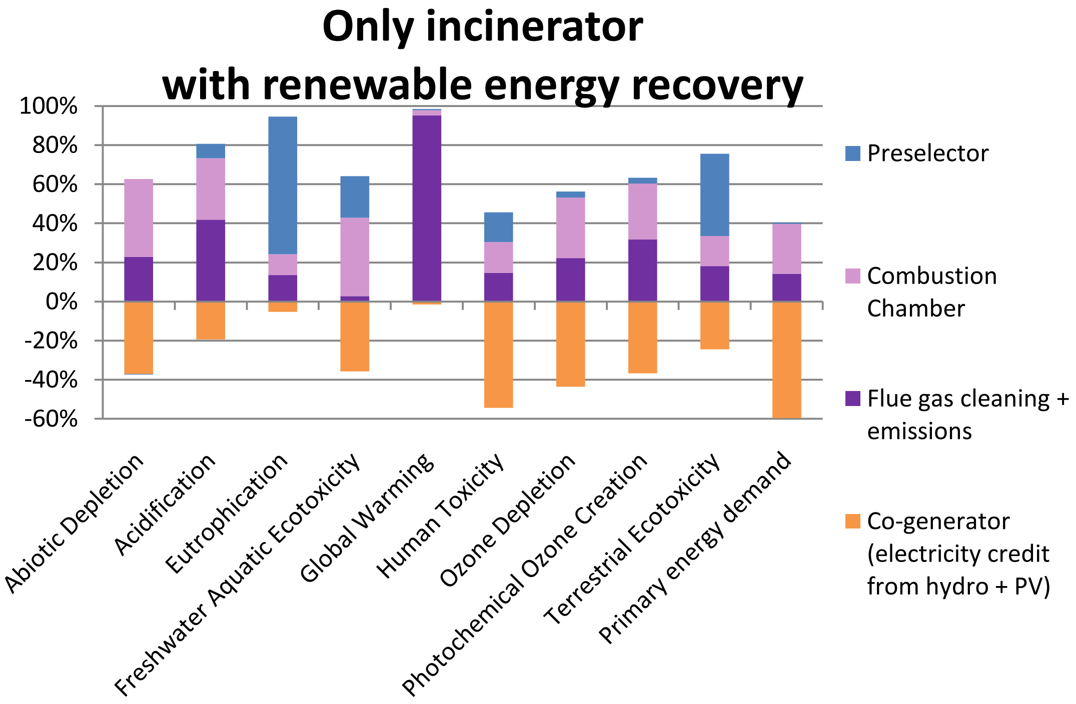


**Figure 3.6 Relative impact contributions from the phases included in the incineration plant, with the source of electricity recovered by co-generator changed into a mix of hydropower and photovoltaic**

In conclusion, as far as concerns the incinerator plant, some processes are conducted in the most efficient way: for example, the use of chemicals and the SOF production and use. Also, there are some processes with an improving potential. For example, the sludge generated by wastewater treatment in preselector phase and the landfill gas generated from sludge disposal in combustion chamber phase can be managed in a more sustainable way. In addition to these, other processes with an improving potential are the ones associated to auxiliary energy consumption. It is interesting to note that the high impact derived by the use of auxiliary energy (in form of electricity and natural gas) occurs both in combustion chamber and in flue gas cleaning and emission phases. An idea to decrease the necessity of auxiliary energy can consist in finding out a system to rise the LHV of the incinerated waste. If an higher amount of waste was submitted to preselector, the amount of wet fraction biostabilized instead of being incinerated would be higher. This choice would rise LHV of the incinerated waste. The problems that can emerge by carrying out this option are various. In fact, the relative impact of the preselector stage would further increase. In addition to this, a lower amount of waste would be incinerated, therefore the LHV would not improve significantly. The same occurs in the Consonni and collaborators analysis (2012). Last but not least, it is proved that model assumptions and design are able to influence incinerator analysis' results: it happens in the case of the variation of the source of the energy replaced in co-generation phase. If the electricity supply is expected to change in the following years, through an higher use of electricity coming from renewable sources, the incineration plant will result less sustainable.

## 3.2 Relative contributions for each scenario

In this paragraph bottom and fly ash treatments are introduced. The relative impact contributions are showed for each category. The analysis will focus exclusively on relative contributions that bottom and fly ash treatment alternatives assume in each scenario. Only the most significant and important scenarios are discussed (Base, BA Road, BA OdA, FA Ferrox, FA vitrification); the other four, that represent the combinations of these scenarios, are not discussed in this paragraph due their similarity with the scenarios about to be discussed, and can be consulted in Paragraph 7.2.1.

### 3.2.1 Base scenario

Figure 3.7 illustrates the relative contributions associated with Base scenario, in which bottom ash is landfilled and fly ash is inertized with cement. As occurs if only the incinerator plant is considered, the co-generator phase keeps representing a relevant avoided impact contribution. In general, the percentages of caused impacts are not above 20%. More specifically, most of the categories are able to reach a relevant impact reduction, due to the combined impact reduction of co-generator and bottom ash landfilling. Co-generator contributions are between -76% and -68% for ADP, AP, ODP, POCP, PED. They are lower in EP (-31%), FAETP (-12%), GWP (-18%), HTP (-52%), TETP (-27%) categories. Nevertheless, in EP and GWP the caused impacts are higher as the ones avoided: the causes of these results are already explained in Paragraph 3.1.1.

As far as concerns bottom ash contribution, it consists in an avoided impact for all the categories, in particular for FAETP (-54%) and TETP (-51%) Instead, it is irrelevant for AP, EP, GWP and ODP (which relative contributions are between -4% and -1%).

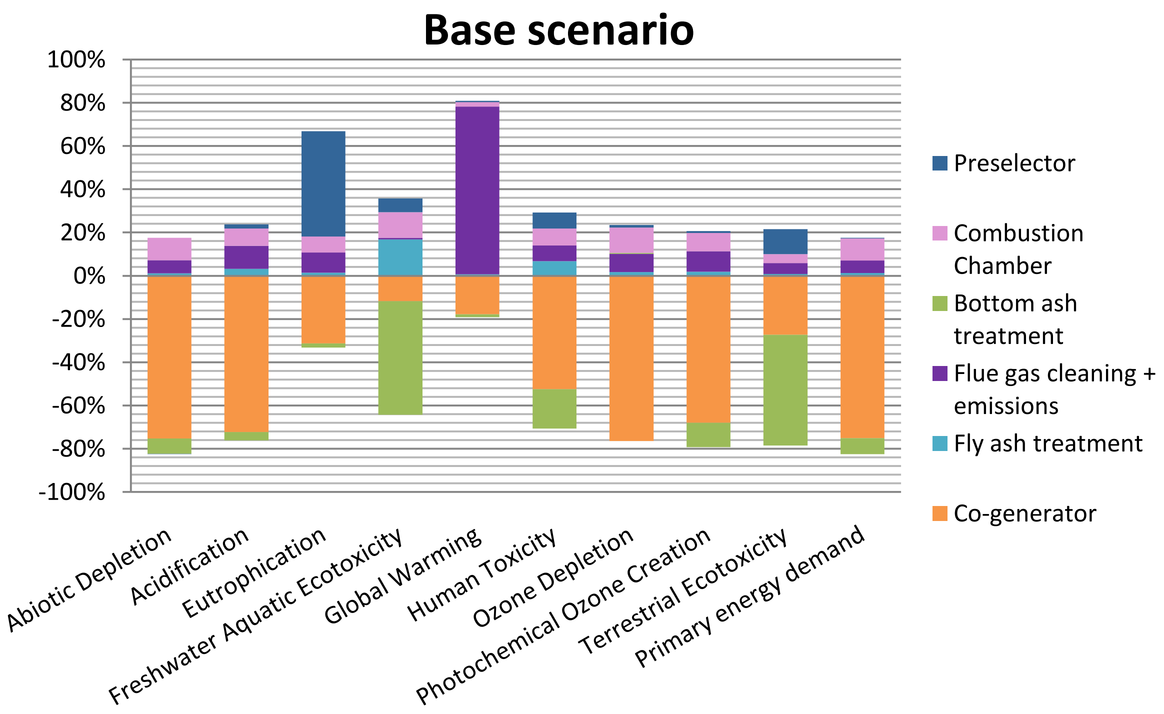


**Figure 3.7 Relative contributions in Base scenario, made for each category**

The reason why FAETP and TETP categories are significantly influenced by bottom ash landfilling phase is the avoided impact due to the prevented iron extraction. In Table 3.4 the FAETP and TETP impact scores related to the processes that make up the landfilling of bottom ash are listed. It can be observed that the scores associated to the process "Iron credit" are of three orders of magnitude higher than the ones of the other processes, and therefore they affect significantly the global impact scores of the bottom ash treatment phase.

| **FRESHWATER AQUATIC ECOTOXICITY [kg DCB-Equiv.]** | | | | |
|---|---|---|---|---|
| **BA LANDFILL SCORE** | **Transport 30 + 100 km** | **Electricity: grid mix IT** | **Disposal in an inert waste landfill** | **Iron credit** |
| -2,05E+06 | 3,36E+03 | 3,70E+03 | 6,66E+03 | **-2,06E+06** |
| **TERRESTRIAL ECOTOXICITY [kg DCB-Equiv.]** | | | | |
| **BA LANDFILL SCORE** | **Transport 30 + 100 km** | **Electricity: grid mix IT** | **Disposal in an inert waste landfill** | **Iron credit** |
| -1,60E+05 | 3,90E+02 | 6,93E+02 | 4,66E+02 | **-1,62E+05** |

**Table 3.4 FAETP and TETP impact scores of bottom ash landfilling, and how they are partitioned among the processes they are composed by**

Even if the table takes only in consideration FAETP and TETP categories, the high influence of the process "Iron credit" is common among the categories considered.

As far as concerns fly ash, in this scenario it is inertized with the treatment actually conducted to it: cement is added, before the disposal in a sanitary landfill. From Figure 3.7 it can be seen that fly ash treatment impact is irrelevant for all the categories considered, with the exception of FAETP, which fly ash relative contribution is of 17%, and, even to a lesser extent, HTP, which relative contribution is of 7%. The cause of this difference is showed in Table 3.5, in which the FAETP and HTP impact scores related to the processes that make up the cement inertization of fly ash are listed. It can be observed that the disposal of the inertized fly ash is the process most affecting the total impact score. In fact, the disposal of this hazardous waste often arises leaching problems, that have to be handled.

| **FRESHWATER AQUATIC ECOTOXICITY [kg DCB-Equiv.]** | | | | |
|---|---|---|---|---|
| **FA CEMENT INERTIZATION SCORE** | **Transport 30 + 300 km** | **Electricity: grid mix IT** | **Cement** | **Disposal in sanitary landfill** |
| 6,55E+05 | 8,36E+03 | 1,32E+03 | 6,81E+03 | **6,47E+05** |
| **HUMAN TOXICITY [kg DCB-Equiv.]** | | | | |
| **FA CEMENT INERTIZATION SCORE** | **Transport 30 + 300 km** | **Electricity: grid mix IT** | **Cement** | **Disposal in sanitary landfill** |
| 4,27E+05 | 8,36E+03 | 1,32E+03 | 4,83E+04 | **3,69E+05** |

**Table 3.5 FAETP and HTP impact scores of fly ash cement inertization, and how they are partitioned among the processes they are composed by**

### 3.2.2 BA Road scenario

In BA Road scenario bottom ash is submitted to mechanical treatment in order to be transformed in a gravel used in road construction; fly ash is inertized with cement. Figure 3.8 illustrates the relative contributions associated with Base scenario. It noteworthy that the trend of the relative contributions of the phases is almost identical to the one of the Base scenario. Even in this scenario, most of the categories are able to reach a relevant impact reduction, due to the combined avoided impact scores of co-generator and bottom ash landfilling. Co-generator contributions are between -76% and -67% for ADP, AP, ODP, POCP, PED. They are lower in EP (-31%), FAETP (-12%), GWP (-18%), HTP (-52%), TETP (-27%) categories. In the categories for which the co-generator contribution is smaller (EP, FAETP, GWP and TETP), there are generated impacts that counterbalance the energy savings, as already explained in Paragraph 3.1.1.

As it occurs in Base scenario, bottom ash contribution represents an avoided impact for all the categories, in particular for FAETP (-53%) and TETP (-50%). Instead, it is irrelevant for AP, EP, GWP and ODP categories (which relative contributions are between -8% and -1%).

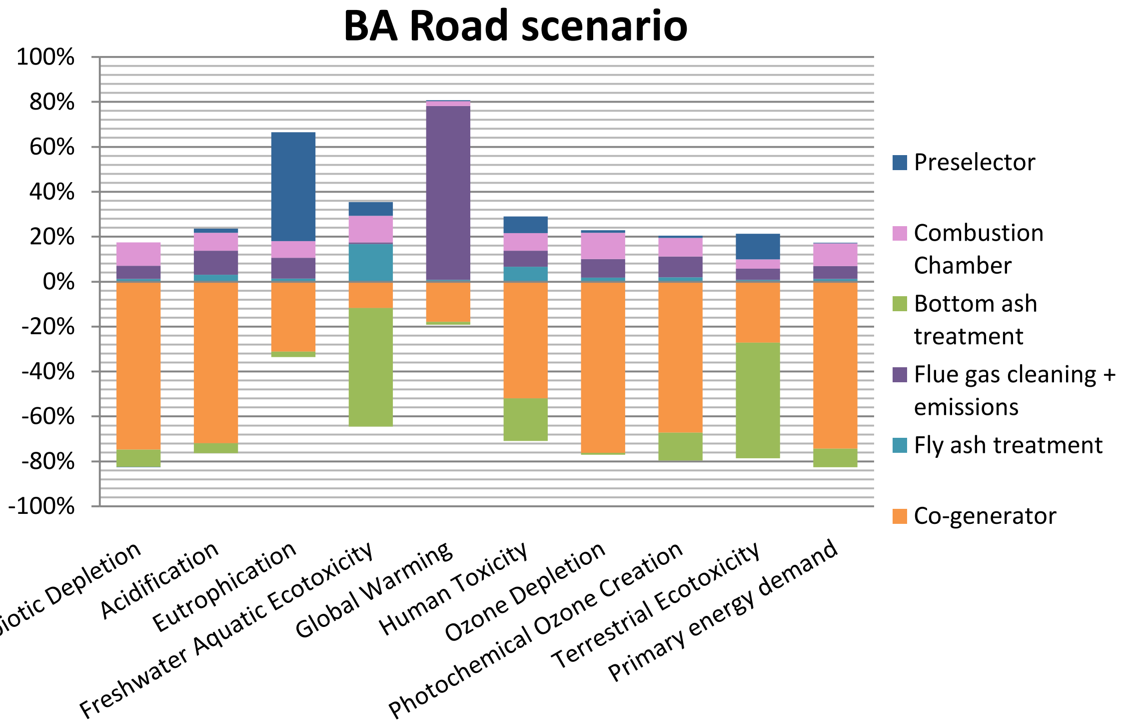


**Figure 3.8 Relative plans contributions in BA Road scenario**

Even in this scenario, it would be interesting to analyze the cause of the significant avoided impact contribution given by bottom ash recycling in road construction in FAETP and TETP. In Table 3.6 the FAETP and TETP impact scores related to the processes that make up bottom ash recycling in road construction are listed. It can be observed that there is another process which, together with the avoided production of iron due to its extraction from bottom ash and recycling, contributes to the net avoided impact score of the phase: it is the process "Gravel credit". More specifically, it is the avoided impact given by the prevented extraction and production of gravel, due to bottom ash transformation in a suitable aggregate. This relative contribution is one order of magnitude higher than the impacts generated by transport and electricity used in mechanical treatments. Nevertheless, this contribution is one order of magnitude lower than the one of the iron credit process, therefore the first does not affect the global phase impact as significantly as the second does.

| **FRESHWATER AQUATIC ECOTOXICITY [kg DCB-Equiv.]** | | | | |
|---|---|---|---|---|
| **BA ROAD SCORE** | **Transport 100 + 100 km** | **Electricity: grid mix IT** | **Iron credit** | **Gravel credit** |

| | | | | |
|---|---|---|---|---|
| -2,07E+06 | 4,47E+03 | 4,22E+03 | -2,06E+06 | **-1,84E+04** |
| **TERRESTRIAL ECOTOXICITY [kg DCB-Equiv.]** | | | | |
| **BA ROAD SCORE** | **Transport 100 + 100 km** | **Electricity: grid mix IT** | **Iron credit** | **Gravel credit** |
| -1,62E+05 | 5,19E+02 | 7,91E+02 | -1,62E+05 | **-1,59E+03** |

**Table 3.6 FAETP and TETP impact scores of bottom ash recycling in road construction, and how they are partitioned among the processes they are composed by**

As far as concerns fly ash, the same discussion made in Base scenario is also valid for BA Road, as in both cases fly ash is inertized with cement and disposed in a sanitary landfill. From Figure 3.8 it can be seen that fly ash treatment impact scores of categories exclusively affected by it (FAETP and HTP) are characterized by relative contributions of, respectively, 16% and 7%.

### 3.2.3 BA OdA scenario

In BA OdA scenario bottom ash is submitted to mechanical treatment and aerobic stabilization in order to be transformed in a gravel used in construction sector; fly ash is inertized with cement. Figure 3.9, that shows relative plans contributions in BA OdA scenario, is very similar to the ones of the Base and BA Road scenarios. At a first glance, Figure 3.9 seems to have the same trend of Figure 3.8. In fact, as it occurs in Base and BA Road scenarios, most of the categories are able to reach a relevant impact reduction, due to the combined avoided impact scores of co-generator and bottom ash recycling. Even in this case, the avoided impact contribution is mainly caused by iron recycling and by prevented gravel production. Co-generator contributions are between -77% and -68% for ADP, AP, ODP, POCP, PED. They are lower in EP (-30%), FAETP (-12%), GWP (-18%), HTP (-52%), TETP (-28%) categories. The most important bottom ash relative contributions are the ones of FAETP (-52%), TETP (-51%), HTP (-19%), POCP (-12%).

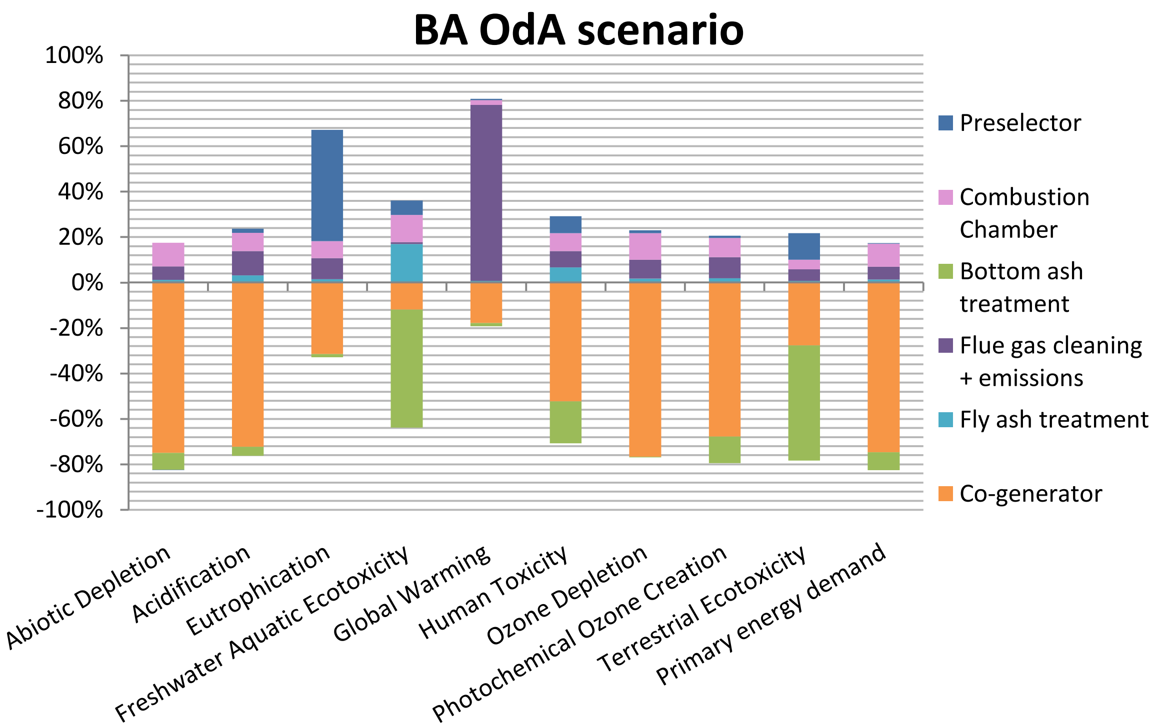


**Figure 3.9 Relative plans contributions in BA OdA scenario**

As far as concerns fly ash, the same discussion made in Base and BA Road scenarios are also valid for this, as fly ash is still inertized with cement and disposed in a sanitary landfill. The relative contributions related to this process do not change at all.

### 3.2.4 FA Ferrox scenario

In FA Ferrox scenario bottom ash is directly landfilled, fly ash is inertized through an iron sulphate solution. Figure 3.10 shows relative phases contributions in FA Ferrox scenario. As far as concerns bottom ash treatment (i.e. landfilling), the considerations about the impact scores obtained are the same as the ones discussed in Paragraph 3.2.1. About fly ash treatment, comparing Figure 3.10 to Figure 3.7 showing the base scenario, it can be seen that the relevant impact contributions of fly ash treatment among the impact categories are similar. FAETP contributes with a 15% relative impact and HTP with 9%.

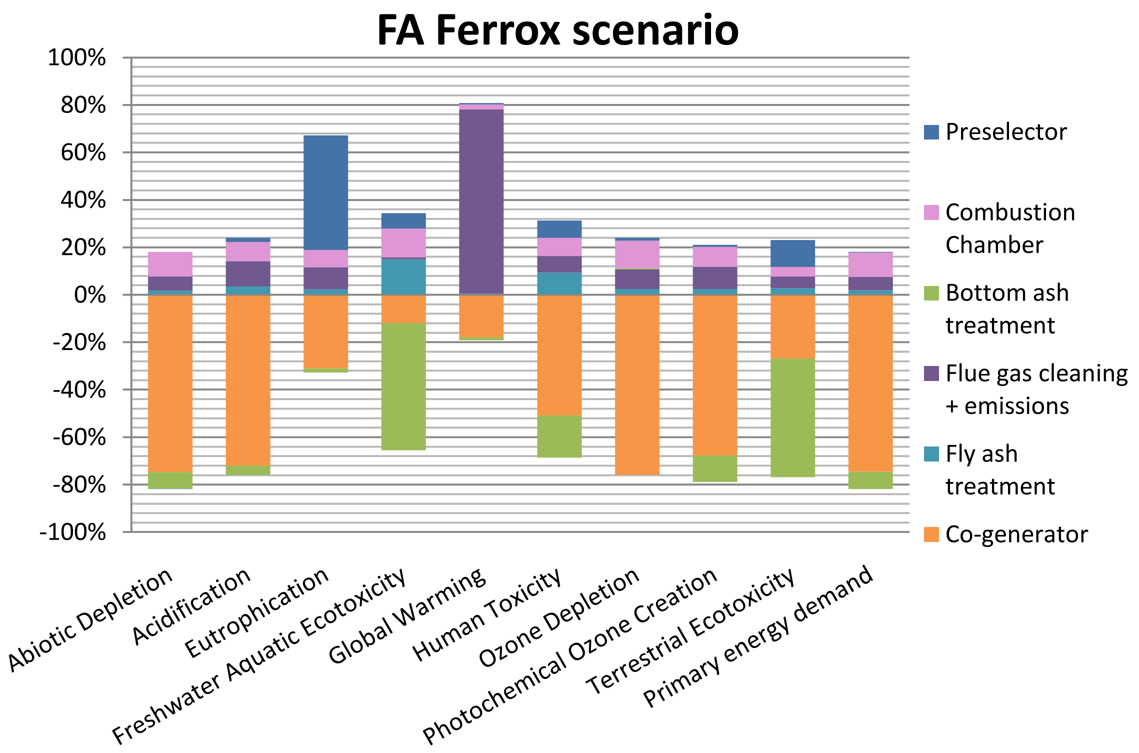


**Figure 3.10 Relative plans contributions in FA Ferrox scenario**

It is interesting to deduce that these values are similar to the ones related to inertization with cement alternative discussed in the first three scenarios, even if the cause of these relative impact scores are different. The cause of this difference is showed in Table 3.7, in which the FAETP and TETP impact scores related to the processes that make up the fly ash Ferrox stabilization are listed. It can be observed that the process most affecting fly ash treatment impact score in FAETP and HTP categories is the production of iron sulphate, combined with the disposal of the inertized fly ash in the sanitary landfill. In particular, these two processes affect the whole impact score at the same way.

| FRESHWATER AQUATIC ECOTOXICITY [kg DCB-Equiv.] | | | | | | |
|---|---|---|---|---|---|---|
| **FA FERROX SCORE** | **Transport 100 + 300 km** | **Electricity: grid mix IT** | **Iron sulphate** | **Deionized water** | **Wastewater treatment** | **Disposal in sanitary landfill** |
| 5,73E+05 | 1,23E+03 | 1,43E+03 | **6,12E+04** | 1,48E+03 | 2,06E+03 | **5,06E+05** |
| **HUMAN TOXICITY [kg DCB-Equiv.]** | | | | | | |
| **FA FERROX SCORE** | **Transport 100 + 300 km** | **Electricity: grid mix IT** | **Iron sulphate** | **Deionized water** | **Wastewater treatment** | **Disposal in sanitary landfill** |
| 5,98E+05 | 8,47E+03 | 1,06E+04 | **2,82E+05** | 4,20E+03 | 4,24E+03 | **2,88E+05** |

**Table 3.7 FAETP and HTP impact scores of fly ash Ferrox stabilization, and how they are partitioned among the processes they are composed by**

### 3.2.5 FA Vitrification

In FA Vitrification scenario the bottom ash is directly landfilled, the fly ash is inertized through a thermal treatment. Figure 3.11 shows relative plans contributions in FA Vitrification scenario. FAETP and HTP are, even in this case, the categories most affected by the fly ash treatment, with relative contributions of, respectively, 15% and 8%. As regards the other categories, the relative impact scores related to fly ash vitrification are between 1% and 8%.

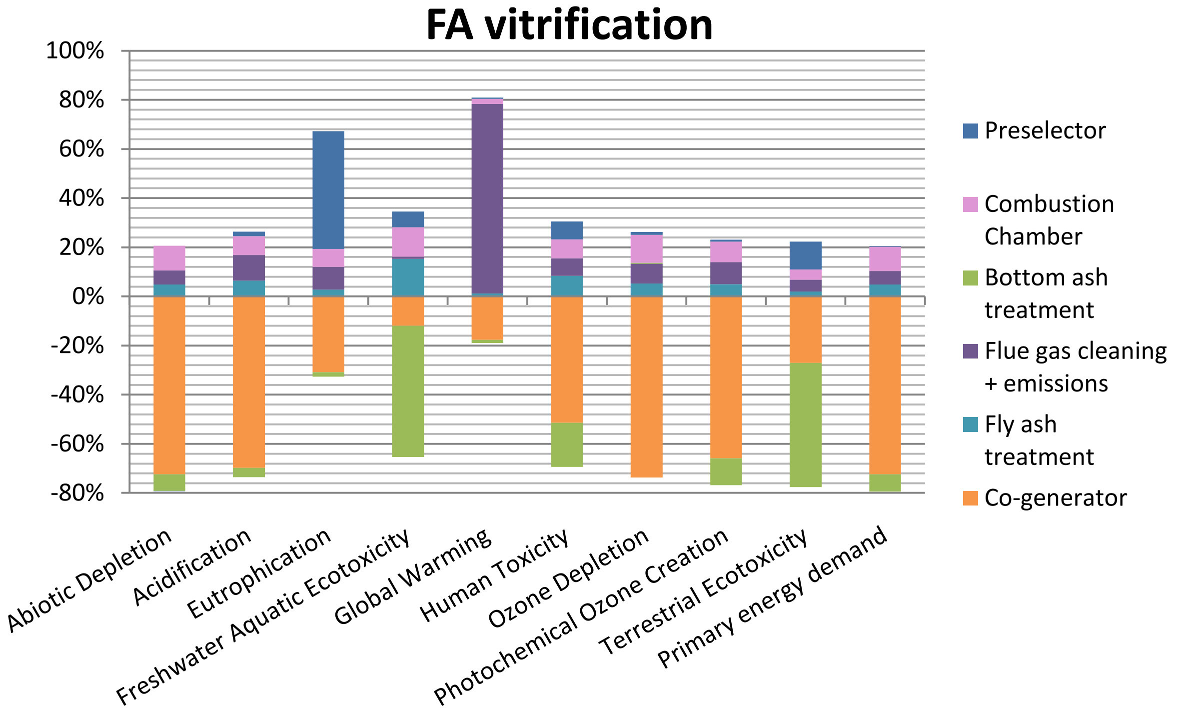


**Figure 3.11 Relative plans contributions in FA Vitrification scenario**

It would be interesting to find out why the vitrification impact scores are higher than the ones of the other fly ash treatment scenarios. The cause of this difference is showed in Table 3.8, in which the impact scores related to the processes that make up the vitrification are listed, for all the categories analyzed. It can be observed that the most impacting process is the electricity consumption: in fact, its impact score is almost of one order of magnitude higher than the ones of the other processes taken in consideration. This is valid for the whole set of impact categories, except for FAETP and HTP, for which the impact given by the disposal of the inertized fly ash keeps being the most affecting process.

| FA VITRIFICATION |
|---|

| | **FA VITRIFICATION SCORE** | **Transport 100 + 100 + 300 km** | **Disposal in sanitary landfill** | **Electricity: grid mix IT** | **Sodium silicate** |
|---|---|---|---|---|---|
| Abiotic Depletion [kg Sb-Equiv.] | 1,59E+04 | 1,03E+03 | 5,54E+02 | **1,43E+04** | 2,44E+01 |
| Acidification [kg $SO_2$-Equiv.] | 1,38E+04 | 1,04E+03 | 3,16E+03 | **9,55E+03** | 1,12E+01 |
| Eutrophication [kg $PO_4^{3-}$-Equiv.] | 1,14E+03 | 2,27E+02 | 9,22E+01 | **8,23E+02** | 1,21E+00 |
| Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.] | 5,88E+05 | 1,31E+03 | 5,57E+05 | **2,95E+04** | 5,01E+02 |
| Global Warming [kg $CO_2$-Equiv.] | 2,34E+06 | 1,59E+05 | 5,06E+04 | **2,13E+06** | 3,39E+03 |
| Human Toxicity [kg DCB-Equiv.] | 5,45E+05 | 9,07E+03 | 3,17E+05 | **2,18E+05** | 1,43E+03 |
| Ozone Depletion [kg R11-Equiv.] | 2,03E-01 | 1,99E-02 | 1,27E-02 | **1,70E-01** | 3,04E-04 |
| Photochemical Ozone Creation [kg Ethene-Equiv.] | 8,91E+02 | 8,96E+01 | 5,71E+01 | **7,43E+02** | 1,08E+00 |
| Terrestrial Ecotoxicity [kg DCB-Equiv.] | 6,13E+03 | 1,52E+02 | 4,01E+02 | **5,53E+03** | 5,31E+01 |
| Primary energy demand [MJ] | 3,57E+07 | 2,18E+06 | 1,26E+06 | **3,22E+07** | 6,38E+04 |

**Table 3.8 Impact scores of fly ash FA Vitrification stabilization, and how they are partitioned among the processes they are composed by. This is made for all the categories.**

To sum up, as far as concerns fly ash treatment, it results that its relative impact contributions are not relevant, except for FAETP and, to a lesser extent, HTP. This is valid in all scenarios. The processes most affecting the net fly ash impact score turn out to be the disposal of the inertized fly ash for all the fly ash treatment alternatives, the iron sulphate production for FA Ferrox scenario and the high electricity consumption for FA Vitrification scenario.

## 3.3 Comparative analysis of the scenarios

In this paragraph, the analysis is conducted studying the variation of the net impact scores for each category, in order to find out and discuss the variations throughout the nine scenarios.

### 3.3.1 Abiotic Depletion (ADP)

Figure 3.12 shows ADP net impact scores for each of the nine scenarios. From data, it is possible to conduct that all the categories (with the exceptions of EP and GWP) are characterized by avoided impacts throughout all the nine scenarios, due to the relevant contribution of co-generator. As far as concerns bottom ash, it is apparent that the impact scores of the three alternative treatments (Base, BA Road and BA OdA) are very similar, of the same order of magnitude. For example, the ADP bottom ash impact scores for the three alternatives are the following: -22359,89 kg $Sb_{eq}$. for Base, -24443,58 kg $Sb_{eq}$ for BA Road, -23467,92 kg $Sb_{eq}$ for BA OdA. As far as concerns fly ash alternatives, it is apparent that the scenarios that include vitrification (FA Vitrification, Road + Vitrification and OdA + Vitrification), have an higher impact score compared to the other two treatment alternatives.

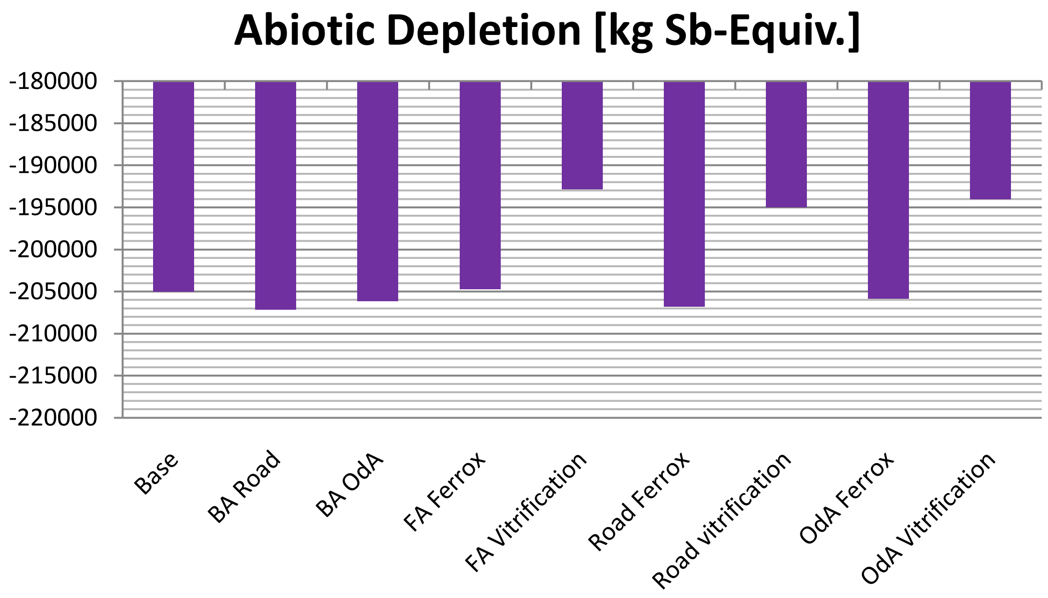


**Figure 3.12 Net impacts of the Abiotic Depletion category, for each scenario**

It would be interesting to analyze which phases make up the whole net impact showed in Figure 3.12. In Figure 3.13, the impact scores related to each phase are showed, for all the scenarios. It has to be specified that co-generator phase is not taken in consideration because its relevant contribution decreases excessively the impacts given by the other phases. It can be observed that, if co-generator is not considered, combustion chamber becomes the most influential process for ADP category. As already explained in Paragraph 3.1.1.2, the cause of its relevant impact is the consumption of auxiliary electricity. As far as concerns bottom ash treatments, they have similar impact scores among the nine scenarios. Instead, fly ash impact scores show a certain variability: they have the highest impact scores in scenarios in which fly ash is vitrificated. The scores decrease relevantly is fly ash is inertized with cement or chemically with the Ferrox method: these two treatment alternatives are characterized by almost identical impacts.

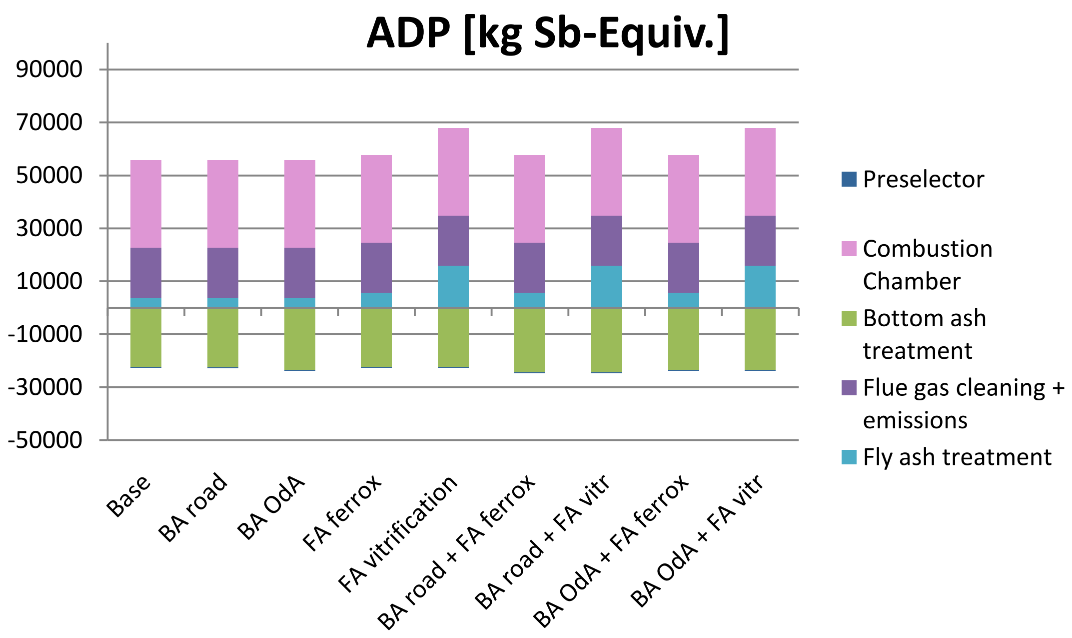


**Figure 3.13 Relative contributions of the incinerator processes to ADP score, for each scenario. Co-generator contributions are not taken in consideration**

Focusing exclusively on the trend of the three bottom ash alternatives (Base, BA Road and BA OdA), the main cause of their similarity can be explained by the fact that there is a common process that affects relevantly and similarly the impact scores. It is the avoided extraction of iron, as it is shown in Table 3.9, in which a comparison between the ADP impact scores of the three bottom ash treatment scenarios is made. In this comparison only the contributions of iron and gravel recycling are taken in consideration. Even if the fates of the bottom ash are different in the three alternatives, in all of these treatments it is deironized before being landfilled or recycled. From data, it is possible to deduce that the plan scores are of the same order of magnitude as the impact scores related to the avoided extraction and production of iron. The avoided production of gravel, made only in BA Road and BA OdA scenarios, does not affect plans score as relevantly as iron credit does. This result is in line with the deductions of Buttol and collaborators (2007) and of Jeswani and coauthors (2013), which found that metal recycling leads to higher energy and resources savings. The other processes that are included in bottom ash treatment scenarios (e.g. electricity, transport, gravel avoided production) are not as influential as the process "REE: cast iron, at plant", as seen in Table 3.4, and therefore they have a secondary importance on the whole impact score. It is noteworthy that the amounts of iron scraps recovered in the three bottom ash scenarios are very similar (7.37% for Base and BA Road; 7.11% for BA OdA).

| **ABIOTIC DEPLETION [kg Sb-Equiv.]** |
|---|

| | **PLAN SCORE** | **Iron credit** | **Gravel credit** |
|---|---|---|---|
| **BASE** | -2,24E+04 | -2,92E+04 | / |
| **BA ROAD** | -2,44E+04 | -2,92E+04 | -8,03E+02 |
| **BA OdA** | -2,35E+04 | -2,82E+04 | -8,05E+02 |

**Table 3.9 Comparison between the ADP plan scores of the three bottom ash treatment scenarios, placed next to respective impact scores given by the avoided iron extraction**

To sum up, from an environmental point of view, the disposal of the bottom ash as it is in landfill gives impacts of the same order of magnitude of the impacts obtained by the bottom ash recycling in gravel. Therefore, the deironization results to be the most important recycling process made from incinerator residues.

Regarding fly ash treatment scenarios, as they differ for the amounts and the nature of the chemicals used for stabilization, it would be interesting to analyze the contributions of the reagents used for ADP category. Table 3.10 compares ADP plan scores of the three fly ash recycling scenarios, listing the impact scores related to the processes of chemicals production and of electricity consumption. The table shows that the electricity consumption is the most affecting process in vitrification treatment, as it makes up almost the total plan score. Regarding chemicals production, cement results to be the material with the highest impact, and its value contributes most to the total plan impact score. On the other hand, fly ash inertization with cement requires a low amount of electricity: this compensates the impact associated with cement production, therefore this treatment reaches an impact score similar to the one of the Ferrox process, characterized by medium values of electricity and chemical consumptions.

| | **ABIOTIC DEPLETION [kg Sb-Equiv.]** | | |
|---|---|---|---|
| **FA INERTIZATION WITH CEMENT** | **PLAN VALUE** | **Electricity: grid mix IT** | **Cement** |
| | 3,74E+03 | 8,66E+01 | **2,05E+03** |
| **FA FERROX** | **PLAN VALUE** | **Electricity: grid mix IT** | **Iron sulphate** |
| | 5,61E+03 | 6,93E+02 | 1,79E+03 |
| **FA VITRIFICATION** | **PLAN VALUE** | **Electricity: grid mix IT** | **Sodium silicate** |
| | 1,59E+04 | **1,43E+04** | 2,44E+01 |

**Table 3.10 Comparison between the ADP plan scores of the three fly ash recycling scenarios, placed next to respective impact scores given by the electricity and chemicals expenditures**

### 3.3.2 Acidification (AP)

Figure 3.14 shows AP net impact scores for each of the nine scenarios. It is possible to observe that ADP is characterized by net avoided impacts throughout all the nine scenarios, due to the relevant contribution of co-generator. As far as concerns bottom ash treatments, they have similar impact scores among the nine scenarios. Instead, fly ash impact scores are highest in scenarios in which fly ash is vitrificated. The scores decrease relevantly is fly ash is inertized with cement or chemically with the Ferrox method: these two treatment alternatives are characterized by almost identical impacts. Trend is pretty similar to Figure 3.12 one (representing the ADP net impact scores).

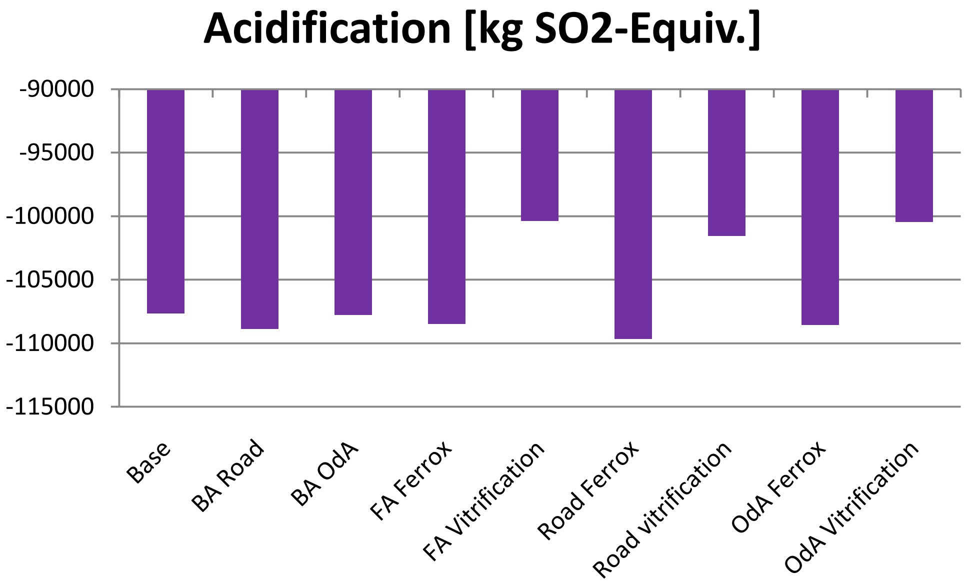


**Figure 3.14 Net impacts of the Acidification category, for each scenario**

It would be interesting to analyze which phases make up the whole net impact showed in Figure 3.14. In Figure 3., the impact scores related to each phase are showed, for all the scenarios. It has to be specified that co-generator phase is not taken in consideration because its relevant contribution decreases excessively the impacts given by the other phases. It can be observed that, if co-generator is not considered, combustion chamber and flue gas cleaning and emissions become the most influent processes for ADP category. The cause of the relevant impact of the combustion chamber is the consumption of auxiliary electricity; instead, the cause of the significant impact of the flue gas cleaning and emissions is the emissions of substances like $SO_x$ and $NO_x$. As far as concerns bottom ash treatments, it is reaffirmed that they do not vary significantly throughout scenarios. Instead, fly ash impact scores have the highest impact scores in scenarios in which fly ash is vitrificated (6% of relative contribution against the 3% of Base and FA Ferrox alternatives). The scores decrease relevantly is fly ash is inertized with cement or chemically with the Ferrox method: in these two cases, the impact scores are almost identical.

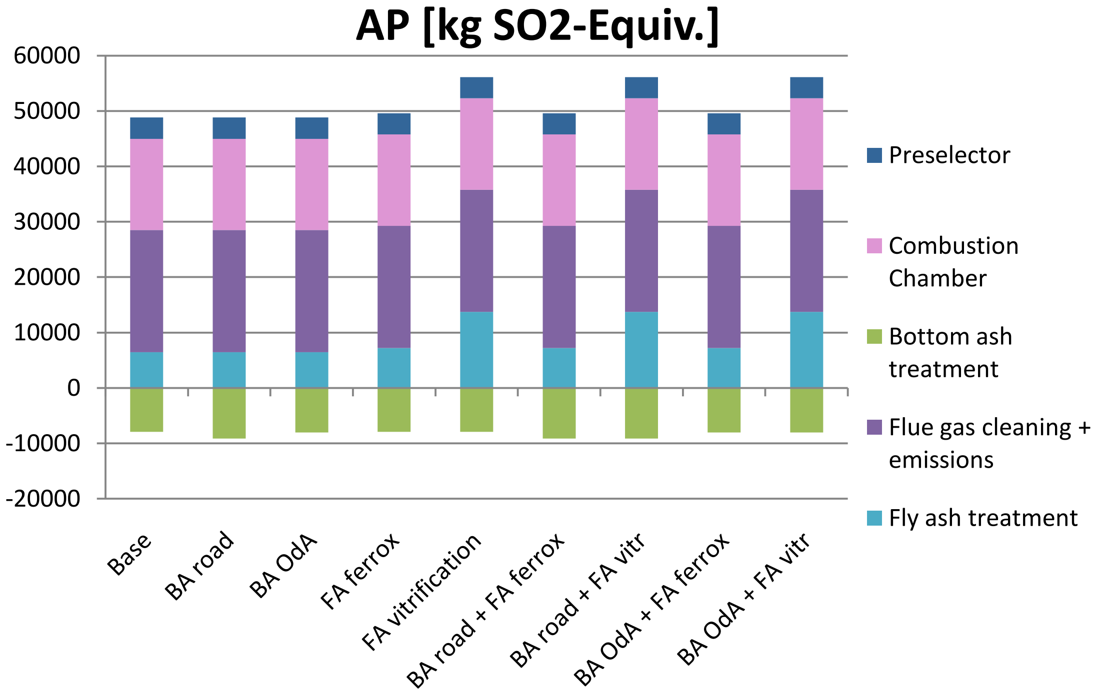


**Figure 3.Relative contributions of the incinerator plant to AP score, for each scenario. Co-generator contributions are not taken in consideration, in order to underline the relative contributions of the other five phases**

In particular, it would be interesting to find out why the BA Road scenario has a slightly lower environmentally impact compared to its similar alternative BA OdA. In Table 3.11 a comparison between the plan scores of BA OdA and BA Road is made, considering also the impact scores of the processes that make up these plans. It can be observed that the plan scores are similar, of the same order of magnitude, but that BA OdA one is slightly higher than the BA Road one. This happens despite the fact that BA OdA electricity impact score is of two orders of magnitude lower than the BA Road one, due to the use of renewable energy sources. Nevertheless, it has to be accounted that BA OdA treatment includes two processes not considered in BA Road: the use of water in the mechanical treatments which bottom ash is submitted to, and its depuration. These processes are not included in BA Road scenario due to the lack of information: in both Cuijie and collaborators study (2010) and Birgisdóttir and coauthors (2012) analysis, there is not any information or data about water use and/or treatment. Therefore, if this factor was not taken into account, BA OdA alternative would result to be more sustainable than BA Road alternative, because they have similar impact scores despite BA OdA takes in consideration two more processes. This result proves that the two scenarios, even if they treat bottom ash in similar ways, cannot be directly compared.

| | **ACIDIFICATION [kg $SO_2$-Equiv.]** | | | | | | |
|---|---|---|---|---|---|---|---|
| **BA ROAD** | **PLAN SCORE** | **Transport 100 + 100 km** | **Electricity: grid mix IT** | **Iron credit** | **Gravel credit** | | |
| | -9,14E+03 | 1,69E+03 | **1,37E+03** | -1,33E+04 | -7,71E+02 | | |
| **BA OdA** | **PLAN SCORE** | **Transport 300 km** | **Electricity (PV + hydropower)** | **Tap water** | **Wastewater treatment** | **Iron credit** | **Gravel credit** |
| | -8,04E+03 | 5,49E+03 | **2,41E+01** | **1,37E+01** | **1,59E+01** | -1,28E+04 | -7,73E+02 |

**Table 3.11 Comparison between the AP plan scores of the two bottom ash recycling scenarios, placed next to the impact scores of the processes that make up these two treatment alternatives**

### 3.3.3 Eutrophication (EP)

Eutrophication is, together with GWP, one of the categories for which the impacts caused are greater than the ones avoided. As already explained in Paragraph 3.1.1.1, the main cause of the influence of the preselector stage on EP is the leachate depuration. This is apparent in Figure 3.15, in which the relative contributions of the incinerator processes to EP score are showed, for each scenario. It can be observed that the relative impact contribution given by preselector is so relevant that the variation of the values of the bottom and fly ash treatment contributions throughout scenarios is not visible.

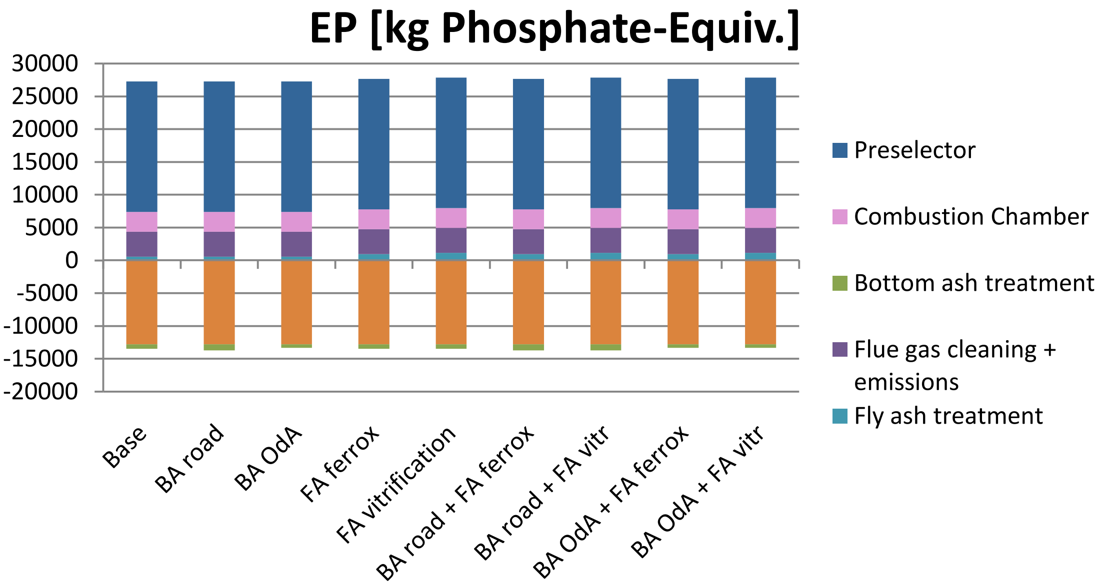


Figure 3.15 Relative contributions of the incinerator plant to EP score, for each scenario

Figure 3.16 shows EP net impact scores for each of the nine scenarios. At a first glance, all the scenarios are characterized by net impact score ranging between 13,500 and 14,500 kg $PO_4^{3-}$-equiv., therefore they are very similar. In particular, BA Road and Road + Ferrox seem to be the most sustainable scenarios, whilst OdA + Vitrification seem to be the worst, as they is characterized by the highest net impact score.

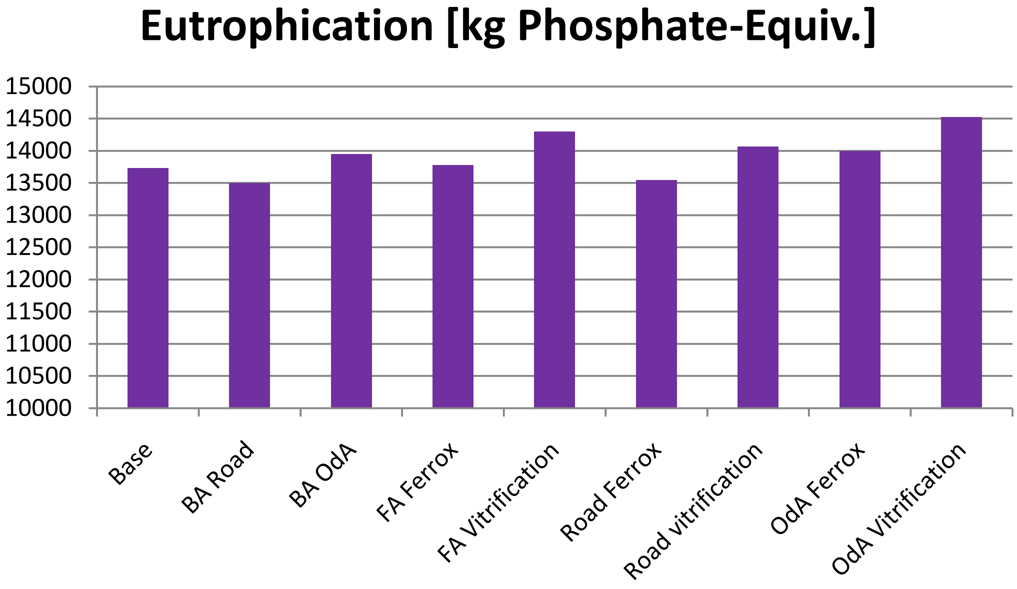


Figure 3.16 Net impacts of the Eutrophication category, for each scenario

Table 3.12 shows the EP impact scores for BA OdA, the scenario that results to have an impact score slightly higher than the other bottom ash treatments, slightly split among its processes. Observing the processes in which the contributions of the impacts caused are higher than the ones of the impacts avoided, the most affecting is the transport, as the plant is far 300 km far from the WTE plant, and due to the fact that the amount of waste to be transported on this distance is enormous. This impact is of the same order of magnitude of the impact avoided due to the prevented iron extraction.

| | **BA OdA** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **PLAN SCORE** | **Transport 300 km** | **Electricity (PV + hydro)** | **Gravel credit** | **Waste-water treatment** | **Iron credit** | **Tap water** |
| Eutrophication [kg $PO_4^{3-}$-Equiv.] | -5,41E+02 | **1,20E+03** | 3,99E+00 | -1,38E+02 | 7,83E+01 | -1,69E+03 | 1,11E+00 |

Table 3.12 EP impact score of the BA OdA bottom ash treatment plan, and how it is partitioned among its processes

About fly ash treatment, from Table 3.13, that shows the EP impact scores of the three fly ash treatment alternatives spread among their processes, it can be seen that vitrification is the worst alternative, whilst the inertization with cement is the most feasible. The vitrification impact score is one order of magnitude higher than the one of the other two alternative treatments, due to the high electricity consumption. This process has an impact score of one order of magnitude higher than the Ferrox one and two orders of magnitude higher than the inertization with cement one. In fact, this last treatment does not require an elevated electricity consumption; similarly, Ferrox treatment requires a medium energetic consumption, as the inertization is carried out by the chemical reaction.

| | **EUTROPHICATION [kg $PO_4^{3-}$-Equiv.]** | | | | | | |
|---|---|---|---|---|---|---|---|
| **FA inertization with cement** | **PLAN SCORE** | **Transport 30 + 300 km** | **Electricity: grid mix IT** | **Cement** | **Disposal in sanitary landfill** | | |
| | 5,72E+02 | 2,09E+02 | 5,00E+00 | 2,51E+02 | 1,07E+02 | | |
| **FA Ferrox** | **PLAN SCORE** | **Transport 100 + 300 km** | **Electricity: grid mix IT** | **Iron sulphate** | **Deionized water** | **Wastewater treatment** | **Disposal in sanitary landfill** |
| | 6,19E+02 | 2,12E+02 | 4,00E+01 | 1,27E+02 | 4,56E+00 | 1,52E+02 | 8,38E+01 |
| **FA vitrification** | **PLAN SCORE** | **Transport 100 + 300 + 300 km** | **Electricity: grid mix IT** | **Sodium silicate** | **Disposal in sanitary landfill** | | |
| | 1,14E+03 | 2,27E+02 | **8,23E+02** | 1,21E+00 | 9,22E+01 | | |

**Table 3.13 EP impact scores of the fly ash treatment plans, and how they is partitioned among their processes**

### 3.3.4 Freshwater Aquatic Ecotoxicity (FAETP)

Figure 3.17 shows FAETP net impact scores for each of the nine scenarios. From data, it is possible to observe that, among bottom ash treatments, BA OdA seems to be the most impacting and Road looks the least impacting, whilst the inertization with cement seem to be the most impacting among fly ash treatments, while Ferrox is the least.

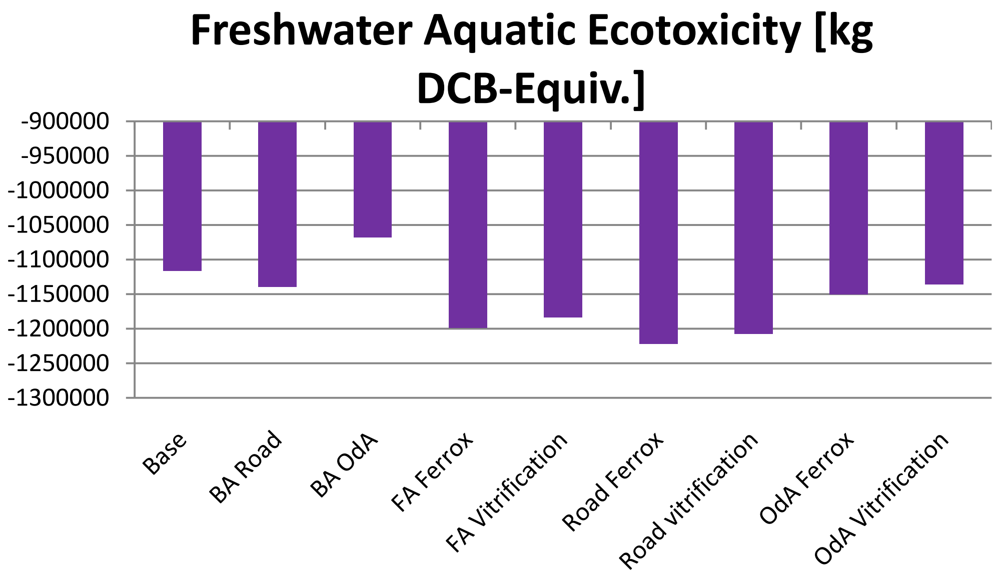


**Figure 3.17 Net impacts of the FAETP category, for each scenario**

Figure 3.18 shows the relative contributions of the incinerator processes to FAETP score, for each scenario. It can be observed that, differently from the other impact categories analyzed, FAETP is strongly influenced by the bottom ash treatment avoided impact scores. It is mostly due to the avoided iron extraction, which is characterized by a value of -1911380,90 kg $DCB_{eq}$ for the Base scenario (the least impacting). The reason of this relevant environmental saving could be found in the environmental burdens generated from the processes carried out to obtain the iron which production is prevented. Actually, in some technologies used for iron extraction from raw minerals water solutions are used, such as in hydro-metallurgic iron extraction, in which iron mineral and its impurities are immersed into an aqueous solution, in which a salt separates the iron from the impurities and the minerals. The treatment of the water used in this process can affect significantly FAETP category.

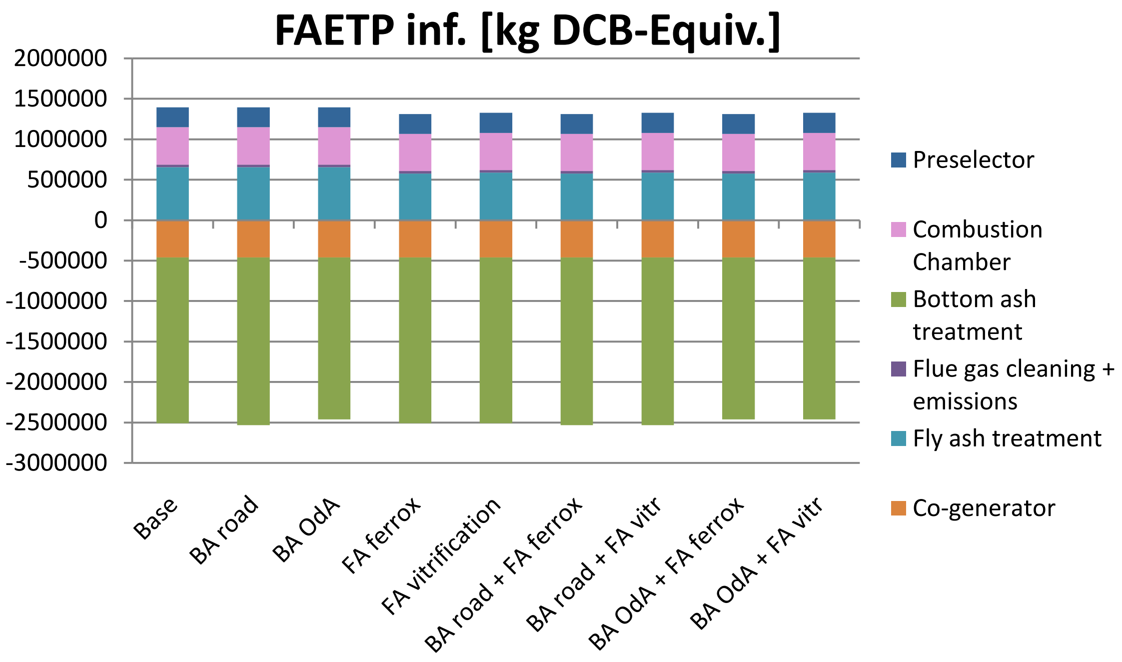


**Figure 3.18 Relative contributions of the incinerator plant to FAETP score, for each scenario**

Regarding fly ash treatment, the Ferrox alternative turns out to be the best choice, whilst the inertization with cement is the scenario with the worse impact. As it can be seen from Table 3.14, the impact scores of fly ash disposal processes are of the same order of magnitude, but the one of the inertization with cement is the highest, whilst the FA Ferrox score is the lowest. The difference between the disposal impact scores is relevant, even if the amount of residues disposed in inertization with cement is only 100 t higher than the amount disposed in Ferrox treatment. On the other hand, iron sulphate impact is higher than the one of the other two chemicals compared: but it does not contribute significantly to the whole impact.

| | **FRESHWATER AQUATIC ECOTOXICITY [kg DCB-Equiv.]** | | |
|---|---|---|---|
| **FA INERTIZATION WITH CEMENT** | **PLAN SCORE** | **Cement** | **Disposal in sanitary landfill** |
| | 6,55E+05 | 6,81E+03 | **6,47E+05** |
| **FA FERROX** | **PLAN SCORE** | **Iron sulphate** | **Disposal in sanitary landfill** |
| | 5,73E+05 | 6,12E+04 | 5,06E+05 |
| **FA VITRIFICATION** | **PLAN SCORE** | **Sodium silicate** | **Disposal in sanitary landfill** |
| | 5,88E+05 | 5,57E+05 | 5,01E+02 |

**Table 3.14 FAETP chemicals and disposal impact scores for the three fly ash treatments**

### 3.3.5 Global Warming (GWP)

GWP is, together with EP, the category for which the impact caused are greater than the ones avoided. The cause of this is showed in Figure 3.19: the flue gas treatment and emissions phase affects heavily all the scenarios with a relative impact of 77%, and it has even a heavier contribution than the one given by the energy saving of the co-generator phase (-18%). The bottom and fly ash impact contributions look negligible for this category.

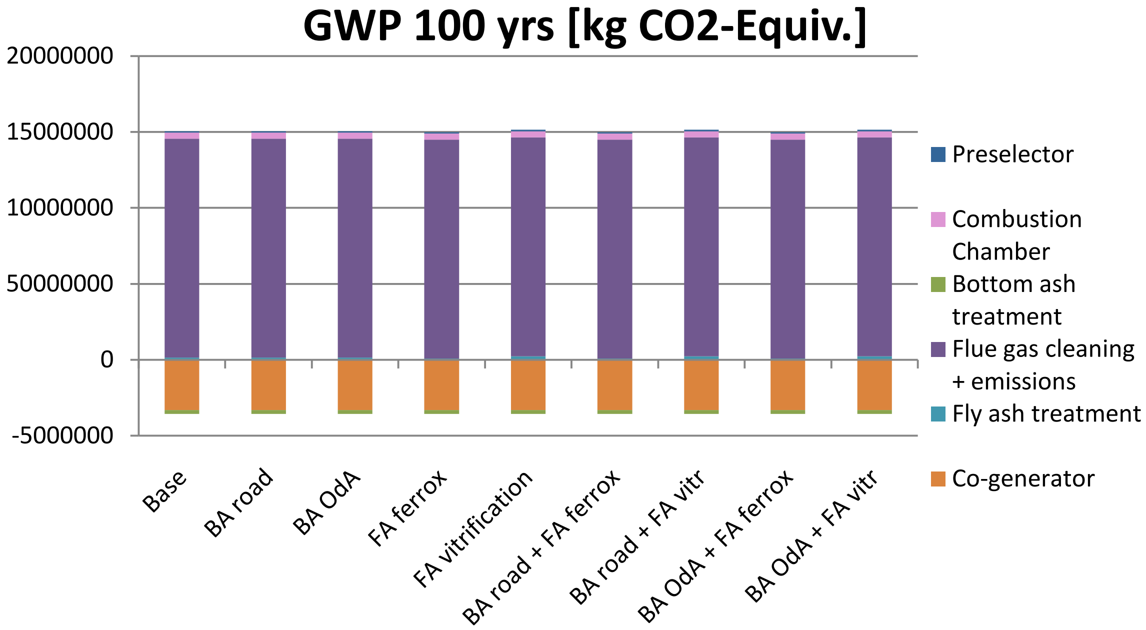


**Figure 3.19 Relative contributions of the incinerator plant to GWP score, for each scenario**

As it can be observed from Figure 3.20, that shows GWP net impact scores, the scenarios with the lowest impact score are the ones which fly ash is submitted to Ferrox treatment, whilst the highest impact is associated to the scenarios in which fly ash is vitrificated. The scenarios do not seem to be affected by the bottom ash alternative treatments, which has a relative contribution only of -1%.

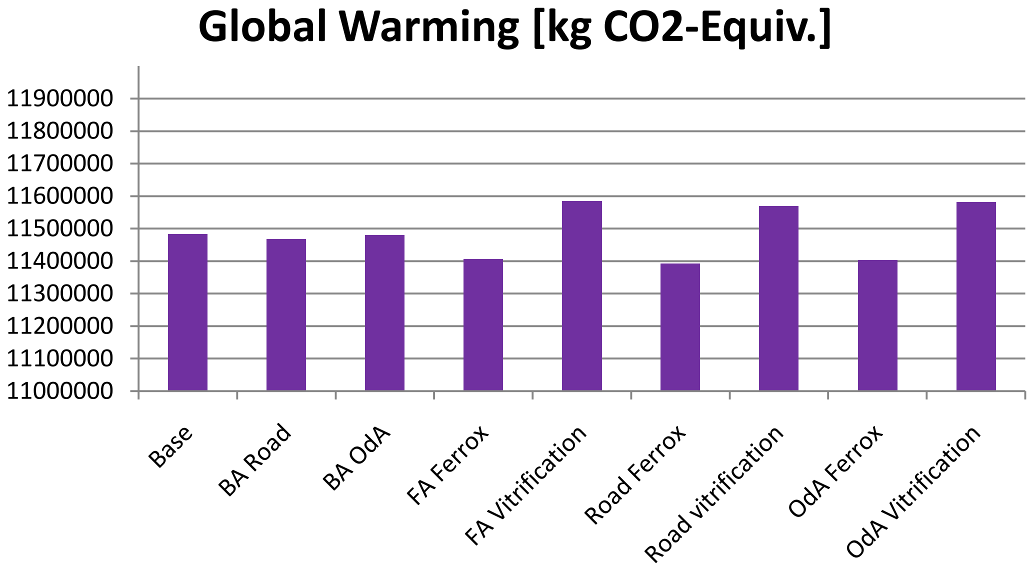


**Figure 3.20 Net impacts of the Global warming category, for each scenario**

It would be interesting to analyze the impact scores relative to the processes that make up the Ferrox and vitrification treatments. Table 3.15 lists the process impact scores of Ferrox and vitrification treatments for GWP. It can be observed that the high electricity consumption is the cause of the fact that the vitrification plan score is one order of magnitude higher than the one of the Ferrox plan. The lower impact of the sodium silicate compared to the impact associated with iron sulphate, and the absence of the wastewater treatment due to the avoided water use are not able to overcompensate the huge impact given by electricity consumption.

| | GLOBAL WARMING [kg $CO_2$-Equiv.] | | | | | | |
|---|---|---|---|---|---|---|---|
| **FA FERROX** | **PLAN SCORE** | **Transport 100+ 300 km** | **Electricity: grid mix IT** | **Iron sulphate** | **Deionized water** | **Wastewater treatment** | **Disposal in sanitary landfill** |
| | 5,76E+05 | 1,48E+05 | 1,03E+05 | 2,59E+05 | 1,33E+04 | 5,85E+03 | 4,59E+04 |
| **FA VITR.** | **PLAN SCORE** | **Transport 100 + 300 + 300 km** | **Electricity: grid mix IT** | **Sodium silicate** | **Disposal in sanitary landfill** | | |
| | 2,34E+06 | 1,59E+05 | **2,13E+06** | 3,39E+03 | 5,06E+04 | | |

**Table 3.15 GWP Impact scores of two of the bottom ash treatment plans, and how they are partitioned among processes**

In the categories analyzed in the following paragraphs, the discussion will be shorter, because the results obtained are similar to the ones already discussed above.

### 3.3.6 Human Toxicity (HTP)

From Figure 3.21, that shows HTP net impact scores for each of the nine scenarios, it can be observed that HTP scores represent avoided impacts for all the impact categories. BA Road seems to be the favorite scenario, whilst the worst seems to be FA Ferrox.

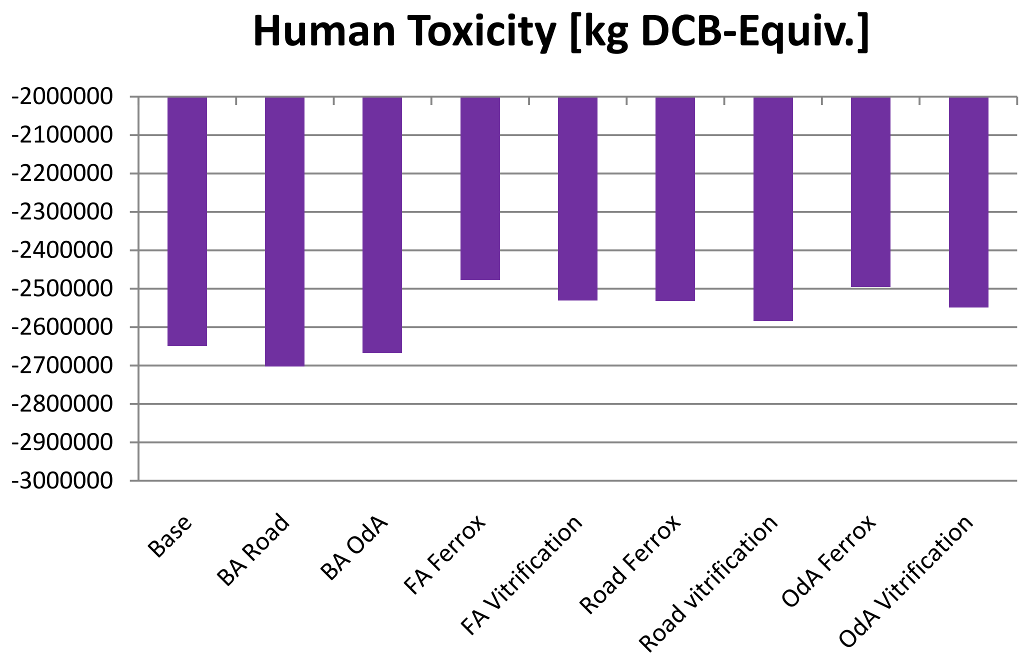


**Figure 3.21 Net impacts of the Human toxicity category, for each scenario**

From data, it is possible to conduct that the lack of a recycling process that creates a product that prevents the extraction of gravel, coupled with the necessary bottom ash disposal, make the alternatives in which bottom ash is landfilled the least sustainable.

As far as concerns the fly ash treatment impacts, Ferrox results the least favorite due to the high impact given by the use of iron sulphate. The vitrification alternative is unsustainable due to the high electricity consumption. The inertization with cement turns out to be the best alternative due to the lower resources requirements, such as the less energy consumption.

### 3.3.7 Ozone Depletion (ODP)

From Figure 3.22, that shows ODP net impact scores for each of the nine scenarios, it can be deduced that all the scenarios have a similar environmental profile, as the results are ranging between -2.1 and -8 kg R11-equiv. Therefore, talking about better and worse scenarios could result too meticulous. Nevertheless, Road + Ferrox seems to be the less impacting scenario together with BA Road, whilst, FA Vitrification seems to be the worst. As far as concerns bottom ash treatments, the higher transport distance is the reason why OdA scenarios are worse than ones with Road. Regarding fly ash treatments, Ferrox results to be the most sustainable among the alternatives because the impact score of the wastewater treatment of effluents generated by the chemical process is irrelevant. Instead, electricity consumption keeps affecting significantly vitrification alternative.

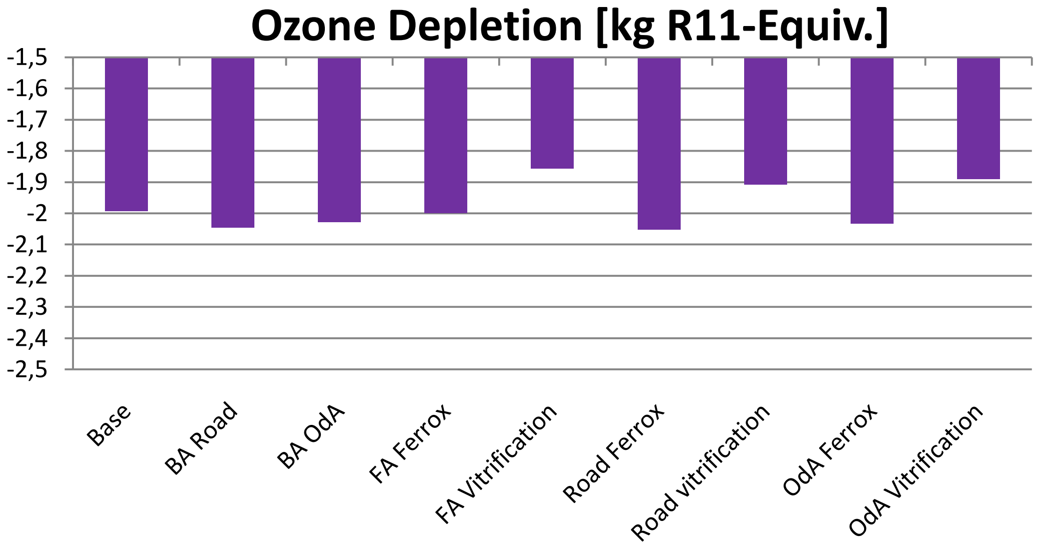


**Figure 3.22 Net impact scores of Ozone depletion category, for each scenario**

### 3.3.8 Photochemical Ozone Creation (POCP)

It is interesting to observe that the trend of the impact scores for POCP category showed in Figure 3.23, is the same as ODP one (Figure 3.22). From data, it is possible to deduce that all the scenarios have a similar environmental profile, as the result are ranging between -10,500 and -9,500 kg ethene-equiv.. The only noticeable result consist in the high net impact score of scenarios with vitrification, due to the elevated electricity consumption. The scenarios that take in consideration Ferrox treatment (FA Ferrox, Road + Ferrox and OdA + Ferrox) seem to be environmentally favorite because, even if POCP impact score is highly influenced by iron sulphate production, this polluting process is widely compensated by the fact that the other processes that compose FA Ferrox treatment are characterized by low impact scores (e.g. electricity, wastewater treatment, etc).

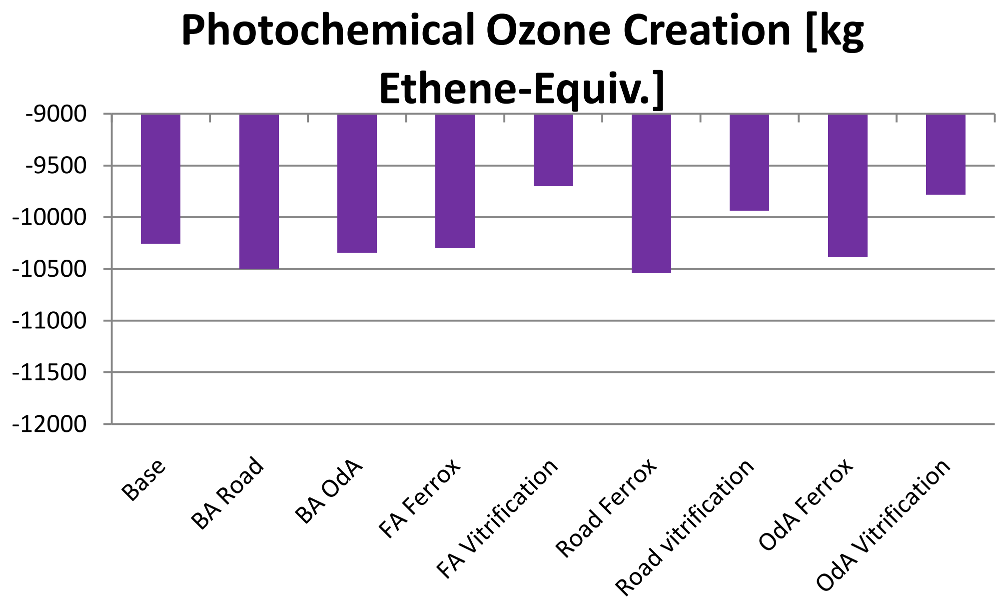


**Figure 3.23 Net impacts of the Ozone depletion category, for each scenario**

### 3.3.9 Terrestrial Ecotoxicity (TETP)

The impact scores of TETP category for each scenario are showed in Figure 3.24. This category has a different trend compared to the other categories. In fact, Ferrox seems the least sustainable alternative. As far as concerns fly ash, it is noteworthy that the contribution given by the high electricity consumption by vitrification treatment is lower than the impact score associated to iron sulphate production process. This is why Ferrox is the worst fly ash treatment alternative for TETP.

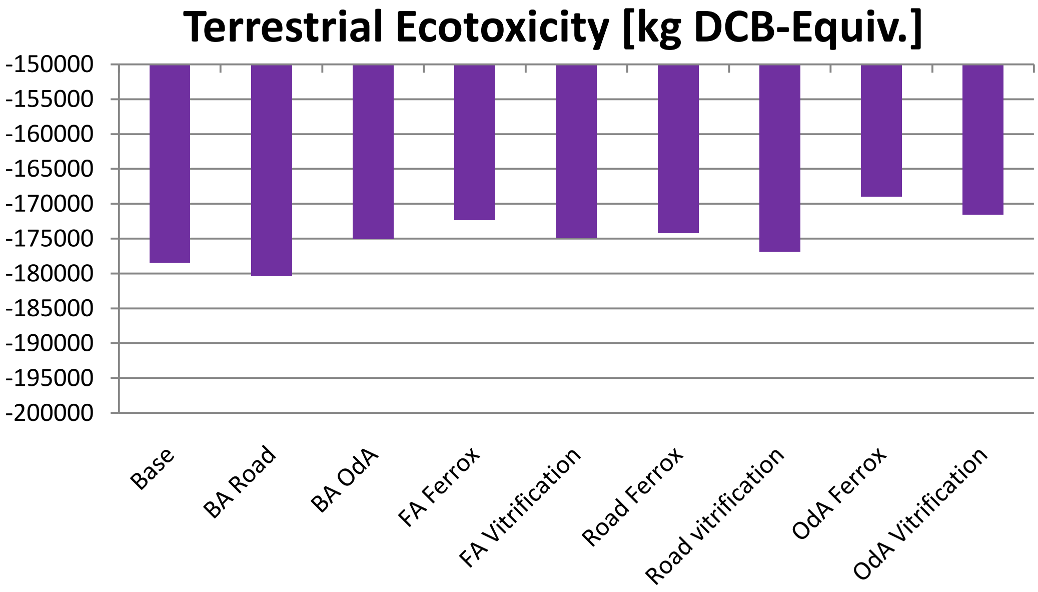


**Figure 3.24 Net impact scores of the Terrestrial Ecotoxicity category, for each scenario**

### 3.3.10 Primary Energy Demand (PED)

From Figure 3.25, that illustrates ODP net impact scores for each of the nine scenarios, it can be observed that six categories are characterized by very similar impact scores, varying between -4.7*10$^{-8}$ MJ and -4.6*10$^{-8}$ MJ. Among the scenarios, the most impacting are the ones in which vitrification is considered (FA Vitrification, Road Vitrification and OdA Vitrification). Even for this category, the electricity expenditures affect significantly the net impact score of the fly ash alternatives.

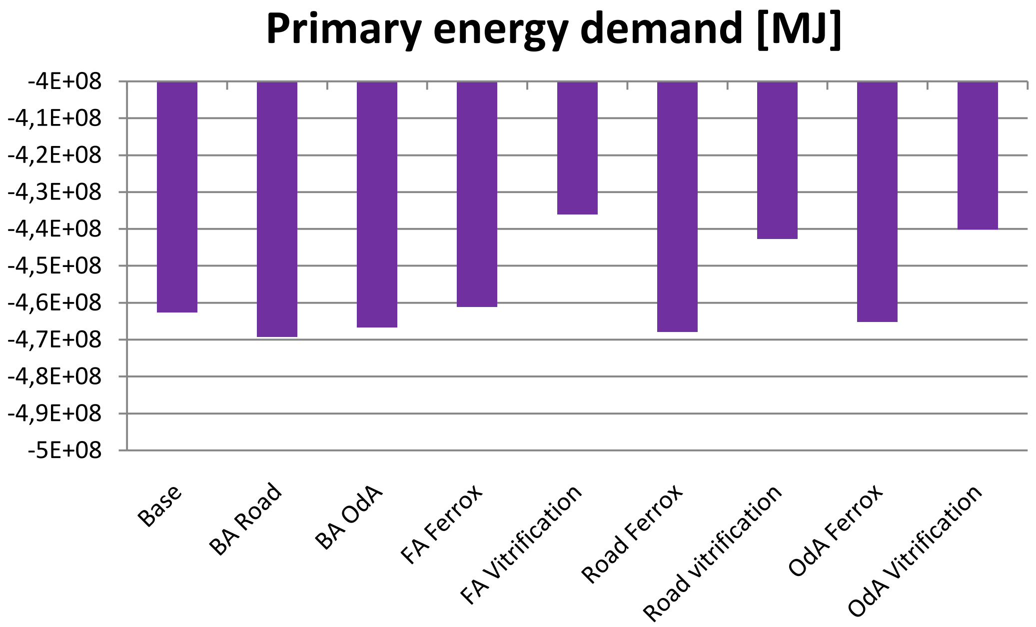


**Figure 3.25 net impact scores of the Primary Energy Demand category, for each scenario**

## 3.4 Normalization

LCIA results are normalized, in order to be directly comparable. The normalization factors are taken from CML. They are referred to the average emissions of each category in West Europe zone, in 1995. Considering the similarity between scenarios, the normalization is applied only to Base scenario impact scores. The normalized total impact scores are shown in Figure 3.26. At a first glance, the normalized data do not seem to change significantly, in comparison with the original set of data. The only categories influenced in a relevant way by the impacts are APD and, secondarily, GWP. ADP is highly affected by the avoided impacts of the process. Otherwise, GWP is influenced by the impacts generated. The data obtained suggest that the process is environmentally sustainable as far as concerns the avoided depletion of abiotic resources. From data shown in Paragraphs 3.2 and 3.3, it can be conducted that the main responsible of this environmentally positive result is the iron recycling. As far as regards GWP, the study demonstrates that the stack emissions have great influence on this category. Consequently, interventions have to be conducted in order to reduce the amount of greenhouse gases emitted.

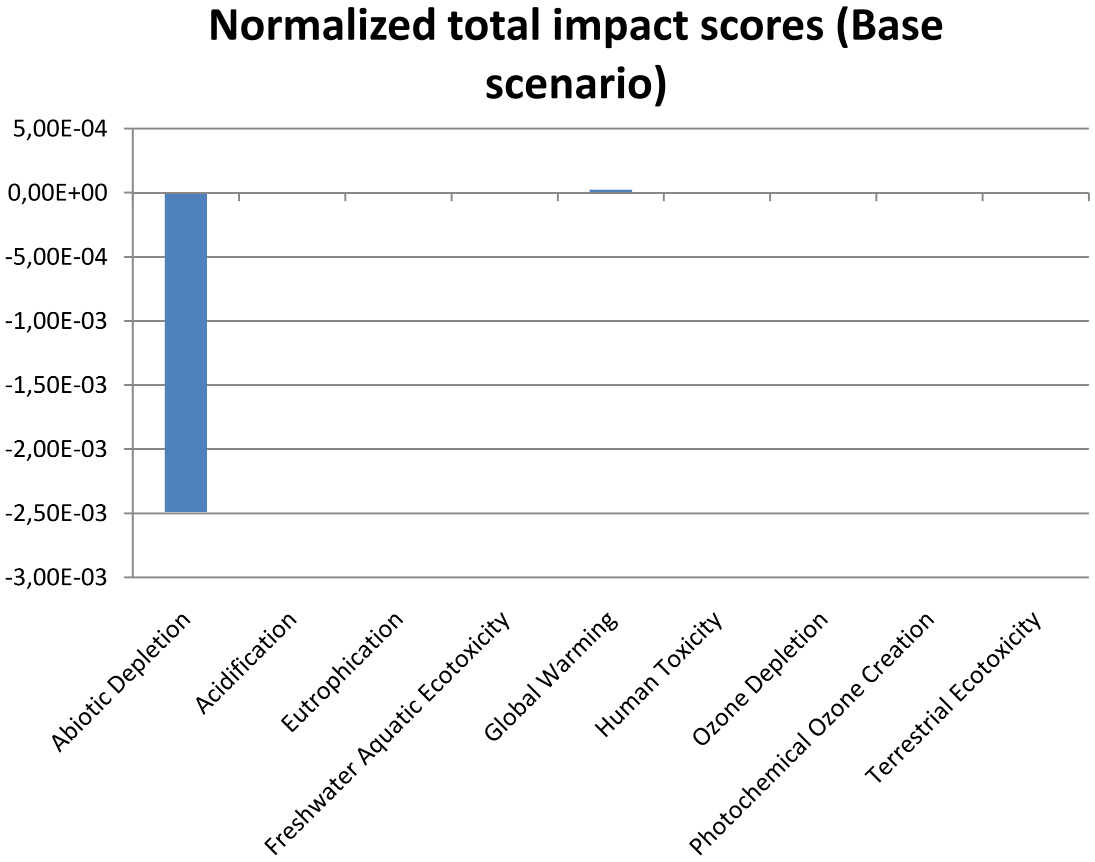


**Figure 3.26 Total impact scores of Base scenario, with normalized data**

## 3.5 Scenarios discussion

From Paragraphs 3.2 and 3.3, some issues can be discussed about the bottom and fly ash treatment alternatives analyzed. As far as concerns bottom ash, in general the three alternatives studied (Base, BA Road and BA OdA) show similar results in all the categories taken in consideration. In fact, the study demonstrates that iron scraps magnetic separation and recycling, made in all of the three alternatives, is the most affecting process. Therefore, as they actually recover similar fractions of iron, the impact scores of this process are very similar. The avoided impact contribution given by the prevented iron extraction is so relevant that the other processes affecting bottom ash treatment impact scores turn out to be less influent. It is noteworthy to underline that in the prevented iron extraction process, the impacts derived from the treatment necessary to extract iron from the iron scraps removed from bottom ash are not considered, due to the lack of information. In general, BA Road and BA OdA scenarios result environmentally better than Base because they avoid landfilling; in addition to this, gravel extraction and production is prevented. In Paragraphs 3.2 and 3.3 the various differences between BA Road and BA OdA are enlightened. Road treatment uses electricity coming from the national grid mix; it does not take in consideration the use of water. Instead, OdA uses renewable electricity; it considers both the use and the purification of water and the distance covered in bottom ash transport is longer. Even if it is established and proved by the results that these two bottom ash treatments cannot be compared, the results have highlighted some issues to be discussed, regarding transport and electricity source. It would be interesting to find out what happens if variations are applied on these factors affecting Road and OdA treatments. As far as regards electricity use, Road treatment, as it is not alternatively specified in the literature study, is assumed to use electricity coming from national grid mix. Instead, in OdA treatment, as explained in *Officina dell'Ambiente* 2013 Environmental Declaration, electricity coming from a photovoltaic plant and from a hydropower plant is used. It could be interesting to analyze how much the electricity source affects BA OdA impact scores, by switching the electricity source from the renewable mix to the national grid mix.

| | **BA OdA** | |
|---|---|---|
| | **PLAN SCORE (PV + hydro)** | **PLAN SCORE (Grid mix IT)** |
| Abiotic Depletion [kg Sb-Equiv.] | -2,35E+04 | -2,26E+04 |
| Acidification [kg $SO_2$-Equiv.] | -8,04E+03 | -7,42E+03 |
| Eutrophication [kg $PO_4^{3-}$-Equiv.] | -5,41E+02 | -4,91E+02 |
| Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.] | -2,00E+06 | -2,00E+06 |
| Global Warming [kg $CO_2$-Equiv.] | -2,46E+06 | -2,32E+06 |
| Human Toxicity [kg DCB-Equiv.] | -1,19E+06 | -1,18E+06 |
| Ozone Depletion [kg R11-Equiv.] | -1,51E-02 | -4,77E-03 |
| Photochemical Ozone Creation [kg Ethene-Equiv.] | -2,05E+03 | -2,01E+03 |
| Terrestrial Ecotoxicity [kg DCB-Equiv.] | -1,57E+05 | -1,56E+05 |

| | | |
|---|---|---|
| Primary energy demand [MJ] | -5,69E+07 | -5,54E+07 |

**Table 3.16 Comparison in BA OdA scenario between actual impacts scores and their variation if electricity source is changed**

Another factor that affects significantly the two alternatives compared is transport. BA OdA transport process score is higher because it takes a longer distance to get to *Officina dell'Ambiente* plant. Also, in BA OdA alternative an higher amount of product is globally transported. Actually, as the BA Road scenario is hypothetical, the distance between the WTE plant and the facility in which bottom ash is sent to be deironized and then to be transformed in a material for road construction is not known. Therefore, 200 (100 + 100) km is the assumed to be the distance covered by the truck. Consequently, in BA Road scenario the distance chosen is only an assumption. Road plan can be changed, in order to see what occurs to its impact score if the distance covered by the truck to recycling plant is supposed to be 300 km. In Table 3.17, showing the comparison between the Road actual impact scores and their variability if transport distance is changed, it is assumed that truck has to drive 300 km instead of 100 + 100 km (the distance to get to the de-ironization plant plus the distance to get to the recycling facility), as occurs in OdA plan. Comparing the new set of data with the OdA impact scores, it can be observed that Road plan impact scores increase, getting closer to OdA. This means that transport is a crucial factor, too.

| | **BA Road** | | **BA OdA** |
|---|---|---|---|
| | **PLAN SCORE (100+100 km)** | **PLAN SCORE (300 km)** | **PLAN SCORE OdA** |
| Abiotic Depletion [kg Sb-Equiv.] | -2,44E+04 | -2,25E+04 | -2,35E+04 |
| Acidification [kg SO2-Equiv.] | -9,14E+03 | -7,17E+03 | -8,04E+03 |
| Eutrophication [kg PO43--Equiv.] | -9,96E+02 | -5,66E+02 | -5,41E+02 |
| Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.] | -2,07E+06 | -2,07E+06 | -2,00E+06 |
| Global Warming [kg CO2-Equiv.] | -2,58E+06 | -2,28E+06 | -2,46E+06 |
| Human Toxicity [kg DCB-Equiv.] | -1,22E+06 | -1,21E+06 | -1,19E+06 |
| Ozone Depletion [kg R11-Equiv.] | -3,36E-02 | 4,05E-03 | -1,51E-02 |

| | | | |
|---|---|---|---|
| Photochemical Ozone Creation [kg Ethene-Equiv.] | -2,21E+03 | -2,04E+03 | -2,05E+03 |
| Terrestrial Ecotoxicity [kg DCB-Equiv.] | -1,62E+05 | -1,62E+05 | -1,57E+05 |
| Primary energy demand [MJ] | -5,95E+07 | -5,53E+07 | -5,69E+07 |

**Table 3.17 Comparison in BA Road scenario between actual impacts scores and their variation if distance is changed in transport process**

To sum up, it can be said that BA Road and BA OdA are both valid alternatives to bottom ash recycling. In addition to this, the most important treatment, that cannot be omitted, is the prior iron scraps separation. Despite the good environmental results of BA Road scenario, as already specified in Paragraph 2.1.1 bottom ash recycling in road construction is not actually possible in Italy. Therefore, BA OdA turns out to be the most environmentally viable option for bottom ash treatment.

As far as concerns fly ash, in general the vitrification results the least favorite alternative for almost all the categories (ADP, AP, EP, GWP, ODP, POCP, PED). This is due to the high impact scores associated to electricity consumption process. This is shown in Table 3.10, Table 3.13 and Table 3.15. FA Ferrox results a more sustainable scenario than FA Vitrification, because it is characterized by medium energetic and chemicals consumptions. Nevertheless, FA Ferrox results the most impacting alternative for toxicity categories HTP and TETP: the cause is the high impact score associated to iron sulphate production. In general, iron sulphate impact does not affect significantly all the categories, as this chemical is obtained as a by-product of the steel and iron manufacturing: there is not any production line dedicated to this compound. As the amount of water used in Ferrox treatment is not remarkable (about 2.7 $m^3$ per ton of fly ash treated), the impact generated by wastewater treatment is not relevant. This contradicts the opinion of Colangelo and coauthors (2012), for which the most affecting process in fly ash chemical stabilization is the high amount of water to purify. In their study, they assume that water consumption can reach 20 $m^3$ per ton of fly ash treated. Base treatment, that consists in the inertization with cement, results the best fly ash alternative for AP (slightly better than Ferrox), GWP, HTP (much lower impact scores than Ferrox) TETP. In addition to this, its impact scores are similar than Ferrox ones in categories ADP, EP, ODP, PED, POCP. In other words, FAETP is the only category for which Base treatment is worse than the Ferrox one. The only process in Base alternative which presents an higher impact score than the other two alternatives is the disposal of the inertized fly ash, as it is showed in Table 3.14, that lists the impact scores related to the inertized fly ash disposal. This occurs because in Base scenario an higher amount of residue has to be disposed: the amount of fly ash is summed up to the quantity of cement needed to inertized it. It results that the whole amount to be disposed is 100 t higher than in the other two scenarios. This is in line with the assertion made by Karagiannidis and collaborators (2003), for which the addition of cementitious materials, even if it consists in a cheap technology, creates a huge amount of final product to be disposed. Considering the results obtained by bottom ash, it can be thought that, if metal separation was considered also in fly ash treatment, the total impact would decrease. In this case, the separation would involve metals like Zn and Cu. As these are not metals subjected to magnetism, the only way in which their separation would be conducted is like in the study of Shen and Fossberg made in 2003, in which non-magnetic metals are extracted through the use of an acidic solution and a subsequent filtration. The problem is that this process needs a relevant amount of harmful wastewater to be purified, despite the fraction of metals extracted make up only few percentage units. Therefore, if it is not well-conducted, it consists in an unfeasible process.

To sum up, Ferrox and inertization with cement are the most environmentally feasible alternatives. Even if vitrification is one of the safest stabilization methods, the impact derived from its high electricity consumption makes it excessively impacting. As authors as Colangelo and collaborators (2012) propose the combination of two treatments to make sure that the stabilized fly ash is stable enough to be even recycled, an idea would be put together the Ferrox and the vitrification process. The processes combination would result in a total electricity use that is not necessarily the sum of the electricity consumptions of the two treatments taken separately, but a lower value. Unfortunately, in this thesis it is impossible to combine these two treatments due to the lack of data and information. In fact, Colangelo and coauthors proved the combination, but using the inertization with cement instead of a thermal treatment. Ferone and collaborators (2013) tested the combination too, but using an alkali-activated Al-Si material, leading to the formation of a geopolymer as a residue. As this field of study is currently in development, it is difficult to make any treatment alternative based on this process.

# 4 CONCLUSIONS

In this work, the environmental impacts associated to the life cycle of waste incineration are assessed. The analysis starts from the arrival of waste at the incinerator plant and it ends with the disposal of all the residues originating from waste combustion. The aim of this analysis is to find out and study the most impacting processes, and to compare different recovery/disposal methods for the residues coming out from incineration. The results obtained shall be able to find out if the whole process can be further improved or if it has already reached the maximum sustainability and efficiency. As in northern Italy many incineration processes are similar to the one studied in this thesis (like the Italian plant analyzed in 2011 Turconi and collaborators study), the considerations coming out from the results can be relevant for the whole territory.

The subject of this study, and the plant from which all the residues parameterized in scenarios come from, is the Forlì incineration plant, located in Emilia-Romagna region (northern Italy). The main data source is primary, coming from Italian companies which actually treat these incineration residues. In the case it is chosen a process treatment which company is not known, secondary data are used, adapted to the quantities entering and exiting the Forlì WTE plant. This plant already uses the best technologies about waste combustion, flue gas cleaning equipment and energy recovery.

The most relevant results are the following:

- Incineration itself (i.e. the residues treatment is not taken in consideration) is sustainable if energy recovery is considered, because the impacts caused by combustion chamber, preselector and flue gas cleaning is well compensated by the avoided impact from co-generator.
- Nevertheless, it is proved that the sustainability of an incineration process with energy recovery is highly affected by the electricity source that co-generator replaces. In fact, if the actual replaced electricity source is replaced with a renewable mix in co-generator phase, the impacts caused on categories as EP and GWP cannot be compensated by the energy recovery anymore. If the electricity supply is expected to go towards an higher use of renewable electricity, the incineration plant will result less sustainable. This is why improving the caused impacts most affecting the plant described above is crucial. As far as concerns the impact generated by incineration, the most impacting process, which have the widest improvement margins, are identified. From the results obtained in Paragraph 3.1 it is possible to conduct that the impact of

the sludge generated by wastewater treatment in preselector phase can be lowered by handling sludge fermentation in a more sustainable way. Also, the landfill gas generated from sludge disposal in combustion chamber phase can be collected and burned in more efficient conditions. Moreover, the relevant consumption of the auxiliary energy required to support waste combustion should be decreased. This can occur only if the amount of waste in arrive at the plant increased, in order to allow the separation of an higher percentage of organic fraction, that would increase LHV of the incinerated waste.

- Keeping focusing on the incineration plant, an important issue regards the limits of an LCA on the analysis of the (eco-)toxicological impact categories. LCA, as it is not a site-specific analysis, is not able to give results about the pollution levels found in the site in which the toxic compounds are emitted. This is a crucial issue, even if all the emission parameters are below the limits prescribed. Moreover, the plant is placed in an industrial area, next to a sanitary waste incinerator and 1 km far from the highway. Even if these factors influence the actual pollution situation of the site, LCA is not able to identify and evaluate their contribution. Toxicity consequences can be evaluated in a proper way only carrying out an Ecological and Human Health Risk Assessment.
- As far as regards bottom ash treatment, there are not relevant differences among the three scenarios analyzed. The process most affecting bottom ash scenarios results to be the iron recycling by separating iron scraps from bottom ash, and therefore the avoided production of iron from raw minerals. The subsequent bottom ash recycling to transform it in an aggregate to be used in road construction or in building sector gives an impact reduction, due to the avoided production of natural aggregate. The net impact of these two alternatives is similar. Nevertheless, it must be specified that, in the Italian legal framework, the recovery of a mechanically treated bottom ash as sub base layer in road construction is generally not allowed because of the high levels of leaching for some heavy metals. For that reason, the OdA alternative is, actually, the most feasible alternative for BA recovery. Despite this crucial consideration, some factors turn out to be environmentally relevant in recycling process, such as the distance travelled from the incineration plant to the recycling plant, and the type of electricity used in the plant.
- As far as concerns fly ash treatment, in general the actual fly ash inertization with cement and the Ferrox treatment are characterized by similar results. The main cause

of the impact generated by the inertization with cement is the disposal of an high amount of residue in landfill, as cement is added to fly ash. Instead, the main cause of the impact generated by Ferrox treatment is the impact caused on toxicological categories by iron sulphate production. However, the inertized fly ash coming out from this processes can maintain its hazardous nature (Colangelo et al., 2012). Despite vitrification is the most reliable inertization method, that allows the production of a safer fly ash, it is the most impacting alternative, due to its need of high amounts of electricity. Unfortunately, LCA is not able to take into account the safety and the quality of a product. One solution to ensure the complete safety of the fly ash disposed could consist in coupling two different stabilization treatments, as Colangelo and collaborators (2012) proposed in their study. In this way, fly ash could be also recycled to be used in many sectors, as it is already done for the bottom ash.

- Considering the encouraging results obtained by bottom ash, it can be thought that, if metal separation was considered also in fly ash treatment, the total impact would decrease. The problem is that the metal extraction process made on fly ash produces a relevant amount of harmful wastewater, despite the fraction of metals extracted make up only few percentage units. Therefore, if it is not well-conducted, it consists in an unfeasible process.
- As Cioffi and collaborators underlined in their study in 2010, even if an ash treatment technology is developed, often the national legislation represents an obstacle to its use as recycled material. Ash stabilization technologies shall improve with the same rate of the flexibility of the national legislation about incineration residues recycling.

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# 7 APPENDIX

## 7.1 Plant planimetry

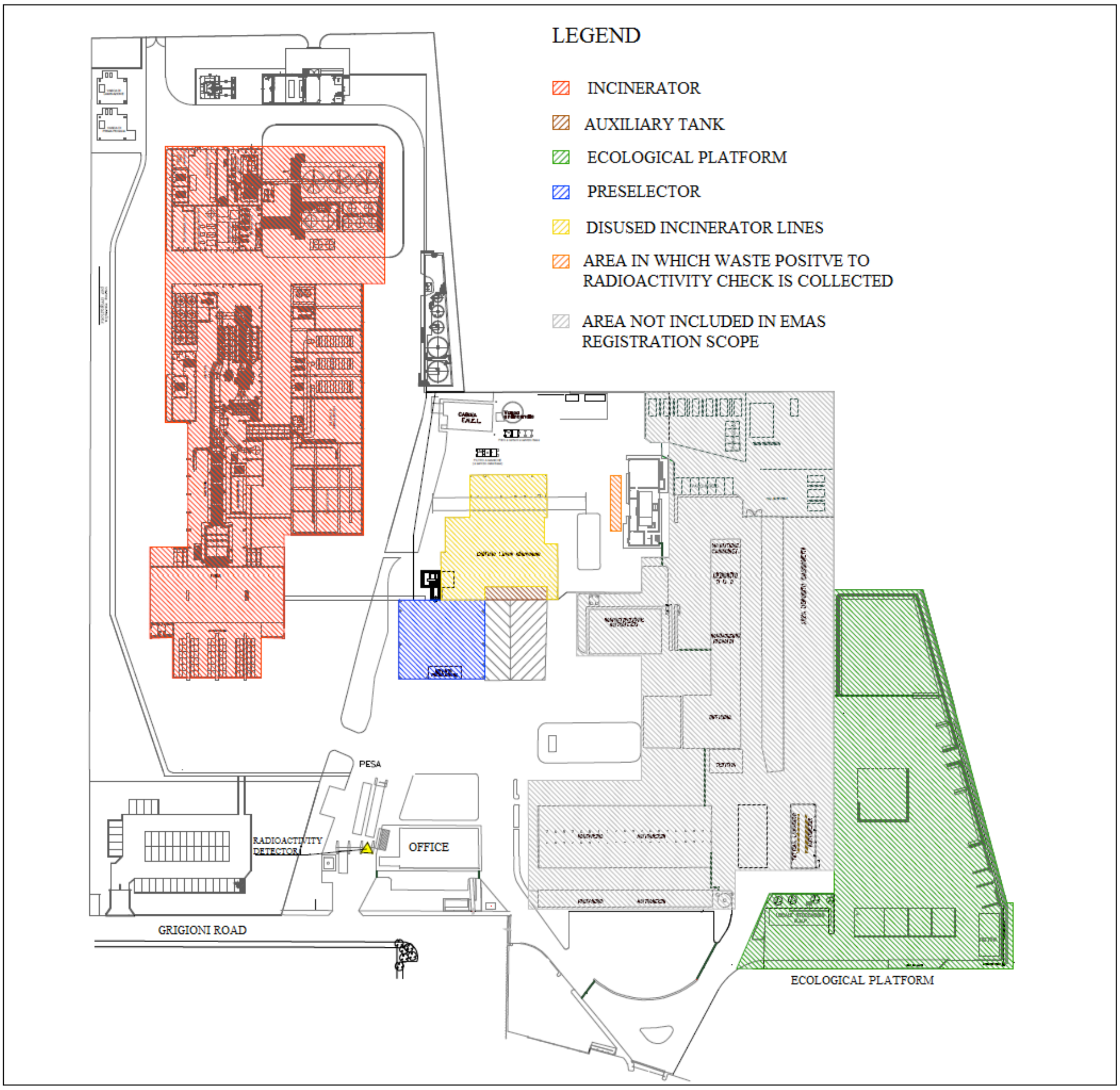

**Figure 7.1 Plant planimetry (Herambiente, EMAS Environmental Declaration, 2011)**

## 7.2 LCIA

In this appendix all the graphs not inserted in Chapter 3 are collected.

### 7.2.1 Scenarios relative contributions

In BA Road + FA Ferrox scenario bottom ash is submitted to mechanical treatment in order to be transformed in a gravel used in road construction; fly ash is inertized with Ferrox process. Figure 7.2 trend is identical to the one of the BA Road scenario.

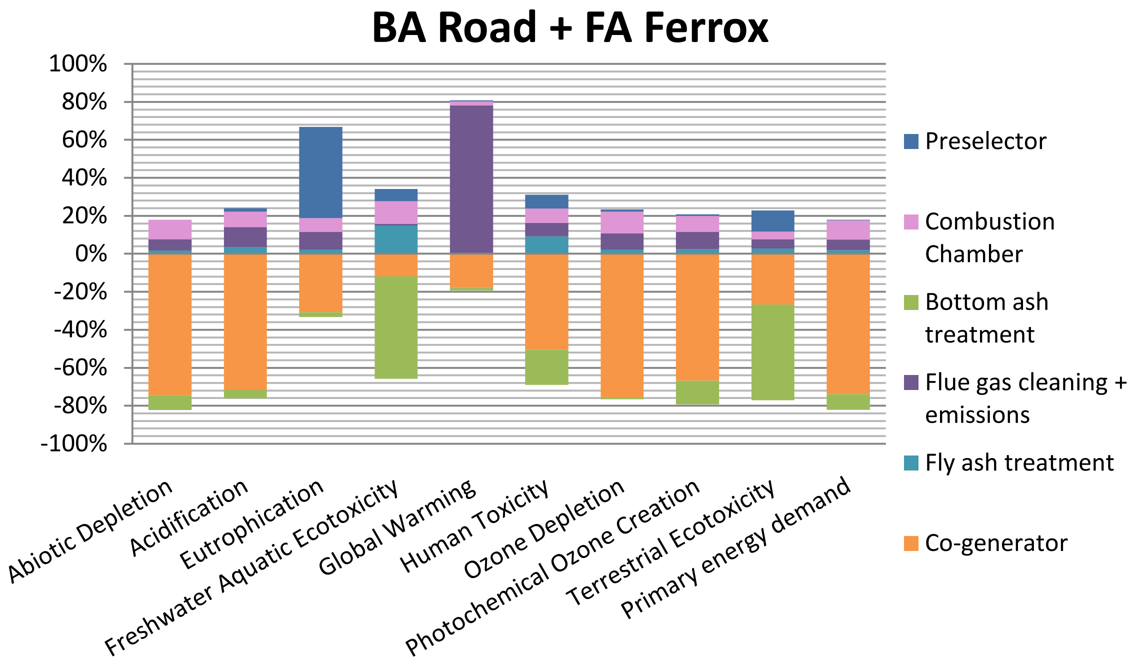

**Figure 7.2 Relative plans contributions in BA Road + FA Ferrox scenario**

In BA Road + FA Ferrox scenario bottom ash is submitted to mechanical treatment in order to be transformed in a gravel used in road construction; fly ash is vitrificated. Figure 7.3 trend is identical to the one of the BA Road scenario.

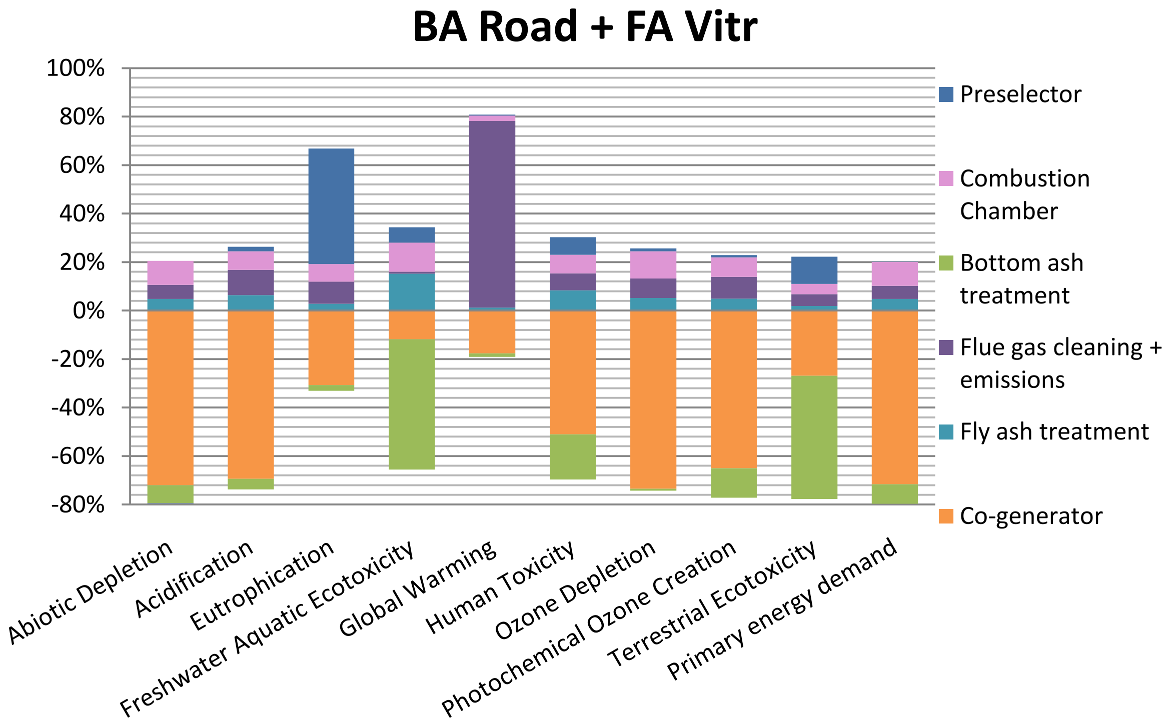

**Figure 7.3 Relative plans contributions in BA Road + FA Vitrification scenario**

In BA OdA + FA Ferrox scenario bottom ash is submitted to mechanical treatment and aerobic stabilization in order to be transformed in a gravel used in construction sector; fly ash is stabilized through Ferrox chemical treatment. Figure 7.4 trend is very similar to the one of the BA OdA scenario.

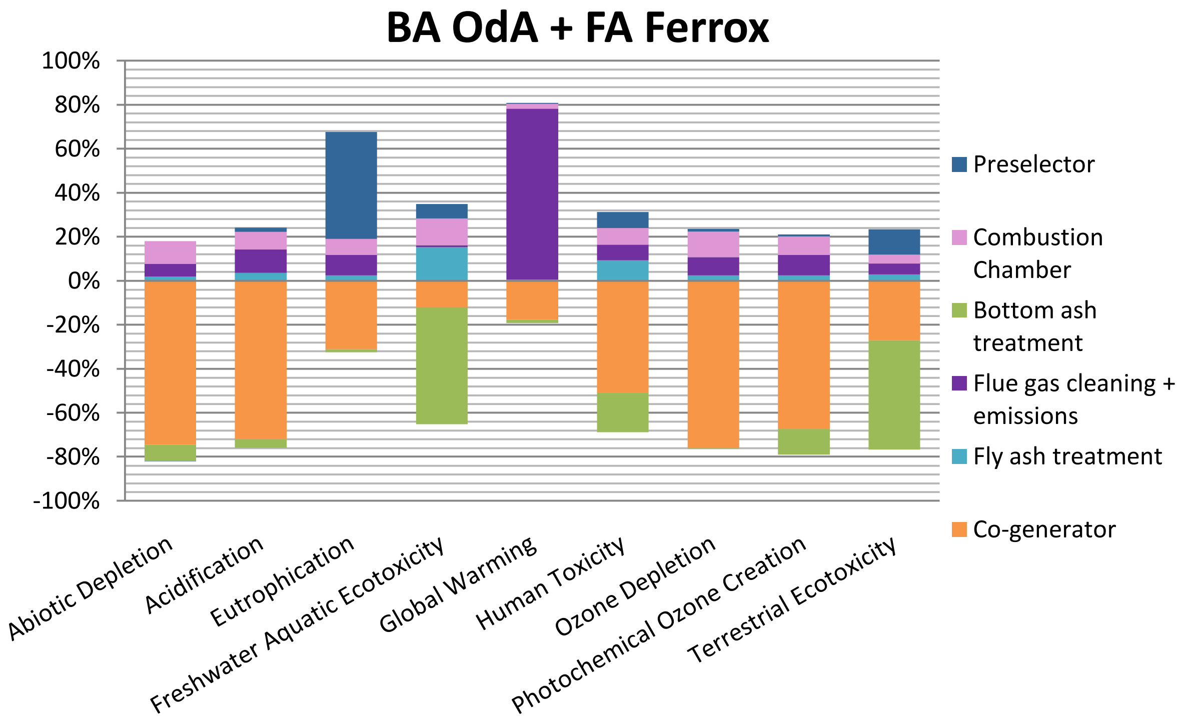

**Figure 7.4 Relative plans contributions in BA OdA + FA Ferrox scenario**

In BA OdA + FA Vitrification scenario bottom ash is submitted to mechanical treatment and aerobic stabilization in order to be transformed in a gravel used in construction sector; fly ash is vitrificated. Figure 7.5 trend is very similar to the one of the BA OdA scenario.

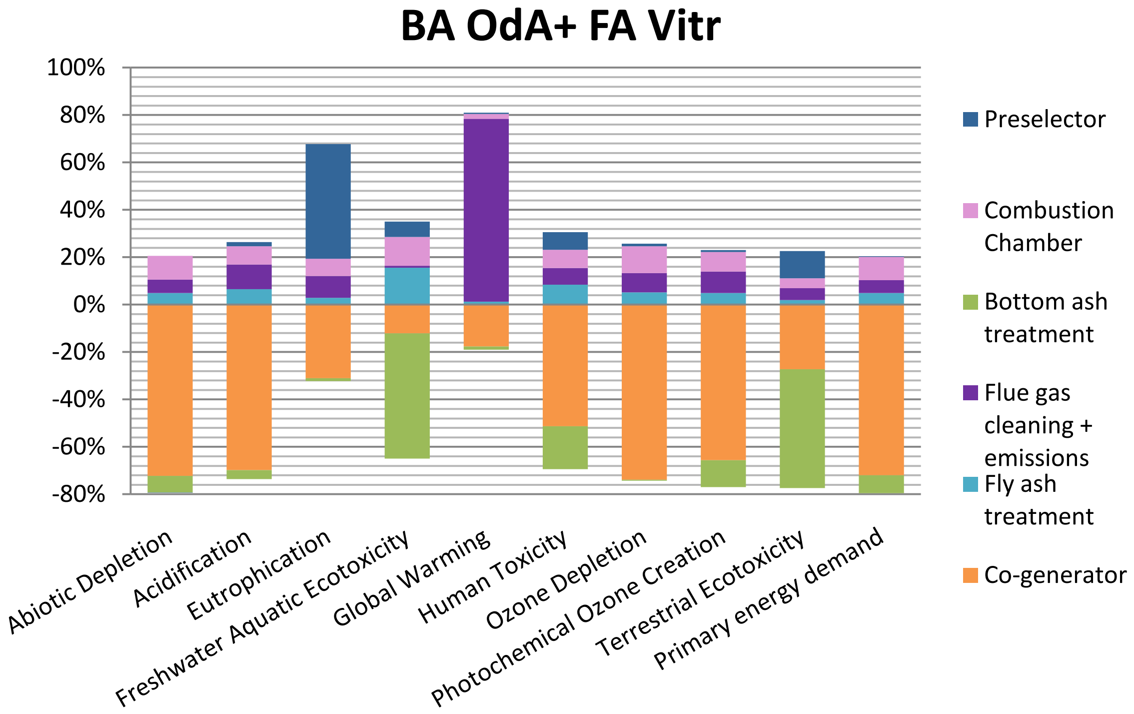

**Figure 7.5 Relative plans contributions in BA OdA + FA Vitrification scenario**

### 7.2.2 Impact categories relative contributions

Figure 7.6 shows that the avoided impact contribution of co-generator is the most affecting process. Among the contributions of the impacts generated, it can be seen that preselector, combustion chamber and fly ash treatment contribute similarly to the whole impacts generated.

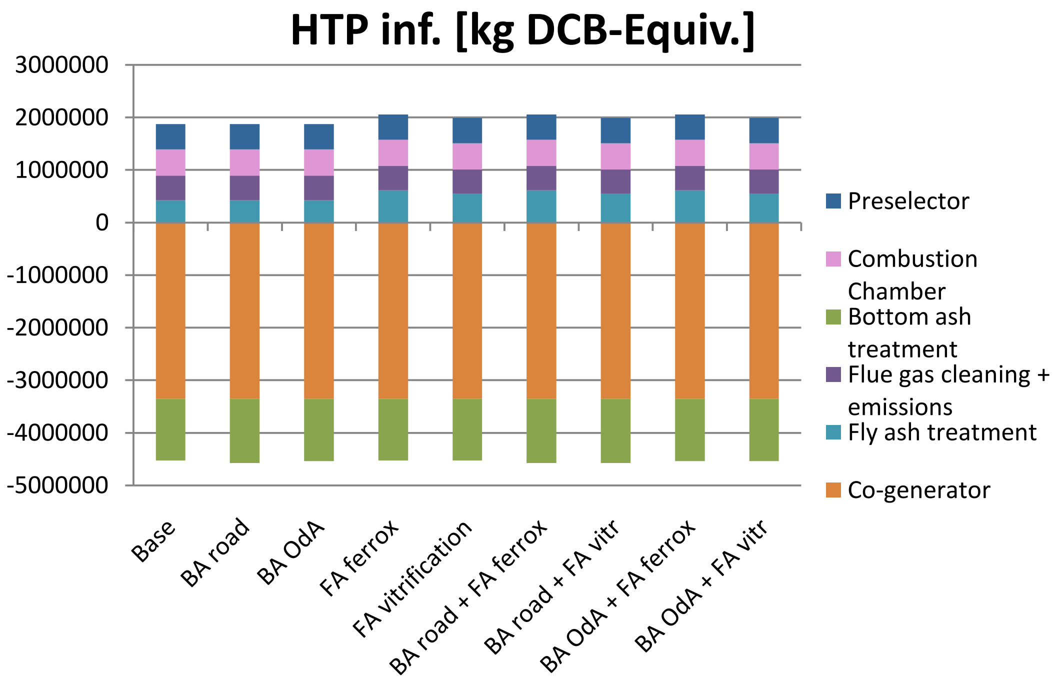

**Figure 7.6 Contributions of the incinerator processes to HTP score, for each scenario**

Figure 7.7 shows that the variation of the impact scores related to fly and bottom ash treatments becomes irrelevant compared to the contribution of co-generator.

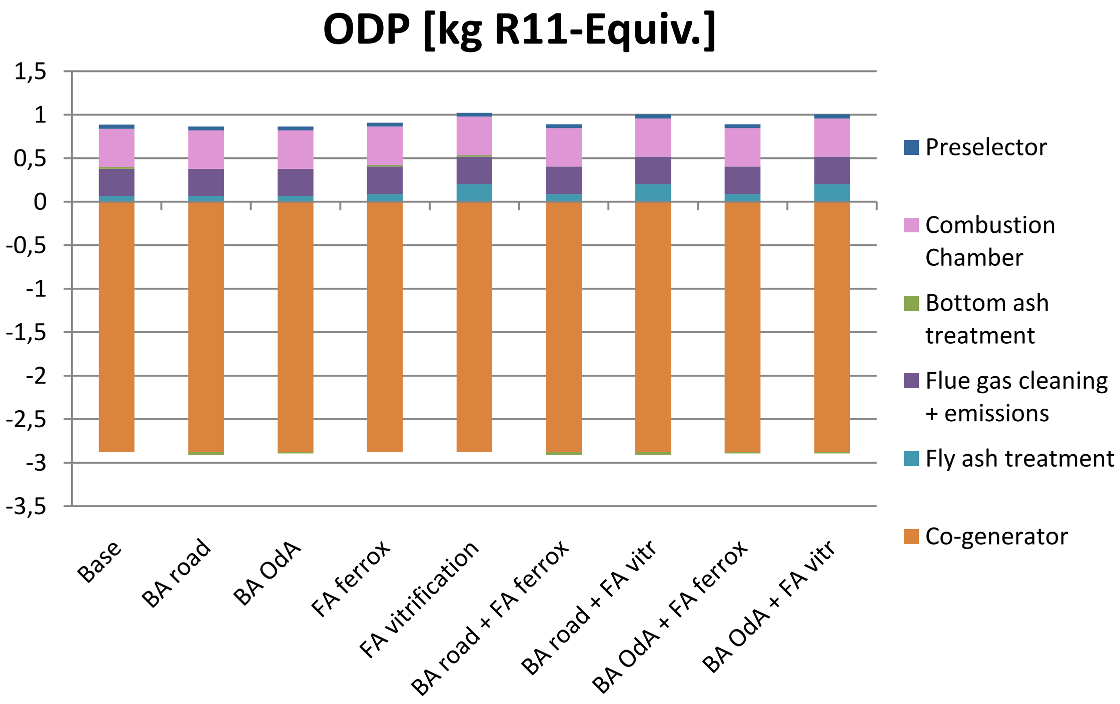

**Figure 7.7 Contributions of the incinerator processes to ODP score, for each scenario**

From Figure 7.8 it can be seen that co-generator affects the whole avoided impact contributions more than the energy savings made by bottom ash treatment. This is valid for all the scenarios. Among the impacts caused, the combustion chamber and the flue gas cleaning and emissions phases are the most affecting.

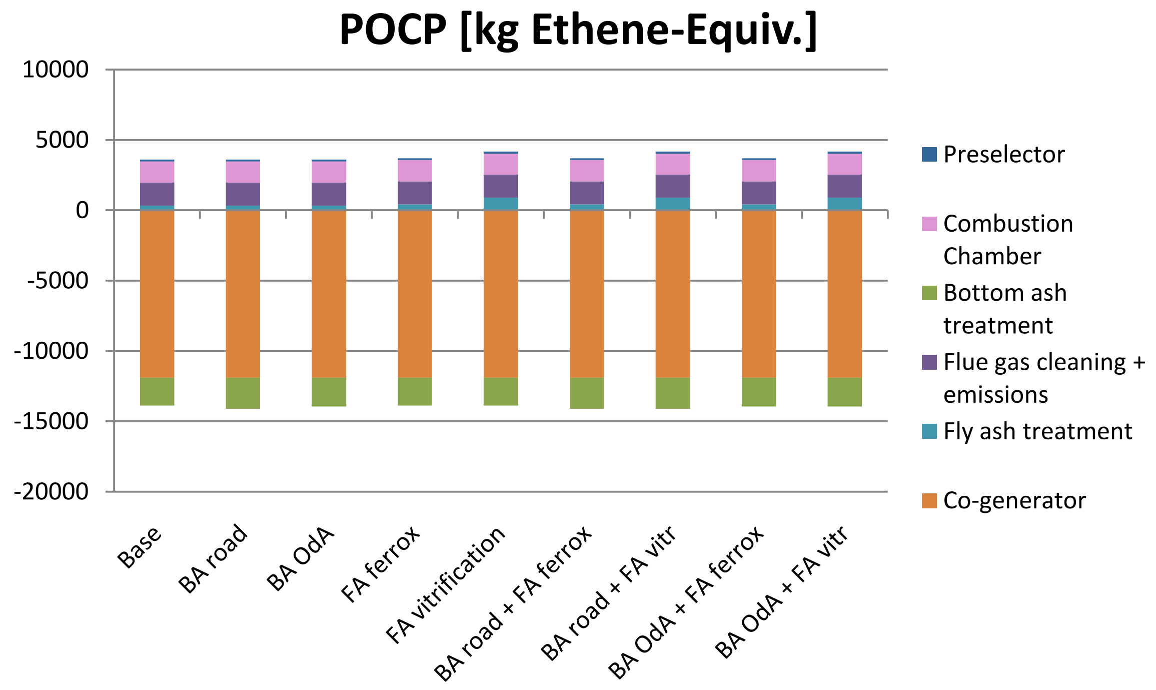

**Figure 7.8 Contributions of the incinerator processes to POCP score, for each scenario**

Figure 7.9 shows that the avoided impact contribution of bottom ash treatment is the process most affecting the whole impact. Among the impacts generated, the most relevant is the one given by the preselector.

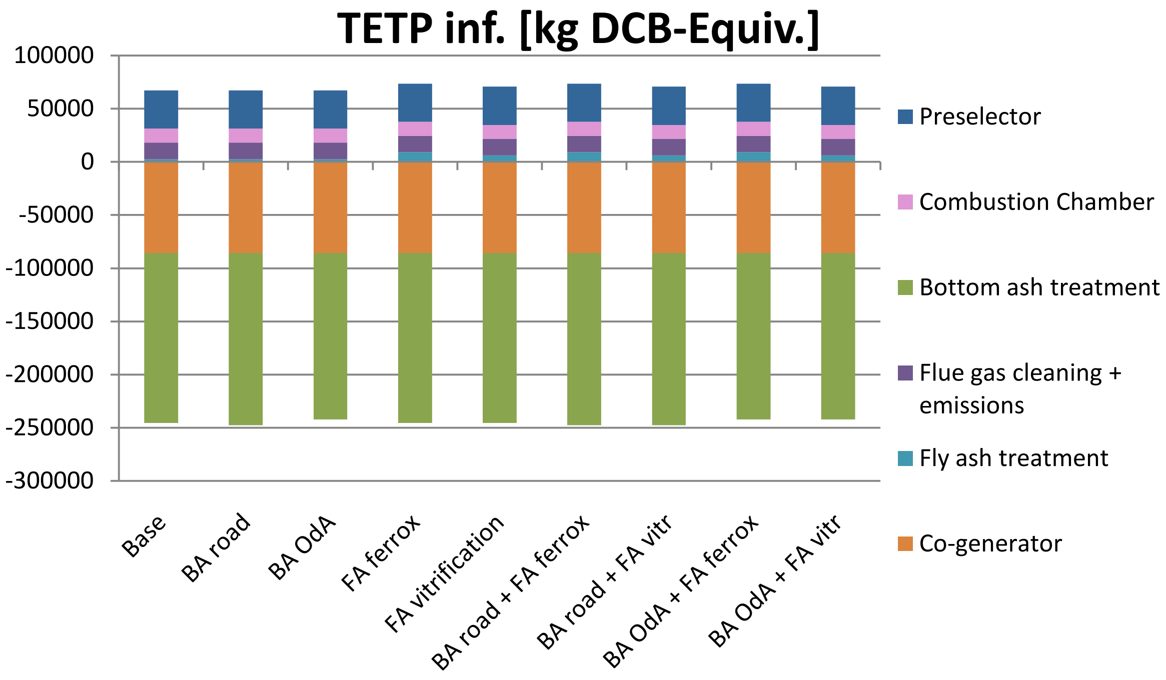

**Figure 7.9 Contributions of the incinerator processes to TETP score, for each scenario**

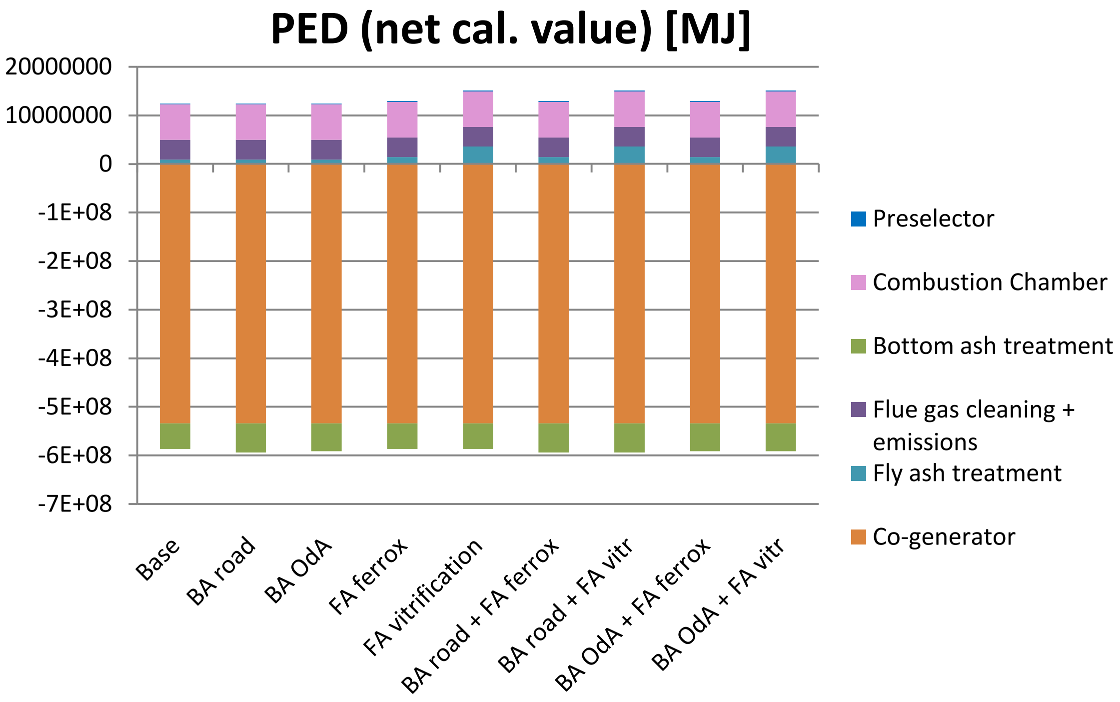

**Figure 7.10 Contributions of the incinerator processes to PED score, for each scenario**