LCA evaluation of different recycling options for incineration bottom ash

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Abstract

Purpose

The aim of this paper is to assess the environmental impacts of bottom ash (BA) treatment, including the recycling of the metal scraps and of the mineral fraction. For the latter, five different uses were considered: in clinker production, in concrete production, in bituminous conglomerate production and in road construction (in the embankment or in the sub-base layers).

Methods

The study was carried out applying the Life Cycle Assessment (LCA) methodology. The system was modelled on the basis of primary data gathered from three BA treatment plants located in northern Italy. The following impact categories were considered: climate change, ozone depletion, photochemical ozone formation, particular matter, acidification. Also the Cumulative Energy Demand (CED) indicator was calculated.

Results

Regardless of the fate of the mineral fraction, the treatment of the BA aimed to material recovery resulted beneficial for all the considered indicators. The main burdens are associated with the transport of the BA to treatment, the incineration of the unburned materials and, except for the scenario of clinker production, the recycling of the mineral fraction. The main benefits are associated with the recovery of the metal scraps, both ferrous and non-ferrous. Focusing on the recycling of the mineral fraction, the best application is in the clinker production. On the contrary, using the mineral fraction in road construction resulted always not beneficial.

Conclusions

The study shows the importance of the type of use for the mineral fraction resulting from the BA treatment, as well as the importance of recovering the metal scraps.

Keywords: incineration bottom ash, LCA, recycling, MSW incineration

1. Introduction

Bottom ash (BA) is the most abundant solid residue generated by waste incineration. Thanks to its technical properties, BA can be sent to recycling instead of being landfilled. However, the environmental and economic impacts of this practice should be assessed.

Recycling options for the BA include the use as construction material, e.g. in road construction or in concrete production, or as input material in clinker production [1, 2, 3, 4].

However, some treatments are required in order to reduce the content of ferrous and non-ferrous metals as well as to prevent the negative environmental impacts that a direct use of the raw BA can cause due to the high content of heavy metals and polluting agents. A further goal of these treatments is to increase the mechanical properties of the BA, in view of the recovery of the mineral fraction. These treatments usually include an ageing process to promote the transformation of BA constituents into more thermodynamically stable forms, a size classification with screens or drums, an extraction of metals through magnetic and eddy current separators, a washing with water or chemical solvents to remove soluble heavy metals and salts, and, eventually, grinding to improve metal recovery [5, 6]. The recovery of ferrous and non-ferrous metals is an essential step of the BA treatment process, both for the environmental advantage associated with metal scraps recycling and for the reduction of the negative effects of metals, especially aluminium, that can result in swelling and expansion in some applications, including road construction and concrete production [7,8].

The aim of this paper is to assess the environmental impacts of municipal solid waste incineration (MSWI) BA treatment, by applying the Life Cycle Assessment (LCA) methodology. The study includes the recycling of the metal scraps, as well as that of the mineral fraction. Regarding this, five different applications were considered: in clinker production, in concrete production, in bituminous conglomerate production and in road construction, the latter in the two alternatives of use in the embankment or in the sub-base layers. The study was carried out according to the ISO 14040 [9] and 14044 [10] standards and the Product Environmental Footprint - PEF Guide [11]. The SimaPro software (version 8.4) supported the data processing.

2. Materials and methods

2.1. Goal and scope definition

In the studied system, the BA is processed in dedicated plants which operate in dry conditions (i.e. without intensive use of water), with the aim of separating the metal scraps from the mineral fraction and to send both to recycling. BA is previously aged to reduce its moisture and improve its quality in view of the following treatments. Then, it is subjected to several steps of sieving and grinding in order to liberate the metals scraps trapped inside the mineral conglomerates and to obtain homogeneous size classes. Downstream these preparatory treatments, the BA is subjected to the actions of magnets and eddy current separators for metal recovery. Ferrous and non-ferrous metal scraps are sent to recycling, while the mineral fraction can be used as a substitute of natural materials in several applications, eventually after a washing treatment to reduce its content of salts. Five possible scenarios were considered in the LCA study:

- Scenario CLINKER: the mineral fraction is used in the production of the raw meal in substitution of the calcareous marl;
- Scenario CONCRETE: the mineral fraction is used in concrete production in substitution of natural gravel;
- Scenario BITUMINOUS CONGLOMERATE: the mineral fraction is used in the bituminous conglomerates production in substitution of natural sand;
- Scenario ROAD A: the mineral fraction is used in the construction of a road embankment in substitution of natural gravel;
- Scenario ROAD B: the mineral fraction is used in the construction of a road sub-base in substitution of natural mixed material from quarry.

The aim of this LCA study is to assess the environmental impacts of the described BA treatment, in order to understand if the benefits associated with the material recovery are able to compensate the burdens due to the treatment itself. Moreover, the LCA is carried out to understand the relative contributions to the eventual benefits of the metals recycling and the mineral fraction recycling. The function of the analysed system is thus the treatment of the BA and the functional unit was defined as 1 tonne of BA treated in an “average” BA treatment plant located in the North of Italy. The system was in fact modelled mainly on the basis of primary data gathered during field visits to three treatment plants located in northern Italy: by averaging such data, we have defined an “average plant”. If primary data were not available, the literature or the ecoinvent 3.3 database were used (in this case adopting the cut-off approach or allocation recycling content approach for the modelling [12]).

The system boundaries (Fig. 1) include:

- the treatment of the bottom ash;
- the disposal of the residues and the treatment of the wastewater produced by the cleaning operations of the service areas, by the dust emission control and by the washing of the mineral fraction (if required);
- the upgrading of the ferrous metals and their recycling;
- the upgrading of the non-ferrous metals and the copper recycling;
- the recycling of the mineral fraction, considering the five possible applications previously described.

The system boundaries, also, include the transport of the BA from the incineration plant to the treatment plant, that of the metal scraps to the upgrading plants and the next recycling plants, the transport of the mineral fraction to recycling and finally the transport of all the chemicals used in the process.

The study adopted the "zero burden assumption" [13], i.e. the BA enters the system without carrying any environmental burden. In addition, cases of multi-functionality were solved by expanding the system boundaries to include the corresponding avoided primary productions [14; 15]. They are the inert natural materials that can be saved because of the recycling of the mineral fraction of BA, and primary steel, Al99.7 and copper thanks to the recovery of the metal scraps.

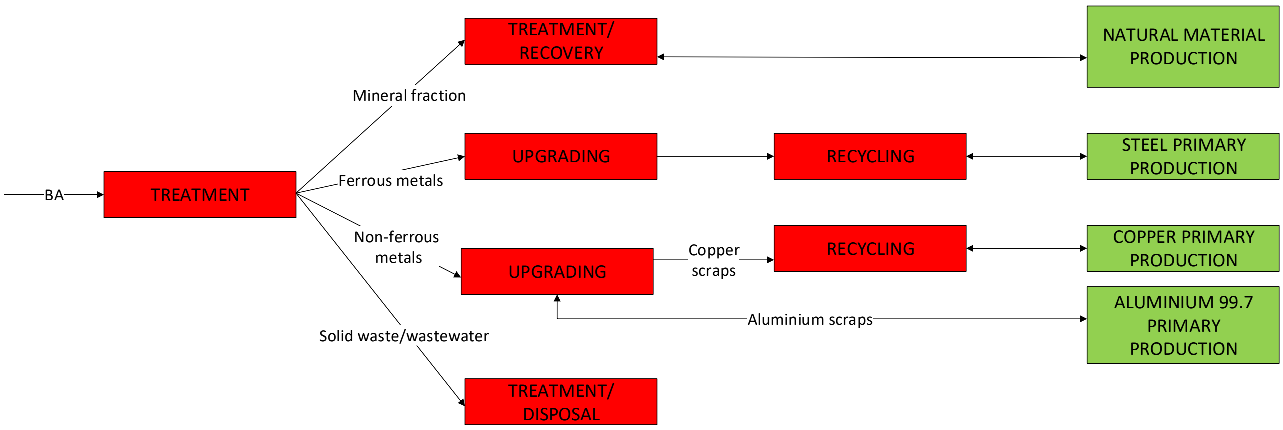

Fig.1 Main activities included in the system boundaries

The geographical scope of the study is the north of Italy, where most of the WTE and BA treatment plants are located, while the timeframe is the years 2013-2016.

Five environmental impact categories were considered: *climate change*, *ozone depletion*, *photochemical ozone formation*, *particular matter* and *acidification*. They were calculated on the basis of the characterization models reported in the Product Environmental Footprint (PEF) guide [11]. In this first part of the project, the *human toxicity*, *ecotoxicity* and *eutrophication* impact categories were not included because leaching tests to assess the release of metals and salts associated with the use of the BA mineral fraction in the five applications are still ongoing. The *water resource depletion* indicator, as defined by the PEF guide, was not included in the study because it has still some problems of implementation and thus it was not considered completely reliable. The *mineral resources depletion* indicator as defined by the PEF guide was also excluded from the study because it does not consider the consumption of sand and gravel, which are unmapped flows. Due to the importance of considering the sand and gravel consumption in the studied system, a *mineral resources* *depletion* indicator was tailored built from the SimaPro inventory to quantify the consumption/saving of natural minerals. Finally, also the *land use* and the *ionizing radiation* indicators were not included because primary data about these aspects were not collected. In addition to the impact categories suggested by the PEF guide, the *cumulative energy demand* indicator was evaluated as proposed by Hischier et al. [16].

2.2. Inventory

2.2.1. BA treatment plant

The representative average BA treatment process is shown in Fig. 2. Based on the data collected from three treatment plants, on average the treatment of 1 tonne of BA results in the recovery of 78 kg of ferrous scraps, 19 kg of non-ferrous scraps and 870 kg of minerals. In addition, 25 kg of unburned waste are separated and sent back to incineration, while 8 kg of water is evaporated during the process. The average energy consumption of the plant is around 7.4 kWh per tonne of BA sent to treatment, and 0.32 m^3 of water are consumed for washing the pavement of the service areas, for controlling dust emissions and for washing the mineral fraction aimed at salts removal, when this is applied.

The wastewater generated by the process (0.13 m^3/t of BA) is delivered to a physical-chemical treatment plant located within the site, and then discharged in the public drainage system and further treated in a biological treatment plant. The treatment of 1 m^3 of wastewater in the dedicated physical-chemical plant requires 0.16 kg of a cationic polyelectrolyte, 0.2 kg of ferrous sulphate and 0.037 kg of soda. The energy consumption of the physical-chemical wastewater treatment plant is included in the energy consumption of the BA treatment plant.

For what concerns the transport, an average distance of 100 km was assumed for both the delivery of BA from the incineration plant to the treatment plant and the delivery of chemicals to the BA treatment plant.

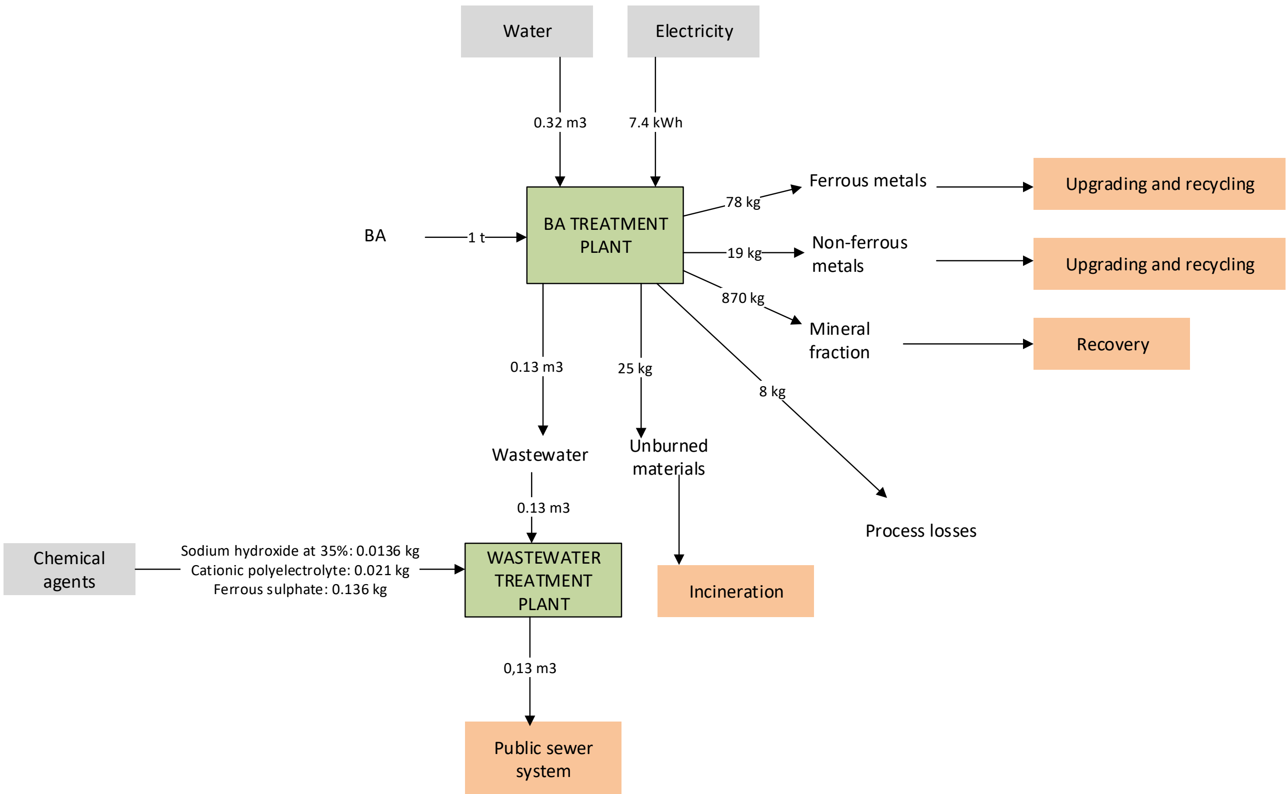

Fig.2 Representative average BA treatment process modelled in the study

2.2.2. Recovery of the metal scraps

Metal scraps separated from the BA are sent to upgrading plants to improve their quality before recycling.

The ferrous metal scraps are intensively milled to remove the mineral impurities attached to the metal surface and to the oxidation layer, accounting for 50% of the scrap weight. From this process a material stream called "proler" is generated, which can be directly fed to the electric arc furnaces (EAF). The electricity consumption of the process is 40 kWh per tonne of proler. For what concerns the transport, it was assumed that the residues are disposed of in a landfill located 100 km away from the upgrading plant and the upgrading plant is also located 100 km away from the BA treatment plant.

The non-ferrous metal upgrading mainly consists in the separation of the aluminium from the heavy non-ferrous metals. The mass balance of the upgrading plant was defined on the basis of primary data. The non-ferrous scraps contain on average 2-3% of mineral residues that are removed during the upgrading process. The metals consist for 2/3 of aluminium and for 1/3 of heavy non-ferrous metals, of which 45% is copper. In absence of primary data, the electricity and diesel consumption reported in Allegrini et al. [6] for the Dutch context were assumed. The upgrading plant was assumed to be located 100 km away from the BA treatment plant, whereas the residues were assumed to be delivered to a landfill located 100 km away from the upgrading plant.

After upgrading, the scraps are sent to recycling. For the ferrous metals, it was assumed that the foundry is located 50 km away from the upgrading facility. Here, the proler is mixed with other ferrous scraps before being fed to the furnace. The efficiency of the recycling process was assumed equal to 88.1% as reported in Rigamonti et al. [17]. The substitution ratio between secondary and primary steel was calculated from the average composition of the charge reported by the World Steel Association [18] for the electric arc furnace and resulted equal to 1: 0.746 on weight.

For what concerns the aluminium scraps, they are sent to recycling in a foundry that was assumed to be located 50 km away from the upgrading plant, whereas the heavy non-ferrous metals are sent to recycling in plants located in norther Europe, 1000 km away from the upgrading plant. The recycling process of aluminium scraps was not included in the system boundaries, as suggested by Koffler and Florin [19]. The aluminium scraps, at the inlet of the furnace for the production of secondary aluminium, were assumed to substitute the unalloyed Al99.7 at the inlet of the alloying process. The substitution ratio was assumed equal to 1: 0.35 on weight, based on the price of the Al99.7 and of the old mixed scrap aluminium reported in [19].

The heavy non-ferrous metals are recycled in plants that treat copper-based scraps. The process results in the production of secondary copper and secondary precious metals. However, due to the absence of information about precious metals recycling, only copper recycling was included in the system boundaries, as suggested by Allegrini et al. [6]. The efficiency of the copper recycling process was assumed equal to 68% [6] and the substitution ratio between secondary and primary copper was assumed equal to 1:1 on weight.

The amounts of the metal scraps and of the secondary products resulting from the treatment of 1 tonne of BA are reported in Table 1, as well as the amount of avoided primary products.

Table 1 Amounts of metals scraps, secondary material and corresponding avoided primary material derived from the treatment of 1 tonne of BA

<table>
<tr><th>Metal scraps separated from the BA</th><th>Metal scraps after upgrading</th><th>Secondary material</th><th>Avoided product</th></tr>
<tr><td>Ferrous metal scraps:
78 kg</td><td>Ferrous metal scraps:
39 kg</td><td>Secondary steel:
34.4 kg</td><td>Primary steel:
25.6 kg</td></tr>
<tr><td rowspan="2">Non-ferrous metal scraps:
19 kg</td><td>Aluminium scraps:
12.4 kg</td><td>Aluminium scraps:
12.4 kg</td><td>Ingot of Al99.7:
4.3 kg</td></tr>
<tr><td>Heavy non-ferrous metal scraps:
6.1 kg
of which, copper:
2.7 kg</td><td>Secondary copper:
1.87 kg</td><td>Primary copper:
1.87 kg</td></tr>
</table>

2.2.3. Recovery of the mineral fraction

In the scenario CLINKER, the mineral fraction of the BA is used in clinker production substituting calcareous marl (3.2 kg of calcareous marl are avoided per each kg of mineral material from the BA). However, due to the lower content of $CaCO_3$, an additional amount of limestone must be used in the clinker production (2.2 kg of limestone per kg of mineral material from the BA), as reported in Grosso et al. [20].

In the scenario CONCRETE, the BA mineral fraction is used as a substitute of natural gravel in concrete production. The substitution ratio between the two materials is 1:1 in weight. However, in order to be used in this application, the BA must be previously washed with water with the aim of reducing its salts content. Since the water consumption of the BA treatment plant was provided as an aggregate data (as the sum of all the water consumptions of the plant), it was not possible to separately account for the water consumption of the sole washing process.

In the scenario BITUMINOUS CONGLOMERATE, the BA mineral fraction is used in bituminous conglomerates production, replacing natural sand. The substitution ratio between the two materials is 1:1 in weight [21].

In the scenarios ROAD A and ROAD B, the BA mineral fraction is recycled in road construction. Depending on its quality, the mineral material can be used in substitution of natural gravel in the realization of a road embankment layer, or in substitution of the natural mixed material from quarry in the realization of a road sub-base layer. For both scenarios, the substitution ratio between the BA mineral fraction and the gravel/natural mixed material from quarry is 1:1 in weight [22]. However, an addition of cement (2.04% of the weight of the BA mineral fraction) is required to guarantee the same technical properties of the natural raw materials.

The modelling of the avoided production of natural materials (i.e. sand, gravel and natural mixed material from quarry) was based on Borghi et al. [22].

For what concerns the transports, for all scenarios a 100 km distance was assumed between the BA treatment plant and the recycling site, while the avoided natural raw materials are extracted from quarries located only 40 km away from the recycling site.

3. Results and discussion

3.1. Impact assessment

The results of the study are reported in Fig. 3. Regardless of the considered scenario, the treatment and recovery of the BA turns out to be beneficial for the environment. The main benefits are associated with metals scraps recovery, whereas the recycling of the mineral fraction determines additional burdens to all the considered impact categories and also to the CED indicator, with the only exception of the CLINKER scenario. On the contrary, for what concerns the *mineral resources depletion* indicator, for all scenarios the treatment and recycling of 1 t of BA allows to save more than 800 kg of natural resources. The main benefits are associated, in this case, with the recycling of the mineral fraction and the consequent saving of gravel and sand for the scenarios CONCRETE, BITUMINOUS CONGLOMERATE and ROAD A and B, and of calcite and clay for the scenario CLINKER.

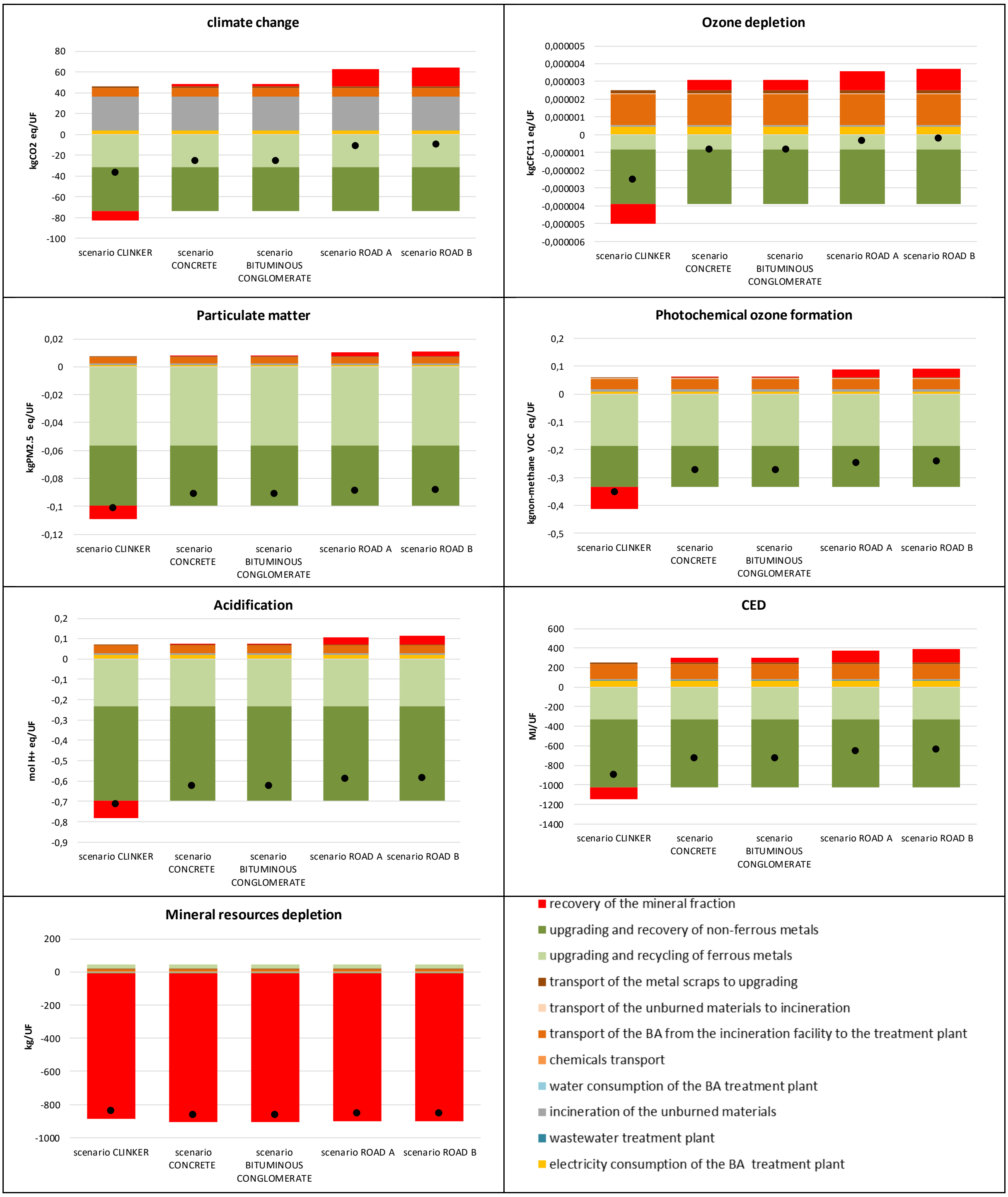

Fig. 3 Environmental impact indicators calculated for the treatment of 1 tonne of BA including the recovery of the metal scraps and of the mineral fraction

Focusing on the recycling of the mineral fraction, the best application is in the clinker production, in substitution of the calcareous marl (Fig. 4). In fact, the avoided production and transport of the marl more than compensate the impacts associated with the production of the additional amount of limestone required when BA is used, as well as of its transport and that of the BA. With the exception of the *mineral resources depletion* indicator, using the BA mineral fraction for road construction or concrete production results in additional burdens to the environment. The benefits associated with the avoided extraction of natural sand and gravel are, in fact, not sufficient to compensate the burdens of the BA treatment process and of the transport. The difference among the scenarios can be explained by the fact that the marl production implies environmental burdens greater than those associated with the gravel and sand production. Moreover, the use of BA for road construction requires the addition of cement (Fig. 4), whose production is responsible for potential environmental burdens much greater than those associated with the production of the natural raw materials.

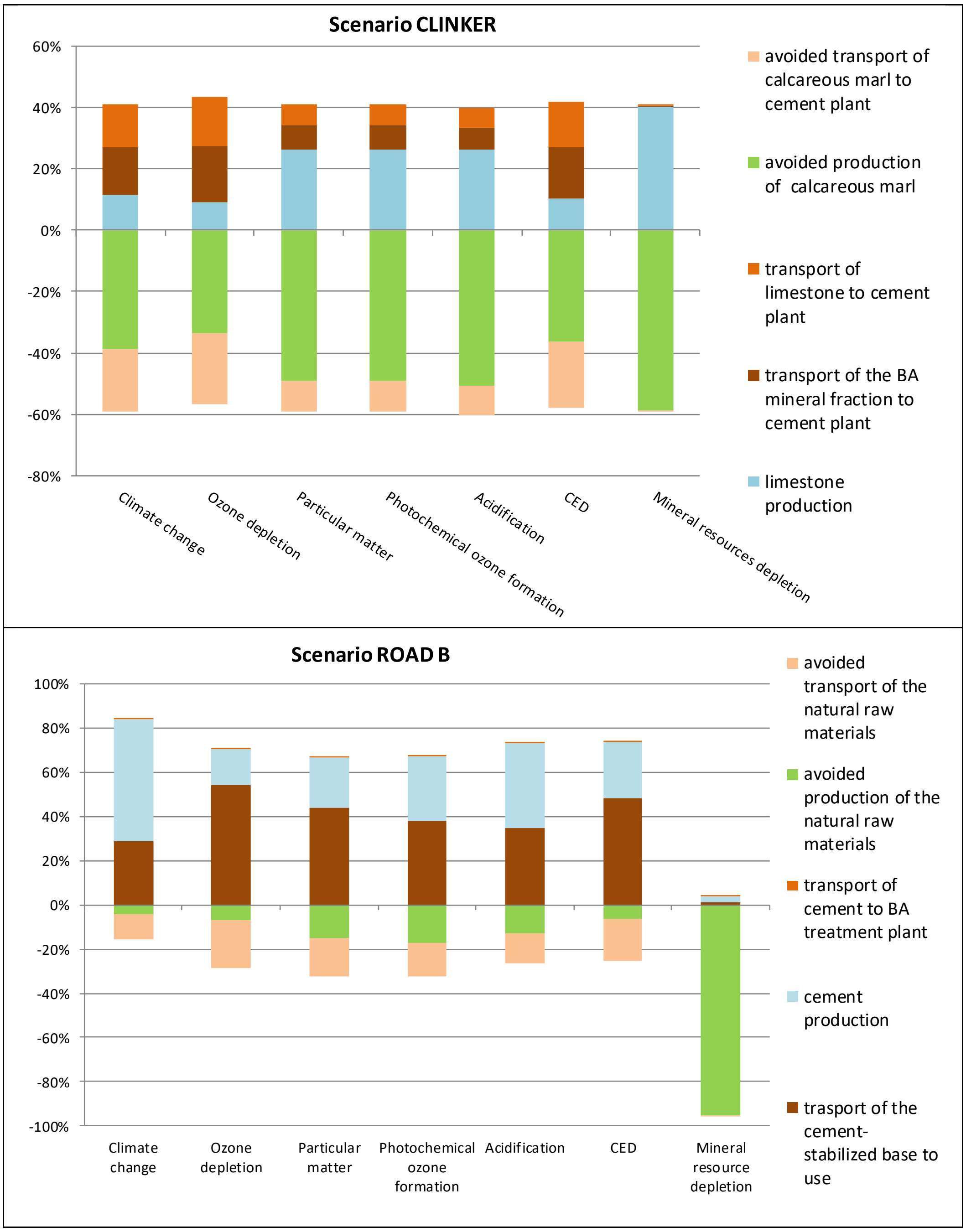

Fig. 4 Analysis of the contributions related to the use of 1 kg of mineral fraction recovered from BA for scenarios CLINKER and ROAD B

Focusing on metals recovery (Fig. 5), for what concerns the ferrous metals, the main burdens are associated with the disposal of the powder generated during the upgrading process, whereas the impacts associated with the energy consumption of the upgrading process are negligible. The main benefits are associated with the proler recycling. Despite about 50% of the mass of the ferrous scraps is lost during the upgrading process, the benefits of the avoided production of primary steel more than compensate the burdens for the disposal of the powder, with the only exception of the *mineral resources depletion* indicator (due to the fact that the powder is landfilled after inertization with addition of cement). For what concerns the non-ferrous metals, the impact of the upgrading process are negligible compared to the benefits of the avoided production of primary copper and Al99.7.

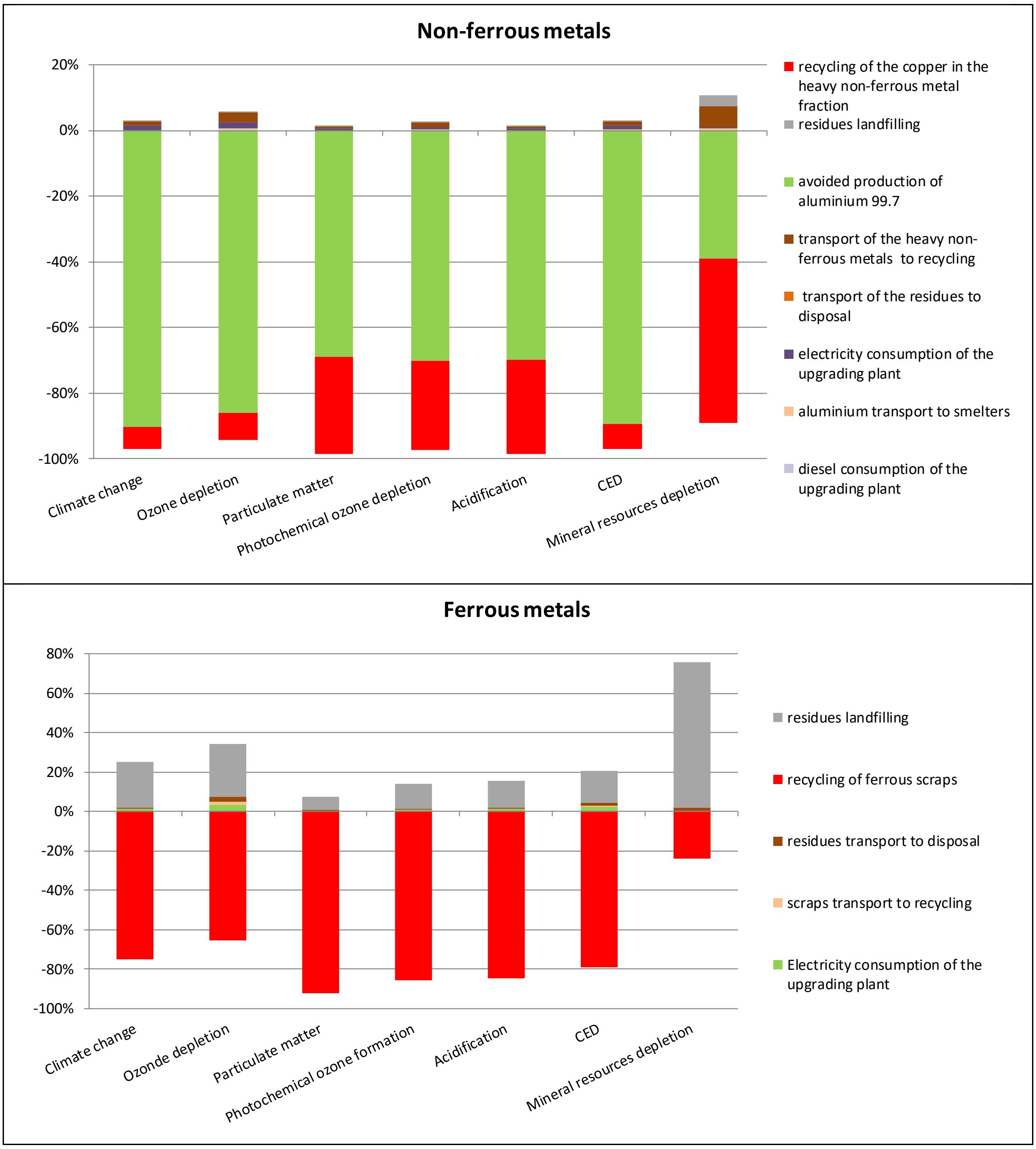

Fig. 5 Analysis of the contributions related to the upgrading and recycling of the metal scraps recovered from the BA

3.2. Sensitivity analysis

Since the impacts associated with the transports are not negligible, two sensitivity analyses were performed to assess the influence on the LCA results of the transport of BA from the incineration plant to the treatment plant and of the mineral fraction to the recycling site.

In the first sensitivity analysis, the distance between the incineration plant and the BA treatment plant, assumed equal to 100 km in the baseline scenario, was changed, ranging from 0 to 350 km. The performance of the system obviously gets worse with increasing distances, but overall the BA treatment and recovery still remains beneficial for all the considered indicators, except for the *ozone depletion* impact indicator when the distance exceeds 110 km.

In the second sensitivity analysis, the distance between the BA treatment plant and the place where the mineral fraction is recycled (equal to 100 km in the baseline scenario) was changed, ranging from 0 to 100 km. Focusing only on the recovery of the BA mineral fraction, scenarios ROAD A and ROAD B result beneficial for the impact categories *ozone depletion*, *particular matter and photochemical ozone formation* only if the BA mineral fraction is recycled close to the BA treatment plant (Fig. 6). For the impact categories *climate change* and *acidification* and for the *CED* indicator, the recycling of the BA for road construction results always not beneficial, regardless of the distance. For what concerns the scenarios CONCRETE and BITUMINOUS CONGLOMERATE, the maximum distance for which the BA mineral fraction recycling results beneficial for the environment is 60 km.

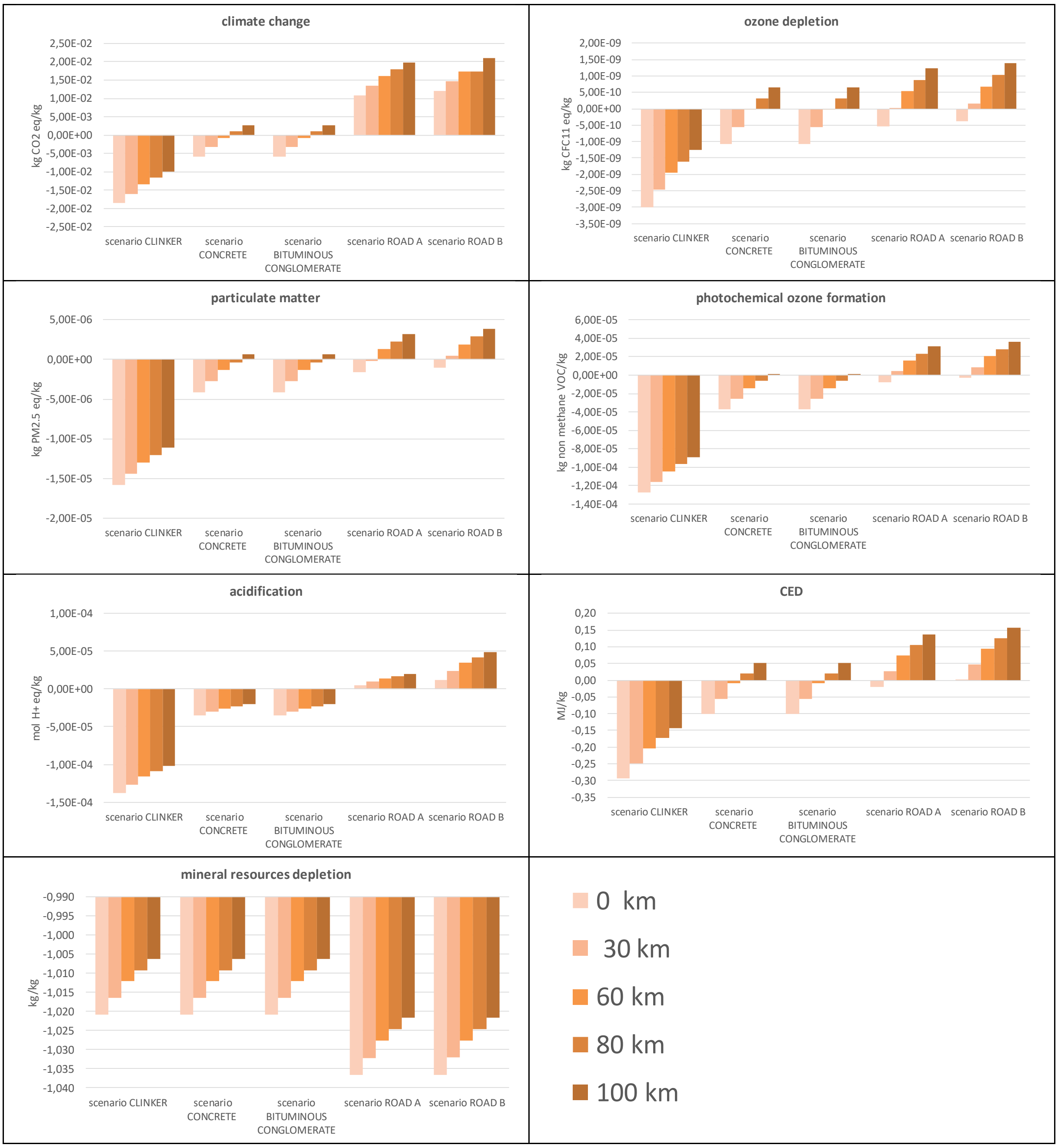

Fig. 6 Environmental indicators calculated for 1 kg of mineral fraction used in the five applications as a function of the distance between the BA treatment plant and the site of use

4. Conclusions and recommendations

The study has quantified the environmental burdens and savings associated with the treatment of waste incineration bottom ash, including the recovery of the metals scraps separated during the process and the recycling of the mineral fractions, by adopting an LCA approach. Five options were considered for the recycling of the mineral fraction: in clinker production, in concrete production, in bituminous conglomerate production and for road construction (in the embankment or in the sub-base layer).

Regardless of the fate of the mineral fraction, the BA treatment results beneficial for all the considered impact indicators, as well as for the CED indicator. The main benefits are associated with the recovery of the metal scraps, both ferrous and non-ferrous, whereas the main burdens are associated with the transport of the BA to the treatment, with the incineration of the unburned materials and, with the exception of the scenario CLINKER, with the recycling of the mineral fraction. For what concerns the tailored indicator *natural resources depletion*, for all the five scenarios, the BA treatment allows to save more than 800 kg of natural resources per tonne of BA sent to the treatment.

Focusing on the recycling of the mineral fraction, the best utilisation option is in the clinker production, replacing the calcareous marl. With the exception of the *mineral resources depletion* indicator, using the BA mineral fraction for road construction or in concrete or bituminous conglomerate production results in additional burdens to the environment. The main burdens are associated with the transport of the mineral fraction to recycling. By reducing the distance between the BA treatment plant and the place where the mineral fraction is recycled to below 60 km (in the baseline scenario it is 100 km), the treatment and recycling of the BA would become beneficial also when the mineral fraction is used in concrete or bituminous conglomerate production. On the contrary, recycling the BA in road construction is always not beneficial, even if the impacts associated with the transport are neglected.

Based on these results, it is thus evident the importance of recovering the metal scraps. The BA treatment plant should then be designed in order to maximize the recovery of ferrous and non-ferrous metals.

Furthermore, the results suggest the importance of a correct siting of the BA treatment plants, which should be located within 100 km from the incineration plants which provide the BA and as close as possible to the potential users of the mineral fraction.

Finally, it is necessary to point out that the results presented in this study are partial, since the impacts associated with the human toxicity impact categories and the eutrophication category have not been calculated yet. The importance of including the human and environmental toxicity indicators in the assessment of the environmental performance of a system has been widely demonstrated in all those situations that imply the direct contact of a waste with the environment [6].

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