Journal of Hazardous Materials 159 (2008) 505–511

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Environmental impacts of waste incineration in a regional system (Emilia Romagna, Italy) evaluated from a life cycle perspective

Luciano Morselli*, Claudia De Robertis, Joseph Luzi, Fabrizio Passarini, Ivano Vassura

Dipartimento di Chimica Industriale e dei Materiali - Università di Bologna, viale Risorgimento 4, 40146 Bologna, Italy

ARTICLE INFO

Article history:
Received 6 July 2007
Received in revised form 19 February 2008
Accepted 19 February 2008
Available online 23 February 2008

Keywords:
Waste management
Incineration plant
Solid residues
Life Cycle Assessment
Heavy metals

ABSTRACT

The advisability of using incineration, among the other technologies in Municipal Solid Waste Management, is still a debated issue. However, technological evolution in the field of waste incineration plants has strongly decreased their environmental impacts in the last years. A description of a regional situation in Northern Italy (Emilia Romagna Region) is here presented, to assess the impacts of incinerators by the application of Life Cycle Assessment (LCA) methodology and to stress the most impacting steps in incineration process. The management of solid residues and heavy metal emission resulted the most important environmental concerns. Furthermore, a tentative comparison with the environmental impact of landfill disposal, for the same amount of waste, pointed out that incineration process must be considered environmentally preferable.

1. Introduction

In the last few years a "methodological shift" occurred in environmental subject approach; the onset of global issues and the progressive local worsening led to re-examine the environment in its whole complexity. Attention widened from problems and possible end-of-pipe intervention in productive processes, towards an integrated approach. In this context, preventive measures become a priority, with the main target of a drastic reduction in resource and energy consumption, and in pollutant emissions to air, water and soil.

From this point of view, the definition of reliable procedures for environmental impact assessment is becoming more and more necessary, in order to estimate every human activity in terms of resources consumption and emissions. One of the most useful procedures for a potential environmental impact evaluation is the Life Cycle Assessment (LCA) procedure, which is standardized by the ISO 14040 [1] series of standards and sanctioned by the UNI EN ISO 14040 regulations in Italy [2].

Recently this methodology, which was initially designed for the environmental impact assessment of products, was further developed for a wide range of applications. Among the others, as for waste management activities and strategic planning: landfills [3], end-of-life of specific product categories [4–6], incineration [7–10], liquid waste treatment [11,12], general waste management [13–16].

LCA methodology applied to integrated waste management systems shows a great development potential, specially as a support tool for decision making, useful for institutional planners and multiservice companies (dealing with waste recovery, recycling and disposal). Indeed, LCA allows the comparison of different technological options and the assessment of different waste management scenarios [17].

The aim of this work is the identification of the most important environmental impacts due to incineration plants operating in Emilia Romagna Region and the most significant pollutants which can be chosen as environmental indicators, applying the state-of-the art of LCA methodology to a waste incineration process. Furthermore, a tentative comparison between the environmental impact due to the Municipal Solid Waste (MSW) incinerated in 2004 and that ascribable to the landfill disposal of the same amount of waste is carried out, to highlight the greater advantages (due to the lower impacts) coming from incineration rather than landfill, from an environmental point of view. Life cycle perspective, indeed, could be particularly useful from a social point of view, when local government must implement waste management choices in the desirable framework of an interested civil participation.

2. Experimental

Regional incineration plants differ for the abatement technologies of gaseous pollutants, age and operating waste capacity. The age of the plants (7 in all) varies between 3 and 30 years, with an operating capacity from 15,000 to 150,000 t/y, raising a total of about 580,000 t/y of burnt waste. The newest plants use a

* Corresponding author. Tel.: +39 051 2093668; fax: +39 051 2093863.
E-mail address: luciano.morselli@unibo.it (L. Morselli).

0304-3894/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2008.02.047

completely dry flue gas abatement equipment, while the other incinerators employ hybrid wet–dry technologies, even if some wet abatement devices have been converted to the sole function of decreasing temperature of gaseous emission.

When a LCA is applied to waste management system, the system boundaries are generally comprised between the moment in which the waste enters the plant and that in which waste vanishes dispersing in the environment as emissions in air, water and soil. Energetic and environmental burdens associated to waste collection are not included in this study, because these considerations would lead beyond the aims of this study.

An inventory of input and output flows has been defined referring to the studied system (Fig. 1); input ones include, in aggregated form, as in a unique regional network, the sum of mass and energy flows relating to building, maintenance and operation of each regional incineration plant. In particular, for plant working, the issues considered are: natural resource consumption, as water; auxiliary substance consumption, as oil and/or natural gas fuels used in post-combustion chamber, and additives for flue gas and wastewater treatment.

Output flows are the total amount (as before, coming from all the different plants which form the regional network) of solid residues of incineration process which are disposed as are or previously made inert, pollutants remaining also after the control and abatement equipment, the energy produced, and, when present, the energy recovery associated to district heating.

This study has been performed by using SimaPro 6.0 LCA Software (PRé Consultants, NL), implemented, when necessary, with Data Base I-LCA ANPA 2000 [18] and with ad hoc models to better characterize Italian situation, and in particular that of Emilia Romagna Region. For the environmental impact assessment (the LCIA phase), Eco-Indicator'99 method has been chosen [19].

Impact Assessment is a crucial step of LCA, in which the most relevant environmental issues are identified and each input or output flow is transformed in a contribution to these issues. During this process, defined as characterization, inputs and outputs have been distributed and aggregated in the selected impact categories, on a local, regional or global scale, and multiplied for a coefficient named characterization factor, which indicates the amount of the potential contribution of the single substance to the overall effect [20]. For example, the amount of greenhouse gases, emitted in the process, can be referred to CO_2-equivalent releases by multiplying them for their Global Warming Potential, and the final result to the category Climate Change can be calculated by summing all the single contributions. Other units adopted by the software to transform the various contributions in the characterization step, are: g H^+-equivalent (for air acidification), g PO_4^{3-}-equivalent (eutrophication), g C_2H_4-equivalent (photochemical oxidant formation), g CFC11-equivalent (ozone layer depletion), g 1–4 $C_6H_4Cl_2$-equivalent (toxicity in different compartments).

An aggregation of the different environmental effects in few damage categories, based on the analysis of impacts deriving from the exposure to definite effects (releases or consumptions), is then performed according to Eco-Indicator'99 method. Thus, damage assessment can be divided in three categories: Human Health, Ecosystem and Resources, which synthetically describe the influence of the investigated processes on the environment, summarizing the information of different impact categories, as synthetically showed in Table 1 [19].

The following normalization and weighting process, aimed to express all environmental impacts with a single indicator, with a unit of measurement expressed in Pt, is performed by the software according to the Egalitarian perspective, which is the most conservative one; in it, the chosen time perspective is extremely long-term, and substances are included even if there is just an indication (not necessarily a consensus) regarding their environmental effects [20].

Finally, in order to observe the differences in environmental impacts for the same amount of MSW, treated (as in our case) by a network of incineration plants, or disposed in landfill, a comparison was made by using, for the latter process (disposal) data contained in the database of SimaPro 6.0. This is considered to simulate all the input and output flows of an average landfill as managed in Europe (and thus, it can be assumed, also in Italy); then, for the purpose of making a preliminary comparison, even considering the difference in quality between these data and those referring to incineration plants (for which we collected direct measures and primary data), the scores associated to the impact categories, in both cases, were calculated.

3. Results and discussion

In Tables 2 and 3, respectively, pollutants monitored in continuous, and heavy metals, PAH and PCDD/F emitted in the atmosphere, are reported, while Table 4 shows electric and thermal energy recovery, all referring to the entire regional incineration network.

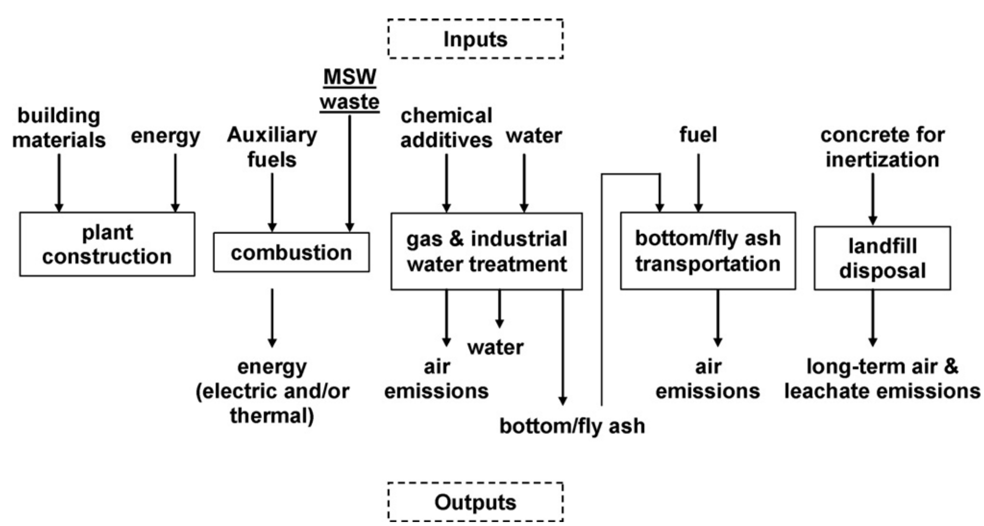

Fig. 1. Input and output flows in the studied system.

Table 1
Damage and impact categories, defined according to the followed Eco-Indicator'99 method (PRé Consultants [19])

Damage categories	Impact categories
Human Health. Unit of measure: DALY[a]	- Carcinogenesis (cancer cases and type) - Respiratory effects (caused by organic substances) (cases and type) - Respiratory effects (caused by inorganic substances) (cases and type) - Climate Change (diseases and displacement) - Ozone layer depletion (cancer and cataract) - Ionizing radiation (cancer cases and type)
Ecosystem quality	- Acidification/eutrophication
Unit of measure: (PDF) m^2 y[b]	- Ecotoxicity - Land use
Resources. Unit of measure: MJ surplus[c]	- Depletion of minerals - Depletion of fossil fuels

[a] Disability adjusted life years (DALY). A damage of 1 means: 1 life year of 1 individual is lost, or 1 person suffers 4 years from a disability with a weight of 0.25.

[b] Potentially Disappeared Fraction (PDF) m^2 y. A damage of 1 means that all species disappear from 1 m^2 during 1 year, or 10% of all species disappear from 10 m^2 during 1 year, or 10% of all species disappear from 1 m^2 during 10 years.

[c] MJ surplus: A damage of 1 means that, due to a certain extraction, further extraction of this resource in the future will require one additional MJ of energy, due to the lower resource concentration, or other unfavourable characteristics of the remaining reserve.

Table 2
Average concentration, mass flows and emission factors of main pollutants from Emilia Romagna incinerators

Parameters	Average concentrations (mg/N m^3)	Mass flows (kg/y)	Emission factors (kg/t burnt waste)
Total particulate	2.65	1.25×10^4	2.16×10^{-2}
CO	10.9	4.90×10^4	8.44×10^{-2}
HCl	3.82	1.81×10^4	3.12×10^{-2}
NO_2	171	7.47×10^5	1.29
SO_2	9.81	4.27×10^4	7.35×10^{-2}

Emission factors are calculated by dividing the total emission for the t of burnt waste.

As for LCIA, in the damage category identified as "Human Health" (Table 5), a damage of 481 DALY is obtained (as previously described). This means that the incineration of 580,000 t of MSW is estimated to provoke a potential loss of 481 life years, apportioned on the entire European population. Of these, 277 lost years are ascribed to the process of bottom ash disposal, i.e. this damage is bound to a future and possible contamination of soil and groundwater (in a very long perspective), due to the loss of non-gathered percolate in the subsoil; other 155 lost life years are attributable to air emission from the plants; finally, 116 years are lost due to the flue gas treatment, almost totally ascribable to fly ash disposal (for the same reasons exposed for bottom ash).

Table 4
Energy production by the whole incineration network in Emilia Romagna

Annual electric energy production	Annual thermal energy production
155,000 MWh	65,000 Gcal

It is interesting to reflect upon the fact that the most part of impacts to Human Health is given by the landfill disposal of waste incineration residues (bottom and fly ash), mainly due to the release in soil and groundwater of toxic substances, in a long-range perspective; on the contrary, direct emissions, which represent the most common cause of concern, are estimated to contribute only for about one-third.

The 67 years of difference between the sum of the single terms and the final result are due to energy recovery.

Energy recovery, indeed, leads to the introduction of a typical LCA concept, i.e. the "avoided" impact or damage: the energy gained from the combustion of solid waste, converted in thermal or electric energy, avoids the consumption of fossil fuels and the emission of pollutants from power plants, for an equivalent energy amount. In order to consider the environmental impact of the energy production with ordinary plants, the energetic mix used in Italy has been taken into account, estimated as follows: carbon (10%), fuel oil (50%), natural gas (20%), hydroelectric (18%) and others renewable (2%), the average efficiency being about 25% [21].

A similar description for the damage category "Ecosystem Quality" can be done. The unit of measurement in this case is (PDF) m^2 y, which means the possibility that species at risk of extinction disappear completely, due to habitat alteration. Also in this case, bottom ash disposal represents the main danger.

Finally, in the damage category "Resources", a net gain in environmental impact can be observed, i.e. a negative value in the scale of mass and energy consumption. In fact, MSW combustion by the incinerators examined lead to an avoided damage of $-8{,}5 \times 10^7$ MJ Surplus, which is the avoidance, expressed in energy consumption, of non-renewable resource depletion due to the production of the same amount of energy with traditional technologies.

As reported in Fig. 2, the damage of each phase of incineration process can be indicated as a percentage of the whole damage for the single category. It can be seen that bottom ash disposal contributes for about 50% to the damage category "Human Health", and for about 90% to the "Ecosystem Quality". In the damage category related to "Resources", a major contribution (apart from the negative one due to energy recovery) is also given by the transportation of incineration residues in landfill, due to the consumption of fuel by lorries (it must be reminded that the collection and transport of MSW to incineration plant is out of the boundaries of this LCA, but the final destination of incineration residues has to be considered).

The following step is the normalization and weighting process, to compare the three damage categories, previously expressed in different units. This process allows a better identification of the more impacting steps and elements in a global perspective. The unit resulting from normalization and weighting process is measured with a single score (Pt and multiples) (Fig. 3).

Table 3
Average concentration, mass flows and emission factors of heavy metals, PAH and PCDD/F (estimated calculating half of the detectable limit when it was below) from Emilia Romagna incinerators

Parameters	Average concentrations (mg/Nm^3)	Mass flows (kg/y)	Emission factors (g/t burnt waste)
Cd + Ti	4.66×10^{-3}	20.5	3.52×10^{-2}
Hg	1.41×10^2	75.1	0.129
As + Pb + Cr + Co + Cu + Mn + Ni + V + Sb + Sn	1.02×10^{-1}	567	0.976
PAH	33.9 g/Nm^3	155 g/y	0.267 mg/t
PCDD/F (I-TEQ)	3.7 g/Nm^3	18 g/y	0.032 mg/t

Table 5
Damage assessment calculation

Damage category	Units	Auxiliary combustion	Plant building	Emission	Energy production	Bottom ash disposal	Transport of ashes and sludge in landfill	Flue gas treatment	Total
Human Health	DALY	4.68×10^{-1}	7.37	1.55×10^{2}	-7.82×10^{1}	2.77×10^{2}	4.14	1.16×10^{2}	4.81×10^{2}
Ecosystem Quality	(PDF) m^2 y	2.90×10^{4}	2.23×10^{5}	5.97×10^{6}	-3.70×10^{6}	7.57×10^{7}	4.02×10^{5}	2.23×10^{6}	8.08×10^{7}
Resources	MJ surplus	5.61×10^{6}	1.79×10^{6}	0.00	-1.20×10^{8}	3.13×10^{6}	1.67×10^{7}	1.16×10^{7}	-8.50×10^{7}

Table 6
Characterization of impact associated with incineration and landfill carcinogens (units: DALY)

Substance	Compartment	Sub-compartment	Incineration	Landfill
Total—all compartments			355	532
Cadmium, ion	Water	Aquifer, long-term	194	503
Arsenic, ion	Water	Aquifer, long-term	155	24
Cadmium, ion	Water	River	0.273	3.38
Arsenic, ion	Water	River	0.254	1.26

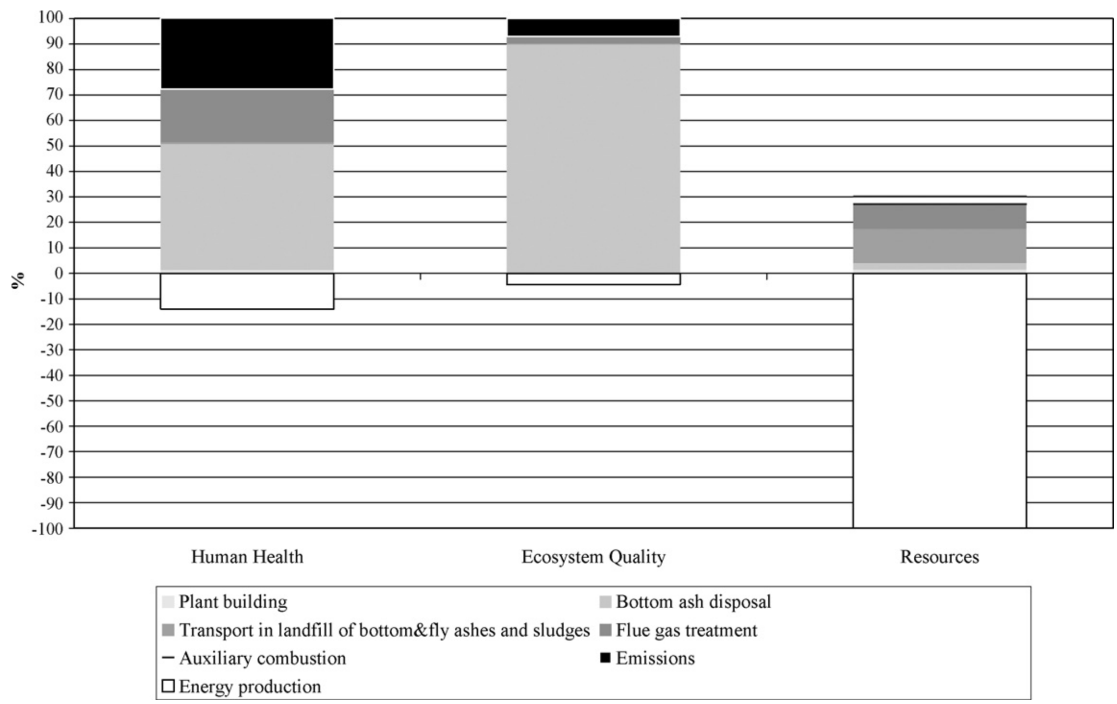

Fig. 2. Damage assessment histogram concerning the contribution of the different steps considered in MSW incineration.

As can be easily observed, the impact categories most affected by incineration process are those bound to the increase of potential carcinogenic species, of inorganic species which induce respiratory disease ("Respiratory inorganics"), of global warming gases, of toxics in the environment. But, again, the contribution due to the direct emissions from the stack is significant only for respiratory disease due to inorganic species, global warming and acidification/eutrophication phenomena. On the other hand, it is quite clear that the contribution, in particular, to the emission in the environment of carcinogens and species causing ecotoxicity, is due, again, to the landfill disposal of incineration residues and the following pollutant partition in soil, surface and groundwater.

A considerable "avoided consumption" can be noted for fossil fuels, as highlighted by the negative value of the white bar (which identifies energy recovery); avoided emission of "Respiratory inorganics" and of species affecting climate change are also evident.

Fig. 4 shows main contributions generating a positive or negative effect on the above-mentioned environmental issues, according to the single score calculation.

Cadmium, copper and arsenic ions, dissolved in water, represent the species which provoke the main damage. They are associated to the presence of carcinogenic and toxic substances in the environment, thus, as seen in Fig. 3, particularly due to the potential leachate loss from landfills (in a long temporal perspective), in which bottom and fly ashes are disposed.

Table 7
Characterization of impact of main substances producing Climate Change, for incineration and landfill (units: DALY)

Substance	Compartment	Incineration	Landfill
CO_2, fossil	Air	59.16	20.375
Methane, fossil	Air	−0.39	57.8
CO, fossil	Air	0.0713	0.00112

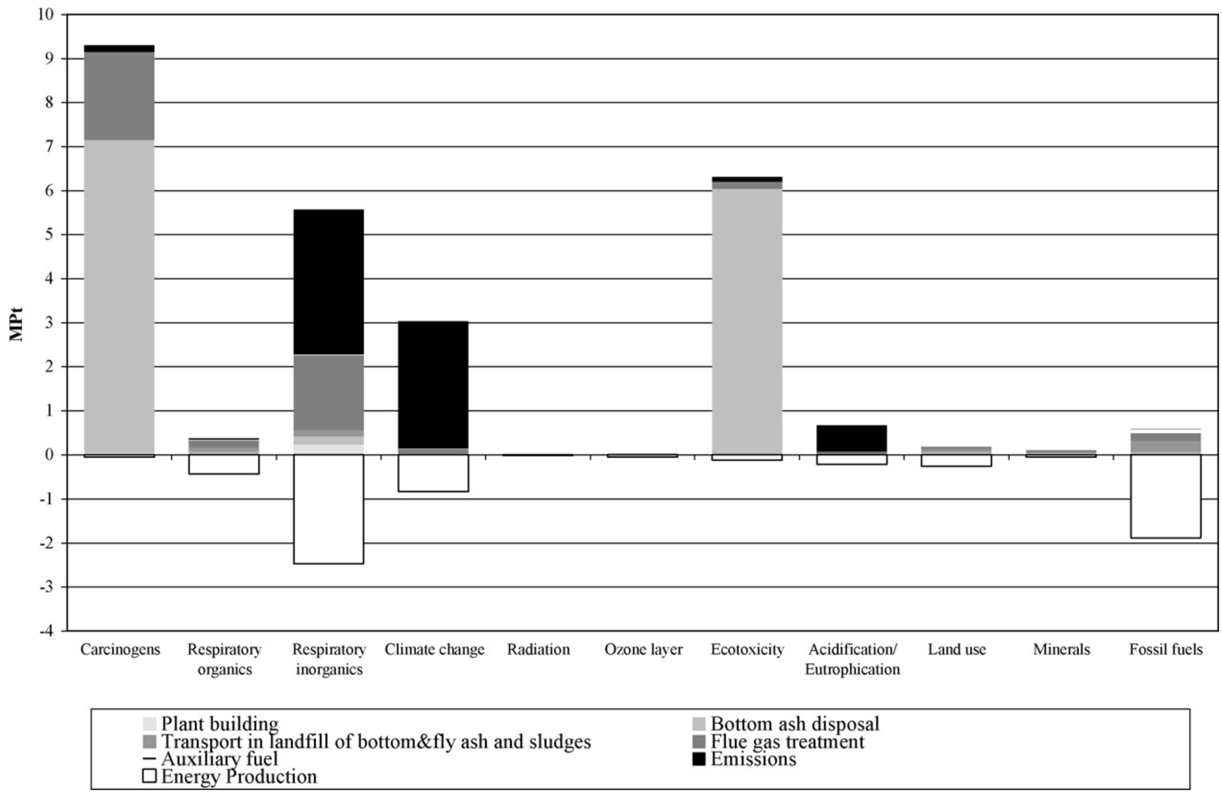

Fig. 3. Single score (Pt × 10^6) calculated for the various impact categories due to the contribution of the different steps in MSW incineration.

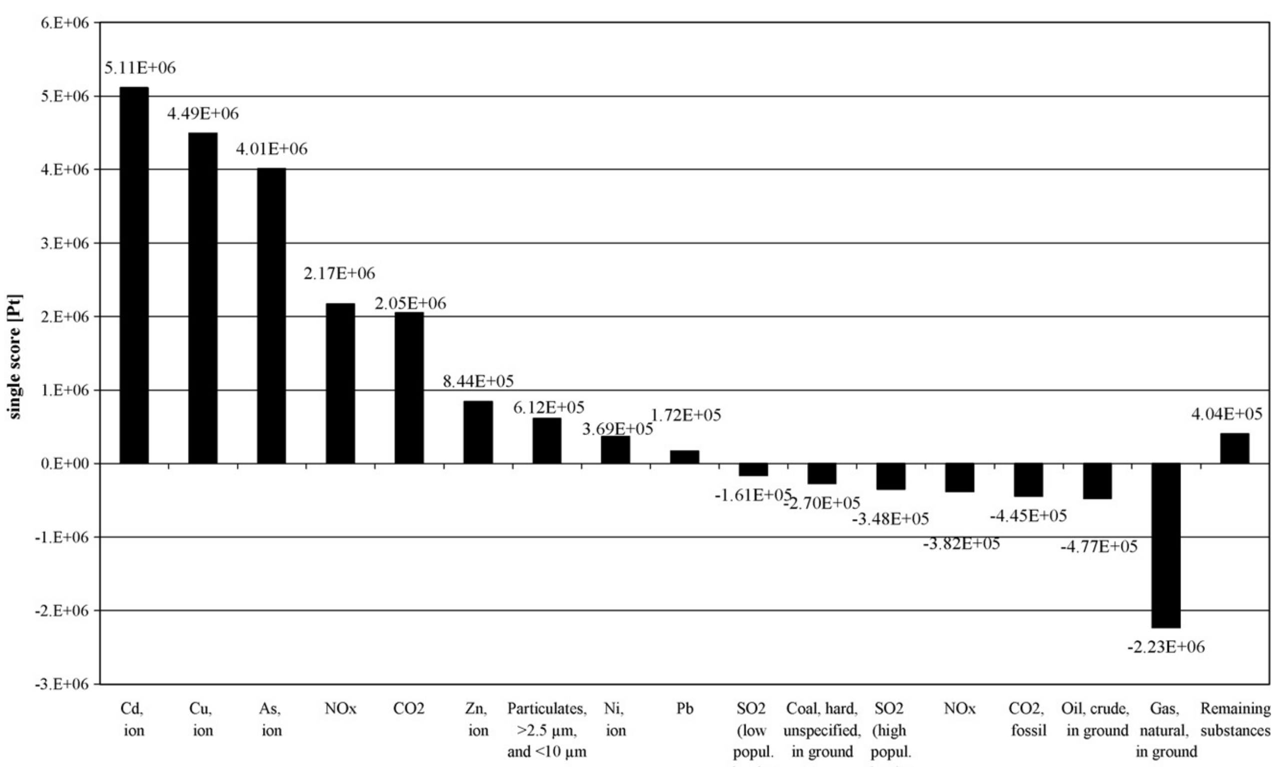

Fig. 4. Single score of environmental impact associated to the emission of pollutants (effective, or avoided due to energy recovery) and the consumption of fossil fuels (used and/or saved) relating to MSW incineration.

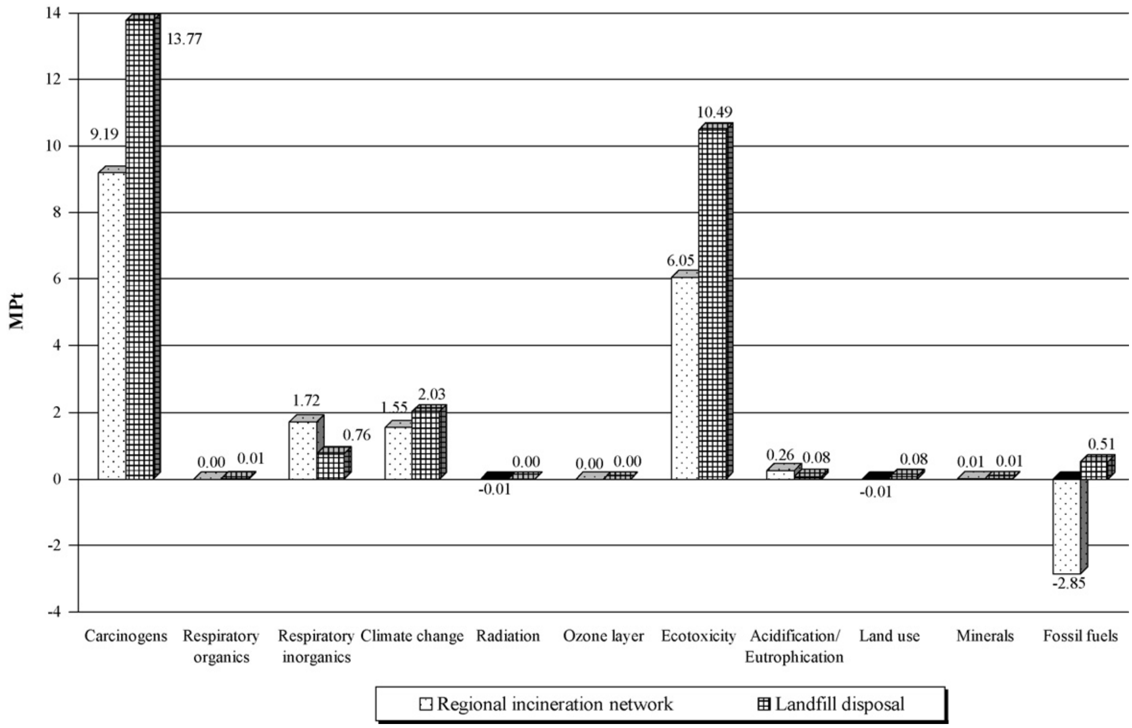

Fig. 5. Comparison between incineration and landfill disposal of the same amount of MSW using the single score for the various impact categories.

NO_x, CO_2 and PM_{10} are also important compounds which produce a significant impact on the environment, in this case associated to the direct emissions from incinerator stacks. Zinc, nickel and lead emissions complete the most important species with a positive score.

As for negative values, which represent avoided environmental impacts, savings of fossil fuels and associated emissions of CO_2, NO_x and SO_x show the greatest values.

Finally, the tentative comparison between MSW incineration and landfill disposal gave the results which can be summarized as in Fig. 5: the impact categories most affected by landfill disposal result Carcinogens, Respiratory inorganics, Climate Change, Ecotoxicity and Fossil Fuel consumption.

It is possible to note, for example, how the impact associated to carcinogen emission is higher in landfill disposal, both for cadmium and arsenic (Table 6), elements which can be found in the formulation of many varnishes (Cd), and in some wood treatments (As), and which can concentrate in landfill leachate if MSW is directly disposed in it.

In the “Respiratory inorganics” category results, as logical, a greater damage associated to incineration process, particularly ascribable to NO_x emission, which is emitted from landfill in a much lower extent (due to biogas combustion).

In the case of “Climate Change” category, instead, the two processes impact in different ways (see Table 7): incineration produce high CO_2 amounts due to the combustion, while landfill emits lower CO_2 but remarkable CH_4 quantities, highly significant in producing climate changes.

Even in the “Ecotoxicity” category, landfilling is more impacting than incineration, especially due to the dispersion in groundwater of heavy metals present in non-gathered leachate. Finally, since the ratio between MJ of energy produced and t of MSW managed by the two processes is not comparable, the avoided impact associated to the non-use of fossil fuels is much higher in the case of incineration rather than landfill disposal.

In the final calculation, the score ascribed to landfill disposal of 608,819 t of MSW is 27,700,000 Pt, far higher than 15,900,000 Pt estimated for the same amount of MSW, burnt by incinerators.

4. Conclusion

Using LCA approach, an estimation of environmental impacts due to the incineration network in a regional territory has been performed. The most important impacts have been ascertained for carcinogens and inorganic pollutants producing respiratory disease. However, a significant avoided impact has been found for many impact categories, and in particular for resource consumption, due to the precious step of energy production.

In a preliminary comparison, landfill disposal resulted more hazardous either for human health, or for ecosystem quality and or for use of resources.

Indeed, from the impacts analysis of the entire process life cycle it is evident that an activity commonly accepted by the average citizen thinking, such as landfill disposal, is far more impacting than MSW burning in an incineration plant with energy recovery. It is true that incineration effects are more direct and evident, but only because impacts of landfills are allocated farther in time.

A Life Cycle Assessment can help people to understand that if one arises from the knowledge of a damage limited to “today” and “near”, it will be possible to have a wider perspective of the real impacts of the activities involved in waste management.

Acknowledgment

Authors want to thank Emilia Romagna Region for the supporting of this research and the help in gathering information about incineration plants.

References

[1] ISO (International Organisation for Standardisation) ISO 14040, Environmental Management, Life Cycle Assessment, Principles and Framework, 1997.

[2] UNI (Ente Nazionale Italiano di Unificazione) UNI EN ISO 14040, Gestione ambientale, Valutazione del ciclo di vita, Principi e quadro di riferimento [Environmental Management, Life Cycle Assessment, Principles and Framework], 1998.

[3] V. Camobreco, R. Ham, M. Barlaz, E. Repa, M. Felker, C. Rousseau, J. Rathle, Life-cycle inventory of a modern municipal solid waste landfill, Waste Manage. Res. 17 (1999) 394–408.

[4] H.-S. Song, J.C. Hyun, A study on the comparison of the various waste management scenarios for PET bottles using the life-cycle assessment (LCA) methodology, Resour. Conserv. Recyl. 27 (1999) 267–284.

[5] O. Ayalon, Y. Avnimelech, M. Shechter, Application of a comparative multidimensional life cycle analysis in solid waste management policy: the case of soft drink containers, Environ. Sci. Policy 3 (2000) 135–144.

[6] L. Roth, M. Eklund, Environmental evaluation of reuse of by-products as road construction materials in Sweden, Waste Manage. 23 (2003) 107–116.

[7] S. Hellweg, T.B. Hofstetter, K. Hungerbühler, Modeling waste incineration for life-cycle inventory analysis in Switzerland, Environ. Model. Assess. 6 (2001) 219–235.

[8] L. Morselli, P. Masoni, L. Luzi, F. Passarini, R. Mezzogori, Processes for hazardous waste recycling and inertization, in: Proceedings of ISWA 2002 World Congress and Fair: Appropriate Environmental and Solid Waste Management and Technologies for Developing Countries, vol. 1, Istanbul, Turkey, July 8–12, 2002, 2002, pp. 257–262.

[9] J. Chevalier, P. Rousseaux, V. Benoit, B. Benadda, Environmental assessment of flue gas cleaning processes of municipal solid waste incinerators by means of the life cycle assessment approach, Chem. Eng. Sci. 58 (2003) 2053–2064.

[10] L. Morselli, M. Bartoli, M. Bertacchini, A. Brighetti, J. Luzi, F. Passarini, P. Masoni, Tools for evaluation of impact associated with MSW incineration: LCA and integrated environmental monitoring system, Waste Manage. 25 (2005) 191–196.

[11] N. Vidal, M. Poch, E. Marti, I. Rodriguez-Roda, Evaluation of the environmental implications to include structural changes in a wastewater treatment plant, J. Chem. Technol. Biotech. 77 (2002) 1206–1211.

[12] T.B. Hofstetter, C. Capello, K. Hungerbuehler, Environmentally preferable treatment options for industrial waste solvent management. A case study of a toluene containing waste solvent, Process Saf. Environ. 81 (2003) 189–202.

[13] G. Finnveden, A.-C. Albertsson, J. Berendson, E. Eriksson, L.O. Höglund, S. Karlsson, J.O. Sundqvis, Solid waste treatment within the framework of life-cycle assessment, J. Clean. Prod. 3 (1995) 189–199.

[14] A. Riva, L. Morselli, M. Furini, LCA and LCI for the management of Municipal Solid Waste (MSW), Ann. Chim. -Rome 88 (1998) 915–924.

[15] G. Finnveden, Methodological aspects of life cycle assessment of integrated solid waste management systems, Resour. Conserv. Recycl. 26 (1999) 173–187.

[16] R. Clift, A. Doig, G. Finnveden, The application of life cycle assessment to integrated solid waste management. Part 1. Methodology, Process Saf. Environ. Protect. 78 (2000) 279–287.

[17] G. Sonnemann, F. Castells, M. Schuhmacher, Integrated Life-Cycle and Risk Assessment for Industrial Processes, Lewis Publishers, Boca Raton, FL, 2004.

[18] ANPA (Italian Environmental Protection Agency) I-LCA ANPA, Banca dati italiana a supporto della valutazione del ciclo di vita, version 2, 2000. Available also at url: http://www.sinanet.apat.it.

[19] PRé Consultants b.v., The Eco-Indicator'99. A damage oriented method for Life Cycle Impact Assessment, Methodology Report & Annex, third edition, Amersfoort, NL, 2001.

[20] PRé Consultants b.v., SimaPro 6 Database Manual, Methods Library, Amersfoort, NL, 2004.

[21] ENEL – Ente Nazionale per l'Energia Elettrica (Italian Electricity Board) Produzione e consumo di energia elettrica in Italia, Rome, Italy, 1995.