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The environmental performance of alternative solid waste management options: a life cycle assessment study

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Abstract

Developed from chemical engineering principles and energy analysis, the life cycle assessment is an internationally standardized method that is able to account for upstream and downstream inputs and emissions related to the life cycle of a product or a service. It is generally considered the best environmental management tool that can be used to obtain an objective quantification of all the environmental impacts related with different solid waste management scenarios. In this study, it is used to assess the environmental performance of alternative solid waste management options that could be used in an area of the South of Italy suffering from a situation of weighty solid waste emergency. The extreme delicacy of the decision-making process to which the results have to contribute suggested increasing the reliability of the assessment conclusions by using a high quality of data and a deepened analysis of technical processes. An analytical comparison between three selected scenarios is reported with reference to some crucial environmental impact categories. The results quantify the relative advantages and disadvantages of different management schemes and suggest some possible improvements in design and operating criteria.

Keywords: Solid waste management; Life cycle assessment; Landfill; Incineration

1. Introduction and framework

The study focuses on the assessment of environmental performance of alternative solid waste management options that can be used in an area of the South of Italy, the Regione Campania, where a poor solid waste management policy created a situation of heavy emergency. The area has an extension of about 13 600 km^2, 5.7 million of inhabitants and a production of municipal solid wastes (MSWs) equal to about 7000 t per day. These were all sent to landfilling until the beginning of 2001, without any significant recourse to separate collection and thermal treatment. This short-sighted solution fast made exhausted the landfill volumes of the area, so that since 2002 no more space for restwaste dumping was available. The Italian Government created a National Committee for Waste Emergency in Campania that decided to apply as soon as possible a new waste management scheme, including seven units for RDF production from restwaste sorting, with a total capability of 8350 t per day, and two units for its combustion with energy recovery, with a total capability of 1 000 000 t per year (Fig. 1). The analysis of the patterns of restwaste management highlights the peculiarity induced by the emergency situation. The RDF facilities have been fast put into service while the construction of incinerators is slower and far away from its completion, mainly as a consequence of the strong opposition of interested population. This created the necessity to have several intermediate storage sites where the RDF bales (about 2000 each day) wait to be burned.

A life cycle assessment (LCA) methodology is an internationally standardized method [1] that has been developed from chemical engineering principles and energy analysis [2,3]. It is generally considered the best environmental management tool that can be used to obtain a proper understanding and an objective quantification of all the environmental impacts related with different solid waste management scenarios [4–6]. The term *life cycle* indicates that every stage of the life cycle of the service, from resource extraction to ultimate end-of-life treatment, is taken into account. For each operation within a stage, the inputs (raw materials, resources and energy) and outputs (emission to air, water and solid waste) are calculated and then aggregated over the life cycle by means of material and energy balances, drawn over the system boundary [4,6].

The study refers to a steady-state condition of the waste management options, i.e. after the conclusion of the present transient state. The aim was the quantification of the difference between the environmental performance of three different scenarios for solid waste disposal in the area of Regione Campania: that planned in the program of the Committee

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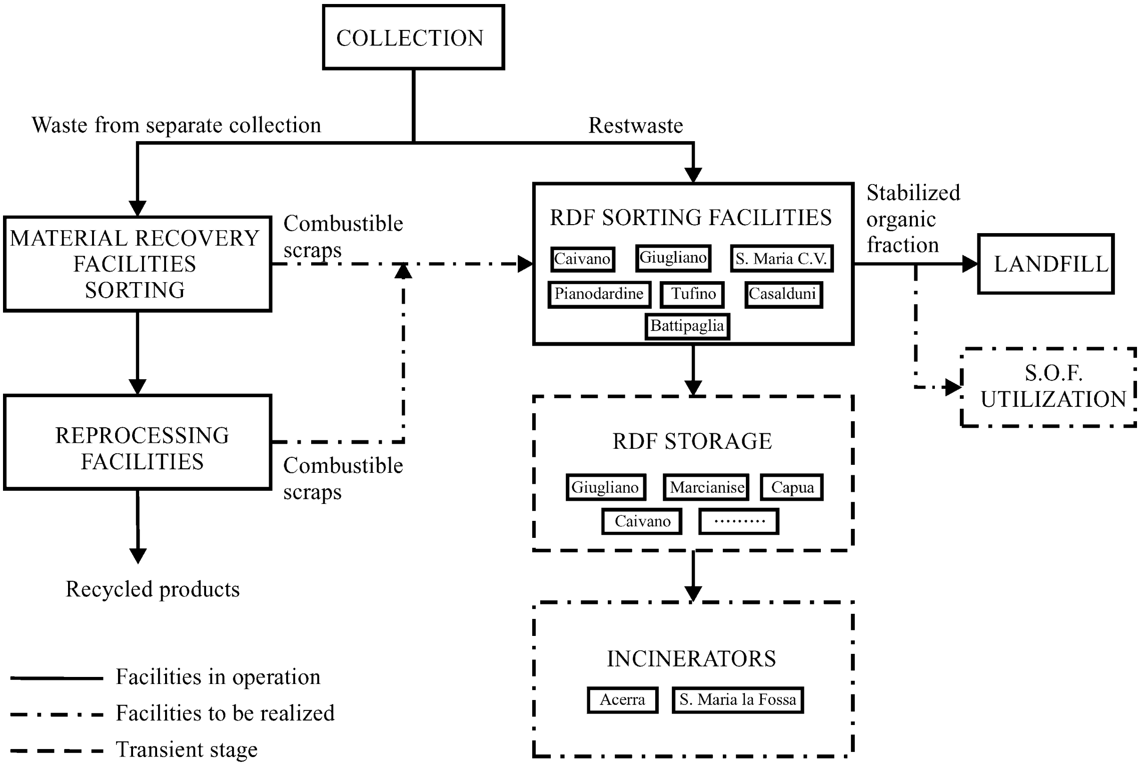

Fig. 1. The waste management scheme applied in Regione Campania. The names inside the smallest boxes indicate the towns where the facilities are in operation or under construction.

for Waste Emergency; an hypothetic scenario that continues to see the landfilling as the only possible option; a scenario where all the restwaste is mass burned without RDF preparation. The paper deals with the LCA of these three solid waste management scenarios. The analysis takes into account that any option influences the environment by consuming resources and releasing emissions and other waste streams, which have to be ultimately disposed, and by replacing energy and conventional products from primary production, which do not have to be produced in case of having available recovered energy and products with suitable properties [7].

2. The LCA approach to the analysed waste management

2.1. The engineering LCA

Environmental professionals, policy makers, and the general public are intensively interested in having the means to look holistically at the environmental consequences associated with the life cycle of a process, a product or a service. One procedure for doing this is the LCA. The international standard ISO 14040-43 defines LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Really, the growing interest in this environmental tool [8] originates different versions of it. Developed from chemical engineering principles and energy analysis, the *Conventional or Engineering LCA* is the most diffused version, defined as “a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements” [9]. In the following, the approach and the procedures of the engineering LCA, will be used. This is because, in the author’s opinion, it allows a more accurate analysis of the process or service as a whole and offers the prospect of mapping the energy and material flows as well as the resources, solid wastes, and emissions of the total system. In other words, it provides a system “map” that sets the stage for a holistic approach. Comparing such system map for different waste management options allows the identification of areas where engineers can intervene to obtain environmental, and economic sustainable, improvements.

The structure of a LCA consists of four distinct phases, which contribute to an integrated approach: (1) *Goal and Scope Definition*, which serves to define the purpose and extent of the study, to indicate the intended audience and to describe the system studied as well as the options that will be compared; (2) *Inventory Analysis or LCI*, which consists in the collection and analysis of all the material and energy inputs and outputs that cross the border between the product or service system and the environment over its whole life cycle. The input and emission flows are termed *environmental burdens* or *environmental interventions* [4,10]. The recommended way to report the LCI for a waste management scheme is [4]: *direct burdens*, associated with the waste management operations themselves; plus *indirect burdens*, associated with providing materials and energy to the waste management operations; minus *avoided burdens*, associated with economic activities which are displaced by materials and/or energy recovered from the waste. Direct burdens are usually definable at least on a regional or national level; the location of indirect and avoided burdens cannot normally be defined and their numerical estimates should be obtained from a reliable database; (3) *Impact Assessment or LCIA*, which aims at understanding and evaluating the magnitude and significance of potential environmental impacts of a system. It organizes the LCI inputs and outputs into specific, selected impact categories and models the inputs and outputs for each category into an aggregate indicator; (4) *Interpretation*, which evaluates the study in order to derive recommendations and conclusions. The role of each of these phases is described in detail in several scientific papers, like, for instance, that by Consoli et al. [9] or Azapagic [11].

The seemingly all-encompassing nature of LCA has proved very attractive. It may appear to new users that it is a single tool that can accomplish “everything” with regard to environmental assessment. As a result, there have been ill-advised efforts to use LCA as the only measurement tool when developing product-labelling systems and during policy making. In particular, LCA does not cover issues of public health, hygiene and site or procedure safety. Some risk factors (dust, heavy metal emissions, etc.) can be taken into account, but pathogenic (virus, bacteria, etc.) and eco-toxicological (dose–response relationship analysis) factors are not. LCA does not address the effect of systems under study in terms of land-use. For instance, the impact of transportation is analysed from the viewpoint of emissions to the air and water, and from an energy-use perspective, without including the risk of accidents or infrastructural saturation (due to increased traffic congestion). LCA does not cover disamenity effects, like odour and visual pollution, noise (e.g. due to increased traffic), destruction of the natural habitat, etc., which have to be taken into account as part of the decision-making process [5]. LCA does not as yet allow for a sufficiently robust quantification of these indicators. To cover these issues, other methodological bases than those used so far in LCA studies are required [12,13].

2.2. The goal and scope definition of the study

The *overall goal* for the project is to develop information and tools to evaluate the environmental performance of alternative MSW management options in the area of Regione Campania. The *primary audience* for this effort is the Italian Committee for Waste Emergency in Campania, which is interested to assess energetic and environmental profile of the current management in comparison with some integrated alternatives. However, the considerations and tools developed through the study will also be of value to local governments and solid waste planners as well as the Italian Consortium for Packaging (CONAI), the industry active in the field of solid waste management, the environmental organizations and LCA practitioners.

The main feature of the proposed life cycle approach takes in mind the above recalled intended use of results as well as the intended audience of the study and, in particular, the sensitivity of the peculiar situation of emergency which is still present in Campania. In other words, considered that LCA results should be used as one of the crucial supports to a decision-making process of extreme delicacy, it was decided to make as high as possible the knowledge of the technical processes and the quality of data. First, all the processes of the selected scenarios of waste management were broken down with the aim of identifying and characterizing each single step. This gives the possibility to detect where and how engineers could intervene in order to improve design solution and/or operating criteria. Then, with reference to *data quality*, it is known that LCI needs specific data (in the case of a MSW management, those related to each stage of solid waste management system) and generic data (for energy production, raw material extraction and transportation). Well, a very high quality of data was addressed by means of using, for generic data (mainly indirect and avoided burdens) one of the most valued international data bank, that of the Boustead Ltd., and, for specific data (mainly direct burdens), only those derived from on site investigations. This latter aspect allows meeting a series of requirements for data quality: time-related, geographical and technological issues; the precision and completeness of the data; the representativeness of data sources. For each of the unit processes, all the data of interest have been collected (from November 2001 to November 2002) during technical visits to all the plants active in Campania or deduced by official documents and certificate declarations of the same sites. The data quality was furthermore increased by taking into account the specific characterization of the MSW (as well as the process waste) at the various stages, i.e. at the collection, at the sorting facilities, at the energy recovery sites.

The function of the system under study is to manage solid restwaste, i.e. the MSW residual from separate household collection, having a given quantity and composition. Therefore, the basis for comparison of different systems, named the *functional unit* of the service delivered, was defined as the management of 1 kg of restwaste of the composition measured as average in Campania and reported in Table 1. All the activities required to manage the waste from the time it is sent out for collection to its ultimate disposition are considered. Therefore, the stages of transportation, central sorting, biological treatment, thermal treatment and landfilling are individually analysed and quantified in terms of energy and material consumptions as well as of emissions in the environment at local, regional and global level.

Table 1
Composition of MSW in Campania, as obtained from a specific investigation made by the National Committee for Waste Emergency

Waste component	Content in restwaste (%$_w$)
Glass	5.7
Metals	3.25
Wood	1.75
Food wastes	30.1
Greens	3.88
Paper and paperboard	23.15
Plastics, light	7.92
Plastics, hard	2.84
Textiles	4.48
Leather	1.76
Oversize	0.7
Inert materials	1.26
Miscellaneous	4.49
Fines	8.7

It is assumed that the waste enters the *system boundaries* when it is delivered to a collection site for restwaste, whether it is a kerbside collection site or a drop-off site. Fig. 2 reports these boundaries, together with the indication of the main environmental burdens, for the scenario “RDF production and combustion”, i.e. that planned in the program of the Committee for Waste Emergency. It is noteworthy that, in addition to processing operations, transports have been included explicitly since logistics can represent a significant part of the overall environmental impacts as well as of economic costs. In agreement with similar studies [6,14,15], all upstream life cycle activities (raw materials extraction, manufacturing, and use) are assumed to be held constant. Moreover, the scope of this study does not include bulky items (televisions, refrigerators, etc.), waste from sewage works, construction and demolition waste (building debris and rubble, etc.), green waste from local authorities (pruning waste, etc.) as well as general industrial and commercial waste not collected with the MSW. Finally, the study does not cover the economic aspects of waste management: no assessment will be made of the economic impact of the various scenarios.

3. The life cycle inventory

The phase of life cycle inventory aimed at identifying and quantifying the environmental interventions crossing system boundaries. It resulted in an *inventory table*, i.e. a list of raw materials and energy inputs, and of individual emissions to

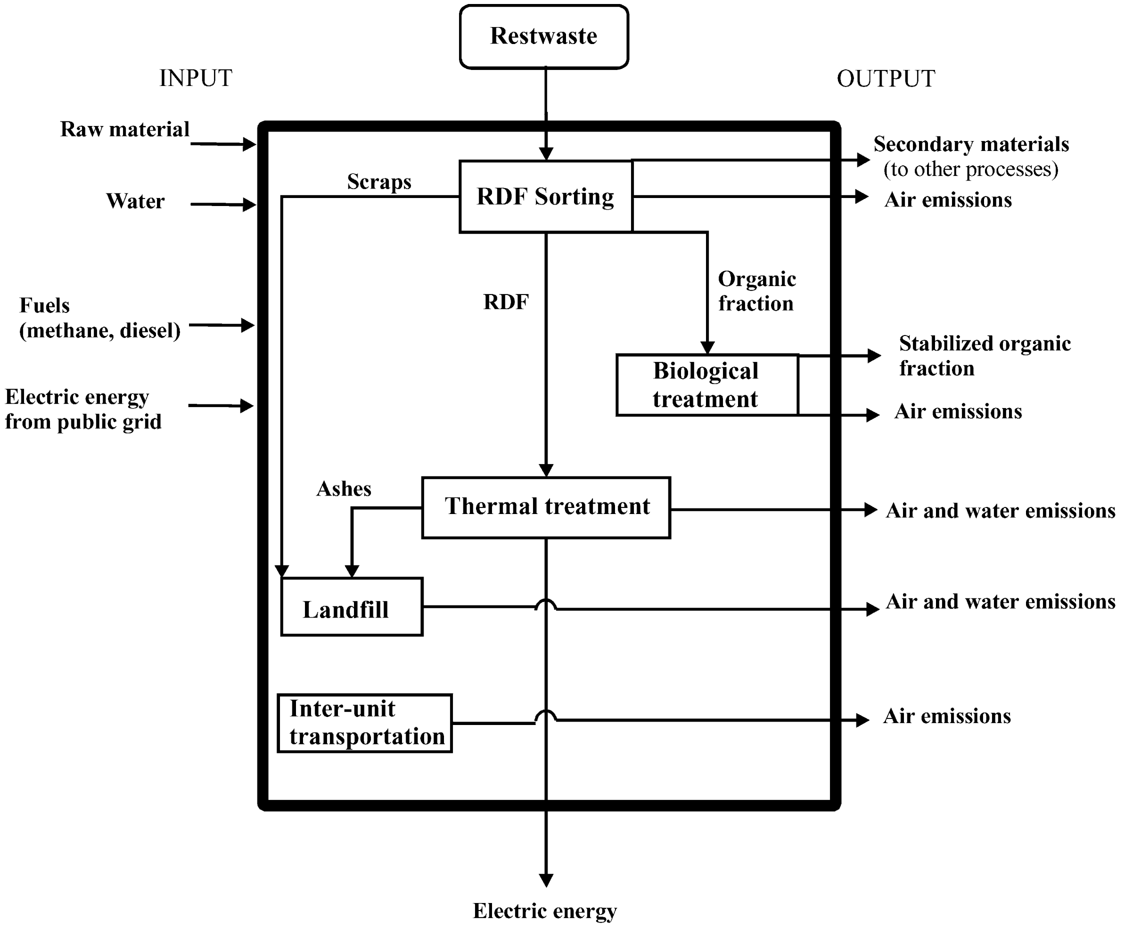

Fig. 2. System boundaries with the indication of typology of environmental burdens (RDF production and combustion scenario).

air and water and solid waste generation, that is then utilized in the LCIA phase. In the following, the detail of technical analysis of the processes and of the collection of different environmental interventions is reported with reference to each of the selected management scenario.

3.1. The landfilling scenario

It should first be noted that, like all the other waste options examined in the study, landfilling is a unit process: solid wastes form the inputs, along with some energy to run the process; the process itself involves the decomposition of part of the landfilled waste; the outputs are the final stabilized solid waste, the gaseous and aqueous products of decomposition, which emerge as landfill gas and leachate. Moreover, as in all processes, the amounts and quality of the products as well as the efficiency of the process itself depend on the inputs and the way that the process is operated and controlled. According to this perspective, Fig. 3A describes the reference system considered in the study: it includes the landfill where the restwaste is directly disposed, and the sections for biogas and leachate collection and treatment.

The type of landfill chosen as reference was selected according to the criterion that the RDF production/combustion scenario has to be compared with alternative options characterized by best available technologies and design criteria. Therefore, the landfill is equipped with high quality bottom and top barriers (e.g. made of HDPE or of another low permeability material, such as clay) for leachate containment as well as with up-to-date technologies for leachate treatments and energy recovery from biogas. A recent study which investigated all the landfills in operation in Campania until 2000 [16] indicated that the amount of the leaked leachate can be assumed as negligible. This conclusion was then acquired in the study. The technology selected for the treatment of collected leachate is that of reverse osmosis, which has not yet been installed in Campania but that it is considered one of the best available technologies. The utilization of semipermeable membrane gives the possibility to remove the dissolved solids and organic compounds with high efficiencies and without production of any sludge fraction [17]. The biogas collection and treatment system was of high efficiency too. It was assumed that the biogas collection efficiency is equal to 55% and that the 60% of this collected biogas is burned in a gas engine with an electric conversion efficiency of 35%. The remaining 40% is sent to a flare to reduce greenhouse effect.

Table 2
Inventory of direct environmental burdens related to the landfilling scenario

Input		Output	
Restwaste	1 kg	Occupied landfill volume	0.7 m^3
Diesel for dumping vehicles	0.026 MJ	Electric energy from biogas combustion	0.3 MJ
Electric energy	0.0074 MJ	Purified landfill leachate	0.3 dm^3
		Air emissions	
		CH_4	21 g
		CO_2	178 g
		CO	119 mg
		NO_x	107 mg
		H_2S	
		Dusts	
		Water emissions	
		COD	64 mg
		BOD_5	16 mg
		Phosphorus (P)	4 mg
		Nitrite	0.24 mg
		Nitrate	8 mg
		Sulphate (SO_4)	400 mg
		Sulphite (SO_2)	0.2 mg
		Chloride	480 mg
		Fluoride	2.4 mg
		Ammonia (NH_4)	6 mg
		Copper	0.04 mg
		Iron	0.8 mg
		Lead	0.08 mg
		Cadmium	0.008 mg
		Zinc	0.2 mg
		Mercury	0.002 mg
		Manganese	0.8 mg
		Chromium	0.8 mg
		Nickel	0.8 mg
		Tin	4 mg
		Arsenic	0.2 mg

The data quality was increased by coupling literature data (mainly from McDougall et al. [6]) and on-site data obtained by the landfills located in Pugliano, Paenzano and Maruzzella. The energy consumptions as well as the air and water emissions were quantified and reported in Table 2. In particular, the fuel consumption for landfill process has been estimated to be about 0.5 dm^3 of diesel per cubic meter of void space filled. The amount of produced leachate was estimated to be equal to 400 dm^3/t of restwaste landfilled in a period of 30 years: the value mainly depends on the rainfall of the area, the quality of the landfill sealing and the original water content of the buried waste. The plant for leachate treatment is able to treat an input having a composition varying in a wide range [18] and requires about 0.09 MJ of electric energy to treat 1 m^3 of leachate. A conservative approach was utilized for the liquid effluent, whose composition was assumed to be that of the law limits.

A biogas production of 250 m^3 N t^{-1} of biodegradable waste, that means 120 m^3 N t^{-1} of restwaste having the reference composition, was estimated and compared with that reported by recent literature [6]. The major components of the landfill gas are methane, which usually has a content of 50–55%, carbon dioxide and limited amounts of hydrogen sulphide ($<1\%$) and other organic compounds. A heat content of 22 MJ/m^3 N was obtained as average from the data measured in the analysed landfills. The air emissions can be distinguished in a diffuse emission, due to the not collected biogas fraction, and in the release to the atmosphere

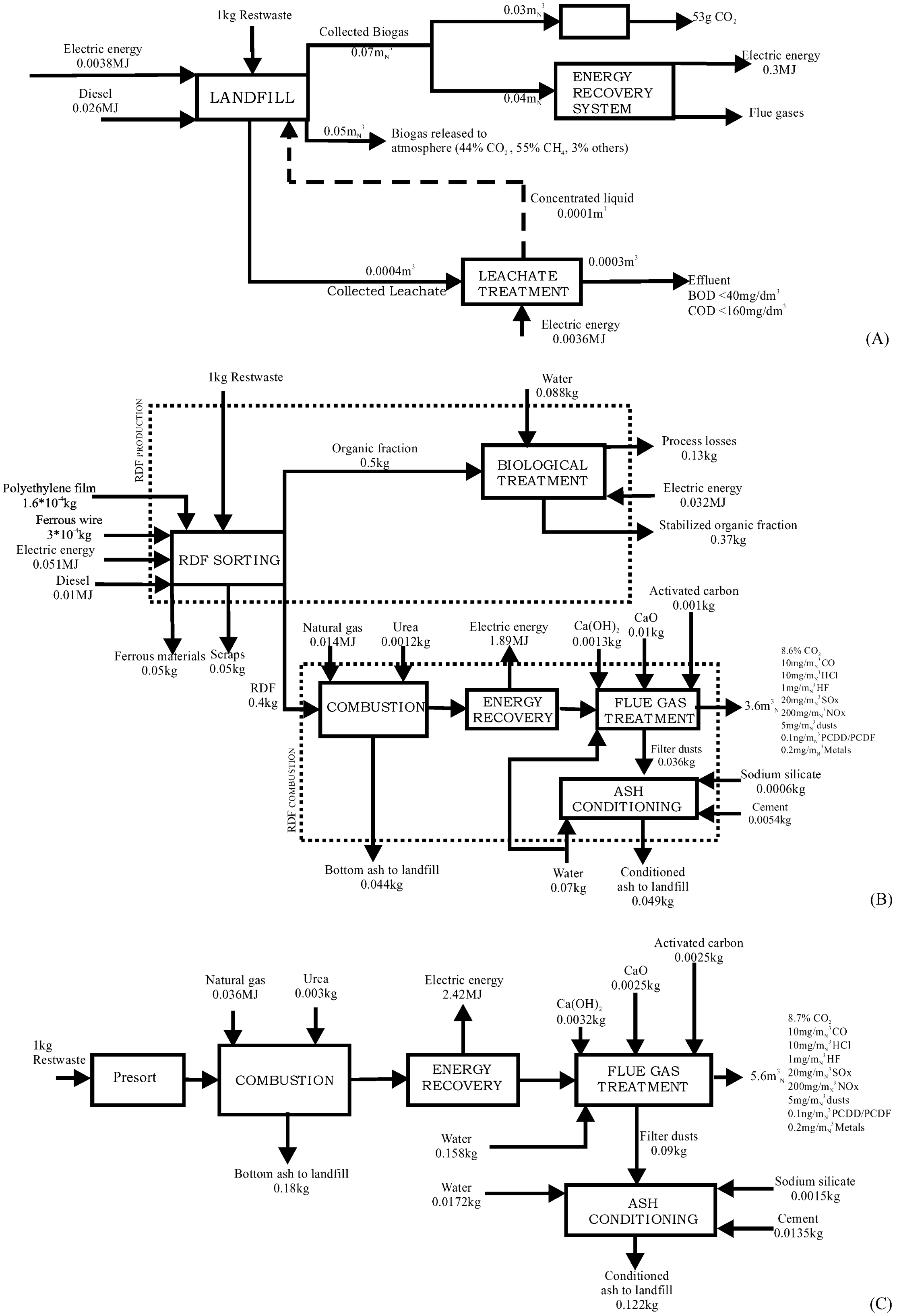

Fig. 3. Inventory of direct environmental burdens of the three scenarios for restwaste management: (A) landfilling; (B) RDF production and combustion; (C) mass burn combustion.

of the flue gases from gas engine and flare. For these latter the regulation limits have been assumed, in order to use a conservative criterion.

3.2. The RDF production and combustion scenario

Fig. 3B reports the layout of the restwaste management scenario proposed for Regione Campania and composed by two main sections, RDF production and combustion.

The *RDF production* consists of a sorting process, which produces RDF bales and ferrous materials, and a biological treatment process, which produces a stabilized organic fraction (SOF) that can be used for contaminated soil remediation. All data for the inventory of direct and avoided burdens have been obtained by averaging those measured during on-site investigations in two RDF facilities, located in Caivano and Pianodardine and having throughput of 2000 and 400 t per day of restwaste, respectively. Mixed waste, delivered by garbage trucks, is dumped on the tipping floor of the storage building where any unwanted items (car engines, logs, etc.) can be removed. A flail mill provides for the bag opening and for a size reduction of the input material, and then a first trommel screen removes the undersize fraction ($<$120 mm). The oversize fraction, which consists mainly of paper, board, wood, plastic, film, is then sent to a magnetic separation and, finally, to a manual screening. A secondary screening is performed on the undersize fraction and allows to separate a fraction larger than 60 mm, which contains a high heating value material then recovered by means of a ballistic separator, and a finer fraction, which contains a high moist organic material then sent to the biological treatment. This latter occurs under aerobic conditions in a stabilization building for a period as long as 4 weeks during which air is continuously forced through the waste pile to keep high the decomposition rate. The exhausted air is finally sent to a scrubber and a bio-filter to reduce odours and pollutants before release. This allows assuming that carbon dioxide is the only gas to be considered in the direct burdens related to air emissions.

The data measured during technical visits are related to material and energy balances as well as air and water emissions. A detail of different contributions to electric energy consumption related to the whole RDF production section is reported in Table 3. Table 4 gives the total inventory of direct environmental burdens related to the production of 1 kg of RDF, as it is obtained as average over the two recalled facilities. Note that the production of 1 kg of RDF it is obtained with an overall efficiency of 40% and an electric energy consumption of 0.083 MJ.

Table 3
Electric energy consumption of Caivano RDF facility

Unit operations	Electric energy consumptions (%)
Bag opening	34
Sorting	18
SOF preparation	38
Compaction	9
Auxiliary services	1

Table 4
Inventory of direct environmental burdens related to RDF production

Input		Output	
Restwaste	1 kg	Air emissions	
Auxiliary materials		CO_2	200 g
Water	0.088 kg	Residues	
Ferrous wire	3×10^{-4} kg	Scraps	0.05 kg
Polyethylene film	1.6×10^{-4} kg	Products	
Auxiliary energy		RDF	0.4 kg
Diesel	0.01 MJ	Stabilized organic fraction	0.37 kg
Electric energy	0.083 MJ	Ferrous material	0.05 kg

The stage of *RDF combustion* is composed by three sections: combustion, energy recovery and flue gas treatment. For each section several technologies and design layout are possible. The waste-to-energy plant taken as reference for the inventory compilation is that under construction: it is then not yet in operation so that the last version of its detailed engineering plan has been taken as reference to deduce material and energy data as well as environmental performances. Moreover, in order to increase data quality, information obtained during technical visits at the RDF combustion facility in Parona, in the North of Italy, was used to validate design data. The reference plant has three parallel lines, each with a capability of 27 t/h and characterized by a mobile grate, constituted by a series of alternate fixed and mobile bars where the fuel undergoes the primary stages of combustion. The grate is cooled by water since the LHV of RDF is remarkably higher than that of the MSW (17 vs. 8.85 MJ/kg). The furnace can be divided in three zones: the feeding zone, the central zone, where combustion takes place, and the final zone, where the ashes are discharged. In the combustion zone the alternate movement of bars allows to have a good mixing of waste that is exposed to flame radiation for a time suitable to guarantee very high combustion efficiency. The grate is inclined by 10° in order to ensure a continuous movement of the waste. The combustion process is regulated by taking into account: the steam mass flow, the oxygen and carbon monoxide concentrations in the flue gases, the primary combustion temperature and the flame length over the grate. In the secondary chamber, the combustion of volatile unburned compounds is ended by adding a secondary air stream. A semidry scrubber for acid treatment, a fabric filter for removing fly ashes and a SCR $DeNO_x$ that uses a catalyst to reduce NO_x and organic micro-pollutants, composes the flue gas treatment. The scrubber uses a water–lime solution that is sprayed counter currently with hot gas; the lime neutralizes the acids and the water content is enough small to be totally vaporized. In this way the water effluent treatment is not necessary.

Table 5
Inventory of direct environmental burdens related to RDF combustion

Input		Output	
RDF	1 kg	Air emissions	
Auxiliary materials		CO_2	1515 g
Air (moist)	10.6 kg	H_2O	679 g
Process water	0.158 kg	O_2	839 g
Ash conditioning water	0.0172 kg	N_2	8249 g
CaO	0.025 kg	NO_x	3335 mg
Sodium silicate (30%)	0.0015 kg	SO_2	333 mg
Activated carbon	0.0025 kg	HCl	167 mg
$Ca(OH_2)$	0.0032 kg	Dusts	83 mg
Cement	0.00135 kg	TOC	4 mg
Urea	0.003 kg	CO	167 mg
Auxiliary energy		PCDD/F	0.0000017 mg
Heat from natural gas	0.036 MJ	Hg	1 mg
Electric energy	–	Cd	1 mg
		Heavy metals	3 mg
		Residues	
		Filter dusts	0.09 kg
		Bottom ash	0.11 kg
		Products	
		Electric energy	4.09 MJ
		Heat	–

Table 5 shows the inventory of direct environmental burdens related to combustion of 1 kg of RDF produced in the facilities of Regione Campania. It should be noted again that, since the incinerators are not yet in operation, almost all the data are design data with the exception of air emissions. For these latter, a conservative approach would suggest utilizing the regulations limits. Nevertheless, for some compounds (CO, SO_x, total heavy metals and dusts), the acknowledged performances of some selected best available technologies allow to affirm that the facility is able to obtain lower concentrations. Note how this approach, with the above-described breakdown of processes, gives the possibility to compare LCI related to different design solutions (e.g. having a different selection of technologies). Moreover, it allows a correct allocation [9,11] of the environmental burdens related to a specific process or part of it: this latter aspect it is particularly relevant to identify where the design efforts have to be focused.

3.3. The mass burn scenario

This management scenario is an alternative option to waste valorization by recovering energy without a careful preliminary sorting process. The data were collected during technical visits to a couple of modern mass burn incinerators that are in operation since 2001 in North Italy, in the Milan area (Silla 2) and in Cremona. Fig. 3C reports the layout while Table 6 the inventory of direct burdens related to this scenario. The latter is not analysed in depth here, considering that the technology (mobile grate cooled by water) is the same of the RDF combustion facility under construction.

Table 6
Inventory of direct environmental burdens related to the mass burn scenario

Input		Output	
Restwaste	1 kg	Air emissions (in clean gas)	
Auxiliary materials		CO_2	953 g
Air (moist)	5.6 kg	H_2O	301 g
Process water	0.158 kg	O_2	560 g
Ash conditioning water	0.0172 kg	N_2	4765 g
CaO	0.025 kg	NO_x	1965 mg
Sodium silicate (30%)	0.0015 kg	SO_2	197 mg
Activated carbon	0.0025 kg	HCl	98 mg
$Ca(OH_2)$	0.0032 kg	Dusts	49 mg
Cement	0.0135 kg	TOC	2 mg
Urea	0.003 kg	CO	98 mg
Auxiliary energy		PCDD/F	0.0000010 mg
Heat from natural gas	0.036 MJ	Hg	0.66 mg
Electric energy	–	Cd	0.66 mg
		Heavy metals	2 mg
		Residues	
		Filter dusts	0.09 kg
		Bottom ash	0.17 kg
		Products	
		Electric energy	2.42 MJ
		Heat	–

3.4. The transportation stage

A parallel analysis was developed in order to estimate the length of the average transport route that the waste has to travel between two successive process units. The distances of the main Campania towns (for a total of 168) from treatment or final disposal units have been taken into account. For the three analysed scenarios, all the possible paths for restwastes, RDF bales, sorting scraps, SOF scraps and incineration ashes have been considered, taking into account the sites of the existing seven RDF sorting facilities, those of the incinerators under construction, those of adequate landfills for municipal or industrial wastes. The capacity of the

Table 7
Estimated consumptions for the different inter-unit transportations

Transportation stage	Average consumption (km/t)
Landfilling scenario	
Restwaste from towns to landfills	2.0
RDF production and combustion scenario	
Restwaste from towns to RDF facilities	1.9
Sorting and SOF scraps from RDF facilities to landfills	1.3
RDF bales from RDF facilities to incinerators	0.8
Ashes from incinerators to landfills	1.2
Mass burn combustion scenario	
Restwaste from towns to incinerators	3.1
Ashes from incinerators to landfills	1.2

lorries was assumed to be always equal to 32 m^3. The waste density was assumed to be: 0.7 t/m^3 for restwaste from towns to landfills, RDF facilities or incinerators and for sorting scraps from sorting units to landfills; 1 t/m^3 for RDF bales from RDF facilities to incinerators; 1.2 t/m^3 for conditioned ashes from incinerators to landfills. The specific (average) consumptions are reported in Table 7: they were then coupled with the lorry fuel consumption to give the related direct and indirect burdens by means of the Boustead data bank.

4. The life cycle impact assessment

4.1. The methodology for life cycle impact assessment

The phase of life cycle impact assessment aims at quantifying the relative importance of all environmental burdens contained in a LCI and at aggregating them to a small set of category indicators, or, in some cases, to a single indicator. LCIA is divided into several mandatory or optional elements [1]. The mandatory elements are: *classification*, an assignment of the inventory data to different impact categories (such as climate change, ozone depletion, etc.) and *characterization*, a quantification of category indicator results for each impact category by using characterization factors. The optional elements, which can be used depending on the goal and scope of the LCA, are: *normalization*, which relates the magnitude of the impacts in the different categories to reference values (such as the emissions in a nation); *grouping*, which assigns impact categories to groups of similar impacts or ranking categories in a given hierarchy; *weighting*, which converts indicator results of different impact categories to a common scale, sometimes including a final aggregation to a single indicator [3,4]. This traditional approach of organizing the work starting from the environmental burdens has been called bottom-up and codified in the ISO 14042 standard on LCIA: it follows environmental themes, also called problem areas, such as, for instance, acid rain or global warming. One of the limiting aspect of this approach is its inability to adequately model expected impacts, particularly because it aggregates over time and over space, i.e. all inputs and outputs over the whole life cycle are included in the analysis regardless of when they occur and where they are located. As a consequence, it can quantify the impacts on the basis of inventory results, but it can just estimate the related environmental effects on the basis of hypotheses and conventions.

A variety of impact assessment methods may be appropriately applied depending on the geographical scale, type and duration of the effect, the level of accuracy desired [19]. These methods range from a straightforward interpretation of the significance of a loading to site-specific risk assessments, which require significant additional data beyond that normally developed in the inventory: the appropriate level of sophistication and comprehensiveness is a key to effective environmental decision making [13,20].

These considerations lead to the conclusion that the phase of methodological and scientific framework for life cycle impact assessing is still being developed [4], even though some relevant improvements have been obtained in the last years [19]. As a consequence, in this analysis, according to almost all of similar studies [5,14,15], the impact categories, bottom-up method was utilized. The following categories were assumed as principal indicators of environmental impact related to each step of restwaste life cycle:

- consumption of natural resources (net energy consumption; not-renewable source consumption; water consumption);
- air pollution (increase in the greenhouse effect over 100 years; air acidification; emission of pollutants);
- water pollution;
- quantities of solid waste generated (which is strictly related to the requirements of landfill volume).

4.2. The LCIA results

The expansion of the compared systems is an approach specifically recommended by ISO 14041 and LCA scientists [4] to avoid the allocation problem, typical of multiple-output processes as those of a waste management system. Therefore, the analytical comparison between the three selected scenarios was carried out by means of the system expansion method visualized in Fig. 4. It focus on the functional output of primary interest, i.e. the management of 1 kg of restwaste of the composition measured as average in Campania, and subtracts equivalent alternative production of additional functional outputs from each systems.

The LCIA results are described by the diagrams reported in the following with reference to some crucial impact categories. Note that for some of these categories, the contributions given by the different phases (“energy production and use”, “raw material production”, “energy recovery”, “material recovery”, “transportation”, “process”) of the three solid waste management options are highlighted in order to suggest what are the crucial ones. On the basis of previous definitions, the negative values in the figures indicate the predominance of avoided environmental burdens.

4.2.1. Energy and resource consumption

Fig. 5 shows the net energy consumptions for all the examined scenarios. Note that, only for this impact category, the label “process” is not present in the legend since its contribution is included in that of the phase “energy production and use”. The first observation is that the avoided burdens, related to the production of a certain quantity of electric energy provided to the grid, are always greater than others, so that all the scenarios have a positive environmental performance for this impact category. The two scenarios with a thermal treatment of solid wastes show, as expected, a remarkable higher energy savings: with reference to landfilling, these savings are equal to 640 and 850%, respectively,

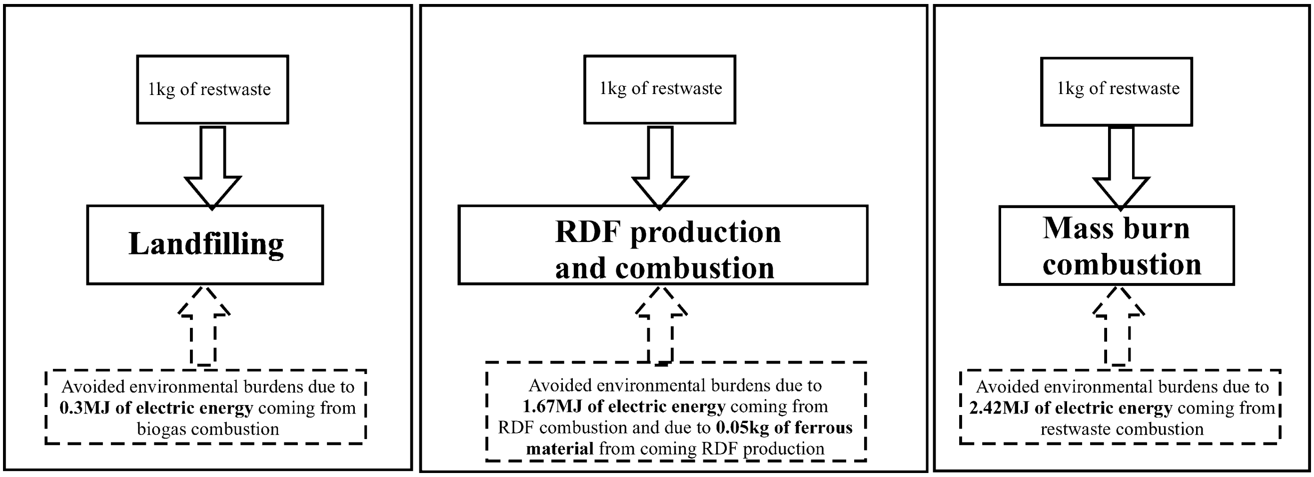

Fig. 4. The system expansion method used in the study, with the indication of the functional output of primary interest and of avoided burdens coming from additional functional outputs from each systems.

for RDF production/combustion and for mass burn combustion. The data also allow the quantification of the following conclusions: transportations always play a negligible role; RDF scenario needs a high local consumption of energy (due to sorting and stabilization processes); mass burn scenario presents a remarkable contribution to energy consumption related to raw materials preparation.

The above-described energy savings can be converted in savings of primary sources, on the basis of the Italian energetic mix in the reference period (47% oil, 22% gas, 11% coal, 11% nuclear, 9% hydroelectric). Fig. 6 visualizes these quantities, highlighting the great saving of these (mainly not-renewable) sources of energy that characterize the combustion scenarios, as well as the minor necessity of nuclear energy import. The reported data allow the following quantifications: each kilogram of restwaste treated in one of the combustion scenarios implies a saving of 52 or 68 g of oil, 19 or 23 g of gas and 19 or 21 g of coal, respectively, for RDF and mass burn combustion scenarios (Fig. 7). Assuming that the separate collection in Campania is at a level of 10%, there are about 6300 t per day of restwaste to be treated. Therefore, the complete implementation of the waste management system planned by the National Committee for Waste Emergency will give a saving of 120 000 t per year (327 t per day)

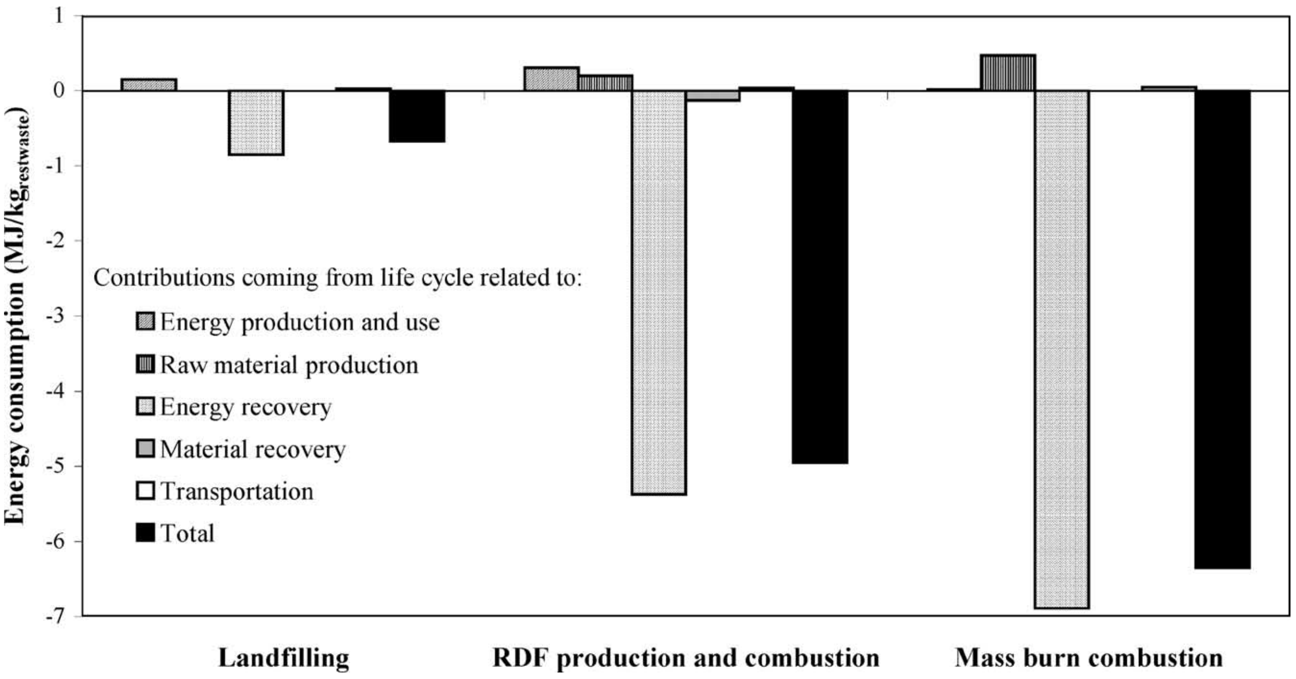

Fig. 5. The net energy consumption related to each restwaste management scenario with the indication of contributions coming from the different stages.

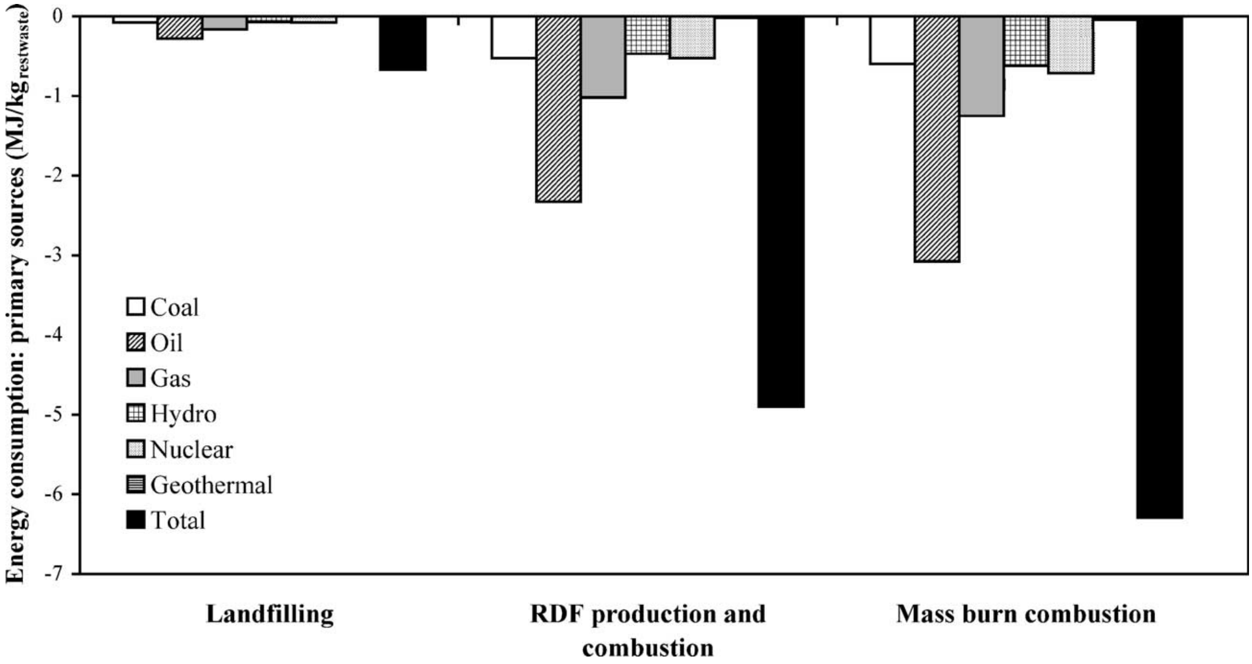

Fig. 6. The net energy consumption related to each restwaste management scenario, reported in terms of primary sources.

of oil, 43 500 t per year of methane and 43 000 t per year of coal. These data confirm and quantify the already common opinion that each energy saving turns out in an appreciable environmental advantage.

This conclusion is further supported by diagrams in Fig. 8, where water consumptions related to each restwaste management scenario are compared. Diagrams also point out the contributions coming from the different life cycle stages of considered scenarios. In particular, water consumption has been assumed zero for landfilling process (since the humidification, sometimes adopted in landfill management, has been neglected) while it is remarkable for combustion scenarios. For RDF production/combustion, water mainly needs for sorting process and ash conditioning; for mass burn scenario, mainly for ash conditioning. The comparison shows that, in this latter case, the avoided burdens related to

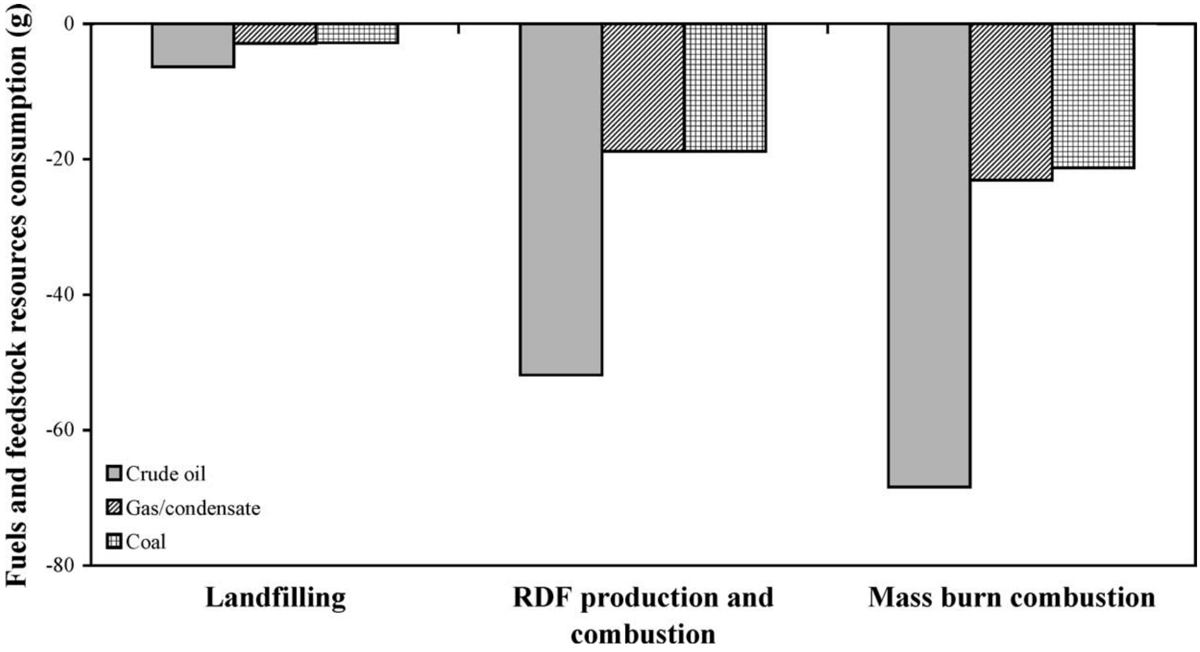

Fig. 7. The consumption of not-renewable resources related to each restwaste management scenario.

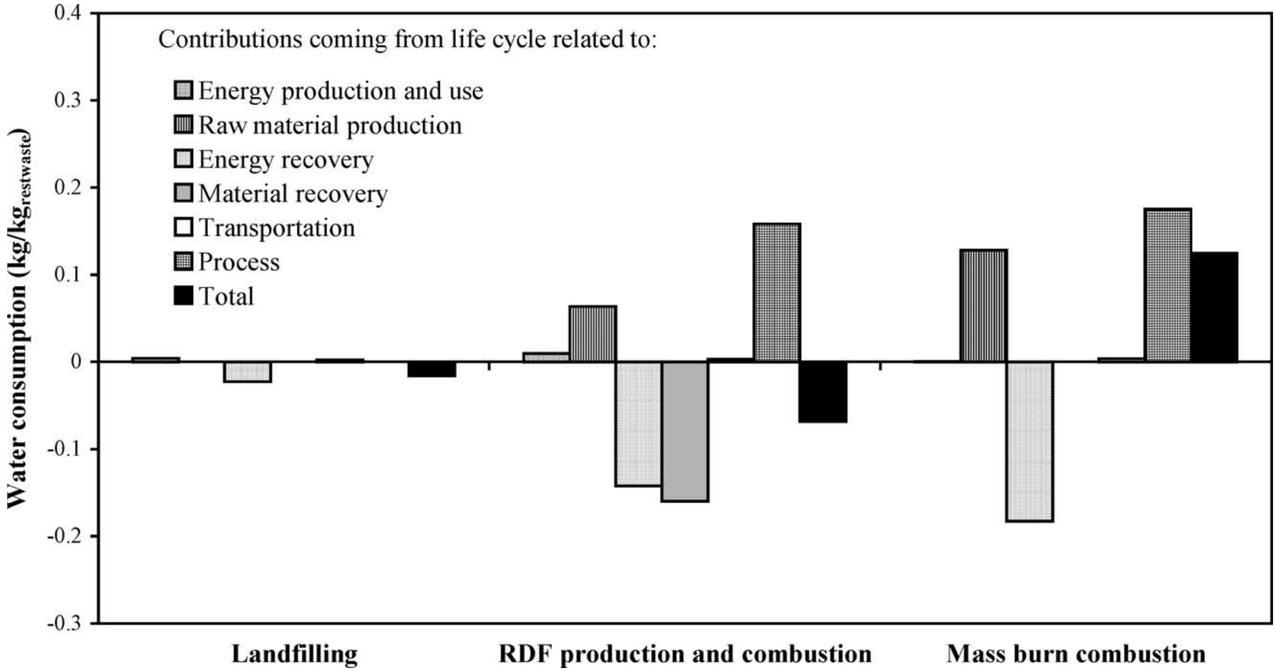

Fig. 8. The water consumption related to each restwaste management scenario with the indication of contributions coming from the different stages.

energy saving are not sufficient to offset the direct and indirect burdens. They are instead capable to offset negative burdens for RDF scenario, even for the remarkable contribution due to the recovery of ferrous materials. As a consequence, the waste management scheme proposed for Campania will allow a water saving of about 160 000 m^3 per year (therefore larger than that of landfilling of about 325%) that has to be compared with the water consumption of the mass burn scenario that is of about 290 000 m^3 per year. This relevant result suggests that the proposed scheme for solid waste management in Campania could greatly improve its environmental performances along the whole life cycle if a more extended sorting and recovery of materials will be implemented. The choice should be focused on materials for which it is easier (from an economic and technological point of view) the input on the market.

4.2.2. *Climate change*

The basis of the impact category “climate change” is the enhanced greenhouse effect attributed to human influence. The enhanced radiative forcing and thereby enhanced global warming is the primary effects caused by the increase of greenhouse gases (GHGs) in the atmosphere. Note that, since the average tropospheric lifetime of all these gases exceeds the tropospheric mixing time, it is not important where the emissions occur, i.e. climate change is truly a global impact

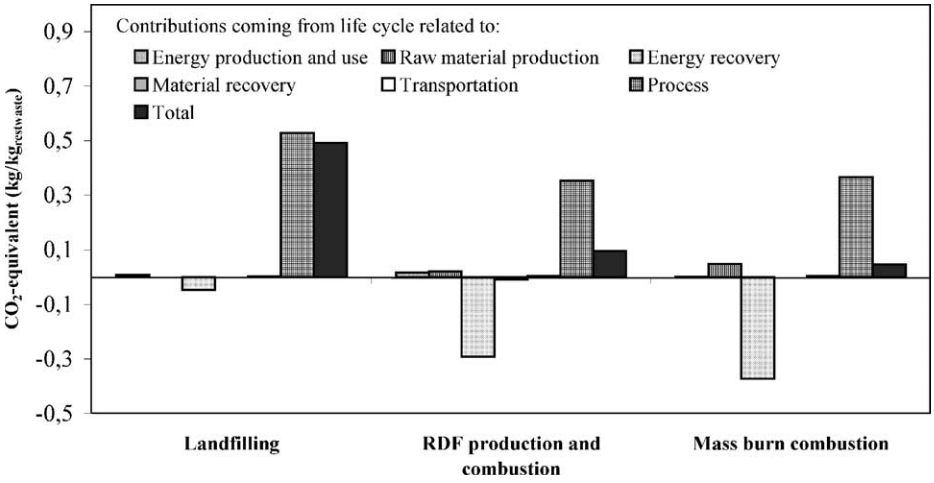

Fig. 9. The generation of GHGs (expressed as kilograms of CO_2-equivalent) related to each restwaste management scenario with the indication of contributions coming from the different stages.

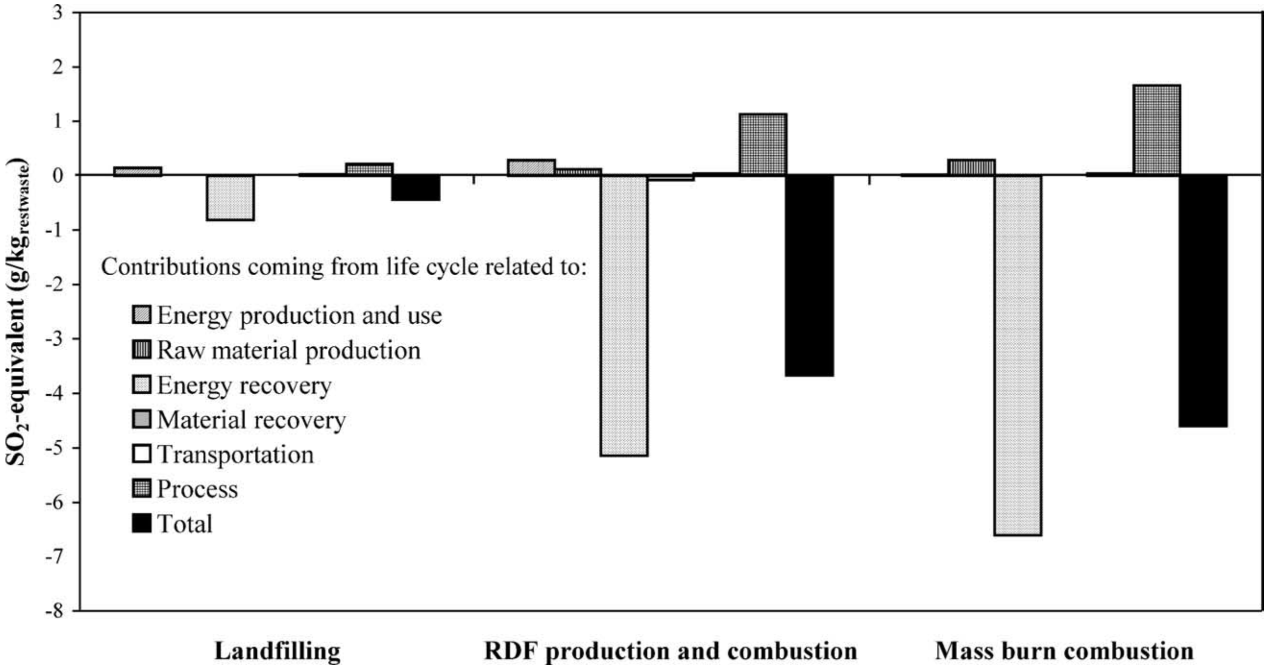

Fig. 10. The acidification potential (expressed as grams of SO_2-equivalent) related to each restwaste management scenario with the indication of contributions coming from the different stages.

category [21]. Fig. 9 quantifies the generation of GHG (expressed as kilograms of CO_2-equivalent, for a time horizon of 100 years) for each restwaste management scenario, with the indication of contributions related to the different stages of life cycle. It is noteworthy that the carbon dioxide emission has been split in a “renewable” and a “not-renewable” fraction: in particular, the carbon contained in organic fraction (when it is present), paper and carton board fraction as well as wood fraction, together with 50% of that contained in textile fraction, is considered as renewable and, as a consequence, not taken into account in the evaluation of GWP index. Note that the combustion processes present a GHG generation remarkably lower than that of landfilling scenario, mainly because the global warming potential of methane (which is generated only by the anaerobic digestion occurring in landfills) is 21 times higher than that of carbon dioxide. The mass burn combustion scenario has a slight better performance in comparison with that of RDF combustion, mainly as a consequence of the increased energy savings.

4.2.3. *Acidification and emissions in the environment*

Acidification refers to processes that increase the acidity of water and soil systems. Emissions of potentially acidifying substances (NO_x, SO_x, NH_3, HCl, etc.) lead to deposition, which in turn can lead to damages to animal and plant populations. Fig. 10 quantifies this impact category as grams of SO_2-equivalent, by means of the hydrogen release potential reported by Hauschild and Wenzel [22]. It is particularly highlighted the environmental positive performance of combustion scenarios, again related to the remarkable saving of energy.

The LCA study also quantified emissions in air and water as well as solid waste productions. Emission in air and water

Table 8
The indicators of principal environmental impact categories, as evaluated for the three scenarios for restwaste management[a]

Impact category	Landfilling	RDF production and combustion	Mass burn combustion
Energy consumption ($MJ/kg_{restwaste}$)	*−0.67*	−4.95	**−6.35**
Crude oil consumption ($g/kg_{restwaste}$)	*−6.32*	−51.9	**−68.4**
Water consumption ($g/kg_{restwaste}$)	−16.2	**−69.1**	*124.7*
CO_2-equivalent ($kg/kg_{restwaste}$)	*0.49*	0.095	**0.046**
Air emissions of organic compounds ($g/kg_{restwaste}$)	*2.96*	−1.70	**−2.24**
Air emissions of dusts ($g/kg_{restwaste}$)	**−0.04**	0.006	*0.39*
SO_2-equivalent ($g/kg_{restwaste}$)	*−0.44*	−3.66	**−4.6**
Water emissions of suspended solids ($g/kg_{restwaste}$)	**0.03**	1.23	*6.79*
Occupied landfill volume (m^3/t)	*1.43*	0.49	**0.27**

[a] The bold types indicate the best environmental performance while the italic types indicate the worst.

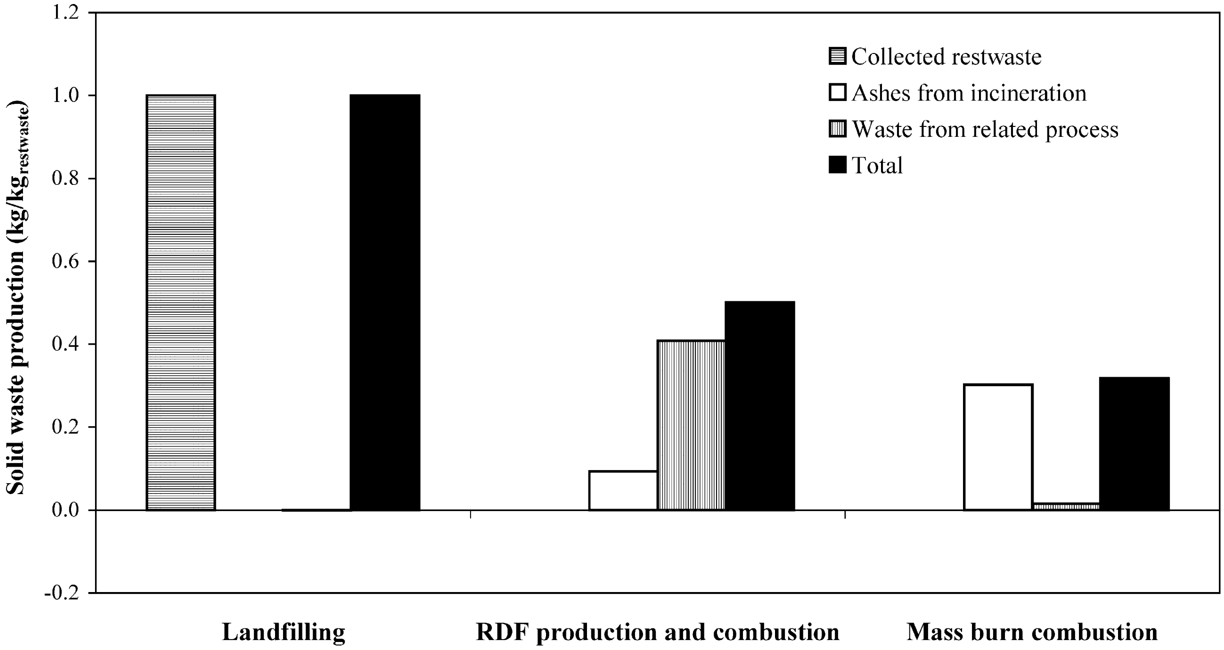

Fig. 11. The solid waste generation related to each restwaste management scenario with the indication of the origin of the different streams.

are reported in Table 8 to which the next section refers. Note that the COD and BOD values are not reported since for all the scenarios they are very low: 64 and 16 mg/kg$_{restwaste}$, respectively, for landfilling and about zero for thermal treatment scenarios. The different streams that contributed to the generation of solid wastes are instead shown in Fig. 11. As expected, the thermal treatment scenarios present a very low amount of solid wastes, even though large parts of these (particularly in the case of mass burn combustion) are conditioned ashes from incineration, which require special landfills.

4.2.4. Overall evaluation

Table 8 summarizes the indicators of principal environmental impact categories, as evaluated for the three scenarios for restwaste management. It is immediate to note the poor environmental performances of landfill, even though a series of advantageous hypotheses were utilized in the study. An even worse overall assessment for this option is then predictable, taking in mind that LCA does not cover disamenity effects, like odour and visual pollution, destruction of the natural habitat, etc.

The overall performance of waste management scheme proposed for Regione Campania appears rather satisfactory. The obtained results can also be used to quantify the magnitude of potential improved environmental performances related to some changes in the proposed design and operating criteria. In the following two of these changes are considered. First (Table 9), it has been evaluated the possible positive implications of a substantial recovery of glass and aluminium in the RDF production facility, as it could be obtained by means of market available devices. Data

Table 9
The variation of indicators related to principal environmental impact categories, as evaluated for the RDF production and combustion scenario for 1 kg of restwaste, under the hypothesis of the utilization of sorting devices for glass and aluminium recovery

	Scenario	Modified scenario	Variation (%)
Sorting efficiency of materials to recycling			
Glass	0%	70%	
Aluminium	0%	85%	
Ferrous materials	76.5%	76.5%	
Environmental indicator			
Energy consumption	−4.95 MJ	−5.99 MJ	21
Energetic resources consumption			
Crude oil	−51.9 g	−61.4 g	18.3
Gas/condensate	−18.8 g	−21.9 g	16.5
Coal	−18.8 g	−20.0 g	6.4
Other raw materials consumption			
Calcium sulphate	0.27 g	0.19 g	−29.6
Limestone	30.5 g	21.8 g	−28.5
Sodium chloride	0.15 g	−6.89 g	−4693.3
Air emissions			
CO_2-equivalent (100 years)	0.095 kg	0.05 kg	−47.4
Dusts	0.006 g	−0.003 g	−150
Organics	−1.7 g	−2 g	17.6
SO_2-equivalent	−3.66 g	−4.22 g	15.3
Water consumption	−69.1 g	−445.2 g	544.3
Water emissions			
COD	−0.003 g	−0.003 g	0
BOD	−0.002 g	−0.003 g	50
Suspended solids	1.23 g	−0.91 g	−174
Solid wastes	0.501 kg	0.436 kg	−13

Table 10
The variation of indicators related to principal environmental impact categories, as evaluated for the RDF production and combustion scenario for 1 kg of restwaste under the hypothesis of a more severe regulation limits

	Scenario	Modified scenario	Variation (%)
Concentration of combustion flue gases			
Dusts	5 mg/m^3 N	5 mg/m^3 N	0
NO$_x$	200 mg/m^3 N	100 mg/m^3 N	−50
SO$_x$	20 mg/m^3 N	20 mg/m^3 N	0
HCl	10 mg/m^3 N	8 mg/m^3 N	−20
HF	1 mg/m^3 N	0.8 mg/m^3 N	−20
PCDD/PCDF	0.1 mg/m^3 N	0.04 mg/m^3 N	−60
COV	10 mg/m^3 N	5 mg/m^3 N	−50
CO	10 mg/m^3 N	10 mg/m^3 N	0
Cd, Tl, Hg	0.05 mg/m^3 N	0.02 mg/m^3 N	−60
Heavy metals	0.2 mg/m^3 N	0.2 mg/m^3 N	0
Environmental indicator			
Air emissions			
CO$_2$-equivalent (100 years)	0.095 kg	0.095 kg	0
Dusts	0.006 g	0.006 g	0
Organics	−1.7 g	−1.7 g	0
SO$_2$-equivalent	−3.66 g	−4.15 g	13.4
NO$_x$	−0.4 g	−1.06 g	165
HCl	0.058 g	0.045 g	−22.4
HF	0.007 g	0.005 g	−28.6

reported in the table highlight that several indicators greatly improve: this is particularly evident for consumption of water, some raw materials and energy as well as for air emissions. These results, together with the acknowledged technical feasibility of the solution, suggest the opportunity of an economic evaluation to complete the decision process. Then (Table 10), it has been evaluated the magnitude of improvements related to the acceptance of more severe limits for air emissions. The assumed values of gas concentrations, that for some compounds (CO, SO$_x$, heavy metals and dusts) were already defined on the basis of acknowledged performances of some selected best available technologies (see Section 3 and [23]), have been here further lowered. As expected, the results are absolutely relevant, so that the contract winner accepted to assume them as the new regulatory limits.

5. Concluding remarks

Three alternative solid waste management options that could be used in Regione Campania, an area of the South of Italy suffering from a situation of weighty waste emergency, have been assessed by means of the internationally standardized method of LCA.

The phase of environmental burdens quantification for each options has been specifically characterized taking into account that results should be used as one of the crucial supports of a decision-making process of extreme delicacy. A very high quality of data was addressed by means of using, for generic data, one of the most valued international data bank and, for specific data, only those derived from on site investigations.

An analytical comparison between the three selected scenarios has been developed and quantified with reference to some crucial impact categories, like energy and material consumptions, climate change, acidification, air and water emissions, solid waste production. The results quantify the poor performance of landfilling option and validate the waste management scheme proposed for Regione Campania.

The adopted procedure allowed to suggest some changes in the proposed design and operating criteria and to quantify the magnitude of the related improved environmental performances. Two of these suggestions are the utilization of sorting devices for glass and aluminium recovery in the RDF production units, and a strongly lower limits for pollutants concentration in the flue gas from the RDF combustion facility.

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