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International Journal of Thermal Sciences 43 (2004) 519–529
International Journal of Thermal Sciences
www.elsevier.com/locate/ijts

Analysis of technical and environmental parameters for waste-to-energy and recycling: household waste case study

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Received 24 July 2002; accepted 6 October 2003

Abstract

This paper focuses on the treatment of household waste by waste-to-energy conversion. It assesses, in particular, both technical and environmental implications of a waste pre-sorting that may affect the treatment process. To this end, a life cycle assessment study has been undertaken. The scope of the study encompassed material recycling, incineration of household waste, treatment of flue gases, energy recovery, recycling of bottom ash, treatment of fly ash and final disposal of waste. The study showed that material recycling leads to an improvement of the working conditions with respect to the incinerator. However, material recycling leads to a decrease of the energy recovery so that it is necessary to use additional boilers to meet the initial energy demand. The related impacts tend to offset the environmental benefits derived by the waste recycling itself. The study also demonstrated that the life cycle approach is a useful tool for the study of technical and environmental aspects of an energy system. Moreover, those aspects in the process that are open to improvement have been identified.

Keywords: Incineration; Household waste treatment; Material recycling; Life cycle assessment; Energy systems; Waste-to-energy

1. Introduction

Waste generation has changed in the course of the last decades both from the quantitative and qualitative points of view. The causes that contribute to this situation are the constant increase in waste generation, the arrival of new products on the market that have led to the diversification of waste, and the migrations of population that have modified the geographical distribution of waste.

France registers a yearly production of 636 million tons (Mt) of waste, that is classified into five categories [1]:

– industrial waste (207 Mt),
– agricultural waste (376 Mt),
– municipal waste (52 Mt, 25 Mt of which is household waste),
– medical waste (0.7 Mt),
– nuclear waste (0.06 Mt).

In France, this waste production represents 10 tons per capita per year. When only the household waste is taken into account, the production reaches nearly 365 kg per capita per year [2].

Many treatment processes have been considered to deal with this waste. Among the several alternatives, incineration of waste is surpassing the simple landfilling method since the former represents a reliable and easy solution to reduce waste volume while giving the opportunity of recovering energy. At present, 35% of the household waste (in mass) is incinerated (about 9.7 million tons incinerated in 248 plants), and energy is recovered in about 29% of the cases (i.e., about 7.9 million tons incinerated in 100 plants) [2]. In 1998, the energy recovered from waste accounted for more than 7 million MWh, combined heat and power generation plants produced 5.3 million MWh (89% of heat, 11% of electricity) [3]. These advantages, however, must be assessed against the following remarks:

– Energy recovery from waste is a small fraction with respect to the energy independence of countries. For instance, French data show that the maximum contribution of waste incineration to the total energy production may not exceed 4% [4]. However, the role played by waste incineration is not insignificant given the 22% of renewable energy that the

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1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2003.10.001

Nomenclature

C	mass carbon content	%
Cl	chlorine content	%
e	excess of air	%
H	hydrogen content	%
$NCV_{m/HW}$	net calorific value ratio of a material m to the total household waste	%
$MR_{m/HW}$	mass ratio of a material m to the total household waste	%
N	nitrogen content	%
n_{O_2}	number of oxygen molecules	mol
O	oxygen content	%
Q_{HCl}	quantity of HCl in non-treated flue gases	kg·capita^{-1}·year^{-1}
Q_{lime}	quantity of lime required	kg·capita^{-1}·year^{-1}
S	sulphur content	%
$V_{air_{th}}$	theoretical volume of air	Nm^3·ton^{-1}
V_{FG}	volume of flue gases	Nm^3·ton^{-1}
ΔNCV	net calorific value variations in comparison to the reference situation	%

Indices

R	reference situation

European Union wants to impose on the member countries from 2010 onwards [5].

– The production of electricity from heat recovered through incineration is of no economic interest. There is indeed no electricity market because of the EDF (Electricité de France) monopoly. The produced electric power is therefore sold to EDF, production and sale costs balancing out roughly [4]. Conversely, direct use of heat is profitable from an economic point of view, provided that the heat consumer is located near the waste-to-energy facilities. As a matter of fact, the heat market is virtually non-existent since the transportation and storage of heat are not feasible. As a result, the value of heat depends exclusively on the presence of a nearby consumer. In that case, the price of heat reaches 15.24 euros per MWh [4]. In the opposite case, the value of heat may be negative if expenses are needed to disperse it. From then on, the use of the recovered heat falls into the domain of the town and country planning policy.

– The incineration of waste raises environmental concerns especially because it may generate atmospheric pollution. The detection of some dioxins has noticeably undermined the public image of incineration plants these last years. However, this waste treatment process has the advantage of limiting the emissions of gases playing a role in the greenhouse effect.

The European Community has recently decided to increase the recycling of waste. Firms launching packages into the market, for example, have to plan on their recovery as recyclable material. Experience obtained in the field of recycling indicates that the costs involved after a selective collection are on the average twice those of incineration [2]. The recycling policy was encouraged by the desire to spare non-renewable resources, and also by the control of environmental impacts, although not proven at the time. This last aspect is examined in this paper, by assessing environmental impacts in several scenarios including both recycling and waste-to-energy of household waste.

2. General methodology

Life Cycle Assessment (LCA) is a tool of environmental evaluation that has gained wide acceptance in the past decade. This method does provide the elements necessary for the development of an environmental policy combining consistence and transparency. LCA deals with listing and quantifying environmental burdens and related impacts caused by a product, process or activity [6], on the basis of mass-energy balances and the product's total life cycle. The "cradle-to-grave" approach encompasses the extraction and processing of raw materials, the manufacturing and assembly processes, product distribution, use, re-use, maintenance, recycling and final disposal. This "cradle-to-grave" approach takes into account every upstream and downstream steps included in the life cycle of a process so that it enables to identify the pollution transfers that may occur as well as possible future consequences. For instance, driving an electric car avoid emissions involved in the greenhouse effect by comparison with the use of a diesel car, however if the electric power required is produced from coal contribution to the greenhouse effect is still noteworthy: driving is not polluting any more, but supplying electricity is. This is why the Commission of the European Communities has taken LCA as the basis for its Integrated Product Policy [7]. It is also worth mentioning the creation of an international standard (ISO 14040-43) [8–11] for LCA, which is being reviewed and evaluated.

A brief account of LCA could be the following. The LCA's objectives are diagnostic, improvement, control and choice. A first step involves completing an inventory based on the mass and energy balances. A second step deals with impact assessment, which is carried out by means of models (the modelling of transfer phenomena among environments, for example, uses transport models [12]).

The aforementioned considerations set-up the context of the present study devoted to the urban waste treatment by waste-to-energy.

Table 1
Data related to the material recycling

	Paper/cardboard	Plastics				Glass	Steel	Aluminium	Total
		PVC	PET	PE	Total				
P_{TM} (%)	27.00	0.75	0.94	3.30	4.99	11.00	2.46	0.60	46.05
C_{TM} (kg·capita^{-1}·year^{-1})	94	3	3	11	17	38	9	2	161
NCV_{TM} (%)	34				14	0	1	1	50

P_{TM}: Proportion of targeted materials in the household waste flux [13,14].
C_{TM}: Consumption of targeted materials, calculated from the functional unit (348 kg of household waste per capita per year).
NCV_{TM}: Contribution of targeted materials to the net calorific value of household waste.

3. Goal and scope of the study

3.1. Possible changes in the waste-to-energy treatment

The set-up of the pre-sorting and collection of household waste leads to quantitative and qualitative changes in fluxes at the incinerator inlet that affect outlet fluxes from both quantitative and qualitative points of view.

With regard to the incinerator, a number of conditions related to the net calorific value and the waste flow rate have to be fulfilled to keep the plant running in optimal working conditions. Moreover, changes in net calorific value may affect the production of energy from waste incineration making it necessary to seek other energy sources. In view of the foregoing, the present study aims to identify the materials by means of which recycling might disrupt energy production, and then assess the environmental benefits of the energy recovery. Finally, the treatment of flue gases may also be affected by changes at the incinerator's inlet since the dosage of reagents (e.g., lime) depends both on the effluent flow rate and the pollutants' concentration.

With respect to the bottom ash, changes in its composition are likely to involve its downgrading, meaning that it may not be recyclable any more. This study will first identify the materials by means of which the recycling may induce the downgrading of bottom ash, and then assess the quantity of aggregate needed to replace it as a road embankment material.

The final point of analysis will concern the treatment of fly ash (stabilisation and solidification) geared to final disposal. Changes in the residues composition may certainly require that the treatment process be adapted to meet the norm.

3.2. Materials for recycling

Materials targeted for recycling are the following: glass, plastics, paper and cardboard, aluminium, and steel. The proportions of these targeted materials in the household waste flux before the set-up of the pre-sorting are shown in Table 1 [13,14]. Glass and metals are collected in curbside recyclable containers where citizens voluntarily bring the sorted materials. Plastics are collected from door-to-door, and a sorting centre is set up for paper and cardboard collection. The recycling of glass consists of producing brown glass since sorting according to the colour is not conducted yet. As for metals, after a refining step, aluminium is reintroduced in the melting process as a substitute for primary aluminium. The recycled steel originates both from the source sorted collection and the recovery of ferrous metals from bottom ash, and it is used as scrap metal in steelmaking. The collection of paper and cardboard includes newspapers and magazines as well as packages made of at least 50% of these materials. The recycling market of paper and cardboard is quite fluctuating. There are many possibilities for recycling paper, however, the main prospect is the manufacturing of corrugated packaging. Finally, prospects for plastic recycling are still under development and include pipes (drainage, wastewater), punnets, plastic films, clothes, etc.

3.3. Solid waste treatment operations

In existing waste-to-energy plants, incineration, energy recovery, and processing of solid residues operate together. In addition to the combustion chamber, incineration facilities include the treatment process of flue gases (with lime), which is based, after the separation from fly ash (by means of an electrostatic precipitator), on a dry system, and a handling process of bottom ash which involves a quench bath and a magnetic device for the recovery of ferrous metals.

In reference to energy recovery, the boilers, which are used to recover heat from the cooling of flue gases, deliver steam for district heating and hot water as well as process steam for industrial use. Electric power is produced for self-consumption purposes, and the electricity surplus is sold to EDF (Electricité de France). The quantities of energy recovered from waste incineration before the setting up of pre-sorting and collection of household waste are presented in Table 2 [15].

Table 2
Energy production operated by waste incineration (1995) [15]

	Energy (MJ)	Energy (kJ·capita^{-1}·year^{-1})
District heating and hot water	862 500	750
Industrial steam	46 000	40
Electricity sold to EDF	289 000	252
Electricity for self-consumption	103 500	90

The handling of solid residues deals with the recycling of bottom ash and the stabilisation/solidification and final disposal of fly ash.

3.4. Functional unit and system boundaries

The functional unit is the quantified performance of a product system to be used as a reference unit in a LCA study [8]. The primary purpose of the functional unit is to serve as reference for inputs and outputs. So the functional unit is fundamental at the stage of comparability of LCA results and/when several systems are assessed.

In this study, the functional unit is defined as the treatment of 348 kg of household waste per capita per year, and it is based on the data obtained from an urban and semi-urban geographical area, named "Grand Lyon" (France), which covers 48,700 hectares and a population of 1,150,000 inhabitants. In this way, the functional unit meets the three unities: the unity of product, the unity of service and the unity of time.

Based on this functional unit, the influence of the source-separated household waste collection on the waste-to-energy treatment is assessed in the case of two scenarios (Scenarios 1 and 2) and compared with a reference scenario for which there is no source-separation of household waste (Scenario 0, corresponding to a material recovery rate of 0%). Scenario 1, based on real case studies, considers an overall material recovery rate of 35% [16]. The details are provided in Table 3. This scenario can be viewed as the most likely to exist. Conversely, Scenario 2 hypothesises a 100% material recovery rate, accounting for a maximum theoretical scenario.

The system boundaries encompass the material recovery, the incineration treatment including the recovery of energy and ferrous metals, the recycling of bottom ash, the treatment of fly ash and the final disposal of waste. Moreover, the system boundaries include life cycle of products for which the production can be avoided thanks to recycling, that is to say glass, aluminium, steel, paper and cardboard, and plastics, which are salvaged at the sorting centre, but also aggregate, which can be replaced by treated bottom ash. The scenarios on which the assessment of the non-production of raw materials is based are shown Table 4. The production of heat by means of boilers is also taken into account with the view to compare it with the use of energy recovered from waste-to-energy facilities. Fig. 1 summarises the processes included in the study. Transport is taken away from the scope of the study, neither from collection to treatment nor from treatment to materials use stages, this for two reasons. First, the aim of the study is to assess both technical and environmental consequences of a waste pre-sorting on waste-to-energy facilities, and transport has nothing to do with it. Second, the environmental benefits of the material recycling are assessed all the same. To this end, the production of materials from raw materials is compared with the production of materials from recycled ones. The scenarios of material production from raw materials encompass all operations taking place before the introduction of recycled materials in the production process (especially raw material production and production processes). Once again, transport is beyond the scope of the study. However, if one thinks transport is worth considering, it can be easily assumed that the distance covered from collection to treatment is not significantly different from the distances covered from collection to sorting centre and from sorting centre to treatment. As a matter of fact, sorting centres and waste-to-energy facilities are often located at the same place. Moreover, transport of recycled materials from the sorting centre to the production site may be, at worse, similar to the transport of raw materials from the extraction site to the production site, and more likely the distance covered may be shorter for recycled materials. Thus, there is little chance of transport being more environmentally detrimental in the case of recycling, justifying its exclusion from the system boundaries.

3.5. Data: sources, hypotheses, and quality

The mass and energy fluxes related to material packaging production which are used to assess the environmental benefits due to the material recycling are taken from Habersatter [17]. Otherwise, most of data are obtained from the waste-to-energy plant's operators, and will not be shown here for the sake of clarity and concision of the paper but are available somewhere else [15]. It is worth noticing that these

Table 3
Constitutive parameters of material recovery scenarios

	P/C	Plastic	Glass	FM	Aluminium	Average
Scenario 0						
Recovery rate (%)	0	0	0	0	0	0
Scenario 1						
Collection rate (%)	45	35	60	50	50	
Refusal rate* (%)	35	35	0	35	35	
Recovery rate (%)	29.3	22.8	60.0	32.5	32.5	35.4
Scenario 2						
Recovery rate (%)	100	100	100	100	100	100

P/C: paper/cardboard, FM: ferrous materials.
* The refusal rate represents the ratio of material refused at the sorting center to material collected.

Table 4
Scenarios considered for the assessment of the non-production of raw materials

Material	Steps of production taken into account	Avoided function
Aluminium	– production of limestone, bauxite, rock salt, coke, tar – production of alumina, aluminium fluoride, anodes – pyrometallurgy and electrolysis	Primary aluminium production (Bayer process)
Glass	– production of calcine, sand, soda, limestone, dolomite, feldspar	All production processes upstream from the native glass drop
Plastics		Native plastics production
– PVC	– production of rock salt and chlorine electrolysis – refining of oil and cracking of ethylene – monomer and PVC production	
– PET	– refining of oil and steam cracking leading to the formation of ethylene glycol and dimethyl terephtalate – PET production	
– PEhd	– refining of oil and steam cracking – PEhd production	
Steel	– iron ore production – blast furnace	Primary steel production
Paper/cardboard	– production of chemical reagents and wood – production of non bleached pulp	Native pulp production for corrugated cardboard

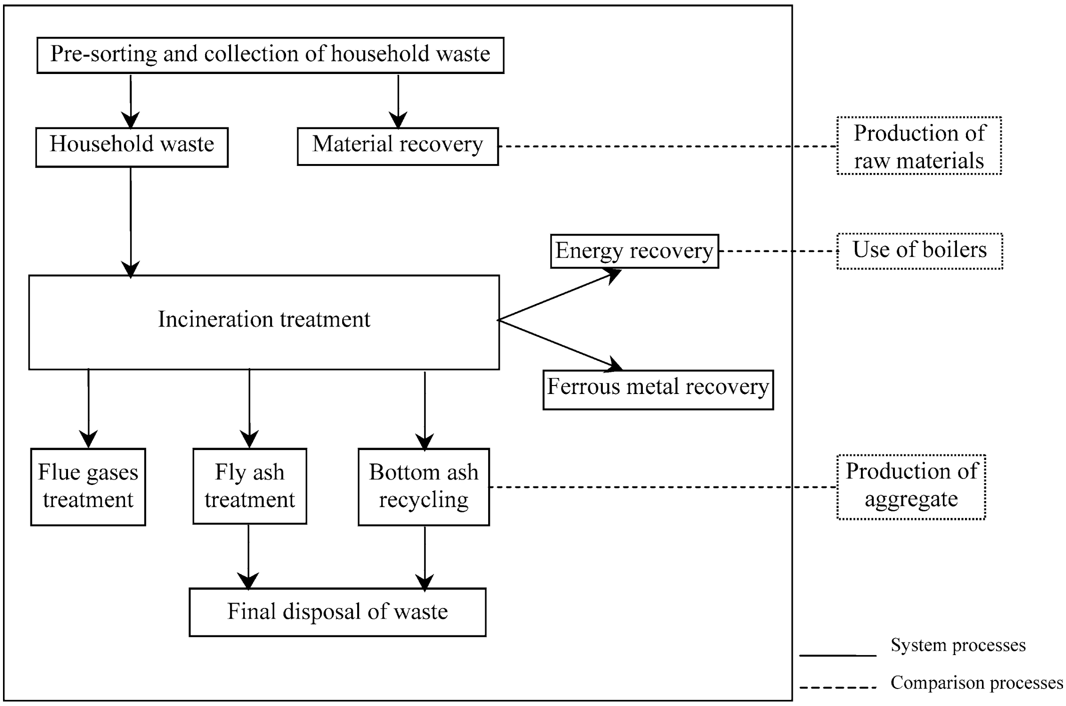

Fig. 1. Scope of the study.

data have been compared with bibliographic references (especially [18]): they are in concordance with national data.

The quality of collected data has been estimated according to the data quality matrix proposed by Weidema and Suhr Wesnos [19]. Scores are attributed according to several quality indicators, namely reliability, completeness, as well as temporal and geographical correlation; scores range from 1 to 5 as the data quality decreases. The data analysis reported by Wenisch [15] shows that in general the data quality is quite satisfactory. A poor data quality was observed for the treatment process of fly ash, justification of this point not be emphasised in this study. The same applies for gaseous emissions due to the energy recovery. Despite the medium quality of data related to material production, this bibliographic reference [17] will be used here since numerous LCA studies are based on it.

4. Inventory analysis

Environmental loads are calculated from mass-energy balances and expressed as environmental impacts. The impacts taken into account in this study are resource depletion, air pollution (including toxicity, acidification, and greenhouse effect), water pollution and production of waste.

4.1. Material recycling

The environmental benefits caused by the recycling of material (scenarios 1 and 2) compared with the reference situation (unsorted material collection) are presented in Table 5. These environmental benefits are assessed supposing recycled materials are used instead of raw materials, what amounts to assess the non-production of raw materials. This assessment is based on the quantification of two points: the saving of resources and the prevention of pollution.

With regard to the saving of resources, it is worth mentioning that the sorted material collection and the recycling may save energy, up to 1500 MJ·capita^{-1}·year^{-1} in the case of Scenario 1, and up to 4943 MJ·capita^{-1}·year^{-1} in the case of Scenario 2. The detailed calculations show that saving of electric power is due mainly to aluminium recycling whereas most of the saving of thermal energy is due to paper/cardboard (66%) and plastics (22%) recycling.

With respect to prevention of pollution, the recycling of glass is mainly responsible for a decrease in air toxicity, especially in dust production, as compared to the use of raw materials. Also, since the manufacturing of paper/cardboard from virgin fibres leads to aqueous streams containing high values of chemical oxygen demand, the recycling of these materials plays an important role in preventing water toxicity. Another result worth of mention is that the acidification potential, mainly caused by nitrogen oxides and sulphur oxides, is reduced to a large extent through the recycling of glass and paper/cardboard. Finally, the data related to waste are more specifically the quantities of prevented waste obtained through material recovery, as compared to the production of materials from raw materials. From this point of view, the benefits of the material recovery are obvious, except in the case of glass. This material is never recycled to a 100% for economic reasons, since the second-generation material is made of both raw and recycled glass. As a result, part of the recovered glass is bound anyway to disposal, justifying in this way the negative values in Table 4.

4.2. Waste-to-energy treatment

In this section, attention will first be given to the working conditions of incinerators, more specifically to their load factor and the net calorific value of waste. The treatment of flue gases will be then discussed and it will be followed by the assessment of environmental impacts.

4.2.1. Working conditions

The waste-to-energy facilities under study (see Table 2) have a rated capacity of 12 tons·h^{-1}, the suitable load factor is assessed to be 85% (corresponding to a household waste flux of 10.2 tons·h^{-1}). If the load factor ranges from 85 to 100%, the plant may be in an overload situation, if it is beyond 100% the plant may be in a saturation situation. In the present case, the flow rate value of waste to be incinerated is 10 tons·h^{-1}, which accounts for 98% of the suitable load factor, meaning that before the set-up of a source-separated household waste collection, waste-to-energy plants are working in conditions close to overloading. This situation can be corrected through the pre-sorting and recycling of targeted materials since a part of waste is diverted from the incineration treatment. Fig. 2 shows how material recovery can reduce the load factor of the waste-to-energy facilities. According to Scenario 1, the rated situation can be reached again, with an 72% load factor, corresponding to a waste flow rate value of 8.6 ton·h^{-1}. Scenario 2,

Table 5
Environmental benefits induced by material recycling

	Saving of resources				Prevented pollution			
	NRM$^{(1)}$	Biomass$^{(1)}$	Water$^{(2)}$	Energy$^{(3)}$	Air toxicity$^{(2)}$	Water toxicity$^{(2)}$	AP$^{(4)}$	Waste$^{(2)}$
Scenario 1	11.7	59.5	1.5	1500	73	26	182	1.5
Glass	–	–	–	239	51	–	97	−0.1
Aluminium	3.5	–	–	136	3	3	3	0.4
Steel	3.5	–	0.3	–	11	–	4	–
Paper/cardboard	–	59.5	1.2	852	7	22	67	1.1
Plastics	4.7	–	–	273	1	1	11	0.1
Scenario 2	65.4	200	5.1	4943	159	83	470	5.4
Glass	–	–	–	341	83	–	157	−0.2
Aluminium	11.7	–	–	68	11	4	15	1.3
Steel	11.7	–	0.8	375	32	–	22	0.1
Paper/cardboard	–	200	4.3	2966	29	76	224	3.9
Plastics	42	–	–	1193	4	3	52	0.3

–: not significant or nonexistent; NRM: non renewable materials; AP: acidification potential.
$^{(1)}$ kg·capita^{-1}·year^{-1}; $^{(2)}$ m^3·capita^{-1}·year^{-1}; $^{(3)}$ MJ·capita^{-1}·year^{-1}; $^{(4)}$ g·capita^{-1}·year^{-1}.

which accounts for a 100% material recovery rate, leads instead to a 40% decrease of the load factor, meaning that undercapacity working conditions will be achieved. In both cases, is was demonstrated that paper/cardboard and plastics had the biggest impact in the reduction of the waste flow rate.

Net calorific value (NCV) of household waste can be estimated according to two types of data. First, the data collected through the energy recovered at the output of the incinerator and available to the waste treatment plant, and second, the information obtained through calculations based on the NCV of each type of incinerated components and their respective parts in the waste. A NCV of 9100 $kJ\cdot kg^{-1}$ has been obtained from operators of the waste-to-energy facilities and a value of 8200 $kJ\cdot kg^{-1}$ has been calculated, the difference between sources reaching 10% can be considered as satisfactory. The rated conditions of the waste-to-energy facilities are 7900 $kJ\cdot kg^{-1}$ (data obtained from operators), so that the reference situation corresponds to a thermal overload operation. The evolution of the NCV resulting from the source-separated collection of household waste is assessed from the mass fractions of the recovered materials and their respective NCV. From these calculations, it appears that Scenario 1 leads to a slight increase (2.1%) of the NCV of waste, whereas Scenario 2 causes a 6.7% decrease of this parameter as shown in Table 6. It can be deduced from this that the recovery of glass and steel results in an increase of the household waste NCV. These materials do not actually take part in the global NCV, so their recovery does not affect the initial heat content of waste but they reduce the total mass of household waste that consequently leads to an increase in the NCV value expressed in $kJ\cdot kg^{-1}$. The recovery of plastics and paper/cardboard, on the other hand, involves a decrease of the global NCV due to the high contribution of these materials to the NCV of household waste. With respect to aluminium, its NCV value is quite low. Its recovery, however, leads to a decrease of global NCV because it has a very small mass ratio ($MR_{\mathrm{m/HW}}/NCV_{\mathrm{m/HW}} < 1$). All in all, both scenarios produce a slight variation of the household waste NCV value, so it is difficult to draw any positive conclusion. However, it would be interesting to find out in which way the recovery of each material affects the global NCV of household waste as discussed above.

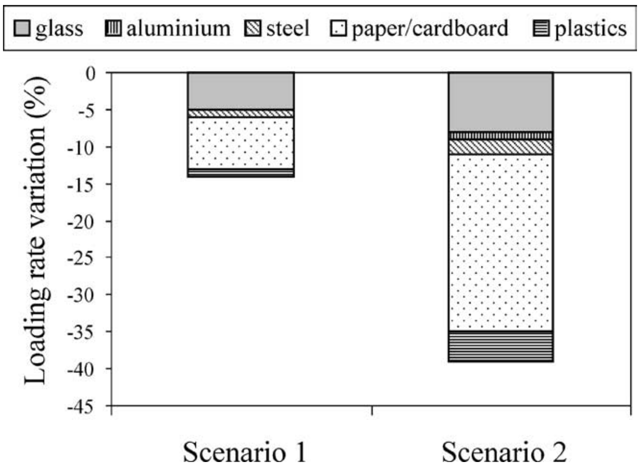

Fig. 2. Variation of the loading rate due to material recycling.

4.2.2. Flue gases treatment

Besides influencing the working conditions of incinerators, material recovery also influences the flue gases treatment. The lower flow rate of waste to be incinerated causes a decrease in the volume of flue gases and a reduction in hydrochloric acid concentration, which consequently leads to a cut-down in the consumption of lime. Without a set-up of a material recovery, the lime quantity needed for the flue gases treatment reaches 6 kg per ton of household waste (that is to say 2 $kg\cdot capita^{-1}\cdot year^{-1}$), allowing the hydrochloric acid concentration to be reduced from 1200 $mg\cdot Nm^{-3}$ (2 $kg\cdot capita^{-1}\cdot year^{-1}$) down to 11 $mg\cdot Nm^{-3}$ (16 $g\cdot capita^{-1}\cdot year^{-1}$). The flue gases volumes have been calculated through the following equations [15], deduced from [20]:

$$V_{\mathrm{air_{th}}} = \frac{100}{21}\cdot 0.0224\cdot n_{\mathrm{O_2}} = 1060\cdot\left(\frac{\mathrm{C}}{12}+\frac{\mathrm{S}}{32.2}+\frac{\mathrm{H}}{4}-\frac{\mathrm{Cl}}{4\cdot 35.5}-\frac{\mathrm{O_2}}{32}\right)$$

$$V_{\mathrm{FG}} = 224\cdot\left(\frac{\mathrm{C}}{12}+\frac{\mathrm{S}}{32.2}+\frac{\mathrm{Cl}}{35.5}+\frac{\mathrm{N}}{28}\right) + \left(\frac{e}{100}+0.79\right)\cdot V_{\mathrm{air_{th}}}$$

Table 6
Change in household waste NCV due to material recovery

	Glass	Aluminium	Steel	Paper/cardboard	Plastics	Total
Scenario 1						
$MR_{\mathrm{m/HW}}$ (%)	5.4	0.2	0.8	8.1	1.2	15.7
$NCV_{\mathrm{m/HW}}$ (%)	0.0	0.3	0.3	9.9	3.2	13.7
ΔNCV (%)	+5.7	−0.1	+0.5	−2.0	−2.0	+2.1
Scenario 2						
$MR_{\mathrm{m/HW}}$ (%)	9.0	0.6	2.5	28.0	5.1	44.6
$NCV_{\mathrm{m/HW}}$ (%)	0	1	1	34	14	50
ΔNCV (%)	+9.9	−0.4	+1.5	−8.3	−9.4	−6.7

$MR_{\mathrm{m/HW}}$: mass ratio of a material m to the total household waste.
$NCV_{\mathrm{m/HW}}$: NCV ratio of a material m to the total household waste.
ΔNCV: NCV variations in comparison to the reference situation.

where $V_{\mathrm{air_{th}}}$ is the theoretical volume of air ($\mathrm{Nm^3 \cdot ton^{-1}}$), n_{O_2} is the number of oxygen molecules necessary to a complete combustion (mole), C, S, H, Cl, O, N, are the elemental contents (%), V_{FG} is the flue gases volume ($\mathrm{Nm^3 \cdot ton^{-1}}$), and e is the excess of air (%).

The results shown in Table 7 are based on the elemental composition of household waste and recovered materials. First, it is worth mentioning that because of their combustible nature, only paper/cardboard and plastics contribute to flues gases volume and HCl concentration. Materials such as glass, steel and aluminium are not eligible because they are not combustible. A close look at Table 7 reveals that the material recovery is responsible for a decrease of the flue gases volume, reaching 16% in Scenario 1 and 57% in Scenario 2. In addition, paper/cardboard recovery plays a more important role in reducing the flue gases volume than the plastics due to the high carbon content of paper/cardboard (39%) compared to the one found in plastics (11%). Results related to the HCl quantity in the non-treated flue gases also show that flue gases volume is also reduced through the recovery of paper/cardboard and plastics. The same applies to the quantity of lime required to accurately treat the flue gases, the lime consumption being directly proportional to the HCl concentration. In both cases, plastic recovery is the one contributing the most to the observed reduction now that plastics have the highest chlorine elemental content (31% of the chlorine content of household waste).

4.2.3. *Environmental impacts*

The last aspect to be discussed is the influence of the material recovery on environmental impacts. The prevented environmental impacts are assessed on the basis of critical volumes from the substances discharged in the reference situation on one hand, and the withdrawal of polluting fractions belonging to collected materials on the other hand. The final results are presented in Table 8. The recovery of paper/cardboard and plastics proved to be the most influential in the reduction of toxic air pollution. These materials are combustible contrary to other materials collected. Therefore, and according to the elemental composition of materials, diverting paper/cardboard and plastics from incineration leads to the reduction of the emission of compounds containing nitrogen, sulphur and cadmium. As far as toxic water pollution is concerned, concentrations of heavy metals like zinc, lead, chromium, copper, nickel, arsenic, cadmium, and mercury range from 29 to 240 $\mathrm{mg \cdot capita^{-1} \cdot year^{-1}}$ in the reference situation, and can be reduced between 0 and 4.6 $\mathrm{mg \cdot capita^{-1} \cdot year^{-1}}$ for Scenario 1, and between 0.3 and 17.1 $\mathrm{mg \cdot capita^{-1} \cdot year^{-1}}$ for Scenario 2, through the recovery of paper/cardboard and plastics. From a quantitative point of view, chlorine resulting from the flue gases treatment contributes to a large extent to water pollution in the aqueous form of chloride, and its occurrence is especially linked to the quantity of plastics which is incinerated. When considering the acidification resulting from the incineration

Table 7
Influence of material recovery on the flue gases treatment

	Scenario 1		Scenario 2	
	Paper/cardboard	Plastics	Paper/cardboard	Plastics
ΔV_{FG} ($\mathrm{Nm^3 \cdot ton^{-1}}$)	−559	−129	−1849	−602
$\Delta V_{\mathrm{FG}}/V_{\mathrm{FGR}}$ (%)	−13	−3	−43	−14
ΔQ_{HCl} ($\mathrm{kg \cdot capita^{-1} \cdot year^{-1}}$)	−0.06	−0.16	−0.18	−0.72
$\Delta Q_{\mathrm{HCl}}/Q_{\mathrm{HClR}}$ (%)	−3	−8	−9	−36
ΔQ_{lime} ($\mathrm{kg \cdot capita^{-1} \cdot year^{-1}}$)	−0.06	−0.16	−0.18	−0.72
$\Delta Q_{\mathrm{lime}}/Q_{\mathrm{lime}\,R}$ (%)	−3	−8	−9	−36

V_{FG}: volume of flue gases; Q_{HCl}: quantity of HCl in non-treated flue gases; Q_{lime}: quantity of lime required; Index R: reference situation.

Table 8
Influence of material recovery on environmental impacts

	Scenario 1	Scenario 2
Toxic air pollution (10^6 $\mathrm{m^3 \cdot capita^{-1} \cdot year^{-1}}$)		
Materials	P/C: −1.3 Plastics: −0.5 Total: −1.8	P/C: −4.2 Plastics: −2.1 Total: −6.3
Components	NO_x: −0.7 SO_2: −0.7 Cd: −0.4	NO_x: −2.5 SO_2: −2.2 Cd: −1.2 HCl: −0.1 Zn, Pb, Ni, As: −0.3
Toxic water pollution ($\mathrm{m^3 \cdot capita^{-1} \cdot year^{-1}}$)		
Materials	Plastics: −144.7	Plastics: −625.5
Acidification potential ($\mathrm{g \cdot capita^{-1} \cdot year^{-1}}$)		
Materials	P/C: −35 Plastics: −10 Total: −45	P/C: −120 Plastics: −43 Total: −163
Components	NO_x: −26 SO_2: −19	HCl: −6 NO_x: −91 SO_2: −66
Global warming potential ($\mathrm{kg \cdot capita^{-1} \cdot year^{-1}}$)		
Material	Plastics: −14	Plastics: −60

P/C: paper/cardboard.

Table 9
Energy recovery: influence of extra energy supply

	Energy loss ($MJ \cdot capita^{-1} \cdot year^{-1}$)	Critical volume ($10^6\ m^3 \cdot capita^{-1} \cdot year^{-1}$)	ΔAP ($g \cdot capita^{-1} \cdot year^{-1}$)	ΔGWP ($kg \cdot capita^{-1} \cdot year^{-1}$)
Scenario 1				
Paper/cardboard	174	2.1	68	9.1
Plastics	41	0.8	19	2.3
Steel	13	0.05	7	1.1
Aluminium	13	0.05	10	–
Total	241	3.1	104	12.5
Scenario 2				
Paper/cardboard	580	7.2	238	30.3
Plastics	240	2.9	93	11.4
Steel	21	0.3	8	1.7
Aluminium	21	0.3	11	1.1
Total	862	10.7	350	44.5

of household waste, it appears that once again, the compounds called into question, that is hydrochloride, nitrogen oxides and sulphur dioxide, originate from paper/cardboard and plastics. Finally, the greenhouse effect induced by incineration is mostly due to carbon dioxide since it is produced to a much larger amount than nitrogen oxides or methane (several magnitude categories). Their contribution to the greenhouse effect is assessed using the well-known GWP (Global Warming Potential). As it is usually done in most LCA studies, only the CO_2 of fossil origin is considered to take part into the greenhouse effect. The CO_2 coming from the biomass burning is really the one supposed to be part of the carbon cycle. So, a reduction of the GWP is observed through plastics recovery.

4.3. Energy recovery

The set-up of the pre-sorting and collection of household waste involves a decrease of the quantity of combustible materials, which in turn would lead to a decrease of energy production. It is necessary to make up for this energy loss since the energy initially produced is recovered to deliver steam for district heating and hot water, process steam for industrial use, and to generate electric power. Two solutions can be considered: the first one is to seek additional boilers, and the second is the increase of the energy recovery rate. Both possibilities are discussed below.

The environmental impacts induced by the use of additional boilers are assessed by assuming 50% of coal-fired boilers and 50% of oil-fired boilers. Table 9 shows in the first place that paper/cardboard and plastics are the materials held responsible for recovery to induce the highest loss of energy if compared to the reference situation, for both collection scenarios. No value about glass is reported since this material plays no significant role in energy recovery. Environmental impacts resulting from the replacement of energy recovery by the energy produced by boilers are then reported for each material. The analysis of results shows the use of boilers involves an increase of toxic air pollution (see critical volume) as well as of the acidification potential and the greenhouse effect. Furthermore, toxic air pollution and acidification potential are mainly caused by NO_x and SO_2 with a rough contribution of 50/50. Other pollutants like CO, HC, HCl and dust have trifling effects.

Table 10
Consequences of material recovery on solid residues

Materials	Part of solid residues affected by material recovery	Decrease of the bottom ashes flux ($kg \cdot capita^{-1} \cdot year^{-1}$) Scenario 1	Scenario 2
Paper/cardboard	Combustible and fines	2.2	8.1
Plastics	Combustible and fines	–	0.5
Steel	Ferrous metals	1.1	3.0
Aluminium	Non-combustible	0.3	1.1
Glass	Non-combustible	17.0	28.9
Total		20.6	41.6

The second solution to the energy loss problem is to increase the energy recovery rate of waste-to-energy facilities. This parameter is actually quite low, since the reference situation corresponds to a value of 28%, while a French mean value reaches 67% with a minimum of 20% and a maximum of 80% [21]. Therefore, it would be necessary to increase the energy recovery rate up to 34% in the case of Scenario 1, and up to 60% in the case of Scenario 2, in order to make up for the lost energy. This approach is quite interesting insofar as no additional environmental burdens are induced, maintaining this way the environmental benefits of energy recovery.

4.4. Bottom ash recycling

Bottom ash is made of non-combustible materials, ferrous metals that have not been recovered, and ash resulting from the incineration of fines and combustibles materials. Concerning this aspect, Table 10 shows the part taken by each material targeted by the selective collection. Since the material recovery affects the flux of waste at the incinerator's inlet, it also affects the flux of bottom ash. According to the results given in Table 10, glass is the material that contributes the most to reduce bottom ash production. In the

Table 11
Impacts of material recovery on fly ash treatment

	Scenario 1	Scenario 2
Flying ashes flux (%)	−9%	−33%
Energy consumption (Wh·capita^{-1}·year^{-1})	−4	−12
Water consumption (L·capita^{-1}·year^{-1})	0.3	1.0
Reagent consumption	no change	no change
Hydraulic binder (kg·capita^{-1}·year^{-1})	−0.2	−0.5

reference situation, solid residues are recovered and used as embankment material, meaning that the non-produced quantity of bottom ash must be replaced by aggregate. Thus, whereas the production of 65 kg·capita^{-1}·year^{-1} of aggregate was initially prevented, this amount falls down to 44.4 kg·capita^{-1}·year^{-1} in the case of Scenario 1 and to 23.4 kg·capita^{-1}·year^{-1} in the case of Scenario 2 as a result of material recycling.

The selective collection of household waste is also likely to induce the downgrading of bottom ash since a change in its elemental content may occur. Glass is the material by means of which recovery may create the largest downgrading risk, as its removal from the waste flux involves a concentration increase of heavy metals, sulphates and chlorides in bottom ash. It can be concluded then that Scenario 2 is more capable of inducing a downgrading of bottom ash than Scenario 1.

4.5. *Treatment of fly ash*

Fly ash is mostly due to the incineration of fines and combustible materials, which means that the quantity and quality of fly ash may be affected by the removal of paper/cardboard and plastics. In Scenario 1, the fly ash downgrading risk is not significant since the elemental content variations with respect to chlorine, fluorine, sulphur and heavy metals are lower than 10%. In Scenario 2, these values range between 15 and 48%, increasing the downgrading risk.

Since this study does not focus on the treatment of fly ash, details will not be provided regarding this aspect. Nevertheless, the main results are summarised in Table 11, which shows that the most probable recovery scenario (Scenario 1) leads to non significant changes with respect to the fly ash treatment.

5. Interpretation

5.1. *Technical consequences*

As it appeared in the inventory analysis, the selective collection of household waste has some positive technical consequences. First, it allows the initial overload working conditions to be corrected by decreasing the waste flux at the incinerator's inlet. Second, the qualitative changes of this flux have an effect on waste NCV, and more specifically, the recovery of glass induces an increase of the NCV value. Third, the decrease of the HCl concentration in the flue gases due to the material recovery results in a cut-down of the lime consumption.

However, the main drawback of the selective collection of household waste is that it involves a decrease of the energy produced by waste incineration mainly caused by the recovery of paper/cardboard and plastics. Therefore the loss of energy recovered makes it necessary to seek either alternative energy resources or better energy recovery rate, so as to meet the initial energy demand.

5.2. *Environmental consequences*

Environmental benefits that take place out of the territory are obvious since material recovery prevents the extraction of raw materials and drastically reduces the quantity of waste intended to final disposal.

Environmental benefits inside the territory, on the contrary, remain more controversial, especially because of the use of additional boilers, which aim to make up for the loss of energy recovered from the waste incineration. Nonetheless, the additional production of energy is compensated by energy saving achieved through material recovery. The same applies for the greenhouse effect. The production of CO_2 due to the use of boilers is compensated by the non-combustion of plastics that are recycled. Moreover, the selective household waste collection allows the environmental burdens involved in the incineration treatment to be partially reduced. The environmental performance of waste-to-energy facilities have improved for the most part as a result of the recovery of the combustible fraction of waste, namely paper/cardboard and plastics. So, a decrease of air pollution can be obtained through the recovery of these materials, which affects in particular the amounts of NO_x, SO_2 and cadmium released into the environment. In regard to the water pollution, which is due mostly to chlorides, its reduction is linked more specifically to the recovery of plastics. Finally, since the recovery of paper/cardboard and particularly of plastics, leads to a reduction of both the flue gases volume and the HCl concentration in non-treated flue gases, it allows the reduction of the lime consumption to take place, which reflects in resources savings.

6. Conclusion

The goal of the present study was to assess both technical and environmental consequences caused by the set-up of a source-separated household waste collection with regard to existing waste-to-energy facilities. To this end, a life cycle assessment has been conducted, with system boundaries that encompassed material recycling, incineration treatment, energy recovery and handling of solid residues. The technical aspects taken into account in this study were the load factor of incinerators, the net calorific value of waste, the treatment of flue gases, the recycling of bottom ash and the treatment of fly ash. From the environmental point of view, the studied impacts were the resource depletion, air toxicity, the acidification, the greenhouse effect, water pollution and production of waste.

Regarding the technical field, the benefits brought about by the selective collection of waste were obvious, since it allowed the improvement of the working conditions of incinerators. Environmental benefits, especially inside the territory, were, on the contrary, less obvious due to the loss of energy recovered during the incineration of waste. As a matter of fact, the environmental benefits induced by waste recycling were compensated by use of additional boilers. The life cycle assessment stressed that an improvement of the energy recovery rate of incinerators may be of great interest with the view to achieving real environmental benefits.

In the light of this study, the life cycle assessment has proved to be an interesting and successful tool for the study of energy systems, and from a more general perspective, for its applications in the field of energy. In this field in particular, like in any other field, LCA may be used in five different ways. First in ecodesign, so the environmental aspects are considered as soon as possible. Second, in the selection of the most environmental-friendly process among several alternatives. Third, in the improvement of a process as a result of the identification of steps inducing the strongest impact on the environment. Fourth, in the management of a process by comparing its performance with a reference. Finally, in the comparison of several processes fulfilling the same services with respect to regulations.

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