Material and energy recovery in integrated waste management systems. An evaluation based on life cycle assessment

Michele Giugliano, Stefano Cernuschi, Mario Grosso *, Lucia Rigamonti

Politecnico di Milano – DIAR, Environmental Section, P.zza Leonardo da Vinci, 32, 20133 Milano, Italy

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A B S T R A C T

This paper reports the environmental results, integrated with those arising from mass and energy balances, of a research project on the comparative analysis of strategies for material and energy recovery from waste, funded by the Italian Ministry of Education, University and Research. The project, involving the cooperation of five University research groups, was devoted to the optimisation of material and energy recovery activities within integrated municipal solid waste (MSW) management systems.

Four scenarios of separate collection (overall value of 35%, 50% without the collection of food waste, 50% including the collection of food waste, 65%) were defined for the implementation of energetic, environmental and economic balances. Two sizes of integrated MSW management system (IWMS) were considered: a metropolitan area, with a gross MSW production of 750,000 t/year and an average province, with a gross MSW production of 150,000 t/year.

The environmental analysis was conducted using Life Cycle Assessment methodology (LCA), for both material and energy recovery activities. In order to avoid allocation we have used the technique of the expansion of the system boundaries. This means taking into consideration the impact on the environment related to the waste management activities in comparison with the avoided impacts related to the saving of raw materials and primary energy.

Under the hypotheses of the study, both for the large and for the small IWMS, the energetic and environmental benefits are higher than the energetic and environmental impacts for all the scenarios analysed in terms of all the indicators considered: the scenario with 50% separate collection in a drop-off scheme excluding food waste shows the most promising perspectives, mainly arising from the highest collection (and recycling) of all the packaging materials, which is the activity giving the biggest energetic and environmental benefits. Main conclusions of the study in the general field of the assessment of the environmental performance of any integrated waste management scheme address the importance of properly defining, beyond the design value assumed for the separate collection as a whole, also the yields of each material recovered; particular significance is finally related to the amount of residues deriving from material recovery activities, resulting on average in the order of 20% of the collected materials.

1. Introduction

This paper reports the environmental results of the research project “Material and energy recovery in integrated waste management systems” on the comparative analysis of strategies for material and energy recovery from waste, funded by the Italian Ministry of Education, University and Research. The project, whose background a scope are depicted in Consonni et al. (2011), has involved the cooperation of five University research groups, and was devoted to the optimisation of material and energy recovery activities within integrated municipal solid waste (MSW) management systems.

The study was conducted by firstly identifying the different energy and materials recovery strategies to be considered, and defining in detail, for each of them, the system boundaries, the plant and data requirements, the hypotheses adopted and the mass flows. Special attention was given to the role of different collection systems (kerbside and drop-off; mono-material and multi-material) and their corresponding performance in the separation of recyclables. Kerbside collection is characterised by the absence of any stable street container, as citizens are asked to hang out daily the different waste fractions based on a detailed collection schedule; on the contrary, drop-off collection relies on the presence of stable street containers for the different fractions, where citizens are free to dispose waste at any time of the day and any day of the week.

Irrespective of the two types of collections, waste fractions can be collected on a mono- or on a multi-material basis. The latter case includes a number of different aggregations of fractions,
generally based on economic issues and on the easiness of subsequent sorting.

This has led to the definition of four scenarios of overall source separate collection for the implementation of energetic, environmental and economic balances, developed in the second stage of the project. A detailed description of the rationale behind the definition of scenarios is given in Consonni et al., 2011.

The environmental analysis was conducted using Life Cycle Assessment methodology (LCA) following the ISO standards, for both material and energy recovery activities. This methodology applied to alternative waste management strategies is becoming a commonly utilised tool for addressing the decision makers (Finnveden, 1999), but only a few studies analysed MSW management from a system perspective. Many LCA studies are in fact focused on the single sections of the waste management system (i.e. waste collection schemes, pre-treatment technologies, waste-to-energy plants, packaging materials recycling activities, composting or anaerobic digestion plants, landfills), while others compare different treatments used in the disposal of single fractions (i.e. food and green waste, packaging materials, unsorted residual waste). On the other hand, studies that analyse MSW management from a system perspective cover the whole waste stream with the aim of evaluating the total impact of possible changes in the collection system and in the treatment of specific fractions. For example, Eriksson et al. (2005) analysed different combinations of incineration, material recycling of separated plastic and cardboard containers, and biological treatment of biodegradable waste in comparison with landfilling. The evaluation covered use of energy resources, environmental impact and financial and environmental costs. Kirkeby et al. (2006) evaluated the environmental impacts from MSW management in the municipality of Aarhus in Denmark. In Buttoli et al. (2007) the LCA methodology is used to support the development of the new waste management plan for Bologna District, where three scenarios characterised by different types of collection and different waste treatment methods have been compared. De Feo and Malvano (2009) compare twelve management scenarios operating on a provincial scale in Southern Italy, characterised by a separate collection varying in the range of 35–80% and different options in the disposal of treatment residues. Rigamonti (2009) analysed material recovery from source-separated materials and energy recovery from the unsorted residual waste, with the final aim to evaluate possible optimum levels of separate collection that lead to the most favourable energetic and environmental results. Finally, Calabrò (2009), starting from the average composition of gross waste in Italy, has assessed the effect of separate collection on greenhouse gases emissions from municipal waste management.

In general, the main conclusion of the studies that analyse the whole MSW management system is that to reduce the overall energy demand and the emission of pollutants in the environment, an integrated approach to MSW management should be adopted, since the planning of separate collection can have major effects on the different subsequent treatments. Still the debate is ongoing about the complementary or antithetic role of material vs. energy recovery. This paper aims to provide some indications about the optimisation of material and energy recovery activities within integrated waste management systems (IWMS). The comparison among different IWMS should allow the identification of the best practices in terms of typology of separate collection and treatments for the collected materials and the residual waste.

2. Materials and methods

2.1. Integrated waste management scenarios

The different scenarios of IWMS analysed in this study are depicted in Fig. 1. Each scenario starts with the separate collection of packaging materials and eventually of organic wastes (green and food waste). These materials are sent to material recovery (i.e. recycling or composting), whereas the unsorted residual waste is sent to energy recovery in a dedicated waste-to-energy (WTE) plant. In the sensitivity analysis we have also analysed the case of anaerobic digestion instead of composting for food waste.

According to Consonni et al. (2011), two sizes of IWMS were considered: a large metropolitan area, with a gross MSW production of 750,000 t/year and an average province, with a gross MSW production of 150,000 t/year. The size plays a major role when some of the waste treatment plants (namely the WTE ones) are designed. Larger WTE plants are in fact more efficient in terms of electricity production than smaller ones due to several factors, as described in Consonni et al. (2005), including economic scale effects (it makes economic sense for larger plants to adopt more sophisticated configurations of the steam cycle), a better efficiency of large steam turbines compared to small one, a lower relative energy requirement for the auxiliary equipment of the plant (European Commission, 2006a,b; Reimann, 2005).

An extended literature survey (Rigamonti et al., 2008) supported with specific evaluations focused on representative Italian districts was carried out, with the aim of characterising real and sustainable interception levels for each waste fraction. Interception levels were differentiated according to the collection scheme hypothesised (i.e. drop-off or kerbside, multi-material or monomaterial). The three overall levels of source separation achieved in the different scenarios have been defined according to the
targets set by the Italian Legislative Decree 152/06: 35% (end of year 2006), 50% (end of year 2008), 65% (end of year 2012).

Each scenario is solely based on drop-off collection, or solely on kerbside collection: possible hybrid situations (which are actually carried out at some Italian municipalities) were not considered in this study. When it comes to the specific collection typology, in each scenario a proper mixture of mono-material and multi-material systems was selected. In particular:

- The first scenario (D-35) is based on a drop-off collection system with 35% of overall separate collection. It does not include the collection of food waste, which is typically not convenient with this kind of system, due to the low quality of the collected material. It is made up by a paper mono-material collection, a glass–plastics–metals multi-material collection (so called “heavy multi-material”) and an ecological platform where wood, green waste and metals are delivered.
- The second scenario (D-50) is made up by paper, plastics and glass mono-material drop-off collections, whereas wood, green waste and metals are delivered in ecological platforms. The only possibility to reach the 50% target of separate collection is to assume the highest interception levels for all the materials. So, we can state that 50% is a sort of upper physiological limit for a mono-material drop-off waste collection which does not include food waste separate collection.
- The third scenario (K-50) is made up by kerbside mono-material collections only, except for wood, green waste and metals that are delivered in the ecological platform. The interception levels adopted to give the overall value of 50% are included between minimum and maximum literature values for each waste fraction, including food waste.
- The fourth scenario (K-65) relies on a kerbside collection system, including the separation of the food waste, that reaches the overall separate collection value of 65%. It is made up by paper, glass and food waste mono-material collections with interception levels approaching the maximum literature values, while plastics and metals are collected together (“light multi-material”). Moreover, wood, green waste and metals are delivered in the ecological platform.

Table 1 summarises the interception levels assumed for each scenario. In the scenario K-50, the interception levels for the packaging materials have been reduced compared to those assumed in the scenario D-50. Moreover, all interception levels of the packaging materials in the scenario K-65 are also lower (with the exception of that for plastics) than those assumed in the scenario D-50, because the gap to achieve the 65% level is filled up by the food waste collection.

### 2.2. Waste of reference

The composition of the gross municipal waste (i.e. the waste produced upstream any form of collection) used in this study is representative of Italian average (Fig. 2). This was obtained by combining the data of source-separated waste derived from the “Waste Report” compiled by APAT-ONR, with a number of representative analyses of the unsorted residual waste (URW) which is disposed of.

Special attention was dedicated to the fraction “fines” included in the gross waste, which represents a significant amount (13%) and it is formally defined as the material smaller than 20 mm. This was split between a fraction of inert material (accounting for 30% of fines) and a fraction of organic material (accounting for 70% of fines) assimilated to food waste in the modelling of the collection.

### 2.3. Material recovery: selection and recycling efficiencies

Before being addressed to the material recovery industry, each source-separated stream needs a selection stage to separate inappropriate materials from the recoverable ones. The selection efficiency is the parameter that measures the amount of material which is actually addressed to recovery.

Table 2 reports the selection efficiencies of mono-material collections assumed for the different scenarios.

In the case of multi-material collection, a further preliminary separation stage is required before selection in order to split the different waste fractions. Table 3 shows the composition of multi-material streams of scenarios D-35 and K-65.

In the scenario D-35, a heavy multi-material collection is active. After separation, residues account for 7% and are mainly composed by plastics. Moreover, we have assumed that separated iron (4.5% of the stream) and aluminium (0.5% of the stream) are then

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Table 1: Collection efficiency for each material in the four scenarios analysed (values in percentage).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Scenario D-35</th>
<th>Scenario D-50</th>
<th>Scenario K-50</th>
<th>Scenario K-65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>65.0</td>
<td>70.0</td>
<td>47.0</td>
<td>64.0</td>
</tr>
<tr>
<td>Wood</td>
<td>64.0</td>
<td>88.0</td>
<td>65.0</td>
<td>80.0</td>
</tr>
<tr>
<td>Plastics</td>
<td>4.7</td>
<td>57.0</td>
<td>45.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Glass</td>
<td>62.0</td>
<td>96.0</td>
<td>60.0</td>
<td>90.5</td>
</tr>
<tr>
<td>Metals no Al</td>
<td>55.4</td>
<td>70.0</td>
<td>27.5</td>
<td>40.0</td>
</tr>
<tr>
<td>Aluminium</td>
<td>55.1</td>
<td>92.0</td>
<td>34.0</td>
<td>88.0</td>
</tr>
<tr>
<td>Food waste</td>
<td>0.0</td>
<td>0.0</td>
<td>48.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Green waste</td>
<td>75.0</td>
<td>100.0</td>
<td>75.0</td>
<td>92.0</td>
</tr>
</tbody>
</table>

Table 2: Selection efficiency of mono-material collections.

<table>
<thead>
<tr>
<th>Waste fractions</th>
<th>References</th>
<th>Selection efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron/Steel</td>
<td>CNA (2006)</td>
<td>90.0</td>
</tr>
<tr>
<td>Aluminium</td>
<td>CIAL (2005)</td>
<td>95.0</td>
</tr>
<tr>
<td>Glass</td>
<td>COREVE (2005)</td>
<td>94.2</td>
</tr>
<tr>
<td></td>
<td>Examined plants</td>
<td>86.0</td>
</tr>
<tr>
<td>Paper</td>
<td>Ambiente Italia – Comieco (2001)</td>
<td>95.5</td>
</tr>
<tr>
<td></td>
<td>Examined plants</td>
<td>98.0</td>
</tr>
<tr>
<td>Wood</td>
<td>Examined plants</td>
<td>86.5</td>
</tr>
<tr>
<td>Plastic</td>
<td>Adapted from Arianna (2000)</td>
<td>65.0</td>
</tr>
<tr>
<td></td>
<td>Examined plants</td>
<td>84.5</td>
</tr>
<tr>
<td>Green waste</td>
<td>CITEC (2004)</td>
<td>80.0</td>
</tr>
<tr>
<td>Food waste</td>
<td>CITEC (2004)</td>
<td>80.0</td>
</tr>
</tbody>
</table>
selected with an efficiency of 94% and 85%, respectively. Separated glass (73% of the stream) is selected with an efficiency of 70% (COREVE, 2005) and separated plastics (15% of the stream) are selected with an efficiency of 50%.

In the scenario K-65, a light multi-material collection is active. If total waste flow at the separation plant is considered, about 75% is made by recoverable plastics, that is then selected with an efficiency of 56%, which is higher than that in the scenario D-35 because of the absence of glass contamination. Recoverable iron and aluminium are about 6.7% and 1.7%, respectively, and they are then selected with the same efficiencies as scenario D-35.

Finally, all the selected fractions are addressed to the actual recycling processes, that are characterised by their own efficiency. So, again, an extended literature survey supported with specific evaluations focused on representative Italian plants was carried out to identify the recovery efficiencies for each material. The results are shown in Table 4.

Both green waste and food waste are addressed to a composting plant. Process losses and screening residues are, respectively, 50% and 20% of the inlet flow (CITEC, 2004); compost thus represents about 30% of the inlet flow. In the alternative option of anaerobic digestion, evaluated within the sensitivity analysis, we have supposed that the produced digestate amounts to 260 kg per tonne of organic fraction in input and the compost produced from this digestate is about 100 kg. The biogas is used in engines for the production of electricity (obtaining about 180 kWh net per tonne of organic fraction in input).

2.4. Materials sent to energy recovery

We have assumed that the unsorted residual waste (URW) is sent to a WTE plant, together with all residues from the sorting of multi-material collection and from the selection of each source-separated material (selection residues – SR).

By subtracting from each fraction of the gross waste the corresponding amount of intercepted and selected material, one can obtain the composition of the overall residual waste that is sent to energy recovery, which is then constituted by the sum of URW and SR.

Further fluxes of waste, constituted by the residues of the recycling activities (recycling residues – RR), might be well suited for energy recovery, as it is the case for paper, plastics and wood recovery. We have assumed these materials to be directly sent to energy recovery, after proper mixing with the other residual waste. On the other side, the residues from the recycling of iron and aluminium, mainly constituted of slag, are disposed of in landfill. Finally, the recycling of glass does not produce any residue, being 100% the efficiency of glass production furnaces (Table 4).

2.5. Main hypotheses in the life cycle assessment

The environmental analysis was conducted, for both material and energy recovery activities, using the Life Cycle Assessment methodology (LCA) (Finnveden, 1999; Finnveden et al., 2005; Moberg et al., 2005; Pennington et al., 2004; Rebitzer et al., 2004), following ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards.

The functional unit is the amount of MSW to be managed, i.e. 750,000 t/year and 150,000 t/year for the large and small IWMS, respectively.

In order to avoid allocation we have used the expansion of the system boundaries technique. This means taking into consideration the impact on the environment related to the waste management activities in comparison with the avoided impacts related to the saving of raw materials and primary energy. In particular, we have supposed that:

- The secondary materials produced by the recycling of the packaging waste replace the corresponding primary materials (i.e. those produced starting from virgin raw materials). An exception is the recycling of the polyolephinic mix obtained from plastic selection: in this case, we have supposed that the recycled mix replaces for 1/3 sand, 1/3 wood and 1/3 nothing (because it is assumed to be used for new applications without actual substitution). Moreover, we have taken into account the possible degradation of plastic, paper and wood during the recycling process, i.e. the fact that the quality of secondary materials may be worse than that of primary materials, using a substitution ratio of 0.81, 0.83, and 0.6, respectively: this means that 1 unit of secondary material replaces <1 unit of primary material (Rigamonti et al., 2009b). A detailed description of primary and secondary productions used in the study can be found in Rigamonti et al. (2009a) and Rigamonti and Grosso (2009).

- 34% of the compost produced during the composting or anaerobic digestion of food and green waste is used in garden centres in substitution of peat, 62% in agriculture in substitution of mineral fertilizers with the same content of nutrients (N, P and K) and 4% in environmental reclamations without any substitution (Blengini, 2008; Rigamonti et al., 2010).

- The electricity produced in the anaerobic digestion plant considered in the sensitivity analysis is supposed to displace the same amount of electricity produced by the thermoelectric Italian mix as of year 2007, fuelled by coal for 18%, fuel oil for 9%, natural gas for 10% and natural gas in combined cycles for 63% (Terna, 2008).

- The material sent to energy recovery is directly treated in a WTE plant, whose performances were modelled in Consonni and Viganò (2011) as part of this research project. Two different
Two characterisation methods were used: the Cumulative Energy Demand – CED (Jungbluth and Frischknecht, 2004), and the CML 2001 (CML et al., 2001), to evaluate the environmental impacts. In this second method, properly adapted according to Rigamonti (2007), the following impact categories have been selected:

- Global Warming Potential (GWP100), which accounts for the emission of greenhouse gases; we recall that in GWP100 only fossil CO2 emission are considered, since biogenic ones (i.e. those deriving from the aerobic decomposition – thermal or biological – of carbon contained in biomass) have a null global warming potential. Then for this study we have not accounted for biogenic CO2 emissions. It has also to be kept in mind that the time horizons of CO2 emissions are relatively different in the systems considered, with a very short-time release for WTE plants and longer one for composting and especially landfilling; in this sense, the GWP100 indicator is based on a 100 years time horizon (IPCC, 2007).
- Human Toxicity Potential (HTP), which includes a wide range of toxic substances: in this study, we have added the impact of the secondary fine particulate in order to better take into account the atmospheric situation of the North of Italy (Lonati et al., 2008).
- Acidification Potential (AP), which accounts for the emissions of NOx, SOx and ammonia.
- Photochemical Ozone Creation Potential (POCP), which accounts for the substances that cause the photochemical ozone production in the troposphere: in this study, we have eliminated the distinction between NO and NO2 and we have added NOx (as NO2) because, in most of the processes, the emission factor is given as NOx and it is not always straightforward to split it properly. Moreover, we have added the characterisation factor for NMVOC as a whole (Heijungs, 1992).

Normalisation and weighting, defined as optional elements in ISO standards, were not performed in this study due to the uncertainty associated with the calculation of the normalisation factors (Heijungs et al., 2007) and the loss of transparency in the results when weights are used (Reap et al., 2008).

3. Results and discussion

3.1. Quantity of secondary materials and of residues

Table 7 reports, for each scenario, the splitting of materials collected with source separation between the different fluxes: collection of particular wastes (i.e. batteries, medicines, used oil etc. corresponding to the fraction “other” of the gross municipal waste), secondary material obtained from the recovery operations, SR, RR and process losses that take place during composting. On the other hand, Table 8 shows, for each scenario, the quantity of material sent to the energy recovery stage, given by the sum of URW, SR and the residues of wood, paper and plastic recycling. By considering 100 kg of gross municipal waste as the reference input flux, main results obtained might be outlined as follows:

- 35 kg of waste source separated with a drop-off collection system (and therefore excluding the food waste) lead to 22.4 kg of new secondary materials (including 1.9 kg of green compost), while the material sent to energy recovery amounts to 71.1 kg;
- 50 kg of waste source separated with a drop-off collection system (and therefore excluding the food waste) lead to 32.4 kg of new secondary materials (including 2.6 kg of green compost), while the material sent to energy recovery amounts to 60.0 kg.
50 kg of waste source separated with a kerbside collection system including the food waste lead to 27.4 kg of new secondary materials (including 6.4 kg of compost), while the material sent to energy recovery amounts to 58.8 kg.

65 kg of waste source separated with a kerbside collection system including the food waste lead to 34.1 kg of new secondary materials (including 7.9 kg of compost), while the material sent to energy recovery amounts to 49.5 kg.

In conclusion, the material recovery produces a quantity of residues which is on average 20% of the collected materials. This means that when separate collection levels ranging from 35% to 65% are reached, the total amount of residues to be disposed of is included between 70% and 50% of the MSW produced, respectively; most of these residues can actually be sent to energy recovery, in order to optimise the overall performance of the IWMS.

3.2. Life cycle assessment results

We remind that in a LCA study, a negative result indicates a benefit for the environment (avoided impacts are bigger than added impacts) whereas a positive one indicates a disadvantage. Such an approach has its limitations, being not suitable for assessing waste prevention activities. In this sense it might lead to the false conclusion that, in case of negative results, the more waste you produce the more advantages for the environment you get. Assessment of waste prevention is out of the scope of this paper.

Table 7
Destinations of the material intercepted with source separation (%).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Selective collection (fraction “other” of the gross waste)</th>
<th>Secondary material (obtained after material recovering)</th>
<th>Selection residues – SR (separation + selection)</th>
<th>Recycling residues – RR</th>
<th>Process losses during composting</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-35</td>
<td>3.1</td>
<td>22.4</td>
<td>4.2</td>
<td>1.9</td>
<td>0.2</td>
<td>3.2</td>
</tr>
<tr>
<td>D-50</td>
<td>3.1</td>
<td>32.4</td>
<td>6.5</td>
<td>3.2</td>
<td>0.2</td>
<td>4.3</td>
</tr>
<tr>
<td>K-50</td>
<td>3.1</td>
<td>27.4</td>
<td>6.5</td>
<td>2.6</td>
<td>0.1</td>
<td>10.6</td>
</tr>
<tr>
<td>K-65</td>
<td>3.1</td>
<td>34.1</td>
<td>11.8</td>
<td>2.8</td>
<td>0.1</td>
<td>13.2</td>
</tr>
</tbody>
</table>

- Residues from paper, wood and plastic recycling which are sent to energy recovery.
- Slag from iron and aluminium recovery sent to landfill.

Table 8
Material sent to energy recovery (%).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Unsorted residual waste – URW</th>
<th>Selection residues – SR</th>
<th>Paper, plastic and wood recycling residues – RR-E</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-35</td>
<td>65.0</td>
<td>4.2</td>
<td>1.9</td>
<td>71.1</td>
</tr>
<tr>
<td>D-50</td>
<td>50.3</td>
<td>6.5</td>
<td>3.2</td>
<td>60.0</td>
</tr>
<tr>
<td>K-50</td>
<td>49.7</td>
<td>6.5</td>
<td>2.6</td>
<td>58.8</td>
</tr>
<tr>
<td>K-65</td>
<td>34.9</td>
<td>11.8</td>
<td>2.8</td>
<td>49.5</td>
</tr>
</tbody>
</table>

- 50 kg of waste source separated with a kerbside collection system including the food waste lead to 27.4 kg of new secondary materials (including 6.4 kg of compost), while the material sent to energy recovery amounts to 58.8 kg.
- 65 kg of waste source separated with a kerbside collection system including the food waste lead to 34.1 kg of new secondary materials (including 7.9 kg of compost), while the material sent to energy recovery amounts to 49.5 kg.

In conclusion, the material recovery produces a quantity of residues which is on average 20% of the collected materials. This means that when separate collection levels ranging from 35% to 65% are reached, the total amount of residues to be disposed of is included between 70% and 50% of the MSW produced, respectively; most of these residues can actually be sent to energy recovery, in order to optimise the overall performance of the IWMS.

3.2. Life cycle assessment results

We remind that in a LCA study, a negative result indicates a benefit for the environment (avoided impacts are bigger than added impacts) whereas a positive one indicates a disadvantage. Such an approach has its limitations, being not suitable for assessing waste prevention activities. In this sense it might lead to the false conclusion that, in case of negative results, the more waste you produce the more advantages for the environment you get. Assessment of waste prevention is out of the scope of this paper.
as it requires a different approach in the modelling. And we have to bear in mind that when a whole IWMS is considered, waste prevention can lead only to very minor effects compared to the total waste produced.

Fig. 3 shows the LCA results for the four scenarios in the large IWMS, when the residual waste is sent to the WTE plant producing only electricity. The figure is divided in two parts: on the top it shows the quantities of packaging materials and organic fractions yearly collected in each scenario, whereas on the bottom it reports for each scenario the impact indicators expressed in percentage, where the indicator of the scenario performing best is set equal to −100%. In this way, all the indicators can be represented in the same graph having overcome the problem of their different units of measures but maintaining at the same time for each indicator both the real sign and the scenarios ranking. Fig. 4 shows the LCA results for the four scenarios in the large IWMS, but when the residual waste is sent to the WTE plant operating in a CHP mode. Fig. 4 can be directly compared to Fig. 3 because the percentage values of the indicators are calculated assuming as a reference the scenario D-50 with the residual waste

![Figure 3](image1.png)

**Fig. 3.** Impacts of the different scenarios of the large IWMS when the residual waste is sent to the WTE plant producing only electricity. The indicators of the scenario D-50 when the residual waste is sent to the WTE plant producing only electricity are set equal to −100%.

![Figure 4](image2.png)

**Fig. 4.** Impacts of the different scenarios of the large IWMS when the residual waste is sent to the WTE plant operating in a CHP mode (the indicators of the scenario D-50 when the residual waste is sent to the WTE plant producing only electricity are set equal to −100%).

![Figure 5](image3.png)

**Fig. 5.** Impacts of the different scenarios of the small IWMS (the indicator of the scenario performing best is set equal to −100%).

![Figure 6](image4.png)

**Fig. 6.** Global warming indicator for the different scenarios analysed in the large IWMS when the residual waste is sent to the large WTE plant producing only electricity.
sent to the large incinerator producing only electricity. Finally, Fig. 5 shows the LCA results for the four scenarios in the small IWMS.

As shown in Figs. 3–5, all the impact indicators for the four scenarios analysed, both in the large and in the small IWMS, have a negative value: this means that the energetic and environmental gains associated with material and energy recovery are higher than the energetic and environmental impacts due to MSW management. In all cases the best scenario is the D-50: this is because it is the one that allows the highest collection (and recycling) of all the packaging materials, which is the activity that produces the biggest energetic and environmental benefits.

Comparing the two cases for the large IWMS (Figs. 3 and 4), almost all of the indicators improve when the WTE plant operates in CHP mode, the only exception being represented by the acidification potential, which is substantially unchanged. In particular, the benefit associated with the global warming indicator increases by 20–48% according to the different scenarios considered.

Fig. 6 shows, as an example, the global warming indicator for the four scenarios in the large IWMS when the residual waste is sent to the WTE plant producing only electricity. The indicator is split between the three major contributions: recycling of packaging materials, composting of food and green waste, energy recovery from the combustible residues. It can be noticed that the main contribution is the one associated with the recycling of packaging materials. Energy recovery has a positive or negative sign mainly depending on the content of fossil carbon in the combustible residues. This value comes from the composition of combustible residues and in the four scenarios it is respectively 12.3%, 10.5%, 10.6% and 14% (as percentage in weight). Composting shows benefits, but only when it is applied to green waste alone (scenarios D-35 and D-50). The global warming indicator for the composting of food waste (like the other indicators, not shown here) is in fact positive in sign. This is due to the combination of two factors: first, the significant impact of the collection that requires an average of 65 km per tonne and second, the small benefits associated with the substitution of peat and mineral fertilizers. The situation slightly improves when food and green wastes are sent to anaerobic digestion instead of composting (Table 9), but the advantages are still modest in comparison with those of the recycling of packaging materials (Fig. 7).

Indeed, the material recovery allows a different benefit for each material. In general, for the impacts calculated in this research, the most significant advantage is associated with the recycling of aluminium, followed by iron, glass, plastic, paper and finally wood (Fig. 7).

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Table 9
Comparison between the impact indicators for scenarios K-50 and K-65 in the large IWMS when food and green waste are sent to composting (base case) and when they are sent to anaerobic digestion – AD (sensitivity analysis) (the residual waste is in both cases sent to the large WTE plant producing only electricity).

<table>
<thead>
<tr>
<th></th>
<th>K-50</th>
<th>K-65</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per year</td>
<td>Composting</td>
</tr>
<tr>
<td>CED</td>
<td>GJ eq.</td>
<td>-7,171,139</td>
</tr>
<tr>
<td>GWP</td>
<td>t CO₂ eq.</td>
<td>-107,783</td>
</tr>
<tr>
<td>AP</td>
<td>t SO₂ eq.</td>
<td>-1049</td>
</tr>
<tr>
<td>HTP</td>
<td>t 1,4-DCB eq.</td>
<td>-111,696</td>
</tr>
<tr>
<td>POCP</td>
<td>t C₂H₄ eq.</td>
<td>-92</td>
</tr>
</tbody>
</table>

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Fig. 7. Global warming indicator for the recovery of each material (expressed in kg CO₂ eq. per tonne of collected material) (AD = anaerobic digestion; C = composting).
4. Conclusions

The study shows that all the impact indicators for the four scenarios analysed, both in the large and in the small IWMS, have a negative value: this means that the energetic and environmental gains associated with material and energy recovery are higher than the energetic and environmental impacts due to MSW management. In all cases the scenario performing best is the D-50, with 50% separate collection in a drop-off scheme excluding food waste: this is because it is the one that allows the highest collection (and recycling) of all the packaging materials, which is the activity that produces the biggest energetic and environmental benefits.

In LCA evaluations the recycling of packaging materials is always energetically and environmentally convenient, especially for metals, glass, homogenous plastic and paper. On the contrary, the indicators for the composting of food waste are positive in sign, due to the combination of two factors: first, the significant impact of the collection that requires an average of 65 km per tonne and second, the small benefits associated with the substitution of peat and mineral fertilizers. The situation slightly improves when food and green wastes are sent to anaerobic digestion instead of composting, but the advantages are still modest in comparison with those of the recycling of packaging materials. This explains why, when comparing the different scenarios, the one with the highest value of separate collection (K-65) is not the one performing best. In fact, this scenario is characterized by high yields of green and food waste at the expense of the packaging materials.

When the large IWMS is considered, the CHP operation of the WTE plant allows to improve environmental performances compared to the electric-only functioning.

According to these general considerations, we can conclude that two important aspects should be always taken into consideration in the planning of a new MSW management system, or in the improvement of an existing one.

First, it has to be kept in mind that the material recovery produces a quantity of residues which is on average 20% of the collected materials. This means that overall separate collections ranging from 35% to 65% produce residues to be disposed of in a quantity included between 70% and 50% of the MSW produced, respectively; most of these residues can actually be sent to energy recovery, in order to optimise overall performances of the system. This indication is important for a proper design of the plants for the treatment of the residual waste.

Second, in order to assess the environmental performances of an integrated waste management scheme, the overall value of the separate collection is of scarce significance if the yields for each material are not specified. The results of the impact indicators are in fact strictly related to the recycling rate of each material, and not to the overall percentage of separate collection, which might be similar for very different composition of the collection. This means that targets defined on the total percentage of separate collection have scarce significance and should be possibly replaced (or integrated) by specific targets on the recovery of the different fractions.

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References


