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Greenhouse gases emission from municipal waste management: The role of separate collection

Paolo S. Calabrò *

Dipartimento di Meccanica e Materiali, Università degli Studi Mediterranea di Reggio Calabria, via Graziella – loc. Feo di Vito, 89122 Reggio Calabria, Italy

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ABSTRACT

The municipal solid waste management significantly contributes to the emission in the atmosphere of greenhouse gases (e.g. CO_2, CH_4, N_2O) and therefore the management process from collection to treatment and disposal has to be optimized in order to reduce these emissions. In this paper, starting from the average composition of undifferentiated municipal solid waste in Italy, the effect of separate collection on greenhouse gases emissions from municipal waste management has been assessed. Different combinations of separate collection scenarios and disposal options (i.e. landfilling and incineration) have been considered. The effect of energy recovery from waste both in landfills and incinerators has also been addressed. The results outline how a separate collection approach can have a significant effect on the emission of greenhouse gases and how wise municipal solid waste management, implying the adoption of Best Available Technologies (i.e. biogas recovery and exploitation system in landfills and energy recovery system in Waste to Energy plants), can not only significantly reduce greenhouse gases emissions but, in certain cases, can also make the overall process a carbon sink. Moreover it has been shown that separate collection of plastic is a major issue when dealing with global warming relevant emissions from municipal solid waste management.

1. Introduction

Global Warming caused by the emission in the atmosphere of Greenhouse Gases (GHG) (e.g. CO_2, CH_4, N_2O) already has a significant impact on climate and other related issues (i.e. agriculture, forestry, tourism, fishery) raises important questions concerning human development in the near future. In fact one of the main tasks the World must undertake is that of reducing emissions of Global Warming relevant gases without diminishing economic and social development.

The Municipal Solid Waste (MSW) management significantly contributes to these emissions. In fact, according to Skovgaard et al. (2008), the direct GHG emissions from waste management in the year 2005 represented 2.6% of the total emissions in the EU-15.

In order to reduce GHG emissions, an integrated approach to MSW management from the beginning of the process (i.e. waste collection) should be adopted since the planning of separate collection can have major effects on the different subsequent treatments.

An integrated approach to MSW management requires a series of actions and techniques aimed firstly at minimizing the waste production at source, then at reducing the risk to public health and the environment and finally at improving its treatability. Subsequently, separate collection of waste should maximize the quantity and the quality of recyclable materials. Nevertheless, the objective of separate collection is not only the separation of useful materials but also the reduction of the impact of MSW by removing from waste flux items containing dangerous substances, such as batteries, wastes from electric and electronic appliances and drugs. Therefore separate collection represents a real pre-treatment of waste before subsequent treatment. Non-recyclable waste should be, if suitable, treated in Waste to Energy (WTE) plants in order to enable the production of energy in the form of electricity and heat. Simple incineration should be used only when energy recovery is unfeasible or not financially viable. In this paper the term "incinerator" thus refers only to a plant which disposes of waste by combustion without energy recovery whereas the term "Waste to Energy Plant" (WTE plant) is used when amounts of energy are produced during the process.

In this approach, landfilling is the final and absolutely essential step of MSW management, needed to dispose of non-recyclable bottom ash and slag as well as non-combustible waste.

Recent scientific literature presents a large number of studies dealing with the analysis of GHG emissions from MSW management (see for example Skovgaard et al., 2008; Kirkeby et al., 2006a,b; Choate et al., 2005; USEPA, 2002; Thorneloe et al., 2002; Eschenroeder, 2001) mainly carried out by Life Cycle Assessment (LCA). Several of these studies (Skovgaard et al., 2008; Choate et al., 2005; USEPA, 2002) assess GHG emissions for different waste fractions (e.g. food and garden waste, aluminium, steel, plastic,

* Tel.: +39 0965 875 222; fax: +39 0965 875 201.
E-mail address: paolo.calabro@unirc.it

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paper) and different treatments (recycling, incineration, landfilling) while other studies deal with the evaluation of overall GHG emissions from a specific management system already in operation or in the planning phase (Kirkeby et al., 2006b; Thorneloe et al., 2002) considering various management options. These studies demonstrate how recycling can allow a reduction of GHG emissions while incineration and landfilling performance greatly depends on the technologies adopted (i.e. energy recovery both from landfilling and incineration, accurate control of biogas emissions from landfilling).

This paper aims to evaluate how the separate collection approach can influence the emissions of greenhouse gases from MSW management. In the analysis carried out only emissions of CH_4 and CO_2 due to waste management are considered while energy produced is converted in avoided CO_2 emissions considering the average CO_2 emission for each kWh of electricity produced in Italy. Table 1 shows the MSW management unit operations considered in this paper. Waste collection and transport have not been considered since related literature (Skovgaard et al., 2008; USEPA, 2002) shows how emissions related to these operations are significantly lower than those due to waste treatment. Moreover these emissions depend slightly on the approach taken for separate collection: in general if the various treatment plants (recycling plants, incinerators, WTE plants, landfills) are located at the same distance from the collection area greenhouse gases emissions due to transport of the various waste fractions are almost identical.

2. Separate collection scenarios

In order to simulate separate collection, the average composition of MSW in Italy adopted in a previous research work was used (Calabrò, submitted for publication; see Table 2). In such a composition those materials, present in very small quantities and not easily assessable (e.g. toner and computer ink printer cartridges, drugs, batteries and accumulators) or separately collected with specific settings and methodologies (e.g. electric and electronic appliances, pieces of furniture and bulky waste) in order to remove them before incineration or disposal in landfill, have not been considered.

Although this procedure leads to some unavoidable simplifications and, probably, to an overestimation of the presence of inert waste, the adopted composition of the undifferentiated waste can be considered sufficiently representative of the Italian situation. Nevertheless, the presence in MSW of inert materials in quantities higher than 10% is mentioned in other studies related to industrialized countries (Rodriguez-Añòn et al., 1998; Ljungrenn Söderman, 2003). The adopted waste composition is significantly similar to the one at European level (paper and cardboard, 35%; food and garden waste, 25%; plastic, 11%; glass, 6%; metals, 3%; textiles, 2%; others, 18% (EIONET, 2008)).

The water content of each waste material at the moment of the delivery to the collection system has been assessed thanks both to literature data (De Fraja Frangipane and Cossu, 1995; APAT, 2005) and, especially, to direct laboratory measurement (see Table 2).

Different levels of separation rate and different approaches to separate collection have been considered in this research (see Table 3 adapted from Calabrò, submitted for publication):

Separate collection of food and garden waste (Organics), paper and cardboard, metals, plastic, wood, textiles – Approach A – separation rates considered (15%, 35% and 50%).

Separate collection of food and garden waste (Organics), paper and cardboard, metals, wood, textiles (plastic is not recovered in this approach) – Approach B – separation rates considered (15%, 35% and 50%).

Separate collection of paper and cardboard, metals, plastic, wood, textiles (food and garden waste is not collected in this scenario) – Approach C – separation rates considered (15% and 35%).

The combination of the approaches and of the separate collection rates presented above gives a total of eight scenarios. The hypothesis of performing no separate collection has been also considered, making a total of nine scenarios.

The hypothesis of avoiding plastic recycling (Approach B) has been included since the separate collection of plastic has been recently debated. Against a non-negligible cost for collection, transport and recycling the material produced is only slightly attractive for the industry because it is often not competitive in terms of quality and cost with virgin plastic. Especially where the request for recycled plastic is minimal, during the planning of MSW management, the option of avoiding the separate collection of plastic should be properly evaluated. Nevertheless issues such as the increase in landfill volume use, if the residual waste is disposed of in landfills, or the increase in energy production, in the emission of Global Warming relevant gases and the possible emission of noxious substances (e.g. dioxins), if it is disposed of by incinerators or WTE plants, must also be carefully considered.

Table 1
Waste Management unit operations.

Unit operation	GHG emissions and sinks	Considered
Collection (recyclable and mixed waste)	Combustion of fossil fuel used by collection vehicles	NO
Transportation to treatment plants (recycling, WTE, landfill)	Combustion of fossil fuel used by collection vehicles	NO
Recycling	Energy consumption by the machinery used in the plant *GHG emissions reduction compared to production from virgin raw materials*	YES
Composting	Energy consumption by the machinery used in the plant	YES
Anaerobic digestion	Energy consumption by the machinery used in the plant Energy production by biogas	YES
Incineration	Energy consumption by the machinery used in the plant (negligible compared to the other emissions) Waste combustion	YES
Waste to Energy	Energy consumption by the machinery used in the plant Waste combustion Energy production	YES
Mechanical biological pre-treatment	Energy consumption by the machinery used in the plant Reduction in the potential production of biogas	NO
Landfilling	Energy consumption by the machinery used in the plant (negligible compared to the other emissions) Uncontrolled biogas emissions Energy production by biogas	YES

Table 2
Undifferentiated MSW composition and water content of different waste materials at production.

	Undifferentiated MSW composition [%]	Water content [%]	Water content assessment based on
Paper and cardboard	24.0	5	
Plastic	11.0	10	
Glass	8.0	5	Direct measurement
Metals (aluminium and steel)	4.0	10	
Textiles	4.0	0	
Wood	4.0	0	
Food and garden waste (Organics)	31.0	85	Direct measurement and relevant literature
Composite materials	2.0	10	
Ceramics and inert matter	9.0	0	Direct measurement
Leather and rubber	1.5	0	
Diapers and pads	1.5	90	
Total other waste	14.0		

Table 3
Separate collection approaches considered.

Separate collection approach materials collected separately (recyclable)		Separation rate
Approach A	Food and garden waste (Organics), paper and cardboard, plastic, glass, wood, metals, textiles	15%, 35%, 50%
Approach B	Food and garden waste (Organics), paper and cardboard, glass, wood, metals, textiles	15%, 35%, 50%
Approach C	Paper and cardboard, plastic, glass, wood, metals, textiles	15%, 35%

The separation rate of 50% for Approach C has not been considered because it is, as a matter of fact, unrealistic. In fact the total amount of recyclable materials in this approach, considering the adopted composition of MSW, is about 55%. According to recent Italian data (APAT, 2008), when separate collection of organics is not performed the separation rate rarely exceeds 30%.

Considering the different approaches to separate collection presented in Table 3 and a uniform withdrawal of the different materials to be recycled, the average composition of the residual waste for each Scenario has been generated, and the results are shown in Table 4.

The main characteristics of the undifferentiated waste and of the residual waste for the various separate collection scenarios are presented in Table 5; the data are based on laboratory measurement by using synthetic samples of MSW (Calabrò, submitted for publication).

Because of the MSW composition and the approaches to separate collection selected, the increase in the separation rate has led to a decrease in the percentage of combustible materials in the residual waste. The separate collection of food and garden waste (Organics) allows a significant reduction of the water content of residual waste that instead increases significantly when it is not recycled.

The Lower Calorific Value of the humid waste (LCV_{HW}) has been assessed from the measurements carried out by a bomb calorimeter using a proposed National Standard procedure (Calabrò, submitted for publication).

The measured LCV_{HW} shows an average value of about 7610 kJ/kg, with a maximum of 9252 kJ/kg for the samples related to Approach B with a separation rate of 50% and a minimum of 5419 kJ/kg for the samples related to Approach C with a separation rate of 35%. Related literature (European Commission, 2006) reports the average value of the LCV for (undifferentiated) MSW in the range 6300–10,500 kJ/kg and for residual waste after recycling operations (also mechanically carried out) in the range 6300–11,500 kJ/kg.

The calculation of the emission from landfills and incinerators is based on the knowledge of the elemental composition of waste reported in Tchobanoglous et al. (1993).

3. Emissions reduction due to separate collection

Literature clearly reports that recycling allows the production of new raw materials, significantly reducing GHG emissions (see for example Skovgaard et al., 2008; Choate et al., 2005; USEPA, 2002) mainly by the reduction of the energy needed in the production process but also because of the avoidance of other process emissions (for example during steel and aluminium manufacturing lime is needed and CO_2 is emitted when limestone is converted to lime). Nevertheless significant differences are possible depending on the separate collection and treatment scheme adopted. Normally, recycling systems are designed in order to obtain maximum benefits (high recycling rate, high quality of the recovered materials and simplification of the whole process from collection to waste treatment) at minimum cost, unfortunately some of these targets are conflicting. In fact, in order to simplify the recycling process and to obtain high quality recovered materials, separate collection

Table 4
Residual waste composition for each separate collection approach and separation rate.

	Appr. A 15%	Appr. A 35%	Appr. A 50%	Appr. B 15%	Appr. B 35%	Appr. B 50%	Appr. C 15%	Appr. C 35%
Paper and cardboard [%]	23.3	21.9	20.1	22.6	19.7	16.0	20.5	13.4
Plastic [%]	10.7	10.0	9.2	12.9	16.9	22.0	9.4	6.2
Glass [%]	7.8	7.3	6.7	7.5	6.6	5.3	6.8	4.5
Metals [%]	3.9	3.6	3.3	3.8	3.3	2.7	3.4	2.2
Textiles [%]	3.9	3.6	3.3	3.8	3.3	2.7	3.4	2.2
Wood [%]	3.9	3.6	3.3	3.8	3.3	2.7	3.4	2.2
Food and garden waste (Organics) [%]	30.1	28.3	26.0	29.2	25.4	20.7	36.5	47.7
Other waste [%]	16.5	21.5	28.0	16.5	21.5	28.0	16.5	21.5

Table 5
Characteristics of the residual waste (adapted from Calabro, submitted for publication).

	Undiff. MSW	Appr. A 15%	Appr. A 35%	Appr. A 50%	Appr. B 15%	Appr. B 35%	Appr. B 50%	Appr. C 15%	Appr. C 35%
Combustible materials [%]	79	78	75	72	78	76	74	79	79
Incombustible materials [%]	21	22	25	28	22	24	26	21	21
Water content [%]	31	30	29	28	30	27	24	36	45
Average LCV_{HW} [kJ/kg]	6859	7797	7187	7394	7888	8839	9252	7834	5419

should be carried out to the extremes (e.g. separating clear glass, brown glass and green glass rather than collecting mixed glass, aluminium and steel instead of mixed metals, PVC, PE and PS rather than mixed plastic). In spite of this, to simplify separate collection, it is quite common that different types of glass, plastic and metals are collected together increasing the complexity and the energy demand of the recycling process.

Since food and garden waste (Organics) separately collected can be treated either aerobically (composting) or anaerobically, the two different options have been individually considered.

Aerobic treatment (composting) is energy consuming, implies GHG emissions and leads to the production of compost. The benefits of this kind of treatment on GHG emissions reduction are indirect and are mainly linked to the reduction of the emissions from the disposal system should the waste not be separately collected.

Anaerobic treatment allows the production of a significant amount of biogas that is normally used to produce electric energy. After anaerobic stabilization the treated waste can be further aerobically stabilized leading to the production of compost. The GHG emissions balance of this treatment is negative (emissions reduction) since the avoided emissions due to energy production are greater than those due to energy consumption (APAT, 2005).

Greenhouse relevant emissions saved in MSW recycling (see Table 6) for different waste fractions have been evaluated according to the model (Skovgaard et al., 2008) developed by the European Environment Agency and the European Topic Centre on Resource and Waste Management to be used for estimation of greenhouse gas emissions associated with the management of waste in the European Union. Moreover evaluation of GHG emissions linked to organics treatment (i.e. composting and anaerobic process) have been evaluated according to data from APAT (2005).

The equivalent CO_2 emissions savings for the various separate collection/treatment scenarios are reported in Table 7. Emissions savings related to recycling are significant for all the scenarios tested and are mainly due (75% or more) to the recycling of paper, cardboard and metals (especially aluminium). It is peculiar that the three approaches at the maximum separation rate tested (respectively 50% for A and B, 35% for C) present the same equivalent CO_2 emissions saving. It should be underlined that since in Approach C organics are not recycled, the amount of materials separately collected which provide great benefit in terms of avoided emissions (i.e. paper, cardboard and metals) is similar to one of the other two approaches at 50% separation rate.

Table 6
Avoided emissions due to recycling for different materials.

Material	Avoided emissions [$kgCO_2$/ton]
Paper and cardboard	565
Plastic (mixed)	396
Glass	159
Metals (mix of aluminium and steel)	3205
Food and garden waste – composting	−42*
Food and garden waste – anaerobic digestion	92

* Composting is energy consuming and for this reason CO_2 is emitted.

4. Emissions from landfills

The greenhouse gases emissions related to landfilling are mainly due to methane (CH_4) and carbon dioxide (CO_2) present in the biogas produced by anaerobic bacteria using as carbon source the biodegradable carbon contained in the waste. Nevertheless only methane emission is relevant to Global Warming since the CO_2 release is only a partial "return" to the atmosphere of the same gas used by photosynthetic organisms to build their biomass.

To evaluate these emissions a simplified schematization of a landfill has been adopted (see Fig. 1) according to the landfill mass balance concept (Cossu et al., 2005) and the following hypotheses have been made:

The bottom barrier is perfectly sealed and the dispersion of leachate is negligible.
The leachate is properly treated (e.g. membrane treatment) and the associated emission of CO_2 or of other greenhouse gases is neglected; treated water is discharged while treatment byproducts containing carbon (e.g. concentrate, sludge) are recirculated.
The biogas produced is composed of methane and carbon dioxide in equal proportions by volume (as in the methanogenic phase in conventional landfills (Christensen and Kjeldsen, 1989; Ham, 1979; Themelis and Ulloa, 2007) and other components are neglected.
The reactivity of waste is not influenced by the composition but only by the quantity and biodegradability of carbon available.
According to the hypotheses above the emissions relevant to Global Warming are related to the production of biogas only.

The efficiency of the biogas collection system is a key issue when dealing with greenhouse gases emissions and it is very difficult to assess. Literature examined (Themelis and Ulloa, 2007; Lombardi et al., 2006; Thorneloe et al., 2002; Eschenroeder, 2001; USEPA,

Table 7
Avoided Emissions due to recycling for the different separate collection scenarios.

	Appr. A 15%	Appr. A 35%	Appr. A 50%	Appr. B 15%	Appr. B 35%	Appr. B 50%	Appr. C 15%	Appr. C 35%
Emission saving (food and garden waste composted) (kg Eq. $CO_2/t_{waste\ prod.}$)	49	116	165	48	113	162	81*	189*
Emission saving (food and garden waste anaerobically digested) (kg Eq. $CO_2/t_{waste\ prod.}$)	56	133	189	56	133	189		

* Food and garden waste non collected separately.

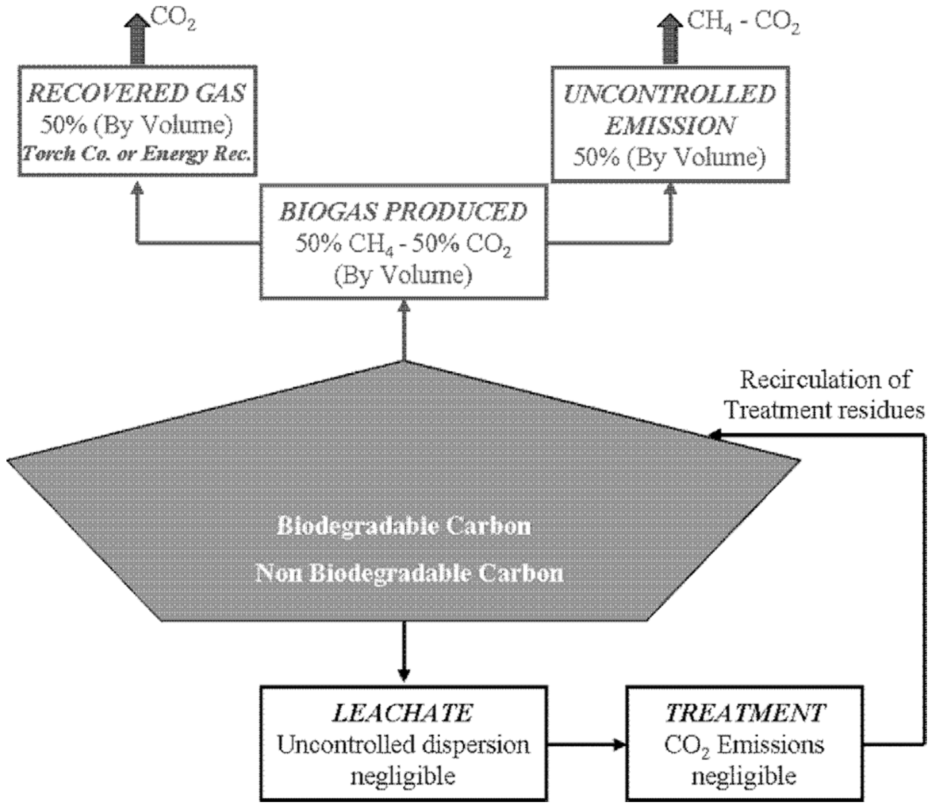

Fig. 1. Landfill scheme.

1995; De Fraja Frangipane and Cossu, 1995; Tchobanoglous et al., 1993) reports efficiency levels from 30% to 90% depending on several factors such as the timing of the construction of the system (after or during the filling of the landfill), the system type (active or passive), the layout adopted (number and position of the biogas collecting wells), the accuracy of design, construction and management. For these reasons three levels of efficiency (50%, 75% and 90%) have been tested. The highest efficiency can be considered representative of a state-of-the-art system and of an extremely accurate management of the landfill optimized in order to reduce biogas emissions, the intermediate of a landfill designed, built and managed according to Best Management Practice (for Italy see Gazzetta Ufficiale della Repubblica Italiana (2007)) while the lowest should be representative of an ordinary engineered landfill.

The biogas recovered can be burned in a torch or used for energy production, in both cases the emissions contain the same quantity of CO_2 (complete combustion has been assumed). The electric energy production from collected biogas is also beneficial since for each kWh of energy produced the generation of the same quantity of electricity from conventional sources and the related emission can be avoided. In this way the emission reduction depends directly on the energy mix adopted in a specific country (electricity production from atomic, solar, wind, hydroelectric energy do not emit greenhouse gases that are associated with the energy production from fossil fuels such as coal, gas, oil) and it is normally measured, as already mentioned, by the average equivalent CO_2 emission for each kWh of electricity produced (0.527 kg eq. CO_2/kWh for Italy, Enerpresse, 2007).

In order to assess the energy production from biogas the most recent data referring to the 36 Italian Plants recovering electricity from biogas have been used (APAT, 2008). For each installation the specific production in kWh/t_{biogas} has been calculated, the 5% most productive and the 5% least productive plants have been excluded and the average specific production has been calculated. It was equal to 1473.4 kWh/t_{biogas} (standard deviation was lower than 7% of the average value).

The CH_4 emission has been converted to CO_2 equivalent emission considering that the CH_4 Global Warming Potential (GWP) can be evaluated to be, over a 100 year time span, 25 times greater than that of CO_2 (Forster et al., 2007). Therefore the discharge of 1 kg of CH_4 is equivalent to the release of 25 kg of CO_2.

The evaluation of the biogas produced in the landfill has been made according to the biochemical model method from Andreottola and Cossu (1996). It considers, albeit in a simplified way, the anaerobic biochemical processes occurring in the landfill environment.

For the application of the model, as already mentioned, literature data (Tchobanoglous et al., 1993) about elemental composition of the different materials present in the waste have been used.

To take into account the effect of the separate collection, all the calculations have been made using as a base 1 ton of MSW produced before separate collection, therefore the biogas production has been calculated only with reference to the residual waste, for example considering a separation rate of 35% the amount of waste considered for biogas production was 650 kg/$t_{waste\ prod.}$.

Tables 8–10 summarize the result obtained in terms of biogas produced, biogas (divided into its components) recovered and emitted, energy production, avoided emissions, emissions and carbon sequestered for the three levels of efficiency in biogas recovery tested.

From the analysis of the data it is evident that the efficiency of the biogas collection system is, as previously mentioned, extremely important. In fact for the highest level of efficiency net emissions due to CH_4 (i.e. equivalent emissions from dispersed methane decreased of the avoided emissions due to energy production) are negative and this means that the combined effect of biogas recov-

Table 8
Landfill emissions, energy production, sequestered carbon for the various separate collection scenarios – biogas collection efficiency 50%.

	Undiff. MSW	App. A 15%	App. A 35%	App. A 50%	App. B 15%	App. B 35%	App. B 50%	App. C 15%	App. C 35%
Biogas production [m^3 biogas/tonwaste prod.]	185	156	117	88	152	107	74	150	103
CO_2 dispersed [$kgCO_2$/tonwaste prod.]	90	76	57	43	74	52	36	73	50
CH_4 dispersed [$kgCH_4$/tonwaste prod.]	33	28	21	16	27	19	13	27	18
CO_2 recovered [$kgCO_2$/tonwaste prod.]	90	76	57	43	74	52	36	73	50
CH_4 recovered [kg_4CH_4/tonwaste prod.]	33	28	21	16	27	19	13	27	18
Equiv. emiss. from CH_4 [$kgCO_2$/tonwaste prod.]	824	697	521	392	679	479	331	668	457
Emission from CO_2 emitted [$kgCO_2$/tonwaste prod.]	90	76	57	43	74	52	36	73	50
Energy produced [kWh/tonwaste prod.]	181	153	114	86	149	105	73	147	100
Avoided emission [$kgCO_2$/tonwaste prod.]	181	153	114	86	149	105	73	146	100
Total emiss. without en. rec. [$kgCO_2$/tonwaste prod.]	95	81	60	45	79	55	38	77	53
Total emiss. with ener. recov. [$kgCO_2$/tonwaste prod.]	1094	926	692	521	902	636	440	887	608
Net equiv. emiss. from CH_4 [$kgCO_2$/tonwaste prod.]	728	616	460	347	601	423	293	590	404
Sequestered carbon [kgC/ton waste prod.]	159	137	110	88	146	129	117	127	85

Table 9
Landfill emissions, energy production, sequestered carbon for the various separate collection scenarios – biogas collection efficiency 75%.

	Undiff. MSW	App. A 15%	App. A 35%	App. A 50%	App. B 15%	App. B 35%	App. B 50%	App. C 15%	App. C 35%
Biogas production [m^3 biogas/tonwaste prod.]	185	156	117	88	152	107	74	150	103
CO_2 dispersed [$kgCO_2$/tonwaste prod.]	45	38	29	22	37	26	18	37	25
CH_4 dispersed [$kgCH_4$/tonwaste prod.]	17	14	10	8	14	10	7	13	9
CO_2 recovered [$kgCO_2$/tonwaste prod.]	136	115	86	65	112	79	55	110	75
CH_4 recovered [kg CH_4/tonwaste prod.]	49	42	31	24	41	29	20	40	27
Equiv. emiss. from CH_4 [$kgCO_2$/tonwaste prod.]	165	139	104	78	136	96	66	134	91
Emission from CO_2 emitted [$kgCO_2$/tonwaste prod.]	326	276	206	155	269	190	131	264	181
Energy produced [kWh/tonwaste prod.]	271	229	171	129	223	157	109	220	150
Avoided emission [$kgCO_2$/tonwaste prod.]	143	121	90	68	118	83	57	116	79
Total emiss. without en. rec. [$kgCO_2$/tonwaste prod.]	729	616	461	347	601	424	293	591	405
Total emiss. with ener. recov. [$kgCO_2$/tonwaste prod.]	586	496	370	279	483	341	236	475	325
Net equiv. emiss. from CH_4 [$kgCO_2$/tonwaste prod.]	269	228	170	128	222	156	108	218	149
Sequestered carbon [KgC/ton waste prod.]	159	137	110	88	146	129	117	127	85

Table 10
Landfill emissions, energy production, sequestered carbon for the various separate collection scenarios – Biogas collection efficiency 90%.

	Undiff. MSW	App. A 15%	App. A 35%	App. A 50%	App. B 15%	App. B 35%	App. B 50%	App. C 15%	App. C 35%
Biogas production [m_3 Biogas/tonwaste prod.]	185	156	117	88	152	107	74	150	103
CO_2 dispersed [$kgCO_2$/tonwaste prod.]	18	15	12	9	15	11	7	15	10
CH_4 dispersed [$kgCH_4$/tonwaste prod.]	7	6	4	3	5	4	3	5	4
CO_2 recovered [$kgCO_2$/tonwaste prod.]	163	138	103	78	134	95	66	132	91
CH_4 recovered [$kgCH_4$/tonwaste prod.]	59	50	38	28	49	35	24	48	33
Equiv. emiss. from CH_4 [$kgCO_2$/tonwaste prod.]	165	139	104	78	136	96	66	134	91
Emission from CO_2 emitted [$kgCO_2$/tonwaste prod.]	326	276	206	155	269	190	131	264	181
Energy produced [kWh/tonwaste prod.]	325	275	206	155	268	189	131	264	181
Avoided emission [$kgCO_2$/tonwaste prod.]	171	145	108	82	141	100	69	139	95
Total emiss. without en. rec. [$kgCO_2$/tonwaste prod.]	509	430	322	242	420	296	205	413	283
Total emiss. with ener. recov. [$kgCO_2$/tonwaste prod.]	338	286	213	161	278	196	136	274	187
Net equiv. emiss. from CH_4 [$kgCO_2$/tonwaste prod.]	−7	−6	−4	−3	−6	−4	−3	−5	−4
Sequestered carbon [kgC/ton waste prod.]	159	137	110	88	146	129	117	127	85

ery and energy production cancels the GHG relevant emissions from landfill disposal. Biogas production, emissions, energy production and carbon sequestered decrease with the increase of separation rate. This is due to the reduction of the mass of biodegradable materials in the residual waste subsequent to separate collection. For Approach A, biogas production decrease is almost perfectly proportional to the separation rate, while for the other two approaches the impact of the change in residual waste composition due to separate collection is greater. For Approach B this is due to the concentration in the residual waste of non-biodegradable materials and especially plastic. For Approach C the reduction of biogas production is slightly higher than one of the other two approaches at the same separation rate. In fact, as already mentioned, Approach C allows the recovery of a higher quantity of paper, cardboard, wood and textiles compared to those where organics also are collected. These materials, according to the biochemical model used, are the largest source of biodegradable carbon in the residual waste. Nevertheless, the maximum GHG reduction is registered for the two scenarios where food and garden waste is separately collected at 50% of separation rate.

The quantity of carbon sequestered is in line with literature data (USEPA, 2002) and confirms that landfills can play as significant a role as a Carbon sink.

5. Emissions from incinerators and Waste to Energy plants

Incineration can be considered the most extreme pre-treatment of MSW before landfilling; its main objective is to reduce the various concerns related to biodegradable waste and to minimize the volume of waste to be disposed of in landfills.

As already mentioned, the integrated approach to MSW management requires that non-recyclable, combustible waste be treated in WTE plants, exploiting the energy released during combustion to produce electric energy or superheated steam used for heating, air conditioning or industrial purposes.

The treatment of flue gas and the energy production from waste are the main ways to reduce the relatively high environmental impact of incineration. As said above, simple incineration without energy recovery should be limited to the treatment of special waste, when for technical or economic reasons the energy production from waste is not feasible.

For the purposes of this paper only global warming relevant emissions from incineration are considered in the discussion. Nevertheless other emissions from waste incineration such as heavy metals, fine and ultrafine dust, dioxins (due to the combustion of materials containing chlorine, such as chlorinated plastic – i.e. PVC) must be considered during the evaluation of the possible adoption of this technology.

Incineration contributes to the global emissions of greenhouse gases mainly because of the release of carbon dioxide (CO_2) and nitrous oxide (N_2O). Although nitrous oxide (N_2O) has a GWP, over a 100 year time span, 310 times greater than that of CO_2 (Forster et al., 2007), it accounts for less than 1% of the total greenhouse gases emission (converted in equivalent CO_2) due to incineration (Johnke, 2000); for this reason the emission of CO_2 alone has been considered in this study.

As already mentioned, in order to calculate the amount of CO_2 released for each ton of MSW produced (considering the mass reduction due to separate collection), the Carbon content of the residual waste has been assessed according to literature data (Tchobanoglous et al., 1993). Since the CO_2 originated from fossil carbon only is relevant for Global Warming, the carbon content of residual waste has been divided in fossil and renewable.

Of the carbon present in waste 98% (European Commission, 2006) has been considered released with flue gas, exclusively under the form of CO_2, while the remaining 2% is transferred into ashes and slag.

To evaluate the energy recovery from treatment in WTE plants, the Lower Calorific Value of the undifferentiated and residual waste has been assessed by means of experimental data (Calabrò, submitted for publication; see Table 5). Only electric energy production has been considered since it is more common than the combined recovery of steam and electricity or of steam only.

To take into account the different efficiencies of the energy recovery plants, net efficiencies (only energy effectively transferred out of the plant has been accounted for) of 15%, 20% and 25% have been considered (Gazzetta Ufficiale della Repubblica Italiana, 2007).

The lowest net efficiency can be considered representative of an ordinary WTE plant, the intermediate of a sufficiently modern plant built and managed according to Best Management Practice while the highest could be representative of a state-of-the-art plant where the entire incineration process, including the treatment of flue gas, is optimized for energy recovery.

The avoided emissions are calculated, as shown above, considering the average Italian Carbon emission factor (0.527 $kgCO_2$/kWh; (Enerpresse, 2007)).

Table 11 summarizes the results related to the calculations for the various scenarios considered for incineration. Carbon dioxide emissions, sequestered carbon, energy produced, net emission of fossil CO_2 and carbon emission factor for energy production are shown. Net fossil carbon dioxide emission is, as already mentioned, the only one relevant to global warming. It has been calculated as the total CO_2 emission due to the combustion of non-biodegradable materials (i.e. plastic) minus the avoided emissions due to energy production.

The CO_2 emissions calculated are congruent with the data reported in relevant literature (see for example Johnke, 2000; European Commission, 2006).

The relationship between CO_2 emission and separate collection rate is evident: both the mass reduction of the waste to be inciner-

Table 11
Incinerators and WTE plants emissions, energy production, sequestered carbon for the various separate collection scenarios.

	Undiff. MSW	Scen. A 15%	Scen. A 35%	Scen. A 50%	Scen. B 15%	Scen. B 35%	Scen. B 50%	Scen. C 15%	Scen. C 35%
Fossil CO_2 emission [$kgCO_2$/tonwaste prod.]	353	305	249	203	341	331	321	282	189
Renew. CO_2 emission [$kgCO_2$/tonwaste prod.]	592	562	383	293	492	353	251	479	324
Electricity prod. $n = 15\%$ [kWh/tonwaste prod.]	286	276	195	154	279	239	193	277	147
Electricity prod. $n = 20\%$ [kWh/tonwaste prod.]	381	368	260	205	373	319	257	370	196
Electricity prod. $n = 25\%$ [kWh/tonwaste prod.]	476	460	324	257	466	399	321	462	245
Net fossil CO_2 em. $n = 15\%$ [$kgCO_2$/tonwaste prod.]	203	160	146	121	193	205	220	136	112
Net fossil CO_2 em. $n = 20\%$ [$kgCO_2$/tonwaste prod.]	153	111	112	94	144	163	186	87	86
Net fossil CO_2 em. $n = 25\%$ [$kgCO_2$/tonwaste prod.]	102	63	78	67	95	121	152	38	60
Carbon em. factor $n = 15\%$ [$kgCO_2$/kWh]	1.24	1.11	1.28	1.31	1.22	1.38	1.67	1.02	1.29
Carbon em. factor $n = 20\%$ [$kgCO_2$/kWh]	0.93	0.83	0.96	0.99	0.91	1.04	1.25	0.76	0.97
Carbon em. factor $n = 25\%$ [$kgCO_2$/kWh]	0.74	0.66	0.77	0.79	0.73	0.83	1	0.61	0.77
Sequestered carbon [KgC/ton waste prod.]	5.3	3.6	2.6	2.1	3.5	2.9	2.4	3.2	2.1

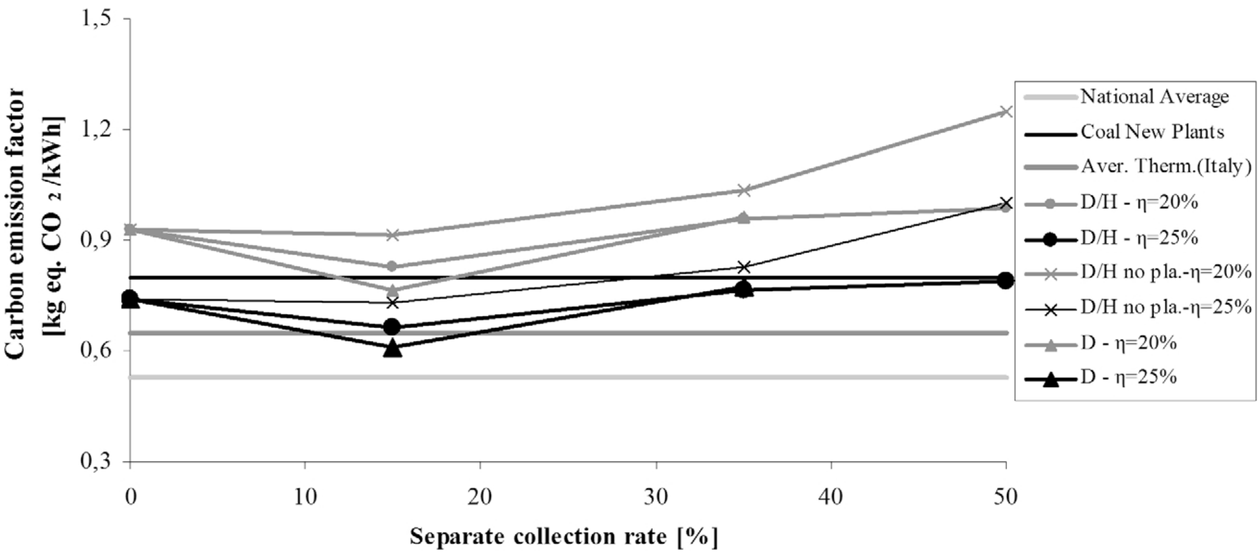

Fig. 2. Carbon emission factors.

ated and the composition variation due to recycling greatly influence the emissions; in fact the highest emissions are those related to undifferentiated waste (highest mass) and to Approach B (highest concentration in fossil carbon).

As already stated, separate collection of plastic is a key issue when residual waste has to be incinerated, considering only GHG emissions, the increase in Lower Calorific value with separate collection rate in Approach B (related to the concentration of plastic in the residual waste) and the subsequent increase in electricity production and avoided emissions does not counterbalance the increase in the release of fossil CO_2. For all the scenarios tested the carbon sequestered is negligible.

The carbon emission factor provides relevant information on the effectiveness of a given energy production setup (technology adopted and fuel) as regards to Global Warming relevant gases emissions: the lower the emission factor the better the setup adopted; in this case, the highest emission factors are those in Approach B.

Fig. 2 shows the relationship between separate collection rate and carbon emission factors for electricity production for net efficiencies of 20% and 25%. The emission factors are compared with the values referring to electric energy production from coal (new generation plants, the so called "clean coal" plants), from thermoelectric sources in Italy and with the Italian average carbon factor. The data show how for some of the scenarios considered the carbon emission factor for electricity production from waste is below the one for the production from coal. In two cases the Carbon emission factor is lower than the one for electricity production from conventional thermoelectric sources in Italy.

6. Comparison of GHG emissions for different management scenarios

As mentioned above, the objective of this paper is to evaluate how separate collection of MSW can influence GHG emissions in the entire management process.

Table 12
Comparison of Global Warming relevant gaseous emissions from different MSW management scenarios.

	Undiff. MSW	App. A 15%	App. A 35%	App. A 50%	App. B 15%	App. B 35%	App. B 50%	App. C 15%	App. C 35%
Recycling and landfill disposal (biogas collection efficiency 50%) without energy recovery	823	640	388	203	623	346	141	586	268
Recycling and landfill disposal (biogas collection efficiency 50%) with energy recovery	728	560	327	157	544	291	103	509	216
Recycling and landfill disposal (biogas collection efficiency 75%) without energy recovery	412	292	127	7	283	107	−24	252	40
Recycling and landfill disposal (biogas collection efficiency 75%) with energy recovery	269	171	37	−61	166	24	−81	137	−39
Recycling and landfill disposal (biogas collection efficiency 90%) without energy recovery	165	83	−29	−111	80	−37	−123	52	−97
Recycling and landfill disposal (biogas collection efficiency 90%) with energy recovery	−7	−62	−137	−192	−62	−136	−192	−87	−192
Recycling and incineration	353	249	116	13	284	198	132	201	0
Recycling and WTE plant treatment – en. prod. eff. $n = 15\%$	203	104	13	−68	137	72	30	54	−77
Recycling and WTE plant treatment – en. prod. eff. $n = 20\%$	152	55	−21	−95	88	30	−4	6	−103
Recycling and WTE plant treatment – en. prod. eff. $n = 25\%$	102	7	−55	−122	39	−12	−38	−43	−129
Minimum	−7	−62	−131	−192	−62	−136	−192	−87	−192
Maximum	823	640	388	203	623	346	141	586	268
Average	320	210	11	−21	218	88	−6	167	−11

In order to make a comparison among the different management scenarios, obtained coupling recycling and disposal options (i.e. landfilling, incineration, WTE), and considering only the emissions of Global Warming Relevant gases (methane emissions from landfills and fossil CO_2 from incineration) total emissions, in terms of equivalent CO_2, have been calculated. The results are presented in Table 12.

The results clearly demonstrate how separate collection and recycling have a beneficial effect in terms of GHG emissions reduction, in fact emissions decrease if separation rate increases. It is extremely relevant that if the disposal technology is properly chosen MSW management can become a carbon sink (minimum emissions are always negative).

The largest emissions are those obtained by the management of undifferentiated MSW without separate collection. Nevertheless if undifferentiated MSW is disposed of in a landfill equipped with state-of-the-art biogas collection and energy recovery systems, total abatement of GHG emissions is guaranteed.

Landfilling with extremely accurate biogas control (90% efficiency) appears to be the best option for residual waste management while WTE plants assure significantly better results than landfill disposal for lower efficiencies of the biogas recovery system.

The option of not recycling plastic (Approach B) gives interesting results if residual waste is landfilled (emissions for Approach B lower than Approach A of 16 kg eq. $CO_2/t_{waste\ prod.}$ on average; amount of sequestered carbon for Approach B higher than Approach A of 19 kgC/$t_{waste\ prod.}$ on average) while, as already mentioned, if it is sent to a WTE plant the increase in energy production does not counterbalance the increase in GHG emissions (increase in net emissions of 58 kg eq. $CO_2/t_{waste\ prod.}$ on average). The effects are boosted by the increase in separate collection rate.

The objective of the European Union regarding GHG emissions from MSW management is to reduce net CO_2 emissions to about 30 kg eq. $CO_2/t_{waste\ prod.}$ by 2020 (Skovgaard et al., 2008). According to the results presented above, this emissions level can be reached by combining technologies already available and a sufficient separation rate (higher than 35% except for the highest level in biogas recovery and in energy recovery from combustion, respectively).

7. Conclusions

The analyses carried out in this paper clearly demonstrate how separate collection has a significant impact on Global Warming relevant gases emissions from MSW management. Moreover if the management scenario is properly chosen and if best available technologies are adopted negative emissions are possible.

Disposal in a landfill equipped with state-of-the-art biogas collection (90% efficiency) and energy recovery system is the best option for residual MSW management in all the scenarios tested.

If residual waste is to be disposed of in WTE plants to reduce GHG emissions plastic must be separately collected and recycled.

The results obtained are significantly dependent on the adopted waste composition and therefore refer specifically to the Italian situation. Nevertheless when MSW composition is significantly similar to the Italian one, as in several other industrialized countries, they have a general effectiveness, especially from a qualitative point of view.

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