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ARTICLE *in* WASTE MANAGEMENT · FEBRUARY 2005

Impact Factor: 3.16 · DOI: 10.1016/j.wasman.2004.09.007 · Source: PubMed

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Waste Management 25 (2005) 123–135
www.elsevier.com/locate/wasman

Alternative strategies for energy recovery from municipal solid waste Part A: Mass and energy balances

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Accepted 14 September 2004

Abstract

This two-part paper assesses four strategies for energy recovery from municipal solid waste (MSW) by dedicated waste-to-energy (WTE) plants generating electricity through a steam cycle. The feedstock is the residue after materials recovery (MR), assumed to be 35% by weight of the collected MSW. In strategy 1, the MR residue is fed directly to a grate combustor. In strategy 2, the MR residue is first subjected to light mechanical treatment. In strategies 3 and 4, the MR residue is converted into RDF, which is combusted in a fluidized bed combustor.

To examine the relevance of scale, we considered a small waste management system (WMS) serving 200,000 people and a large WMS serving 1,200,000 people. A variation of strategy 1 shows the potential of cogeneration with district heating.

The assessment is carried out by a Life Cycle Analysis where the electricity generated by the WTE plant displaces electricity generated by fossil fuel-fired steam plants. Part A focuses on mass and energy balances, while Part B focuses on emissions and costs.

Results show that treating the MR residue ahead of the WTE plant reduces energy recovery. The largest energy savings are achieved by combusting the MR residue "as is" in large scale plants; with cogeneration, primary energy savings can reach 2.5% of total societal energy use.

1. Background and scope

This two-part paper reports the results of a comparison of the merits of alternative strategies for energy recovery (ER) from MSW downstream of materials recovery (MR). The research was limited to demonstrated commercial technologies: refused derived fuel (RDF) production with mechanical–biological treatment plants (MBT), grate and fluidized bed combustors dedicated to waste thermal treatment, Rankine steam cycle for power production or cogeneration. Alternative technologies like co-combustion with fossil fuels (Borodula et al., 1995; Rosenauer et al., 1997), gasification or pyrolysis (Niessen et al., 1996; Belgiorno et al., 2003; Malkow, 2004) were not considered because they do not yet meet the requirements for widespread commercial implementation.

The basic goal of the research was to understand whether manipulating residual waste ahead of combustion in dedicated waste-to-energy (WTE) plants can either increase efficiency or reduce environmental impact or costs. The focus on waste manipulation ahead of energy recovery follows the more or less explicit encouragement of RDF found in recent Italian legislation (Ministry of Environment, 1998), in statements of policy makers, and in the plans approved by several Italian utilities and waste management agencies.

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doi:10.1016/j.wasman.2004.09.007

Nomenclature

ECO	economizer
ER	energy recovery from MR residues
kgOE	kg of oil equivalent
LCA	life cycle assessment
LHV	lower heating value
MBT	mechanical biological treatment
MR	materials recovery by selective waste collection
MSW	municipal solid waste
RDF	refuse derived fuel
SH	superheater
SNCR	selective non-catalytic reduction
SOF	stabilized organic fraction
t	metric ton
TOE	ton of oil equivalent
WMS	waste management system
WTE	waste-to-energy

2. System of interest, strategies and scale

Fig. 1 gives a schematic of the system and the alternative strategies considered in this study. Our analysis proceeds from whatever is left downstream of MR carried out by selective waste collection. Following the target set by current Italian legislation for 2003 (Ministry of Environment, 1997), we assume that such MR reduces the amount of MSW by 35% by weight, leaving a residue with the composition and heating value shown in Table 1. The values in the table are an educated guess based on a rather ample collection of data provided by waste management public utilities, results of experimental characterizations carried out in Italy in the late 1990s (Anon, 1999) and the authors' professional experience. Composition and heating value of the residue of material recovery obviously depend on gross MSW production and on how much of each waste constituent is recovered. A correlation between gross MSW production, material recovery and properties of MR residue would allow enlarging the boundary of the system depicted in Fig. 1 to encompass material recovery; however, this would require rather extensive field and laboratory (for heating values) measurements to supplement the scarce and uncertain data available in the literature – an effort that is beyond the scope of this research.

The four alternative strategies depicted in Fig. 1 correspond to the options now being considered by several Italian municipalities to recover energy from MSW

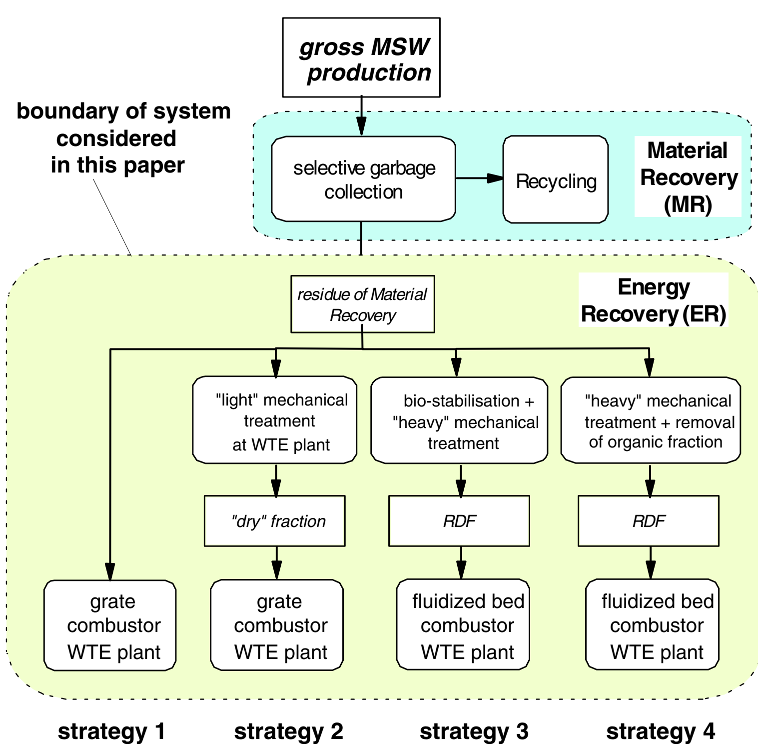

Fig. 1. WMS and strategies considered in this paper.

Table 1
Composition and heating value assumed for the MR residue, as well as for each constituent

Constituent	Content in MR residue	Composition			Carbon content		LHV MJ/kg	Volatile fraction % by weight of total	
		Moisture	Ash	Volatile fraction	Total	% Renewable			
	% By weight								
Paper and cardboard	24.5	14.0	5.0	81.0	37.6	100	13.22	C	27.6
Wood	6.0	22.0	1.5	76.5	37.6	100	13.87	Cl	0.64
Plastic	19.0	6.0	9.0	85.0	55.5	0	26.18	H	3.49
Glass and inert material	3.5	2.5	95.0	2.5	1.0	0	−0.061	O	19.7
Metals	3.5	5.0	92.5	2.5	1.0	0	−0.122	N	0.15
Organic fraction	31.5	70.0	9.0	21.0	9.6	100	1.719	S	0.06
Fines	12.0	30.0	35.0	35.0	20.5	60	4.395		
MR residue	**100**	**31.8**	**16.6**	**51.6**	**27.6**	**16.0**	**10.11**	**Total**	**51.6**

The negative LHV of glass, inert materials and metals is the heat required to vaporize their moisture. The values in the bottom row are the weighted averages of the properties of each constituent. The section to the right gives the atomic composition of the volatile fraction assumed to evaluate the performances of heat and mass balances; minor atomic constituents like F, Br, heavy metals are neglected because their effect on heat and mass balances is irrelevant.

within the framework of so-called ''Integrated'' waste management system (WMS) [1]:

1. Combust the MR residue ''as is'' in a grate combustor;
2. Remove the organic, ''wet'' fraction by sieving the MR residue ahead of combusting it in a grate combustor; the wet fraction is bio-stabilized and then landfilled;
3. Produce RDF with aerobic bio-stabilization of the whole MR residue ahead of sieving, and then feed the RDF to a dedicated fluidized bed combustor;
4. Produce RDF by first removing the organic fraction by sieving and then feed RDF to a dedicated fluidized bed combustor; the organic fraction is bio-stabilized and then landfilled.

In strategy 2, the removal of the organic fraction takes place at the site of the WTE plant, because the ''dry'' fraction to be combusted contains organic material and is not stabilized. The RDF of strategies 3 and 4 does not need to be produced at the WTE site, although storing and transporting it would somewhat increase costs and emissions. For the sake of simplicity, we consider here that the RDF plant and the WTE production plant are at the same site. The mechanical treatment carried out ahead of combustion in strategy 4 is a refinement of strategy 2.

In all cases, the heat generated by the feedstock in the grate or fluidized bed combustor is recovered through a Rankine steam cycle for the production of electricity. To illustrate the benefits of cogeneration, in the framework of strategy 1 we also consider the generation of low-temperature heat for district heating.

[1] An integrated waste management system consists of a number of coordinated actions to recover material and energy and to minimize environmental impact.

An appealing variation of the conventional steam cycle is the export of steam to a nearby combined cycle (Consonni, 2000b; Consonni et al., 2000); this option does not require any new technology, but it was not considered because the implications for generation, emission regulation and sale of electricity are beyond the scope of this work.

The performance – as well as costs – of WTE plants based on Rankine steam cycles is subject to strong scale effects. Larger plants can achieve much higher efficiencies because:

– it makes economic sense to adopt more sophisticated configurations and to enhance steam conditions;
– steam turbine efficiency is higher;
– relative auxiliary power is lower.

To illustrate the relevance of scale, the comparison among the four alternatives listed above is carried out for two system sizes:

– a ''small'' WMS with a gross MSW production of 100,000 tons/year (65,000 tons/year after MR);
– a ''large'' WMS with a gross MSW production of 600,000 tons/year (390,000 tons/year after MR).

Given the specific gross generation of MSW in Italy and most European Union countries – approximately 500 kg per person per year – the small system is representative of a small province or a medium-size city with 200,000 people, whereas the large system is representative of a large city with 1,200,000 people.

3. Basic process and technological features

Table 2 summarizes the basic features and the technologies assumed for the four strategies considered in

Table 2
Summary of the basic treatment processes considered for each strategy

Strategy	Basic treatments			
	Prior to energy recovery	Energy recovery	Bio-stabilization	Material to landfill
1. Combust MR residue as is	None	Grate combustor	None	Combustor bottom ash + stabilized fly ash
2. Light treatment at WTE plant	"light" mechanical treatment with 60 mm sieve	Grate combustor	Applied to wet fraction generated by sifting; exhausts treated with bio-filter	SOF + combustor bottom ash + stabilized fly ash
3. RDF – bio-stabilization ahead of mechanical treatment	Bio-stabilization + "heavy" mechanical treatment	Fluidized-bed combustor	Applied to the whole mass of waste within sealed cells; exhausts fired with natural gas	Non-metallic scraps + inert materials + combustor bottom ash + stabilized fly ash
4. RDF – bio-stabilization after mechanical treatment	"heavy" mechanical treatment	Fluidized-bed combustor	Applied to wet fraction generated by sifting; exhausts treated with bio-filter	SOF + combustor bottom ash + stabilized fly ash

In both combustion technologies, power is generated by a conventional steam Rankine cycle; bottom ash is landfilled as is, while fly ash is first stabilized with a cement-based mixture.

this paper. Fig. 2(a) through (d) are a schematic representation of the process sequence, anticipating the mass and energy flows resulting from the assumptions illustrated in the next chapter.

In strategy 1, the MR residue is fed directly into an air cooled, non-adiabatic grate combustor closely integrated with the boiler that generates steam for the Rankine cycle. The emission control system includes an SNCR fed with urea for NO_x control, dry scrubbing with lime and activated carbon to remove acid gases, heavy metals and dioxins, and a high efficiency fabric filter to remove solid particles. Bottom ash and fly ash are landfilled – the latter after being treated with a cement-based mixture. This strategy is representative of a number of plants recently come on line in several cities in Northern Italy: Bergamo, Brescia (Bonomo, 2003) and Piacenza.

In strategy 2, the MR residue is screened in a 60 mm sieve into a "dry" fraction, to be fed to a grate combustor much like that considered for strategy 1, and a "wet" fraction to be bio-stabilized aerobically in a plant provided with bio-filters to treat exhaust air. The stabilized organic fraction (SOF) and the ash generated by the WTE plant are landfilled. This strategy is representative of a large WTE plant that came on line recently to serve the city of Milano (Salimbeni and Pezzella, 2000; Bonomo, 2004).

In strategy 3, the MR residue is processed in a MBT plant where aerobic bio-stabilization is carried out on the whole mass of waste, right after a preliminary shredding. Stabilization takes place in approximately seven days in sealed cells operated in batch mode and maintained at about 50–60 °C by forcing through them a mixture of fresh air and recycled exhaust air. The stabilized material extracted from the cells undergoes a complex sequence of mechanical treatment – shredding, classification, separation of metals – to produce four output flows: RDF, inert materials, metals and non-metallic scraps. Whatever organic material is left downstream of bio-stabilization ends up in the RDF, so that there is no need to dispose of SOF. Exhaust air from the bio-stabilization cells is heated in a regenerative heat exchanger and then combusted with natural gas to destroy volatile organic compounds and odors. RDF with LHV above 16 MJ/kg is combusted in a fluidized bed combustor feeding a steam cycle and equipped with a flue gas cleaning system similar to those considered in strategies 1 and 2, with one major difference: the SNCR system for NO_x control is not needed due to relatively low and homogeneous combustion temperatures (around 900 °C) and to lower excess air in the fluidized bed. The RDF technology considered in this strategy is representative of the plant that recently came on line in Fusina, near Venice (Teardo et al., 2004).

In strategy 4 the MR residue is first screened through the same sieve size as in strategy 2; the dry fraction is

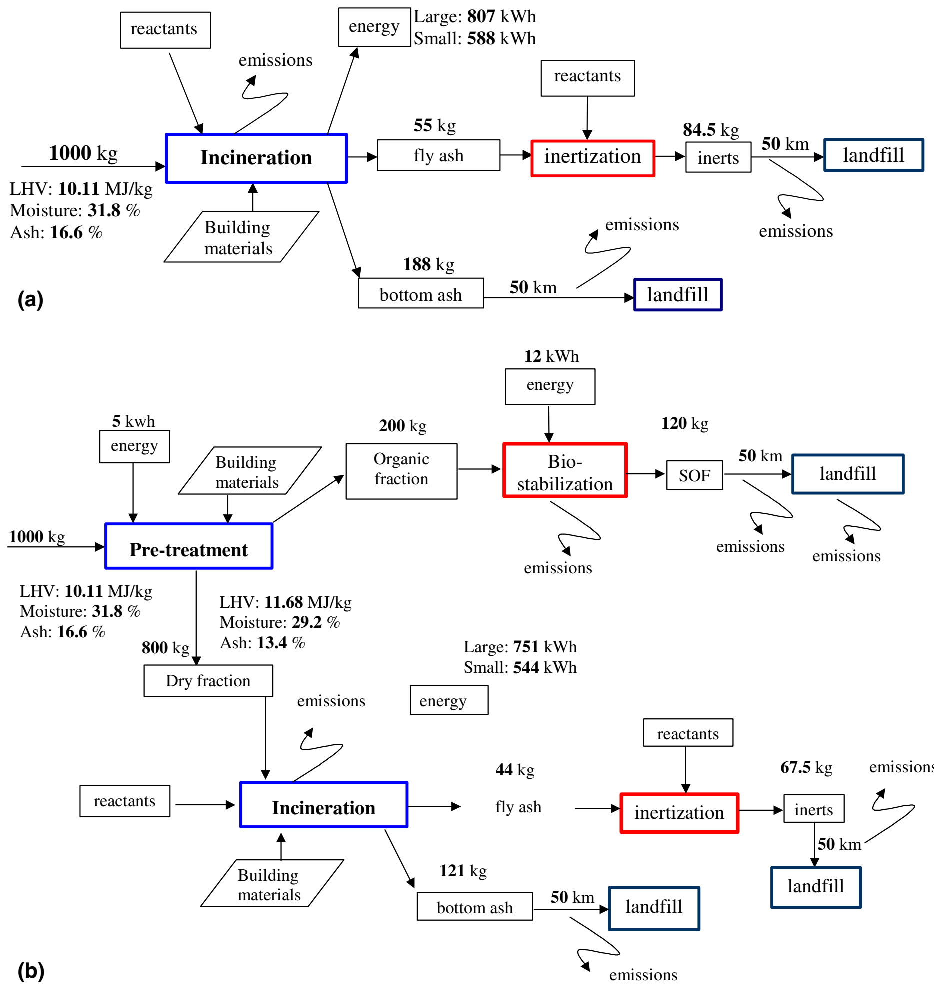

Fig 2. (a) Schematic representation of strategy 1, with basic mass and energy flows for 1 metric ton of MR residue. (b) Schematic representation of strategy 2, with basic mass and energy flows for 1 metric ton of MR residue. (c) Schematic representation of strategy 3, with basic mass and energy flows for 1 metric ton of MR residue. (d) Schematic representation of strategy 4, with basic mass and energy flows for 1 metric ton of MR residue.

then subjected to sieving, classification and metal separation to produce a RDF with LHV around 15 MJ/kg, which is combusted in a fluidized bed similar to that considered for strategy 3. The organic fraction is bio-stabilized in a plant provided with bio-filters and then landfilled. The RDF technology considered in this strategy is representative of the plant operating in Parona, close to the city of Pavia (Fava et al., 2001).

The choice of the combustion technology – air-cooled grate for strategies 1 and 2, fluidized bed for strategies 3 and 4 – follows from the properties of the material to be combusted. The air-cooled grate combustor is by far the most experienced and mature technology for mass burning of untreated material like the MR residue (Themelis, 2003; European Commission, 2004). The same technology is also well suited to combust the flow generated by the light mechanical treatment considered in strategy 2. On the other hand, when the LHV of the material to be combusted exceeds 12–13 MJ/kg – as is the case of the RDF of strategies 3 and 4 – air-cooling becomes inadequate to maintain the grate below the maximum temperature warranting adequate life (typically 350 °C). That is why the combustion of RDF requires either a water-cooled grate or a fluidized bed; [2] in the latter, the risk of overheating the elements supporting the combustible material is avoided, because of the high flow of air through the grate that suspends the combusting mixture of solids and gas (Wheeler et al., 1995).

Independent of the type of combustor, the production of electricity is carried out by a Rankine steam cycle having the characteristics summarized in Table 3. The more advanced operating conditions of large plants follow from their economies of scale, which make available the resources to pay for more sophisticated configurations and materials. In any case however, steam cycle parameters are far from those adopted in large, fossil

[2] Few manufacturers actually offer air-cooled combustors capable of handling material with LHV up to 14–15 MJ/kg, which however may not be enough for the high-quality RDF produced with strategy 3.

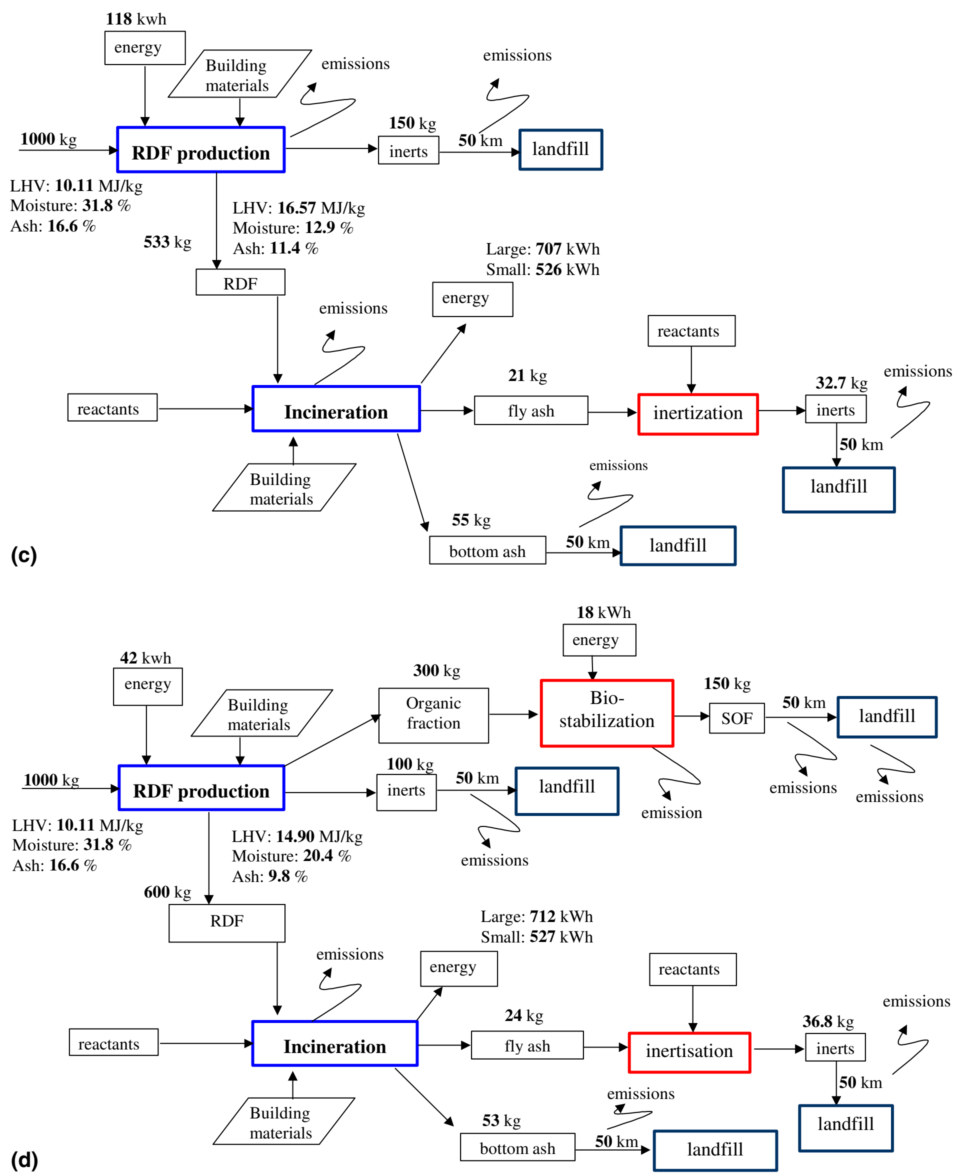

Fig. 2 (*continued*)

fuel-fired power stations, where the fuel characteristics are severely controlled and power output is an order of magnitude (or even more) higher. [3]

The steam cycle configuration considered for all cases is geared toward the production of electricity rather than for district heating. To exemplify the merits of the combined production of power and heat, for the large plant of strategy 1 we have also considered the case where the extraction of steam at 2.6 bar that feeds the air preheaters also feeds a district heating system – a typical cogeneration application of WTE plants.

4. Treatment ahead of WTE plant

In strategy 1, the "fuel" of the WTE plant is the MR residue described in Table 1. In the other strategies, the amount and the heating value of the feedstock supplied to the WTE plant depend on the treatment carried out ahead of it. Table 4 summarizes the assumptions adopted to estimate the properties of such feedstock. Similarly to the data in Table 1, the values in Table 4 are an educated guess based on the characteristics of the technology and of the flows generated by the plants

[3] Being much larger and not being subject to the corrosion and erosion caused by the contaminants typical of MSW, utility-scale steam plants generate steam above 140 bar, 540 °C; condensation can be at 0.05 bar and below, while the oxygen content in the flue gases can be as low as 3%; the configuration includes steam reheat and 7–8 feedwater heaters (or even more). As a result, large fossil fuel-fired plants can reach net electric efficiencies in excess of 40%, while even the most advanced, large WTE plants do not go over 30%.

Table 3
Design parameters assumed to evaluate the performances of WTE plants. "Small" and "large" refer to WMSs serving an equivalent population of 200,000 and 1,200,000, respectively

Design parameter	Unit	Plant size	
		Small	Large
Evaporation pressure	bar	45	65
Extraction for air pre-heating[a]	bar	2.6	2.6
Deaerator pressure	bar	2.0	2.0
Condensation pressure	bar	0.08	0.06
Gas temperature at SH inlet	°C	max 650[b]	max 650[b]
Steam temperature at SH outlet	°C	400	440
Gas temperature at ECO outlet	°C	160	140
Temperature of primary air	°C	120	120
Temperature of secondary air	°C	120	120
LP feedwater heaters ahead of deaerator		1	2
MP feedwater heaters		None	None
Flue gas recirculated	% mass	15	15
Flue gas oxygen content	% volume	6.0	5.0
Loss due to unburnt carbon[c]	% LHV	0.8	0.8

[a] In the large plant of strategy 1, the bleed that feeds the air pre-heaters can also feed a district heating system (see Fig. 4).
[b] In the large plants of strategies 2–4, the gas temperature at the inlet of the superheater is limited to 650 °C by placing a section of the economizer ahead of the superheater. In all other plants this is not necessary, because the gas temperature at the exit of the evaporator is lower than 650 °C. Notice that the steam flow is always determined so to give the specified gas temperature at the exit of the economizer.
[c] This loss is modeled as heat dissipated to the environment.

recently built in Milano, Fusina and Parona. Fig. 3 shows the results of applying the assumptions of Table 4 to the composition in Table 1. Compared to the MR residue combusted in strategy 1, the feedstock generated by light mechanical treatment (strategy 2) or the RDF of strategies 3 and 4 carry less energy to the WTE plant because their higher LHV is more than offset by their lower mass.

In addition to the loss of material and LHV documented in Fig. 3, the manipulation of the MR residue carried out in strategies 2–4 requires electric power to drive the equipment used for mechanical treatment and, in strategy 3, some natural gas to treat the exhaust of bio-stabilization. Table 5, also based on the actual performances of the plants in Milano, Fusina and Parona already mentioned, summarizes such power and fuel consumption. Finally, Table 6 shows the production of SOF and inert materials to be landfilled; the latter are net of the metal scrap recovered in the RDF and the WTE plant.

4.1. Heat balance of bio-stabilization

As already mentioned with regard to the composition of the MR residue in Table 1, it would be highly desirable to confirm the picture given in Fig. 3 with field data allowing a closure of the mass and energy balance of mechanical treatment and of bio-stabilization. This is

Table 4
Percent by weight of each waste constituent removed or consumed in the treatment carried out ahead of energy recovery

Constituent	Strategy				
	2	3			4
	Light mechanical treatment	Bio-stabilization		RDF production	RDF production
		Moisture	Volatile fraction		
Paper and cardboard	5	50	–	6	6
Wood	5	50	–	6	6
Plastic	4	50	–	5	5
Glass and inert material	50	50	–	95	95
Metals	50	50	–	96	96
Organic fraction	30	50	50	71	78
Fines	40	50	50	50	50

The values for strategies 2 and 4 are referred to the whole mass of MR residue being treated. In strategy 3, bio-stabilization first removes half of the moisture by consuming (i.e. oxidizing) 50% of the organic fraction and of fines; then, the residue of bio-stabilization is further refined by removing the percentages in the column "RDF production".

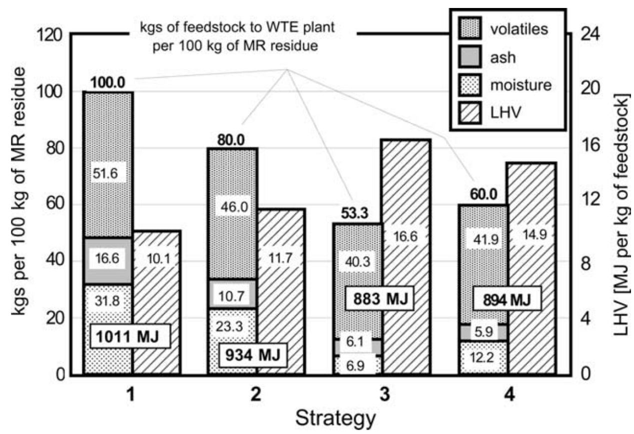

Fig. 3. Characteristics of the feedstock supplied to the WTE plant. The LHV bars (to be read on the right vertical axis) give the heating value specific to 1 kg of feedstock supplied to the WTE plant. Instead, the MJ within boxes are the total LHV supplied to the WTE plant per 100 kg of MR residue.

Table 5
Electricity and natural gas consumption for treating the MR residue ahead of the WTE plant

		Strategy		
		2	3	4
Electricity consumption	(kWh_{el} per 1000 kg of MR residue)	17	118	60
Natural gas consumption	(m^3 per 1000 kg of MR residue)	0	10.3	0

Table 6
SOF and inert materials to be landfilled assumed for each strategy

		Strategy			
		1	2	3	4
SOF	(kg/t of MR residue)	–	120	–	150
Inert materials from RDF plant	(kg/t of MR residue)	–	–	126	82
Inert materials from WTE plant	(kg/t of MR residue)	259	178	88	90
	(kg/t to WTE plant)	259	223	165	150

Non-recyclable inert materials from the WTE plant include bottom ash, inertized fly ash and spent reactants; the moisture content of bottom ash is 20%.

even more true when considering that some of the data found in the technical or commercial literature seem to disregard the energy balance of aerobic stabilization.

Due to the temperature difference between the organic mass being stabilized and the surrounding environment, in most instances stabilization takes place with some heat loss; this heat loss could be offset by solar radiation, which however is rarely the case because the organic material is generally kept indoors or covered to warrant stable, controlled conditions.

The heat released to the environment and the heat required to vaporize part of the moisture is generated by the oxidation of part of the organic material. The latent heat of the moisture evaporated must therefore be significantly smaller than the lower heating value of the organic material consumed in the process.

Table 7 illustrates the mass and energy balance of the bio-stabilization assumed for strategy 3. As reported in Table 4, it is assumed that bio-stabilization results in the loss of 50% of the moisture – for a total of 0.159 kg per kg of input – and 50% of the volatiles in the organic fraction and the fines – for a total of 0.054 kg per kg of input. Assuming for water a latent heat of 2442 kJ/kg (corresponding to phase change at 25 °C), evaporating 0.159 kg of moisture requires 388.4 kJ; such heat must be supplied by the oxidation of 0.0331 kg of volatiles in the organic fraction and 0.021 kg of volatiles in the fines, for which we have assumed a LHV of 16.32 and 14.65 MJ/kg, respectively. The complete oxidation of these volatiles could release 847.6 kJ, 459.2 kJ in excess of what is needed to vaporize the moisture. Such excess basically accounts for three effects: (i) incomplete oxidation of volatiles; (ii) temperature increase of the mass of material being stabilized and (iii) heat loss to the environment. An accurate experimental evaluation of the last two effects and of the mass balance would allow estimating how far oxidation actually proceeds from the energy balance.

5. WTE plant

The data reported in Fig. 3 allows a calculation of the mass flow and the combustion power made available to

Table 7
Mass and energy balance of bio-stabilization ahead of thermal treatment as assumed for Strategy 3

		Mass flows, kg per 100 kg of input			Heat release, kJ per kg of input
		In	Out	Loss	
Organic fraction	Moisture	22.05	11.03	11.03	−269.3
	Ash	2.84	2.84	0	0.0
	Volatiles	6.62	3.31	3.31	540.0
Fines	Moisture	3.60	1.80	1.80	−44.0
	Ash	4.20	4.20	0	0.0
	Volatiles	4.20	2.10	2.10	307.7
Other fractions	Moisture	6.15	3.08	3.08	−75.1
	Ash	9.59	9.59	0	0.0
	Volatiles	40.76	40.76	0	0.0
Total	Moisture	31.80	15.90	15.90	−388.4
	Ash	16.62	16.62	0.00	0.0
	Volatiles	51.58	46.17	5.41	847.6
Grand total		100.0	78.69	21.31	459.2

the WTE plant for each strategy and for each system size. Electric power output and other relevant operating parameters have been estimated by a computer code developed at Dipartimento di Energetica of Politecnico di Milano.

5.1. Design and simulation tool

The code used to estimate the performances of WTE plants was originally developed to simulate Combined Cycles (Consonni, 1992) and then extended to handle essentially all types of power plants based on gas and/or steam cycles (Chiesa et al., 1993; Macchi et al., 1995; Consonni, 2000b), including those fired with unconventional fuels like biomass, heavy residues, waste, etc. The system of interest is defined as an ensemble of components, each belonging to one of 16 basic types: pump, compressor, turbine, heat exchanger, combustor, gas turbine expander, chemical reactor, etc. Basic characteristics and mass/energy balances of each component are calculated sequentially and iteratively until the conditions at all interconnections converge to stable values.

The model accounts for all major phenomena and mechanisms affecting the performances of WTE systems: combustion; heat transfer; heat losses; losses due to unburnt fractions; pressure drops, variation of turbomachinery efficiency with scale and stage similarity parameters; auxiliary power consumption, etc. Thermodynamic properties are calculated according to the JANAF tables (Stull et al., 1971; Gardiner, 1984) except for water and steam, which conform to SI tables (Schmidt, 1982).

5.2. Performance estimates

The composition of the volatile fraction is assumed to be the one shown in Table 1. Differentiating among the various strategies would require information that was not available – with essentially no improvement in accuracy; in fact, for a given heating value, any variation of the atomic composition of the volatile fraction implies only very small variations of the heat lost at the stack.

The configurations considered for the grate combustor and the fluidized bed combustor are illustrated in Figs. 4 and 5. As already mentioned, all plants generate only electricity except for the large grate combustor of strategy 1, where we also considered two cogeneration applications. In cogeneration mode, the flow of steam at 2.6 bar extracted from the steam turbine to feed the air pre-heaters is greatly increased in order to also feed a district heating system, where hot pressurized water is distributed at 115–120 °C. The two cogeneration applications differ only in the amount of steam sent to district heating:

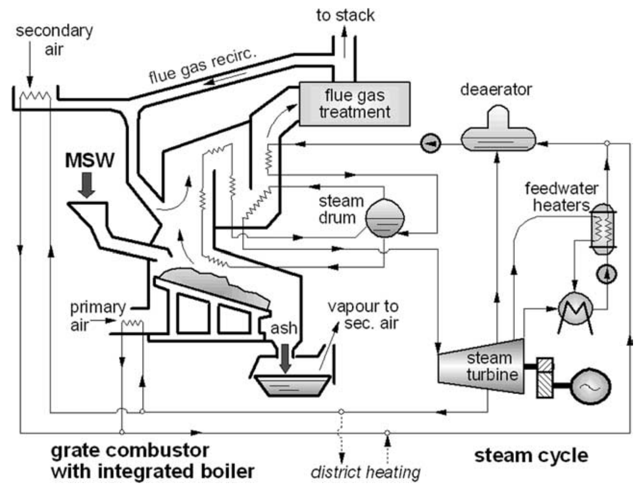

Fig. 4. Configuration of grate combustor considered for strategies 1 and 2. The extraction of steam (at 2.6 bar) for district heating is considered for the large plant of strategy 1 to assess the cogeneration of power and heat. In the large plant of strategy 2, a section of the economizer is placed ahead of the superheater to limit the temperature of the gas entering the superheater to 650 °C.

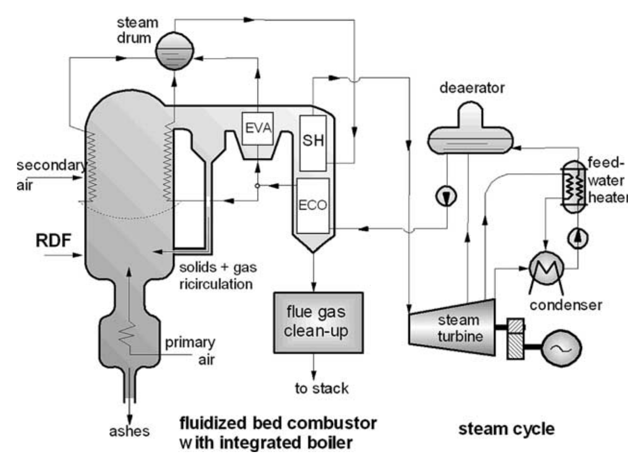

Fig. 5. Configuration of fluidized bed combustor considered for strategies 3 and 4. In large plants, a section of the economizer is placed ahead of the superheater to limit the temperature of the gas entering the superheater to 650 °C.

– 30% of the total flow entering the steam turbine for case "cog A";
– 60% of the total flow entering the steam turbine for case "cog B".

Case A is representative of the yearly average of district heating systems where the peak thermal demand is smaller than the maximum thermal power provided by the WTE plant (with full extraction); as a consequence, the yearly average of the flow extracted for heat production is relatively small. Case B is representative of the yearly average of district heating systems where the peak thermal demand is larger than the maximum thermal power provided by the WTE plant; as a consequence, the yearly average of the flow extracted for heat production is relatively large (and the system requires auxiliary heat generation).

Table 8 summarizes the performances estimated for each strategy for both plant sizes. In addition to the design parameters reported in Table 3, the results in Table 8 account for all major elements affecting the efficiency of energy conversion:

- differences in the properties of the feedstock (LHV, moisture and ash content) and the specific heat of combustion gases;
- variations in the efficiency of the main rotating equipment (steam turbine, pumps, fans, electric generator) with their size;
- differences in auxiliary power consumption originating from variations of the gas and solid flows to be handled.

As such, the estimates in Table 8 allow a coherent, realistic comparison of strategies and plant sizes. The results point out the following:

- pre-treating the MR residue and increasing the heating value of the feedstock fed to the WTE plant has marginal effects on net LHV efficiency;
- despite the increase in the heating value of the feedstock, pre-treating reduces the total amount of electricity which can be produced, because the loss of combustible material more than offsets the (marginal) gain in efficiency;
- the higher the degree of pre-treatment, the smaller is the energy recovered per unit of MR residue: compared to strategy 1, the net electricity generated per ton of MR residue decreases by 7–8% with strategy 2, and by 10–12% with strategies 3 and 4. As shown in the next section, this is even more pronounced after accounting for the consumption of the pre-treatment system;
- for a definite strategy, large plants provide noteworthy improvements of net LHV efficiency and thus of electricity generated per unit of MR residue. In our case, the sixfold increase in capacity from a plant serving a gross MSW production of 100,000 tons/year to a plant serving a gross production of 600,000 tons/year increases specific electricity production (kWh/ton of MR residue) by 35–38%. This strong, well-known scale effect (Consonni and Capra, 1998; Consonni, 2000a) is due to more favorable design parameters (see Table 3) and higher efficiencies achievable by turbomachines, particularly the steam turbine.

6. Overall energy balance

The performances of the WTE plants shown in Table 8 provide a crucial but still incomplete picture. A proper assessment of recovery strategy must include all the processes upstream and downstream of combustion, as well as the power stations displaced by the WTE plant (and, for cogeneration, the systems supplying heat). The energy balance of the whole system, as delimited by the

Table 8
Overall performances of WTE plants

WMS size		Small				Large					
Gross MSW production	(t/yr)	100,000				600,000					
MR residue	(t/yr)	65,000				390,000					
Strategy		1	2	3	4	1			2	3	4
WTE plant output		Electricity				Electricity	Cog A	Cog B	Electricity		
Feedstock to WTE plant	MJ_{LHV}/kg	10.11	11.68	16.57	14.90	10.11	10.11	10.11	11.68	16.57	14.90
	t/yr	65,000	51,977	34,635	38,977	390,000	390,000	390,000	311,864	207,807	233,864
	MW_{LHV}	25.4	23.4	22.2	22.4	152.1	152.1	152.1	140.5	132.9	134.5
Steam flow to turbine	kg/s	8.70	8.08	7.63	7.70	51,87	51,87	51,87	48,18	44,97	45,41
Gas flow (dry, 11% O_2)	Nm^3/s	15.55	13.84	12.06	12.58	91.93	91.93	91.93	81.91	71.69	74.63
Dry ashes in feedstock	t/yr	10,805	6940	3951	3822	64,828	64,828	64,828	41,639	23,706	22,932
Inert materials to landfill		16,835	11,570	5720	5850	101,010	101,010	101,010	69,420	34,320	35,100
Gross electric power	MWel	6.68	6.17	5.95	6.01	49.26	42.94	36.48	45.64	43.58	44.03
Net electric power	MWel	5.31	4.91	4.75	4.76	43.73	37.84	31.81	40.66	38.32	38.56
Net LHV efficiency	%	20.9	21.0	21.4	21.2	28.8	24.9	20.9	28.9	28.8	28.7
kWh per t of feedstock		588	680	987	879	807	699	587	938	1327	1186
kWh per t of MR residue		588	544	526	527	807	699	587	751	707	712
Useful thermal power	MWth	0	0	0	0	0	34.4	68.8	0	0	0
MJ_{th} per t of feedstock		0	0	0	0	0	2287	4574	0	0	0
MJ_{th} per t of MR residue		0	0	0	0	0	2287	4574	0	0	0

Table 9
Assumptions adopted to estimate the overall energy balance of ER from MR residues

Power generation	
Technology	Steam cycle
Primary energy (LHV)	50% heavy oil + 50% natural gas
Average net efficiency	37.5% (LHV)
kgOE per MWh_{el}	229.3
Transport of solid residues	
Average distance	50 km
Diesel fuel consumption	0.051 kgOE/t-km
District heating (only for cogen cases)	
Thermal losses	19% of heat input
Efficiency of displaced boilers	80%
Total energy use	
3.2 TOE per yr per capita	

boundary shown in Fig. 1, has been evaluated based on the assumptions in Tables 5 and 9. The results are shown in Table 10.

The distance actually covered for the disposal of solid residues may differ significantly from the 50 km indicated in Table 9 but, as shown in Table 10, its impact on the results is minimal. The thermal losses and efficiency of displaced boilers assumed for district heating are meant to represent annual averages, i.e., they include the effect of start-ups, shut-downs and cycling (Consonni, 1997). The total energy use of 3.2 TOE per year per capita is the average consumption in Italy in 2001 (Anon, 2003).

6.1. Power displaced by energy recovery from MR residues

The most crucial assumptions in Table 9 are those regarding the power stations displaced by the WTE plant, because they affect both the energy balances in Table 10 and the emission estimates illustrated in Part B. Assuming that the WTE plant displaces conventional steam plants fired with heavy oil and natural gas (each providing 50% of the LHV input) is representative of current Italian conditions, where dual-fuel conventional steam plants still account for most of the generating capacity. Should energy from MSW displace high-efficiency, natural gas-fired combined cycles, the net reduction of primary energy use (in Table 10, net ΔF of ER) would be significantly smaller; the opposite would be true if energy from MSW displaced relatively inefficient coal-fired plants.

To establish the generating mix displaced by the WTE plant requires a thorough analysis of generating capacity and distribution rules, including the effects of incentives that may be available for the production of energy from MSW. Such involved analysis is beyond the scope of this work.

Table 10
Overall energy balance of each strategy

WMS size		Small				Large					
Strategy		1	2	3	4	1			2	3	4
WTE plant output		Electricity				Electricity	cog A	cog B	Electricity		
E for pre treating	kWh_{el} per t of MR residue	0	17	118	60	0	0	0	17	118	60
E from WTE plant	kWh_{el} per t of MR residue	588	544	526	527	807	699	587	751	707	712
Net E	kWh_{el} per t of MR residue	588	527	408	467	807	699	587	734	589	652
ΔF for electricity generation	kgOE per t of MR residue	−134.9	−120.8	−93.6	−107.2	−185.1	−160.2	−134.7	−168.3	−135.2	−149.5
ΔF for heat generation	kgOE per t of MR residue	0	0	0	0	0	−55.3	−110.5	0	0	0
F for pre-treatment	kgOE per t of MR residue	0	0	8.5	0	0	0	0	0	8.5	0
F for solids transport	kgOE per t of MR residue	0.8	0.9	0.6	0.6	0.8	0.8	0.8	0.9	0.6	0.6
Net ΔF of ER	kgOE per t of MR residue	−134.1	−119.9	−84.5	−106.6	−184.3	−214.7	−244.4	−167.4	−126.1	−148.9
People served		200,000				1,200,000					
Total energy use	TOE/yr	640,000				3,840,000					
Net ΔF of ER, absolute	TOE/yr	−8716	−7796	−5493	−6926	−71,896	−83,724	−95,322	−65,286	−49,179	−58,070
Net ΔF of ER, relative	%	−1.36	−1.22	−0.86	−1.08	−1.87	−2.18	−2.48	−1.70	−1.28	−1.51

E = electricity, F = primary energy.

6.2. Reductions of primary energy use

Table 10 shows that energy recovery from MR residues allows reducing the fossil fuel use of the whole society between 1% to 2.5%.

In all cases, pre-treatment decreases overall energy savings. With respect to strategy 1, which is the most energy efficient, the "loss" of energy savings incurred with the other strategies ranges from 11% (strategy 2, small plants) to 37% (strategy 3, small plants).

For the same strategy, large plants serving a population of over one million people result in energy savings 30–60% higher than small plants serving a population of just few hundred thousand.

The cogeneration of power and low-temperature heat for district heating greatly increases the overall reduction of energy use.

Should the WTE plant displace high-efficiency combined cycles, instead of the conventional steam cycles assumed here, energy savings would be smaller, but the relative merits of each strategy and the superiority of large-scale WMSs would still hold. On the other hand, the merit of strategies 3 and 4 may improve when considering the co-combustion of the RDF in large steam power stations with electric efficiencies much above those attainable by WTE plants. This option has been proposed to make best use of the RDF, but it is subject to significant technological uncertainties – first of all the effects of the exposure of the boiler tubes to RDF combustion byproducts.

7. Conclusions

Part A of this study has examined the mass and energy balances of four alternative strategies for energy recovery from MR residues by dedicated WTE plants.

Pre-treating the MR residue and increasing the heating value of the feedstock fed to the WTE plant has marginal effects on the energy efficiency of the WTE plant; however, it reduces net electricity production, because the loss of combustible material more than offsets the (marginal) gain in efficiency. The energy efficiency of pre-treatment strategies is reduced further when enlarging the boundary to encompass the pre-treatment of the MR residue and the disposal of inert materials. The more thorough the pre-treatment, the smaller the amount of energy recovered per unit of MR residue.

For the same strategy, the net amount of electricity that can be generated per unit of MR residue increases significantly when the size of the WMS increases. Large WMSs serving a population of over one million people result in energy savings 30–60% higher than small WMSs serving smaller population centers.

The option resulting in the highest overall energy savings is the combustion of the MR residue "as is" in large-scale plants. If this is done by cogenerating large amounts of low-temperature heat for district heating, the primary energy savings can be as high as 2.5% of total societal energy use. These energy savings depend on the assumptions on the power stations displaced by the WTE plant; the displacement of conventional steam plants fired with heavy oil and natural gas (each providing 50% of the LHV input) assumed here is representative of the current Italian situation.

Acknowledgements

The research described in this paper has been commissioned to Politecnico di Milano by Federambiente (Federation of Italian Waste Management Municipal Utilities). The financial support and the cooperation of Federambiente are gratefully acknowledged.

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