The mass and energy balance of an integrated solution for municipal solid waste treatment

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Abstract

This paper describes a study conducted to evaluate the best scenario regarding the integrated management of municipal solid waste (MSW) in a large basin in North of Italy. Three different scenarios were defined with various technological solutions, having as principal core the selective collection, the energy recovery and the modality of final disposal. The comparison was done considering both mass and energy balance, trying to focus on the most suitable solution. The solutions cannot be definitive without having also developed a survey on the environmental and economic sustainability of the various alternative cases. However, an assessment made by developing balances of mass and energy demonstrates that the more interesting and favorable scenarios involve greater energy recovery, in particular with gasification and anaerobic digestion of the organic matter.
Keywords: energy, mass balance, recovery, waste management.

1 Introduction

The main methods for waste disposal in the 27 countries of the European Union (EU-27) are landfilling (about 48%) and recovery (about 47%). The data vary greatly from country to country, from Bulgaria, where 99% of the waste is dumped, to the Netherlands, where 83% is recovered. Denmark (23%),

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Belgium (15%), Finland (13%) and Sweden (10%) are above the European average in terms of energy recovery [1].

The amount of recycled MSW increased from 21.8 million tons (46 kg per capita) in 1995 to 59.2 million tons (118 kg per capita) in 2009 [1]. Selective collection (SC) varies greatly from country to country but also from system to system [2, 3, 4], with more significant increases for some types of waste, for example, waste electronic and electrical equipment (WEEE) and organic fraction municipal solid waste (OFMSW) [5, 6]. The recovery of organic matter by composting is the treatment that increased the most, with an annual growth rate of 9.1%. In general, the recovery of energy from organic fractions, not only by aerobic processes, but also through anaerobic digestion (AD), by exploiting the contribution of companies that operate in the fields of agriculture, zootechnology and the food industry, has had a significant boost [7–12]. There has been a constant increase in MSW incineration, from 65 kg per capita, in 1995, to 101 kg per capita in 2009, reaching recently 20% of the total amount of waste disposed [13], even if new plants are expected in areas with a high concentration of waste generation.

The choice of waste management system is linked to EU regulations and the laws of the marketplace. The integrated solutions applied to managing MSW must thus be based on the local situation, taking into account environmental problems, the renewable energy request at national and international level, the quantity and quality of the waste produced and the economic requirements [4, 14, 15].

The environmental sustainability of the various solutions related to the choice processes typology and waste treatment plants is strategically important given the public's concern about environmental issues. Relaying information [16] is also very important in order to focus attention on waste treatment. Particularly with regard to environmental pressures and atmospheric pollution [17–23].

Based on the quality and quantity of waste produced in the province in Trento, northern Italy, a study was carried out to compare different scenarios related to different integrated waste management solutions.

2 Materials and methods

The chosen case-study, a province in the North part of Italy, occupies an area of 6207 km^2. In 2010, the resident population was 524,826. The annual production of waste is about 297,217 tons [24]. Three integrated MSW scenarios have been developed and are presented in this paper.

In the first scenario reported in Fig. 1:

- *recyclable materials* are sent to the market; the residues resulted from the residual waste (RMSW) processing and from the recycling line are exploited for energy (paper and cardboard, wood, plastic) through gasification after shredding; the residues that cannot be energetically recovered are landfilled;
- *compostable materials*: OFMSW is sent to AD; produced biogas is collected and used in an internal combustion engine to produce electricity

and heat. The digestate is sent to post-composting plant together with the green fraction. A part of the pre-treatment residues are subject to shredding and bio-drying treatment before being exploited for energy;
- *materials recovery, treatment, disposal flows*: the not reused fractions (textiles, WEEE, inert, bulky waste, waste swept from the road, etc.) are sent to dedicated disposal platforms.

In the case of RMSW, the bags are first opened mechanically, and the waste then undergoes magnetic separation system in order to recover valuable metals. The material that has had its metal part removed undergoes to a pressure-extrusion system, which separates the stream in two flows: wet and dry fractions. The residues of the pre-treatment and post-refining are added to the wet fraction, which is bio-dried in order to reduce the moisture present and to increase the LHV [25], before being sent to gasification. A ballistic separator is used to sort the combustible dry fraction. The syngas produced is first treated, and then flows into an internal combustion engine to produce electricity and heat; the slag from the gasification and syngas cleaning processes are landfilled (Fig. 1).

The *second and third* developed cases, have a slightly different scheme in comparison with the first one. In the second case the wet fraction coming out of the pressure extruder is sent for AD to produce biogas, and in the third is sent to thermal drying. In the *third case*, the thermal drying in addition to electricity, needs a considerable amount of heat, which will be recovered by exploiting the energy contained in the hot gases and in the cooling system of the cogenerator, which works thanks to the biogas that comes from the OFMSW anaerobic digestion.

In all the considered cases, the efficiency values and the parameters that relate to the various treatments, which are necessary to establish the balances, were determined from the technical literature, in particular: bag splitter (blade shredder: energy consumption), primary shredder (energy consumption), magnetic separation, extrusion, and ballistic separator (efficiency and energy consumption), internal combustion engine (running parameters), AD (running parameters and energy consumption), mechanical drying (running parameters and energy consumption), post-composting (energy consumption), thermal drying (thermal and energy consumptions), bio-drying (running parameters and energy consumption), gasification and syngas cleaning (running parameters and energy efficiency) [26–38]. Each process that transforms the waste into reusable material has its own recovery efficiency [26–38].

For the material sent for composting, 25% of residue of the total ingoing material was considered valid, as the sum of the residues for the pre-treatment of the material going into the AD and the residues from the refining of the compost, which take place at the end of the process.

The recycling of some fractions of the waste leads to some energy saving, preventing emissions into the atmosphere, and reduces the use of new raw materials for the production of consumer goods. To calculate the electrical and thermal energy saved, for inclusion in the overall costs, the distribution of the electrical/thermal consumption linked to the production of each type of recycled material was calculated. This distribution was then maintained to calculate the energy saved: steel 27,176 MJ/ton$_{produced}$, aluminium 187,834 MJ/ton$_{produced}$, glass 6424 MJ/ton$_{produced}$, wood 29,438 MJ/m$^3_{produced}$, paper 42,044 MJ/ton$_{produced}$, plastic 72,573 MJ/ton$_{produced}$ [39].

In order to take into account the possible degradation of the material produced from recycled matter, replacement rates were introduced for the paper, wood and plastic fractions: 1.0 for metals and glass, 0.6 for wood, 0.83 for paper and 0.85 for plastic 0.9.

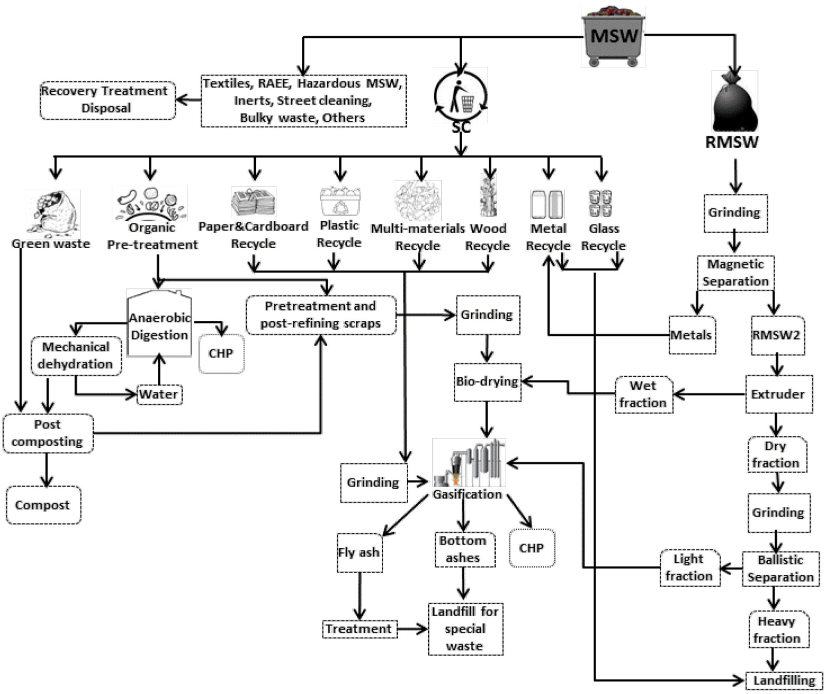

Figure 1: MSW treatments: scenario 1.

3 Results and discussion

Table 1 shows the final destinations in various scenarios, while Tables 2 and 3 show the mass and energy balances for scenario 1.

Table 1: Final destination of the waste in the considered scenarios.

	Case 1	Case 2	Case 3
Material to landfill	12%	11%	12%
Produced compost	7%	10%	7%
Recycled material	28%	28%	28%
Mass loss	40%	38%	40%
Material to be recovered, treated, disposed of	13%	13%	13%

Table 2: Benchmarks in all cases.

Flux	Case 1		Case 2		Case 3	
Mass balance	Mass [%]	LHV [kJ kg^{-1}]	Mass [%]	LHV [kJ kg^{-1}]	Mass [%]	LHV [kJ kg^{-1}]
MSW	100	9,883	100	9,883	100	9,883
RMSW	33	14,439	33	14,439	33	14,439
Material from SC to recycling	10	10,093	10	10,093	10	10,093
Material from SC to biological treatment	13	4,160	13	4,160	13	4,160
Material from SC to other treatment	13	6,803	13	6,803	13	6,803
Metals from RMSW to recycling	1	0	1	0	1	0
Residuals from SC to landfill	1	0	1	0	1	0
Residuals from pre-treatment and post refinement	5	22,706	5	22,706	5	22,706
Residuals from recycling and treatment	6	12,685	6	12,685	6	12,685
Material to press-extrusion	32	14,899	32	14,899	32	14,899
Dry fraction to ballistic separation	23	17,766	23	17,766	23	17,766
Wet fraction to drying process	9	8,020			9	8,020
Bio-dried fraction	11	17,144			6	9,514
Wet fraction to anaerobic digestion	9	8,020	9	8,020	9	8,020
Digested dehydrated from RMSW to post-composting	11	17,144	7	-	11	17,144
Light fraction	19	20,239	19	20,239	19	20,239
Heavy fraction to landfill	3	3,024	3	3,024	3	3,024
Material to landfill	4	2,335	3	3,024	4	2,335
Material to gasification	36	18,111	36	19,283	6	17,649
Bottom ash	6	-			1	-
Residuals from syngas treatment	1	-			1	-
Material to landfill for hazardous waste	8	-	7	-	8	-
Produced compost	7	-	30	-	7	-

It is interesting to note the mass loss due to the different treatments provided in the system and determined essentially by the loss of moisture or volatile solids. The AD exploits the content of carbon, hydrogen and oxygen present in the waste for the production of biogas, while the bio-drying increases the temperature in the waste, and decreases the moisture involving the use of a part of volatile solids. Compost production consumes the volatile solids in the degradation of the organic substance, while thermal drying causes a loss of water, and finally the thermal treatment breaks down what remains of the moisture and volatile solids.

Considering the global energy balance (Table 3) in the first scenario the amount produced by the whole system is greater than the consumed one. Only 21% of the electricity produced, and 3% of that thermal energy produced is required for the operation of the system. The other two scenarios have similar behavior. Table 4 shows the values of energy saved by recycling materials that replace each percentage in the material produced from virgin raw materials.

The total electrical energy transferred to the electric network is equal to 120 GWh per year, while the thermal energy is 165 GWh.

Table 3: Total energy.

	Case 1		Case 2		Case 3	
PRODUCED	[kWh t^{-1}]	[GWh y^{-1}]	[kWh t^{-1}]	[GWh y^{-1}]	[kWh t^{-1}]	[GWh y^{-1}]
Gasifier, electric energy	1,359	144,399	1,447	130,47	1,324	141,146
AD, electric energy	209	7,612	209	7,612	209	7,612
From RMSW, electric energy	-	-	343	9,55	-	-
Gasifier, thermal energy	1,532	162,797	1,631	147,098	1,493	159,130
AD, thermal energy	214	7,780	214	7,780	214	7,780
From RMSW, thermal energy	-	-	350	9,762	-	-
CONSUMED	-	-	-	-	-	-
First open bags grinding	3	293	3	293	3	293
Deferrization	1	127	1	127	1	127
Press-extruder	11	1,043	11	1,043	11	1,043
Primary grinding	12	1,185	12	1,197	12	1,185
Ballistic separator	1	50	1	50	1	50
Bio-dryer	33	1,420			33	1,420
Electric dryer	-	-	-	-	93	1,358
Thermal dryer	-	-	-	-	930	13,580
Gasifier and gas treatment	202	23,104	215	20,87	196	22,583
AD pre-treatments (grinding and sieving)	13	583	13	583	13	583
AD, electric	30	1,091	30	1,09	30	1,091
AD, thermal	107	3,902	107	3,902	107	3,902
Sludge dewatering	6	758	6	758	6	758
Sludge dewatering from RMSW	-	-	6	889		
Pre-treatment before composting	12	188	12	188	12	188
Composting	20	942	20	1,362	20	942
Post refinement (sieving)	1	27	1	37	1	27
Electric energy consumption for management	-	1,200	-	1,200	-	1,200
Thermal energy consumption for management	-	1,000	-	1,000	-	1,000
TOTAL electric	-	32,010	-	30,531	-	31,428
TOTAL thermal	-	4,902	-	9,596	-	18,481
PARTIAL BALANCE (E.E.):	-	120,001	-	117,106	-	117,331
PARZIAL BALANCE (Thermal Energy)	-	165,676	-	155,044	-	148,429
Energy saved thanks to recycling						
Electric energy	-	139,008	-	139,008	-	139,008
Thermal energy	-	139,131	-	139,131	-	139,131
GLOBAL BALANCE (E.E.):	-	259,009	-	256,114	-	256,338
GLOBAL BALANCE (Thermal Energy)	-	304,807	-	294,175	-	287,560

Table 4: Energy saved by recycling materials instead of producing from raw materials.

Case 1 – 2 – 3		
Type of material	Electrical energy [GWh]	Thermal energy [GWh_{th}]
Metal	8,339	7,553
Wood	121	9,946
Glass	7,895	39,942
Paper	113,435	67,521
Plastic	9,217	14,169

Calculation showed that an average of 59 kWh t^{-1} and 64 kWh_{th} t^{-1} of electrical and thermal energy in all scenarios are needed to treat organic and green waste from selective collections. The obtained energy (209 kWh t^{-1} and 214 kWh_{th} t^{-1} electrical and thermal) is abundantly greater than that consumed, and thus the balance is positive.

In the *first case*, the balance is positive because the energy production is far higher than the energy consumption for the waste treatment. The specific electrical energy cost to treat RMSW and residues from recycling and composting as input to the gasifier is 278 kWh t^{-1}. The consumptions necessary for these treatments, including the self-consumption of the gasifier, are equal to 19% of the electricity produced.

The gasifier is quite energy-intensive as is the process of bio-drying of the wet fraction from the press-extruder, while the other treatments are relatively inexpensive in terms of energy consumption. The high energy production from the gasifier is due to the high energy content of the feed material; its net electrical efficiency reaching a value of 23%. The LHV of gasifier input increased by 24% starting from the moment in which the waste enters the process at the point when it is fed to the gasification. Of course this balanced by a decrease of the mass flow.

In the *second case*, the energy produced is again far greater than the energy consumed. The total energy transferred to the electric network is 117 GWh annually, while the thermal energy is 155 GWh_{th}. In this scenario there is an additional source of electricity production represented by the second anaerobic digestion plant. The pre-treatments for the gasification required an electricity consumption of 254 kWh t^{-1}. The consumption requested for the treatments, including the gasifier self-consumption are 18% and 3% respectively of the electricity and thermal energy produced. By bringing a mix of materials to the gasifier with a high energy content (more than 19,000 kJ kg^{-1}), low moisture (20%) and low content of NVS (13%), good results can be obtained in terms of the amount of energy produced from the syngas.

In the *third case*, the overall energy balance is positive, but less than the previous cases because the waste thermal drying consumes a significant amount of energy. The energy consumed to ensure the operation of the integrated waste management, is 21% of the electricity and 11% of the thermal energy produced. The total annual energy transferred to the network is 117 GWh, while the thermal energy is 148 GWh_{th}. The treatments needed before gasification required an electricity consumption of 272 kWh t^{-1} of electricity and 139 kWh_{th} t^{-1} of thermal energy.

The first case is the best from the point of view of electricity production followed closely (4÷5 GWh less) by the second one. The exploitation of energy from biological treatment does not significantly influence the balance.

4 Conclusions

The present study has highlighted how difficult it is to determine a priori the best technologies for the waste management, regardless of the composition of the waste, the plant size and location in the territory. An environmental analysis certainly could help to define which technologies together have a minor impact. The energy balance helps to determine the most efficient way to recover the energy contained in the waste. The mass balance is necessary for the correct dimensioning of the various plants. Thus, all these analyses (together with the financial evaluation) are necessary to determine a correct MSW integrated system. However the proposed systems must take into account the social and geographical context, and may also help to foster any changes in the lifestyle and routines of the local population which are needed for the entire waste cycle to be managed correctly.

Of course, the study assumes that the technical solutions contained in the various scenarios are environmentally and economically sustainable and that the market is able to receive flows from recycling, and the production of compost, etc.

Referring to the considered scenarios, the first two cases appear to be preferable in the context of the considered area. Nonetheless, the first scenario has its merit in obtaining a higher production of electricity and heat, while the second scenario ensures a greater production of compost (assuming that this does not constitute a problem for the identification of the end users). The last scenario is less interesting. The presence of an anaerobic digester does not affect the global energy balance much. Exploiting a thermal dryer is not sustainable due to the high energy consumption.

As a future step the authors planned to develop a sensitivity analysis in order to better understand the differences among the presented scenarios.

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