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Municipal Solid Waste treatment by integrated solutions: energy and environmental balances

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Abstract

This paper reports a comparison between two scenarios developed in order to manage the municipal solid waste in an area in the North part of Italy. In the proposed scenarios various technological solutions, regarding the selective collection, the energy recovery and the modality of final disposal were taken into account. The comparison was done considering both mass/energy and environmental balance, trying to focus the most suitable solution. The experience can be completed with other scenarios containing different technical solution intermediate between the two considered in this study.

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Keywords: bio-drying, environmental balance; energy balance; integrated solutions; mass balance; MSW treatment; selective collection.

1. Introduction

The data provided by the European environmental agencies, as evidenced by heterogeneous integrated systems of waste management are used in the various EU countries [1,2]. There are a lot of variable data on all phases involving the integrated cycle of waste management, from collection to processing choices, the mode of disposal within the

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environmental and economic costs. For example, the recycling percentages are different from country to country and even within the same country it can vary greatly from region to region. A common finding is the increase almost everywhere on the separate collection of the organic fraction of Municipal Solid Waste (OFMSW) and electronics (WEEE) [3,4]. Another common factor is the increase in the total annual production of MSW.

The collection of the organic fraction has had significant boost (annual growth rate of 9.1 % [5]). This is to be related both to critical environmental aspects related to its disposal in landfill, and to the opportunity to exploit this fraction of waste for secondary products or energy recovery. For this reason, while in the recent past the aerobic treatments (and therefore energy-aimed at the production of compost) were very considered, the anaerobic treatment of organic waste had a strong impulse, as the only matrix, or in co-digestion with other organic fractions. The economic incentives on energy production played an important role, which has guided many companies in the agricultural sector, the food industry and the livestock to develop treatment solutions considering organic waste anaerobic digestion for energy production [6,7,8].

As mentioned above, large differences also affect the integrated system of treatment and disposal of waste in the various countries of the European community. The differences are also due to different laws and regulations and are highly influenced by many variables. An important variable is the economic one, because there are different energy costs moving from country to country and also the costs of the various treatment systems contained in a waste management integrated system [9,10]. Another significant variable is made up of the environmental pressures associated with waste management and the sensitivity of the population with respect to these. And in turn, these aspects are related to local environmental, climatic conditions, social structure, etc. and accurate information between stakeholders combined with a system of integrated waste management and population. The environmental sustainability of the various solutions related to the choice of the type of processes and systems for the treatment of waste is strategically important given the growing public concern about environmental issues [11]. In this regard, environmental issues related to the decisions on waste management are mainly made up of the critical issues related to the problems of public health and therefore especially the pollution of the atmosphere [12,13,14].

This paper describes a study carried out in a wide region of Northern Italy, with a relatively low population density, but with strong tourist activity, which is linked to a significant seasonality of users. The objective was to identify criteria to choose between two alternative integrated management systems, based not strictly on economic evaluations, but only on mass, energy and the environment balances.

2. Materials and methods

In the chosen case-study, the annual production of MSW is 297,217 tons [15,16]. The selective collection (SC) reaches up to 67%. Two scenarios are developed and presented concentrating the results on their environmental balance. The first scenario presents a complex approach of MSW management system that has been analysed in previous works developed by the authors [17,18]. In order to have a global image, a brief description of the first scenario scheme sequence is presented in the following:

➢ *SC waste fractions*

- The recyclable materials, such as (paper and cardboard, plastic, wood, metals and glass) are designated for direct recovery as raw materials. Due to the each treatment recycling efficiency [19] the residues resulted from the recycling process are sent to landfill in the non-combustible waste case (metals and glass) or energetically recovered where combustible waste (paper and cardboard, wood and plastics) is exploited as support fuel in thermal facilities after their shredding;
- The organic fraction is pre-treated and sent to anaerobic digestion (AD); the biogas collected is used in an internal combustion engine electricity and heat production (CHP). The digestate is sent to a post-composting station; with the addition of the green fraction, compost is produced. The pretreatment of the ingoing organic fraction, the drying of the digestate and the refining of the compost produce water, which is recirculated in the digester, and residues that undergo shredding and bio-drying before being exploited for energy;
- The other flows defined by textiles, Waste Electrical and Electronic Equipments (WEEE), hazardous waste, Inerts, Street cleaning and Bulky waste are designated for treatment, recovery or disposal.

➢ *Residual Municipal Solid Waste (RMSW) fraction* undergoes to a multi-sequential system that aims to recover recyclable materials (metals and glass) and combustibles materials (plastics).

- In order to facilitate the magnetic separation stage of the system, first the waste bags are open mechanically. The recovered ferrous metals are sent to the metals recycling facility.
- The extruder receives the rest of the waste resulted from the later process. This on pressure treatment separates the material into two flows: wet and dry fraction.
- The bio-drying treatment receives the wet fraction coming from the extrusion process and the post-refining scarps resulted from the AD. The present treatment fits into the scheme, in order to reduce the stream moisture and to increase its LHV, before being sent for gasification.
- A shredder and a ballistic separator receive the dry extruded fraction. The later treatments aim to homogenize the waste and reduce the heavy fraction of the flow that is stored in the dump.
- The gasification plant receives the combustible waste flows: paper, cardboard, plastic and wood refused material from recycling facilities, dry flow from bio-drying process and medium/light fraction from the ballistic separator. The syngas produced is first passing through a cleaning system in order to line with the gas quality requirements suitable for gas turbine/electric engine. The slag from the gasification and gas purification processes is stored in the dump. Also in this stage, a CHP is assigned.

The second scenario represents a more simplified version that is differentiated from the first one by:

- The RMSW are sent to a direct thermal treatment, using a widely tested technology (an incinerator with thermal recovery);
- The simplification of the scenario is considered in order to reduce consumption, spaces occupied, and the possibility of malfunctioning or breakage, which may cause the plant to stop functioning.

The methodology for the mass and energy balance determination, considering all the treatments used in the systems, energy efficiencies and compositions has been previously described in the work [17].

As mentioned before, the present research concentrates on the environmental impact assessment of the scenarios developed. The impact categories that are most important from the environmental point of view for an MSW management system, in terms of energy recovery, are the Global Warming Potential (kg CO_2 eq. kg^{-1}), Human Toxicity Potentials (kg 1,4-dichlorobenzene eq. kg^{-1}), the Photochemical Ozone Creation Potential (kg C_2H_4 eq. kg^{-1}), and the Acidification Potential (kg SO_2eq. kg^{-1}). All the potentials considered were assumed from the technical literature [20,21,22], such as the specific emissions from the different treatment process (anaerobic digestion, composting, landfilling with biogas collection, bio-drying, thermal drying, incineration and syngas combustion in power plant) [23-27]. In the impact assessment phase, we only considered the compulsory operations, in accordance with the ISO 14042 norm: classification and characterization. In the environmental balance, the emissions avoided thanks to the SC were also considered:

$$\text{Equivalent emission } [kg_{eq}] = \sum_{1}^{n} \text{material to recycling } [t] \cdot \sum_{1}^{n} \text{avoided emissions } [kg_{eq}\ t^{-1}] \qquad (1)$$

where n is he number of material classes to recycling.

This creates the possibility of allocating part of the waste to the material recovery, thereby avoiding or reducing the use of new raw materials [28]. For the packaging material, it was assumed that, for the metals and glass, 1 kg of "secondary" material (produced from recycled material) was equivalent to the same quantity of "primary" material, produced from new raw material, and for the remaining categories, replacement rates that took account of the fact that the recycled material might be of inferior quality to that produced from new material, and could not be recycled an infinite number of times, were introduced. The compost obtained from the biological treatments of the compostable OFMSW was used as a replacement for land amendments and fertilizers. Then, for the packaging material, from a comparison of the data concerning the energy and the emissions produced by the production of this from new or recycled material, it was possible to establish the energy and environmental balances; from the emissions released during the production from new material, we subtracted those due to the production of the same quantity from recycled material (metals, glass, wood, paper and plastic), in terms of kg CO_2eq. t^{-1} for Global warning, kg SO_2eq. t^{-1} for acidification, kg 1,4-DCBeq. t^{-1} for human toxicity and kg CO_2H_4eq. t^{-1} for Photochemical Ozone Creation [28].

For the assessment of the emissions avoided for the production of only electricity, a plant with a steam cycle (net electrical yield, 37.5%), fed for 50% of the thermal power, with fuel oil, with an average sulfur content, and for 50% with natural gas, was taken as a reference. Furthermore, as internal combustion engines operate with a co-generative set up, it was necessary also to estimate the emissions avoided for the production of heat. Also in this case, the emissions were considered, and compared with those from the planned treatments of the waste, from domestic boilers that run on fuel oil, serving a district heating. The boilers considered for the production of thermal energy, from the combustion of fuel oil with a low sulfur content, have an installed potential of 100 kW, with a yield of 87%; system losses (of 7%) and losses from the exchanger (13%) were also taken into consideration. The emission factors related to the thermoelectric plant and to the production of 1MJ thermic with a domestic boiler running on fuel oil, are available in the technical literature [29].

3. Results

The MSW scenarios are presented in Figure 1.

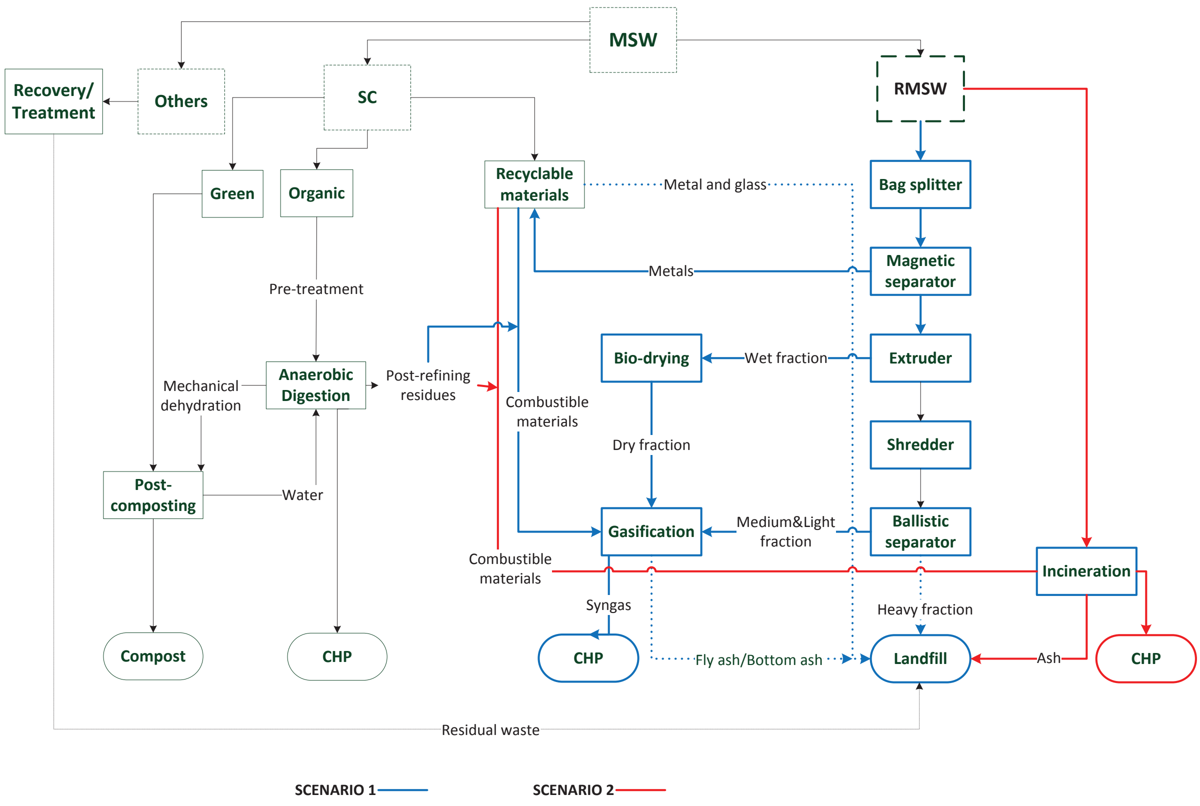

Fig. 1. Scenario 1 and Scenario 2 MSW integrated management system.

Figure 2 shows the waste final destinations by type of treatment stage. The following step was the mass balance [17] necessary also to determine the distribution of the LHVs related to the different waste flows. The material actually recycled, not considering the residuals, is 27-28%.

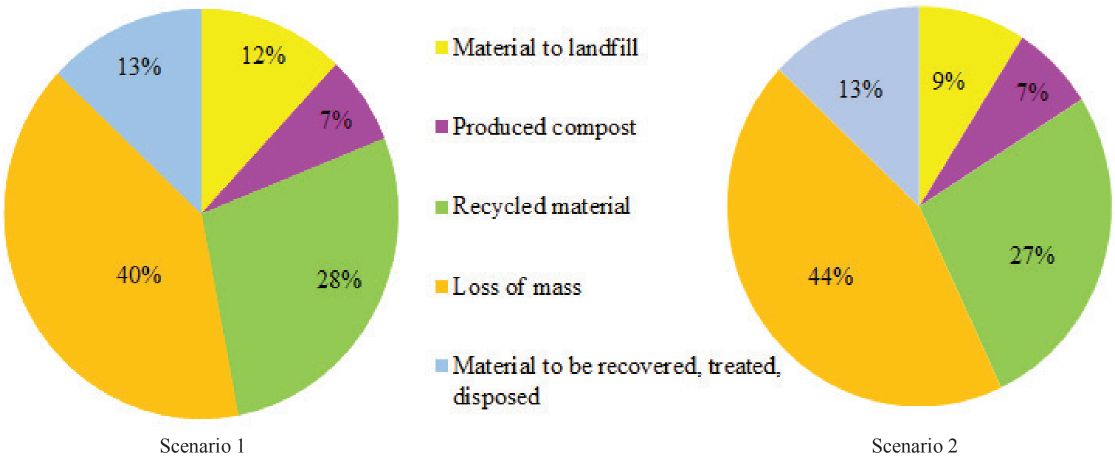

Fig. 2. Final destination of the waste in the two scenarios.

It is interesting to note the mass loss due to the different treatments provided in the system and determined essentially by the moisture or volatile solids losses (Figure 3). The AD exploits the carbon, hydrogen and oxygen content present in the waste for the biogas production, while the bio-drying increases the temperature in the waste pile, and decreases the moisture involving the use of a part of volatile solids [30]. Compost production consumes the volatile solids in the degradation of the organic substance, while thermal drying causes a water loss, and finally the thermal treatment breaks down what remains from moisture and volatile solids. The thermal treatment causes most of the decrease in the mass percentage of the waste, followed by composting.

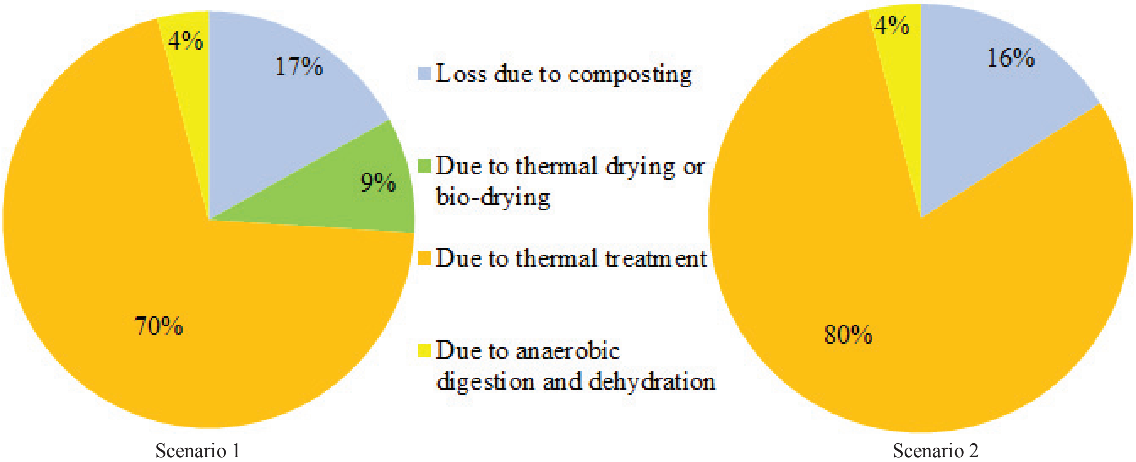

Fig. 3. Global mass balance

These data entered in the calculation of the energy balance where in the first case resulted (considering also the energy saved thanks to recycling materials that replace each percentage in the material produced from virgin raw materials and the energy consumption related to the treatment of the organic and green fractions from separated collection [17] a global balance in terms of electric energy of 259 GWh t^{-1} (264 GWh y^{-1}, in terms of thermal energy), while in the second case resulted 304 GWh t^{-1} (438 GWh y^{-1}, thermal energy). Considering the global energy balance in the first scenario the amount produced by the whole system is greater than that consumed. Only 21% of the electricity produced, and 3% of that thermal energy produced is required for the operation of the system. The second scenario behaves similarly. Table 1 presents the results of life cycle assessment, which includes the overall emissions in the various cases considered. The values are given by summing the emissions of the individual processes considered. The pollutants counted in this way were individually weighted to obtain a value expressed in kg eq., to represent each impact indicator. In order to obtain a balance, it is necessary to identify a comparison term, which, in our case, was a station and a district heating; the emissions of these systems were taken as the so-called emissions avoided by energy production. In addition to these, the emissions avoided by producing material by recycling, instead of from new matter, were also included in the balance. The balance of the quantities just mentioned is summarized in the last two lines, which refer to each individual scenario. In the case of scenario 1, the result is less than zero, as the emissions avoided are much greater than the energy production from conventional sources. The impacts as a result of managing the waste in accordance with what is suggested by the treatments done in the first case analyzed were, consequently, lower; this is true for each indicator considered. The impacts were lower and this is true for each indicator considered. In the second case, for the human toxicity indicator, and the photochemical smog formation, we find values not as positive as in the other cases considered, with the last indicator showing almost no difference between the emissions caused and those prevented.

Table 1. Environmental balance.

	Global warming	**Acidification**	**Human toxicity**	**Photo-chemical ozone formation**
	kg CO_2eq.	*kg SO_2eq.*	*kg 1,4-DCB eq.*	*kg C_2H_4eq.*
Case 1				
Waste treatment emissions	105,565,753	32,540	803,295	3062
Emissions avoided by recycling	41,127,329	220,439	49,344,115	21,133
Emissions avoided by energy production	237,857,634	1,189,555	2,023,161	11,509
BALANCE [kg eq.]	-173,419,210	-1,377,453	-50,563,981	-29,580
BALANCE [kg/kWh eq.]	-0.463	-0.004	-0.135	0.000
Case 2				
Waste treatment emissions	57,911,675	136,673	11,302,515	30,251
Emissions avoided by recycling	37,080,077	202,221	32,586,420	19,236
Emissions avoided by energy production	282,548,786	1,264,032	2,304,202	12,222
BALANCE [kg eq.]	-261,717,187	-1,329,580	-23,588,107	-1207
BALANCE [kg/kWh eq.]	-0.606	-0.003	-0.055	0.000

Table 2 shows the emissions related to greenhouse effect potential, acidification, human toxicity and photochemical ozone formation potential. For the greenhouse effect potential the case that manages to prevent greater impacts is the second. The results are less than zero, as the impacts prevented are greater than what they would be if the waste were treated. Table 3 shows the environmental balances.

Table 2. Emissions relating to the greenhouse effect potential, acidification potential, human toxicity potential, emissions relating to the photochemical ozone formation potential.

Emissions	**GHG emission** ***[10^6 kg CO_2eq]***		**Acidification** ***[kg SO_2eq]***		**Human toxicity** ***[10^3 kg 1,4-DCB eq]***		**Photochemical ozone** ***[kg C_2H_4eq]***	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Waste treatment	107	58	35	134	0.8	11.4	3.1	30.2
Recycling	-40	-37	-218	-203	-49.3	-32.6	-21.2	-19.4
Heat and Power production	-235	-278	-1185	-1260	-1.9	-2.2	-11.6	-12.1
Global balance	-168	-257	-1369	-1330	-50.4	-23.4	-29.7	-1.3
Produced/Avoided [%]	39	19	2	9	2	33	9	96

Table 3. Environmental balance for the cases analyzed.

	Global warming	**Acidification**	Human toxicity	Photochemical ozone formation
Emissions compared to the waste within the system limits				
	[kg t^{-1} $_{MSW}$]	*[kg t^{-1} $_{MSW}$]*	*[kg t^{-1} $_{MSW}$]*	*[kg t^{-1} $_{MSW}$]*
case 1	-671.61	-5.33	-195.82	-0.11
case 2	-1013.56	-5.15	-91.35	0.00
Emissions produced, compared to those prevented				
case 1	38%	2%	2%	9%
case 2	18%	9%	32%	96%

From the analyses carried out, no case emerges that has better values than the others for all of the impact indicators considered; for the overall balance we can say that the second case is valid for the impacts linked to the greenhouse effect, but it is inadequate for the other indicators linked to human toxicity and ozone formation, where the first case remains the best one. Thus, the first case analyzed is better than the others in terms of environmental balance, although it is not for all of the indicators considered.

4. Conclusions

The study has highlighted how difficult is to determine a priori the best technologies for the disposal of waste, regardless of the composition of the waste, the plant size and location in the territory. An environmental analysis certainly helps to define which technologies together have a minor impact. An energy analysis helps to determine the most efficient way to recover the energy contained in the waste. And a mass analysis is however 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 system should take into account the social and geographical context, and may also help to facilitate 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 of the 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 two scenarios considered, especially considering the energy balance, the second case (which involves the incineration) is preferable, given the option of not having pre-treatments on the incoming waste since efficient waste separation has removed the previously non-combustible and putrescible fraction. Nonetheless, the first scenario has its merit in obtaining a higher production of electricity and heat. The presence of an anaerobic digester does not affect the global energy balance much. The choice of one of these two cases depends on the weight that is assigned to the various parameters. In the current situation where the attention of the public is more on the environmental aspects than on energy production, the first scenario would seem to be the best option. It is important to emphasize also the potential provided by a system that can treat, in an economically sustainable way, also smaller quantities of material, with the possibility of increasing capacity with the simple addition of other modules.

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