

Evaluation of municipal solid waste management performance by material flow analysis: Theoretical approach and case study

Waste Management & Research
1–15
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DOI: 10.1177/0734242X15595284
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Abstract

The main role of a waste management plan is to define which is the combination of waste management strategies and method needed to collect and manage the waste in such a way to ensure a given set of targets is reached. Objectives have to be sustainable and realistic, consistent with the environmental policies and regulations and monitored to verify the progressive achievement of the given targets. To get the aim, the setting up and quantification of indicators can allow the measurement of efficiency of a waste management system. The quantification of efficiency indicators requires the developing of a material flow analysis over the system boundary, from waste collection to secondary materials selling, processing and disposal. The material flow analysis has been carried out with reference to a case study for which a reliable, time- and site-specific database was available. The material flow analysis allowed the evaluation of the amount of materials sent to recycling, to landfilling and to waste-to-energy, by highlighting that the sorting of residual waste can further increase the secondary materials amount. The utilisation of energy recovery to treat the low-grade waste allows the maximisation of waste diversion from landfill with a low production of hazardous ash. A preliminary economic balance has been carried out to define the gate fee of the waste management system that was in the range of 84–145€t⁻¹ without including the separate collection cost. The cost of door-by-door separate collection, designed to ensure the collection of five separate streams, resulted in 250€t⁻¹ ±30%.

Keywords

Waste management, assessment, indicators, material flow analysis, separate collection, recycling, recovery

Introduction

Europe has enjoyed many decades of growth in wealth and well-being based on intensive use of material and energetic resources. To promote efficient use of these resources needs a policy framework that rewards innovation and resource efficiency, creates economic opportunities and improved security of supply through product redesign, sustainable management of environmental resources, resource savings and increased reuse, recycling and replacement of primary materials. To decouple growth from resources' use and unlock these new sources needs coherence and integration in the policies that shape our economy and our lifestyles (Bain et al., 2012; European Commission, 2011). In particular, the secondary resources obtained from a municipal waste management system should be increased in amount and quality by designing a proper waste management strategy. This planning is a complex process involving many disciplines, processes and technologies that compose the infrastructural network of the waste management system and allows to design different scenarios whose sustainability can be evaluated only by carrying out the waste management system itself, within existing legal, social and environmental guidelines that protect the public health and

the environment (Moy et al., 2008) and are, at same time, aesthetically and economically acceptable (Nemerow et al., 2009). Generally, to fulfil the objectives of sustainable waste management, the general following objectives must be reached: minimisation of consumption of raw materials and energy without yielding a real overall environmental advantage; recovery of materials, albeit in respect of the principles laid down previously; recovery of energy since, in a life-cycle approach, energy recovery from waste allows decreasing consumption of fossil fuels and overall emissions from all energy conversion systems (Azapagic

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et al., 2004; Brunner, 2011) and minimisation of landfill use (European Commission, 2011).

The evaluation of a waste management system sustainability of methodological tools needs to measure the distance to targets of a selected series of performance indicators (Arendse and Godfrey, 2010; Ristic, 2005; Teixeira et al., 2014). Material flow analysis, life-cycle assessment and risk analysis are different tools that can be used to measure the performance of a waste management system by evaluating a set of indicators as a final result of an accurate modelling (Beigl et al., 2008; Cleary, 2009; Gunamantha and Sarto, 2012; Mastellone et al., 2009; Pires et al., 2011). First question is defining the aspects to be measured and the proper indicators. Regarding the municipal solid waste management, a crucial question is 'does a high percentage of municipal solid waste fractions, collected for potential recycling, translate into maximum sustainable resource efficiency?' (Velis and Brunner, 2013), by pointing out the necessity of a metric to measure the sustainability of the system.

Scope of this article is: to apply the material flow analysis to a waste management system by using a case-study data inventory; to evaluate the efficiency of the base case scenario by means of a set of indicators set up to this end; to propose an alternative scenario ensuring the maximisation of both diversion of waste from landfill and materials recovery. A set of alternative scenarios have been also included in the analysis, by considering the best available technologies in the waste treatment sector and by referring to the industrial data provided by the scientific literature, on-site visits to industrial facilities and private communications.

The performance assessment does not include environmental considerations and exclusively refers to the material balances carried out over the system boundaries of the waste management system. The environmental impacts owing to a waste management can be evaluated by means of a life-cycle assessment, with reference to the global burdens, and by a risk assessment, with reference to local effects on public health. The future implementation of the research will apply these methods by starting from the inventory presented in this article.

A preliminary economic assessment has been also carried out with reference to the base-case scenario, by collecting data related to: operating costs of the facilities included in the system boundaries; commercial values of the material streams; commercial value of energy vector (biogas and syngas).

General framework, methods and tools

General waste management system description

The municipal solid waste can be addressed to different processes, mainly aiming to recycling of secondary materials, recovery of energy, waste-derived fuels production and, only for a residual fraction, to landfilling. The sustainability and the efficiency of the recycling chain are both affected by the waste composition and by the successive separation and cleaning treatments

that allow each material to be reprocessed. The efficiency of waste producers to recognise and separate the different waste streams affects efficiency and cost of the whole waste management system; this efficiency has been evaluated in the present study by means of proper indicators. The efficiency of waste collection can be considered unitary, except anomalies not included in this analysis.

Waste delivering and collection systems can be classified on the basis of the waste separation degree and on the collection point decentralisation respect to the generation points (houses, shops, markets, etc.). Two opposite extremes can be considered for waste delivering systems: (a) commingled waste collection followed by an intense mechanical separation at centralised facilities; (b) intense homemade waste separation followed by a mild mechanical separation process. Two opposite extremes, having different costs and efficiencies, can be also considered for collection systems: (a) door-by-door collection; (b) kerbside collection. Several intermediate possibilities are developed in different countries by taking into account local policies, social sensitivity, educational degree, urbanisation characteristics, industrial infrastructures, etc.

The system to which this research refers as a base case is characterised by an intense separation made at a household level and by a door-by-door collection system. A sketch of the routes of the waste categories intercepted by the collection system is given in Figure 1.

Methods and tools

Several methodological tools can be used alone, or in conjunction each to other, in order to design and evaluate the waste management scenarios (Beigl et al., 2008; Li et al., 2008; Oliveira et al., 2007; Salhofer et al., 2007; Wang et al., 1996), but the crucial point is always the reliability, the representativeness and the accuracy of input data and parameters utilised to perform the analyses. Data quality has a great influence on the integrity of the models' results and, in particular, data sources are crucial to perform the scenario analysis, planning and improving (Beigl et al., 2008). Moreover, the experimental data has to be general enough to be used to draw considerations that are widely applicable to other cases. In this article, the experimental data has been used to evaluate the performance of the waste management actually in operation in the reference system and to obtain provisional models. The provisional models have been built to evaluate the effect of the changes of some parameters on the performance indicators. The tool used to compare the results is the indexing carried out by using the indicators reported in Table 1. The evaluation method is the comparison of different scenarios, each of which have been quantified by using the material flow analysis.

Definition of indicators and indicators

The use of indicators to assess the performance of open or closed systems is reported in the literature with reference to waste management (Arendse and Godfrey, 2010; Li et al., 2008; Moy et al.,

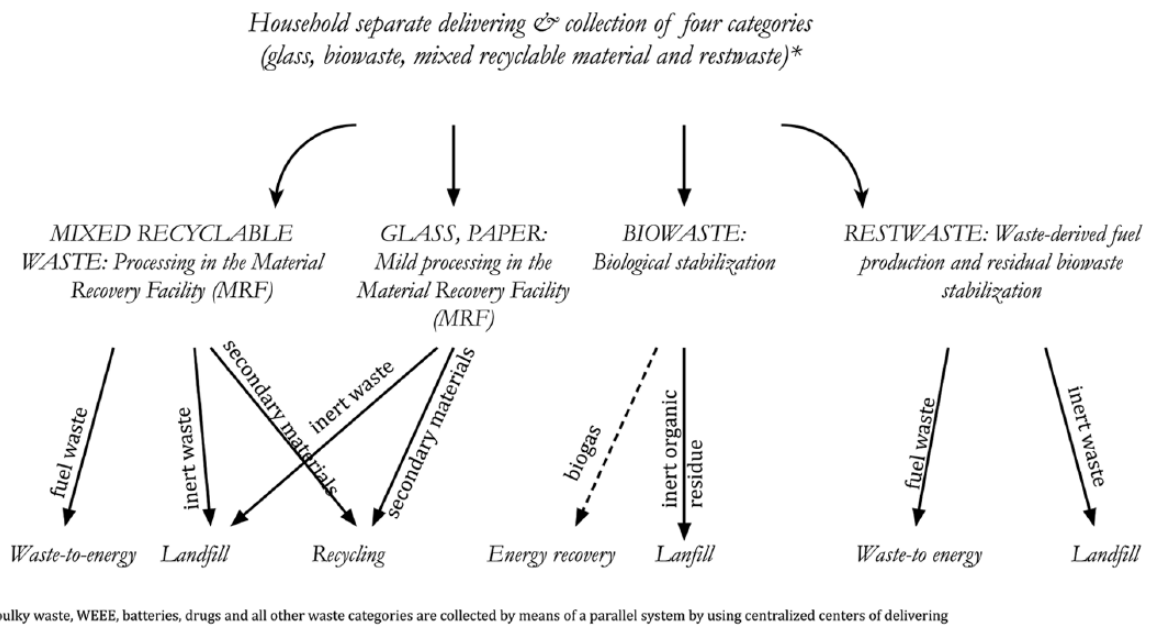


Figure 1. Classification of waste categories delivered and collected to be addressed to the successive treatment processes.

Table 1. Set of partial and aggregated indicators.

Description	Acronyms	Equations
<i>Partial indicators (waste category i)</i>		
Nominal interception efficiency	nie_i	m'_i/g_i
Actual interception efficiency	aie_i	m_i/g_i
Landfill disposing	dcr_i	d_i/g_i
Recycled-collected ratio	rcr_i	r_i/g_i
<i>Aggregated indicators (total waste)</i>		
Separate delivery rate = nominal interception efficiency	NIE=SDR	$\sum_i m'_i / \sum_i g_i$
Actual interception efficiency	AIE	$\sum_i m_i / \sum_i g_i$
Recycled-collected ratio	RCR	$\sum_i r_i / \sum_i g_i$
Recovered-collected ratio	RECR	$\sum_i re_i / \sum_i g_i$
Disposal-collected ratio	DCR	$\sum_i d_i / \sum_i g_i$
Diversion from landfill	DVR	$1-DCR$

i: waste category (i.e. biowaste, paper, etc.); m_i : real amount of a given waste fraction (*i*) collected; m'_i : nominal amount of a given waste fraction (*i*); r_i : amount of a given waste fraction (*i*) sent to recycle; re_i : amount of a given waste fraction (*i*) sent to recovery; g_i : amount of a given waste fraction (*i*) generated; d_i : amount of a given waste fraction (*i*) disposed in the landfill; assuming that: $\sum_i m_i = \sum_i m'_i = \sum_i g_i$

2008; Ristic, 2005). The choice of the set of indicators is driven by the availability of data and by the capacity to measure the performance. A way to evaluate the waste management system's global efficiency is to measure the waste diversion, i.e. the prevention and reduction of generated waste through source reduction, recycling, reuse, energy recovery, composting, feedstock and biogas production (European Environmental Agency, 2009). Waste diversion generates a host of environmental, financial and social benefits, including conserving energy, reducing disposal costs and reducing the burden on landfills and other waste disposal methods (Environmental Protection Agency, 2012). The waste diversion indicator is a measure of the amount of mass of each waste component diverted from the landfill and addressed to recovery or recycling. To increase the waste diversion is generally adopted as a household separate collection, because it is

considered the best option to minimise the sorting cost of the waste downstream of the collection. The separate collection efficiency must be evaluated on the basis of the amount of contaminating materials included in the waste stream. This is the rationale behind the designing of the following indicators whose detailed description is reported in the following paragraphs.

Separate delivery rate indicator. The widespread indicator utilised to assess the efficiency of a management system of waste is the separate delivery rate (SDR), defined as the ratio between the amount of waste collected as separated streams and the total produced waste. This indicator just takes into account the collected waste streams, without considering how much is actually addressed to recycling/recovery, and which are the environmental and economic costs correlated to the following treatments.

Nominal interception efficiency. The nominal interception efficiency (nie) is defined as the ratio between the amount of the waste category (i) that is collected as a separated stream (m'_i), including an undesired amount of contaminating materials and the total amount of the generated waste (g_i). It measures the capability to recognise and intercept specific categories of waste by diverting it from the commingled waste, i.e. the residual waste/restwaste. In the case of analysing data of an existing waste management plan, the nie can be calculated; in the case of a new waste management system planning the set of nie indicators, each of them related to a given waste fraction i , has to be fixed (Mastellone, 2015). The aggregate indicator NIE, which represents the sum of the m'_i for the separate collection streams divided by the totality of the waste (municipal solid waste), coincides with SDR (Table 1). This indicator has been defined 'nominal', because the collected amount of waste includes the so-called 'contaminating materials' that usually ranges between 10% and 35%. To perform a material flow analysis, the nie represents the composition of the municipal solid waste collection.

Actual interception efficiency. The actual interception efficiency (aie) is defined as the ratio between the amount of the material category present in the intercepted waste (m_i) and the produced one (g_i); aie is the indicator assessing the efficiency of the separate delivery/collection system. Its estimation, starting from nie indicators, is possible by knowing the detailed composition of each stream i and, in particular, the amount of contaminating materials fraction to be removed during the sorting process. In the material flow analysis, the aie/nie allows the separation of input flowrate (e.g. biowaste) into its components (e.g. biodegradable and inorganic contaminants).

Recycled-collected ratio. The recycled-collected ratio (rcr) is defined as the ratio between the amounts of waste i actually addressed to be reprocessed as secondary materials (r_i) and the collected i stream (m'_i). It can be calculated with respect to a specific waste fraction i , thus obtaining the indicator relative to the given waste fraction i , or with respect to the overall recycled waste fractions, thus obtaining the overall indicator *RCR*. The *RCR* gives information about the efficiency of the sorting, selection and reprocessing steps to obtain the secondary materials.

Recovered-collected ratio. The recovered-collected ratio (recr) is defined as the ratio between the amounts of waste (re_i) addressed to different recovery options (biogas and compost production, energy recovery, etc.) and the collected one (m_i). The *RECR* indicator gives information about the amount of waste that is converted into biogas, compost, synthetic natural gas, energy, etc.

Disposal-collected ratio and diversion-collected ratio. The disposal-collected ratio (dcr/DCR) and diversion-collected ratio (dvr/DVR) are correlated to each other. The indicator 'DCR' is the ratio between the amount of waste actually addressed to landfill and the generated waste, while the 'DVR' measures the relative amount of waste diverted by landfill compared with the generated one. The DCR indicator refers to the waste that cannot be re-used, recycled or recovered but, in a sustainable waste management system, is inert (e.g. stones, glass) or inertised (e.g. encapsulated fly ash, stabilised organic matter (SOM) from

anaerobic digestion and composting, slag from plasma gasification, etc.). The sum of RCR, RECR and DCR indicators should, in theory, be unitary, but it is actually less than 1 owing to metabolic losses during bio-drying and aerobic processes.

Experimental: Data sources and data evaluation

Processing the set of indicators reported in Table 1 needs the availability of a wide range of reliable data on a disaggregated level (Beigl et al., 2008), accounting for spatial and temporal variability (Clavreul et al., 2012) related to:

- generated waste amount for each category i ;
- separately collected waste amounts;
- efficiencies of the treatment processes;
- commodity analyses of each type of waste entering the processing facilities;
- secondary materials amounts obtained by the collected waste.

Data used in this article came from the Caserta Provincial Observatory for Waste the National Consortium for Packaging (CONAI) and, by means of on-site compilation of specific databases, from the facilities that treat the separate and residual waste of Caserta municipalities. In particular, this research work processed and evaluated the following data, available on different aggregation levels.

- Daily data at a municipal level related to all the collection streams, available at the Provincial Waste Observatory, as aggregated in the Waste Report (Romeo, 2013).
- Annual data related to the waste streams processed by the recycling plants and introduced in the market as secondary materials.
- Commodity-related analysis of residual waste, as obtained by the sorting processes at the mechanical-biological treatment (MBT) plant.
- Commodity-related analysis of mixed recyclable waste coming from separate collection as obtained by the material recovery facilities (MRFs).

Commodity analyses of municipal solid waste and residual waste

The main data source to obtain the single mass rate (expressed in Mg day^{-1}) of the collected streams for each municipality is the official database managed by the Provincial Waste Observatory. Each municipality daily updates their own data related to the collected amount of given waste streams by means of a web-friendly interactive interface. A careful comparison between data provided by municipalities after collection and those provided by the treatment plants receiving the waste increases the level of accuracy. Table 2 reports an extract of the available data that has been processed in order to obtain the total amount of each waste category for a set of municipalities. Table 2 also reports on the

Table 2. Data of waste categories amounts for each municipality in an ambit – units are in Mgy⁻¹. Blank cells corresponds to 0 Mgy⁻¹.

Waste category	Municipality																	Ambit
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	
Inhabitants	5364	9747	18,839	14,159	78,693	5062	7234	10,845	38,690	40,439	7737	7557	17,675	6483	21,746	12,196	14,210	316,676
Inhabitants, %	1.7	3.1	5.9	4.5	24.8	1.6	2.3	3.4	12.2	12.8	2.4	2.4	5.6	2.0	6.9	3.9	4.5	100
Density, inh km ⁻²	382	2869	390	2172	1426	619	4207	1385	1070	1328	4101	2396	644	1126	4691	1568	1306	1163
Restwaste	880	2776	6253	3969	23,259	678	1412	2186	11,746	9860	1505	1402	2624	1824	4866	3570	2328	81,136
Biowaste	723	1070	2056	1332	10,449	480	1169	1312	4414	6763	1312	978	2624	894	2905	1451	1913	41,845
Mixed recyclable	111	215	261	226	1677	59	137	201	776	1167	196	153	396	154	532	174	247	6681
Paper and cardboard	128	154	632	294	2279	99	404	435	1285	800	116	59	312	117	878	212	206	8411
Glass	155	53	310	234	1143	83	155	223	879	755	135	147	312	132	559	65	176	5516
Plastics (CC)	-	24	-	-	-	-	-	-	-	11	-	2	1	-	-	-	6	44
Metals (CC)	39	12	-	-	130	-	-	-	-	-	-	19	-	-	-	-	42	243
Bulky waste	-	-	155	34	1430	-	62	129	265	68	55	-	19	45	143	61	-	2467
Batteries	0.2	-	0.5	0.2	13.9	-	0.9	0.5	-	0.5	0.3	0.0	0.1	0.1	-	0.1	0.3	18
Drugs	0.1	-	0.5	0.9	2.9	-	0.2	0.2	-	2.9	0.3	0.0	0.5	0.4	1.8	0.3	0.2	11
WEEE	14.3	67.1	26.4	6.8	315.4	1.2	14.2	25.9	74.0	51.3	12.8	22.1	19.4	11.9	49.4	30.3	23.0	765
Textiles	19.0	135.5	62.8	14.5	65.0	-	11.3	4.7	60.3	153.3	2.7	29.3	23.3	-	19.1	14.2	28.5	643
Wood	21.0	40.1	24.8	-	-	3.1	-	-	-	83.6	-	24.7	27.3	-	-	-	48.2	273
Oils	0.4	0.3	1.4	-	3.6	-	-	0.5	3.0	0.8	-	0.7	1.4	0.1	2.6	-	1.8	17
Inerts	58.0	-	-	-	124.1	-	-	-	-	388.4	-	-	75.7	-	-	-	0.3	646
Tyres	0.7	0.6	1.2	-	-	-	-	-	-	3.2	-	5.2	0.8	6.1	-	-	0.4	18
Toner	-	-	-	-	1.2	-	-	-	-	-	-	-	-	-	-	-	-	1
Dyes	-	-	-	-	11.0	-	-	-	-	-	-	-	-	-	-	-	-	11
DSR, %	59.1	38.9	36.1	35.1	43.1	51.7	58.1	51.6	39.8	51.0	54.9	50.7	59.2	42.7	51.1	36.0	53.6	45.5
Pro-capita amount of residual waste, kg inh ⁻¹ day ⁻¹	0.45	0.78	0.91	0.77	0.81	0.37	0.53	0.55	0.83	0.67	0.53	0.51	0.41	0.77	0.61	0.80	0.45	0.70
Total	2150	4547	9785	6113	40,905	1403	3366	4518	19,501	20,108	3336	2842	6436	3183	9957	5577	5022	148,746

--: no available data; CC: collection center ; DSR: delivery separate rate; WEEE: waste electrical & electronic equipment.

number of inhabitants for each municipality and the population density values in order to provide some territorial information. The collection system, for all municipalities, consists in a door-by-door collection for which the biowaste is delivered and collected three times a week, glass, paper and mixed recyclable waste once a week and the residual waste once a week. The treatment plants are: composting plants for biowaste aerobic digestion (private ownership), MRFs for plastics, metals, aluminium and cellulosic sorting and cleaning (private ownership), a mechanical-biological plant (public ownership), a landfill (public ownership) and an incinerator (public/private ownership).

The elaboration of the mass flow data allows calculation of the pro-capita waste production that was equal to 1.29 kg inh⁻¹ day⁻¹, consistent with data of high-income country regions, not including very large cities (Hoorweg and Bhada-Tata, 2012). The elaboration of mass flowrate data also provides the composition of the collected waste. By using the composition of the solid waste generated *ab origine* as an input data, the restwaste composition has been estimated. Each waste fraction in the restwaste can be obtained by the following relationship, which represents the mass balance for the waste category *i*:

$$i_{\text{restwaste}} = \left(i_{\text{MSW}} P_{\text{MSW}} - i_{\text{SC}} P_{\text{SC}} \right) / P_{\text{RES}} \quad (1)$$

$$= i_{\text{MSW}} / (1 - \text{SDR}) - i_{\text{SC}} \text{SDR} / (1 - \text{SDR})$$

where *i* indicates the waste category, that is: biowaste, metals, plastics, etc.; SDR is the diversion rate indicator; P represents the mass rate (generally expressed in Mgy⁻¹) for municipal solid waste

(MSW), residual waste (RES), and separate collected waste (SC). The resulting composition of the restwaste, together with that taken as reference for municipal solid waste, is reported in Table 3. This table also reports the value of nie indicators for the residual and separate waste. It should be noted that a certain number of commodity analyses were available for the residual waste at the entrance of the MBT facility. They were obtained by sampling 1.5 t of the residual waste and by following the ANPA RTI CTN_RIF 1/2000 guidelines. The analysis separates the waste into the following fractions: fine fraction <50mm, biowaste, paper, cardboard, composites, textiles, sanitary textiles, plastic sheets, plastic packaging, plastics (miscellaneous), rubber, glass, metals (ferrous), metals (non-ferrous), wood, inert, leather, hazardous, electrical and electronic equipment waste, others (unclassified). The resulting mean composition of the residual waste is in line with that obtained by calculation and reported in Table 3.

Commodity analysis of the mixed recyclable waste

The composition of the mixed recyclable waste, coming from the separate delivery and collection system, has been obtained by means of analyses made at the MRF entrance. In this facility, the recyclable waste is separated by the contaminating materials, the polymers are selected on the basis of type and colour and bailed to send them to the mechanical reprocessing. Several samples of the input waste have been analysed in order to detect and quantify the contaminating materials, i.e. materials that cannot be recycled (e.g. thermosets, composites) or that should not be

Table 3. Commodity composition of municipal solid waste, separate collected waste and restwaste, as obtained by experimental data (base case).

		nie	Amount, Mgy ⁻¹
<i>MSW</i>			
Metals	3.4%		5057
Biowaste	36.3%		53,995
Plastics	18.0%		26,774
Paper and cardboard	21.6%		32,129
Glass	7.0%		10,412
Other	13.7%		20,378
Total	100.0%		148,746
<i>Residual waste</i>			
Metals	5.0%	80%	4048
Biowaste	17.5%	26%	14,050
Plastics	26.7%	80%	21,432
Paper and cardboard	31.2%	78%	25,117
Glass	5.9%	45%	4733
Other	13.7%	54%	11,004
Total	100%	54%	80,385
<i>Separate delivered and collected waste</i>			
Metals in MRW	1.5%	20%	1009
Biowaste	58.5%	74%	39,945
Plastics in MRW	7.8%	20%	5342
Paper and cardboard	10.2%	22%	7012
Glass	8.3%	55%	5679
Other	13.7%	46%	9374
Total	100%	46%	68,361

MRW: mixed recyclable waste; MSW: municipal solid waste.

present (e.g. biowaste). The commodity analysis of the mixed waste entering the MRF is presented in Table 3. The sampling programme is structured in the following way: (a) each day a certain amount of waste is taken from different trucks just after the weighing; (b) when a given amount, not less than 100 kg, is available, the sampling and analysis begins; (c) the analysts carry out the sampling by following a specific guideline to determine the liquid containers (3D), sheets larger and smaller than A3 size (2D), biowaste, metals, contaminating material. The number of samples utilised in this study related to the commodity analysis of mixed recyclable waste is not less than 176. The sampling programme is an obligation for all the MRFs and it is issued by the National Consortium for Plastics Packaging in the framework of a convention between the Italian municipalities and the National Consortium for Packaging recycling (CONAI, 2015).

Results and discussion

Description of the base case and alternative scenarios

The quantified block diagram of the case study is reported in Figure 2. The flows and stocks are defined and quantified by means of mass balances carried out by using the STAN freeware for material flow analysis (Cencic and Rechberger, 2008). Each block represents a process or a sub-system included in the system boundaries, while each arrow is related to mass flowrate of a

waste/material. The base case includes: a door-by-door separate collection; a composting plant to treat the biowaste by producing a compost fraction (after refining) and a stabilised matter containing the contaminating materials collected with the biowaste and the partially stabilised biowaste; a MRF where the recyclable waste is sorted, cleaned and addressed to reprocessing by also producing other waste outputs mainly constituted by plastic materials; a MBT facility that divides the residual waste into two main streams – the combustible waste addressed to incineration and the biowaste that was not intercepted by the separate collection (about 17%) contaminated by fine fractions as glass, stones, ceramics, metals, etc. having a size <50 mm. This latter is aerobically stabilised before landfilling.

The alternative scenarios have been designed by substituting the MBT facility with a MRF able to separate recyclable materials from the restwaste and to transform the non-recyclable fraction into a high-quality, waste-derived fuel. The composting plant has been substituted by an anaerobic–aerobic integrated facility in order to produce biogas and reduce the fugitive (i.e. not intercepted) volatile organic compounds emissions.

The unit processes included in the scenarios are described in the following.

MBT. A plant that treats the residual waste by removing the biowaste (putrescible organic matter) and heavy and small particles (glass, stones, etc.) in order to produce a proper fuel for the waste-to-energy plant (Archer et al., 2005). The biowaste, mixed

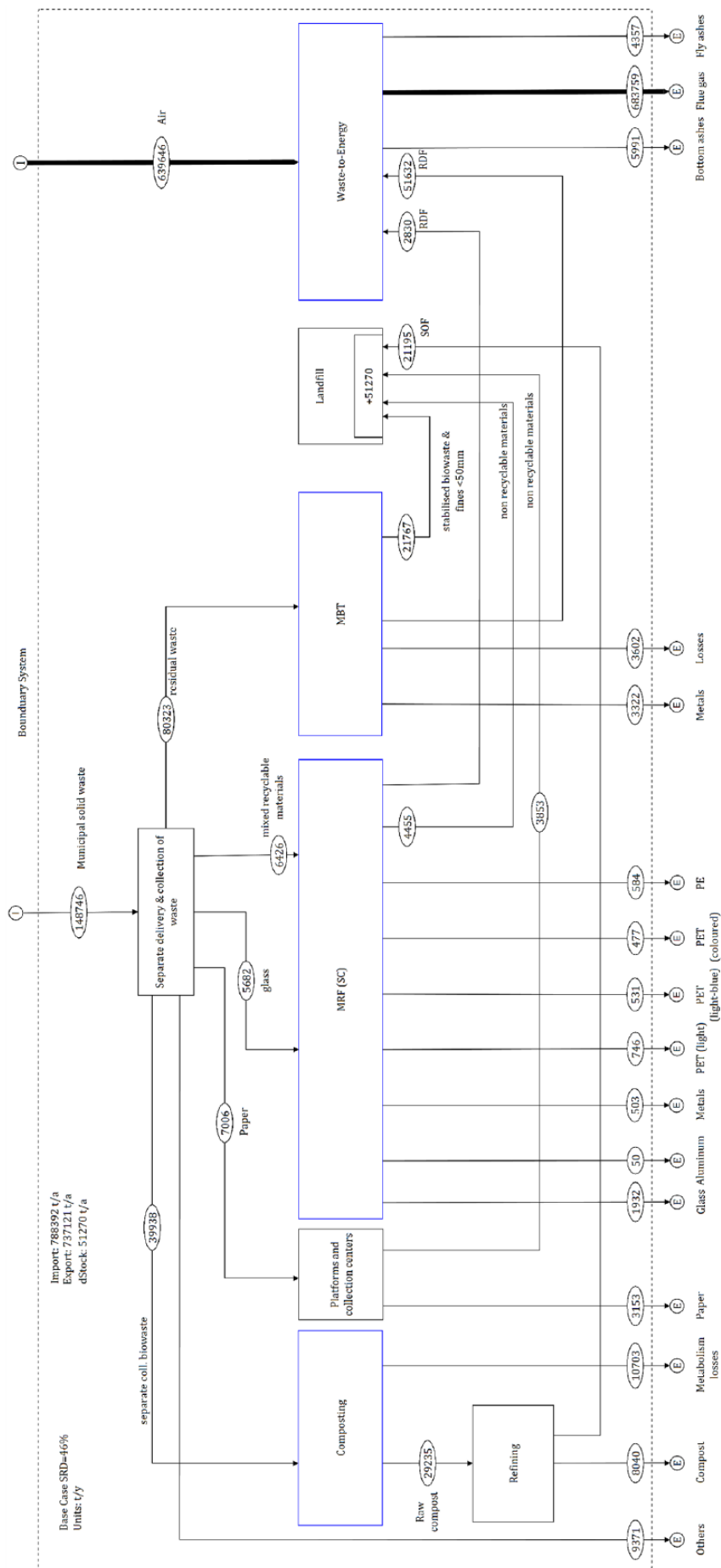


Figure 2. Base case scenario A1: material flow analysis.

with a high inert fraction, undergoes aerobic stabilisation to be transformed in a stabilised organic matter (SOM). Refuse-derived fuel (UNI, 2011) is obtained by solid waste by recurring to this kind of facility (MBT).

MRF. A facility that selects ferrous metals, glass, aluminium and plastics from the mixed recyclable waste (Craig et al., 2003; PeerConsultants and CalRecovery, 1991). The material is disentangled by breaking up any bags and separating the compacted material. The feed passes through a rotating trommel screen that splits the material into three streams:

- <50 mm fraction collected as a waste stream for disposal;
- 50–200 mm fraction, which is fed onto a ballistic separator;
- oversize fraction (>200 mm) for manual hand sorting.

Any plastic or metal from the oversize hand sort is added back into the feed at this point. The ballistic separator divides flat and light materials (i.e. paper, card, plastic film, etc.) from heavier rolling materials (i.e. metals, plastic bottles, etc.). Any fines that remain in the feed are also removed at this stage. The following secondary materials can be obtained: light, light-blue and coloured polyethylene-terephthalate (PET), polyethylene (PE), metals (ferrous), aluminium, glass.

Platforms, PL. Transfer stations, often included in the same MRF site, where the mono-material streams of paper, glass, metals, etc., coming from commercial sector or by collection centres, are stored before sending it to a recycling plants.

Waste-to-energy plant – combustion based. A facility where the waste, or the waste-derived fuel, is converted into energy by means of oxidation carried out with an excess of air. The waste combustion uses excess air ranging between 80–120% (up to 200% for hazardous waste), depending on waste characteristics and furnace technology (Niessen, 2002). The waste-to-energy plant in the case study is a typical combustion facility equipped with a cooled moving grate furnace. The air-to-fuel ratio is equal to 12t/t to ensure 11%_v of free oxygen in the flue gas, the bottom ash is non-hazardous waste addressed to recovery processes, the fly ash can be addressed to special landfill for hazardous waste or inertised by vitrification or solidification.

Waste-to-energy plant – plasma gasification based. A facility where the waste/waste-derived fuel is converted into a synthetic gaseous fuel composed of carbon monoxide, hydrogen, carbon dioxide, light hydrocarbons (including methane, hydrogen sulfide, ammonia, etc.) by means of a thermochemical process under sub-stoichiometric conditions. This process transforms the fuel into gaseous fuels (syngas), synthetic natural gas, hydrogen and liquid fuels (Byun et al., 2012; E4tech, 2009; Higman and Burgt, 2003; Mastellone, 2015). The waste-to-energy plant in the alternative scenarios is an oxygen plasma gasifier that works with an oxygen-to-fuel ratio equal to 0.21, produces inert slag and a low amount of fly ash (Alter NRG, 2014).

Anaerobic digestion plant, AD. A biotechnological facility where the biodegradable fraction of biowaste is stabilised thanks

to a complex microbiological activity. During the anaerobic process, a part of biowaste (generally 12–18%_w) is transformed into a mixture composed mainly by methane and carbon dioxide (biogas), and in a stabilised inert solid substrate (raw compost) by means of an anaerobic–aerobic in series process. Generally, compost, useful for agricultural purposes, can be obtained, starting with clean biowaste (from separate collection), while the SOM should be exclusively used as covering material in the landfill.

Evaluation of base case scenario indicators

The values of *nie*, referred to the base case, have been reported in the Table 3 and are used to quantify the first block (separate collection) of the material flow analysis reported in Figure 2 (by using STAN the *nie* corresponds to the transfer coefficients). The values of *aie* has been obtained by knowing the amount of contaminating material fraction in the MRF for the base case, and by using relationships similar to equation (2), written with reference to metals. The values of contaminating material (CM) have been obtained by on-site investigations and analyses at the MRF:

$$aie = nie - \left[\frac{(CM_{metals} \cdot \%metals_{sep-col} \cdot SDR)}{\%metals_{MSW}} \right] \quad (2)$$

The values of all indicators are obtained by using the results of the material flow analysis, based on the values of *nie* and *aie*. To clarify the calculation procedure, Table 4 reports the calculations details.

The values of indicators can be calculated with reference to the single process of the waste management system and with reference to the whole system. In Table 5, the indicators related to the mass flows intercepted by means of separate collection are reported together with those obtained by considering the whole system. In the calculation of global indicators the following assumptions have been made.

RRCR: paper, glass, polymers, metals, 30% of bottom ashes and 30% of ‘others’ are included.

RCER: compost, biogas, sum of waste to incineration (by subtracting fly ashes and bottom ashes), 30% of bottom ashes and 30% of ‘others’ are included for base case scenarios; compost, biogas, syngas (by subtracting oxygen), are included for alternative scenarios.

DCR: the 40% of bottom ash, the fly ash, the 40% of ‘others’ and all the waste accumulated in the process ‘landfill’ are considered.

Indicators obtained for the base case (SDR=46%) shows that household separation allows a high interception of biowaste (74%), while that of metals and plastics (20%) is more difficult, so that a large amount of these materials remains in the residual waste. A large amount of plastics is then addressed to energy recovery so that the recycling indicator for this material is only 9.3%. The 73% of the plastics separated and collected as a separate stream is transformed into secondary polymers (PET, PE)

Table 4. Example of the calculation procedure to evaluate the indicator values starting from material flow analysis data.

Commodity analysis, %	Generated amount, Mgy ⁻¹	nie %	Intercepted amount (nominal), Mgy ⁻¹	aie %	Intercepted amount (actual), Mgy ⁻¹	Amount in the restwaste (nominal), gy ⁻¹	rcr %	Recycled amount (from MFA), Mgy ⁻¹	recr %	Recovered amount (from MFA), Mgy ⁻¹	dcr %	Disposed amount (from MFA), Mgy ⁻¹	
Metals	3.4	5057	20	1009	15	773	4048	10.9	553	0.0	0.0	84	4504
Biowaste	36.3	53,994	74	39,944	50	26,907	14,050	0.0	0.0	14.9	8040	65	35,251
Plastics	18.0	26,774	20	5342	15	4093	21,432	9.3	2496	72.6	19,443	18	4835
Paper	21.6	32,129	22	7011	12	3960	25,117	9.8	3153	71.9	23,111	18	5865
Glass	7.0	10,412	54	5678	31	32,078	4733	15.3	1591	0.0	0.0	85	8821

aie: actual interception efficiency; dcr: disposal-collected ratio; MFA: material flow analysis; nie: nominal interception efficiency; rcr: recycled-collected ratio; recr: recovered-collected ratio.

Table 5. Values of indicators for the base case scenario at SDR equal to 46%.

Waste category	Indicators for base case scenario – SDR=46%				
	nie	aie	rcr	recr	dcr
With reference to the separate collection system					
Metals in mixed recyclable waste	20%	15%	11%	0%	89%
Plastics in mixed recyclable waste	20%	15%	9%	73%	18%
Biowaste in separate collection	74%	50%	0%	15%	39%
Paper and cardboard in separate collection	22%	12%	10%	72%	18%
Glass in separate collection	55%	31%	15%	0%	85%
With reference to the waste management system					
MSW	46%	30%	10%	38%	41%

aie: actual interception efficiency; dcr: diversion-collected ratio; MSW: municipal solid waste; nie: nominal interception efficiency; recr: recovered-collected ratio; rcr: recycled-collected ratio; SDR: separate delivery rate.

owing to the contaminating materials and unrecyclable polymers presence. The global RCR indicator referred to the municipal solid waste is only 10%: this indicates that, even though the separate delivering is high (46%), the material recycling is low. The largest part of metals is not intercepted by means of the separate collection of mixed recyclable waste: an rcr of 11% demonstrates that the 89% of metals is in other streams.

The recovery indicator (RECR) is high thanks to the transformation of the refuse-derived fuel (RDF) into energy (68% of municipal solid waste is addressed to energy recovery), while the contribution of compost from biowaste is <6%. The waste diversion reached an acceptable level (48%), but it can be improved by increasing the recycling rate (i.e. reducing 'residual waste' and 'others' streams).

Material flow analysis and evaluation of alternative scenario indicators

The alternative scenarios aim to maximise the performance indicators related to the recycling of materials (RCR) and energy (RECR), and to minimise landfilling, i.e. DCR. Two sets of scenarios have been designed: in the first one (A2) the configuration of the waste management system is the same as the base case without any change regarding the technological aspects, but the nie values have been increased until they reach the maximum achievable value of SDR (60%). In the second set of scenarios (B1 and B2), a different choice has been made regarding the treatment processes.

1. The composting process of biowaste has been integrated with an anaerobic digestion section in order to produce biogas in addition to compost. The biogas is produced with a yield of 17% by weight by referring to the biowaste and it is composed by 65% methane. With reference to the SDR of 46%, the aie/nie value for biowaste indicates that 33% of the input is not really biowaste, so that the biogas is calculated on the real amount of organic matter present in the stream. The ratio aie/nie at SDR=60% is higher (0.74).
2. The MBT has been upgraded to a MRF in order to maximise the material recycling instead of energy recovery. A processing unit has been added in order to produce a high-quality solid secondary fuel instead of a RDF. This unit reduces the amount of metals, glass, ceramics, etc., in the fuel, reduces and homogenises the mean size and densifies the waste.
3. A plasma gasification process has been considered instead of the incineration process to convert the solid secondary fuel into a syngas instead of energy by means of a plant much smaller than an incinerator. The high-quality secondary fuel contains a low amount of metals and inorganics thanks to the intense pre-processing (later shown in detail) and it produces slag instead of bottom ash with a consequent decreasing of economic costs and environmental concerns. The production of inert slag is a better choice to obtain recoverable materials that can be used, for instance, for road construction. The

gasifier is fed by oxygen (98% purity) and produces a syngas, having a low heating value (dry basis) of 8.7 MJ kg⁻¹.

The nie as a function of SDR

In order to reach a given value of the SDR indicator, it is necessary to properly choose a set of nie values. It is then necessary to know the relationship between the nie values and SDR that has been obtained by using data related to 5 years (from 2008 to 2012) by correlating the amount of each category *i* to the resulting SDR of the period. Figure 3 shows the experimental values of nie–SDR data, together with its interpolation curve. It must be noteworthy that the functions are not valid in the entire range 0–100%, because the household interception capacity cannot be indiscriminately increased. It is also interesting that the increasing rate of biowaste interception is well interpolated by a log function, while the increasing of the other categories follows a power law as expected because the biowaste recognition and interception is easier. An important consequence of this behaviour is that is not possible to overcome the value of 60% for the SDR by fixing the nie for the categories glass, metals, plastics, paper and biowaste at their maximum value, without the interception of other categories of waste as WEEE, textiles, tyres, bulky, etc. This modelling result is in accordance with several empirical data that demonstrate that 60–65% is the maximum SDR achievable by means of the best performance of the delivering stage (Consonni et al., 2011). With regard to the contaminating materials present in the mixed recyclable waste entering the MRF processing, a mathematical correlation has been obtained by fitting the empirical values of contaminating materials at different values of SDR obtained by the on-site investigations. The correlation is:

$$CM = 0.509 \cdot SDR \quad (3)$$

The values of contaminating materials in the other streams, i.e. biowaste, paper, glass and other, have been maintained at fixed values, experimentally obtained with reference to the base case (SDR=46%), since their variation with SDR is limited and not enough data are available to fit.

The indicators related to the alternative scenarios have been designed and modelled under the following hypotheses.

- The rules for separating household waste are unvaried (glass, mixed recyclable waste, biowaste, restwaste).
- The municipal solid waste composition is that given in Table 3.
- The nominal interception efficiencies for each waste category can be evaluated by the relationships of Figure 3.

Figure 4 reports the material flow analysis related to the alternative scenario B2, for which the nominal interception efficiencies of the separately collected waste streams are the same of base case-A2, but with a different technological infrastructure (MRF instead of MBT) to manage the waste. The MRF flow

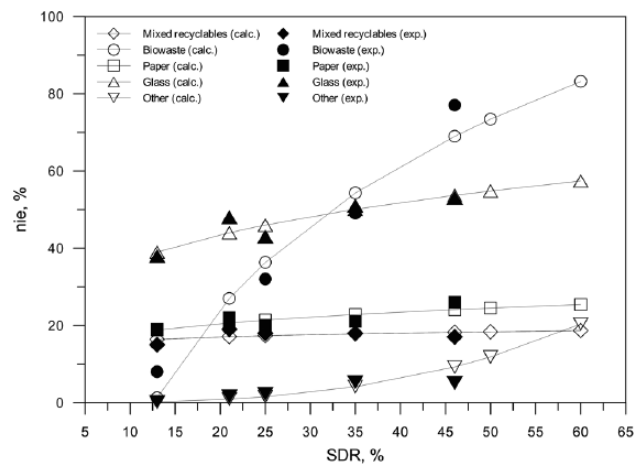


Figure 3. Experimental (blanked) and calculated (shaded) values of nie at different values of SDR. nie: nominal interception efficiency; SDR: separate delivery rate.

diagram is reported in Figure 5. The material processing and recovery facility increases the amount of secondary materials addressed to recycling and the production of a high-quality secondary fuel converted into syngas.

The main results in terms of performance indicators for all scenarios are reported in Table 6. The SOM obtained by the biowaste treatment is addressed to landfill as covering material for scenarios A1 and A2; on the contrary, in the alternative scenarios B1 and B2, it is used as a low-calorific value fuel. The material recovery is increased thanks to the sorting and selection processes occurring in the MRF (restwaste).

The good results in term of RCR indicators obtained by moving from A to B scenarios, indicate that an intense separate sorting by householders is not useful. In fact, the RCR values at SDR equal to 46% and 60% are quite similar (10% vs 13% and 15% vs 17%, for A and B scenarios, respectively).

Preliminary economic considerations

The quantification of the performance indicators reported in the preceding paragraphs allows us to make considerations about the effects of technological choices on the output material flows. These choices have effects also on the environmental features and on the economy of the waste management chain. The environmental effects will be analysed by using life-cycle assessment and risk assessment methods in the future development of the research. The economic performance has been evaluated and reported here by considering the same system boundary of the material flow assessment and by making the following considerations.

- (a) The processing costs do not contain financial items (interests on the debt) and administrative costs. They include workers costs, fixed capital amortisation in 10 years, energy and materials consumption, etc.
- (b) The revenues from the selling of secondary materials, energy vectors (biogas and syngas), electric and thermal energy are considered separately by the processing costs of the facility.

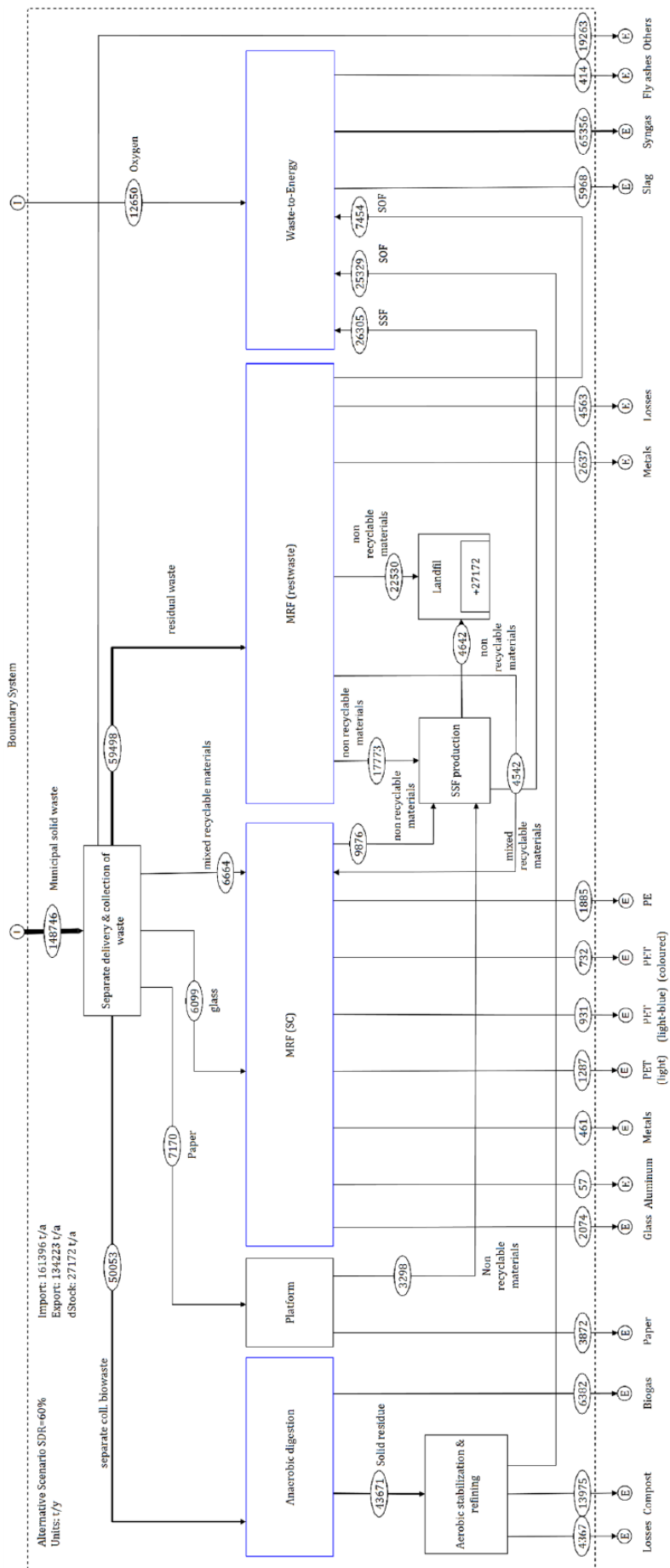


Figure 4. Alternative scenario B2: material flow analysis.

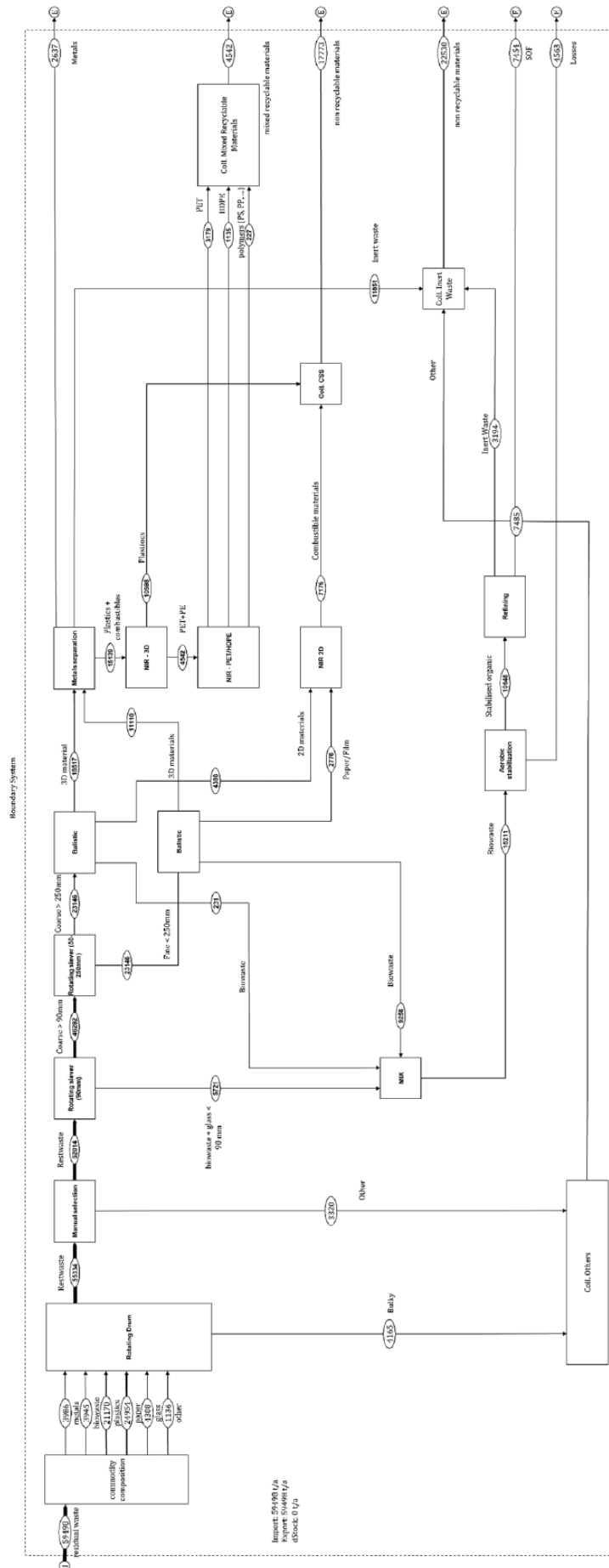


Figure 5. Material flow analysis related to the MRF that processes the residual waste with reference to the alternative scenario B2.

- (c) The gate fee is the net value resulting by the economic balance carried out around the whole waste management scenario.
- (d) The processing cost for the separate collection system is mainly composed by the following items: workers' salaries, capital, amortisation and maintenance costs for trucks, transportation fuel cost (that depends on urban highway configuration and by localisation of facilities), insurances, etc. The cost of this step has been considered not variable with SDR for values larger than 50%, because the kerbside collection method is not able to reach these values and the chosen method is necessarily the door-by-door collection. Its cost does not vary with the variation of the collected waste composition if the total production is constant, because the number of workers and the transport fleet remains the same. The unitary cost of separate collection is in the range 180–330€t⁻¹ for the set of municipalities considered.
- (e) The processing costs of anaerobic digestion and composting plant are quite similar, because the composting plant requires more electric energy for air introduction, but the digestion plant requires more maintenance. Their processing cost has been fixed to 80€t⁻¹.
- (f) The processing cost of the waste-to-energy combustion facility related to the base case is comparable with that of other incinerators in Europe, but the revenue by the electric energy transferred to the grid is much higher owing to high economic incentives. While in Europe the gate fee of incineration is in the range 100–150€t⁻¹, the reference facility has a gate fee of 70€t⁻¹ thanks to the incentives. The calculation of the base-case scenario considers of the net cost of 70€t⁻¹ that includes the revenues (i.e. it represents the gate fee and not the processing costs).
- (g) In the alternative scenarios, two different calculations have been made: in one case the gate fee has been considered the same of the incinerator (including the revenue from energy); in a second case, more generally applicable, the processing costs of the high-temperature gasifier has been considered equal to 130€t⁻¹. In this latter case, the syngas has been considered as having an economic value equivalent to its calorific value by referring to methane.
- (h) The processing costs of MRF is 70€t⁻¹.

Table 6. Summary of indicators for the compared scenario.

	A1	A2	B1	B2
RCR	10%	13%	15%	17%
RECR	38%	38%	51%	53%
DCR	41%	37%	27%	24%

1 refers to SDR=46%; 2 refers to SDR=60%; A refers to the base case process configuration; B refers to the alternative process configuration.

DCR: disposal-collected ratio; RCR: recycled-collected ratio; RECR: recovered-collected ratio.

Table 7. Gate fee calculation for the base case scenario.

Material flow				Cash flow				
Process	Input, ty ⁻¹		Output, ty ⁻¹		Input, €		Output, €	
Separate delivery	Waste	148,746			Waste	-37,186,500		
Composting and refining	Biowaste	39,938	Solid residue	29,235	Biowaste	-2,396,280	Solid residue	0
			Compost	8040			Compost	241,200
			SOM	21,195			SOM	-847,800
Platform	Paper	7006	Paper	3153	Paper	-210,180	Paper	157,650
	Others	9371	Others	5154	Others	-281,130	Others	0
MRF (SC)			Non-recyclable material	8070			Non-recyclable material	-322,800
	Glass	5682	Glass	1591	Glass	-340,920	Glass	29,211
	Mixed recyclable materials	6426	Aluminium	69	Mixed recyclable materials	-385,560	Aluminium	8958
			Metals	554			Metals	47,129
			PET light	735			PET light	143,134
			PET light blue	523			PET light blue	101,849
			PET coloured	470			PET coloured	91,528
			PE	768			PE	149,560
			Non-recyclable material	4775			Non-recyclable materials	-191,000
			MRF	49,426			See waste to energy	

(Continued)

Table 7. (Continued)

Material flow				Cash flow					
Process	Input, ty ⁻¹		Output, ty ⁻¹		Input, €		Output, €		
Separate delivery	Waste	148,746			Waste	-37,186,500			
MBT	Residual waste	80,323	SOM	23,297	Residual waste	-5,622,610			
			Metals	3322				Metals	282,603
			RDF	2622				See waste to energy	
Waste to Energy	RDF	49,426	Fly ash	4164	RDF	-3,459,820	Fly ash	-1,041,000	
	RDF	2622	Bottom ash	5725	RDF	-183,540	Bottom ash	171,500	
					Total costs		-52,802,009€		
					Gate fee		-355€t ⁻¹		

MBT: mechanical-biological treatment; MRF: material recovery facility; PE: polyethylene; PET: polyethylene-terephthalate; RDF: refuse-derived fuel; SC: separate collection; SOM: stabilised organic matter.

Table 8. Comparison between the gate fees as calculated for all scenarios.

	Separate collection, €t ⁻¹	Processing, €t ⁻¹	Gate fee, €t ⁻¹
Base scenario 46% ^a	-250	-105	-355
Base scenario 60% ^a	-250	-102	-352
Alternative scenario 46% ^a	-250	-106	-356
Alternative scenario 60% ^a	-250	-89	-339
Base scenario 46% ^a	-250	-105	-355
Base scenario 60% ^a	-250	-102	-352
Alternative scenario 46% ^b	-250	-64	-314
Alternative scenario 60% ^b	-250	1	-249

^aGate fee at the waste-to-energy facility = 70€t⁻¹.

^bProcessing cost at the gasification facility = 130€t⁻¹.

A comparison of gate fees, as calculated for all scenarios, is summarised in Table 8. The comparison shows the best performance of the alternative scenario B2 that corresponds to the best option for all indicators, including the economic issues.

Conclusions

Indicators able to evaluate the efficiency of a waste management system have been proposed and quantified by referring to a specific case study and by using a database including waste amount and composition data daily collected over 5 years. Detailed calculations over the base case and alternative scenarios' system boundary have been realised by means of the material flow analysis method. Indicators – nie and aie – have been used as input data in the quantification of the material flow assessment, while other indicators – RCR, RECR, DCR – have been obtained as output data.

The analysis has clearly shown the role of technological issues on the capability of the waste management system to ensure high values of recycling and diversion from landfill and minimise the economic cost. The role of the separate collection is crucial to separate biowaste from the residual waste, but it appears that a well-organised technological infrastructure can allow us to reach the same result of a collection with SDR, equal to 60%. In other words,

A moderate separate collection followed by an efficient waste treatment system allows to obtain the maximum diversion of waste from landfill and the maximum recycling and recovery rates. From an economic point of view, the best scenario corresponds to the alternative scenario with SDR 60% and a production of syngas instead of energy; this result is a calculation made without considering the electric energy economic incentives but by considering the syngas as a substitute of methane, taken as reference fuel.

Acknowledgements

The authors wish to thank Dr E Romeo for the valuable help in data validation, the Province of Caserta and CONAI for providing the data about waste production and composition at a municipal level and recycled waste amount and composition at a provincial level, respectively.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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