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A waste management planning based on substance flow analysis

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ABSTRACT

The paper describes the results of a municipal solid waste management planning based on an extensive utilization of material and substance flow analysis, combined with the results of specific life cycle assessment studies. The mass flow rates of wastes and their main chemical elements were quantified with a view to providing scientific support to the decision-making process and to ensure that the technical inputs to this process are transparent and rigorous. The role of each waste management option (recycling chains, biological and thermal treatments), as well as that of different levels of household source separation and collection (SSC), was quantitatively determined. The plant requirements were consequently evaluated, by assessing the benefits afforded by the application of high quality SSC, biological treatment of the wet organic fraction, and thermal treatment of unsorted residual waste. Landfill volumes and greenhouse gas emissions are minimized, toxic organic materials are mineralized, heavy metals are concentrated in a small fraction of the total former solid waste volume, and the accumulation of atmophilic metals in the air pollution control residues allows new recycling schemes to be designed for metals. The results also highlight that the sustainability of very high levels of SSC is reduced by the large quantities of sorting and recycling residues, amounts of toxic substances in the recycled products, as well as logistic and economic difficulties of obtaining very high interception levels. The combination of material and substance flow analysis with an environmental assessment method such as life cycle assessment appears an attractive tool-box for comparing alternative waste management technologies and scenarios, and then to support waste management decisions on both strategic and operating levels.

1. Introduction

The decision making process over waste management (WM) policy is a complex issue, which has to evaluate and suitably take into account the environmental impacts, technical aspects, implementation and operating costs (preferably in a welfare economic perspective) of each specific treatment and disposal option as well as the social implications (Kinnaman, 2009; Massarutto et al., 2011; Ferreira da Cruz et al., 2012). The process often involves accurate as well as inaccurate or missing data, expert evaluation as well as ill-defined and changing public opinion, and sometimes it is guided by preconceptions for or against specific waste management solutions, generally based on perception rather than on objective scientific evidence (Brunner and Ma, 2008). In the last decades, this framework has become increasingly complicated due to the growing generation and complexity of municipal solid wastes (MSWs) and the far-reaching changes that consequently occurred in their management. The latter have shifted from oversimplified procedures, such as the collection of unsorted wastes and their disposal in landfills, to integrated and sustainable systems, which have to work as a filter between human activities and the environment, providing a suitable balance between waste reduction practices, material recycling techniques, biological and thermal processes, and engineered landfill disposal (Arena et al., 2012). On the other hand, the decision making within this complicated framework does not appear adequately supported by existing regulations, such as those laid down by European Community Waste Framework Directive 2008/98. Such regulations are generally inspired by a precise ranking of solutions (the "waste hierarchy"), with material recovery to be preferred to energy recovery, and landfill to be considered as a last resort (EC, 2008). It could be argued that the issue concerning the optimal ranking of alternative treatments and solutions is still debated and that, at all events, hierarchies of whatever consistency do not always lead to the most effective waste management system and are not sufficient to develop complete, fully integrated and sustainable WM planning (Kinnaman, 2009). The same Waste Framework Directive is open to potential deviations from the hierarchy "where this is justified by life cycle thinking on the overall impacts of the generation and management of such waste [. . .]" (article 4(2)).

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Nomenclature

AD	anaerobic digestion
APC	air pollution control
LCA	life cycle assessment
LHV	lower heating value
MBT	mechanical biological treatment
MFA	material flow analysis
MSW	municipal solid waste
OF_{MSW}	organic fraction of MSW
PCBs	polychlorinated biphenyls
PBDEs	polybrominated diphenyl ethers
SFA	substance flow analysis
SSC	source separation and collection
SOF	stabilized organic fraction
SR	selection residues
SSL	source separation level
RR	recycling residues
URW	unsorted residual waste
WEEE	waste from electrical and electronic equipments
WM	waste management
WtE	waste-to-energy

The considerations reported above indicate the need to adopt a comprehensive, systemic, goal-oriented approach based on in-depth knowledge of the system behavior and able to provide reliable information about how environmental hazards can be minimized and potential resources maximized (Brunner and Ma, 2008; Mastellone et al., 2009). Since there is a general consensus about the main goals (protection of human health and environment; conservation of resources; and after-care-free management), and since these are all substance-oriented, the assessment tools cannot refer just to bulk flows of wastes and residues. The flows of individual substances also have to be investigated, controlled, and directed to appropriate treatments and sinks. In other words, given that individual substances are responsible for environmental loadings and resource potentials, it is necessary to observe the system even at the substance level.

The aim of the study is to describe the results of a WM planning that, in accordance with the observations reported above, is based on a substance-oriented approach. The final goal is to quantify the mass flow rates of wastes and their main chemical elements in order to provide scientific support to the decision-making process and ensure that the technical inputs to this process are transparent and rigorous. In this way, the stakeholders, i.e. any individual or organization with a legitimate interest, may be effectively involved in the decisional process (Clift, 2012). The approach was recently applied to three Italian areas, having different extension (from 2600 km^2 to 13,600 km^2), population densities (from 72 inh/km^2 to 428 inh/km^2) and per-capita waste generation rates (from 426 kg/(inh y) to 467 kg/(inh y)) (Provincia Caserta, 2011; Regione Campania, 2011; Arena and Di Gregorio, 2013a).

2. Methods and input data

The utilized approach is based on the extensive utilization of two valuable tools, the material flow analysis (MFA) and substance flow analysis (SFA), which can be efficiently used to support waste management decisions on both strategic and operating levels. MFA is a systemic assessment of the flows and stocks of materials and elements within a system defined in space and time (Brunner, 2004), which is called SFA when referring to a specific chemical species. Today, SFA is largely used to link the inputs and outputs of treatment processes and management systems, thereby supplying data that are crucial for the design, operation, and control of waste treatment systems. Due to the increasing complexity of solid waste composition (Bilitewsky, 2009; Brunner, 2009) what is highly attractive is SFA's ability to connect the sources, pathways, and intermediate and final sinks of each species in a specific process, as demonstrated by its use in the assessment of thermal treatments (Arena et al., 2011; Arena and Di Gregorio, 2013b), recycling options (Rotter et al., 2004) and waste management scenarios (Mastellone et al., 2009).

Following this approach, the methodology adopted for the desired substance-oriented waste management planning is made of a sequence of three steps. First, a series of life cycle analysis (LCA) studies is utilized to define the overall WM scheme and then to identify specific technical solutions to be included in the scheme. Only fully tested technologies, with proven technical reliability and environmental sustainability and with known total costs for treatment and aftercare were selected. In the second step, a specific MFA/SFA is developed for each of the recycling, biological, and thermo-chemical technologies of the defined management scheme, with the support of the freeware STAN (subSTance flow ANalysis) implemented by the Vienna University of Technology (Cencic and Rechberger, 2008). The final step applies the MFA/SFA to a series of alternative management scenarios, which are finally compared to each other. It is noteworthy that all the material and substance flow analyses have been developed on the basis of the transfer coefficients of the selected waste treatment processes, as obtained by mass balances extended to some crucial atomic species.

The composition of the municipal solid waste assumed as input data, i.e. the waste produced upstream of any form of separation and collection, was evaluated and averaged, in terms of different waste fractions, on the basis of different analyses carried out for Italian areas (Giugliano et al., 2011). Table 1 reports this composition, together with the ultimate analysis of each waste fraction, as obtained by different sources: Consonni and Viganò (2011) for the main elements, and Rotter et al. (2004), CEWEP (2009) and Zhang et al. (2011) for the trace elements. It should be noted that a certain variation in the value of cadmium, chromium and lead was found, in particular for the wet organic fraction, as may also be expected on the basis of different dietary habits. That said, the variation is always in the range of a few mg/kg (0.5–2 mg/kg for Cd, 3–12 mg/kg for Cr, 4–11 mg/kg for Pb) and was thus assumed to be negligible for the purposes of this study. The ultimate analyses were extended to these trace elements since a substance-oriented approach was adopted for WM planning. As mentioned above, a WM system cannot focus on the amount of total waste alone; it must also address the amounts of constituent substances (i.e., chemical elements and chemical compounds) since these determine whether waste has a resource potential or constitutes hazardous material. For instance, it is the content of heavy metals in the bottom ash of a waste-to-energy unit that determines whether this ash can be re-used, can be landfilled directly, or requires treatment before landfilling (Rocca et al., 2012; Arena and Di Gregorio, 2013b); similarly, it is the content of hazardous substances, such as persistent organic molecules and heavy metals, in waste of durable and non-durable goods or packaging that determines whether or not it can be safely recycled (Döberl et al., 2002; Brunner, 2009; Mastellone et al., 2009).

3. Results and discussion

3.1. Definition of the overall WM scheme

An integrated and sustainable waste management system should be defined and developed according to the following

Table 1
Composition of municipal solid waste assumed as reference in the material and substance flow analysis.

MSW composition	%	C (%)	Cl (%)	F (%)	H (%)	O (%)	N (%)	S (%)	Cd (mg/kg)	Cr (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	Ash (%)	Moisture (%)	LHV (MJ/kg)
Organic fraction	35.0	15.49	0.20	0.00	2.51	13.62	0.76	0.03	1.80	12	0.057	11	4.89	62.49	4.85
Paper	25.0	30.97	0.11	0.00	4.65	34.07	0.37	0.03	1.90	25	0.047	11	7.80	22.00	10.84
Glass	6.0	0.43	0.03	0.02	0.01	1.08	0.87	0.13	2.60	370	0.007	430	96.43	1.00	−0.02
Plastics	15.0	60.61	0.67	0.00	9.29	8.21	0.72	0.04	16.00	120	0.072	170	6.45	14.00	25.63
Metals	3.0	0.42	0.18	0.01	0.02	0.83	1.04	0.08	4.40	800	0.23	2300	96.43	1.00	−0.02
Aluminum	1.0	0.42	0.18	0.01	0.02	0.83	1.04	0.08	0.95	80	0.26	37	96.43	1.00	−0.02
Wood and textiles	4.0	39.32	0.05	0.00	5.14	33.16	1.53	0.08	2.25	57.5	0.027	144	2.74	18.00	14.92
Bulky waste and WEEE	11.0	21.97	0.52	0.00	3.56	16.74	0.94	0.14	57.00	630	1.8	460	23.63	32.50	8.06
Total	100.0	26.29	0.27	0.00	4.03	17.78	0.73	0.05	10.2	147	0.3	184	17.0	33.9	9.7

criteria (EC, 2008): (i) to minimize use of landfills and ensure that no landfilled waste is biologically active or contains mobile hazardous substances. These aspects could become crucial due to the continuously reducing space for locating sanitary landfills, which is becoming a major concern worldwide (UNEP, 2012); (ii) to minimize operations that entail excessive consumption of raw materials and energy without yielding an overall environmental advantage (McDougall et al., 2001); (iii) to maximize recovery of materials, albeit in respect of the previous point; and (iv) to maximize energy recovery for materials that cannot be efficiently recycled, in order to save both landfill volumes and fossil-fuel resources (Azapagic et al., 2004; Rechberger and Schöller, 2006). The waste management systems that are operating successfully worldwide were all developed taking into account the above criteria (EAI, 2005; Dornburg et al., 2006). In particular, they demonstrate that no one process is suitable for all waste streams; and no single waste management practice (i.e. landfill, recycling, biochemical or thermochemical conversion) can handle the full array of waste types and, at the same time, satisfy the waste management planning criteria reported above (Mastellone et al., 2009; Izquierdo López, 2010).

In the light of such considerations and on the basis of a series of LCA investigations (Clift et al., 2000; McDougall et al., 2001; Arena et al., 2003; Azapagic et al., 2004; Bjorklund and Finnveden, 2005; Izquierdo López, 2010; Rigamonti et al., 2010; Giugliano et al., 2011), an overall WM scheme was built and adequate technical solutions to be included in this scheme were identified. The recalled LCA studies assessed impacts for different sub-units composing a MSW management system generally concluding that the best treatment for packaging materials is recycling, the best one for organic waste is anaerobic digestion, while the unsorted residual waste should be treated by thermo-chemical conversion with energy recovery (Rigamonti et al., 2010). The WM reference scenario sketched in Fig. 1 is thereby based on the fundamental and crucial role of source separation and collection, which works as the first stage of the recycling chain and then of material recovery, but also as unavoidable preliminary sorting to best prepare the dry and humid waste fractions for downstream processes. These are: (i) recycling of dry fraction mainly made of packaging waste, and containing glass, paper and cardboard, wood, plastics and metals; (ii) biological treatment of the organic wet fraction (OF_{MSW}), obtained by separate collection; (iii) thermal treatment of the remaining unsorted residual waste (URW), i.e. the dry fraction that cannot conveniently be recycled, from both environmental and economic points of view; and (iv) landfill disposal of all the residues from the recycling, biological and thermal processes. This WM scheme utilizes each of these options to the extent that is compatible with their technical, economic and environmental performance and that is suited to the characteristics of the specific catchment area (waste composition, population density, etc.). Importantly, source separation and collection is assumed to be applied at high quantitative levels. The qualitative level is also assumed to be high, even at the highest source separation levels (SSLs), such that the amount of residues to be taken into account is limited as much as possible. The SSL is always sufficiently high to make the mechanical biological treatment (MBT) neither environmentally nor economically feasible (Read and Godley, 2011). Moreover, when the SSL is larger than 50%, the residual waste often contains insufficient organic material to activate the biostabilization process (Ragazzi and Rada, 2009). The poor environmental and economic sustainability of MBT plants is further supported by SFA studies showing the limitations of their "garbage in-gold out" approach: "waste inputs usually contain substances that are either detrimental due to their subsequent use (e.g., copper in iron scraps) or hazardous for the environment (e.g., cadmium in sorted fractions for compost production)" (Brunner and Ma, 2008).

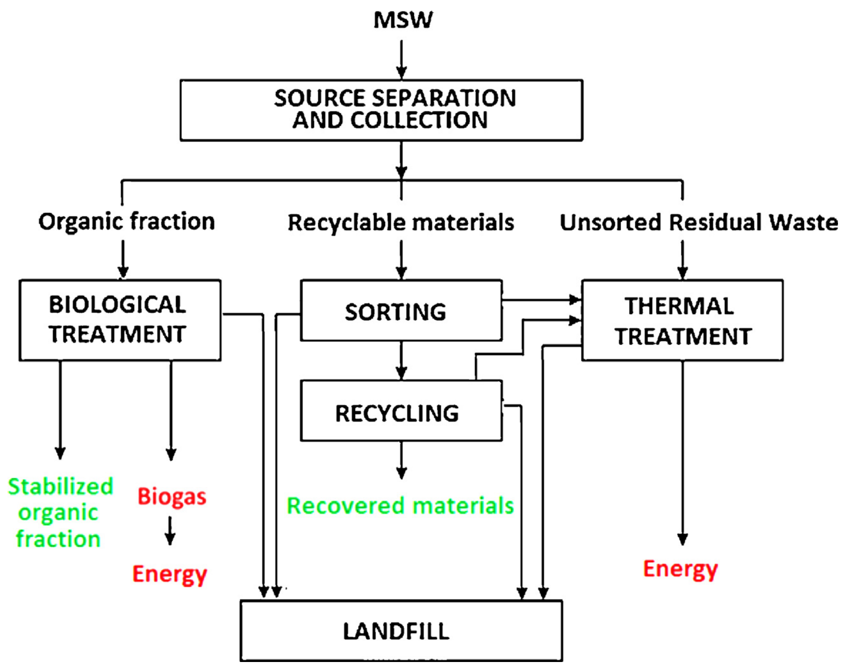

Fig. 1. Flow diagram of the MSW scenario assumed as reference.

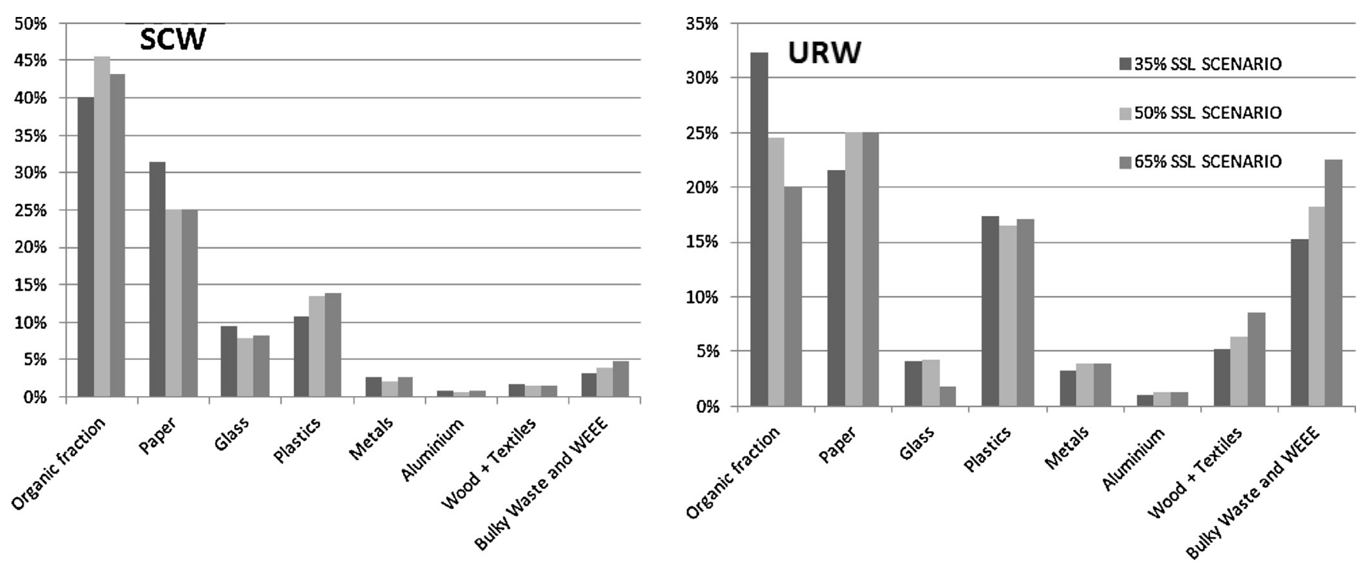

Fig. 2. Compositions of separately collected and unsorted residual wastes in the scenarios with 35%, 50% and 65% of source separation level.

Table 2
Interception efficiencies assumed for the scenarios 35%, 50% and 65% of source separation levels (MSW production = 1000 t/d).

Waste fractions	Organic fraction	Paper	Glass	Plastics	Metals	Aluminum	Wood + textiles	Bulky waste and WEEE	Total
In MSW, %	35.0	25.0	6.0	15.0	3.0	1.0	4.0	11.0	100
SCENARIO SSL 35%									
Interception efficiency, %	40.0	44.0	55.0	25.0	30.0	30.0	15.0	10.0	35%
Separate collection waste, t/d	140.0	110.0	33.0	37.5	9.0	3.0	6.0	11.0	349.5
Unsorted residual waste, t/d	210.0	140.0	27.0	112.5	21.0	7.0	34.0	99.0	650.5
SCENARIO SSL 50%									
Interception efficiency, %	65.0	50.0	65.0	45.0	35.0	35.0	20.0	17.5	50%
Separate collection waste, t/d	227.5	125.0	39.0	67.5	10.5	3.5	8.0	19.3	500.3
Unsorted residual waste, t/d	122.5	125.0	21.0	82.5	19.5	6.5	32.0	90.8	499.7
SCENARIO SSL 65%									
Interception efficiency, %	80.0	65.0	90.0	60.0	55.0	55.0	25.0	28.2	65%
Separate collection waste, t/d	280.0	162.5	54.0	90.0	16.5	5.5	10.0	31.0	649.5
Unsorted residual waste, t/d	70.0	87.5	6.0	60.0	13.5	4.5	30.0	79.0	350.5

Table 3
Solid residues for each fraction of MSW, expressed as percentage of treated materials in the sorting and recycling units, for the scenarios SSL 35%, 50% and 65% of source separation levels.

MSW fractions	SSL 35%			SSL 50%			SSL 65%		
	SR, %	RR, %	SR + RR, %	SR, %	RR, %	SR +RR, %	SR, %	RR, %	SR +RR, %
Organic fraction	20.0	9.7[a]	25.7	22.0	9.7[a]	27.6	24.0	9.7[a]	29.5
Paper	5.0	11.0	15.5	6.5	11.0	16.9	8.0	11.0	18.1
Glass	6.0	0.0	6.0	14.0	0.0	14.0	16.0	0.0	16.0
Plastics[b]	35.0	25.5	51.6	40.0	25.5	55.3	44.0	25.5	58.3
Metals[b]	6.0	9.5	14.9	6.0	9.5	14.9	6.0	9.5	14.9
Aluminum[b]	15.0	16.5	29.0	15.0	16.5	29.0	15.0	16.5	29.0
Wood and textiles	13.5	5.0	17.8	13.5	5.0	17.8	13.5	5.0	17.8
Bulky waste and WEEE[c]	10.0	10.0	19.0	12.0	12.0	22.6	14.0	14.0	26.0
Total	14.7	9.5	22.8	19.0	9.8	27.0	20.9	9.9	28.8

[a] This is the percentage of residues produced during the aerobic step of the digestate, as obtained by Grosso et al. (2009).
[b] It has been assumed that plastics, metals and aluminum are collected together by means of a multi-materials collection system.
[c] The data related to this fraction derive from Bianchi (2008) by assuming conservative average values, i.e. close to the lowest ones.

The WM scheme adopted was further divided into a number of scenarios, which differ only in the source separation level, assumed to be equal to 35%, 50% and 65%. These values were selected because they are able to describe a possible high-quality evolution of source separation and collection practices and because they have already been used by some LCA studies aiming to determine the best MSW management system (De Feo and Malvano, 2009) or to quantify the best level of source separation (Giugliano et al., 2011; Massarutto et al., 2011). Each of these SSLs has to be considered as an average of those that can actually be obtained for each waste fraction (Table 2). Provided that suitable collection and storage logistics are set up, in order to obtain a high or very high SSL, it is useful to considerably increase the interception efficiency of some waste fractions, such as wet organic waste, paper, and glass. The first, in particular, is predominant in MSW composition (about 1/3 of the total) and can be intercepted at very high levels since it is easily recognized by the public. Moreover, wet organic waste requires special downstream treatment and its interception greatly improves the quality of the remaining waste. On the contrary, fractions with low densities (such as plastics) or little abundance (such as ferrous and non-ferrous metals) are more difficult to collect at high rates, i.e. rates higher than those obtainable just with the interception of packaging waste. These considerations have to be taken into account particularly for scenarios assuming the highest average SSL: 65% of source separation and collection calls for very high interception levels also for plastics, metals, and "others" including bulky wastes and WEEE, as indicated in Table 2. Data in Tables 1 and 2 were then processed to obtain the composition of separately collected waste (SCW) to be sent to the recycling chain and biological treatment, and that of unsorted residual waste (URW) to be sent to thermal treatment together with the residues of plastics, paper, and wood recycling chains (Fig. 2).

3.2. Material and substance flow analysis of the WM options

All the waste treatment options that compose the WM scenario assumed as reference were defined on the basis of the above-mentioned LCA studies and Best Reference Documents of the European Community (EC-IPPC, 2006a, 2006b). A specific MFA/SFA was developed for each of these recycling, biological, and thermo-chemical technologies. The results are schematically reported below.

Recycling chain. Recyclable dry fractions of separate collections, mainly made of packaging waste, are sent to a sorting stage and then to the specific recycling process. The whole chain of the separate waste recovery/recycling process of paper, plastic, metals, wood, bulky waste and WEEE as well as that of the wet organic fraction have different process efficiencies. In other words, there is a non-negligible amount of material discarded in the sorting process (SR, selection residues) and of residues from the final recycling process (RR, recycling residues). The SSL is thus always higher than the fraction of materials actually recycled. The amounts of sorting

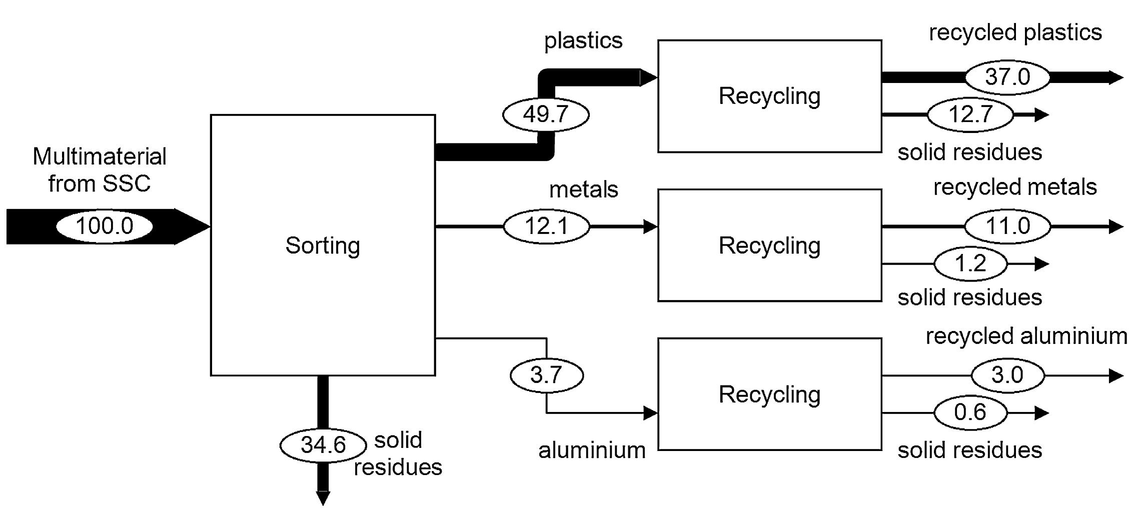

Fig. 3. Material flow analysis of the recycling chain of the multi-material dry recyclable fraction obtained from source separation and collection, in the scenario SSL 50%. Data are in t/d.
Main sources of input data are: Perugini et al. (2005); Giugliano et al. (2011).

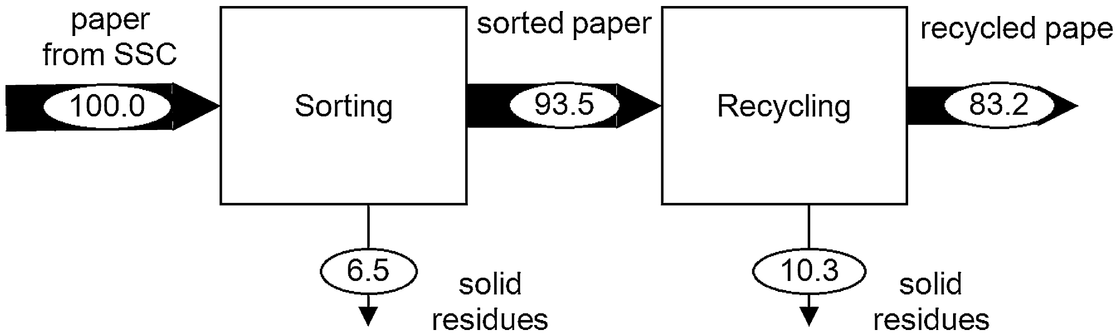

Fig. 4. Material flow analysis of the recycling chain of the paper and cardboard fraction obtained from source separation and collection, in the scenario SSL 50%. Data are in t/d.
Main sources of input data are: Arena et al. (2004), Giugliano et al. (2011).

residues were determined on the basis of investigations carried out in Italian areas characterized by "best practices" of separate collection (Giugliano et al., 2011), while those of recycling residues derive from a number of LCA studies focused on the specific recycling chains (McDougall et al., 2001; Arena et al., 2004; Perugini et al., 2005; Giugliano et al., 2011). In particular, Table 3 indicates that the percentages of RR are constant for all the SSLs taken into account, while those of SR increase when the level of source separation and collection increases, as reported by different sources (Bianchi, 2008; Giugliano et al., 2011). The results of the material flow analyses are reported here for the two main waste fractions. They are shown in Fig. 3 for the recycling chain of the multi-material waste stream, which includes recyclable packaging made of plastic, ferrous metals and aluminum, and in Fig. 4 for the recycling chain of the paper waste stream. Both flow diagrams refer to an SSL of 50%. The input data for all these MFAs were mainly derived from the inventory tables of some of the LCA studies cited above (Arena et al., 2004; Perugini et al., 2005; Giugliano et al., 2011).

Biological treatment. The organic fraction from household source separation and successive separate collection (OF_{MSW}) is sent to a preliminary sorting stage and to an integrated anaerobic digestion (AD) plant, including a final aerobic treatment. At the AD plant, the obtained biogas is used for energy generation and the resulting digestate is post-composted in order to obtain a material for agriculture, landfill capping or restoration of contaminated sites, thereby further reducing the mass of solid residues to be landfilled. AD is considered the best available process for biochemical conversion for several reasons: minimization of greenhouse gas emissions, stabilization of the organic fraction, energy recovery from the produced biogas, absence of emissions of bio-aerosols and bad odors, limited land surface use, and economic sustainability (Mata-Alvarez et al., 2000; Defra, 2007; Zhang et al., 2007; Khalid et al., 2009). From an LCA perspective, all these reasons contribute to largely higher environmental sustainability with respect to other biological treatments, like aerobic composting (Arena et al., 2005; Hermann et al., 2011; Yoshida et al., 2012). MFA applied to the composition reported in Table 1 takes into account the amounts of SR and RR indicated in Table 3 and the transfer coefficients inferred from the scientific literature for a dry process (Mata-Alvarez et al., 2000; Grosso et al., 2009; Zhang et al., 2011). The biogas produced (about 60% methane and 39% carbon dioxide) is then burnt for electrical and thermal energy production. The estimated biogas production depends on a series of factors, such as the quality of the substrate, the hydraulic retention time, and the specific technology of the digester. Evaluation of electricity exported has to take into account that roughly a quarter of the total produced electricity is used internally for running the digester and the cleaning section (scrubbers and membrane filters) upstream of the internal combustion engine (Izquierdo López, 2010; Hermann et al., 2011; Banks et al., 2011). A conservative value of 0.12 MWhe per ton of OF_{MSW} was used for the net production of electricity while that of total (electrical and thermal) energy produced was assumed to be 0.5 MWh per ton of OF_{MSW}. Digestion also leads to the production of a digestate, which is sent to a post-composting section, considered as a typical industrial composting unit. The results are shown in Fig. 5. It should be noted that the post-composting process typically includes an addition of ligneous cellulosic organic materials (such as cardboard and wood), which was not considered in the analysis and therefore does not appear in the quantified flow diagram.

Thermal treatment. The unsorted residual waste is sent for thermal treatment as it is, i.e. without preliminary MBT, as a positive consequence of the source separation levels that characterize the proposed scenarios and work as a preliminary and efficient sorting stage. It was also assumed that all the combustible residues

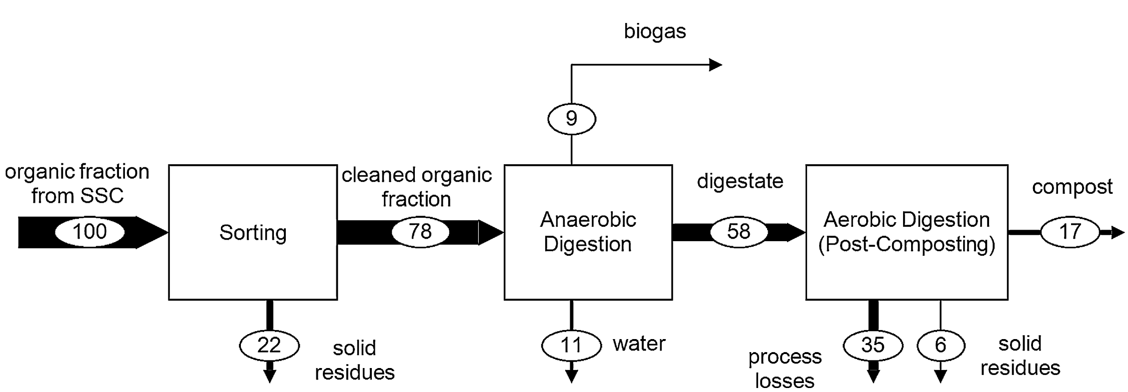

Fig. 5. Material flow analysis of the biological treatment of wet organic fraction obtained from source separation and collection, in the scenario SSL 50%. Data are in t/d.
Main sources of input data are: Grosso et al. (2009), Giugliano et al. (2011).

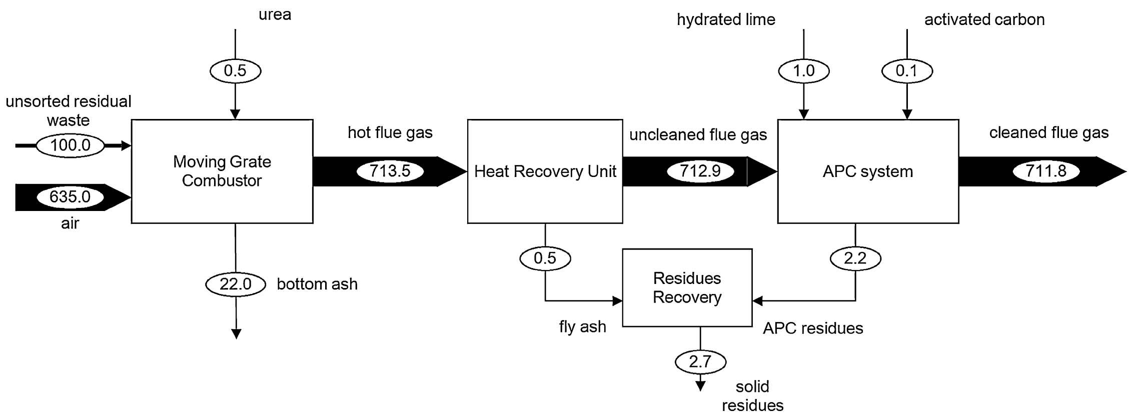

Fig. 6. Material flow analysis for thermal treatment by means of a combustion-based process of URW. Data are in t/d. Source of input data: Arena and Di Gregorio (2013b).

from recycling chains of paper, plastics and wood have to be sent to thermal treatment, for the following reasons: (i) the opportunity for a further reduction in landfill use, (ii) the possibility to reduce the wastage of feedstock energy (McDougall et al., 2001), and (iii) compliance with the European Directive 1999/31/EC prohibiting landfill disposal of any material having a heating value greater than 13 MJ/kg (EC, 1999). Thermal treatment is recognized as an essential component of any sustainable integrated MSW management system (Porteous, 2005; Psomopoulos et al., 2009). It can play a number of important roles: it reduces the mass and volume of waste, thereby preserving landfill space; it recovers energy from the solid waste stream; it allows the recovery of materials from solid residues; it destroys a number of organic contaminants that may be present in the waste stream; and it reduces greenhouse gas emissions with respect to anaerobic decomposition in landfills (Arena et al., 2012). It affords a further fundamental benefit, namely that of being able to separate inorganic components (metals such as iron, cadmium, lead, and non-metals such as chlorine, bromine, etc.) from the organic fraction (consisting of carbon, hydrogen and oxygen). This allows reuse or inertization, thereby preventing dispersion and accumulation of hazardous constituents not only in the environment but also in recycled products, where they can reach

Table 4
Summary of material, volume and energy flow analysis for the scenarios 35%, 50% and 65% of source separation levels (MSW production = 1000 t/d).

Scenario	SSL 35%	SSL 50%	SSL 65%
Mass of waste to landfill, $\%_{entering\ MSW}$			
From sorting and recycling chain	0.7	1.2	2.0
From biological treatment	3.6	6.3	8.2
From thermal treatment	17.0	13.8	10.7
Total	21.3	21.3	20.9
Volume of Waste to Landfill, m^3/d ($\%_{entering\ MSW}$[a])			
From sorting and recycling chain	10.8	20.3	32.8
From biological treatment	60.0	105	137
From thermal treatment	101	82.4	64.0
Total	172 (*8.3*)	207 (*10.0*)	234 (*11.2*)
Energy net production, GWh/y			
Electric energy	126	108	92
Thermal energy (in cogeneration)	313	265	211
Total	439	373	303
Lost and available feedstock energy, GWh/y ($\%_{entering\ waste\ energy}$)			
Converted in electric and thermal energy	770 (*78.1*)	691 (*70.1*)	612 (*62.1*)
Lost in landfill	45 (*4.5*)	68 (*6.9*)	85 (*8.6*)
Recovered materials, t/d ($\%_{entering\ MSW}$)			
Glass	31.0	33.5	45.4
Plastics	19.5	32.5	41.2
Metals	12.8	17.6	27.8
Aluminum	2.7	3.4	5.3
Paper	93.0	104	133
Textiles	2.5	3.3	4.1
Wood	4.2	6.2	8.7
Compost	24.3	38.5	46.1
Total	190 (*19.0*)	239 (*23.9*)	312 (*31.2*)

[a] Assuming a bulk density of collected MSW of 0.48 t/m^3.

Table 5
Summary of substance flow analysis for the scenarios 35%, 50% and 65% of source separation levels (MSW production = 1000 t/d).

Scenario	SSL 35%	SSL 50%	SSL 65%
Carbon to landfill, t/d ($\%_{input\ C}$)			
From sorting and recycling chain	0.8 (*0.3*)	1.4 (*0.5*)	2.2 (*0.8*)
From biological treatment	11.0 (*4.2*)	18.3 (*7.0*)	23.0 (*8.7*)
From bottom ash	2.0 (*0.8*)	1.7 (*0.6*)	1.5 (*0.6*)
From APC residues	0.9 (*0.3*)	0.8 (*0.3*)	0.7 (*0.3*)
Total	14.7 (*5.6*)	22.2 (*8.4*)	27.4 (*10.4*)
Cadmium to landfill, g/d ($\%_{input\ Cd}$)			
From sorting and recycling chain	898 (*8.9*)	1,577 (*15.6*)	2,536 (*25.1*)
From biological treatment	249 (*2.5*)	405 (*4.0*)	499 (*4.9*)
Partial total	1150 (*11.4*)	1980 (*19.6*)	3030 (*30.0*)
From bottom ash	831 (*8.2*)	721 (*7.1*)	589 (*5.8*)
From APC residues	7477 (*74.0*)	6488 (*64.2*)	5293 (*52.4*)
Total	9450 (*93.6*)	9190 (*91.0*)	8920 (*88.3*)
Cadmium in recycled product, g/d ($\%_{input\ Cd}$)			
Glass	81 (*0.8*)	87 (*0.9*)	118 (*1.2*)
Plastics	312 (*3.1*)	521 (*5.2*)	660 (*6.5*)
Metals	56 (*0.6*)	78 (*0.8*)	122 (*1.2*)
Aluminum	3 (*0.03*)	3 (*0.03*)	5 (*0.05*)
Paper	177 (*1.8*)	198 (*2.0*)	253 (*2.5*)
Textiles	5 (*0.05*)	7 (*0.07*)	9 (*0.09*)
Wood	4 (*0.04*)	6 (*0.06*)	8 (*0.08*)
Compost	2 (*0.02*)	4 (*0.04*)	5 (*0.05*)
Total	640 (*6.3*)	903 (*8.9*)	1180 (*11.7*)
Lead to landfill, kg/d ($\%_{input\ Pb}$)			
From sorting and recycling chain	10.2 (*5.5*)	16.3 (*8.9*)	26.7 (*14.5*)
From biological treatment	1.2 (*0.7*)	2.0 (*1.1*)	2.5 (*1.3*)
Partial total	11.4 (*6.2*)	18.3 (*10.0*)	29.2 (*15.8*)
From bottom ash	64.9 (*35.3*)	51.8 (*28.1*)	26.4 (*14.4*)
From APC residues	53.1 (*28.8*)	42.3 (*23.0*)	21.6 (*11.7*)
Total	129 (*70.3*)	112 (*61.1*)	77.2 (*41.9*)
Lead in recycled product, kg/d ($\%_{input\ Pb}$)			
Glass	13.3 (*7.2*)	14.4 (*7.8*)	19.5 (*10.6*)
Plastics	3.3 (*1.8*)	5.5 (*3.0*)	7.0 (*3.8*)
Metals	29.3 (*15.9*)	40.5 (*22.0*)	63.9 (*34.7*)
Aluminum	6.1 (*3.3*)	7.9 (*4.3*)	12.2 (*6.6*)
Paper	1.0 (*0.6*)	1.1 (*0.6*)	1.5 (*0.8*)
Textiles	0.2 (*0.1*)	0.3 (*0.2*)	0.4 (*0.2*)
Wood	0.8 (*0.5*)	1.2 (*0.7*)	1.7 (*0.9*)
Compost	0.3 (*0.2*)	0.5 (*0.2*)	0.5 (*0.3*)
Total	54.5 (*29.6*)	71.5 (*38.9*)	107 (*58.0*)

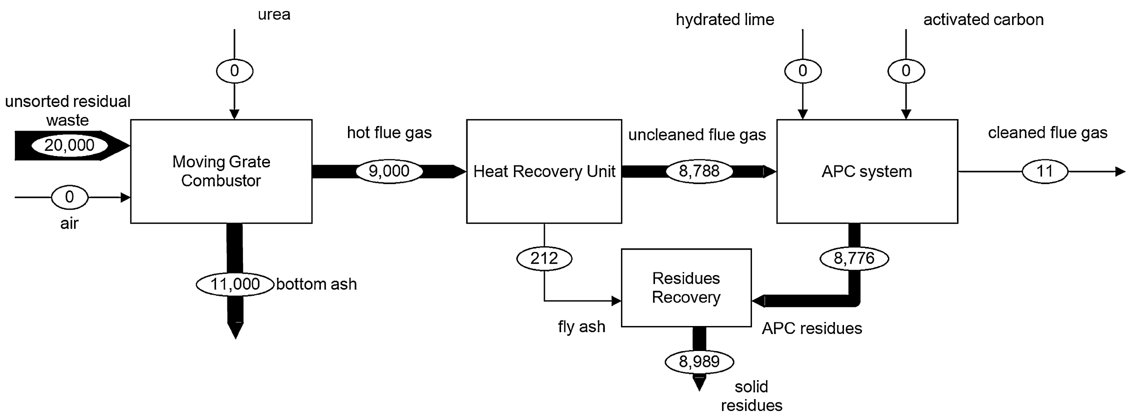

Fig. 7. Substance flow analysis of lead element for thermal treatment by means of a combustion-based process of URW. Data are in g/d. Source of input data: Arena and Di Gregorio (2013b).

hazardous concentrations (Brunner et al., 2004; Porteous, 2005; Kellner et al., 2011; Arena and Di Gregorio, 2013b).

The thermo-chemical conversion technologies can be grouped into two main categories: combustion-based and gasification-based thermal treatments. The specific thermo-chemical technology considered in this study was the mass-burn moving-grate incinerator, which is that most utilized worldwide (CEWEP, 2009). The developed MFA/SFA quantifies the partitioning of total mass as well as that of some crucial elements throughout the different output streams, by taking into account the ultimate

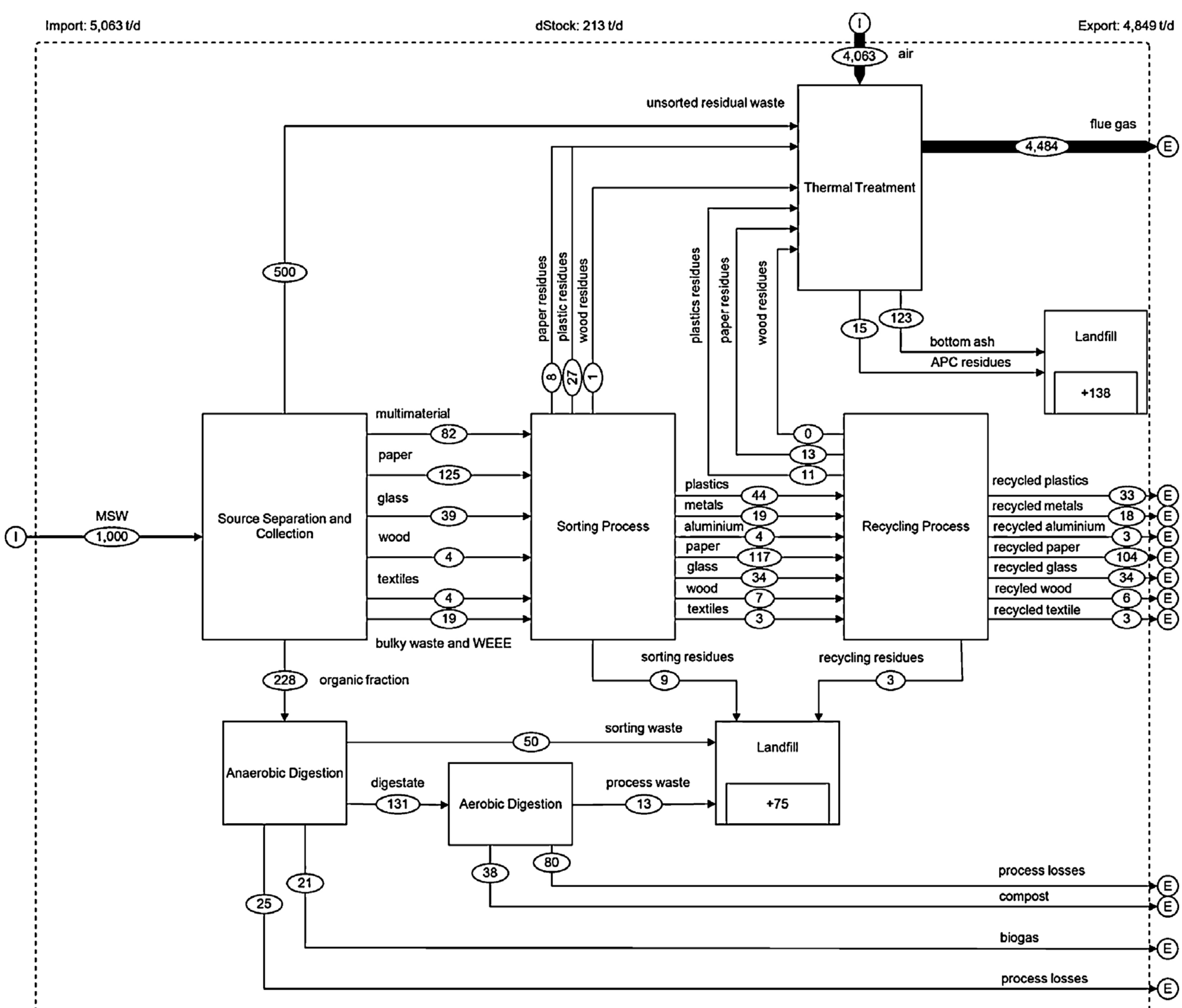

Fig. 8. Material flow analysis of the waste management system for the scenario 50% of source separation level, for a 1000 t/d MSW production (I: import flow; E: export flow; dStock: amount of accumulated material).

analyses of URW and combustible residues from recycling chains of plastics, paper and wood. Particular attention was paid to the partitioning of volatile heavy metals and to their concentration in output solid streams with reference to reuse or disposal scenarios (Jung et al., 2004, 2006; Rocca et al., 2012; Arena and Di Gregorio, 2013b). This aspect is crucial to define the potential for reducing the final amounts to be sent to landfill disposal, which used to be particularly relevant to densely populated areas but is now becoming increasingly important worldwide (UNEP, 2012). For the sake of simplicity, only two of the quantified flow sheets obtained by the MFA/SFA (and generally named "layers") are reported: that related to mass flow rates of the URW (Fig. 6) and the one pertaining to lead (Fig. 7). The net production of electricity has been assumed to be equal to 0.55 MWhe per ton of burned waste, which the Best REFerence Document of European Community on Best Available Technologies for Waste Incineration (EC, 2006a) reports as an average value. It is below the range 0.65–0.75 MWhe that can be obtained by an optimized installation for heat and power, which could be taken into account for WM planning for large catchment areas (Consonni and Viganò, 2011; Simoes and van Berlo, 2013).

3.3. Material and substance flow analysis of the alternative WM scenarios

A material and substance flow analysis was developed for each of the alternative scenarios of waste management. Tables 4 and 5 summarize most of the obtained results in terms of total mass, total volume, feedstock energy, carbon, cadmium, and lead, which are assumed as main environmental indicators on the basis of previous studies on goal-oriented WM planning (Brunner and Ma, 2008; Mastellone et al., 2009). The overall set of data allows to compare the scenarios and quantify the recycling, biological, thermal, and landfill facilities required for the good operation of a WM system. For space limitations, only 3 of the 18 quantified flow diagrams which result from MFA/SFA analysis are reported here, in Figs. 8–10: they refer to total mass, carbon and feedstock energy flow rates, as obtained for the scenario SSL 50% and a hypothetical MSW production of 1000 t/d. As shown in Fig. 8, wet organic waste is the largest fraction of materials from source separation and collection, due to the high interception level (about 45%, as reported in Fig. 2), and is sent for co-digestion treatment. The dry recyclable fractions (plastics, glass, paper, metals, etc.) are sent to

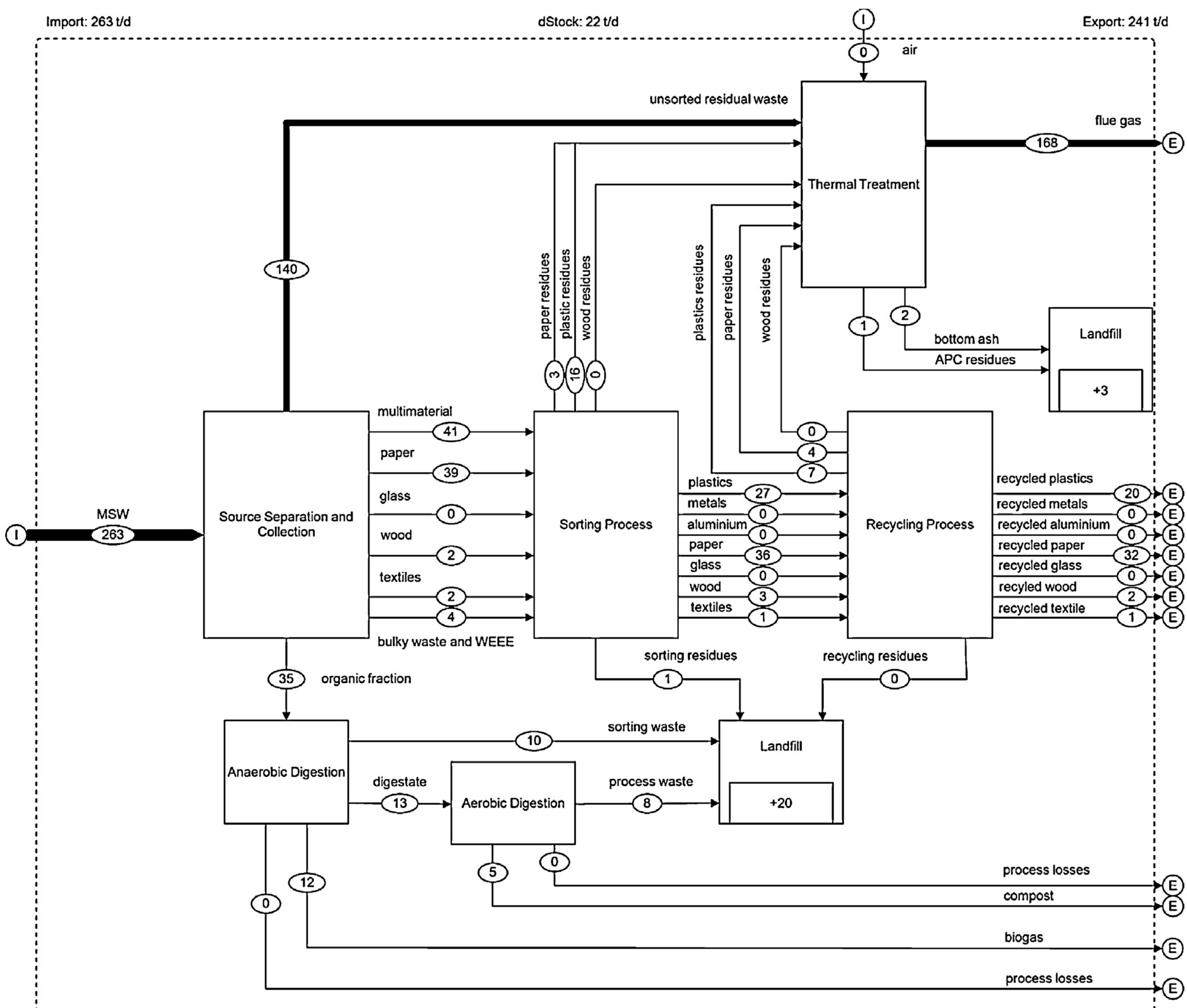

Fig. 9. Substance flow analysis of the waste management system for the carbon element for the scenario 50% of source separation level, for a 1000 t/d MSW production (I: import flow; E: export flow; dStock: amount of accumulated material).

the appropriate sorting and reprocessing chain. Residues of the sorting and recycling processes of plastics, paper, and wood, which together account for 6% of total MSW, are sent to the WtE process along with the URW, thereby obtaining energy recovery and a mass reduction of 77% (138 t/d instead of 560 t/d). Only the residues that are not energetically valuable due to their low heating value or very limited amount (glass, ferrous metals, aluminum, organic and textiles) are sent for landfill disposal: they represent the 7.5% of total MSW, and then 15% of the stream obtained by household separation. It is noteworthy that the residues from the pre-treatment of the organic waste for anaerobic digestion could be energetically recovered, in order to further reduce the amount of waste in landfill. This option appears interesting but it has not been taken into account in the examined scenarios since it is strongly affected by the quality of household source separation, and the available information is not sufficient to develop a material and substance flow analysis. With reference to the whole SSL 50% scenario, 21.3% of total MSW is sent to landfills while the materials actually recovered, i.e. the fraction that comes back to the process industries, amounts to 23.9%, hence less than half of the source separation level.

Fig. 9 quantitatively reports the mass flow rates for the carbon element for scenario SSL 50%, the carbon data for the other scenarios being summarized in Table 5. Carbon is an indicator of resource potential, such as energy and biomass, but also of environmental hazard, such as greenhouse gases and persistent and toxic organic substances (Mastellone et al., 2009). The main goals are to transform hazardous organic compounds into relatively harmless substances such as carbon dioxide and water, and to produce energy while mineralizing carbon to CO_2. The flow diagram in Fig. 9 indicates that carbon in scenario SSL 50% is mainly transferred to the export streams from thermal and biological energy recovery processes (68.4%) and to a lesser extent (23.1%) to recycled materials. This means that only 8.4% of the carbon present in total MSW produced is disposed via landfill (see also Table 5), thus preventing its accumulation and reducing greenhouse gas production. With reference to all the proposed scenarios, substantially no organic carbon is landfilled and the amount of

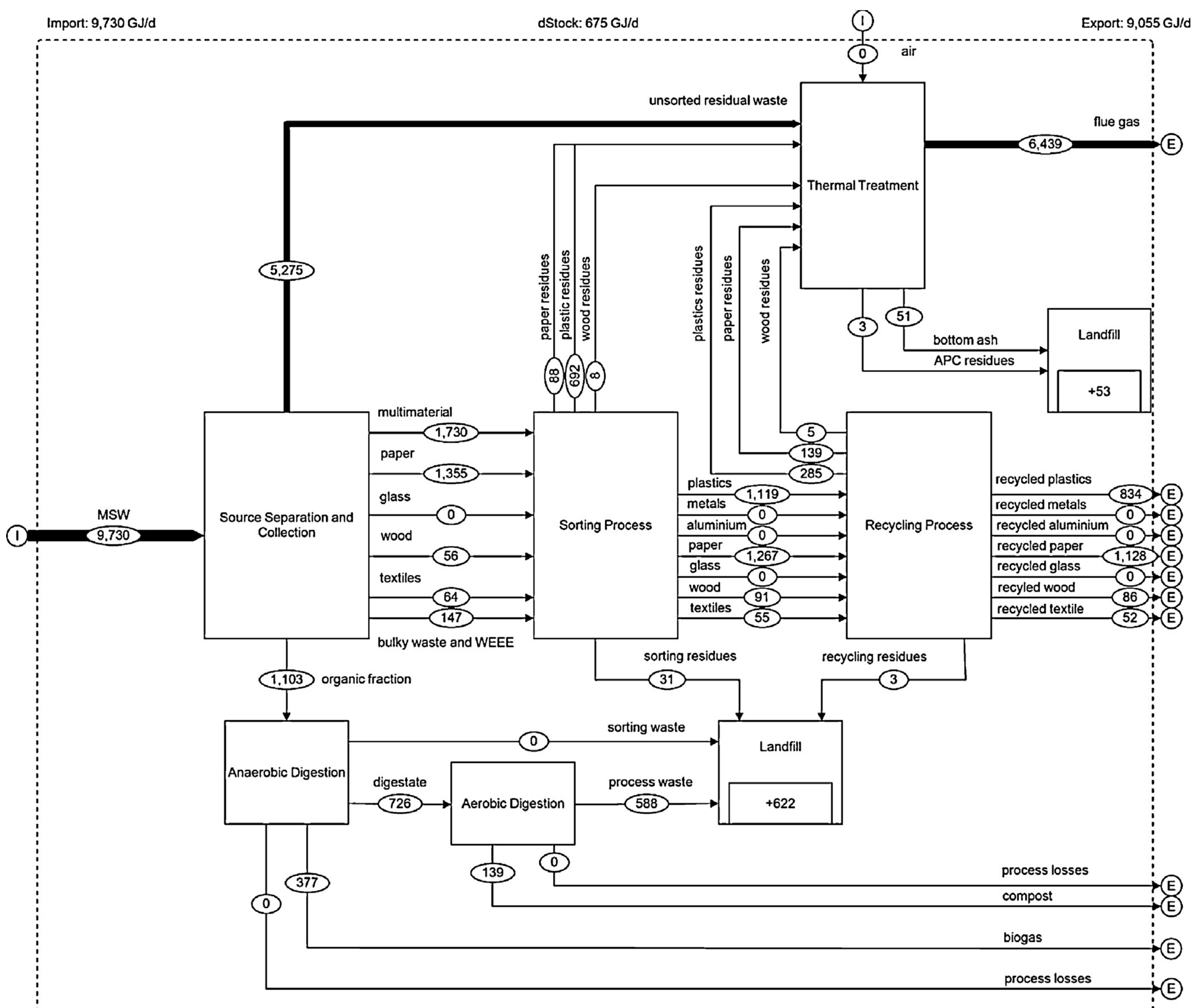

Fig. 10. Energy feedstock flow analysis of the waste management system for the scenario 50% of Source Separation Level, for a 1000 t/d MSW production. All the data are reported in GJ/d (I: import flow; E: export flow dStock: amount of accumulated material).

inorganic carbon in incineration residues to be landfilled is limited. This confers various benefits. The amount of greenhouse gas is reduced through high recycling rates (which in turn depend on the SSL and the best practices of separate collection and recycling processes): the carbon that is reutilized in the form of compost (from integrated biological treatment), polymers (from the plastic recycling chain) and cellulose (from the paper recycling chain) is not landfilled and will not contribute to greenhouse gases. The energy produced by thermal treatment and, to a lesser extent, by the AD process, replaces other energy sources, thereby reducing related environmental burdens (Clift et al., 2000; McDougall et al., 2001). Moreover, about half of the energy produced by WtE and AD plants derives from non-fossil materials and therefore does not contribute to climate change. With reference to hazardous organic carbon compounds, the WtE process is able to degrade them in a controlled way (i.e. in a plant equipped with an advanced APC system), while during landfilling and biological treatment most of these substances are released into the environment (Kellner et al., 2011).

The feedstock energy analysis layer reported in Fig. 10 shows that only 6.9% of chemical energy entering with MSW is wasted while 70.1% is available for power and heat generation and the remaining 23% is stored in the recycled materials. The data related to all the scenarios, reported in Table 4, confirm this positive aspect. It is also evident that the amount of feedstock energy converted to electric and thermal energy decreases (from 78.1% to 62.1%) when SSL increases from 35% to 65%, due to the reduced flow rates of URW; correspondingly, the feedstock energy lost in landfill increases, as a consequence of the larger amounts of sorting and recycling residues.

Data in Tables 4 and 5 allow the scenario evaluation to be extended also to volume, cadmium and lead. First of all, the amount of material sent back to the process industry, i.e. effectively recovered, is about half of that separated and collected at source (Table 4). The amounts recovered include the compost produced by the integrated digestion plants and are equal to 19.0%, 23.9% and 31.2% for SSL 35%, SSL 50%, and SSL 65%, respectively. Moreover, for higher SSLs, a larger volume of waste has to be sent to landfill ($11.2\%_{\mathrm{enteringMSW}}$ instead of $10.0\%_{\mathrm{enteringMSW}}$ and $8.3\%_{\mathrm{enteringMSW}}$), since the higher amounts of residues generated from the recycling chains and from biological treatments are not balanced by the lower amounts generated from thermal treatments (Table 4). This consideration applies (Table 5) also to cadmium and lead. Importantly, the Cd sent to landfill from the sorting and recycling chain increases from $8.9\%_{\mathrm{inputCd}}$ to $25.1\%_{\mathrm{inputCd}}$ when the SSL increases from 35% to 65% and, correspondingly, the Pb sent to landfill from the sorting and recycling chain increases from $5.5\%_{\mathrm{inputPb}}$ to $14.5\%_{\mathrm{inputPb}}$. There is also a similar increase in the amount of these toxic substances in the totality of recycled products, as a direct consequence of the larger amounts of waste that are sent to the recycling chain. It is worth pointing out that, when higher SSLs and recycling rates have to obtained, long-lasting non-packaging plastic waste has to be included in the recyclable fractions. These materials are typically stabilized with metals, such as lead and cadmium but also zinc, antimony, PCBs, PBDEs, in order to fulfill their functions over a certain lifetime (Schlummer et al., 2007). Over time the recycling of waste containing these hazardous substances could lead to new material stocks that, in turn, could generate not only risks for its users but also problems for future waste management as a consequence of successive accumulations (Brunner, 2009). Thus, it appears crucial that waste management systems must take due measures to allow for the potentially high growth of such additives. The results and considerations reported above, together with the complex logistics and high cost necessary to collect materials with high interception levels (Giugliano et al., 2011; Massarutto et al., 2011), indicate

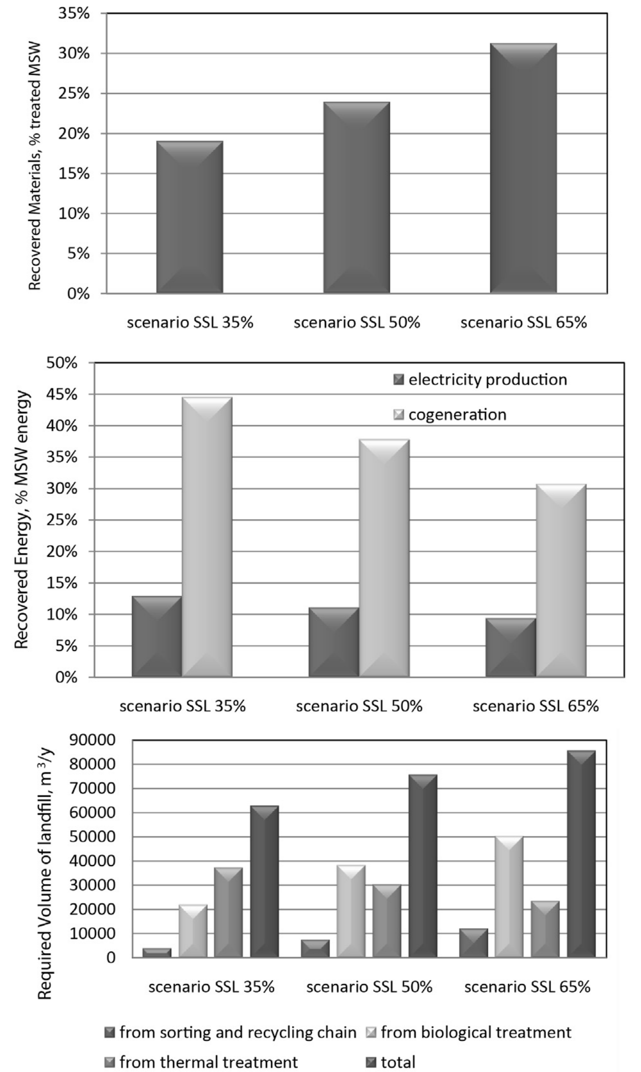

Fig. 11. Recovered materials, recovered energy and required landfill volume for the scenarios 35%, 50% and 65% of source separation levels.

that levels of source separation and collection as high as 65% could have a limited sustainability. A great innovation and improvement in the recycling technology of each waste fraction (for instance, to obtain an efficient separation of toxic additives) appears to be the real challenge for the near future, with a view to maintaining or, better, to improving the environmental sustainability of recycling.

In order to make it easier to compare the three scenarios proposed, and thus the quality of the technical input provided for the WM decision-making process, Fig. 11 shows the results in terms of recovered resources (materials and energy) and required volume of landfill. SSL 35% maximizes energy recovery (126 GWh/y for power generation, 439 GWh/y in cogeneration) but has lower amounts of recycled products (69 kt/y). By contrast, SSL 65% represents the maximum source separation and collection effort, permitting larger amounts of recovered materials (114 kt/y) but limiting energy recovery (92 GWh/y for power generation, 303 GWh/y in cogeneration). The implementation of a high quality source separation and collection system, together with the availability of up-to-date plants for biological and thermal treatments, strongly reduces the need of landfill volumes. Anyway, there is a slightly higher requirement for landfill volume in the SSL 65% scenario ($234\,\mathrm{m}^3$/d, i.e.

36.1% more than that for SSL 35%), due to the necessity of disposing the increased residues from the recycling chain (186% more than in SSL 35%) and from biological treatment (128% more than in SSL 35%).

4. Conclusions

A waste management planning was developed on the basis of an extensive utilization of material and substance flow analysis, taking into account a series of life cycle assessment studies on waste management systems and specific technological options. The approach appears able to compare alternative waste management technologies and scenarios, even though the results obtainable are just part of the input data to the decision-making process, which should further take into account a variety of economic and social aspects. Future work will investigate the possibility to complete the set of input data for the scenarios selected and assessed by the proposed approach. A Life Cycle Assessment, able to include the main social implications, and a Life Cycle Costing, carried out in a welfare economy perspective, could be adequate tools for this aim.

The study quantified the benefits afforded by the application of high-quality household source separation and collection, biological treatment of the organic fraction from this separate collection, and thermal treatment of unsorted residual waste. Landfill volumes and greenhouse gas emissions are minimized, toxic organic materials are mineralized, heavy metals are concentrated in a small fraction of the total former MSW volume, and accumulation of atmophilic metals in the APC residue allows new recycling schemes to be designed for metals. An efficient household source separation level (i.e. 50% or more) works as a pre-sorting stage for MSW, preparing it for the different material and energy recovery chains. As a consequence, the resulting unsorted residual waste contains too limited an amount of both dry recyclable waste (to be sent to material recovery) and wet organic waste (to be sent to biological stabilization) to make the choice of an MBT sustainable. Moreover, the contamination level of the wet fraction produced by the MBT plant is usually so high that the "stabilized" organic fraction cannot be used for any purpose other than landfill cover.

A significant reduction in the requirement of landfill volume can only be achieved by sending the unsorted waste, which is residual from source separation and collection, to a waste-to-energy process. As regards greenhouse gas emissions, the scenarios with high energy recovery provide more benefits, since they allow full utilization of the energy produced by carbon oxidation. On the other hand, landfills of residues from thermal treatments do not emit any greenhouse gases. Moreover, the combination of high recycling rates and efficient thermal and biological treatment means that inorganic materials are mainly concentrated in the residues of WtE plants while the hazardous organic compounds are completely destroyed.

The reported results and considerations also suggest that the maximum level of source separation and collection should be defined on the basis of the overall sustainability, and then also on basis of the quantities of sorting and recycling residues, complexity and cost of logistics to obtain very high interception levels, and the amounts of toxic substances that could be present in the recycled products. This means that very high levels of separate collection could ensure the desired sustainability only with considerable improvements in sorting and recycling technologies, which should become also able to separate toxic additives (such as cadmium, lead, zinc, antimony, but also PCBs, PBDEs, etc.) from materials of value, thereby preventing their accumulation in recycled products.

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