Resources, Conservation and Recycling 85 (2014) 54–66

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

A waste management planning based on substance flow analysis

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ARTICLE INFO

Article history:
Received 2 November 2012
Received in revised form 13 May 2013
Accepted 17 May 2013

Keywords:
Waste management planning
Substance flow analysis
Household separation
Separate collection
Recycling

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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http://dx.doi.org/10.1016/j.resconrec.2013.05.008

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