Scenarios of Waste Management for a Waste Emergency Area

A Substance Flow Analysis

Maria Laura Mastellone, Paul H. Brunner, and Umberto Arena

Keywords:

incineration
industrial ecology
material flow analysis (MFA)
mechanical-biological treatment (MBT)
municipal solid waste (MSW)
recycling

Summary

In the Campania region, an area in the south of Italy with 5.7 million inhabitants and a production of about 7,900 tonnes of municipal solid waste per day, an emergency situation was created by inappropriate waste management policy and practice. In order to support decisions regarding future solutions for this crisis, reliable, transparent, and impartial strategies and concepts are needed. For this purpose, six waste management scenarios have been defined and quantitatively assessed by means of substance flow analysis (SFA). The scenarios are based on firm objectives and recent legislation for waste management and take into account regional waste production and composition as well as existing waste treatment infrastructure. They are evaluated and compared with the status quo in view of reaching the goals of waste management. For each scenario, the following material flows were quantified: wastes that would be sent to different processes, such as those of mechanical-biological treatment, incineration, or anaerobic digestion; treatment residues (in mass and volume) to be diverted to landfills; materials recoverable by recycling processes; and energy obtainable by waste-to-energy and anaerobic digestion plants. The results demonstrate that a future waste management system that is based on a combination of more recycling, thermal treatment, anaerobic digestion, and improved landfilling reaches the objectives of waste management much more closely than the present, inadequate system.

Address correspondence to:
Umberto Arena
Department of Environmental Sciences
Second University of Naples
Via Antonio Vivaldi, 43
81100 Caserta, Italy
umberto.arena@unina2.it

DOI: 10.1111/j.1530-9290.2009.00155.x

Volume 13, Number 5

Introduction and Framework

The European Commission (EC) recently took legal action against Italy over the dramatic waste crisis that has plagued Naples and the Campania region for more than ten years, and the last year in particular (EC 2008). The EC said: "The piles of uncollected rubbish in the streets of Campania visually illustrate the threat to the environment and human health that results when waste management is inadequate" (EC 2008). During the spring of 2007, waste was left uncollected for weeks, forcing the closure of schools for health reasons and leading residents to set fire to refuse bags piled up in the streets. The uncollected waste and open fires "posed serious health and environmental risks through the spread of disease and pollution of air, water and land." This situation repeated itself at the end of December 2007, and the Commission takes the view that measures being taken by the Waste Emergency Commissioner of the Italian Government are inadequate to address Campania's waste problems in the long term and prevent a repeat of the unacceptable events seen over the past year. Political and scientific analyses of the waste crisis indicate that the emergency situation was created by inappropriate waste management policy and practice (Commissione Parlamentare 2007). Waste management decisions must take into account multiple sets of criteria from the fields of social as well as natural and engineering science; the crisis in Campania is the result of failures in all of these areas.

This study aims to provide scientific support to the decision makers who are managing the waste crisis. It focuses on natural and engineering science criteria only and does not cover social science issues. It investigates and suggests future strategic and conceptual directions and draws conclusions regarding the effectiveness of a new waste management system in view of the objectives of waste management. The boundary conditions of the study are as follows: the production of municipal solid waste in Campania in the year 2006 (about 7,900 tonnes/day [t/d] in an area of about 13,600 square kilometers [km^2] with 5.7 million inhabitants)[1] and the existing waste management structures; the objectives of waste management from a general point of view; and the European and, in particular, Italian legislation.

Objectives of Waste Management

The main purpose of waste management is to supply a service, specifically to remove waste from the human habitat to ensure hygienic living conditions. This very basic task, which was the main aim of waste management in the developed world until the end of the 19th century and still is in many developing countries, was attained in Europe with the introduction of modern sanitation practices. Today, waste management meets hygienic requirements so well and as a matter of course that the public does not perceive the need for this service except in emergencies. In parallel with increasing production and consumption, the growing need and role for waste management as a "filter" between human activities and the environment became apparent, resulting in the development of safe and reliable technologies such as modern collection systems, incinerators, and sanitary landfills. In addition, recycling was introduced and soon became recognized as a means to reduce the exploitation of primary resources and thus to reduce pollution created by mining and ore processing.

With today's goal-oriented waste management, it is important to start with a consensus on objectives. In particular, if several options for waste management are evaluated for a region, it is indispensable to have shared goals as a common denominator. To assess the options chosen, evaluation criteria must be selected. The basis for selecting these criteria lies in the waste management objectives, as defined in the waste management policy of the European Union and, in particular, of Italy. To ensure full respect of the main principles enshrined in the European Union Waste Framework Directive (that of *Environmental Action* and that of *Sustainable Development*), the various implementation forms and phases of waste management planning must do the following:

- ensure conservation of nature and resources by reducing the production of waste as well

as providing their proper treatment and disposal;
- ensure a reduction in the impact that waste management has on health and the environment, also by reducing at source the hazardousness of generated waste;
- ensure that waste is properly packaged, labeled, and handled during the phases of collection, transport, temporary storage, treatment, and definitive disposal;
- ensure suitable infrastructures for efficient treatment of the various types of solid waste (municipal and industrial) produced in the region to achieve regional self-sufficiency in terms of safe treatment and disposal;
- ensure the traceability of waste, from its production, through the transport phase up to its definitive disposal;
- ensure continuous, transparent, and reliable monitoring of plants used in waste treatment and disposal, hence including landfill sites, with regard to both the administration and procedures for waste acceptance and delivery to the plants as well as the measurement and control of all the main parameters concerned in the various environmental sectors.

Accordingly, the following objectives have been used as a basis for developing a strategy for sustainable waste management in the Campania region: (1) protection of human health and the environment; (2) conservation of resources such as materials, energy, and space; (3) aftercare-free waste management, meaning that neither landfills nor incineration, recycling, or other treatments should leave problems to be solved by future generations. The following particulars about these objectives are noteworthy.

First, these objectives do not include prevention or recycling, which are measures taken and not end goals; they are instrumental for reaching the objectives but should not be mixed up with goals. The so-called waste hierarchy—"prevention," "recycling," and "disposal"—which is often used as the underlying principle for waste management decisions, seeks to prioritize prevention before recycling and disposal. Although it could be argued that this principle does not always lead to the most cost-effective waste management system, the waste hierarchy has been taken into account as a guiding principle: It is assumed that in the region all possible measures are taken to prevent waste production, and that because of the increasing effect of prevention measures, the waste amount stays constant despite the growth in waste generation observed in the last years. Regarding recycling, two sets of scenarios with different separate collection rates are taken into account.[2] According to Italian legislation (G.U. 2006), 65% of waste is to be obtained by separate collection by the end of year 2012. Because it is not clear yet whether the increase from the present 11.3% to the future hypothetic 65% of the separate collection rate can be achieved in Campania within the time frame of the next few years, two scenarios, with separate collection rates of 25% and 35%, respectively, also were investigated.

Second, because the objectives *protection of human health and the environment* and *conservation of resources* both depend on the content of certain substances in waste, a substance-oriented approach is necessary. Waste management and treatment cannot focus on the level of wastes as products only. It is indispensable to address the levels of substances (chemical elements and chemical compounds) contained in waste, too. The reason is that these substances determine whether a waste has a resource potential or whether it constitutes hazardous material. It is the content, for example, of cadmium as a stabilizer in plastics that determines whether or not plastic waste can be recycled, and it is the copper content in the bottom ash of an incinerator that determines whether this bottom ash can be landfilled directly, or whether it has to be treated before landfilling. Thus, it is important to have sufficient information about the composition of waste and to know what happens with waste and its constituents when it undergoes treatment. To assess whether the goals are reached by a certain waste management system, a comprehensive material flow analysis (MFA) is needed that covers waste flows, chemical composition of waste, and transfer coefficients of waste treatment processes.

Third, the *aftercare-free waste management* objective has severe implications on landfilling and recycling: According to recent findings, today's landfills require leachate treatment, monitoring, and control for several centuries (Belevi & Baccini 1989). The main reason is the large fraction of biodegradable constituents in waste resulting in high nitrogen and organic carbon loads of landfill leachates. If waste is incinerated, this organic fraction (OF) is mineralized, yielding hygienic bottom ash that does not contain any degradable organic matter. However, because this incineration residue may still leach inorganic salts and metals, bottom ash has to be treated to fulfill the objectives. For recycling, the *aftercare-free waste management* objective requires "clean cycles." Hazardous substances have to be eliminated from cycles when waste is recycled into new products, and the eliminated hazardous substances need to be disposed of in safe final sinks. Thus, this third objective of sustainable waste management implies that materials in waste are either directed toward clean cycles or that they are eliminated and directed toward safe final sinks.

The Existing Waste Management System in Campania

The overall production of municipal solid waste (MSW) in Campania in 2006, as estimated by the official Italian authority, was about 2,880,000 tonnes (i.e., 500 kilograms per inhabitant per year [kg/inh*year]; APAT 2007).[3] (Table 1 gives explanations of various abbreviations used throughout this article.) The production of 7,891 tonnes per day is subdivided into the following: 6,917 t/d of mixed collection sent to treatment and disposal; 81 t/d of bulky waste sent to disposal, and 893 t/d of separate collection (i.e., 11.3% of the total production) sent to recycling. At present, the system of municipal waste treatment and disposal in Campania is organized as follows: seven mechanical and biological treatment (MBT) plants, for a total treatment capacity of about 7,700 t/d; some landfills; a number of storage platforms, situated in more than 50 different sites, where about 6 million tonnes of refuse-derived fuel (RDF; known as waste bales or *ecoballe*) obtained as almost dry fraction of MSW by mechanical-biological treatment plants are stored; a series of sites for shipment and storage such as transshipment areas, and municipal and intermunicipal storage sites; provisional storage sites authorized during the years under the special commissioner to get through the various "critical phases"; and the plants belonging to the chain of separate collection (platforms of collection and temporary storage of separated collection materials, sorting platforms, some plants for composting and some plants for end-use packaging reprocessing).

Table 1 List of abbreviations

APC	air pollution control
DM	dry matter
LCA	life cycle analysis
MBT	mechanical and biological treatment
MFA	material flow analysis
MSW	municipal solid waste
OF	organic fraction
RDF	refuse-derived fuel
SFA	substance flow analysis
SOF	stabilized organic fraction
VS	volatile solids
WEEE	waste of electric and electronic equipment
WTE	waste-to-energy

Continual reports expose the chronic lack of available space in active landfills, and new space in those being established is long awaited. Likewise, attention is drawn by the difficulty in finding other storage sites for placing ecoballe while waiting for it to be used as fuel in heat-recovery plants by direct combustion. The critical nature of the situation that has led to the crisis in Campania may be attributed, besides social factors, to the following technical factors:

1. The nominal treatment capacity of MBT plants is very close to the production of nonseparated waste. This means that any interruption in service of any of the seven existing plants (due to ordinary or extraordinary maintenance or other causes) may lead to the collapse of the system and the impossibility of disposing of daily waste production.
2. Also in the presence of hoped-for but unlikely service without interruption and running at full capacity, the experience of recent years shows that MBT plants generate two low-quality products: (1)

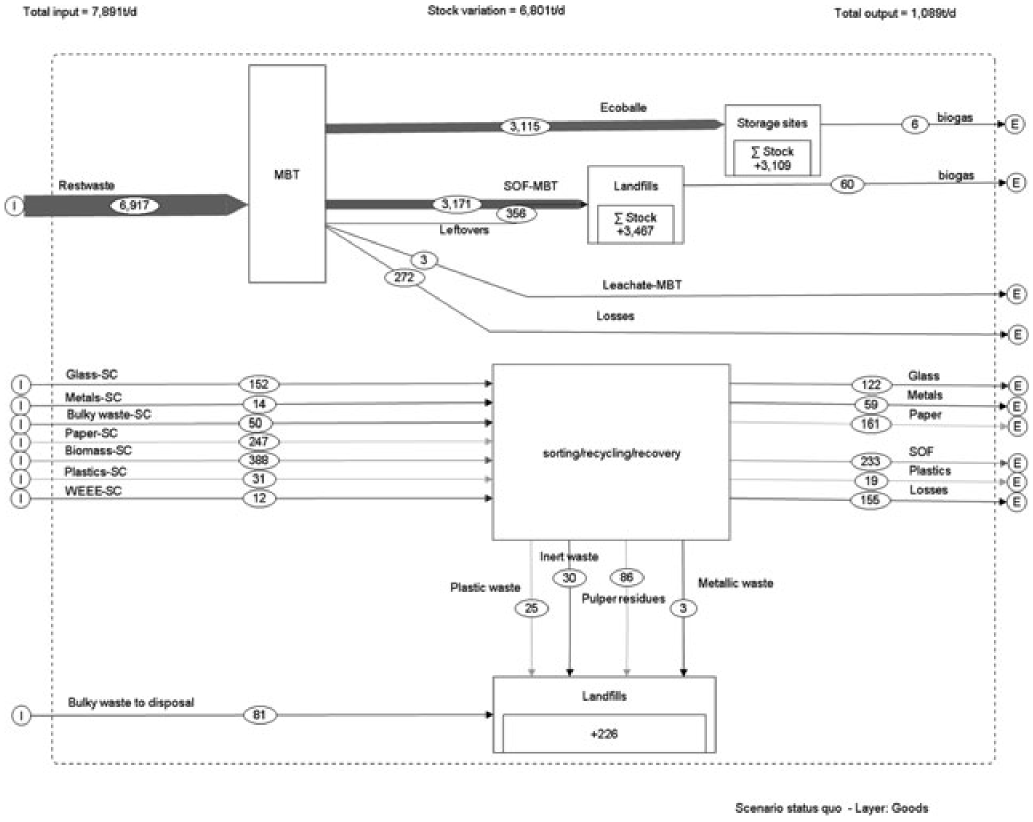

Figure 1 Mass balance for Status Quo scenario. Layer "mass of waste". t/d = tonnes per day.

material that has been downgraded from refuse-derived fuel (European Waste Catalogue [EWC] 191210) to dry fraction (EWC 191212); and (2) material that has been downgraded from stabilized organic fraction (EWC 190503) to humid fraction (EWC 190501).

3. For both of these materials, there are no processes in Campania for materials or energy recovery, and provision is made for more or less definitive storage: The humid fraction is diverted to landfills while the dry fraction is sent to storage sites. This has led to a desperate and continuous search for new landfill sites or storage areas, resulting in well-known difficulties of finding suitable legally approved sites and with constant protests on the part of the concerned population.
4. Separate collection fractions are not 100% recyclable. Thus, when such fractions are recycled, a nonnegligible quantity of residues is produced, which must be diverted to landfill. In some cases, this amount reaches up to 50% of the separately collected fraction.
5. The considerations above indicate that storage sites and landfills are required with a capacity of more than 85% of the quantity produced daily.
6. Moreover, today, nearly all hazardous organic and inorganic substances are landfilled and stored with unknown future consequences; this does not comply with the goal of *aftercare-free landfills*.

Figure 1 reports a sketch of the existing facilities together with an overall mass balance of the current situation (Status Quo). The emergencies occurring during the last 12 years indicate that all the goals of waste management are not being reached in Campania today. The current management system is unsustainable because it lacks basic components and has serious shortcomings in the components that it *does* have. In particular:

- separate collection is not widespread and makes up too small a proportion of overall waste production;
- no waste-to-energy (WTE) plants exist to which to send the residual dry fractions from separate collection;
- a lack of biological treatment plants exists. This forces the municipalities that achieve high percentages of separate collection of the organic fraction to export it to other regions at high cost;
- the ongoing emergency actually prevents landfill design and management according to principles and standards established by the European Waste Directive. This hampers the building up of confidence by citizens who are looking for transparent sound management of landfill sites observing criteria of efficiency and good management;
- communication and information to citizens is lacking both in quantity and quality and, when present, rarely occurs with advance notice. This contributes to strengthening across-the-board opposition, which also is intensified by inaccurate or partial news.

The last two aspects touch the social side of the waste emergency in Campania: the lack of acceptance for today's situation, the long-lasting complaints due to odor, air, and soil pollution and bad management, the broken promises of changing the present situation. Even though they are not discussed here, it is evident that these aspects are of high and crucial importance.

Alternatives for the Future

Criteria for the Definition of a New Waste Management System

To fulfill the objectives of waste management as defined above, it is necessary to (1) prevent waste by mass, volume, and hazardous composition; (2) recycle as much of the waste fractions as is economically feasible and ecologically beneficial; (3) completely mineralize organic substances contained in nonrecycled waste to avoid landfill aftercare; (4) immobilize the constituents of the residues of mineralization; and (5) dispose of immobilized residues in appropriate sinks, that is, geological formations where the residues do not require aftercare. Thus, a new waste management system has to be developed for Campania that takes all five of these aspects into account. As a procedure for designing and selecting this new system, scenario analysis is chosen for this study: based on the boundary conditions recalled above (such as type and amount of waste, collection logistics, waste treatment facilities, and landfills), and on the requirements set by the objectives given above, scenarios for waste management are developed. The scenarios have been defined in accordance with the following criteria:

1. Use of landfilling is minimized, and it is ensured that no waste that is not biologically inert or that contains mobilizable hazardous substances is landfilled.
2. Operations are minimized that entail excessive consumption of raw materials and energy without yielding a real overall environmental advantage. Approaches such as those of substance flow analysis (SFA) and life cycle analysis (LCA) are generally considered valid tools to ensure proper examination of the management scenarios (Clift et al. 2000; Döberl et al. 2002; Arena et al. 2003; EC-IPPC 2006a).
3. Recovery of materials is maximized, albeit in accordance to the principles laid down in the previous point.
4. Energy recovery is maximized, given that, in a life cycle approach, energy recovery from waste allows decreasing consumption of fossil fuels and overall emissions from all energy conversion systems (Clift et al. 2000; McDougall et al. 2001). Energy recovery using thermal treatments (combustion, gasification and pyrolysis) affords a further fundamental benefit, namely that of being able to separate inorganic components (metals such as iron, cadmium, lead, and nonmetals such as chlorine, bromine, etc.) from the organic fraction (consisting of carbon, hydrogen, and oxygen),

> allowing reuse or inertization and thereby preventing dispersion and accumulation of hazardous constituents in the environment or in recycled products reaching hazardous concentrations.

The scenarios also take into account goal-oriented waste management systems that are operating successfully elsewhere in Italy and in Europe (Döberl et al. 2002). They include only technologies that have been fully tried and tested, that are state-of-the-art and have already proven high reliability and dependability, with known total costs for treatment and aftercare (EC-IPPC 2006a; 2006b). In particular, anaerobic digestion is considered the best available technology for biological treatments, for a series of reasons: the minimization of greenhouse gas emissions, the stabilization of the organic fraction, the energy recovery obtainable from the produced biogas, the absence of emissions of bio-aerosols and bad odors, the limited occupancy of land surface, and the economic sustainability.

The Defined Scenarios of Waste Management

Two sets of municipal waste management scenarios have been defined and indicated as scenarios A and B. In scenarios A and B, wastes are separately collected with the objective of separating as far as possible the organic fraction suited for biological treatment. Plastic, paper, metals, hazardous urban waste, bulky waste, and electric and electronic waste (WEEE) also are separately collected. They differ only in the combination of treatments of restwaste, that is, all of the household waste collected in a completely mixed state: mechanical-biological treatment, incineration, and landfilling for scenarios A; incineration and landfilling for scenarios B. Each set is further divided into three scenarios that differ only in the percentage of waste collected separately. This percentage may be easily changed, inserting more appropriate values into the calculation model developed by using the STAN software (Cencic & Rechberger 2008).[4]

Scenarios A were defined in view of optimizing the waste management that was set up by the Campania region in 1997 (BURC 1997). Scenarios A differ from Status Quo insofar as

1. the amount of waste separately collected is considerably higher than in the Status Quo (25% in A-1, 35% in A-2, and 65% in A-3 versus 11.3% in Status Quo);
2. the separately collected biomass is treated in anaerobic digestion plants;
3. the MBT plants work according to design. They produce two main output streams: The first is made up of an RDF sent to a WTE plant, and the second is a well-stabilized organic fraction that is sent to landfill to be used as cover material;
4. wastes generated by the recycling chain of paper and plastics are incinerated; and
5. the residues from anaerobic digestion of separately collected biomass are assumed to be used as compost or material for remediation of contaminated sites.

The restwaste is thus sent to the mechanical-biological treatment plant, which produces a fraction of refuse-derived fuel, an organic fraction stabilized by aerobic digestion (stabilized organic fraction, or SOF), and a waste fraction consisting of sludges, leachate, and nonrecyclable metals. RDF is delivered for energy recovery in a water-cooled grate furnace; SOF is diverted to landfill. With regard to the separate waste recovery/recycling process, it is known that the chains (sorting + reprocessing) of recycling paper, plastic, metals, WEEE, and bulky waste and that of recovering the organic fraction have different efficiencies (Weitz et al. 1999; McDougall et al. 2001; Arena et al. 2003, 2004; Perugini et al. 2005). Hence, each of these produces a waste flow for landfill disposal that could in part be incinerated, as it consists of some combustible fractions (nonrecyclable plastics, pulper waste, and SOF from anaerobic digestion plants for the separately collected putrescible organic fraction). It has been assumed that only wastes from paper and plastics recycling are incinerated together with RDF.

The three percentages of separate collection rates in scenarios A (and B) are to be considered average among those that can actually be obtained for each waste fraction (table 2). Provided that the necessary collection and storage logistics

Table 2 Input data (in italics) and obtained data for the Status Quo and alternative scenarios of waste management

	Biomass	*Paper*	*Glass*	*Plastics*	*Metals*	*Aluminum*	*Wood*	*Other*	*Total*
Production of MSW, t/d	*2236*	*1959*	*519*	*1178*	*157*	*183*	*122*	*1538*	*7891*
Composition of MSW, %	28	25	7	15	2	2	2	19	100
Scenario Status Quo									
Fraction of separate collection, %	14	13	29	3	9	*	54	3	11
Separate collection t/d	*321*	*247*	*152*	*31*	*14*	*	66	63	*893*
Mixed collection (restwaste), t/d	1915	1712	367	1147	143	183	56	1475	6998
Composition of separate collection, %	36	28	17	3	2	*	7	7	100
Composition of restwaste, %	27	24	5	16	2	3	1	21	100
Scenarios A-1, B-1									
Fraction of separate collection, %	*40*	*30*	*30*	*15*	*15*	*15*	*15*	*8*	*25*
Separate collection, t/d	895	588	156	177	23	28	18	123	2007
Mixed collection (restwaste), t/d	1342	1371	363	1001	133	156	103	1415	5884
Composition of separate collection, %	45	29	8	9	1	1	1	6	100
Composition of restwaste, %	23	23	6	17	2	3	2	24	100
Scenarios A-2, B-2									
Fraction of separate collection, %	*50*	*40*	*35*	*30*	*30*	*30*	*15*	*15*	*35*
Separate collection, t/d	1118	784	182	353	47	55	18	231	2787
Mixed collection (restwaste), t/d	1118	1175	337	824	110	128	103	1307	5104
Composition of separate collection, %	40	28	7	13	2	2	1	8	100
Composition of restwaste, %	22	23	7	16	2	3	2	26	100
Scenarios A-3, B-3									
Fraction of separate collection, %	*70*	*70*	*70*	*50*	*50*	*50*	*50*	*65*	*65*
Separate collection, t/d	1565	1371	363	589	78	92	61	1000	5119
Mixed collection (restwaste), t/d	671	588	156	589	78	92	61	538	2772
Composition of separate collection,%	31	27	7	12	2	2	1	20	100
Composition of restwaste,%	24	21	6	21	3	3	2	19	100

Note: Data for aluminum in Status Quo are included in "metals". t/d = tonnes per day.

are set up, it is possible to considerably increase the separate collection percentage of paper, glass, and the organic fraction. Fractions with low density (plastics) or little abundance (metals) will be more of a challenge to collect at high rates. These considerations are more important for scenario A-3. It assumes an average recycling rate of 65% as mandated by Italian law to be reached before the end of 2012. This high recycling rate is not likely to be realized and demands that more than 50% of plastics, metals, and "other," including bulky wastes and WEEE, are collected separately (table 2).

By contrast, scenarios B propose significant simplification in waste management and a major reduction in economic and social costs because the restwaste is incinerated without prior mechanical-biological treatment. Thus, in scenarios B the items 1 through 2 and 4 through 5 are the same as those assumed for scenarios A. Scenarios B differ from scenarios A insofar as

3. the mixed collected waste ("restwaste") is directly incinerated; no MBT plants are considered.

This choice implies some interesting advantages, such as (1) elimination of recourse to plants, which should be modernized and which do not actually allow any recovery of materials nor real decreases in mass, volume, or hazardousness of waste; and (2) the technology of water-cooled moving grate furnace that has already been chosen for the incinerators planned in the region is the preferred technology to burn restwaste (Niessen 1995; Consonni et al. 2005a, 2005b; EC-IPPC 2006b); (3) this technology also is well suited to burn residues from the recycling/recovery chain, such as off-specification compost, the residues of anaerobic digestors, and some nonhazardous special waste. The combustion of waste without foregoing MBT produces more bottom ash and scrap metal because MBT removes such inert items. Because bottom ash will be landfilled as well as MBT residues, there is not much difference in terms of landfill volumes needed.

Scenario Evaluation

Criteria

An exemplary approach is chosen for evaluation: A few criteria are selected that are able to represent best the objectives of waste management. The first and most important question when selecting criteria is the following: which indicators describe best whether the goals of a certain waste management system are reached? The answer is goal-specific: For the objective *protection of human health and the environment*, hazardous materials such as heavy metals or persistent and toxic organic substances are appropriate indicators. Because it is not the mere presence of a substance that poses a hazard, it is important to follow the substance through the waste management system and to ascertain whether, along or at the end of this path, substances accumulate or have negative impacts on health and the environment. The mass balance principle as applied in MFA is instrumental in observing all substance flows and their accumulation or transformation in different compounds. For "protection of health and the environment," volume can be an important indicator as well, because waste transportation and land use for landfilling have impacts on the environment too. Carbon as a source of climate change also is relevant, particularly because various studies show that optimizing waste management can result in a considerable decrease in greenhouse gas emissions. Regarding the objective *conservation of resources*, energy and resources such as metals and biomass are important. In addition, volumes of waste and residues are critical in view of land being used as a resource. Also, a strong link exists between "conservation of resources" and "protection of health and the environment": Probably the greatest effect on environmental protection is caused by recycling, which replaces primary resources. Because mining and processing of ores are usually associated with the greatest environmental impacts within the whole life cycle of a material (McDougall et al. 2001), the replacement of primary ores with secondary resources from recycling has the potential to decrease total pollution markedly.

When selecting criteria and indicators, it is important to check for their overall relevance. Some materials are more important for waste management than others. For certain heavy metals such as mercury and cadmium, the ratio of mass flows in total municipal solid waste to mass flows in total national imports is comparatively high and reaches up to 50%. Thus, on a national scale, MSW is an important carrier of such hazardous substances such as cadmium and mercury (Brunner et al. 2004); hence, it is important to ensure that all waste collection, treatment, recycling, and disposal processes handle these heavy metals with care and either recycle them safely with a high recovery percentage or divert them to safe ultimate sinks. Conversely, elements such as nitrogen, phosphorous, and chlorine have a low percentage flowing through waste management (Baccini and Brunner 1991). Thus, from a national perspective, their importance in waste management is small in terms of both environmental protection and resource conservation. In consideration of the reasons given above, the following criteria were selected for evaluation: mass flow, volume, energy, carbon, and cadmium. The reasons for this selection are as follows:

Mass flows determine the amount and capacity of waste collection, treatment, and disposal facilities. Following the flows allows identification of the impact of changes in a waste management system on the various elements in the system: Additional recycling reduces not only the need for incineration capacity, but also for subsequent landfilling or "final disposal." Conversely, additional recycling results in new waste, namely the waste from recycling, which requires new treatment and disposal capacities. Only a mass flow approach takes into account all effects of a change in a waste treatment scenario and gives an overall picture of the total plant capacity needed.

Similarly, *volume* is crucial to consider for collection, treatment, and disposal. Especially because landfill space is scarce, and expanding landfills is often opposed by the public, volume is an important parameter for landfilling. Also, for transportation, volume is a crucial issue. Because the *energy content* of waste in general, and in particular certain waste fractions such as plastic and waste wood can be substantial, it is important to include energy as an evaluation criterion. In some waste treatment processes such as WTE plants, a high percentage of energy is recovered: if heat is the product utilized, recovery rates of 60% to 70% are observed; if electricity is the output, still 20% to 29% of the energy contained in waste can be recovered (Consonni et al. 2005a; EC-IPPC 2006b). Conversely, during composting, the energy content of waste is not recovered, and carbon is oxidized to carbon dioxide without utilizing the energy that is produced during this process. In contrast, anaerobic digestion of waste produces methane that is used as a fuel and thus allows some of the energy contained in waste to be recovered. *Carbon* is an indicator of resource potential (energy, biomass) as well as environmental hazard (greenhouse gas, persistent and toxic organic substances). To distinguish these aspects, it is usually necessary to know the different speciations of carbon. On the input side, it makes a great difference whether carbon consists of synthetic polymers (plastics) that are not easily degradable, of cellulose (paper and food waste), which *is* biodegradable and can be used in biochemical treatment to produce energy and materials, or of hazardous organic compounds that need to be specially treated. On the output side the main goal is to transform hazardous organic compounds to harmless substances such as CO_2. Other objectives, as stated above, are to produce energy while mineralizing carbon to CO_2. *Cadmium* is an indicator for toxic metals. As stated above, a large percentage of cadmium (used from the 1970s to the 1990s as an important additive in long-lasting plastic materials) flows through waste management. Thus it is a major hazardous element that has to be taken into account in every waste management evaluation. It serves to investigate whether a certain waste management system is able to concentrate this conservative (i.e., "nondestructible") element in a fraction where it cannot cause any harm to public health and the environment. Due to its chemical properties (low boiling point), it acts as an example for other atmophilic metals such as zinc, tin, and antimony.

The following important criteria are not considered in this work: Although *hygiene* is the most important aspect of waste management, it has not been included because all modern waste collection, treatment, and disposal systems fulfill the requirements set by sanitation. *Dioxin* emissions, which were major problems of thermal waste treatment processes in the past, are not investigated here because, since the 1990s, modern WTE plants are equipped with furnaces and air pollution control devices that minimize the emissions of dioxins to a negligible level far below other anthropogenic activities (Consonni et al. 2005b; Lonati et al. 2007). *Acidification* and *eutrophication* from sources such as agriculture and waste water management are orders of magnitude greater than those from waste management and have thus been neglected. The same is true for *ozone formation potential*, which is negligible when compared with other sources; stratospheric *ozone depletion potential* is in part discussed within the carbon flows. *Organic substances* are partly considered when the flow of carbon is discussed. *Metals* of value, such as copper, aluminum, and iron, are not included as criteria but are taken into account by the recycling rates. In summary, it can be stated that criteria have been selected that are exemplary for a number of other, similar criteria, and that they have been chosen in a way to ensure their relevance and sensitivity. Thus, it is concluded that the results received are robust with regards to the choice of criteria.

Data

To construct and quantify the reference scenario (Status Quo), and then the alternative scenarios for the future, it was necessary to acquire and draw up data on the per capita production of MSW, its material composition and the quantity of waste separated at source as well as the composition of waste flows produced by MBT plants (APAT 2007; ARPAC 2008). These input data together with all the calculated data for each waste type are reported in table 2 for the different scenarios.

Table 3 Composition of the municipal solid waste (MSW) organic fraction assumed as input to aerobic biological treatment

	Percentage, %	*Mass flow rate tonnes/day*
Organic fraction of municipal solid waste (OF_{MSW})		1,000
Proximate analysis,% wb		
Dry matter (DM/OF_{MSW})	73	
Volatile solids (VS/DM)	68	
Water	21	
Inerts	6	
Biomass/substrate yield coefficient ($Y_{X/S}$)	30	
Synthesized biomass		382.5
Water		210.0
Inerts		60.0
Gas losses (catabolism)		347.5
Stabilized organic fraction (SOF) composition		
Water	32	
Total solids	68	
VS/DM	40	
Inerts/DM	60	
Water		210.0
VS-SOF		177.0
i-SOF		265.0

Note: The SOF flow estimated in the table is that which is theoretically obtainable if the process is properly conducted, as assumed in the scenarios A. t/d = tonnes per day; wb = weight basis; VS/DM = volatile solids, as a fraction of DM; VS-SOF = volatile solids of the stabilized organic fraction (biodegradable fraction); i-SOF = inerts of the stabilized organic fraction (portion that is not biodegradable).

Aerobic Treatment of the Organic Fraction Separated Mechanically from MSW in MBT Plants

The organic fraction separated mechanically in MBT plants is aerobically treated in aerated tanks where biological stabilization takes place to obtain a SOF. In the present situation of plants in Campania, stabilization is inefficient and the output of the aerobic tanks has not been classified as SOF but as “a non-composted part of municipal waste and similar waste” identified with EWC 190501. To ensure (as in scenarios A) that these plants stabilize the biodegradable organic fraction separated by mechanical systems, the potential loss in weight must be estimated. During aerobic biological treatment the volatile part of organic waste is converted into microbial biomass and into metabolic waste products (gas losses). To be able to estimate the actual weight loss obtainable by aerobic treatment of this type, it is necessary to know the proximate waste analysis (i.e., subdivision into dry matter [DM], water, and inert material, and further subdivision of the dry fraction into volatile [VS] and nonvolatile solids) as well as to estimate the biomass/substrate yield coefficient ($Y_{X/S}$) to calculate what part of the volatile matter (i.e., the part that is actually biodegradable by micro-organisms) is converted into biomass (and contributes to the SOF) and what part is converted into metabolic waste gases. These data were obtained from literature (Dunn et al. 2003), processed and summarized in table 3. In particular, the SOF should be about 65% in mass of the original MSW organic fraction.

Anaerobic Treatment of the Separately Collected Organic Fraction

The organic fraction of waste may be anaerobically digested, thereby leading to a similar weight loss to that of aerobic digestion yet recovering methane at the same time. The process

Table 4 Input data and estimated data (in italics) for an anaerobic digestion process of organic fraction of municipal solid wastes

Organic fraction of municipal solid waste (OF_{MSW})	1,000 t/d
SOF/OF_{MSW}	50–60%
Biogas yield	150 m^3/t
Volumetric flow rate of produced biogas	*150,000 m^3/d*
Methane (CH_4) level	65%
Low heating value of biogas	6.24 kWh/m^3
Total energy	*936 MWh/d*
Thermal performance	25%
Thermal energy produced	*234 MWh/d*
Electrical performance	40%
Electrical energy (EE) produced	*374 MWh/d*
EE self-consumption	5%
Electrical energy to the grid	*356 MWh/d*
Power	*14.8 MWe*

Note: SOF = stabilized organic fraction. t/d = tonnes per day; m^3/t = cubic meters per tonne; m^3/d = cubic meters per day; kWh/m^3 = kilowatt-hours per cubic meter; MWh/d = megawatt-hours per day; MWe = megawatt electrical.

is economically feasible and allows the organic fraction to be pre-stabilized without emitting any odor or pathogenic micro-organisms to the atmosphere. Table 4 reports the estimates of such a process of efficient and commercially mature technology. It allows stabilization of the MSW organic fraction and at the same time produces thermal and electric energy. The data used were obtained from the literature and from theoretical calculations (Dunn et al. 2003).

Landfill

A landfill, if appropriately managed with the interlay of cover materials, acts as an anaerobic digester. Some of the methane is dispersed into the atmosphere, and the biochemical process is much slower than in a biogas plant (McDougall et al. 2001; Arena et al. 2003). Conversion efficiencies to biogas and, especially, conversion kinetics are different and require new calculations. In particular, when discussing landfills one must consider a different time scale than for any industrial reactor: Biogas is emitted from landfills for decades even after the closure of the landfill; in small amounts, landfill gas will emanate for centuries (see figure 2). As landfills are an indispensable element of any management scenario, the data listed in table 5 attribute annual or daily biogas emissions to the unit mass of biodegradable waste. These estimates were made by using a simplified first-order biochemical model, which can provide an indication of biogas emitted by a landfill according to the fraction of biodegradable material that it contains (Cossu et al. 1996). The quantity of biogas emitted by the MSW organic fraction in a landfill is calculated as 0.057 tonnes of gas per tonne of waste landfilled.

In a landfill, not only biogas is produced but also percolate or leachate that contains different organic and inorganic compounds. The percolate must be adequately collected and treated in a waste water treatment plant, equipped with both chemical-physical and biological systems, in order to avoid a potential contamination of the hydrosphere and the soil (Woodard and Curran 2006). The estimate of the daily

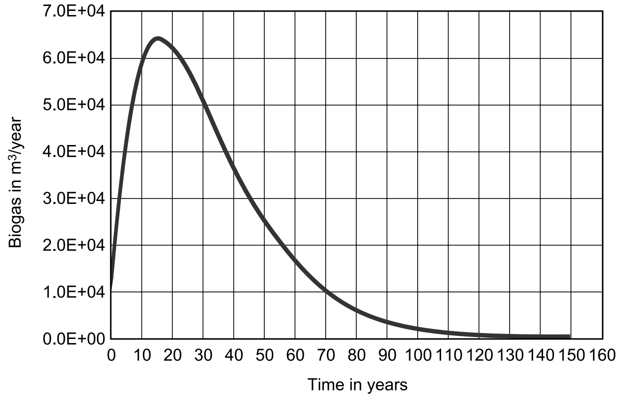

Figure 2 Time trend of biogas production for a landfill with a ten-year lifetime and a quantity of biodegradable waste of 1,000 tonnes per year. m^3/year = cubic meters per year.

Table 5 Input and output data of the biochemical biogas production model

Quantity of landfilled municipal solid waste organic fraction	1,000 t/year
Current time	1 year
Closure time	10 years
K (kinetic parameter)	0.06 1/year
L (kinetic parameter)	90 m^3/t
Quantity of biogas at the current time	9,300 m^3/year
Produced biogas	
Total volume production for 150 years	2,890,000 m^3
Average for 150 years	19,300 m^3/year
Average for 50 years	46,900 m^3/year
Average for 50 years	128 m^3/day
Total mass production for 150 years	3,550 t
Average for 150 years	24 t/year
Average for 50 years	57 t/year
Average for 50 years	0.16 t/day

Note: m^3 = cubic meters; t = tonne.

quantity of leachate generated in a landfill should be based on site-specific data, such as frequency and magnitude of precipitation and evaporation, and the exposed surface of the landfill. This kind of data was not available; thus, percolate flow rates have been estimated equally for actual and future scenarios.

Results and Discussion

The main results of the MFA and SFA for total mass, energy, carbon, and cadmium for all the examined scenarios are listed in table 6. The whole set of results is reported, as an example, in the figures 1 and 3–4 and figures 5–7, for scenarios Status Quo and B2, respectively. It should be noted that the uncertainty about the values of the main input data as well as those that drive the performance of each of the main process units is an important issue that may influence the planning of waste management systems and the comparison between the proposed scenarios. In this study, only the following uncertainty of data has been taken into account: overall waste production, sorting efficiency of MBT plants, biogas production from aerobic and anaerobic digestors, and bottom and fly ash from WTE plants. When scenarios A and B were compared, the results did not change for the mass balance layer. Further studies are being planned to evaluate the role of uncertainty for the carbon and cadmium layers.

Regarding the *mass flows of materials*, the most striking difference between the Status Quo and the future scenarios A and B is that there is no further increase in the stock of ecoballe, that is, of bales of dry fraction of MSW. With regard to the objective of *aftercare-free waste management*, scenarios A and B are very effective: They both prevent the most important future concerns and solve the bulk of the waste problems "here and now." The next important difference between scenarios A and B and the Status Quo is that the total amount of waste being landfilled does not decrease so much as expected on the basis of the higher rates of separate collection, the number of anaerobic digestion plants, and the number of WTE plants. This is due to the fact that, in the Status Quo, a large fraction of MSW is stored as ecoballe; without this intermediate storage, the need for landfills in the Status Quo would be, from a mass point of view, about 2.5 times or 4.5 times higher with regard to scenarios A and B, respectively (table 6). The total waste flow to landfills decreases apparently by 26% or 58% for a separate collection rate of 25% (A-1 and B-1), and of 32% or 60% for a scenario with a rate of 35% (A-2 and B-2). Today 85% of MSW (6,800/7,891) is sent to the combined landfill and sites for ecoballe storage. Scenarios A reduce this amount by 60% in case A-1 and by 63% in case A-2, while scenarios B provide a reduction of 77% in case B-1 and of 78% in case B-2. The amount of residues to be landfilled would of course be much more if residues from paper and plastics recycling are not incinerated. In scenario A-1, 338 t/d of residues from recycling are landfilled (instead of 62 t/d), and in scenario A-2, 515 t/d (instead of 142 t/d). Similar considerations apply to scenario A-3 with a separate collection rate of 65%, that is, about six times that of Status Quo—which can hardly be reached within a short to medium time frame. Assuming that MBT plants, and in particular the biological stabilization part, are working as designed, biogas and SOF sent to landfilling will significantly be reduced in scenarios A.

Table 6 Main outputs from all the scenarios of waste management

Scenarios	*Status Quo*	*A-1*	*A-2*	*A-3*	*B-1*	*B-2*	*B-3*
Mass of waste to landfill, t/d[a]							
From MBT	3,465 (+3109)	2,053	1,780	986	0	0	0
From recycling chain	226	62	142	715	62	142	715
From waste-to-energy	0	611	566	409	1,498	1,334	826
Total	3,691 (6,800)	2,726	2,488	2,110	1,560	1,476	1,542
Volume of waste to landfill, m^3/d[a]							
From MBT	4,620 (+4,318)	2,737	2,373	1,315	0	0	0
From recycling chain[b]	226	62	142	715	62	142	715
From waste-to-energy[c]	0	524	486	351	1,252	1,115	693
Total	4,846 (9,164)	3,323	3,001	2,381	1,314	1,257	1,408
Net electric energy, MJ/d	0	11,200,000	10,500,000	6,700,000	16,200,000	14,500,000	9,000,000
Recycled material, t/d							
Glass	122	140	163	327	140	163	327
Plastics	19	129	250	443	129	250	443
Metals	59	105	178	403	105	178	403
Paper	161	382	510	891	382	510	891
Stabilized organic fraction	233	365	454	649	365	454	649
Total	594	1,121	1,555	2,713	1,121	1,555	2,713
Carbon in landfills, t/d[a]	639 (+1,415)	380	317	358	19	32	161
Cadmium in landfills, kg/d[a]							
From MBT	47.9 (+18.7)	25.3	12.6	1.3	0	0	0
From waste-to-energy (bottom ash)	0	1.0	1.0	0.4	1.9	1.4	0.4
From waste-to-energy (APC residues)	0	33.2	31.0	12.6	59.5	44.9	14.0
From recycling chain	1.9	8.1	17.1	35.0	8.1	17.1	35.0
Total	49.8 (68.5)	67.6	61.7	49.3	69.5	63.4	49.4

Continued.

Table 6 Continued

Scenarios	*Status Quo*	*A-1*	*A-2*	*A-3*	*B-1*	*B-2*	*B-3*
Cadmium in recycled material, kg/d							
Glass	0.01	1.4	1.6	3.3	1.4	1.6	3.3
Plastics	0.9	3.9	7.5	13.3	3.9	7.5	13.3
Metals	1.1	3.2	5.3	12.1	3.2	5.3	12.1
Paper	0.05	0.1	0.2	0.3	0.1	0.2	0.3
Stabilized organic fraction	0.10	0.2	0.3	0.4	0.2	0.3	0.4
Total	2.2	8.8	14.9	29.4	8.8	14.9	29.4

Note: MBT = mechanical and biological treatment; t/d = tonnes per day; m^3/d = cubic meters per day; MJ/d = megajoules per day; kg/d = kilograms per day; APC = air pollution control.

[a] Data inside brackets relate to ecoballe, that is, stored bales of dry fraction of waste.

[b] Due to lack of data, a maximum density of 1 t/m^3 has been assumed.

[c] For fly ashes (APC residues) the increased mass as a consequence of processes necessary for immobilization has been taken into account.

The kind of landfills required will change in the future. Although at present, most waste landfilled is pretreated MSW, two new types of residues will have to be disposed of: bottom ash, and residue from air pollution control (APC) of incineration. Bottom ash requires little treatment before landfilling and, due to the lack of organic substances, does not yield landfill gas and has only slight leachate flows. By contrast, APC residues are highly concentrated in hazardous substances and need special treatment before landfilling. Regarding scenarios B, the incineration drastically changes the pathways of wastes and residues: For B-1 and B-2 (compared with A-1 and A-2), the mass landfilled is reduced by about 40%, the volume by about 60% (table 6). For B-1 and B-2, more than half of the total amount of waste is transformed into purified off gas by WTE plants. As in scenarios A, recycling is enhanced, and biomass is used to produce methane in digestion plants.

With regard to *carbon*, again the prevention of accumulation of carbon in the storage sites is a large benefit of all of these future scenarios of waste management. As in the case of total mass flow, the amount of carbon in the landfill greatly changes, with a reduction of 40% for A-1 and 50% for A-2, which become 81% and 85%, respectively, if the carbon in stored ecoballe is taken into account. The carbon flow of scenarios B is distinctly different from the Status Quo and scenarios A (table 6 and, in particular, figures 3 and 6): No organic carbon is landfilled, and the amount of inorganic carbon in incineration residues going to landfills is small. The change in carbon flows has two substantial benefits regarding waste management objectives. First, the amount of greenhouse gases is reduced due to increased recycling rates (the reuse of carbon in the form of compost, cellulose, and polymers is beneficial because this carbon will not be landfilled and will not contribute to greenhouse gases); and due to the introduction of WTE plants (energy produced in the WTE plant replaces other energy sources, and about half of the WTE energy derives from nonfossil fuel products, and does not *a priori* contribute to climate change). Second, as stated above, carbon flows have to be differentiated into the flow of carbon compounds, such as cellulose, PVC, CFCs (chlorinated and

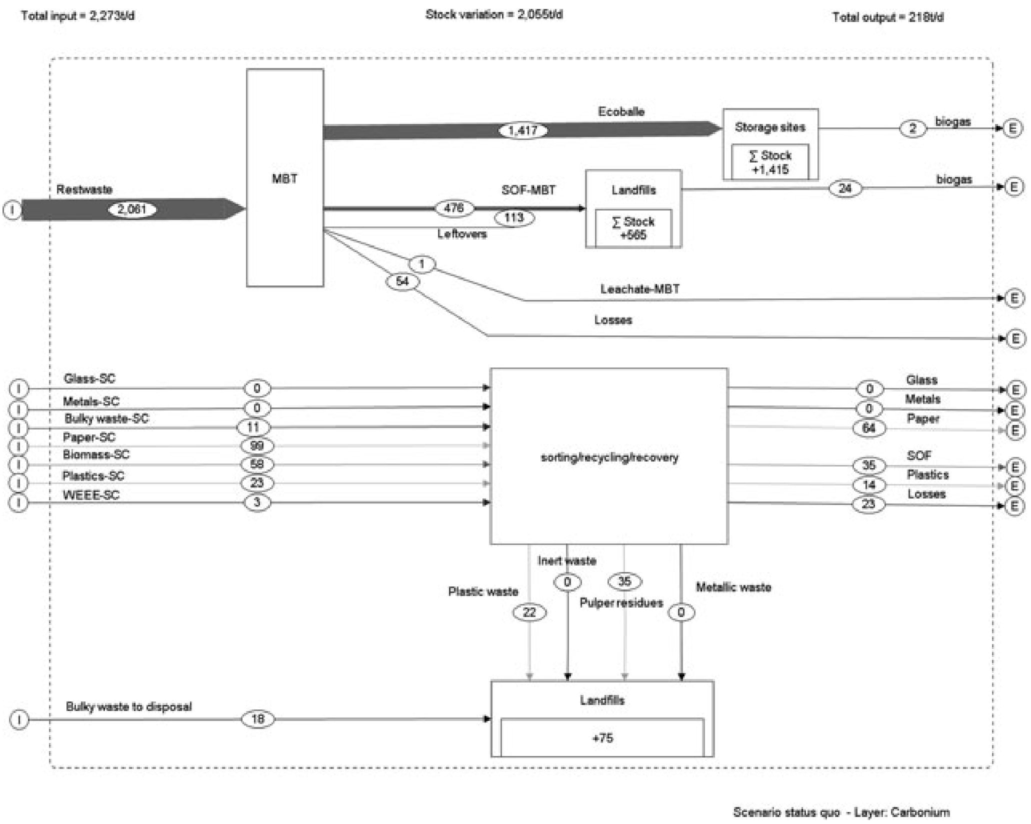

Figure 3 Mass balance on carbon for Status Quo scenario. t/d = tonnes per day.

fluorinated carbohydrates), and so on. The fate of these carbon compounds during waste treatment differs for each compound and is determined by chemical properties such as biodegradability, vapor pressure, Henry coefficient, and so on. During composting and anaerobic digestion, readily biodegradable compounds are rapidly degraded; such degradation takes much longer in landfills but goes further because of the very long residence times. Thus, carbon emissions are to be expected in leachates and off gas from landfills for centuries. Conversely, modern WTE plants are able to mineralize more than 99% of all carbon, resulting in carbon dioxide, water, and energy. Thus, incineration is the main waste treatment process that can degrade hazardous organic carbon compounds in a controlled and highly efficient way. Particularly for substances in consumer products such as CFCs with a potential to damage the ozone layer, or SF_6 that have a large greenhouse gas potential, it is important to have incineration as a reliable method for complete destruction. During landfilling and biological treatment, most of these substances are released into the environment.

Cadmium is a toxic heavy metal and has been used extensively as an additive in plastics, for batteries, in paints, and as a surface coating element. At present, the use of cadmium is under severe pressure due to its toxicity. Applications as additives are decreasing, while cadmium in batteries is still the main use of this metal. With increasing separate collection and recycling rates, more cadmium is recycled as can be deduced by table 6. In particular, for scenarios A-3 and B-3, about 99% of Cd in output is inside the recycled products. It will be a new task for recyclers to extract cadmium and other hazardous additives from plastic (and other) cycles. This task is new, because for small recycling rates, the collection

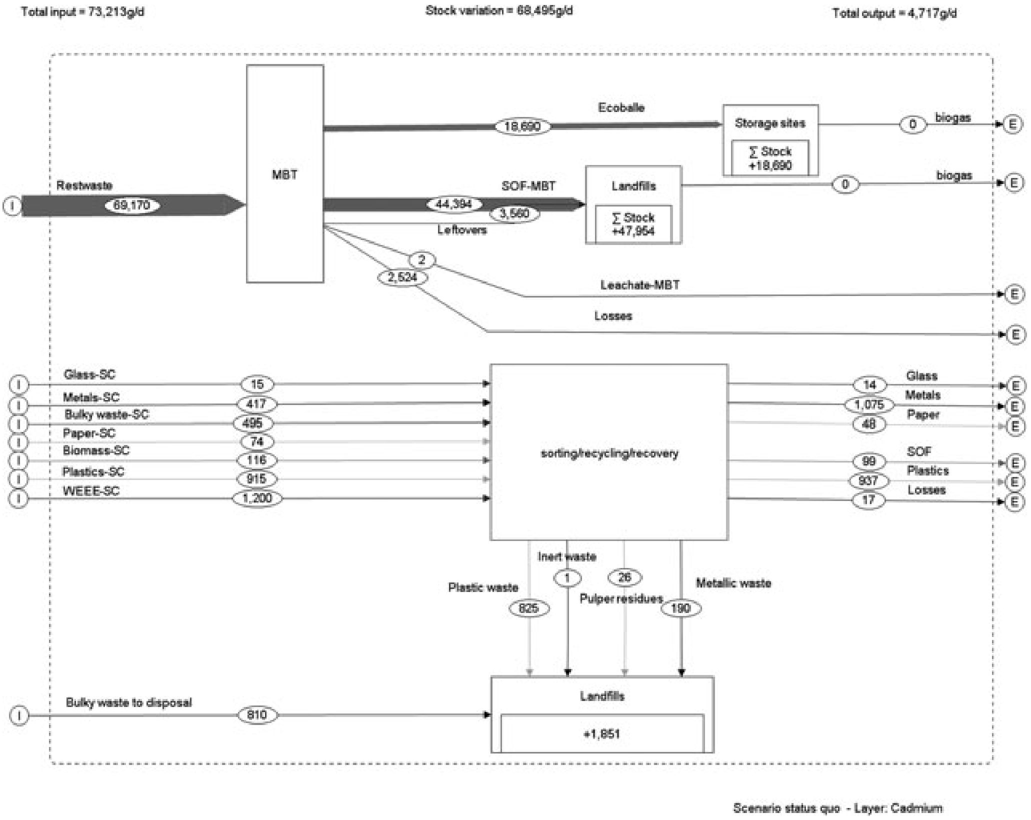

Figure 4 Mass balance on cadmium for Status Quo scenario. g/d = grams per day.

of comparatively clean packaging plastics is sufficient. If larger recycling rates are to be achieved, long-lasting nonpackaging plastic waste has to be recycled, too. To fulfill their functions during long residence times, these long-lasting plastic materials are stabilized with metals such as lead, zinc, antimony, and, formerly, cadmium. Waste management must take into account the growing amount of such additives that will enter the waste stream after the end of the product's life time. With regard to cadmium, it also is important to note that while most of the cadmium in landfilled waste is comparatively immobile, cadmium in APC residues of incinerators is mobile. Thus, these APC residues must be treated and immobilized before landfilling. For bottom ash, there exist studies showing little risk if such ash is pretreated and landfilled properly. During incineration and air pollution control, in scenarios B a high percentage of cadmium is concentrated in APC residues, as reported in table 6 and in figure 7 for scenario B-2. Considering that APC residues are only 5% of the total MSW incinerated, a new scheme for recycling Cd via WTE plants and collection and recycling of APC residues becomes possible. Scenarios B show clearly the potential of incineration to concentrate certain metals not only in APC residues but also in bottom ashes. In the future, these two residues should be investigated further for the recovery of metals such as cadmium, zinc, lead, and antimony (in APC residues), and copper, iron, and aluminum (in bottom ash).

In terms of both economic and environmental sustainability, it is necessary to ascertain how much waste management "costs" in *energy* terms. It is therefore necessary to assess, for each of the various scenarios, which operations consume energy (and hence consume combustibles and emit substances into the environment) and which are

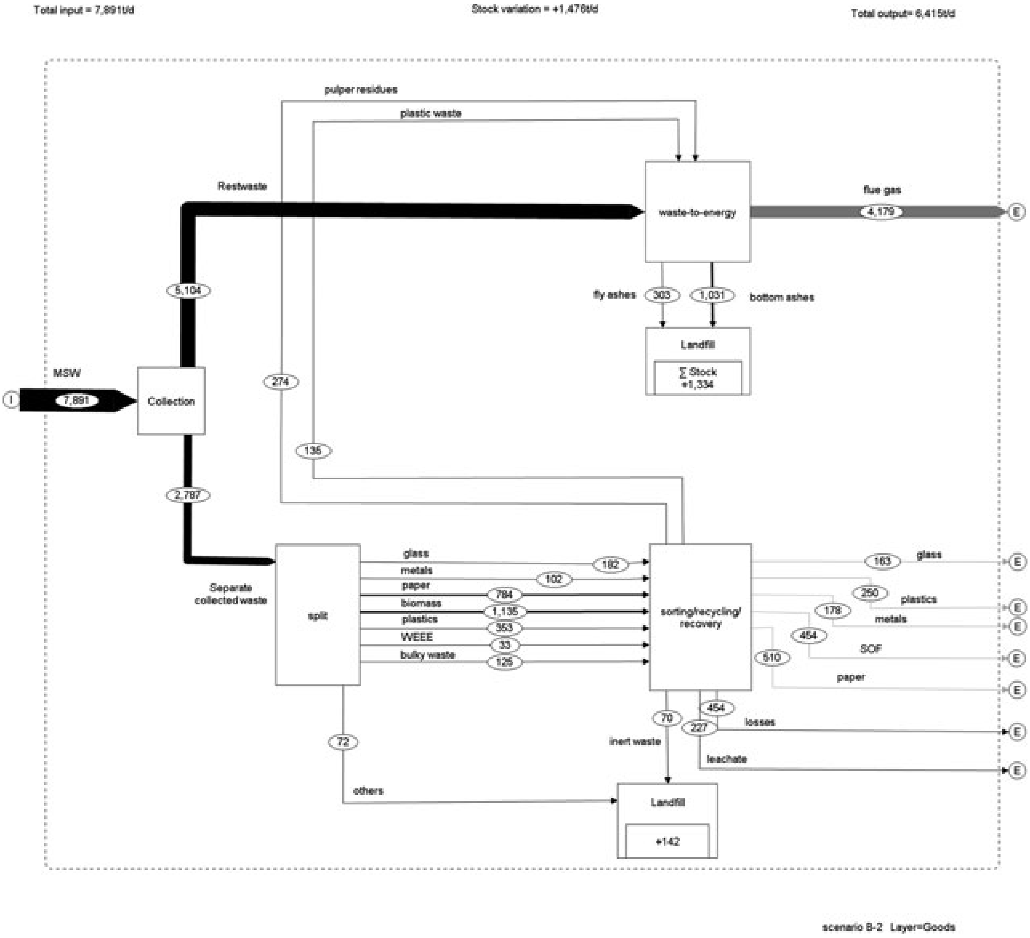

Figure 5 Mass balance for scenario B-2. Layer "mass of waste." t/d = tonnes per day.

those that allow its production. The energy costs of separate collection and recycling (glass, metals, plastic, paper, bulky waste, WEEE) have not been taken into account. Such costs increase with the intensification of separate collection. The main reason why such energy costs were not assessed is that all the recycling processes (apart from that of organic fraction recovery) are linked into industrial production chains. For these chains such separated waste is a raw material to replace primary resources with a market value. They can therefore be considered external to the real waste management chain (at least in economic terms). This applies as long as there is a real economic benefit in recycling. The energy costs and income (i.e., the energy demand and delivery) were thus obtained for the following operations: mechanical-biological treatment (MBT); anaerobic digestion of the putrescible organic fraction collected separately; incineration. Table 7 reports the data for specific energy consumption (negative values) and delivery (positive values) for the main processes in scenarios A and B: they have been used to estimate the net energy obtainable from each scenario.

In terms of waste management goals, the effect of scenarios B is considerable: landfill mass and volume are drastically reduced, greenhouse gas emissions are reduced, toxic organic materials are mineralized, heavy metals are concentrated in a small fraction of the total former MSW volume, and the accumulation of atmophilic metals in the APC residue allows new recycling schemes to be designed for metals. In combination with a

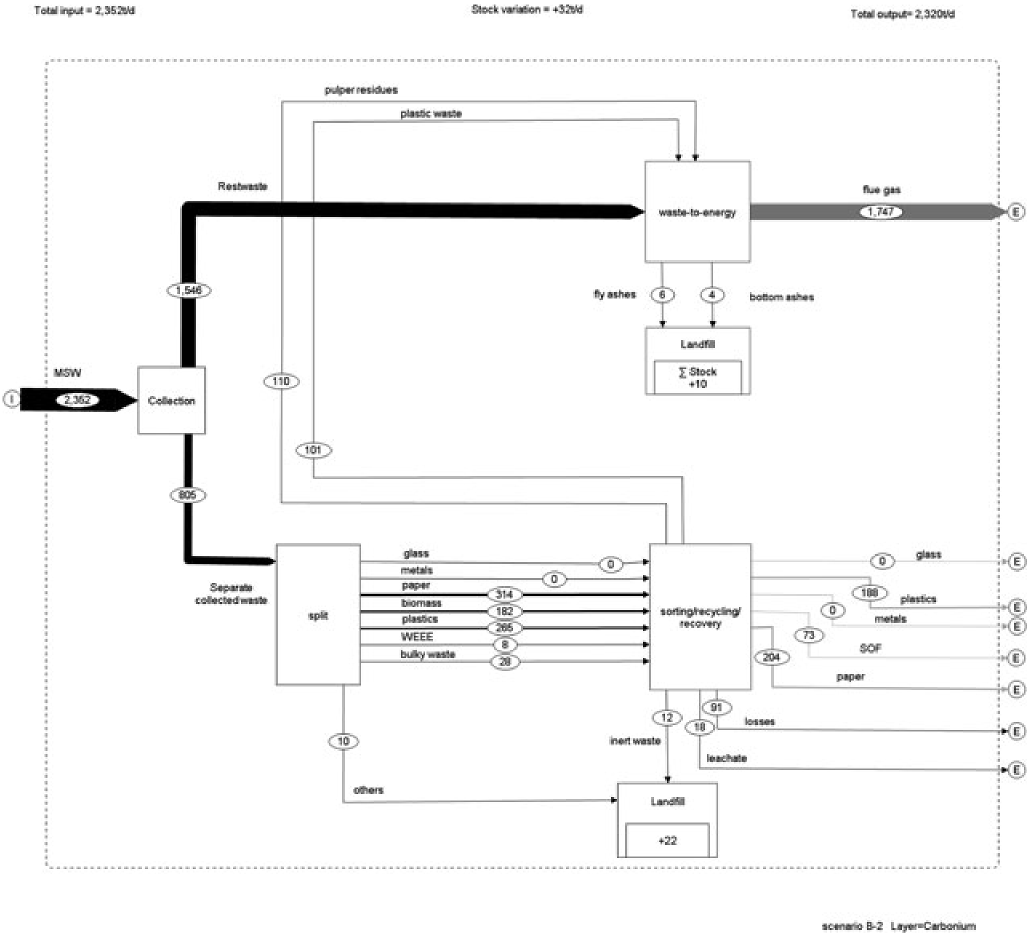

Figure 6 Mass balance for scenario B-2. Layer "carbon." t/d = tonnes per day.

high recycling rate, scenarios B come closest to fulfilling the objectives of waste management.

On the basis of MFA for total mass, an evaluation has been made of the number and capacity of all anaerobic digestion and WTE plants that are necessary to fulfill the hypotheses of different scenarios A and B (table 8). Figures 8 and 9 summarize and compare the indicators "landfill volume" and "net electric energy" for all the scenarios A and B. It is evident from figure 8 that the volume of waste to be sent to landfill is minimum (even for scenarios assuming 65% of separate collection) for scenario B-2, due to the contribution of separate collection at 35%, of 14 anaerobic digesters for the biomass separately collected, and of four incinerators that burn the restwaste and the paper and plastics recycling waste stream. Figure 9 shows that the net energy recovery that can be obtained by scenarios B is clearly larger (between 51 and 69% more) than that of scenarios A. This result, coupled with the lower requirements for landfill volumes, indicates B-2 as a possible best scenario.

Conclusions

Alternative concepts were assessed by SFA and scenario analysis for goal-oriented waste management in Campania. For this purpose, the goals of waste management as stated in European and Italian policy were summarized and broken

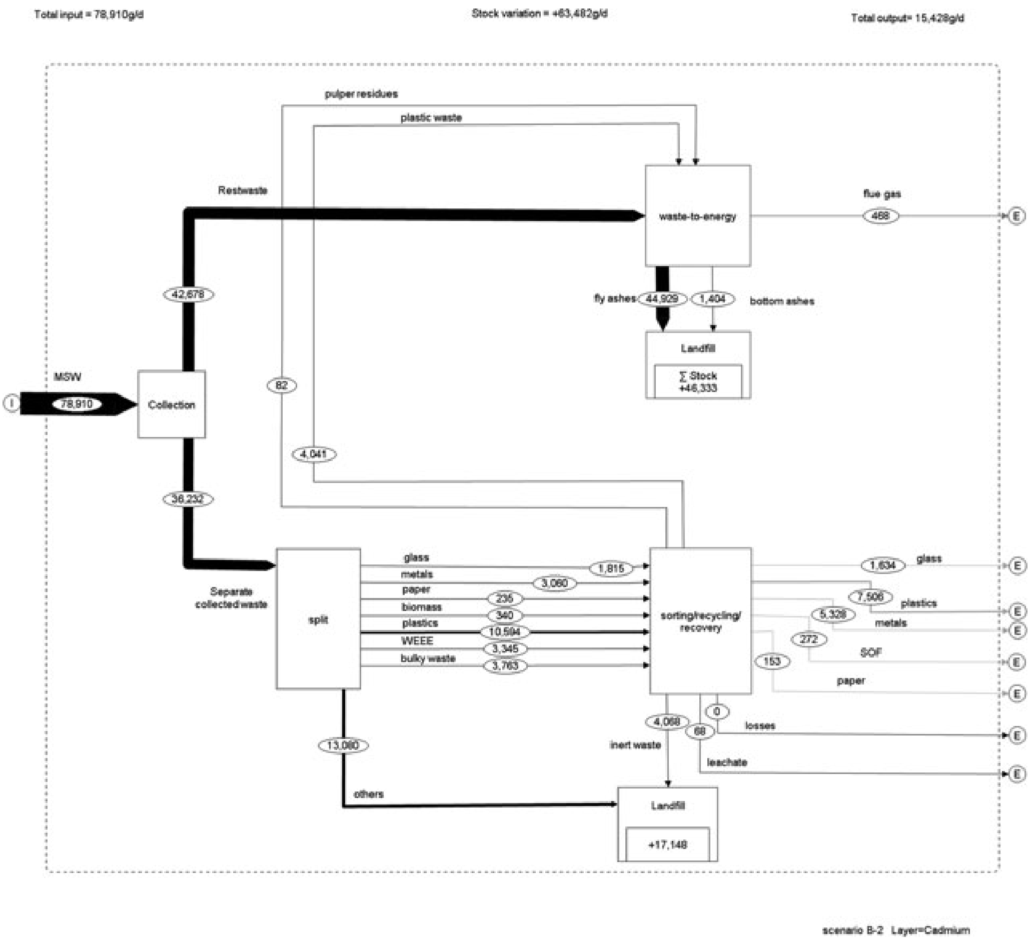

Figure 7 Mass balance for scenario B-2. Layer "cadmium." g/d = grams per day.

down to an operational level. The present waste management system of the region was modeled by MFA and SFA using the software STAN. Alternative scenarios were designed for future waste management, criteria were selected according to waste management objectives, and six future scenarios, focusing on enhancing recycling rates, WTE conversion, and anaerobic digestion were

Table 7 Specific energy demand and delivery to the main processes in the management scenarios

	Mechanical and biological treatment (MBT)		*Anaerobic digestion*	*Incineration*	
	Mechanical treatment	*Treatment of organic fraction*		*Combustion of waste as received*	*Combustion of refuse-derived fuel (RDF)*
Specific energy demand/delivery	−150 MJ/$t_{\mathrm{RestWaste}}$	−220 MJ/t_{OFMSW}	+1,300 MJ/t_{OFMSW}	+2,500 MJ/t_{MSW}	+3,800 MJ/t_{RDF}

Note: MJ/t = megajoules per tonne; OFMSW = organic fraction of municipal solid waste.

Table 8 Number and annual capacity of anaerobic digestion plants and WTE plants assumed for the different scenarios A and B

	Anaerobic digestors		*Waste-to-energy plants*	
Scenario	*Number*	*Plant capacity tonnes/year*	*Number*	*Plant capacity tonnes/year*
A-1	11	30,000	3	360,000
B-1	11	30,000	4	560,000
A-2	14	30,000	3	330,000
B-2	14	30,000	4	500,000
A-3	19	30,000	2	360,000
B-3	19	30,000	3	420,000

compared with the present waste management system.

The results of the study show clearly the benefits for waste management in Campania afforded by the introduction of incineration, increased recycling, and advanced biomass treatment (anaerobic digestion). All scenarios, A with MBT and incineration, and B with incineration only, fulfill the objectives of waste management to a significantly higher degree than the present waste management system.

In all scenarios, a higher rate of separate collection is assumed for the future: The evaluation results of all scenarios confirm that increasing the recycling rate from its present level of 11.3% to 25% and 35% or more in the future will improve

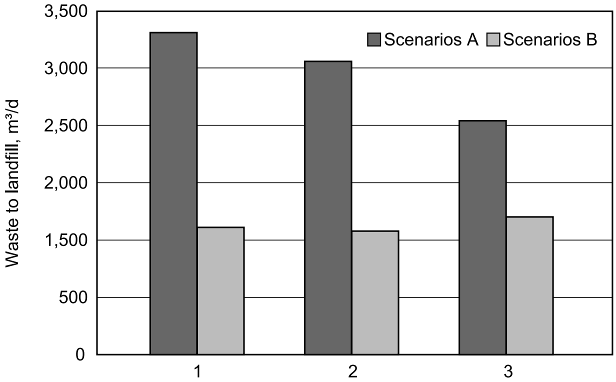

Figure 8 Comparison between the landfill volume required for each future scenario of waste management. m^3/d = cubic meters per day.

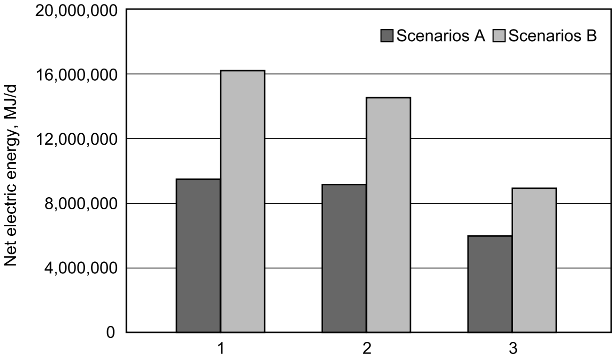

Figure 9 Comparison between the electric power generated by each future scenario of waste management. MJ/d = megajoules per day.

waste management considerably in light of the objectives to be achieved. However, even if separate collection rates are increased, and anaerobic digestion and the combination of MBT and incineration are introduced, the mass and also, with some uncertainty, the volume of waste that will have to be diverted to landfill is reduced only to a limited degree. A significant decrease in landfill volume needed for disposal can only be achieved if the MSW that is not collected separately is incinerated in waste to energy plants. In combination with the incineration of residues from recycling, scenarios B may halve the landfill volume needed for disposal.

With regard to greenhouse gas emissions, scenarios with high WTE rates and high energy recovery rates are most beneficial. They allow full use to be made of the energy that is produced when carbon is oxidized. Methane from landfills that is not captured as well as carbon dioxide from composting increases greenhouse gas emissions; thus it is important to retrofit landfills with gas capturing and utilization devices and to switch from aerobic to anaerobic biowaste treatment with subsequent methane utilization. Landfills of residues from thermal waste treatment do not emit any greenhouse gases.

Some important benefits of a change toward WTE are that hazardous organic waste constituents are completely destroyed and mineralized and that inorganic materials are concentrated in the residues of incineration. The example of cadmium shows that, in an incineration scenario, hazardous materials can be concentrated in a small amount of residues from air pollution control. This is in stark contrast to present-day waste management, where heavy metals and hazardous organic substances are dispersed in MSW landfills, which require long-term aftercare.

As a conclusion, it is recommended to deeply transform the present waste management in Campania, which is mainly based on underperforming mechanical-biological treatment followed by landfilling or storage of *ecoballe*. As SFA has shown, the goals of waste management will be much better fulfilled if the separate collection rate is increased from 11% to not less than 35%, if the separately collected biowaste is anaerobically treated with subsequent methane utilization, and if incineration increasingly replaces mechanical treatment and indiscriminate landfilling.

Acknowledgements

This article is based on a work previously presented in part in a working paper for the AMRA Center, "Scenarios of MSW Management in Regione Campania."

Notes

1. One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons. One square kilometer (km^2, SI) = 100 hectares (ha) ≈ 0.386 square miles ≈ 247 acres.
2. "Separate collection" refers to the collection of specific components of solid waste separately, such as to facilitate recycling and to allow better performances of biological and thermal treatments.
3. One kilogram (kg, SI) ≈ 2.204 pounds (lb).
4. STAN software is provided by the Technical University of Vienna (Austria) and is freely available on the site www.tuwien.ac.at.

References

APAT (Italian Environmental Protection Agency). 2007. Rapporto rifiuti [Waste Report]; available on www.apat.gov.it.

Arena, U., M. L. Mastellone and F. Perugini. 2003. The environmental performance of alternative solid waste management options. *Chemical Engineering Journal* 96: 1–3, 207–222.

Arena, U., M. L. Mastellone, F. Perugini and R. Clift. 2004. Environmental assessment of paper waste management options by means of LCA methodology. *Industrial & Engineering Chemistry Research* 43: 5702–5714.

ARPAC (Regional Protection Agency for Campania). 2008. Rapporto della Divisione Sevizi Tecnici per l'emergenza ambientale [Environmental Emergency Technical Service Division Report. 2007 Waste Flows for All ex-WDFs Except Tufino]. Naples, Italy: ARPAC.

Baccini, P. and P. H. Brunner. 1991. *Metabolism of the anthroposphere*. Berlin, Heidelberg, New York: Springer Verlag.

Belevi, H. and P. Baccini. 1989. Long-term behaviour of municipal solid waste landfills. *Waste Management & Research* 7: 43–56.

BURC (Bolletino Ufficiale della Regione Campania). 1997. Numero speciale del 14 luglio [Special Issue of July 14].

Brunner, P. H., L. Morf and H. Rechberger. 2004. Thermal waste treatment – a necessary element for sustainable waste management. In *Solid Waste: Assessment, Monitoring and Remediation*, edited by Twardowska, Allen, Kettrup and Lacy. Amsterdam, The Netherlands: Elsevier B.Y.

Cencic, O. and H. Rechberger. 2008. Material flow analysis with software STAN. *Journal of Environmental Engineering and Management* 18(1).

Clift, R., A. Doig & G. Finnveden. 2000. The application of life cycle assessment to integrated waste management. Part 1- Methodology, *Transactions of the Institute of Chemical Engineers* 78(B): 279–287.

Commissione Parlamentare di Inchiesta sul ciclo dei rifiuti e sulle attività illecite ad esso connesse. (Parliamentary Committee of Inquiry about the cycle of wastes and of illegal related activities) 2007. *Relazione Territoriale Stralcio sulla Campania* [Extract of the Report related to the Campania area], edited by Roberto Barbieri and Donato Paglionica. Rome, Italy.

Consonni, S., M. Giugliano and M. Grosso. 2005a. Alternative strategies for energy recovery from municipal solid waste. Part A: Mass and energy balances. *Waste Management* 25: 123–135.

Consonni, S., M. Giugliano and M. Grosso. 2005b. Alternative strategies for energy recovery from municipal solid waste. Part B: Emission and cost estimates. *Waste Management* 25: 136–148.

Cossu, R., G. Andreottola and A. Muntoni. 1996. Modelling landfill gas production. In *Landfilling of waste: Biogas*, edited by T. H. Christensen, R. Cossu and R. Stegmann. London, UK: Chapman & Hall.

Döberl, G., R. Huber, P.H. Brunner, M. Eder, R. Pierrard, W. Schönbäck, W. Frühwirth and H. Hutterer. 2002. Longterm assessment of waste management options – a new, integrated and goal-oriented approach. *Waste Management & Research* 20(4): 311–327.

Dunn, I. J., E Heinzle, J. Ingham and J. E. Prenosil. 2003. *Biological reaction engineering*. Chichester, West Sussex, UK: Wiley-VCH Gmbh & Co. KGaA.

EC (European Commission). 2008. Italy: Commission pursues legal action over waste management in the Campania and Lazio regions. IP/08/705 of 8 May 2008. http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/705&.

EC-IPPC (European Commission - Integrated Pollution Prevention and Control). 2006a. Reference document on the best available techniques for waste treatments. http://eippcb.jrc.es/reference/wt.html.

EC-IPPC. 2006b. Reference document on the best available techniques for waste incineration. http://eippcb.jrc.es/reference/wi.html.

GU (Gazzetta Ufficiale della Repubblica Italiana). Law 296 of December 27, 2006 (in Italian).

Lonati, G., S. Cernuschi, M. Giugliano and M. Grosso. 2007. Health risk analysis of PCDD/F emissions from MSW incineration: Comparison of probabilistic and deterministic approaches. *Chemosphere* 67: S334–343.

McDougall, F., P. White, M. Franke and P. Hindle. 2001. *Integrated solid waste management: A life cycle inventory*. Chichester, West Sussex, UK: Blackwell Science Ltd.

Niessen, W. R. 1995. *Combustion and incineration processes: Applications in environmental engineering*. New York: Marcel Dekker.

Perugini, F., M. L. Mastellone and U. Arena. 2005. A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. *Environmental Progress* 24(2): 137–154.

Weitz, K., M. Barlaz, R. Ranjithan, D. Brill, S. Thorneloe and R. Ham. 1999. Life cycle management of municipal solid waste. *The International Journal of Life Cycle Assessment* 4(4): 195–201.

Woodard, F.E. and Curran. 2006. *Industrial waste treatment handbook*, 2nd Ed. Amsterdam, The Netherlands: Butterworth-Heinemann.

About the Authors

Maria Laura Mastellone is a professor of chemical engineering at the Second University of Naples in Caserta, Italy and consultant for the area "Waste and industrial hazards management" of AMRA s.c.a.r.l. **Paul H. Brunner** is the head of the Institute for Water Quality, Resources and Waste Management at the Vienna University of Technology in Vienna, Austria. **Umberto Arena** is a professor of chemical engineering at the Second University of Naples in Caserta, Italy and responsible for the area "Anthropogenic Risk" of AMRA s.c.a.r.l.