LCA Case Studies

Life Cycle Assessment of a Plastic Packaging Recycling System

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Abstract

Goal, Scope and Background. The object of the study is the Italian system of plastic packaging waste recycling, active until 2001, that collected and mechanically recycled the post-consumer PE and PET liquid containers. The phases of collection, compaction, sorting, reprocessing and refuse disposal were individually analysed and quantified in terms of energy and material consumptions as well as of emissions in the environment. The work is the result of a joint research project with the Italian Consortium for Packaging (CONAI), carried out in co-operation with the main Italian companies active in the field. The main aim was the quantification of the real advantage of plastic container recycling and the definition of criteria, at the same time environmentally compatible and economically sustainable, for their management.

Main Features. For each of the unit processes, and in order to increase the data quality, all the data of interest were collected during technical visits to several selected plants active in Italy or deduced by official documents and certificate declarations of the same companies. To allow comparison of resource consumption and environmental pollution from different management scenarios producing different products, the *basket of products method* was applied.

Results. The results indicates that the production of 1 kg of flakes of recycled PET requires a total amount of gross energy that is in the range of between 42 and 55 MJ, depending on whether the process wastes (mainly coming from sorting and reprocessing activities) were sent or not to the energy recovery. The same quantity of virgin PET requires more than 77 MJ. The energetic (and then environmental) saving is so remarkable, even for PE, being 40–49 MJ for the recycled polymer and about 80 MJ that for the virgin polyolefin. The calculations were made with the reasonable assumption that the final utilisation can use the virgin or the recycled polymer without any difference.

Conclusions and Outlook. The analysis defined and verified a suitable tool in the field, based on objective data, for comparing different coherent scenarios of waste management politics. This allows one to propose the extension of the tool under different collection schemes, as well as for different systems of packaging recycling. As an immediate consequence of the success of the present study, the joint-research programme with CONAI has been extended for another three years. The focus will be the Italian system for paper and paperboard recycling and that for all plastic packagings. In parallel, a different study has been scheduled with reference to the integrated solid waste management of the Regione Campania, the largest and most populated area in the South of Italy.

Keywords: Life cycle assessment; PE containers; PET containers; plastic packaging; plastic recycling

1 Background

Plastics constitute the most intelligent application of crude oil, since more than 80% of this valuable resource is still used for the direct production of energy. They are the engineering material of our age, being used to substitute traditional materials, like wood, glass and metal, in a variety of forms. One of the main negative consequences of this 'plastic revolution' is the often-emphasised question of plastic waste disposal. The solution to this problem must include a large utilisation of the various recycling techniques for materials and/or energy recovery. 'Plastics can be recycled' was the motto of the plastics' manufacturers as early as 1989. A relevant part of their programme has been realised, particularly in some occidental countries like Germany, Sweden, Denmark (Brandrup et al. 1996), even though more must be done to obtain an adequate exploitation of this 'waste' (Mastellone 1999). In particular, a proper understanding and an objective quantification of all the environmental impacts related with the recycling process are necessary. They have to provide parameters which allow one to define designing and operating criteria able to make a programme of recycling and recovery of plastics, economically affordable, and, at the same time, socially acceptable and environmentally effective. A Life Cycle Assessment is generally considered the best environmental management tool that can be used to this aim (Boustead 1996, Clift et al. 2000, McDougall et al. 2001), i.e. to understand and compare how a recycling system is provided 'from cradle to grave'.

This study is the result of a joint research project with the Italian Consortium for Packaging (CONAI) (Arena et al. 2001), carried out in co-operation with the main Italian companies active in the field. It comprises an LCA-type analysis of various Italian scenarios for recycling plastic waste from household plastic packaging materials, in particular liquid containers made of polyethylene terephthalate (PET) or polyethylene (PE), which are dominantly present. The analysis takes into account that any recycling option influences the environment by consuming resources and releasing emissions and waste streams, and by replacing conventional products from primary production (Heyde and Kremer 1999).

2 Goal and Scope Definition

The **overall goal** for this project is to acquire information which allows one to quantify the real environmental advantage of recycling of PET and PE containers (in terms of reduction in material and energy consumption and environmental emissions) and to utilise this information in order to define criteria, at the same time environmentally compatible and economically sustainable, for the management of these packaging wastes.

The **primary audience** for this effort is CONAI and its associate CoRePla (the Italian Consortium for plastic recycling). However, the considerations and tools developed through the study will also be of value to local governments and solid waste planners as well as industry active in the field of plastic recycling, environmental organisations and LCA practitioners.

The function of the system under study is to manage (and recycle) plastic containers for liquids, mainly made of PET or PE. Therefore, the **functional unit** has been defined as the management of post-consumer PE and PET liquid containers (obtained by means of a mono-material collection), which leads to the production of 1 kg of flakes of (recycled or virgin) PET or PE. It is assumed that there is a market demand for all recycling products under investigation, and that virgin and recycled material are equivalent for the market. All the activities required to manage plastic containers and to produce the recycled polymers were considered. Therefore, the phases of collection, compaction, transport and sorting of wastes, as well as that of PET/PE reprocessing and that of refuse disposal, were individually analysed and quantified in terms of energy and material consumption as well as of emissions in the environment at local, regional and global level.

The major **unit processes** included in the overall system under study are: **plastic waste management** (Collection, Compaction Station, Sorting Station, PET/PE Reprocessing, Landfill, Combustion with Energy Recovery) and **related processes** (Inter-Unit Process Transportation, Electrical Energy, Manufacturing of Materials from Virgin Resources).

It was assumed that the plastic container for liquids enters the **system boundaries** when it is delivered to a mono-material collection site, whether it be a residential kerbside, apartment collection site, or rural drop-off site (**Fig. 1**). In agreement with similar studies (Weitz et al. 1999, Beccali et al. 2001, McDougall et al. 2001), all upstream life cycle activities (raw materials extraction, manufacturing, and use) are assumed to be held constant. Thus, the production of garbage bags and collection banks has not been included in the study nor has the transport of plastic waste by residents to a collection point.

For each of the unit processes, and in order to increase the **data quality**, all the data of interest was derived from on site investigation, i.e. they were collected (from September 1999 to December 2000) during technical visits to several selected plants active in Italy or deduced by official documents and certificate declarations of the same companies. For instance, the electrical energy consumptions were obtained by adding the consumptions of all the apparatus of each plant and by comparing the result with the related electric bill: this means that the utilised data are true consumptions and not data extrapolated from the installed capacity. The data quality was furthermore increased by taking into account the specific characterisation of the packaging waste (as well as the process waste) at the various stages, i.e. at the collection, at

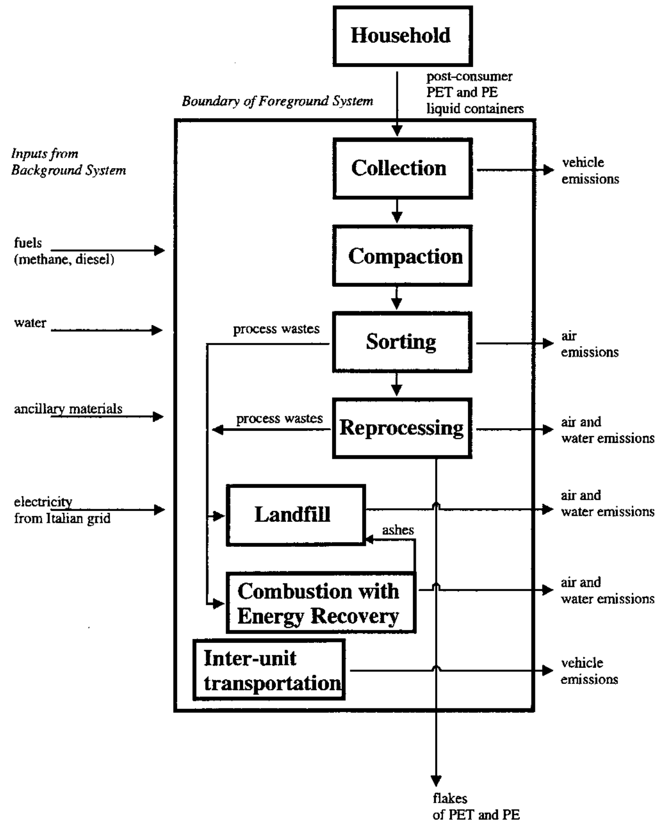

Fig. 1: Foreground system and direct burdens for the system under study

the sorting station, at the reprocessing facilities, etc. In particular, the composition of the collected plastic wastes was that provided by CoRePla as the average in Italy with reference to the year 2000. The composition of waste streams from sorting stations and reprocessing units was evaluated on the basis of data provided by several companies involved in the study.

All collected information constituted a database that allowed quantifying energy and material flows in entrance to and in exit from every phases of the reference plastic recycling system.

3 Inventory Analysis

Life Cycle Inventory (LCI) aims at identifying and quantifying the environmental burdens crossing system boundaries: it will result in a list of raw materials and energy inputs, and of individual emissions to air, to water and as solid waste. In the following, the direct environmental burdens (i.e. those associated with plastic waste recycling activities) were reported for each stage of the recycling chain as averaged from on site investigation data. The indirect burdens (i.e. those associated with the production, transport and use processes of all the needs for carrying out the different plastic waste recycling activities) as well as the avoided burdens (i.e. those which have to be deducted from the total environmental impact account, since these are related to products obtained from one of the processes and therefore no longer to be generated by means of traditional activities) were calculated by means of the Boustead Ltd. data bank.

Table 1: Characteristics of catchment area of the waste collectors examined

Collector	Area type	Population density, inhabitant/km^2	Surface, km^2	Collection systems
A	Super-urban	7418	181	Kerbside
B	Rural / Urban	193	667	Kerbside (urban zone); Bring (rural and urban zones)
C	Urban	1040	283	Kerbside

The collection/compaction stage. The activity of three domestic-waste collectors was examined: the first operates in a super-urban area, the second and the third, active in the North and in the South of Italy, respectively, operate in areas where rural and urban zones are present (**Table 1**).

The major environmental burdens associated with waste collection systems will be due to the transport required, which consumes energy and results in significant air emissions. The data averaged over all the examined collectors indicated an energy consumption of 0.32 MJ/kg of collected plastic waste.

The energy consumptions for the **compaction** station, which is present to some extent in plastic waste management, are relatively limited. The data averaged for three different stations was equal to 0.09 MJ/kg of compacted plastic waste.

The sorting stage. The activity of three sorting companies were examined. They are, respectively, the largest one operating in the North of Italy, the largest one operating in the South and that one utilising the most up-to-date technologies. **Fig. 2** describes the process flow diagram for the first of these companies. Each stage of the sorting process was separately examined by evaluating the energy and material consumptions, the air and water emissions and the waste production. The analytical map of environmental burdens that results from the analysis is a useful tool for the audience in order to obtain an improved performance of the sorting stage. Note that, following Italian market requirements, three different types of PET bottles (coloured, blue and transparent), having a different economic value, are selected in the sorting stage.

The overall sorting efficiency, averaged over the three examined companies, was equal to 56%, while the electric energy and the diesel consumptions were 0.16 and 0.11 MJ/kg of selected plastics, respectively.

The reprocessing stage. The study showed that the Italian organisation of plastic recycling strongly connects the PET and the PE procedures for recycling. As already mentioned, PET and PE are the main components of plastic containers for liquids (never less than 60%) collected by means of mono-material collection and there is no sense in analysing the PET recycling without taking into consideration that of PE. Accordingly, the analysis examined both the PET and the PE-reprocessing stage. All the major companies that reprocess PET and PE were selected for this stage of LCI. **Fig. 3** shows the process flow diagram for a reprocessing company that produces PET flakes while **Fig. 4** indicates the specific and the average energy consumptions, expressed as MJ/kg of reprocessed PET. The corresponding values for PE were instead evaluated as

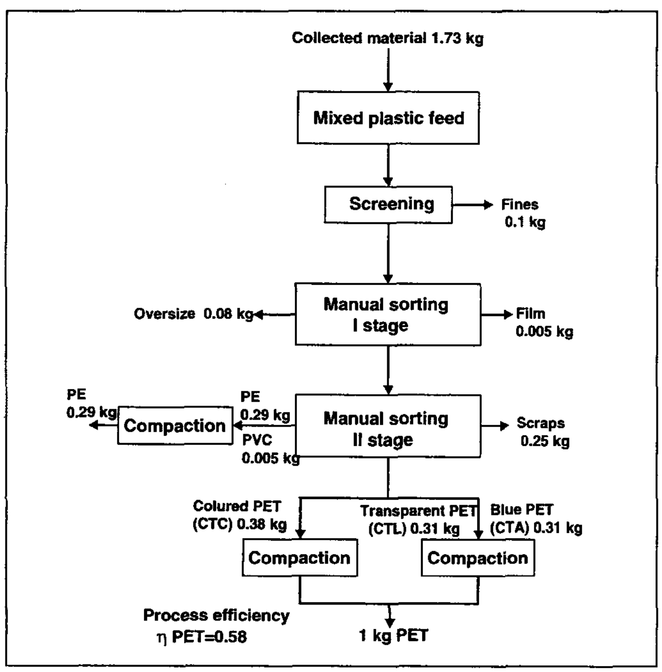

Fig. 2: The process flow diagram for a sorting company

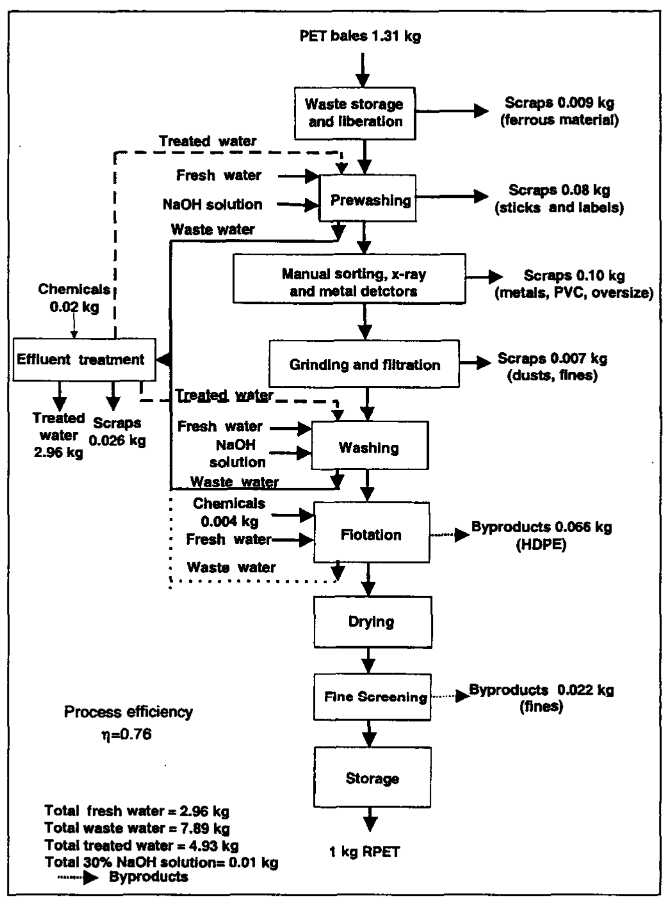

Fig. 3: The process flow diagram for a PET-reprocessing company

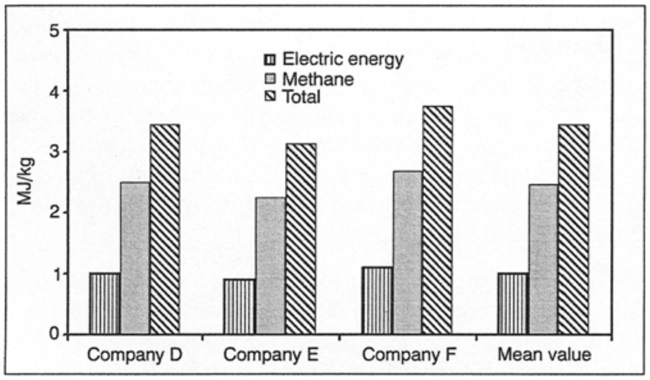

Fig. 4: Comparison between energy consumptions of the three examined PET-reprocessing companies

equal to 2.00 (electric energy) and 0.65 (methane) MJ/kg of reprocessed PE. It should be noted that the percentage of polymer recovery, as well as the energy consumptions, demonstrated very similar results for each kind of reprocessing: this is a consequence of the adoption of the same kind of up-to-date technologies (Mastellone et al. 2002).

Landfilling. Landfilling is a unit process: wastes from the different recycling units form the inputs, along with some energy to run the process; the outputs are the final stabilised waste, the gaseous and aqueous products of decomposition, which emerge as landfill gas and leachate. In the specific case under study, an overwhelming majority of the wastes are made of polymeric scraps. As a consequence, landfill gas and leachate are negligible since only 1–3% (Finnveden et al. 1995, Bez et al. 1998) of the hydrocarbon content can be degraded during the considered time period of 100 years.

Combustion with energy recovery. This unit process is an alternative option to waste valorisation by recovering energy. The heat content of different waste streams was evaluated as 27 MJ/kg for the collected plastics, 24 MJ/kg for the scraps coming from sorting or reprocessing units. The environmental burdens were estimated by assuming a monocombustion of the waste streams, with an overall electric efficiency of 25%.

The transportation stage. A preliminary analysis was developed, on the basis of the actual location of all the sorting and reprocessing facilities in Italy, in order to estimate the length of the average transport route that the (collected or selected) plastic waste has to travel between two successive process units. The results were coupled with the features (fuel consumption, load-carrying capacity) of the different trucks utilised for transportation. An average length of 0.025 km/kg of transported plastic was estimated. The related direct and indirect burdens were evaluated by means of the Boustead data bank.

The overall recycling chain. The processing of all data reported above leads to the quantified flow scheme of **Fig. 5** related to the production of 1 kg of recycled PET flakes. Note that the system boundaries were drawn in order to also include the production of 0.39 kg of recycled PE flakes. **Table 2** reports the energy consumptions normalised to 1 kg of recycled PET or PE related to all the stages described above.

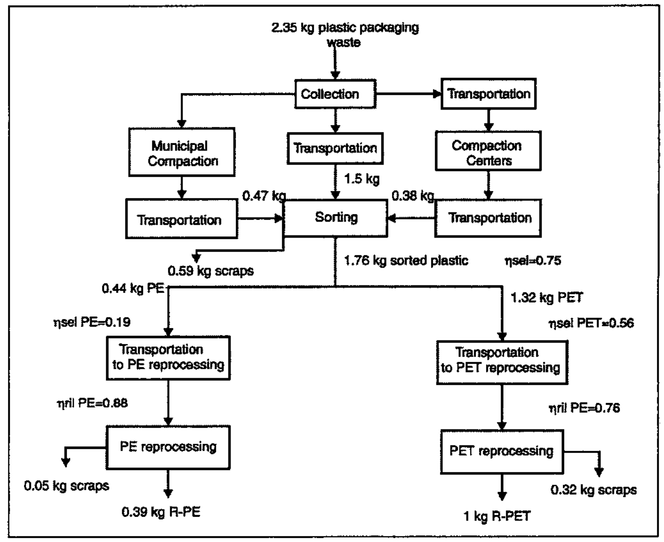

Fig. 5: The quantified mass flow of plastic waste along the recycling chain

Table 2: Energy consumptions of the recycling chain, expressed as MJ/kg of recycled plastics

	Recycled PET	Recycled PE
Electric energy	2.54	6.72
Diesel	2.67	6.97
Methane	2.76	7.01
Total	**7.97**	**20.70**

4 Impact Assessment of Different Plastic Waste Management Scenarios

The stage of impact assessment aims at understanding and evaluating the magnitude and significance of potential environmental impacts of a system. It organises the LCI inputs and outputs into specific, selected impact categories and models the inputs and outputs for each category into an aggregate indicator. Note that the Life Cycle approach aggregates over time and over space, i.e. all inputs and outputs over the whole life cycle are included in the analysis regardless of when they occur and of where they are located.

As a consequence, it is not easy to correlate a given impact (i.e. the physical result of a given operation) with its environmental effects. In other words, we can quantify the impacts on the basis of inventory results, but we can just barely estimate the related environmental effects on the basis of hypotheses and conventions.

A variety of impact assessment methods may be appropriately applied depending on the geographical scale, type and duration of the effect, and the level of accuracy desired. These methods range from a straightforward interpretation of the significance of loading to site-specific risk assessments (Asante-Duah 1998), requiring significant additional data beyond that normally developed in the inventory.

On the other hand, the stage of environmental impact assessing is less well developed than the inventory one. As a consequence, according to almost all of similar studies (Weitz et al. 1999, Ademe/Eco-Emballages 2001, Beccali et al.

2001), the impact categories method was utilised in this analysis. The following categories were assumed to be principal indicators of environmental impact related to each step of plastic waste life cycle:

- consumption of natural resources (gross and net energy consumption; oil consumption; water consumption)
- air pollution (increase in the greenhouse effect over 100 years; air acidification; emission to the air of metals and other pollutants)
- water pollution (water eutrophication; discharge of metals and other pollutants into water)
- quantities of solid waste generated (which is strictly related to the volume requirements in landfill).

Six scenarios of the management of plastic wastes were then defined:

Scenario I	No recycling and landfill disposal of all the collected plastic wastes
Scenario II	No recycling and landfill disposal of 50% of the collected plastic wastes, the remaining being incinerated with energy recovery
Scenario III	No recycling and all the collected plastic wastes sent to incineration with energy recovery
Scenario IV	Mechanical recycling of all the collected plastic wastes and landfill disposal of all the processed wastes
Scenario V	Mechanical recycling of all the collected plastic wastes and landfill disposal of 50% the processed wastes, the remainder being incinerated with energy recovery
Scenario VI	Mechanical recycling of all the collected plastic wastes and all the processed wastes sent to incineration with energy recovery.

The comparison between these scenarios was made by means of the combined use of the collected data, the LCA tool and the international energetic and environmental data bank of Boustead Ltd. Moreover, in order to allow comparison of resource consumption and environmental pollution from management scenarios producing different products, the basket of products method (Ebert et al. 1996, Heyde and Kremer 1999) was applied. This means that, for a fixed input, the basket of products for each of the compared scenarios was filled with the products of the related recovery method. In other words, when a product cannot be produced from one of the management scenario (for instance, the landfill does not produce recycled plastic), it must be produced from traditional processes (in the case of plastics, the petrochemical processes) taking into account the related environmental burdens.

Fig. 6 exemplifies how the basket of products method allows one to compare two different plastic waste management scenarios. The same figure highlights how a modification in the management criteria leads to a relevant increase in the overall avoided burdens.

The analytical comparison between the six selected scenarios is described by the diagrams reported in Fig. 7, where the negative values are due to the relevance of avoided environmental burdens. It appears that the recycling option (Scenarios IV, V, VI) is always environmentally preferable and that an energy recovery from processed scraps (Scenario VI) is strongly convenient. In particular, the comparison between data of scenarios I and IV can be used to quantify the environmental advantage of mechanical recycling. There is, for instance, a considerable saving of energetic resources (93% of crude oil, 84% of gas/condensate and 93% of coal), a large reduction of waste production (59%) and water consumption (91%), and a remarkable decrease in the emission of green-house gases (88%).

Moreover, the comparison between data of scenarios IV and VI suggests the environmental importance of incineration of processed scraps with energy recovery: reduced consumption of energetic resources (178% of crude oil, 79% of gas/condensate and 225% of coal), reduced waste production (91%) and water consumption (13%), reduced air and water emissions with the only increase of green-house gases (53%).

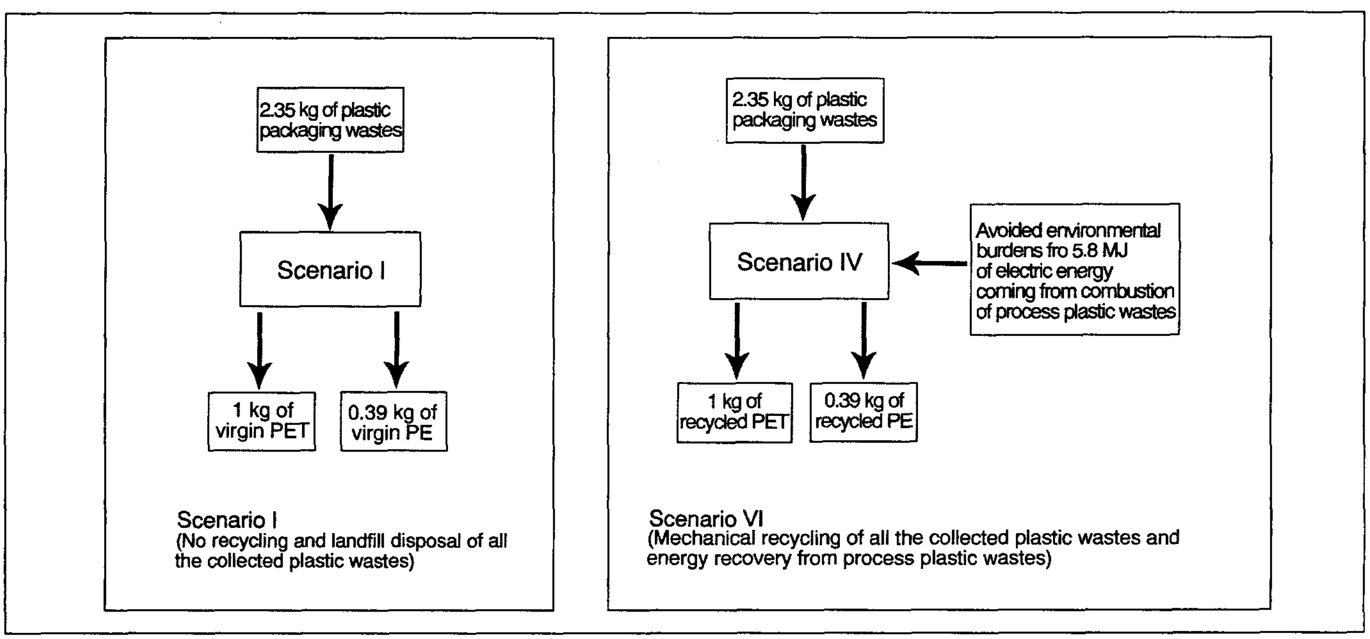

Fig. 6: Basket of products from scenarios I and VI with the highlighting of avoided environmental burdens related to the power production from plastic scrap energy recovery

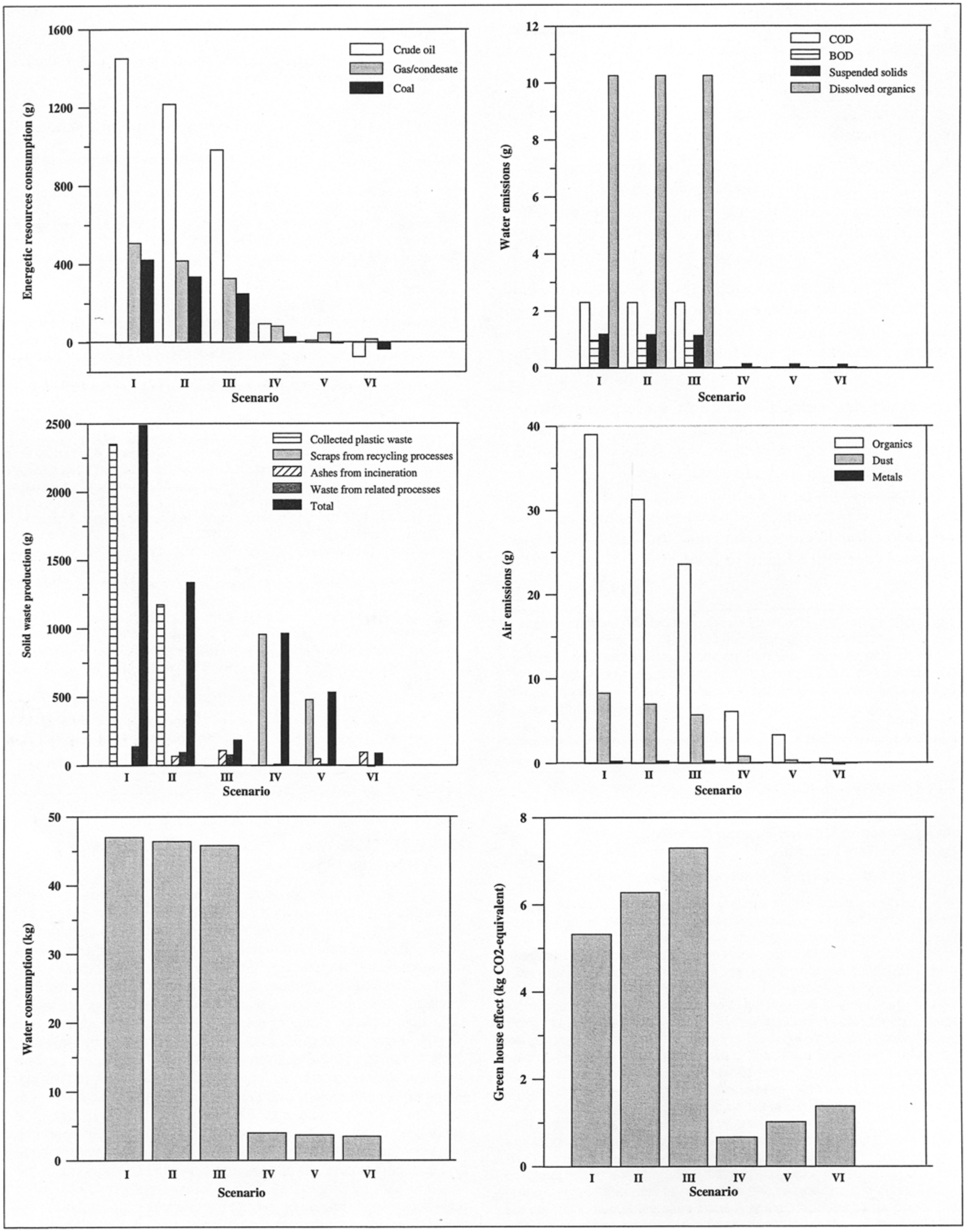

Fig. 7: The main indicators of environmental impacts related to each selected plastic waste management scenario. All the data refer to the production of 1 kg of (recycled or virgin) PET flakes and 0.39 kg of (recycled or virgin) PE flakes (as indicated in Fig. 5)

5 Conclusions

The Italian system for mechanical recycling of rigid plastic packaging made of PET and PE has been analysed. The present waste management strategy has been compared with some alternative scenarios. The results suggest the options most convenient under the energetic and environmental point of view.

The analytical comparison between the six scenarios shows that the recycling option is always environmentally preferable. The analysis quantifies the advantage of plastic recycling in the different environmental impact categories and highlights the importance of energy recovery from processed scraps.

The analysis defined and verified a suitable tool in the field, based on objective data, for comparing different coherent scenarios of waste management politics. This allows to propose an extension of the tool for different collection schemes as well as for different systems of packaging recycling.

As an immediate consequence of the success of the present study, the joint-research programme with CONAI has been extended for another three years. The focus will be the Italian system for paper and paperboard recycling and that for all plastic packagings. In parallel, a different study has been scheduled with reference to the integrated solid waste management of the Regione Campania, the largest and most populated area in the South of Italy.

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Waste Treatment in Product Specific Life Cycle Inventories: An Approach of Material-Related Modelling. Part II: Sanitary Landfill

Jürgen Bez, Michael Heyde, Gertraud Goldhan

The final disposal of waste in sanitary landfills generates environmental impacts in the form of gaseous emissions and effluents in the seepage water. In product specific Life Cycle Assessments, these environmental impacts resulting from the disposal of the product under study frequently have a strong influence on the overall results. The Sanitary Landfill (SL), like the Municipal Solid Waste Incineration (MSWI), is a complex system with a large variety of different types of waste with varying input composition. A direct determination of the environmental impacts resulting from the landfilling of a single input component, e.g. by measurements, is not possible. The model approach described in this paper shows an operationalized concept for the allocation of the environmental effects caused by the landfill process to special input components. The calculation of the landfill emissions in the model is based on the emission spectrum (landfill gas and seepage water) of an average-sized landfill in Germany and the elementary composition of the single waste fraction under consideration. The resulting reactor landfill module comprises an average split for diffuse and captured landfill emissions, the use of captured landfill gases in a gas engine and a cleaning of captured seepage water in a waste water treatment plant. A short case study demonstrates the calculation of the effects of landfilling of a defined waste fraction (bottle fraction in post-consumer, plastic).

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Life Cycle Management of Municipal Solid Waste

Keith Weitz, Morton Barlaz, Ranji Ranjithan, Downey Brill, Susan Thorneloe, Robert Ham

Life cycle assessment concepts and methods are currently being applied to evaluate integrated municipal solid waste management strategies throughout the world. The Research Triangle Institute and the U.S. Environmental Protection Agency are working to develop a computer-based decision support tool to evaluate integrated municipal solid waste management strategies in the United States. The waste management unit processes included in this tool are waste collection, transfer stations, recovery, compost, combustion, and landfill. Additional unit processes included are electrical energy production, transportation, and remanufacturing. The process models include methodologies for environmental and cost analysis. The environmental methodology calculates life cycle inventory type data for the different unit processes. The cost methodology calculates annualized construction and equipment capital costs and operating costs per ton processed at the facility. The resulting environmental and cost parameters are allocated to individual components of the waste stream by process specific allocation methodologies. All of this information is implemented into the decision support tool to provide a life-cycle management evaluation of integrated municipal solid waste management strategies.