TNO-report
TNO-MEP – R 2000/119

Eco-efficiency of recovery scenarios of plastic packaging

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Date
July 2001

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31915

Keywords
- Plastic Packaging
- Recovery scenarios
- Eco-efficiency
- Life Cycle Analysis
- Cost Analysis

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Executive summary

Objectives of the project:

The requirement of the Association of Plastic Manufacturers in Europe (APME) is to be able to apply an integral, typical European model to demonstrate the relative effectiveness, in economic and environmental impact terms of various plastic waste recovery structures.
BASF has developed a user-friendly Eco-efficiency model to demonstrate the relative economics and environmental aspects of various products and processes within their company. Its potential applicability is however much wider.
APME therefore requested TNO to calculate the economics and environmental aspects of several plastic packaging waste processing scenarios and to present the results in terms of Eco-efficiency using the BASF model.

The objectives of the study are to present an overview of the environmental aspects and economical impacts of actual reference scenarios and different possible (theoretical) scenarios of “state of the art” processing routes of packaging plastics, including collection, pre-processing, mechanical recycling, feedstock recycling, energy recovery and residues incineration. The environmental aspects and economical impacts have been compared with the help of model calculations to illustrate how an improved plastic packaging waste processing scenario can be in terms of Eco-efficiency.
With the results of the model output interactive discussions with opinion formers and policy makers can be held by APME. In particular the objectives and targets of the European Packaging and Packaging Waste Directive, and the impending revision of the targets are the basis of such discussions.

The report is divided in two parts. The first part covers a costs inventory and a Life Cycle Assessment (LCA) of environmental impacts of developed theoretical scenarios of packaging plastics, in order to create a data basis for the demonstration of the Eco-efficiency concept. The second part covers the Eco-efficiency calculations. Different scenarios of processing routes of packaging plastics waste are compared and analysed in terms of “Eco-efficiency” and are presented to give an indication of the costs-environmental benefits of adopting various combinations of recovery options.

Executive summary part I: LCA study and costs inventory

Scenarios in the study:

The cost inventory and Life Cycle Analysis (LCA) of environmental impacts are focussed on packaging plastics waste in the EU member states. Packaging in Europe (15 EU-members and Norway and Switzerland) can be considered as a "single" market with respect to plastics consumption, recycling of plastics and to some extent waste treatment. The analysis considers packaging plastics in *Municipal Solid Waste* (MSW) and from *Industrial* distribution packaging *Waste* (IW). The packaging waste data used in the study are average EU data obtained from literature. The technologies in this study are real, "state of the art" examples, representative of developments in various Northern European countries.

Regarding packaging plastics in MSW the following processes for collection and separation of packaging plastics are studied:

- **Bottle bank:** ("bring system"), followed by manual sorting processes.
- **Specific packaging collection:** Collection is focussed at specific (recyclable) packaging fractions from MSW in a separate bin or bag **(yellow bag)**. Recyclable fractions are partly manually sorted and partly mechanically processed.
- **Dry/wet collection:** Collection of MSW occurs by a two bin (dry/wet) system (**grey bag)** and mechanical processes separate collected fractions.
- **Integral collection:** MSW is collected integrally without any separation process.

Regarding IW the following processes for collection and separation of packaging plastics are studied:

- **Separate collection of IW mono-streams** (commercial films, crates and pallets) followed by manual sorting processes.
- **Separate collection of IW mixed plastics** (including non-response mono streams) separated by manual and mechanical operations.
- **Integral IW collection**: without any separation process.

Recycling and treatment processes in this study are:

- **Mechanical Recycling (MR):** manufacturing of films, crates, pallets, thin walled products (e.g. fertiliser bottles) to substitute products made of primary plastics.
- **Mixed plastics recycling (MPR):** production of thick walled products, which substitute products, manufactured from concrete.
- **Feedstock recycling (FR):** plastic mixtures as substitute for heavy fuel oil, as a feed (reducing agent) in a blast furnace process or plastic mixtures as a feed for the Texaco Gasification process as substitute for natural gas based syngas in the methanol synthesis.
- **High efficient energy recovery (ER_{high}):** combustion of plastics in a coal fired cement kiln whereby steam coal is substituted as energy source.

- **Energy recovery by MSWI (ER_{MSWI}):** MSWI installations, which produce useful energy in the form of heat and electricity.
- **Landfill:** Integrally collected plastic packaging waste can be landfilled.

Out of these real processes (routes) theoretical scenarios are built (summarised in Table T1):

- Two reference scenarios are distinguished:
  1. 100% landfill; in South-Europe landfill is the dominating applied waste processing method. It is favourable to demonstrate the environmental benefits when diversion from landfill occurs.
  2. NOW; this scenario approaches the real situation in the EU with respect to MR, FR, ER_{MSWI} and landfill (in 1998/1999).
- Scenario I, R15 (15% mechanical recycling and 85% energy recovery in a MSWI) is based on two main developments:
  - An in-depth analysis and evaluation of market development of secondary packaging plastics has evidenced that the sensible mechanical recycling potential for the foreseeable future will stay around 15%, especially with respect to MR for the year 2006 [38]: the evaluation was made together with key actors in the recycling area. This is the background on which scenario I was built and the level of 15% is related to market limitations. Mechanical recycling (MR) consists of the processing of relatively clean plastic mono-streams (such as plastic films, crates, pallets derived from IW).
  - Diversion from landfill means substitution by municipal solid waste incineration (MSWI) in combination with recycling. The assumption is that landfill will be substituted partly by modern MSWI’s with energy recovery and partly by recycling.
- Scenarios II, III, IV resp. R25, R35, R50:
  - The potential of 15% for sensible mechanical recycling is kept. Additional recycling of more contaminated, more heterogeneous plastic packaging streams is realised by feedstock recycling (FR) and/or mixed plastics recycling (MPR).
  - In scenario II, a first increase of recycling is achieved by feedstock recycling. In Germany this option (blast furnace) is already operational for some years. In this way the increase of 15% to 25% recycling is realised.
  - A future increase from 25% to 35% has been considered in scenario III, via MPR. Some Northern European countries have experience with such mixed plastics recycling (substitution of wood and/or concrete).
  - In scenario IV, a further increase of recycling from 35% to 50% is considered, which is achieved by increasing the recycling rates both via FR and MPR. This scenario is in line with the actual approach in Germany.
  - In all II-IV scenarios, energy recovery in a modern MSWI complements recycling for treating the remaining part of the plastics waste stream.

Table T.1 Recycling targets of main scenarios.

Scenario	Code	Recycling target:					
		MR	MPR	FR	ER_{high}	ER_{MSWI}	Landfill
Reference 1	Landfill [3)]						100%
Reference 2	NOW	10.7%	1.3%	3.0%	2.0%	13.0%	70%
Scenario I	R15 [1)]	15%				85%	
Scenario II	R25y or R25g [2)]	15%		10%		75%	
Scenario III	R35y or R35g [2)]	15%	10%	10%		65%	
Scenario IV	R50y or R35g [2)]	15%	20%	15%		50%	

1) For recycling rates up to 15% it is assumed this target can be achieved by collection of industrial waste mono streams and by bottle bank collection. In the sensitivity analysis of this study some additional scenarios are dealt with 10% recycling rate and 90% energy recovery; see part II, Executive Summary.

2) For higher recycling levels than 15% more comprehensive routes such as a grey bag system or a yellow bag system are required. The code addition “y” and “g” is related to yellow bag and grey bag system respectively.

3) In some figures in this report the Landfill scenario is presented with the abbreviation “Landf”.

Table T.1 presents the defined recycling targets of the scenarios for comparison. The temporal framework of this study is “the late nineties”.
The (theoretical) recycling scenarios I, II, III and IV have been defined as a combination of processing routes and these scenarios reflect the present technology and the developments in the next few years. The increasing recycling rate R of the scenarios II, III and IV can be realised by the recycling of packaging plastics of MSW with two alternative collection routes, either by yellow bag collection (scenarios R25y, R35y and R50y) or by grey bag collection (scenarios R25g, R35g and R50g).

Results costs inventory:

Figure S.1 shows the results of the costs inventory of the reference and recycling scenarios. Total costs are in the range of 0.17 Euro per kg (scenario landfill) to 0.67 Euro per kg packaging plastics (scenario R50y). Costs figures are divided in 4 parts; collection costs, separation and upgrading costs, treatment costs (application processes) and resulting benefits (negative costs) as a consequence of the substitution of products. Figure S.1 demonstrates the increase of costs with increasing R and these increased costs are only partly compensated by increased benefits. The lower total costs level of grey bag scenarios compared with yellow bag scenarios is mainly caused by differences in collection costs.

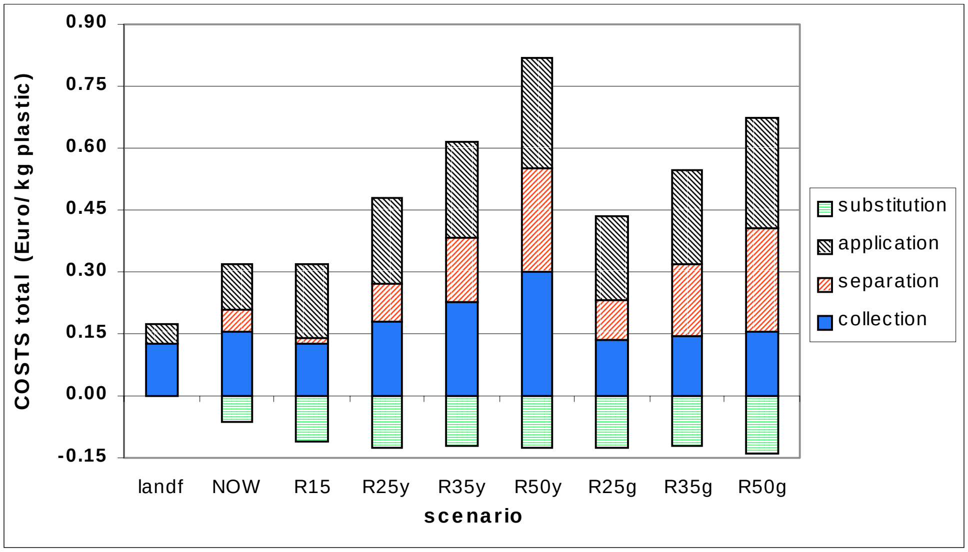

Figure S.1 Results of costs inventory.

Environmental impacts:

Mass balances and energy balances are the calculation basis for environmental “interventions” as emissions, depletions, wastes etc. Process data for mass balances and energy balances in this study are derived from literature. Interventions are translated into “potential” environmental effects. As a consequence environmental impacts are expressed in terms of:

1. Mineral resources depletion potential (ADP),
2. Fuel resources depletion potential (EDP),
3. Global Warming Potential (GWP),
4. Ozone Depletion Potential (ODP),
5. Human Toxicity Potential (HTP),
6. Aquatic Eco Toxicity Potential (AETP),
7. Photochemical Ozone Creation Potential (POCP),
8. Acidification Potential (AP),
9. Nutrification Potential (NP),
10. Final Waste (FW),
11. Specific (hazardous) final waste (TW),
12. Cumulative energy requirement (ENER).

The “overall comparison” of environmental impacts of scenarios in this study is illustrated by normalised bar charts; the average impacts per European capita per year are used as normalisation factors. These graphs give an integral overview of the jointly normalised environmental aspects of the scenarios, including impacts and benefits for the environment. Figure S.2 shows the results of the comparison of yellow bag scenarios R25y, R35y and R50y with both reference scenarios (landfill and NOW) and scenario R15. Figure S.3 shows the results for the comparable grey bag scenarios.

According figures S.2 and S.3 the environmental impacts FW and TW, followed by EDP, ENER, GWP, POCP, AP and AETP, have a relatively significant contribution, considering the comparison of the scenarios. The calculated FW impact is mainly a consequence of the landfill routes, whereas most of the TW impact is generated from residues and fly ash of MSWI. The contributions to AETP, AP, EDP, ENER and POCP are mainly realised by the avoided impacts of the substituted processes. To some extent the AETP, AP, EDP and ENER impacts are partially affected by the energy input of the packaging plastics collection and treatment.

Both reference scenarios cause a relatively high contribution to FW, whereas the recycling scenarios in sequence of R15, R25, R35 and R50 realise relatively high TW loads.

The comparison of the environmental impacts illustrated in figure S.2 and figure S.3 does not result in an obvious image of the consequences of increasing the recycling rate R. The GWP and POCP load reduce with increasing recycling rate R, while the AETP, EDP and AP loads enlarge with increase of the recycling rate R.

Comparison of the yellow bag scenarios (figure S.2) and grey bag scenarios (figure S.3) does not result in any significant differences. The grey bag scenarios have a slightly higher AETP and EDP impact compared with the yellow bag scenarios, due to the energy requirement of mechanical separation in the case of application of grey bag processing routes.

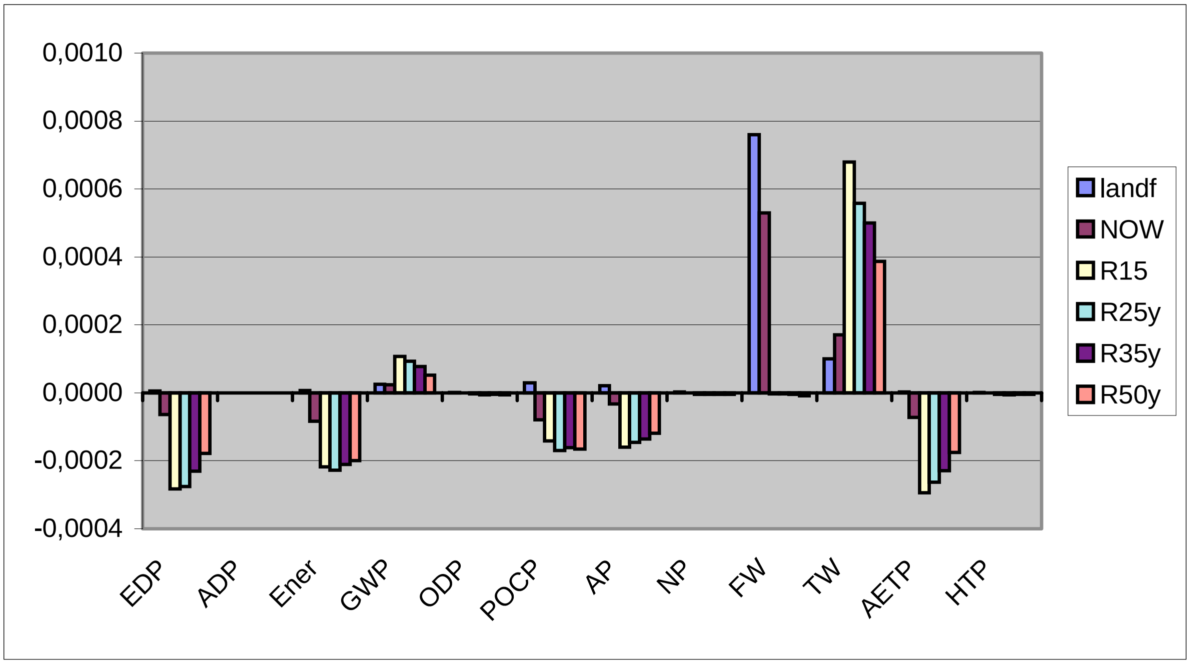

Figure S.2 *Environmental impacts, normalised scores; comparison reference scenarios with R15 (scenario I), R25y, R35y and R50y (scenarios II, III and IV, collection with yellow bag).*

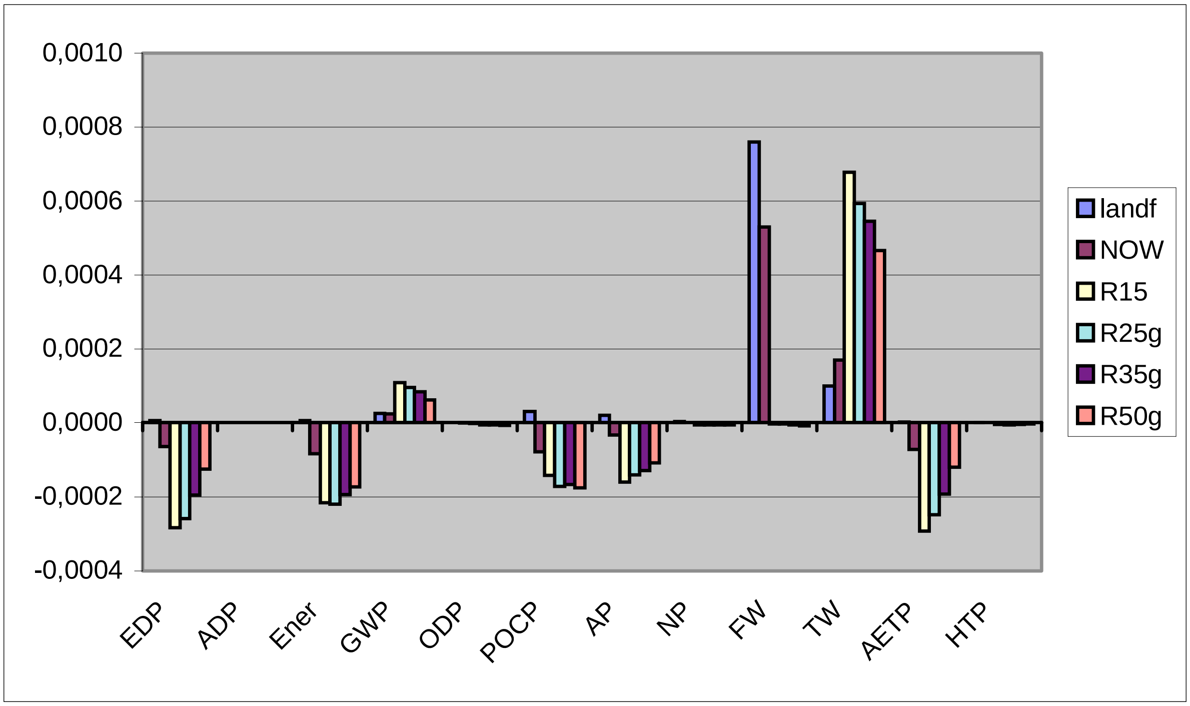

Figure S.3 *Environmental impacts, normalised scores; comparison reference scenarios with R15 (scenario I), R25g, R35g and R50g (scenarios II, III and IV, collection with grey bag).*

Executive summary part II: demonstration of Eco-efficiency

Weighting of environmental impacts:

For the presentation of an integral value of environmental impacts an *aggregated* (or integral) environmental impact score is calculated. As a consequence integral environmental impact scores in this study are based on weighting of the different environmental aspects. Weighting is a subjective item. In order to compensate this objection different weighting methods and weighting factors are used in this study, whereas a clear distinction is made between results with and without weighting. The base weighting method in this study gives all impacts equal weighting, except for both the toxicity themes (AETP and HTP). The weighting factors for toxicity are multiplied with a factor ½, because some uncertainties exist as to how this type of impacts should be modelled.

The combined presentation of integral environmental impacts and total costs of the studied scenarios is based on the Eco-efficiency portfolio presentation, as developed by BASF. This presentation has two important characteristics:

- The *differences* between total costs scores and the differences between integral environmental impact scores of individual scenarios are presented.
- The portfolio is *standardised* and all values are made dimensionless.

Figure S.4 shows the results of the yellow bag scenarios R25y, R35y and R50y together with those of the both reference scenarios (landfill and NOW) and scenario R15. The reference scenarios show the greatest environmental load, but the costs are relatively low. Scenario R15 gives an obvious decrease of the environmental load without a significant increase of costs. With increasing R value the scenarios R25y, R35y and R50y show an increase in costs without an obvious reduction of the environmental impacts. Scenario R15 (and then R25y) is the most favourable scenario with regard to the Eco-efficiency analysis.

The Eco-efficiency method is clearly a demonstration tool for showing the consequences of changed selections of scenario processes, weighting procedures or starting points of calculations. The portfolio presentation can be used for illustration of the sensitivity of these changes.

One of the questions raised is the comparison of the consequences of the grey bag processing routes with those of the yellow bag processing routes. Figure S.5 shows little difference is observed with respect to the Eco-efficiency of yellow bag systems versus the grey bag systems. The yellow bag systems are realised with higher costs while the grey bag systems are characterised by somewhat more environmental load.

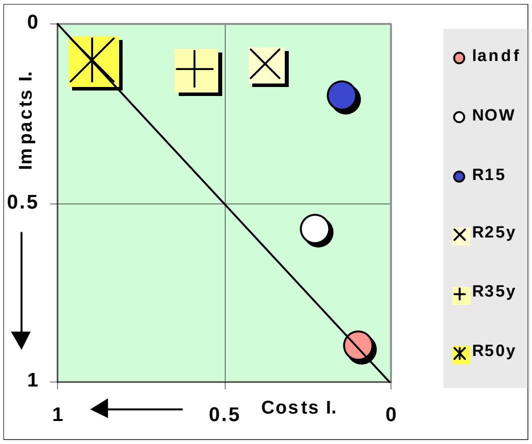

Figure S.4 Eco-efficiency portfolio : Comparison of reference scenarios with R15 (scenario I), R25y, R35y and R50y (scenarios II, III and IV by collection with yellow bag).

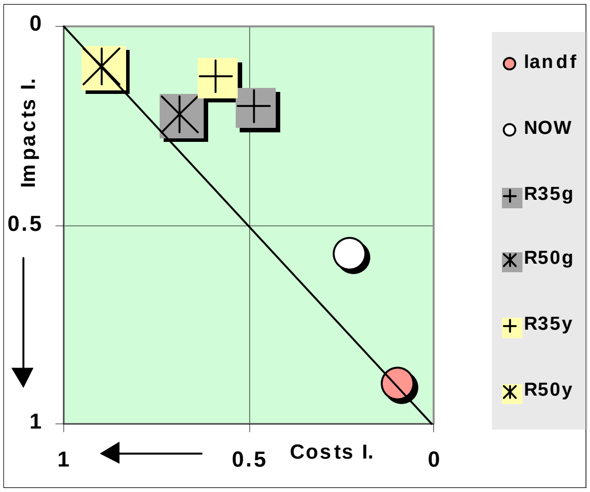

Figure S.5 Eco-efficiency portfolio : Comparison of reference scenarios with R35g, R50g, R35y and R50y (scenarios III and IV by grey bag versus yellow bag).

With respect to the sensitivity analysis, weighting factors and normalisation factors are varied within defined limits. In all analysed cases scenario R15, followed by R25, is the most favourable one from the Eco-efficiency point of view.

In the sensitivity analyses specific assumptions for energy recovery and substituted processes are varied. In the comparison, the exclusion of landfill is an important prior condition for all recycling scenarios. Landfill instead of energy recovery would result in a considerable increase of environmental impacts and a considerable decrease of Eco-efficiency.

In figures S.6, S.7 and S.8 the consequences of specific assumptions for energy recovery and substituted processes are demonstrated comparing reference scenarios and scenarios with yellow bag collection:

- Figure S.6 shows the comparison if a substantial part of the energy recovery in scenario R35y and R50y is realised by co-combustion of plastics in a cement kiln (ER_{high}).
- Figure S.7 demonstrates the portfolio if the energy recovery by MSWI is realised with high efficient heat recovery.
- Figure S.8 demonstrates the portfolio if the feedstock recycling target (FR) in all recycling scenarios is realised by gasification of plastics (Texaco process) instead of the blast furnace.

The sensitivity analysis in figure S.6, S.7 and S.8 illustrates that these changes of underlying specific assumptions for energy recovery and substituted processes has a relatively small influence on the Eco-efficiency profiles. In all analyses scenario R15, followed by R25, shows to be a favourable one with respect to Eco-efficiency.

In the sensitivity analysis some additional scenarios are considered in addition to the main recycling scenarios. The main objective is to illustrate the consequences of a decreasing MR or MPR rate together with an increasing ER rate. In figure S.9 two additional scenarios with 10% mechanical recycling plus 90% energy recovery are compared with the reference scenarios and the main recycling scenarios. In the first additional scenario the 10% mechanical recycling is focused at IW plastic mono streams (R10i/E90), whereas in the second additional scenario mechanical recycling is mainly focussed at plastics in MSW.
Figure S.9 demonstrates that the Eco-efficiency of the 10% mechanical recycling scenario focussed at IW plastic mono streams in this context is nearly equal with the Eco-efficiency of the main scenario with 15% mechanical recycling and 85% energy recovery (R15/E85).
Figure S.9 also demonstrates that the 10% mechanical recycling scenario focussed at MSW plastics (R10m/E90) results in a considerable decrease of Eco-efficiency compared with other scenarios (R15/85E and R10i/90E). The most important factor is the increase of costs of mechanical and mixed plastics recycling of plastics in MSW, compared with mechanical recycling of IW plastic mono streams or energy recovery in a MSWI.

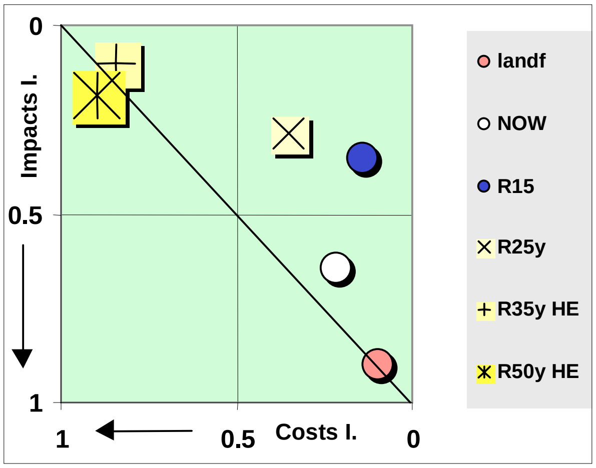

Figure S.6 *Eco-efficiency portfolio :*
Comparison of R35yHE and R50yHE (scenarios III and IV with energy recovery by means of a combination of MSWI and cement kiln) with scenario I (R15), scenario II (R25y) and reference scenarios (landfill and NOW).

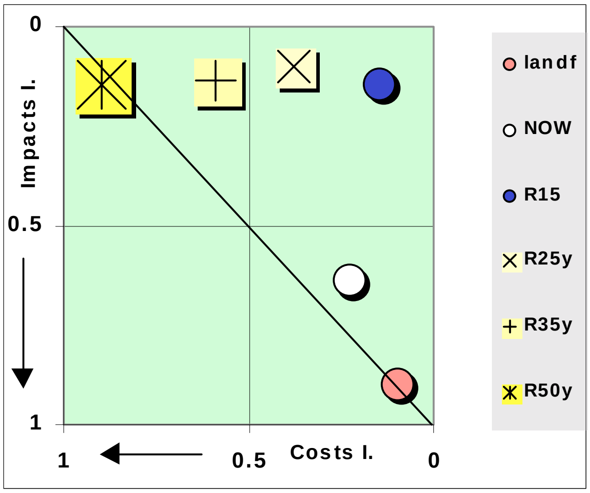

Figure S.7 *Eco-efficiency portfolio :*
Comparison of R15, R25y, R35y and R50y (scenarios I, II, III and IV with energy recovery by means of a MSWI with 65% heat recovery efficiency) with the reference scenarios (landfill and NOW).

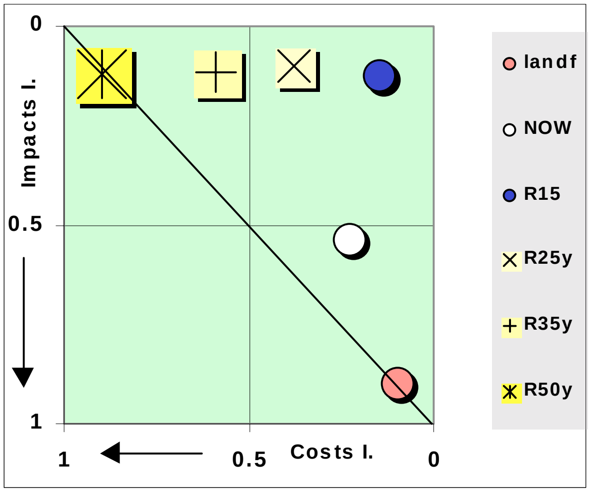

Figure S.8 *Eco-efficiency portfolio :*
Comparison of R15, R25y, R35y and R50y (scenarios I, II, III and IV with feedstock recycling by the Texaco gasification process) with the reference scenarios (landfill and NOW).

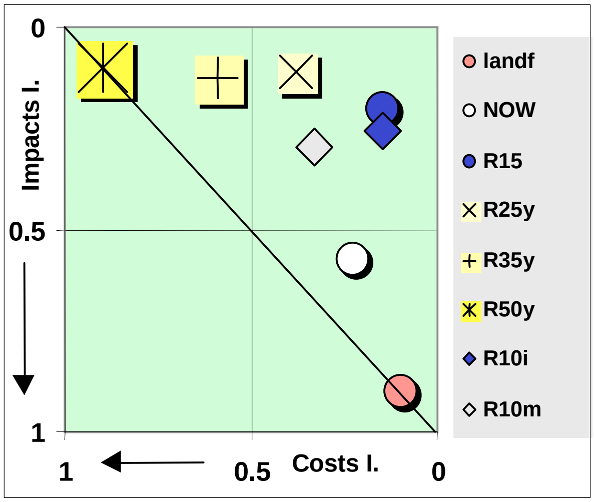

Figure S.9 *Eco-efficiency portfolio :*
Comparison of alternative scenarios with 10% mechanical recycling and 90% energy recovery (R10i, focussed at IW plastics and R10m, focussed at MSW plastics) with scenarios I, II, III and IV (R15, R25y, R35y and R50y) and reference scenarios (landfill and NOW).

The general conclusions are:

- The executed study is a first step with regard to the comparison of scenarios with different levels of material recycling and energy recovery.
- For this study (except the market evolution of recycled plastics) the approach is descriptive rather than change oriented. It is based on theoretical scenarios. As usual for such studies, results may vary according to the data used, the selected primary products and processes which are substituted by secondary products/energy resources, or by the weighting method selected to calculate the integrated environmental impact. Some variants around the basic scenarios I-IV illustrate the impact this can have on the conclusions.
- The calculations are related to the current situation with respect to the composition of plastics (the “average” European composition) and real “state of the art” processes (developed in Northern Europe). The data used are related to the second half of the nineties. This study does not present results of a dynamic approach with respect to composition changes of plastics and improvement of existing processes or introduction of new processes.
- Within the described limitations the study indicates trends for the next decade. The results of the study have to be used on an European level (or possibly country level) and are not applicable for any local/regional situation, because waste volumes, compositions and regional collection systems can vary enormously.
- The results of the study show:
    - The single most positive impact on eco-efficiency comes via diversion from landfill in favour of a combination of mechanical recycling of monomaterial relatively clean waste + energy recovery in moderately efficient modern MSWIs (30% energy recovery efficiency, complying with the new EU Incineration Directive).
    - Increasing the efficiency of energy recovery improves the eco-efficiency of the system.
    - Increasing recycling rates from 15 to 50% (with FR and/or MPR) and correspondingly decreasing the energy recovery rate increases costs by a factor 3 while environmental impact remain broadly similar.
    - With the choice of the recovery options mechanical recycling of monomaterial relatively clean waste + energy recovery in moderately efficient modern MSWIs, significant improvement in environmental impact could be achieved at similar costs compared to the current EU average.
- Further developments based on the results of this study can be:
    - The execution of prospective studies of selected routes for given countries.
    - The execution of a change-oriented approach including changes in plastics composition and innovations in technological processes.
    - An evaluation within 5 years to take into account the evolution of waste composition, waste processing techniques and to include the actual experience in the field of municipal solid waste management.
- The study has been critical reviewed by a panel of independent experts.

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Appendix C: LCA methodological aspects

1. Introduction

1.1 Background

The requirement of the Association of Plastic Manufacturers in Europe (APME) is to be able to apply an integral, typical European model to demonstrate the relative effectiveness, in economic and environmental impact terms of various plastic waste recovery structures.
BASF has developed a user-friendly model to illustrate Eco-efficiency comparisons and BASF has made this concept accessible for use by APME. With this model it is possible to assist APME in developing an integral strategy for the recycling or recovery of plastic waste streams, in particular for packaging plastics. With the results of the model output interactive discussions with opinion formers and policy makers can be conducted. The objectives and targets of the European Packaging and Packaging Waste Directive, and the impending revision of targets are the basis of such discussions.

With the help of the output of the model, the impact of higher recycling amounts/higher recovery amounts is illustrated. This has been done for household packaging waste and industrial packaging waste together. Actual waste processing structures in several European countries and data from integral, technical, environmental and economical studies already executed are the starting point for the model use. Different combinations of mechanical recycling, feedstock recycling, (high) energy recovery, incineration (with energy recovery) and landfill can be applied.
Different scenarios have to be calculated and weighted in terms of economics and environmental aspects to show the relative effectiveness of the different combinations of plastics processing options: Calculations give the results of an “Eco-efficiency” analysis.
The benefits of an “Eco-efficiency” analysis in terms of waste recovery are :

- The most appropriate recovery options can be chosen to optimise the balance between environmental gain and economic costs.
- The reassurance that recovery decisions are based on sound technical data.
- The results identify opportunities for improvement.

APME requested TNO to calculate the economics and environmental aspects of several plastic packaging waste processing scenarios and to present the results in terms of “Eco-efficiency” using the BASF concept.

1.2 Objectives

The objectives of the study are:

- Comparison of the environmental aspects and economical impact of different scenarios of integrated processing routes of packaging plastics, including collection, pre-processing, mechanical recycling, feedstock recycling, energy recovery, residues incineration and as base case landfill.
- Calculation and determination of the Eco-efficiency profiles of theoretical developed scenarios and comparison of them with the Eco-profiles of existing base structures.
- Execution of an analysis to illustrate how a plastic packaging waste processing scenario can be improved in terms of Eco-efficiency.

1.3 Set up of the report

The report is divided in two parts.

Part I contains the LCA study and the costs inventory. This part meets the ISO 14040 LCA standard.
The main items of part I are:

- Goal and scope of the costs inventory and LCA study
- Characteristics of the plastic packaging waste
- Basis for comparison of the different scenarios
- Mass balances of the different scenarios
- Inventory of the environmental and costs data
- Impact assessment of the several environmental aspects
- Normalisation of the different environmental aspects
- Conclusions of part I

Part II contains the demonstration of the Eco-efficiency concept.
The main items of part II are:

- Description of the Eco-efficiency concept
- Calculation and demonstration of the Eco-efficiency impact
- Conclusions of part II

PART I: LCA study and costs inventory

2. Goal and scope of the study

2.1 Goal of the study

2.1.1 Goal and description

The goal of the study is to identify, on the basis of Europe-wide based scenarios, eco-efficient trends in plastics packaging waste management for the next decade. With the help of the results of model calculations several theoretical scenarios based on existing processing routes can be compared with respect to environmental impacts and resulting costs. Based on actual waste processing structures in several European countries (especially Germany, Belgium, The Netherlands) and gathered data from technical, environmental and economical studies already executed, theoretical scenarios are built and compared with reference scenarios. Analysis of the current situation and comparison with theoretical scenarios with more material recycling/energy recovery is the aim of model calculations. Different combinations of mechanical recycling (of mono streams as well as mixed plastics), feedstock recycling, high energy recovery, incineration (with energy recovery) and landfill are compared.

Combination of the calculated and weighted environmental and economic impacts will result in “eco-efficiency” presentations. These presentations will show the relative effectiveness of different combinations of plastic processing options. The results will show in which direction an improved processing of plastic packaging waste will go and opportunities for improvement will be identified.
The study is a first step to illustrate, starting from the present situation, “eco-efficient” options for recycling and recovery; a dynamic oriented follow-up will give more support to the identified improvement options.

The study is focused on that part of Europe (15 EU members and Norway and Switzerland) that can be considered as a “single” market with regard to plastic packaging consumption and recycling of plastics. In practice the EU member states are the relevant region for waste and waste treatment. Real data of processes, “average” European data of (plastic) waste and typical data of other aspects from (regions of) EU member states are applied for the calculations.
The study will indicate trends for the next decade. This means that the results of the study have to be used on a European level (or possibly country level) and are not applicable for any local/regional situation. In accordance to these situations regional waste volumes, waste compositions and regional collection and treatment systems have to be considered.

For this study (except the market evolution of recycled plastics) the approach is descriptive rather than change oriented. It is based on theoretical scenarios. As usual for such studies, results may vary according to the data used, the selected primary products and processes which are substituted by secondary products/energy resources, or by the weighting method selected to calculate the integrated environmental impact.

2.1.2 Target group

With the results of the study interactive discussions with opinion formers and policy makers on a European level can be conducted. The objectives and targets of the European Packaging and Packaging Waste Directive, and the impending revision of targets are mostly the basis of such discussions. In this area at least three groups of actors can be distinguished:

- Policy makers (National government, EU Commission and EU Parliament).
- Industry.
- Non-Governmental Organisations.

Representatives of these groups are in a permanent discussion about the optimal waste management situation and recovery structures for plastic packaging. The results of this study should serve as a common basis of information in this ongoing discussion.

2.1.3 Initiator

Initiator of this study is the APME (Association of Plastics Manufacturers in Europe).

2.2 Scope of the study

2.2.1 Functional unit

The functional unit (FU) is the base for analysis and comparison in this study.

FU in this project is:
the "coherent treatment" of 1 kg "average" packaging plastics out of Municipal Solid Waste (MSW) and out of Industrial packaging Waste (IW).

Explanation:

- "Coherent treatment" in this sense means a specific combination of processes, which allows for an adequate treatment of the mix of plastic packaging.
- "Average" packaging plastics means a *weighted* average in composition and morphology of packaging plastics in European MSW and IW.

For comparisons “a state of the art” selection of application processes has to be made. In chapter 4 an execution of this selection is described.

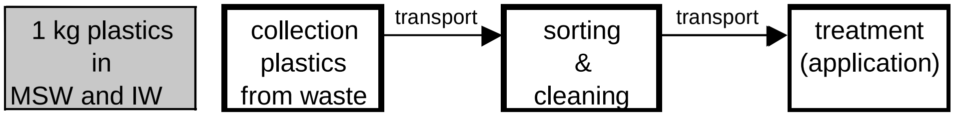


Figure 2.2.1 Functional unit (FU) for comparison in this study: coherent treatment processes of 1 kg plastics.

2.2.2 Recycling categories

In view of the goal of the study, the comparisons should include a reference as well as state of the art examples of “ application ”processes for mechanical recycling, feedstock recycling and energy recovery.
With respect to the different recovery options the following possibilities can be distinguished:

Mechanical Recycling processes (MR/MPR)

- (mono-material) mechanical recycling **(MR);** the recycled plastic substitutes the virgin material
- mixed plastics recycling **(MPR)**; the recycled plastics substitute a non-plastic material (e.g. wood, concrete)

Feedstock Recycling processes (FR)

The recycled plastics substitute the application of fossil resources (feedstock) in production processes (substitution of gas, oil, etc.).

Energy recovery processes (ER)

- The use of recycled plastics as a fuel during energy production (co-combustion), characterised by a high conversion efficiency (**$\mathbf{ER}_{\mathbf{high}}$**)
- Plastics in waste are incinerated and energy application is a side activity (**$\mathbf{ER}_{\mathbf{mswi}}$**)

2.2.3 Comparison of scenarios

In this study the environmental aspects and costs of six defined (theoretical) scenarios based on existing waste processing routes have been compared. Table 2.2.3 presents an overview of the scenarios and the defined recycling targets. The building of the scenarios is as follows:

Out of these real processes (routes) theoretical scenarios are built (summarised in Table T1):

- Two reference scenarios are distinguished:
  1. 100% landfill; in South-Europe landfill is the dominating applied waste processing method. It is favourable to demonstrate the environmental benefits when diversion from landfill occurs.
  2. NOW; this scenario approaches the real situation in the EU with respect to MR, FR, ER_{MSWI} and landfill (in 1998/1999).
- Scenario I, R15 (15% mechanical recycling and 85% energy recovery in a MSWI) is based on two main developments:
  - An in-depth analysis and evaluation of market development of secondary packaging plastics has evidenced that the sensible mechanical recycling potential for the foreseeable future will stay around 15%, especially with respect to MR for the year 2006 [38]: the evaluation was made together with key actors in the recycling area. This is the background on which scenario I was built and the level of 15% is related to market limitations.
    Mechanical recycling (MR) consists of the processing of relatively clean plastic mono-streams (such as plastic films, crates, pallets derived from IW).
  - Diversion from landfill means substitution by municipal solid waste incineration (MSWI) in combination with recycling. The assumption is that landfill will be substituted partly by modern MSWI’s with energy recovery and partly by recycling.
- Scenarios II, III, IV resp. R25, R35, R50:
  - The potential of 15% for sensible mechanical recycling is kept. Additional recycling of more contaminated, more heterogeneous plastic packaging streams is realised by feedstock recycling (FR) and/or mixed plastics recycling (MPR).
  - In scenario II, a first increase of recycling is achieved by feedstock recycling. In Germany this option (blast furnace) is already operational for some years. In this way the increase of 15% to 25% recycling is realised.
  - A future increase from 25% to 35% has been considered in scenario III, via MPR. Some Northern European countries have experience with such mixed plastics recycling (substitution of wood and/or concrete).
  - In scenario IV, a further increase of recycling from 35% to 50% is considered, which is achieved by increasing the recycling rates both via FR and MPR. This scenario is in line with the actual approach in Germany.
  - In all II-IV scenarios, energy recovery in a modern MSWI complements recycling for treating the remaining part of the plastics waste stream.

Table 2.2.3 Recycling targets of scenarios.

Scenario	**Code**	**Recycling target:**					
		MR	**MPR**	**FR**	**ER_{high}**	**ER_{MSWI}**	**Landfill**
Reference 1	Landfill 3)						100%
Reference 2	NOW	10.7%	1.3%	3.0%	2.0%	13.0%	70%
Scenario I	R15 1)	15%				85%	
Scenario II	R25y or R25g 2)	15%		10%		75%	
Scenario III	R35y or R35g 2)	15%	10%	10%		65%	
Scenario IV	R50y or R50g 2)	15%	20%	15%		50%	

1) For recycling rates up to 15% it is assumed this target can be achieved by collection of industrial waste mono streams and by bottle bank collection. In the sensitivity analysis of this study some additional scenarios are dealt with 10% recycling rate and 90% energy recovery.

2) For higher recycling levels than 15% more comprehensive routes such as a grey bag system or a yellow bag system are required. The code addition “y” and “g” is related to yellow bag and grey bag system respectively.

3) In some figures in this report the Landfill scenario is presented with the abbreviation “Landf”.

In scenarios III and IV (see table 2.2.3) there is an alternative for ER_{mswi} as the ER option. This alternative ER option consists of 33.8% ER_{mswi} and 31.2% ER_{high} .in the case of R35, whereas 33.8 % ER_{mswi} and 16.2% ER_{high} .in the case of R50. The calculations of the last mentioned options for R50 and R35 are executed during the sensitivity analysis.

The scenarios can be defined in different ways, with different coherent treatment processes.
For example: the 10% FR target can be reached by means of:

- Two bin (dry/wet) collection, with the MSW plastics in the dry fraction, followed by a mechanical separation of a mixed plastics fraction.
- Yellow bag collected MSW packaging fraction with plastics, followed by combined manual and mechanical separation of mixed plastics.
- Collection of mixed IW plastics, followed by mechanical separation.

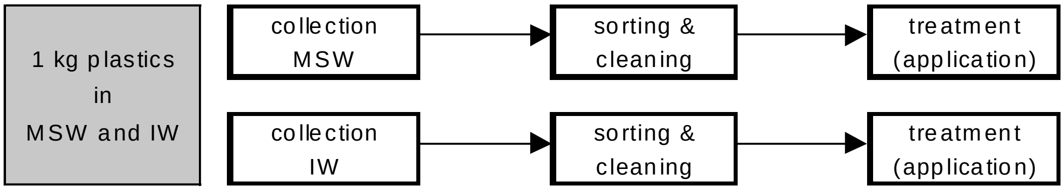


Figure 2.2.3 Separate routes for packaging plastics in MSW and in IW.

Scenarios in this study have been defined as a combination of selected routes of processes with state of the art technologies. In general, packaging plastics in IW are collected separately from packaging plastics in MSW. That is why the routes for packaging plastics in MSW are considered apart from routes for IW packaging plastics (see figure 2.2.3). In chapter 4 the selection of routes and the combination of routes to build up the required scenarios are executed.

The study is focused on that part of Europe (15 EU members and Norway and Switzerland) that can be considered as a “single” market with respect to plastics consumption and recycling of plastics. With regard to waste treatment national (regional) policy is dominating, but more and more EU-directives are becoming the leading starting condition. In practice the EU member states are the relevant region for the waste and the waste treatment. This does not mean that all input data are based on real average EU data. Whereas waste quantities and composition data are based on European averages from inventories in literature (see also chapter 3), the technologies in this study are based on real “state of the art” examples, representative for the actual developments in Northern European countries (see also paragraph 2.5.2).

2.3 Temporal representativity

Data on waste arising and composition refer to the period 1996-1998. Data on the technologies and “fore ground processes” used (see2.5.1), varies per technology:
- landfill (historical data 1990-1998)
- mechanical recycling (1996-1999)
- feedstock recycling (1996-1999)
- energy recovery (1996-1999)

Data for the “background” processes, e.g. electricity production, transport, utilities, etc.(see chapter 2.5.1), refer to the period 1990-1999.

2.4 Analysis-type

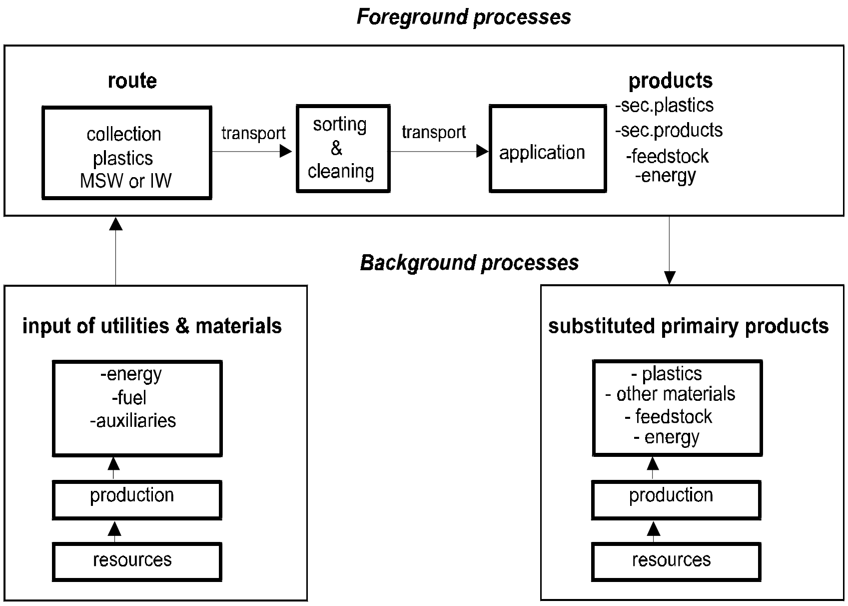
In the current methodology of LCA, a distinction is made between marginal and average analysis. Marginal analysis is change-oriented, whilst average analysis is descriptive.
This study has a descriptive (average) character looking from the waste world to the rest of the economic society. With respect to market outlets for recycled materials, a dynamic approach is applied.

2.5 Inventory aspects

2.5.1 System definition

Figure 2.5.1 shows the basic system for analysing. Scenarios are constructed by routes, including two type of processes:

- Foreground processes: the collection of plastics, sorting and cleaning and application processes
- Background processes; theses processes include inputs for foreground processes and the substituted processes. Substitution is a consequence of the recovery of plastic products.



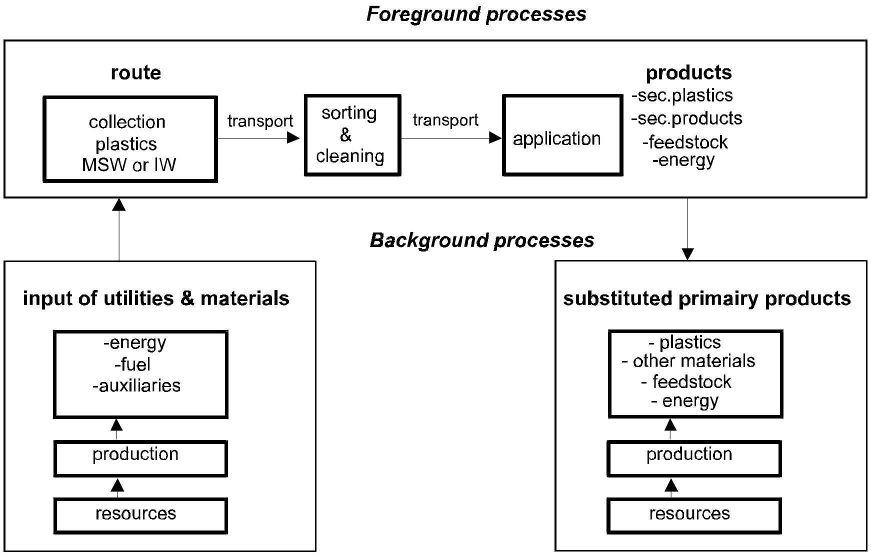


Figure 2.5.1 System outline in this study.

2.5.2 Process data and data quality

Process data for Foreground Processes and costs data are derived from literature.

- Quantities and morphology of plastics are based on the Sofres study (1)
- Collection and separation are mainly based on the Cold Box study (2).
- Application processes are bases on TNO models (15,16), on the Fraunhofer studies (3, 4) and on the Texaco study (5).

A more detailed overview of the processes is given in table 2.5.2.

Table 2.5.2 Overview of the processes/activities.

Name process/activity	Reference(s)	Geographical representativeness	Year (range)	Char data
Collection	(2), (39), (40)	Germany, Belgium, Netherlands, Switzerland, Scandinavia, Italy	1995 - 1999	Typic
Pretreatment/separation/sorting	(2), (39), (40)	Germany, Belgium, Netherlands, Sweden, Norway	1995 - 1999	Typic
Mechanical recycling mono-streams	(4), (40)	Germany, Belgium, Netherlands, Italy	1996 - 1999	Typic
Mixed plastics recycling	(4)	Germany	1996 - 1999	Typic
Blast furnace	(3)	Germany	1996 – 1999	Typic
Texaco gasification	(5)	Netherlands	1996 – 1998	Typic
Cement kiln	(4)	Germany	1996 – 1999	Typic
MSWI	(3), (15), (16), (25)	Netherlands, Germany	1995 – 1999	Aver
Landfill	(15), (16)	Netherlands	1990 - 1998	Aver

The scope of these studies is the European area and the results of these studies are supported (checked) by the main actors with respect to the different aspects.

Process data for background processes are derived from LCA literature (databases):
- Production of primary plastics: APME reports (17)
- Production of fuels, energy conversions and transport processes: BUWAL 250 (18)

BUWAL 250 incorporates the APME data (17) and has added more information to these specified data sets.1) Foreground data as well as background data are from different sources. Data quality is different varying from good to estimations and is dependent of the sources. This is acceptable within the scope of the study.

2.5.3 Allocation

In case of a multi-functional input and /or output process, the interventions of that process should be allocated to the relevant substance flow of the functional unit.

Allocation for multi-input processes like co-combustion, MSW incineration and landfill has been carried out on basis of physical causality (15, 16, 19).

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1) For the production of primary plastics the BUWAL 250 data are not applied, but the original APME data. This inconsistency is of minor relevance, because all recycling scenarios include an amount of 15% MR (substitution of primary plastics), so possible differences between scenarios are leveled out.

In this study the allocation problem occurs mainly at multi-output processes at the end of the routes or the “value” of their end products. Two different approaches exist (13, 14), as defined in ISO (14)*), with the following order:

1) avoid allocation by system enlargement;
2) define a relevant criterion for allocation.

Both approaches are being used in practice. System enlargement has the advantage of avoiding the problem. The disadvantage is that in case of a comparison of different systems, the lowest common multiple might become a very complex system, including almost the whole world of processes. The discriminative power between the results becomes very weak, because the results are mainly determined by the imported processes. For this reason it is more clarifying to present the results in the form of a difference: **the substitution method**. In this case the resulting end products are valued on basis of the production processes, which they are able to avoid, when using them. Theoretically there is a difference between system enlargement and the substitution method, but regarding the present differences between the scenarios both methods are comparable with each other.
If necessary corrections for the difference in primary and secondary material quality, life time differences etc. have to be made by means of substitution factors (see table 4.4.1).

2.6 Impact Assessment

For LCA studies several impact assessment methods are reported. Most important differences between published methods are how to deal with the environmental themes toxicology, depletion and final waste. Each of these impact assessment methods has its own specific merits combined with specific disadvantages. In this field the CML method (6) is one of the most detailed and in the European area most accepted method. Consequently the impact assessment method in this study is mainly based on the CML method (6). According to the CML impact assessment method invented interventions (emissions and depletions) are translated into “potential environmental effects”. Table 2.6 gives an overview of these effects.

This study applies some adaptations to the CML method (concerning ADP, EDP, HTP, AETP, energy (ENER), final waste (FW) and specific final waste (TW); see Table 2.6). The background of these adaptations is discussed in appendix C1.

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*) ISO 14042 gives a detailed description for the allocation procedure in LCA’s.

Table 2.6 Overview of environmental effects.

Environmental effect	Abbreviation	Dimension
Mineral Resources Depletion Potential	ADP	$(kg.y)^{-1}$ E+15
Fuel Resources Depletion Potential	EDP	$(MJ.y)^{-1}$ E+15
Global Warming Potential	GWP	kg eq. CO_2
Ozone Depletion Potential	ODP	kg eq. CFC11
Human Toxicity Potential	HTP	kg eq. htp
Aquatic Eco toxicity Potential	AETP	m^3 eq. aetp
Photochemical Ozone Creation Potential	POCP	kg eq. C_2H_4
Acidification Potential	AP	kg eq. SO_2
Nutrification Potential	NP	kg eq. PO_4
Special categories		
Final Waste	FW	Kg
Specific final Waste (hazardous waste)	TW	Kg
Cumulative energy requirement	ENER	GJ

2.7 Normalisation

A first step in the interpretation of the results is to translate the absolute scores of the environmental effect into relative scores. In this case the absolute scores are expressed as fractions of the total score of that particular environmental effect in a relevant region. The relevant region in this study is Europe. Normalisation factors in this study are derived per capita per year.

Table 2.7 gives an overview of normalisation factors. Background information of normalisation factors is reported in appendix C.2.

Table 2.7 Normalisation factors.

	Unit	Factor
ADP	kg.y. E-15	0.00043
EDP	MJ.y. E-15	0.0016
GWP	1/kg eq. CO_2	0.000085
ODP	1/kg eq. CFC11	11.3
POCP	1/kg eq. C_2H_4	0.11
AP	1/kg eq. SO_2	0.021
NP	1/kg eq. PO_4	0.019
FW	1/kg	0.0008
TW	1/kg	0.013
Ener	1/GJ	0.0073
AETP	$1/m^3$ eq. aetp	0.000014
HTP	1/kg eq. htp	0.000095

2.8 Evaluation

Evaluation of environmental aspects:
The characterisation step (the scores of the potential environmental effects) gives an environmental profile. This profile can be expressed in a bar chart. This can be done both for the absolute scores as well as for the normalised scores. The profile with normalised scores gives information about the relative importance of the various scores.
The environmental analysis (based on LCA methodology) ends with these profiles, according to ISO 14040 - 14043 (13).

Evaluation of costs aspects:
In principle the invented costs are “real” costs, without subsidies, profits, etc. For the scenarios the invented costs per FU can be compared with each other. The costs per scenario can be split up to the different routes, which build up the scenario, or to the different parts of the route (collection, separation, application).

Eco-efficiency:
The results as impacts of individual environmental themes are not used directly as a decision support. In that case the relation between the environmental effects must be determined, viz. weighting of the scores.
In order to describe this process on a transparent way, different weighting procedures, reflecting different starting points, have been used in order to produce a conclusive stage.
The results of the environmental weighting scores of a scenario are presented every time in combination with the normalised costs figure of that scenario: The Eco-efficiency score (a one point score in a graph with two axes). This part of the study is reported in part II of the report.

2.9 Critical review

This study has been critically reviewed by a team of four experts: Mrs. H. Teulon (Price Waterhouse Coopers), Mr. G.C. Bergsma (CE), Mr. R. Hischier (EMPA), Mr. T. Nurrenbach (Fraunhofer Institut).
The critical review process contained the following steps:
- Distribution of the first concept report to the critical review team.
- The critical review team members distributed lists with questions/remarks to the other team members, TNO and APME.
- Explanation of the questions/remarks is given during the joint meeting at October 4th 2000. A summary of the agreements is sent to the others by H. Teulon.
- TNO has labelled the questions of each team member list and has sent the answers to each team member how to handle the remaining questions

- Based on the agreements of the 4 October 2000 meeting and the residual remarks of the critical review team TNO has prepared a second concept report and has sent it to the team and APME.
- During the meeting of March 20th 2001 an agreement is reached on the final adjustments.
- TNO incorperates these adjustments and has sent the upgraded report to the critical review team members.
- Based on this report the team members give their comments to H. Teulon.
- With respect to all comments H. Teulon has written the critical review report agreed by the other team members; see chapter 13.

3. Characteristics of plastic packaging waste

3.1 Quantities of packaging plastics

The subject of this study concerns plastic packaging waste from household sources (MSW) and plastic packaging waste from industrial and commercial sources (IW). With respect to the contribution of both sources the following quantities of packaging plastics in MSW and IW are considered (1):

1 kg plastic packaging (FU) :
- **0.718 kg plastic packaging from MSW**
- **0.282 kg plastic packaging from IW.**

3.2 Composition of packaging plastics

Composition parameters:
Statistical data of plastic type (PE/PP, PET, PVC etc.) and morphology (bottles, films, etc) in this study are derived from the Sofres Study (1). Morphology of packaging plastics is presented in table 3.2.1 (MSW) and table 3.2.2 (IW).
Elemental composition of plastics is presented in appendix A1.1. Elemental composition of the packaging plastic in this study is extracted from the Fraunhofer study (ref. [3] ; table 1.1-4).
Heating values of plastics are calculated by the Boie formula. (ref.[3]; paragraph A1-2.2.2.2)

Contaminants and water content:
The FU of this study is based on 1 kg plastics, without waste contamination and water. During the collection of waste the plastic packaging will be contaminated with other waste components and water.
The other waste components belong to other product systems and are not recognised as a part of this system study. Water is partly descended from other waste components (other product systems) and originates partly from climate circumstances, such as rain.
Only when different processes differ in relation with contaminants and water the consequences for comparisons have to be considered. This results in the following argued assumptions:

- During collection no remarkable presence of contaminants and water is foreseen (assumption: There are no relevant differences between the different collection systems).
- For the estimation of the needed input (the energy requirement and the utility requirement) of separation processes the present contaminants and water are considered. The selected separation processes are based on these aspects. Regarding the calculations of the environmental output of separation processes

(emissions, residues) the influence of contaminants is not considered (assumption: There are no relevant differences).

- The preparation stage of MR, MPR and FR contains a drying process. The specifications of the input of mechanical recycling, feedstock recycling and mixed plastic recycling are as such that the contribution of contaminants and water to the environmental impact is negligible.
- For the ER option MSWI the reduction of energy production because of the presence of water is incorporated. During the calculations water contents of 10 wt% and 15 wt% are included as performed in the Fraunhofer studies (3,4). The presence of contaminants is not assumed.

Table 3.2.1 Plastic type and morphology of MSW category.

Polymer type:	Morphologic fraction:	w%
PE/PP	Large films	21.8%
PE/PP	Small films	25.3%
PE/PP	Bottles	10.2%
PE/PP	Other rigids	8.9%
PET	Bottles	11.7%
PET	Other rigids	1.4%
PS/EPS	Bottles	0.6%
PS/EPS	Other rigids	10.3%
PVC	Large films	1.8%
PVC	Small films	2.1%
PVC	Bottles	3.5%
PVC	other rigids	2.4%
Total		100%

Table 3.2.2 Plastic type and morphology of IW category.

Polymer type:	Morphologic fraction:	w%
PE/PP	Large films	54.4%
PE/PP	Small films	2.9%
PE/PP	Crates & pallets	26.5%
PE/PP	Rigids	10.0%
PS/EPS	Rigids	6.2%
Total		100%

4. Comparison basis

4.1 Starting points for the set up of scenarios

As already described the scenarios to be compared are based on a “coherent” processing of 1 kg packaging plastics, with 718 g from MSW **and** 282 g from IW.

All scenarios consequently are “constructed” from two routes:
- a MSW route for 718 g packaging plastics in MSW and
- a IW route for 282 g packaging plastics in IW.

The filling in of routes with state of the art processes can differ from each other. The several routes each result in a specified recycling score (R) regarding the amount of MR, FR and/or MPR recycling.

$$R = \sum (MR + FR + MPR)$$

The recycling score R of the route is calculated with the mass balance of the regarded route. The distributing parameters of the mass balance (such as response rates, separation efficiencies) are based on practical figures and experience data. The recycling scores R of *individual* routes generally don’t match exactly with the defined recycling targets of the scenarios (table 2.2.3). In this study the scenarios (especially with high recycling targets) consequently are constructed as a *combination* of a number of supplemented routes.

In the next chapter of this report the state of the art processes to build up the routes are described.

4.2 State of art processes

The routes contain state of the art processes for collection, separation and application of plastic packaging waste[1]. The selection of the different processes has the support of the steering group of APME.

The processes are described in detail in appendix A.2 (collection and separation processes) and appendix A.3 (application processes).
Hereafter a short description of the different processes is presented.

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[1] Non packaging plastic waste is excluded.

4.2.1 Processes for packaging plastics in MSW

Regarding MSW the following processes for collection and separation of packaging plastics are studied:

- **Bottle bank:** This collection system only concerns bottles from households etc. ("bring system"). The response rate is limited and is assumed to be 20% in this study. Bottle bank collection is restricted to PP/PE and PET type of bottles. Plastics collected by bottle banks are relatively clean. A simple manual sorting succeeds and after this activity the required specifications are realised. Bottle bank collection will reduce the percentage plastic bottles in the resulting MSW. Bottle Bank collection generally is combined with a black bag or with a grey bag collection method for the other plastic packaging articles.
- **Yellow bag collection:** This collection method includes separate collection of specific (recyclable) packaging fractions from MSW in a separate bin or bag **(yellow bag)**. Generally yellow bag collection includes plastic packaging, beverage cartons, and metal packaging. Response rate is assumed 67% and non-response plastics will be collected with other fractions of MSW. The collected content of the yellow bag is manually sorted and mechanically upgraded. The upgraded output is divided over MR (bottle fraction), MPR (films and mixed plastics) and FR (mixed plastics). Yellow bag collection generally is combined with a black bag collection method for non-response plastic fractions.
- **Dry/wet collection:** The collection of MSW occurs by a two bin (dry/wet) system. The wet bin contains putrescibles and organic wastes, whereas the dry bin (**grey bag**) includes the resulting mixture of all other MSW fractions, including packaging plastics and non-response putrescibles. Grey bag response rate for packaging plastics is assumed 100% because all plastics in the wet bin are separated and transferred to the grey bag processing. The content of the grey bag will be **mechanically separated and upgraded**. The upgraded output does not match specifications for MR. The output will be restricted for MPR, FR or ER purposes.
- **Integral collection:** The integral collected MSW in one bin (**black bag**) contains all MSW fractions. The response rate for packaging plastics is 100% and packaging plastics from integral collected MSW can **not be separated or upgraded** further in an economical way and have to be landfilled or incinerated integrally.

4.2.2 Processes for packaging plastics in IW

Regarding IW the following processes for collection and separation of packaging plastics are studied:

- **Separate collection of IW mono-streams**: Some specific plastic articles in IW (commercial films, crates and pallets) are collected separately. These plastic mono streams are relatively clean. Addition of a relatively simple manual sorting achieves an output with the right specifications for MR.. The response rate is assumed to be 67% for crates and about 50% for films. Non-response packaging plastics from IW have to be collected together with other IW fractions (generally by an integral collection method).

- **Separate collection of IW mixed plastics**: Mixed plastic articles from IW (including non-response mono streams) are collected separately. The response is assumed to be about 50%. Separation and upgrading of IW mixed plastics results in a specified output for MPR processing. Non-response mixed plastics from IW have to be collected with the other IW fractions (generally by an integral collection method).
- **Integral IW collection**: Integral collected IW waste contains a mixture of all IW fractions. Response rate is assumed to be100%. Packaging plastics from integral collected IW can not be upgraded further and have to be landfilled or incinerated.

4.2.3 Application processes

Mechanical Recycling MR

MR processes only can be applied to manual sorted plastic fractions. Application processes include manufacturing of films, crates, pallets, thin walled products (e.g. fertiliser bottles) to substitute products made of primary plastics.

Origin of input for these processes (as secondary granules, flakes etc.) is:

- bottle fraction of MSW by bottle bank collection and yellow bag system
- film fraction of MSW, by yellow bag system
- film fraction of IW, by IW collection system
- crates and pallets of IW, by IW collection system

Mixed plastics recycling MPR

Compared with the processes of mechanical recycling the MPR processes can be applied to some mechanically sorted/separated fractions. Application processes include the production of thick walled products, which substitute products manufactured from concrete. As a result of the properties of the different materials the lifetime of concrete products is assumed shorter than products from recycled mixed plastics.

The upgraded/aggregated plastic mixtures as input for concrete substitution are derived from:

- film fractions of MSW, collected by yellow bag system
- mixed plastic fractions of MSW, by grey bag system
- mixed plastic fractions of IW, by IW collection system

Feedstock recycling (FR)

Compared with the M(P)R processes the FR processes can be applied to mechanically sorted/separated fractions or to residues from manual sorting with limited upgrading.
In this study two different processes are studied for feedstock recycling:

1. Base FR: plastic mixtures as substitute for heavy fuel oil, as a reducing agent in a Blast Furnace process.
2. Plastic mixture as feed for the Texaco Gasification process, producing syngas as substitute for natural gas based syngas in the methanol synthesis.

High efficient energy recovery (ER_{high})

ER_{high} is applied to specific waste mixtures, such as plastic mixtures and sorting residues from yellow bag system and RDF (refuse derived fuel) from grey bag system.
Compared with the processes of mechanical or feedstock recycling the mechanically sorted fractions without upgrading can be applied for ER_{high}. Thermal efficiency is high (> 70%) and conventional fossil fuels are substituted.
In this study a coal fired cement kin is applied for ER_{high} and steam coal is substituted as energy source.

Energy recovery by MSWI (ER_{mswi}):

ERmswi is applied to waste mixtures and sorting residues. Also integral collected waste can be incinerated in a MSWI.
MSWI installations will produce energy in the form of useful heat and electricity. Generally ER_{mswi} has a limited thermal efficiency compared to ER_{high}, A MSWI process has to comply with a strict flue gas cleaning standard. Flue gas cleaning requires additional input of energy, reducing the net energy production.

In this study three typical MSWI configurations (models) are applied as ER_{mswi} option. They differ from each other by flue gas cleaning efficiency and by energy recovery efficiency.

Landfill:

Integral collected plastic packaging waste can be landfilled; the average landfill model is based on literature data.
This model concerns a controlled landfill, which is isolated after 15 years and will be controlled for a period of 85 years afterwards. The biogas is partly captured and the water effluent is purified. The calculations of the environmental consequences of landfill concern an active time period of 100 years. For longer periods than 100 years no data are available.

Within 100 years 5% of the plastic packaging will be degraded in the landfill (assumption). No net energy production will take place (the produced electricity from biogas is applied on behalf of the effluent cleaning, etc).

4.3 Overview of routes

Based on the different collection systems the following routes for MSW and IW can be distinguished:

MSW	A1	Black Bag collection
	A2	Bottle Bank collection (and Black Bag collection)
	A3	Grey Bag collection
	A4	Bottle Bank collection and Grey Bag collection
	A5	Yellow Bag collection
IW	B1	Integral collection
	B2	Separate collection of films and rigids
	B3	Separate collection of films, rigids and mixed plastics

Each of these routes has a different mechanical and feedstock recycling "potential" (regarding the R score). The different application possibilities of the regained plastic fractions for MR, FR or MPR purposes are dependent of the quality of collection methods and the applied sorting and separation processes (especially mixing and contamination of the plastics output during collection, sorting and mechanical separation plays an important role; the choice for manual or mechanical sorting/separation has a relevant impact). Table 4.3.1 shows an overview of the recycling potential of the different routes.

Table 4.3.1 Routes in this study and their recycling potential.

	Route	*Separation/upgrading*	*MR*	*MPR*	*FR*	*ER mswi*
MSW						
A1	Black Bag	None	-	-	-	X
A2	Bottle Bank	Manual	X	-	-	+
A3	Grey Bag	Mechanical	-	X	X	+
A4	Bottle Bank + Grey Bag	Manual + mechanical	X	X	X	+
A5	Yellow Bag	Manual + mechanical	X	X	X	+
IW						
B1	Integral	None	-	-	-	X
B2	Separate collection	Manual	X	-	-	+
B3	Separate collection incl. mixed plastics	Manual + mechanical	X	X	-	+

X = product

\+ = by-product

4.4 Substitution factors

The products as output of the plastic processing routes vary considerably. An output of plastics for bottles, fences and feedstock has to be compared with a plastics output for energy purposes (e.g. electricity and heat).

For each of the substituted primary products the so called “substitution” factor (S) is defined as the ratio of primary material or primary energy replaced by the produced secondary material or secondary energy source during the application processes. Substitution factors applied in this study are presented in table 4.4.1 and explained in appendix A3.

Some examples to illustrate the substitution factors are:

- Substitution factor 1 for bottle recyclate means: each kg bottle recyclate substitutes 1 kg virgin polymers (a mixture of 45 % PE + 15 % PVC + 40 % PET). Underlying assumption is that relevant technical qualifications of the bottle recyclate and virgin polymers are identical.
- Substitution factor 10 for mixed plastics recyclate means each kg recyclate substitutes 10 kg concrete mix in a “fence” application. Underlying assumption is that technical qualifications of recyclate result in an increase of lifetime of the fence by a factor 4, whereas weight reduction by polymer is a factor 2½.
- Substitution factor 1,43 for coal (ER_{high}) means each kg RDF replaces 1,43 kg coal input in the cement kiln (based on LHV), according [4].
- Substitution factor 0,97 for oil (FR) means each kg feedstock mixture replaces 0,97 kg oil input in the blast furnace according [3].
- The efficiency of the electricity production by the MSWI is 20%. Substitution factor 1 for electricity recovery means 1 MJ electricity output is replaced by 1 MJ average grid electricity (UCPTE electricity).
- The efficiency of the heat production by the MSWI is 10%. Substitution factor 1 for heat recovery means 1 MJ MSWI heat output replaces 1 MJ average heat generations (UCPTE heat).

ble 4.4.1 Substitution factors.

	Substitution Factor		**Substituted** **Primary products**
ottle recyclate	1	Kg primary / kg recycled	Primary PE/PVC/PET
ixed plastics recyclate	10	Kg primary / kg recycled	Concrete
films	1	Kg primary / kg recycled	Primary PE
rates and pallets	1	Kg primary / kg recycled	Primary PP
DF (cement kiln)	1.43	Kg primary / kg recycled	Coal
eedstock	0.97	Kg primary / kg recycled	Fuel oil (heavy, S)
lectricity output MSWI	1	MJ / MJ electricity	UCPTE electricity 1)
eat output MSWI	1	MJ / MJ heat	UCPTE heat 2)

Notes:

1) *UCPTE electricity is according [18] generated from UCPTE coal power (17.4%), UCPTE gas power (7.4 %) , UCPTE hydropower (16.4%), UCPTE lignite power (7.8%), UCPTE nuclear power (40.3 %) and UCPTE oil power (10.7 %) with 31 % average efficiency*

2) *UCPTE heat is assumed to be generated from UCPTE coal (30%), UCPTE gas (30 %) and UCPTE oil (40%) with 90 % average thermal efficiency*

4.5 Costs figures

Costs figures are based on one tonne plastics processed (collected, separated etc.).According to literature (2, 11) costs figures in table 4.5.1, table 4.5.2 and table 4.5.3 are used for calculations.

Table 4.5.1 Costs data collection.

	Collection process/route	**EURO per tonne output**
MSW	Black Bag	133
	Bottle Bank	330
	Grey Bag	178
	Yellow Bag	592
IW	Integral collection	100
	Commercial film collection	60
	crates & pallets collection	80
	mixed commercial plastics collection	70

Table 4.5.2 Costs data of separation and upgrading processes.

Route	Flow	EURO per tonne output
Bot.bank	Rec. Bottles	110
Grey bag	RDF low	167
Grey bag	Fines	167
Grey bag	Feed & mixed plastics	630
Yellow bag	Rec Bottles	630
Yellow bag	Mixed film	590
Yellow bag	Feed	630
Yellow bag	RDF (cement kiln)	565
IW collection	Commercial film	105
IW collection	Crates & pallets	80
IW collection	Mixed plastics	65

Table 4.5.3 Gate Fees of application processes.

Route		Application process	Gate fee [1)] EURO per tonne input
Bottle bank	MR	Mechanical bottle recycling	-50
Yellow bag	MR	Mechanical bottle recycling	0
Yellow bag	MR	Mechanical mixed film recycling	0
IW collection	MR	Mechanical PE/PP film recycling	-165
IW collection	MR	Mechanical rigids recycling	-200
IW collection	MPR	Fence (concrete substitution)	275
Grey bag	MPR	Fence (concrete substitution)	275
Yellow bag	MPR	Fence (concrete substitution)	275
Yellow bag	FR	Blast furnace (oil substitution)	250
Grey bag	FR	Blast furnace (oil substitution)	250
All	ER_{high}	Cement kiln	100
All	ER_{mswi}	MSWI	100
All	Landf	Landfill	50

1) Because the LHV values of the different plastics do not show large differences it is assumed the benefits of FR and ER applications are more or less independent of composition.

The “gate fees” shown in table 4.5.3 represent a combination of costs data of application and substitution processes. The gate fee is defined as costs of application process (per ton application) minus the benefits of the specific products subtracted.

Some examples to illustrate the “gate fee” are:

- Application costs (the costs of the recycling process) for PE/PP bottle recyclate via the bottle bank route are about 450 Euro per tonne recyclate. Benefits are 500 Euro tonne recyclate (benefits by substituting virgin polymer). Gate fee is calculated as 450 – 500 = -50 Euro per tonne recyclate, representing a revenue (= net positive economical value) of 50 Euro per tonne recyclate.
- Application costs for mixed plastics in the blast furnace process (FR) are about 450 Euro per tonne mixture, whereas the benefits are 200 Euro per tonne recyclate (benefits by substituting 970 kg heavy fuel oil). Gate fee is about 450 – 200 = 250 Euro per tonne mixture, representing costs (= net negative economical value) of 250 Euro per tonne mixture.

5. Mass balances

This chapter contains the results of the mass balance calculations for routes and scenarios. A more detailed explanation of the mass balance calculations is given in appendix A.2. Recycling and recovery characteristics of routes are summarised in table A4.1 up to Table A4.3 in appendix A4.
The starting points for the calculations are:

- For each A type route the recycling potential is calculated for 0.718 kg MSW packaging plastics.
- For each B type route the recycling potential is calculated for 0.282 kg IW packaging plastics.
- The mass balances of the scenarios are based on combinations of the mass balances of the routes, for 0.282 kg IW plastics and 0.718 kg MSW plastics.

During execution of the sensitivity analysis the impact of another energy recovery option, ER_{high}, on the mass balance is illustrated. These calculations are explained in appendix A.6.

5.1 Mass balances of routes

5.1.1 A1: Black Bag collection (MSW)

Collection:
Total MSW packaging plastics (718 g) are integral collected in mixed MSW with the black bag collection system.

Separation and upgrading:
The black bag content is not separated or upgraded and is transported to the application location.

Application:
The black bag collected plastics are either landfilled or incinerated in a MSWI with energy recovery (ER_{mswi}).

A1: Black Bag collection	**MSW, total = 71.8%**
ER_{mswi} = 71.8%	R = 0%

5.1.2 A2: Bottle Bank collection (MSW)

Collection:

In MSW packaging plastics there are different types (PE/PP, PET, PS/EPS and PVC) of bottles, according table 3.2.1. In relation with the FU of 1 kg packaging plastics the 718 g MSW packaging plastics contain 187 g plastic bottles.
The consumers will bring a part of the non PVC type bottles to the collection point (bottle bank). Bottle Bank collection will reduce in that way:

- The absolute amount of MSW packaging plastics to be collected integrally with MSW fractions.
- The relative contribution of the bottle fraction in the resulting integral collected MSW packaging plastics.

With a bottle bank response rate of 20% for resp. PE/PP, PS and PET type bottles about 32 g bottles are collected per functional unit. The other 686 g MSW packaging plastics are collected with the integral MSW and are not separated or upgraded but directly transported to their application.

Separation and upgrading:

The 32 g Bottle Bank bottles are manually sorted in a sorting installation. The type sorted bottles are pressed and transported to plastic recycling installations. The sorting efficiency of the separation step is assumed to be about 92 %. After sorting the total amount of secondary plastics (rec. bottles) for recycling per functional unit is 30 g whereas as sorting residues (BB res.) 2 g plastics have to be transported to the residual MSW processing (landfill or energy recovery in the MSWI).

Application:

Recycled plastics generated by bottle bank collection/sorting (rec. bottles) will meet quality standards for mechanical recycling (MR). Integral collected plastics and sorting residue (BB res.) are either landfilled or incinerated with energy recovery in a MSWI.

A2: Bottle bank collection	**MSW, total = 71.8%**
MR = 3.0%	
ER_{mswi} = 68.8%	R = 3%

5.1.3 A3: Grey bag collection (MSW)

Collection:

The two bin or grey bag collection includes total MSW. There is 2% of the MSW packaging plastics in the wet compartment and 98% percent in the dry compartment.

Separation and upgrading:
Packaging plastics in the wet compartment of the grey bag system are sorted out manually and transferred to the dry fraction processing. The mechanical separation of the dry fraction (sieving, sifting, pulping and upgrading) results in the following fractions:
= 333 g mixed plastics fraction (main flow)
= 294 g plastics in the “Low” RDF (Refuse Derived Fuel) fraction
= 71 g plastics in the fines fraction
= 16 g plastics in the residue of the upgrading
= 4 g in the paper fraction out of the pulper.

Application:

The mixed plastics fraction will meet quality standards for mixed plastics recycling (MPR) or feedstock recycling (FR). RDF low, fines and residue of the upgrading (UPGR res.) are either landfilled or incinerated with energy recovery in a MSWI (a default option).

A3: Grey bag collection		**MSW, total = 71.8%**
MPR or FR	= 33.3%	
ER_{mswi}	= 38.5%	R = 33.3%

5.1.4 A4: Bottle bank combined with grey bag system (MSW)

Collection:
Consumers bring (a part) of all PE/PP and PET type bottles to the bottle bank. With a bottle bank response rate of 20% 32 g bottles per functional unit are collected and the other 686 g MSW packaging plastics are collected by a grey bag system.

Separation and upgrading:
With a sorting efficiency of 92% the bottle bank bottles are manually sorted, by type. About 30 g secondary plastics are sorted out and 2 g sorting residues are transported to the residual MSW processing. The grey bin packaging plastics are mechanically separated (sieving, sifting, pulping and upgrading) and the following fractions are produced:
= 30 g recycled bottle plastics (rec. bottles)
= 2 g residue from bottle bank (BB res.)
= 327 g (main flow) mixed plastics
= 273 g plastics in the RDF low (Refuse Derived Fuel)
= 66 g in the fines fraction
= 16 g in the residue of the upgrading process
= 3 g in the paper fraction from the pulper.

Application:
Recycled plastics generated after bottle bank collection will meet the quality standards for mechanical recycling (MR). The mixed plastics fraction separated out of the grey bin fraction (feed) will meet the quality standards for mixed plastics recycling (MPR) or feedstock recycling (FR). RDF low, fines and the upgrading residue (UPGR res.) and bottle bank residue (BB res.) are either landfilled or incinerated with energy recovery in a MSWI (default option).

A4: Bottle bank plus grey bag collection MSW, total = 71.8%
MR = 3.0%
MPR or FR = 32.7%
ER_{mswi} = 36.1% R = 3 % + 32.7% = 35.7%

Note:

The reference scenario NOW is constructed a.o. by an adapted route A4 (A4NOW) This adapted route has a limited separation (until sifter and elimination of the pulper) and the output is 346 g sifted "RDF high" with destination energy recovery (ER_{high}) Other plastics output fractions are 30 g recycled bottle plastics (rec. bottles), 2 g residue from bottle bank (BB res.), 273 g plastics in the RDF low and 66 g in the fines fraction.

5.1.5 A5: Yellow bag collection (MSW)

Collection:
Yellow bag collection concerns all plastic packaging waste in MSW (718 g plastics). In Germany the reported yellow bag collection response rates are up to 80%. In this study the average European response rate is assumed to be 67%. Consequently 481 g of MSW packaging plastics are collected by a yellow bag system. The rest of the (237 g) MSW packaging plastics are collected with the other MSW components ("non yellow bag" fractions).

Separation and upgrading:
Yellow bag collected packaging plastics are sorted out manually from other yellow bag recyclables (beverage cartons, metal packaging) with a relatively high separation efficiency (> 95%). Mechanical upgrading of the manual sorted fractions will result in 115 g bottle fraction (Rec.Bottles), 104 g mixed films fraction (Mixed film) and 241 g mixed plastics fraction (feed). The two last mentioned fractions are agglomerated before application.
Finally about 18 g of the collected plastics is processed as a residual fraction (Sorting res.) whereas also the metal packaging fraction is assumed to contain some plastics (4 g). The 237 g packaging plastics in integral collected MSW are not separated or upgraded.

Application:
The generated bottle fraction from the yellow bag system (Rec. Bottles) will meet the quality standards for mechanical recycling (MR). Generally the mixed films fraction (Mixed fim) is directed to MPR application and the mixed plastics fraction (feed) meets the targets for FR purposes. Integral collected plastics (MSW residual) are either landfilled or incinerated with energy recovery in a MSWI.

A5: Yellow bag collection			**MSW, total = 71.8%**
MR	=	11.5%	
MPR	=	10.4%	
FR	=	24.1%	
ER_{mswi}	=	25.8%	R = 11.5% + 10.4% + 24.1% = 46%

5.1.6 B1: Integral collection (IW)

Collection:
Total IW packaging plastics (282 g) are integral collected with other IW fractions.

Separation and upgrading:
The integral collected IW packaging plastics are not separated or upgraded but transported to application location.

Application:
Integral collected IW packaging plastics are either landfilled or incinerated in a MSWI with energy recovery.

B1: Integral collection			**IW, total = 28.2%**
ER_{mswi}	=	28.2%	R = 0%

5.1.7 B2: Separate collection of commercial films and rigids (IW)

Collection:
282 g IW packaging plastics contain about 162 g PE/PP films and about 75 g valuable rigids (crates and pallets). Separate collection of films and valuable rigids in the European area occurs with the assumed response rates of 52% resp. 67%. Out of the total amount of 282 g IW packaging plastics about 84 g films and 50 g valuable rigids are collected separately for separation and mechanical recycling purposes. The resulting 149 g IW packaging plastics are integral collected with other IW fractions.

Separation and upgrading:

Separately collected 84 g films and 50 g rigids are manually sorted in a sorting installation followed by regranulation. The total efficiency of sorting and upgrading is assumed to be 90%. Recycled secondary plastics are 75 g from films (IND films) and 45 g from rigids (IND rigids).

Separation residue (sep.res.) is intended for MSWI or landfill.

The residual integral collected 148 g IW packaging plastics are not separated and with the other IW waste fractions transported to their application.

Application:

The recyclable films can be applied for the production of commercial films whereas the recycled PE/PP rigids can be directed to commercial crate and pallet production. Integral collected plastics are either landfilled or incinerated with energy recovery in a MSWI.

B2: separate collection of films+ rigids			**IW, total = 28.2%**
MR	=	12.0%	
ER_{mswi}	=	16.2%	R = 12%

5.1.8 B3: Maximal separate collection of commercial plastics (IW)

Collection:

Next to recycled commercial films and valuable rigids (crates and pallets) the IW plastics fraction has an additional potential for source separate collection of mixed plastics (PE/PP). In this study it is assumed that next to the collection of 84 g films and 50 g rigids an additional amount of 74 g IW mixed plastics is separately collected for mixed plastics (MPR) purposes.

Separation and upgrading:

Separately collected 84 g films and 50 g valuable rigids are sorted manually whereas 74 g mixed plastics are separated mechanically. The total amounts of regenerated secondary plastics are 75 g from commercial films, 45 g from rigids and 67 gram mixed plastics.

The integral collected IW packaging plastics (74 g) are not separated.

Application:

The recyclable films can be applied for the production of commercial films whereas the recycled rigids are directed to commercial crate or pallet production. Mixed plastics are directed to MPR applications.

Integral collected plastics are either landfilled or incinerated with energy recovery in a MSWI.

B3: Maximal separate collection (films, rigids *and* mixed plastics) **IW, total = 28.2%**

MR = 12.0%

MPR = 6.7 %

ER_{mswi} = 9.5 % R = 12.0 % + 6,7 % = 18.7 %

5.2 Scenarios

For each scenario at least one route of the processing of packaging plastics in MSW has to be combined with at least one route of the processing of packaging plastics in IW (100 % MSW and 100% IW).

5.2.1 Reference scenarios

The reference scenario landfill consists of route A1 (black bag) for packaging plastics in MSW and route B1 (integral collection) for IW packaging plastics. The application MSWI is substituted by the application landfill.

Reference scenario Landfill

MSW
- 100% of route A1 with landfill instead of ER_{mswi}

IW
- 100% of route B1 with landfill instead of ER_{mswi}

The reference scenario NOW consists of combinations of routes, as well as for MSW as for IW packaging plastics. The application MSWI is for the main part substituted by the application landfill. The set up of the NOW scenario is the following:

Reference scenario NOW

MSW
- 56.0% of route A1 with landfill instead of ER_{mswi}
- 20.0% of route A2 with landfill instead of ER_{mswi}
- 5.75% of route A2 with ER_{MSWI}
- 5.75% of route A4 with ER_{high} instead of MR and MPR and ER_{mswi} for residual flows
- 12.5% of route A5 with ER_{MSWI}

IW
- 31.0% of route B1 with landfill instead of ER_{mswi}
- 45.0% of route B2 with landfill instead of ER_{mswi}
- 24.0% of route B2 with ER_{MSWI}

5.2.2 Recycling scenarios

For the procedure of building the scenarios, see 2.2.3.
The starting point for the construction of the recycling scenarios I, II, III and IV is the inclusion of at least route B2. The separate collection and processing of commercial films and rigids out of IW is from the economic point of view the preferred MR option. A further increase in recycling will be realised by a combination of routes for MSW packaging plastics as well as route B3 for IW packaging plastics.

To match exactly the recycling figures of the scenarios as presented in table 2.2.3 some output flows of the described routes in 5.2.1. are shifted. Some MR is redirected to FR or MPR, whereas some FR is redirected to MPR All routes and recycling figures are presented in appendix A4, in table A4.1 up to A4.3.

Scenario I
(15% MR and 85% ER_{mswi})
When route B2 is combined with route A2 (for MSW) the targets 15% MR and 85% ER_{MSWI} are realised.

Scenario I (= R15)

MSW
- 100% of route A2

IW
- 100% of route B2

Scenarios II, III and IV are built up as an extension of the so-called “base” scenario I , regarding the recycling level. Mostly the increase of recycling is realised by the packaging plastics recycling out of MSW. The distinguishing principle then is the source collection via a yellow bag system or a grey bag system.

A: Increasing recycling of MSW by Yellow Bag collection:

Scenario II, yellow bag system
(15% MR, 10% FR and 75% ER$_{mswi}$)
A bottle bank system is not needed when a yellow bag collection system is selected. The aim of the application of this system is to collect all MSW packaging plastics, bottles inclusive. In that case the realisation of 15% MR is a combination of route A5 (3% MR) and route B2 (12% MR).
Route A5 has a recycling potential of 11.5% for MR and 34.5% for FR + MPR. To realise 3 % MR only a small part (3%/11.5%= 26.1%) of route A5 fulfils this aim. At the same time 26.1% * 34.5% = 9% FR is realised with the application of route A5, whereas 10 % FR is the criterium. Route A5 is shifted to A5R25y with 10.8% MR and 35.2 % FR. In that case 28.3 % of route A5R25y realises 3 % MR and 10 % FR. By the application of route A1 the rest of the MSW packaging plastics are processed (100% - 28.3= 71.7%).

Scenario II, yellow bag system (= R25y)

MSW
- 28.3% of route A5 (shifted to A5R25y)
- 71.7% of route A1

IW
- 100% of route B2

Scenario III, yellow bag system
(15% MR, 10% FR, 10% MPR and 35% ER$_{mswi}$)
Route A5 has a potential of 11.5% for MR and a potential of 34.5 % for FR/MPR. The target 20% FR + MPR could be realised by the application of 20/34.5 = 58.0% of route A5, which is combined with 58/100* 11.5% = 6.7 % MR. A shift of route A5 to A5R35y (5.5 % MR → 5,5 % FR/MPR) results in 6 % MR, 20.2% MPR, 20.2% FR and 49.5% of route A5R35y satisfies the required targets. By the application of route A1 the rest of the MSW packaging plastics are processed (100% - 49.5= 50.5%).

Scenario III, yellow bag system (= R35y)

MSW

- 50.5% of route A1
- 49.5% of route A5 (shifted to A5R35y)

IW

- 100% of route B2

Scenario IV, yellow bag system
(15% MR, 15% FR, 20% MPR and 50% ER_{mswi})
Route A5 has a recycling potential of 34.5% for FR + MPR. This means that for the realisation of the target 35% FR + MPR the application of route A5 is not sufficient. But the shift of route A5 to A5R50y (for instance with 7,9 % MR → 7,9 % MPR) increases the FR + MPR potential. Route A5R50y has 3.6% MR, 24.4% MPR and 18.2% FR.. With 82.2% application of route A5R50y the targets of scenario IV will be satisfied. The resulting 17.8% (= 100% - 82.2%) of the MSW packaging plastics are processed via route A1.

Scenario IV, yellow bag system (= R50y)

MSW

- 82.2% of route A5 (shifted to A5R50y)
- 17.8% of route A1

IW

- 100% of route B2

B: Increasing recycling of MSW by Grey Bag collection:

Scenario II, grey bag system
(15% MR, 10% FR and 75 % ER_{mswi})
Route A4 with R =35.7% has a MR potential of 3% and a potential of 32.7% for FR and/or MPR. On behalf of the realisation of the 10% FR target of scenario II a part of 10/32.7 = 30.6% of route A4 satisfies. Route A2 with R = 3% has also a potential of 3% MR out of MSW and so the residual 69.4 % (= 100% - 30.6%) collection of MSW is contributed via route A2.

Scenario II, grey bag system (= R25g)

MSW

- 30.6% of route A4
- 69.4% of route A2

IW

- 100% of route B2

Scenario III, grey bag system
(15% MR, 10% MPR, 10% FR and 65% ER$_{mswi}$)

On behalf of the realisation of the 10% FR and 10% MPR targets a part of 20/32.7 = 61.2% of route A4 satisfies. Route A4 is shifted to A4R35g with 16.35% MPR and 16.35% FR. An additional contribution of 38.8% of route A2 fulfils the 3% MR target for MSW packaging plastics.

Scenario III, grey bag system (= R35g)

MSW

- 61.2% of route A4 (shifted to A4R35g)
- 38.8% of route A2

IW

- 100% of route B2

Scenario IV, grey bag system
(15% MR, 20% MPR, 15% FR and 50% ER$_{mswi}$)

Route A4 with a recycling potential of 32,7% cannot realise the combined targets 15% FR and 20% MPR without additional effort. In combination with route B2 route A4 shows a lack of 2.3% for FR + MPR (= 35% -32.7%). Route A4 is shifted to A4R50g with 15% FR and 17.7% MPR. Combination of A4R50g with route B3 will result in an additional FR + MPR potential of 6.7%. To realise the FR + MPR target of scenario IV consequently 34.3% (= 2,3/6.7) of route B3 has to be incorporated. Application of 65.7% of route B2 realises the complete picture of scenario IV.

Scenario IV, grey bag system (= R50g)

MSW
- 100% of route A4 (shifted to A4R50g)

IW
- 65.7 % of route B2
- 34.3% of route B3

6. Inventory

6.1 Inventory of environmental data

6.1.1 Inventory items

The basis for the environmental inventory analysis of the scenarios is an input/output analysis of all foreground processes (the individual collection, separation and application processes). Regarding the input/output items of foreground processes the following aspects can be distinguished:

1. Input of or output to other foreground processes
2. Input of or output to background processes
3. Environment items (emissions, waste, depletions)

The overview of input/output items for foreground process is shown in the (quantitative) process descriptions presented in appendix A.2 and A.3 of this report.
The data related to items as electricity consumption, transports, input of auxiliaries or substituted primary plastics give an indication to which degree background processes are linked to the foreground processes.

The final inventory step includes a summary of all material and energy flows across the boundary of the systems under study, that are emissions to water and air, depletions of environmental resources and environmental loads by final waste deposits. In this context every link to background processes is translated to environmental items with the help of a background database. Every link has some additional environmental load or some additional environmental benefit for the observed route.

As a consequence the choice of the background database is an important aspect of the environmental analysis. Background processes in this study are derived from the APME database (17), in the case of primary plastics production and from the BUWAL 250 database (18), in the case of production of fuels, energy conversion and transport processes.
Appendix A.5 gives an overview of all background processes used in this study and the corresponding background data.

Appendix B.1 gives a detailed list of all inventory items derived from foreground and/or background processes.

6.1.2 Remarks concerning the inventory items

The data of the foreground processes are related to the time period as mentioned in chapter 2.3. In general it concerns the data of the period 1990-1999.
An exception has to be made for landfill. The landfill application generates emissions during a time period of 100 years after the dumping of plastic wastes (system boundary landfill: see appendix A.3).

Special attention is given to the completeness of the data in this study:

- Foreground data and their references are summarised in the appendices A.2, A.3 and A.6 of this report. Some specific data of foreground processes are missing, because of the incompleteness of the literature sources. For instance the water emissions caused by cleaning of the plastics for MR. The consequences of these missing data are marginal as far as known.
- For the background processes for transport, fuel and energy production the process data from BUWAL 250 are used (18). For the production of primary plastics the published data of APME (17) are used. Because BUWAL 250 also incorporates these APME data most background processes in this study correspond with those described in the BUWAL 250 study.[1)]
  Background processes are reported in appendix A.5.

Remark:
In the BUWAL 250 study only aggregated data of energy conversion processes are reported. The corresponding so-called “precombustion” data for fuels (natural gas, oil and coal) are not reported. TNO has recalculated the fuel data (see appendix A.5) with the information given by the reference mentioned in the BUWAL 250 study.

6.1.3 Classification of inventory items

Life cycle impact assessment is performed as described in chapter 2.6. The classification of inventory items result in scores of 9 impact categories and 3 special categories of environmental aspects (see table 2.6)

6.2 Inventory of costs data

The basis for conducting a costs inventory of the scenarios and routes is a costs calculation for individual (state of the art) processes. Per route and per scenario these costs are summarised (appendix B3 and B4).

[1)] For the production of primary plastics the BUWAL 250 data are not applied, but the original APME data. This inconsistency is of minor relevance, because all recycling scenarios include an amount of 15% MR (substitution of primary plastics), so possibly differences between scenarios are leveled out.

Figures 6.2.1a and 6.2.1b show the results of the costs inventory of the different scenarios. The scenarios with an increasing R illustrate an increase in costs, which are only partly compensated by an increase in benefits. Furthermore the following remarks can be made:

- The collection costs obviously increase with increasing R, especially for the yellow bag scenarios.
- The costs of separation and application increase with increasing R. Regarding these activities the yellow bag scenarios as well as the grey bag scenarios show comparable costs.
- Scenarios R50 and R35 do not show more economical value being created by substitution compared to scenario R25, despite substantial extra costs being involved; both the yellow bag scenarios as the grey bag scenarios show this phenomenon.

The costs difference between comparable grey bag and yellow bag scenarios is caused by differences in collection costs. Application of mixed plastics as concrete substitute does not result in an increase of the benefits compared with the benefits of energy use of waste incineration.

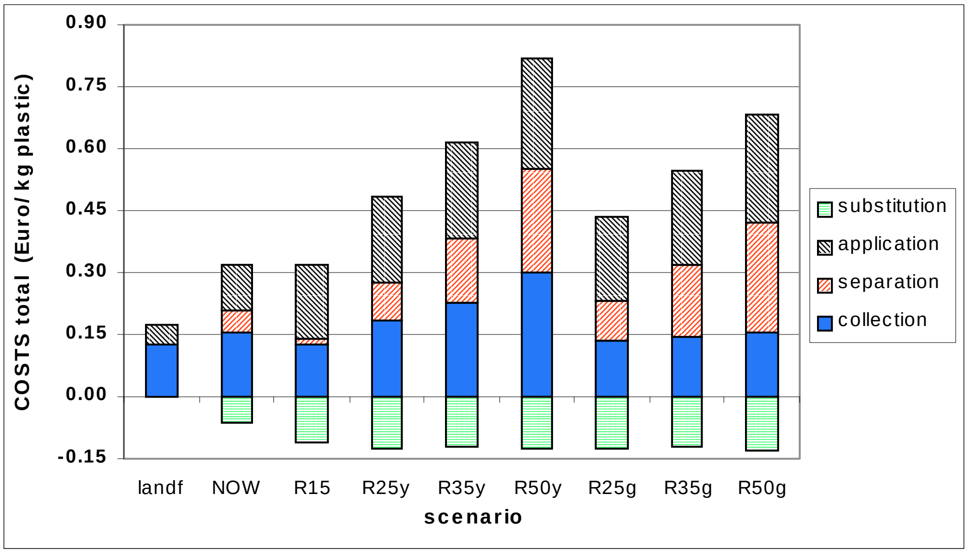


Figure 6.2.1a Results costs inventory : contribution per step.

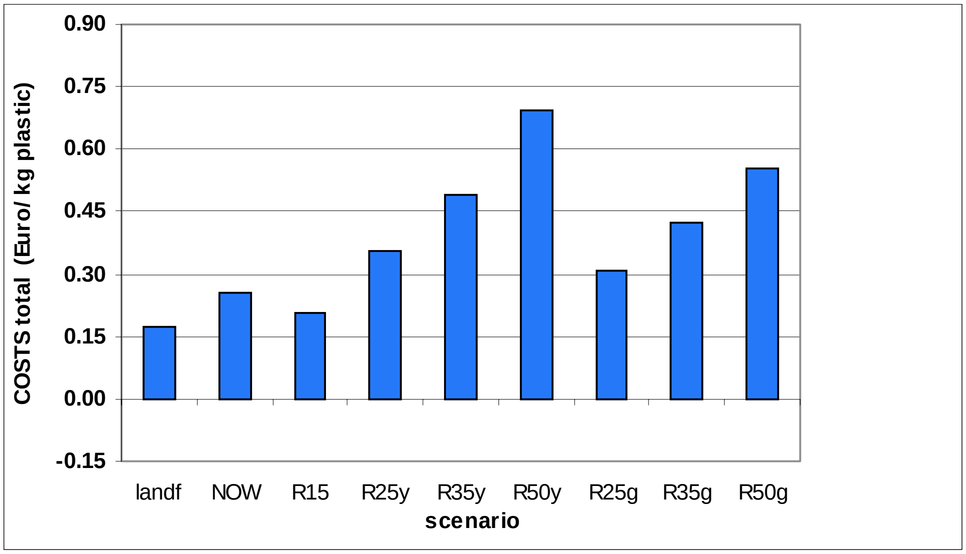


Figure 6.2.1b Results costs inventory : total (complete system)

7. Impact assessment

The estimation of the environmental load of each of the classified impact categories (characterisation) will be carried out starting from the list of inventory items of the scenarios (chapter 6). The characterisation factors are described in appendix B.2.

In order to discuss the results the separate scenarios are compared with each other per impact whereas the scores of the scenarios are divided in:

A. Collection: impacts from collection,
B. Separation: impacts from separation and upgrading
C. Application: impacts from application processes
D. Substitution: impacts as a consequence of the substitution of products.

The complete results of all scenario options (inclusive the calculated options as a part of the sensitivity analysis) are listed in appendix B.5.
An overview of the results of the environmental effects EDP, GWP, POCP, AP, and the environmental aspects FW, TW and ENER are reported in this chapter. After normalisation these items have the greatest contribution to the environmental load (chapter 8).

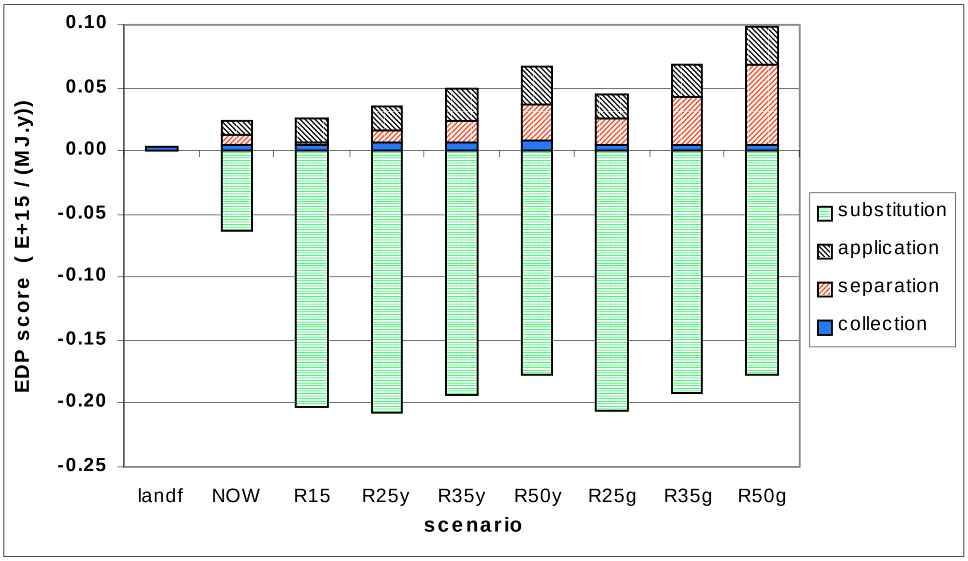


Figure 7.1 Environmental impact assessment:
Characterisation EDP (depletion fuel resources).

Except landfill all scenarios contribute to the net decrease of the EDP load. This decrease in EDP load for these scenarios is mainly caused by the substitution step, because of the substitution of energy and materials. It is remarkable that starting with R25 the EDP saving decreases to some extent with increasing R value. Two reasons can be given:

- The increase of the content MPR looking at R35 and R50 together with a decrease of ER_{mswi} does not result in more energy saving than the amount realised by the incineration of packaging plastics.
- In the case of MPR for R35 and R50 most of the extra saved energy source compared to R25 is coal (regarding MPR and the cement kiln for concrete production). Because of the enormous stocks the saving of coal hardly reduces the EDP load. R25 has a greater EDP reduction by the greater share in application of a MSWI, because in that case the saving of the relatively scarce sources oil and gas occurs.

Figure 7.1 shows that with an increase of the R value the net EDP saving decreases because of the increase of the separation step EDP load. This increase is greater for the grey bag scenarios than for the yellow bag scenarios. The extensive mechanical separation, as part of the grey bag system, is the cause for the higher energy consumption.

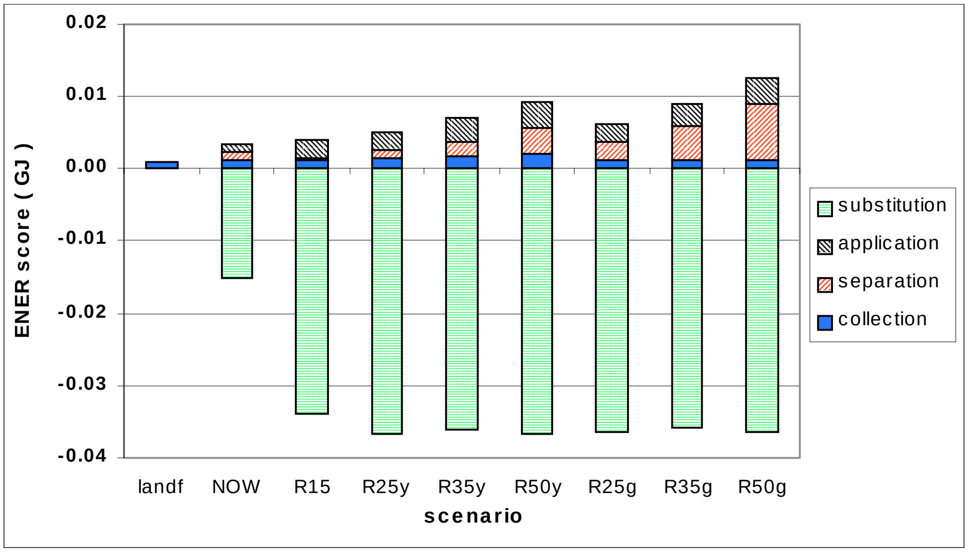


Figure 7.2 Environmental impact assessment: Characterisation ENER (primary energy requirement).

Comparable with EDP also for ENER a reduction of the environmental load exist for all scenarios except landfill. Substitution of primary products causes the saving of energy, regarding the processes of the scenarios.
Starting with R25 an increase of the R value does not result in a decrease of ENER for the application step. The reason for this difference compared with EDP (figure 7.1) is that scarcity of energy sources is not incorporated for judgement of ENER.

Figure 7.2 shows for increasing R values an increase of ENER for the separation step. This increase is greater for the grey bag scenarios than for the yellow bag scenarios (comparable with EDP). The contribution of the separation step causes a small decrease of the total ENER saving, starting from R25, when the R value increases.

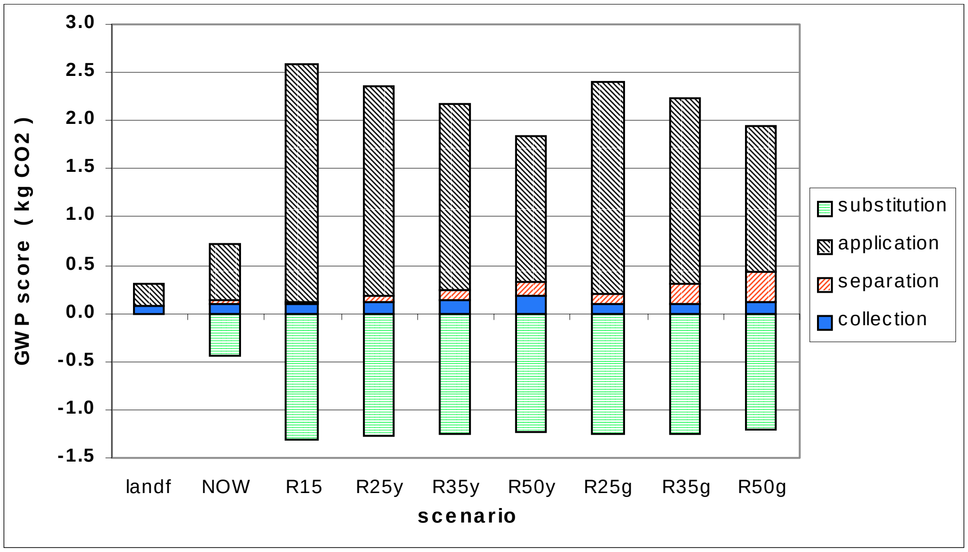


Figure 7.3 *Environmental impact assessment:*
Characterisation GWP (global warming potential).

The picture for GWP shows an increase of the environmental load for all the scenarios. The application step causes this notable increase. For landfill the amount of CO_2 (and also CH_4) emissions is relatively small, because during the considered period of landfill only a very small part of the plastics (5%) is degraded.

Regarding the separation step figure 7.3 shows the GWP load slowly increases with higher R value. This enlargement is greater for the grey bag scenarios than for the yellow bag scenarios. Also this aspect has to be related to the increase of the energy consumption (gives more CO_2 emissions), because of the application of mechanical separation in the case of the grey bag system.

Regarding the application step and starting with R15 an increase of R value (decrease of ER_{mswi}) will decrease the GWP load. In other words the introduction of MPR and FR achieves an obvious reduction of GWP, because the extent of MSW incineration is lowered.

Regarding all scenarios the CO_2 emissions developed during collection, separation and especially application are not compensated by the saved CO_2 emissions of substitution. Starting with R15 an increase of R value (decrease of ER_{mswi}) results in some decrease of the GWP load.

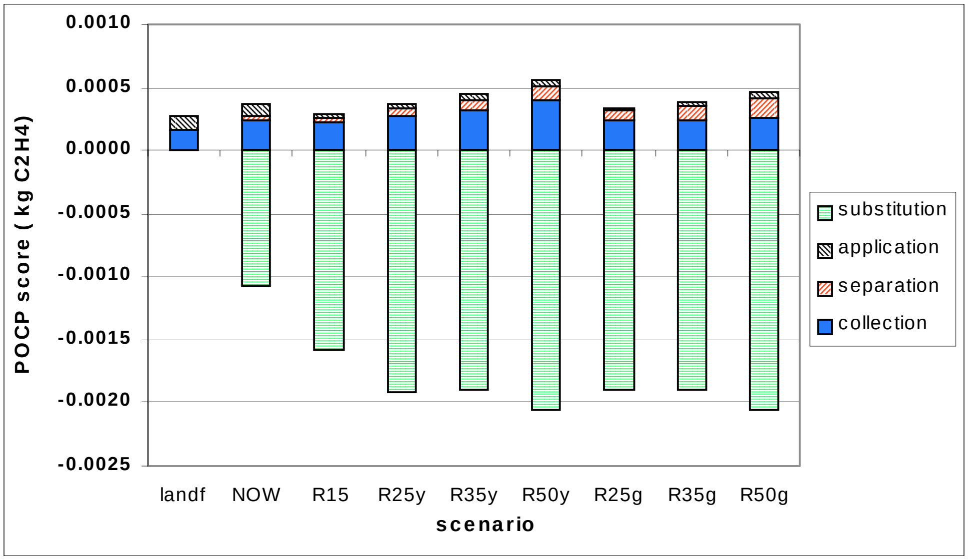


Figure 7.4 Environmental impact assessment: Characterisation POCP (photochemical smog potential).

Except landfill all the scenarios generate a net reduction of the environmental load regarding POCP. The substitution of primary products results in a reduction of POCP. The reduced POCP load can be related to a decrease of the hydrocarbon emissions, which arise during the production of primary monomers and plastics as well as during the production of feedstock and fuels (refineries, exploration and mining).

For all the scenarios the collection obviously contribute to the POCP load. This contribution can be correlated to the hydrocarbon emissions generated during transport (exhaust gas) and during the production of transport fuel (diesel).

Figure 7.4 shows the POCP load for collection will be higher in the case of the yellow bag system compared with the grey bag system; the difference in transport distances is the reason for that (see appendix A.2).

Figure 7.4 shows also that the increase of POCP saving with increasing R value is caused by the substitution of ER_{mswi} by MR and FR. Comparison of R25 with R35 illustrates that replacement of ER_{mswi} by MPR results in no extra POCP savings.

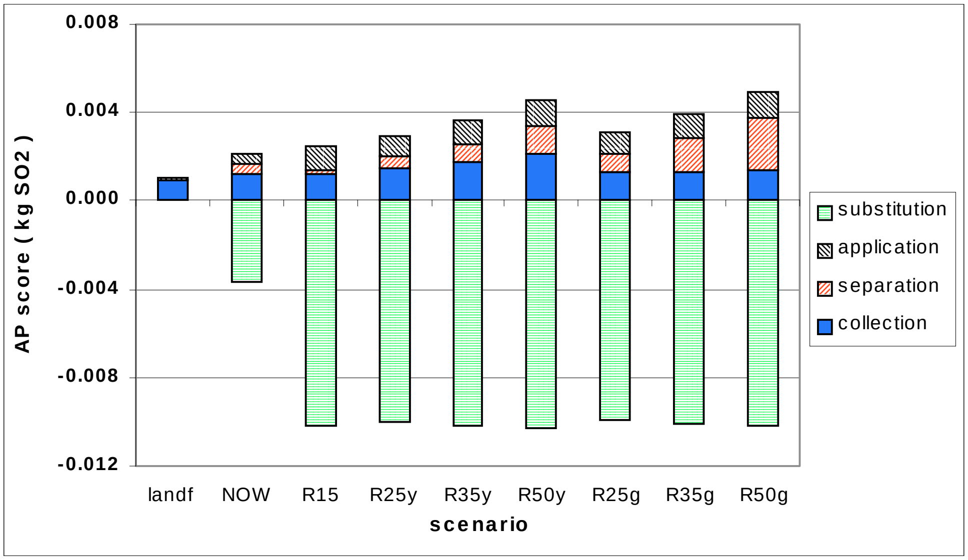


Figure 7.5 Environmental impact assessment: Characterisation AP (acidification potential).

The AP picture is comparable with the POCP one. Except for landfill all scenarios achieve a reduction of the AP environmental load. The substitution of primary products is the reason for this. The (avoided) AP load has to be related to the SO_2 and NO_x emissions; these emissions arise during the production of primary plastics and during the production of feedstock and fuels (refineries, exploration and mining).
Figure 7.5 shows that the avoided AP load (substitution step) does not increase with rising R value of the sequential scenarios. The increase of R because of the replacement of ER_{mswi} by MR and FR does not result in a extra reduction of the AP load.

All the scenarios demonstrate an obvious contribution of the collection step to AP. This is originated by the NO_x emissions during transport (exhaust gas) and by the SO_2 emissions during the production of the transport fuel (diesel).

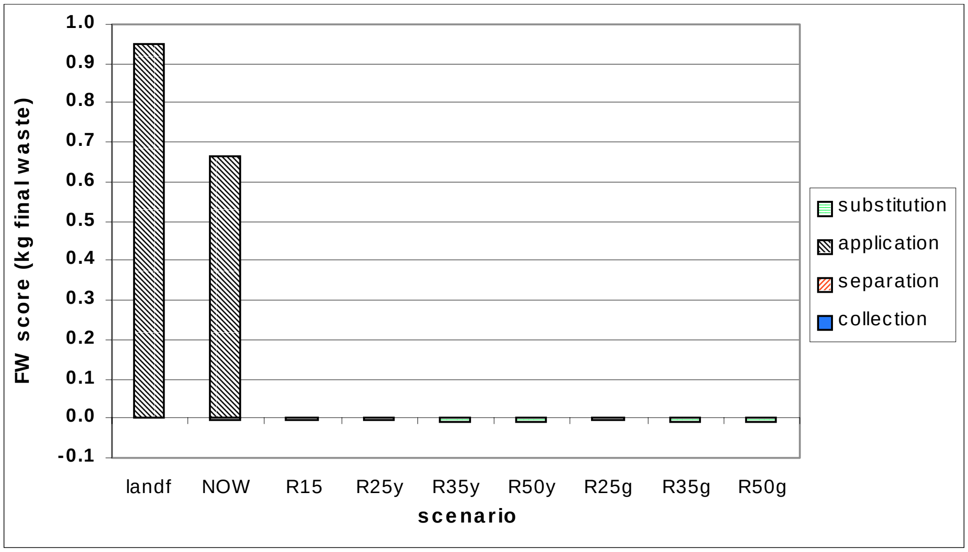


Figure 7.6 Environmental impact assessment: Characterisation FW (final waste).

In comparison with the preceding figures 7.1 up to 7.5 inclusive FW in figure 7.6 shows a discriminative picture.
Regarding the scenarios it appears that the FW load is generated by the application step! Especially the both reference scenarios with landfill (landfill and NOW) result in a considerable FW load. The FW load of the residual scenarios is relatively small. For instance the incineration of the packaging plastics leads to a small contribution to the FW load by the small amount of bottom ashes.
Also the avoided FW load elsewhere (substitution step) because of the substitution of primary products is relatively small (see figure 7.6). It is assumed that the avoided coal mining waste as result of the partial substitution of coal winning is not interpreted (classified) as FW load. The assumption not classifying coal mining waste is in agreement with starting points of other LCA studies (such as (5)).

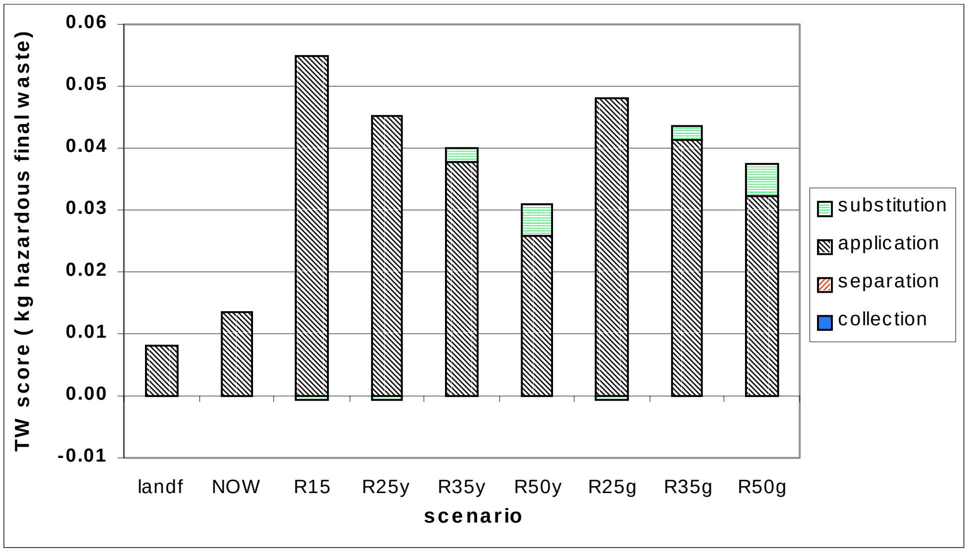


Figure 7.7 Environmental impact assessment: Characterisation TW (final specific waste).

As with the FW load (figure 7.6) to a large extent also the TW load appears to come from the application step. Contrary to the FW load the TW load is not generated by landfill, but by the application of the MSWI. The MSWI creates flue gas cleaning residues and to lesser extent fly ash with a contribution to TW. Especially the incineration of plastics with a high Cl content (PVC) results in a obvious TW load.

Scenarios with an increasing R value show a decrease of the TW load. A reduction of the share of ER_{mswi} is the reason for this. With increasing R a bigger part of PVC is processed in MR and FR operations.
Comparison of the yellow bag systems with the grey bag systems leads to the conclusion that the grey bag systems generate a slightly higher TW load. The separation step of the grey bag systems results in a concentration of the PVC plastics (especially bottles) in specific fractions (“fines” and “low RDF”),which are processed in a MSWI. Application of yellow bag systems achieves feeds for MR, MPR and FR operations with a greater Cl content; compared with grey bag systems less Cl containing plastics are then incinerated.

Regarding R35 and R50 also the contribution of the application step to TW is originated by MSWI. MPR substitution generates plastic products (e.g. fences, as a substitute for concrete), which are incinerated in a MSWI after discarding to an extent of 50%. The resulting flue gas cleaning residues are indicated as an *extra* TW load for substitution in figure 7.7.

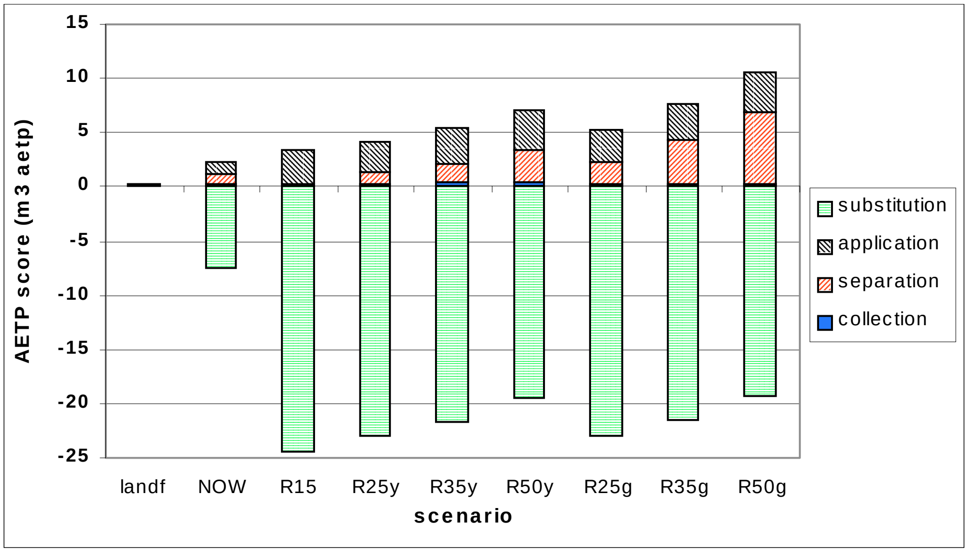


Figure 7.8 Environmental impact assessment:
Characterisation AETP (aquatic ecotoxicity potential).

Roughly the comparison of the AETP load of the different scenarios agrees with that of the AP load (figure 7.5). Except landfill all scenarios achieve a reduction of the net AETP load. The substitution of primary products leads to this AETP saving. Especially the background processes play an important role in this case. The (avoided) AETP load appears to be reduced to the (avoidance of the) load of heavy metal emissions (especially nickel). As well as the mining emissions to water (especially for the oil and coal winning) as the emissions to air (for the sequential energy conversion) play an important role regarding this environmental aspect.

Compared with MR and FR, ER_{mswi} substitutes background processes with more heavy metal emissions; that is why increasing R results in a decrease of avoided AETP. The energy consumption (electricity) of the separation and application steps cause an increase in AETP when the R value increases; more of these activities are applied when more R is activated. Also this phenomenon can be related to more application of the already mentioned background processes.

8. Evaluation

The *relative* environmental load (normalised impacts) is calculated from the *absolute* environmental load (characterised impacts, chapter 7) with the help of normalisation factors (reference framework is Europe). The applied normalisation factors are described in chapter 2.7 (table 2.7).
The normalisation results are presented in two ways, in the form of detailed "bar charts" in chapter 8.1 and in the form of bar charts in chapter 8.2. Chapters 8.3 and 8.4 describe the results of respectively the dominance analysis and the sensitivity analysis. The sensitivity analysis is only performed on the environmental aspects and not on the costs.

8.1 Normalised Environmental Impacts

The normalised results of the aspects EDP, GWP, POCP, AP, FW, TW, ENER and AETP are separately given in the figures 8.1.1 up to figure 8.1.8 inclusive. For all the scenarios these aspects in normalised form relatively give the greatest contribution to the environmental load. In figure 8.1.1 up to figure 8.1.8 inclusive the following differentiation of each scenario is made (comparable with the illustration of the "bar charts" in chapter 7):

- collection processes
- separation processes
- application processes
- consequences of the substituted (avoided) processes

The scale size of the axes in figure 8.1.1 up to figure 8.1.8 inclusive are all comparable. The mutual comparison shows that for all scenarios especially FW and TW have the greatest relative contribution to the environmental load. The contribution of the scenarios to AETP. AP, EDP, ENER and POCP is mainly realised by the substituted processes. Application processes dominate the contribution to FW, TW and GWP for all scenarios. Collection and separation have a relatively small contribution to the environmental load; this remark was already made during the explanation of the characterised impacts (chapter 7).

In figure 8.1.1 up to figure 8.1.8 also the net contribution (of the total system; the different stages are added) to the specific environmental themes are illustrated.

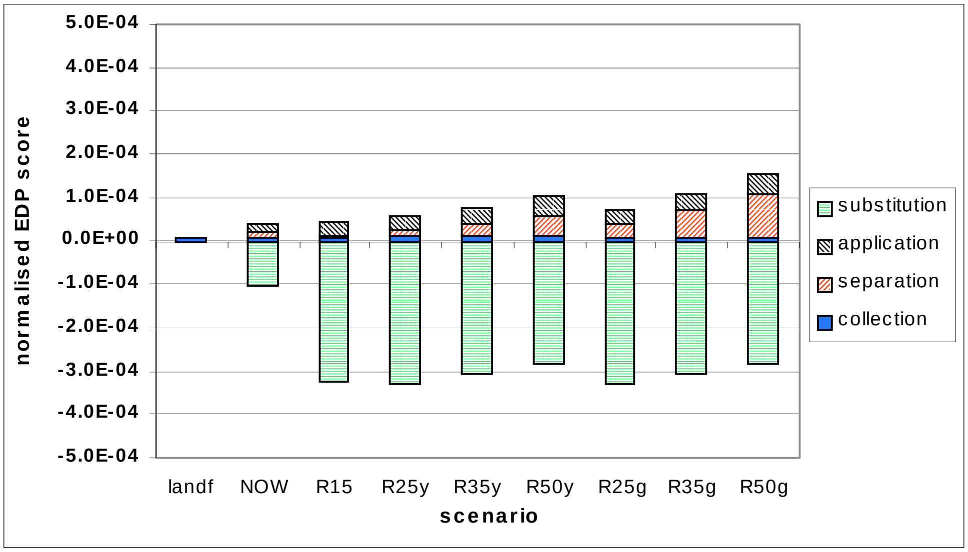


Figure 8.1.1a *Environmental impact assessment: Normalised Fuel depletion (EDP) per step.*

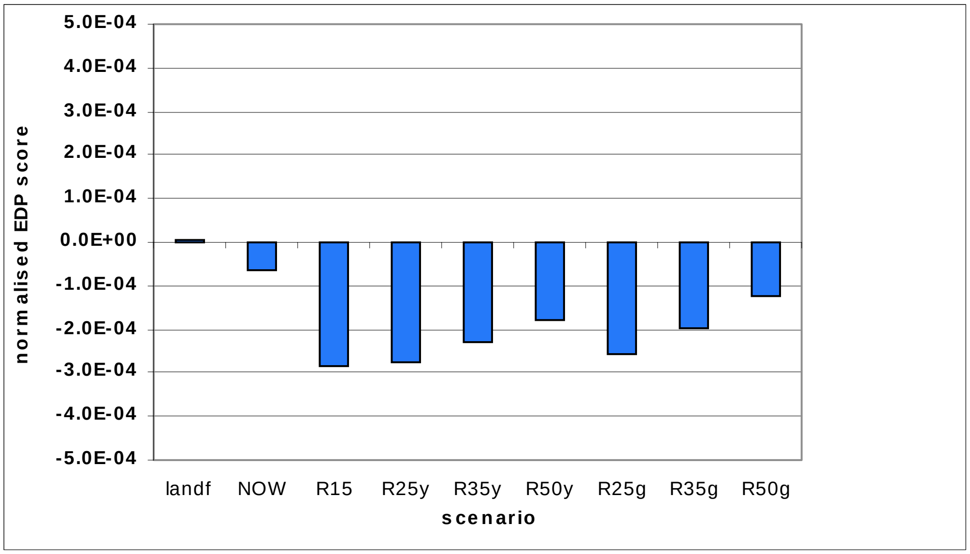


Figure 8.1.1b *Environmental impact assessment: Normalised Fuel depletion (EDP), total.*

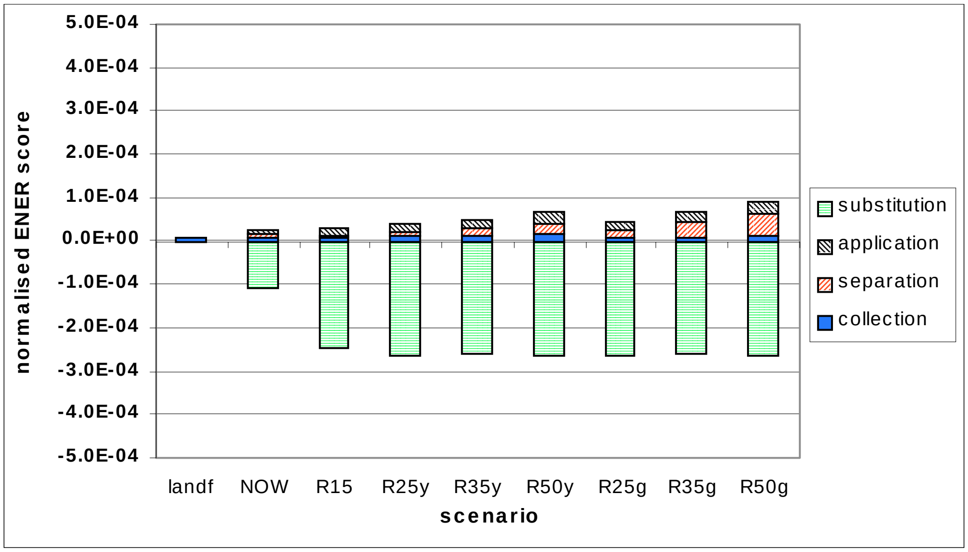


Figure 8.1.2a *Environmental impact assessment:*
Normalised energy requirement (ENER) per step.

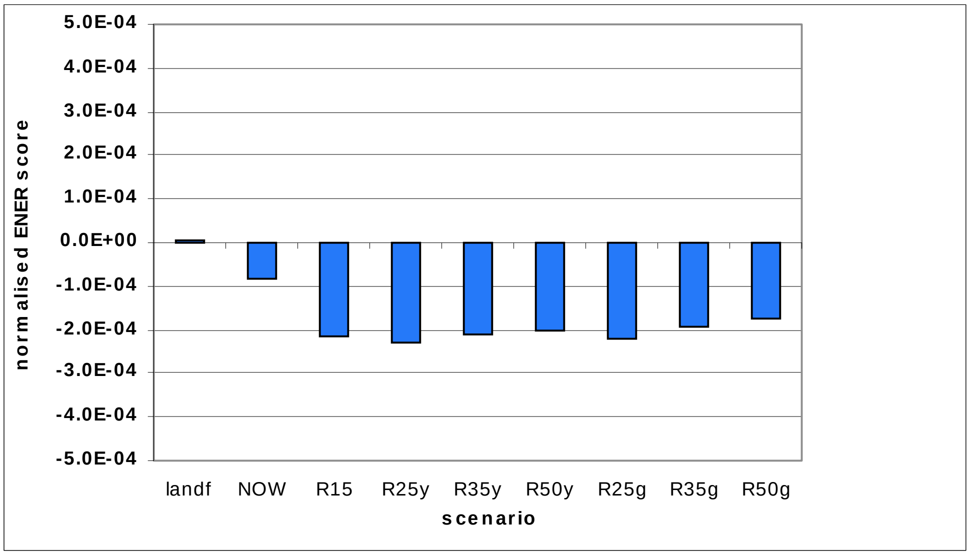


Figure 8.1.2b *Environmental impact assessment:*
Normalised energy requirement (ENER), total.

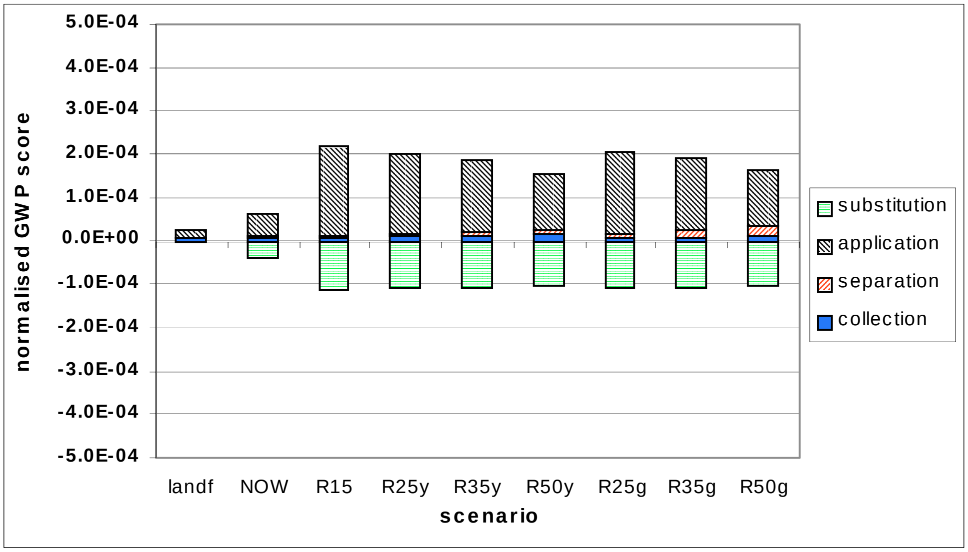


Figure 8.1.3a Environmental impact assessment:
Normalised global warming potential (GWP) per step.

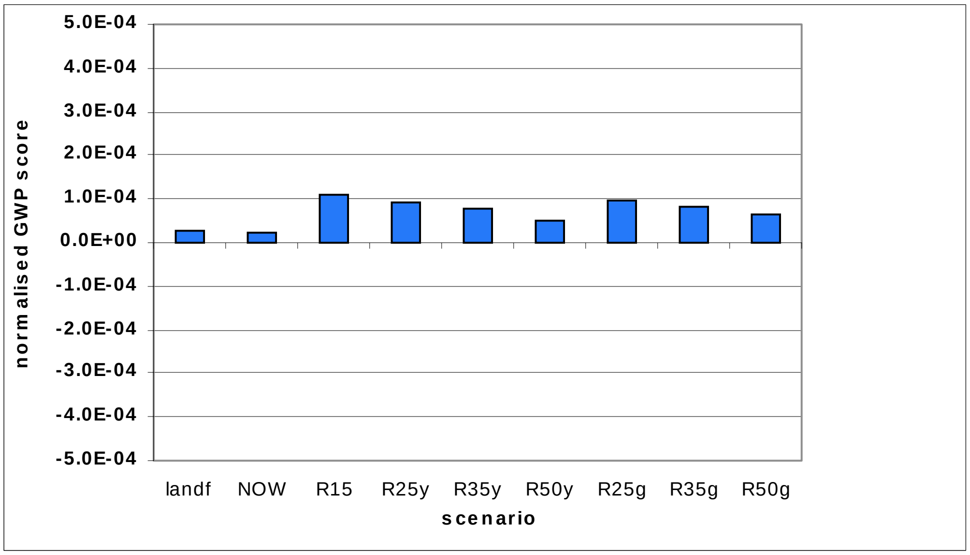


Figure 8.1.3b Environmental impact assessment:
Normalised global warming potential (GWP), total

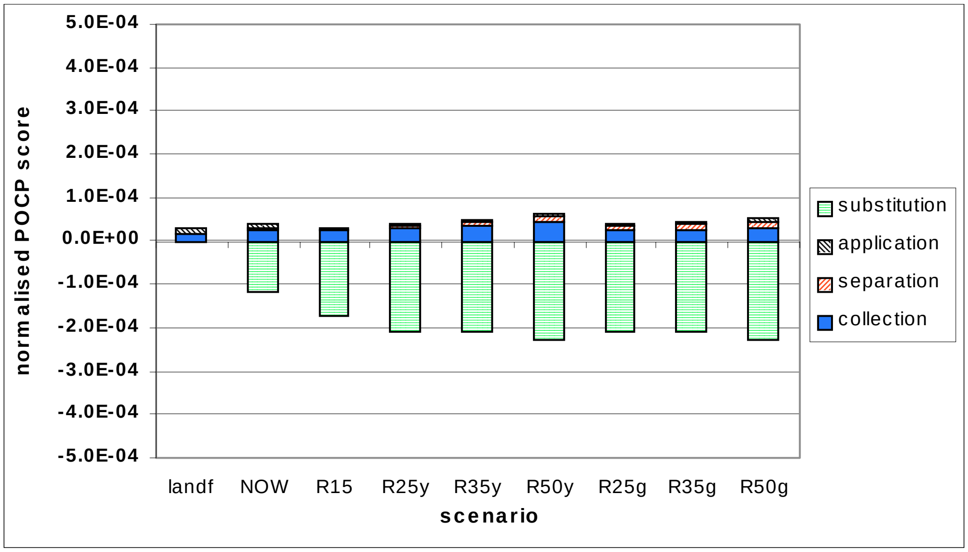


Figure 8.1.4a *Environmental impact assessment:*
Normalised photochemical smog forming potential (POCP) per step

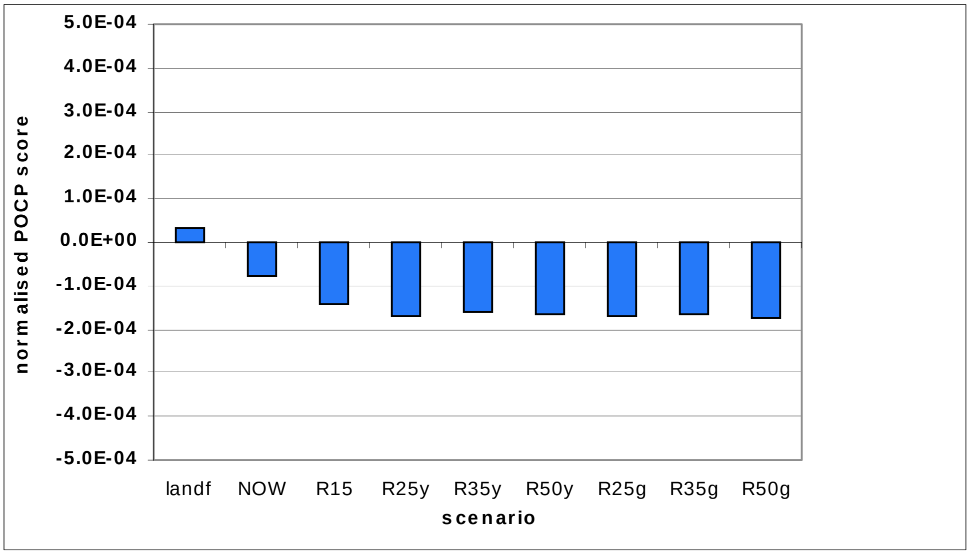


Figure 8.1.4b *Environmental impact assessment:*
Normalised photochemical smog forming potential (POCP), total.

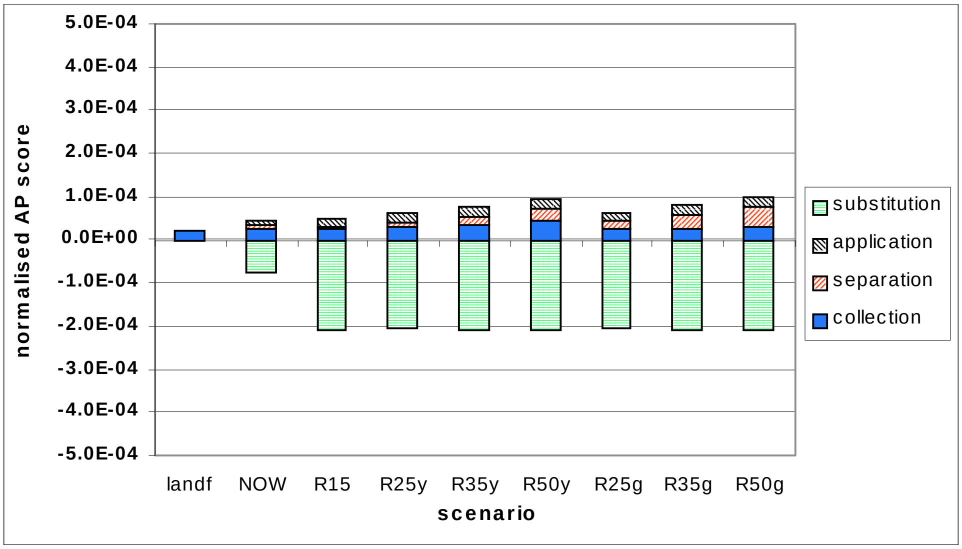


Figure 8.1.5a *Environmental impact assessment: Normalised acidification potential (AP) per step.*

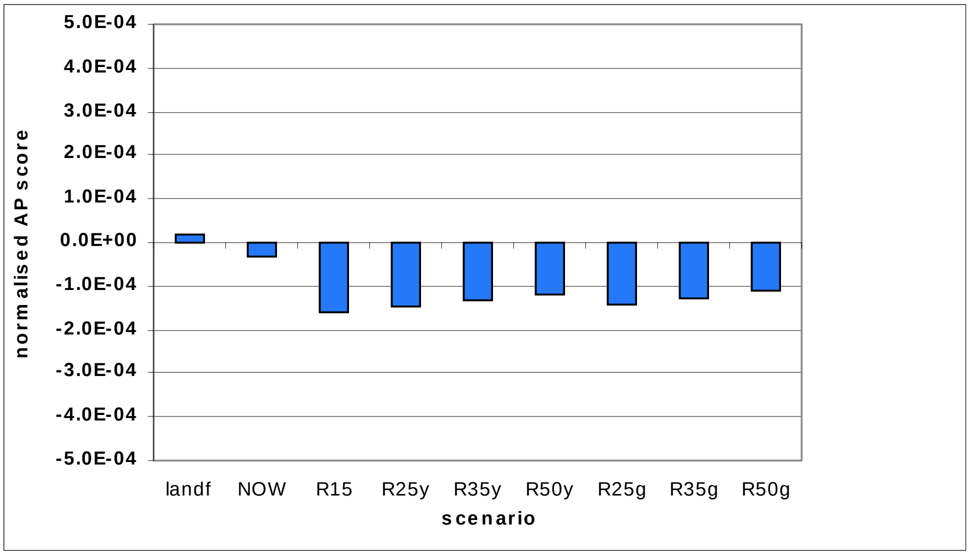


Figure 8.1.5b *Environmental impact assessment: Normalised acidification potential (AP), total.*

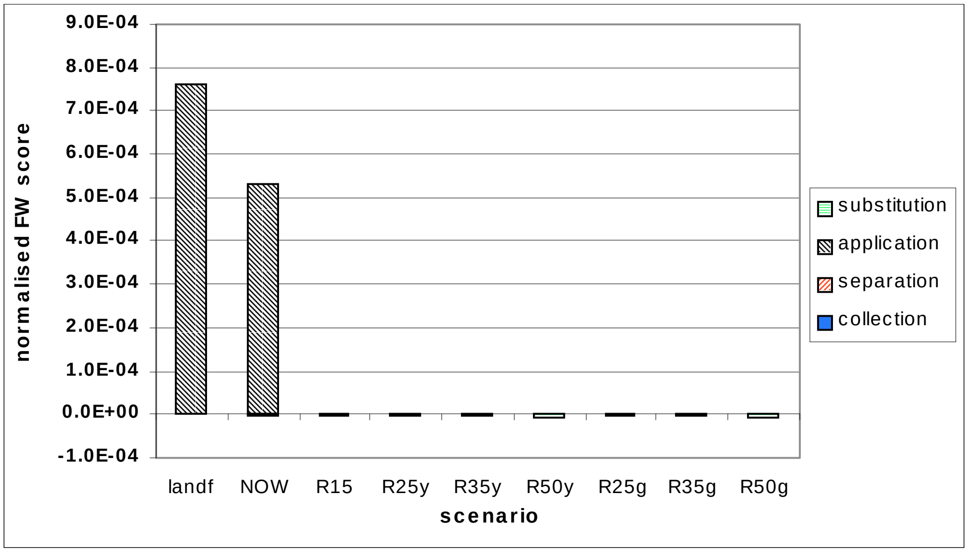


Figure 8.1.6a *Environmental impact assessment: Normalised final waste (FW) per step.*

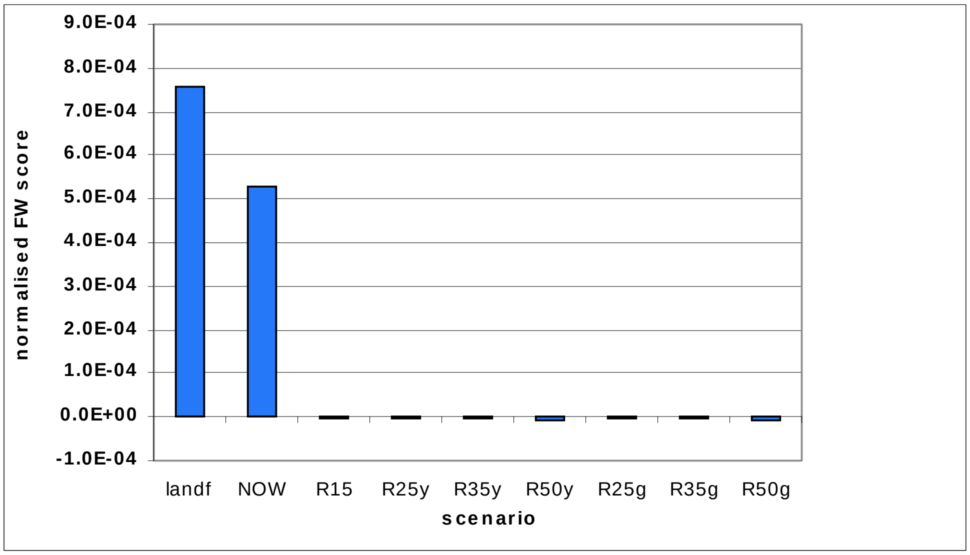


Figure 8.1.6b *Environmental impact assessment: Normalised final waste (FW), total.*

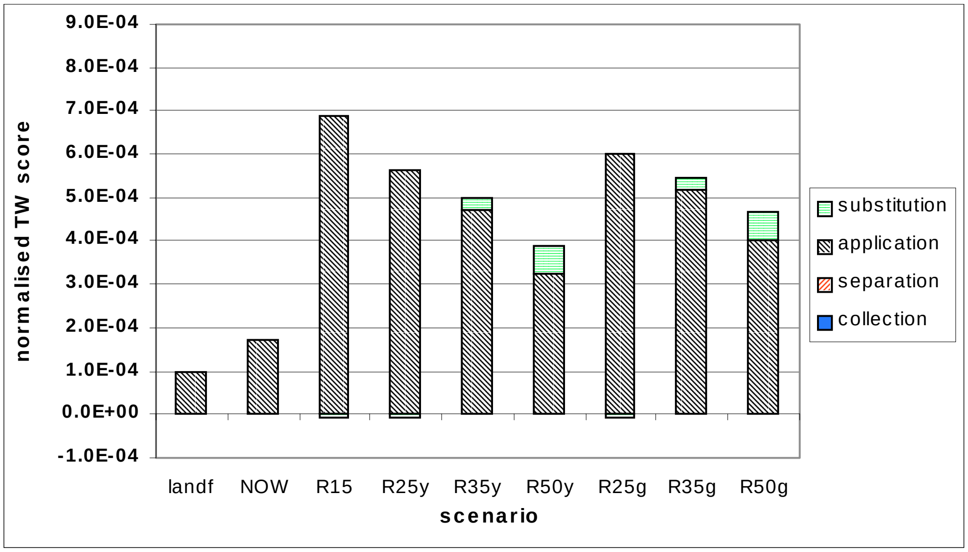


*Figure 8.1.7a Environmental impact assessment:
Normalised final specific waste (TW) per step.*

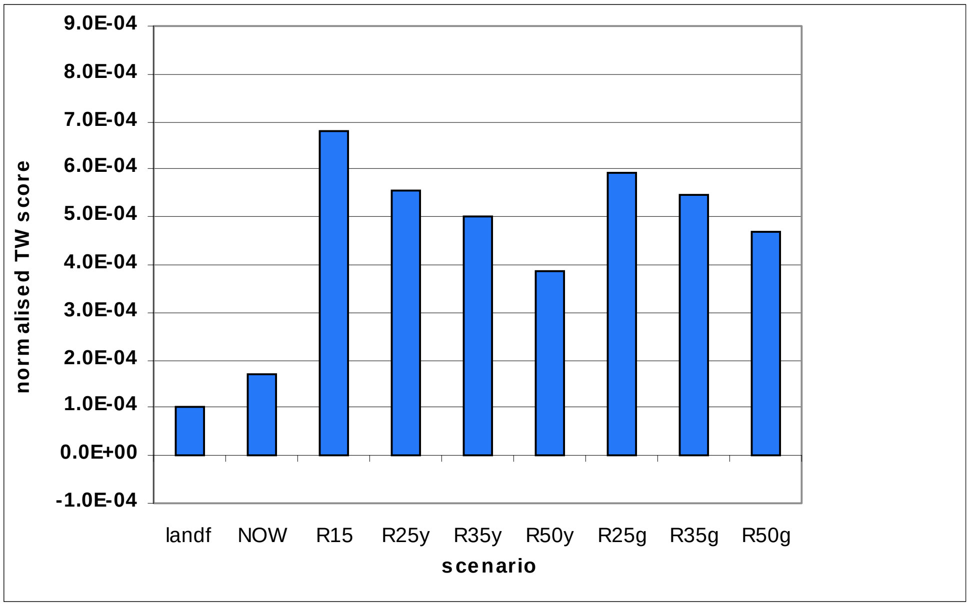


*Figure 8.1.7b Environmental impact assessment:
Normalised final specific waste (TW), total.*

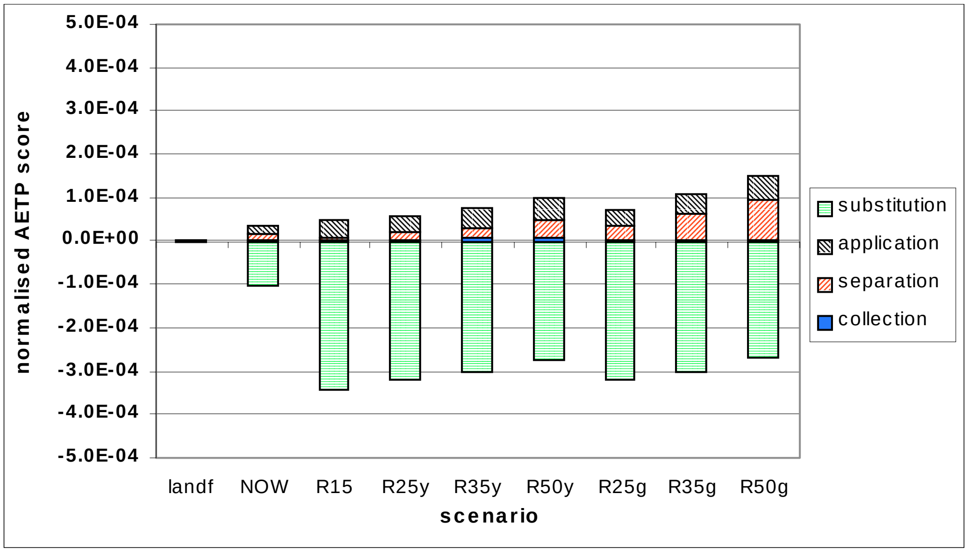


Figure 8.1.8a *Environmental impact assessment:*
Normalised aquatic ecotoxicity potential (AETP) per step.

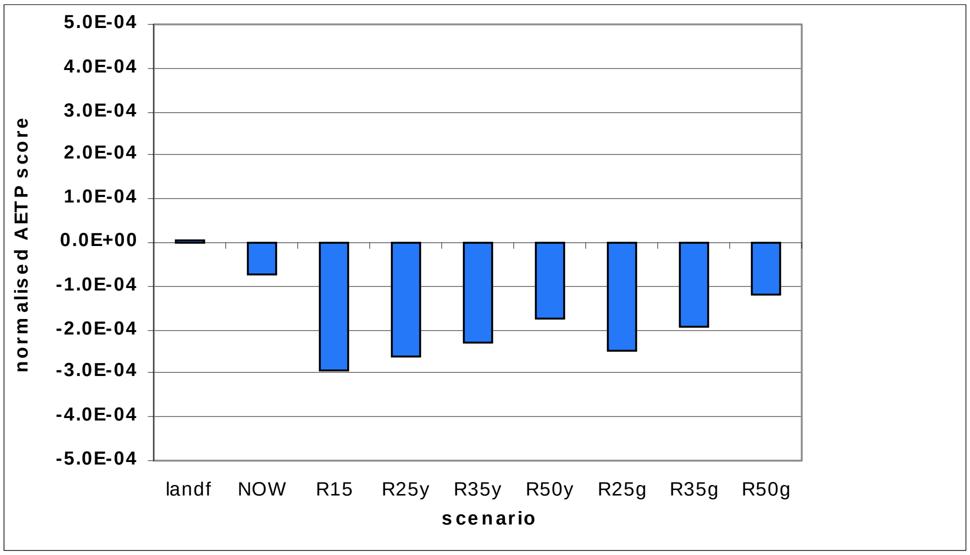


Figure 8.1.8b *Environmental impact assessment:*
Normalised aquatic ecotoxicity potential (AETP), total.

8.2 Integral normalised results

Separate normalised impacts can be presented integral (in one single graph). As example figure 8.2.1 presents in “one graph” combined normalised impacts of the base case scenarios of this study (yellow bag scenarios R25y, R35y and R50y together with scenario R15 and the both reference scenarios landfill and NOW).
For integral presentation of the normalised impacts of scenarios in this study this integral form is applied.

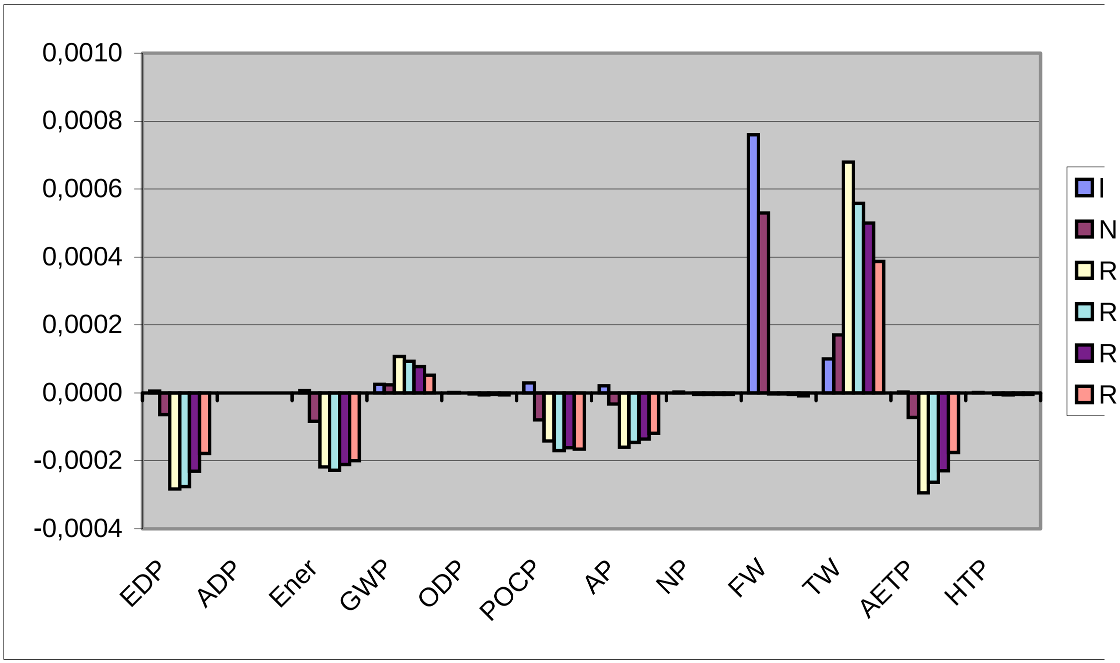
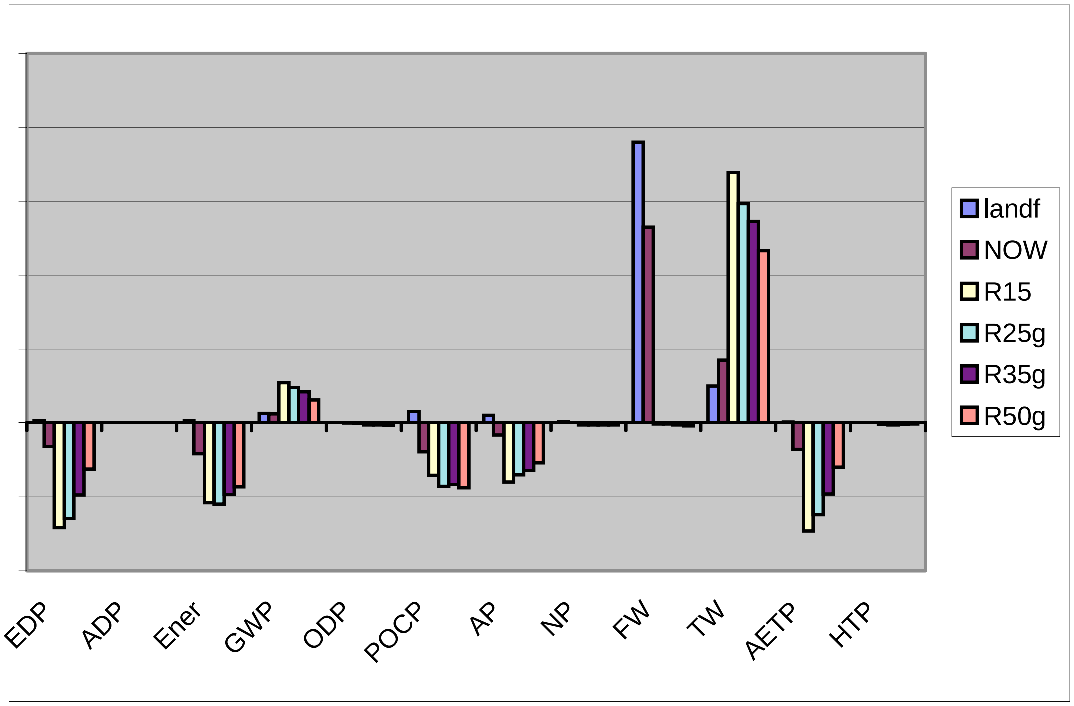


Figure 8.2.1 *Environmental impact assessment: Normalised scores of landf, NOW, R15, R25y, R35y and R50y (scenarios II, III and IV; collection with the yellow bag).*

Figure 8.2.2 illustrates the normalised scores of the scenarios R25g, R35g, R50g and of the both reference scenarios (landfill and NOW) and scenario R15.
Both yellow bag scenario (figure 8.2.1) and grey bag scenario (figure 8.2.2) show FW and TW loads have a relatively important part of the European impact. Also the AETP, EDP, ENER, GW, POCP and AP loads have a relevant part of this integral environmental impact.



Environmental impact assessment: Normalised scores of landf, NOW, R15, R35g and R50g (scenarios II, III and IV; collection by grey bag).

8.3 Dominance analysis

In order to evaluate the results of the environmental impact assessment of this study a (brief) dominance analysis is carried out to examine the effects of individual system sections on the results of the calculations.
The results of the dominance analysis set the priorities for the sensitivity analysis. The objective is to identify those steps in the scenarios, which have a significant influence when the specifications or parameter values are varied.
The dominance analysis still uses a sort of weighting by the application of specific normalisation factors. The application of a different set of factors can result in other conclusions with regard to the dominating environmental themese (see 8.4.4).

The contribution of the several steps (collection, sorting and preparation, application and substitution) of the system to the separate environmental aspects is already presented in the figures 8.1.1 up to 8.1.8 inclusive. The conclusions are:

- The environmental aspects FW, TW followed by EDP, ENER, GWP, POCP, AP and AETP have a relatively important impact.
- The contribution of the collection step and separation step to the already mentioned aspects is small regarding all scenarios.

- The contribution to AETP, AP, EDP, ENER and POCP is especially realised by the substituted processes.
- The contribution to FW, TW and GWP is mainly caused by the application step.

An assumption regarding the figures 8.1.1 up to 8.1.8 inclusive is the validity of the normalisation factors used. As explained in appendix C.2 there exists some uncertainty about the normalisation factors, especially the factors for the themes FW, TW and AETP can have a relevant influence.
The sensitivity of the results of the LCA study in relation to the choice of the value of the normalisation factors is an item, which will be illustrated in par. 8.4.4 and will be further explained in part II of this report (Eco-efficiency model). The sensitivity analysis in chapter 8.4 is related to relevant selections of the substituted processes and application processes.

8.4 Sensitivity analyses

8.4.1 Energy recovery by a combination of MSWI and cement kiln

Considering the definition of the scenarios (chapter 2.2.3) it is indicated that the option of energy recovery is not limited to the MSWI application (ER_{mswi}). Energy recovery can also be realised in a cement kiln (ER_{high}), with an additional greater conversion efficiency. That is why that during the start of this study alternatives (subvariants) for the scenarios R35 and R50 are defined:

- R35yHE contains 35% R, 32½% ER_{mswi} and 32½% ER_{high}
- R50yHE contains 50% R, 25% ER_{mswi} and 25% ER_{high}

During calculation of the mass balances of these subvariants it appears not to be possible to realise the mentioned targets with the yellow bag and grey bag collection systems, including corresponding response rates and the sequential sorting/separation processes with certain separation efficiencies. The separation efficiency of the upgrading process after grey bag collection is insufficient for realisation of the mentioned target for ER_{high} Yellow bag collection (for MSW packaging plastics) combined with route B3 (for IW packaging plastics) results in the following scores:

- R35yHE with 35% R and 65% ER by 33.8% ER_{mswi} and 31.2% ER_{high}
- R50yHE with 50% R and 50% ER by 33.8% ER_{mswi} and 16.2% ER_{high}

The environmental load of the new alternatives R35yHE and R50yHE is calculated in the sensitivity analysis and the normalised results are condensed in figure 8.4.1 (yellow bag system) and compared with the results of the base case; figure 8.2.1. The participation of ER_{high} in both R35y and R50y has especially (positive) consequences for TW and AETP (comparison with figure 8.2.1).

- Because of the participation of ER_{high} the quantity of packaging plastics in the MSWI will be reduced and consequently also the quantity of flue gas cleaning residue will decrease. That is why the TW impact of the scenarios R35y and R50y will decrease.
- Because of the application of ER_{high} (the processing of plastics in a cement kiln) coal is substituted in a conventional cement kiln process. The avoided coal mining has important consequences for the AETP impact. The processing of packaging plastics by means of ER_{high} has a notable influence on reduction of the AETP load, compared with the incineration of plastics in a MSWI.

Of course the application of the scenarios R35yHE and R50yHE has costs consequences. These consequences will be explained in part II of this report (Eco-efficiency model).

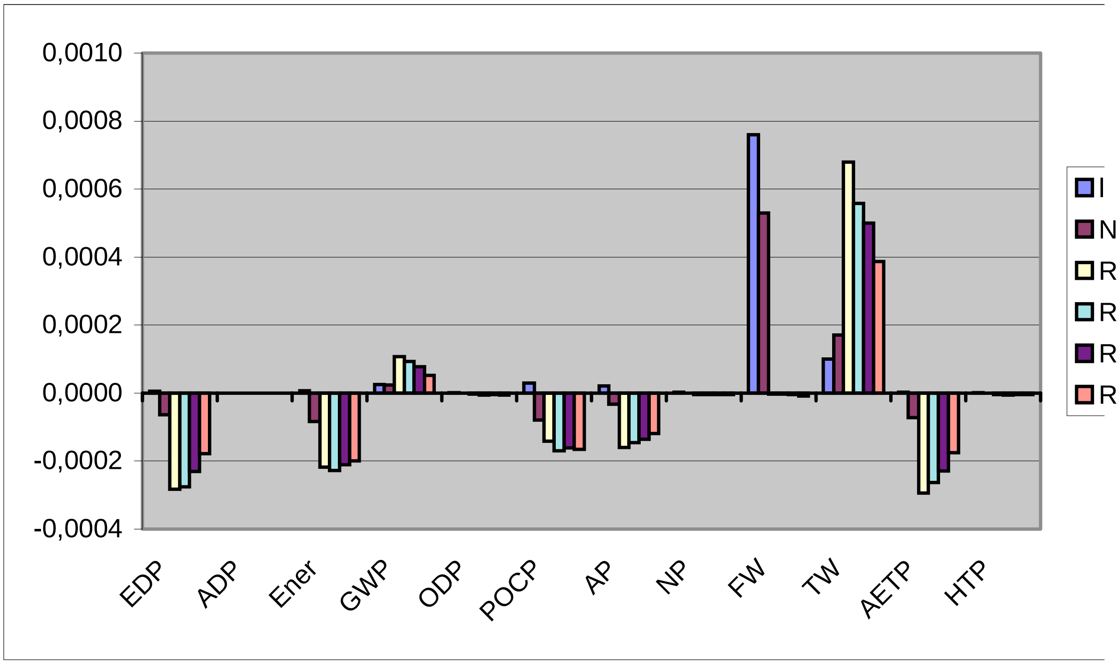


Figure 8.2.1 *Environmental impact assessment: Normalised scores of landf, NOW, R15, R25y, R35y and R50y*

(scenarios II, III and IV; collection with the yellow bag).

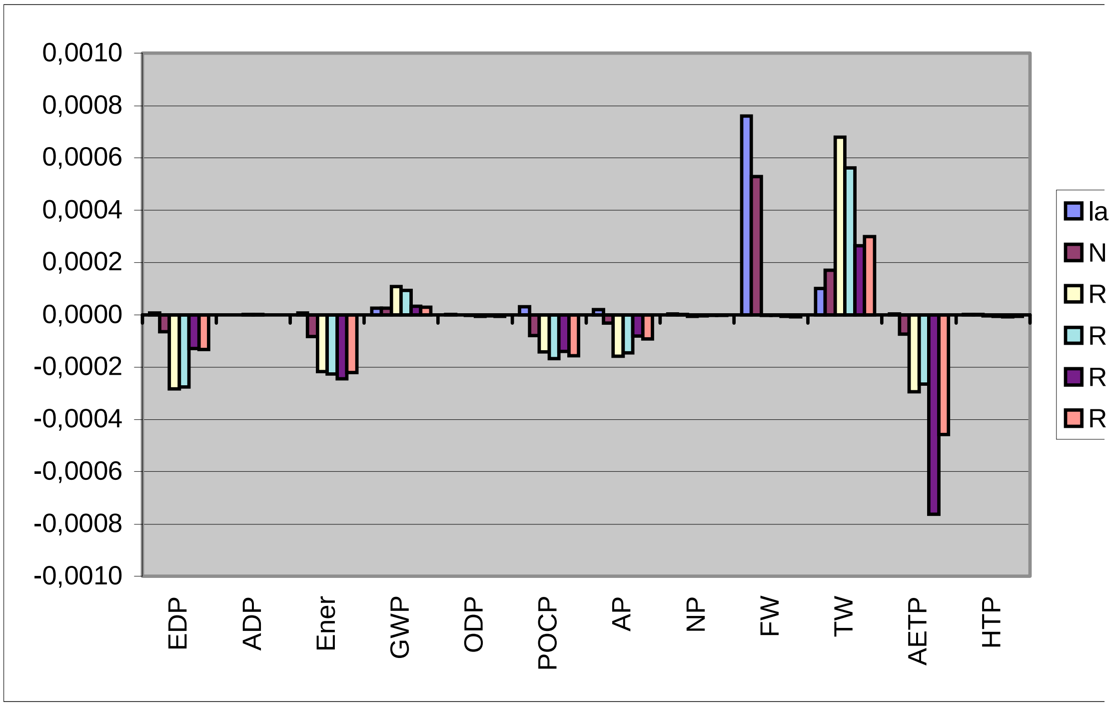


Figure 8.4.1 *Normalised environmental impacts yellow bag routes :*
Energy recovery by MSWI (ER = ER_{mswi}) compared with energy recovery by a combination of MSWI and cement kiln
(ER= ER_{mswi} + ER_{high}).

8.4.2 Energy recovery by a MSWI with 65% heat recovery

The energy yield of the MSWI (ER_{mswi}) is an important starting point of the calculations. In practice the energy output and sequentially the energy consumption can differ enormously per installation. Also the flue gas cleaning of the MSWI can differ per installation. With the help of a sensitivity analysis the consequences of a changing energy yield have been studied.

The assumption that the flue gas cleaning meets the Dutch standards during the processing of the packaging plastics in a MSWI is the base starting point for the calculations. Furthermore the MSWI produces both electricity and heat (to be used for district heating and/or industrial purposes). This energy yield corresponds with the production of a Dutch average MSWI, which means an output of 0.2 MJ electricity and 0.1 MJ heat per MJ (LHV) input. The energy conversion efficiency of the MSWI increases when only heat is generated. Several MSWI installations generate more than 0.65 MJ heat per MJ (LHV) input.
A yield of 0.65 MJ heat per MJ (LHV) input is the starting point for the sensitivity analysis of the scenarios R15, R25y, R35y and R50y. In this case the flue gas cleaning meets the (less severe) German flue gas standards.
With the described adjustment the environmental load of the scenarios R15, R25y, R35y and R50y is calculated and the normalised results are illustrated in figure 8.4.2 (yellow bag system) and compared with the base case results (figure 8.2.1).
Especially the changed energy recovery of the MSWI has consequences for the environmental impacts and particularly for AP, AETP and EDP (comparison with figure 8.2.1):

- The greater heat recovery of the MSWI results in a remarkable saving of conventional heat from coal and oil. The winning and combustion of these fuels deliver a relatively great contribution to AP and AETP, and a strong reduction will take place when “ER_{mswi} = heat” is selected.
- Heat produced by the MSWI results in a greater saving of coal than those of electricity production (based on BUWAL 250 database). However production of electricity by a MSWI results in a saving of relatively scarce fuels such as gas and nuclear fuel. Coal is not a scarce resource. For this reason the EDP saving for “ER_{mswi} = heat + electricity” is to a bigger extent than for “ER_{mswi} = heat” (particularly in the case of R15).

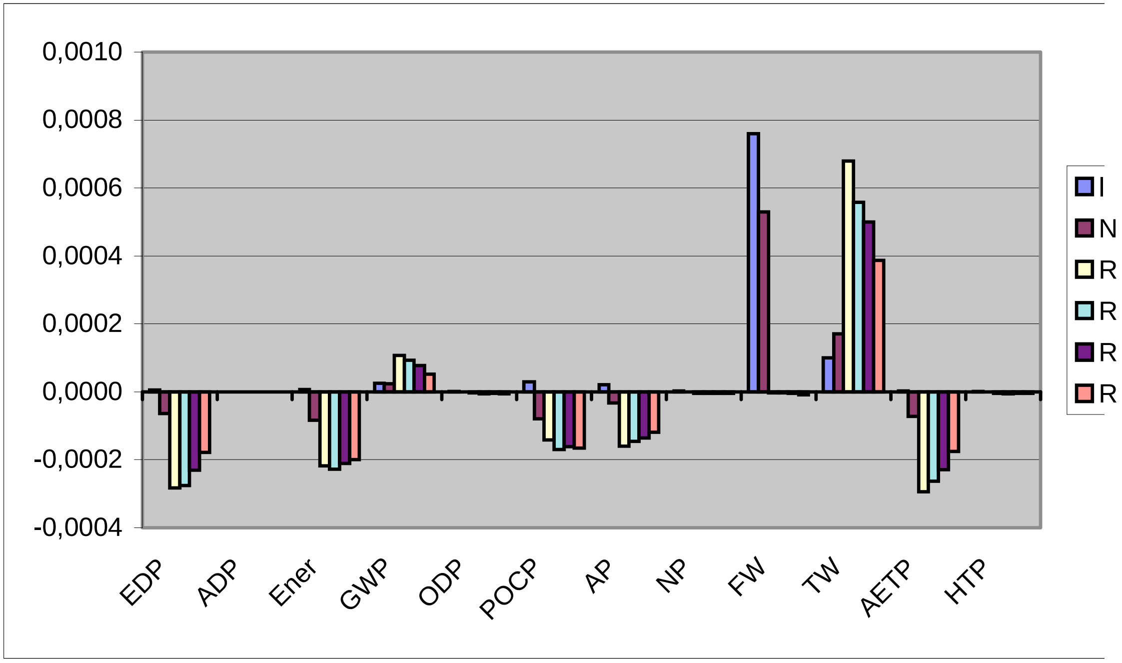


Figure 8.2.1 Environmental impact assessment: Normalised scores of landf, NOW, R15, R25y, R35y and R50y (scenarios II, III and IV; collection with the yellow bag).

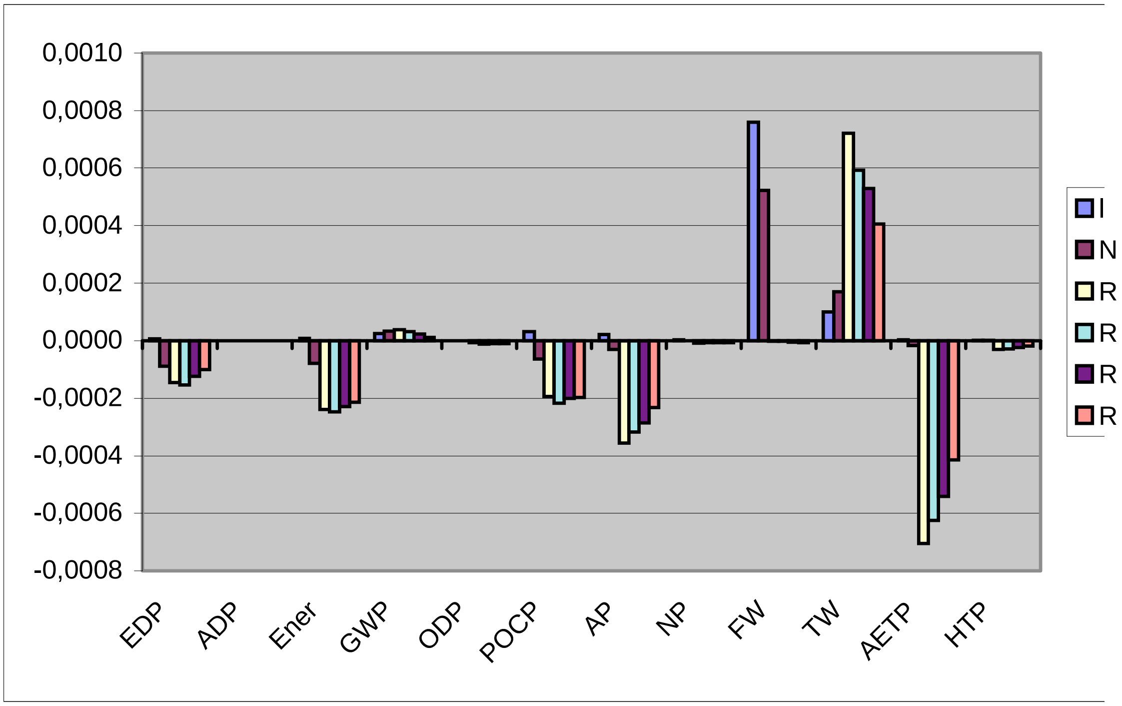


Figure 8.4.2 Normalised environmental impacts yellow bag routes: Electricity and heat recovery by MSWI (ER_{mswi} = heat + electricity) compared with maximal heat recovery by MSWI (ER_{mswi} = heat).

8.4.3 Feedstock recycling by the Texaco gasification process

The feedstock recycling (FR) target of scenarios II, III and IV is realised by processing mixed plastics fractions from grey bag or yellow bag routes. In the base calculations these mixed plastics are processed in a blast furnace, as a substitute of the normal reducing agent, heavy oil.

In the sensitivity analysis FR mixed plastics fractions are processed as feedstock in the Texaco gasification plant. Gasification of plastics in the Texaco process, with additional H_2 supply, produces syngas for methanol production. Syngas from plastics is a substitute for natural gas based syngas.
With the change of the feedstock recycling process the environmental load of the scenarios R25y, R35y and R50y is recalculated. The normalised results are illustrated in figure 8.4.3 (yellow bag system). Comparison with the base situation (comparison with figure 8.2.1) results in the following remarks.

The changed selection of the feedstock recycling option has some minor consequences for the environmental impacts. Compared with the substitution of oil by the blast furnace substitution of natural gas by gasification results for the environmental aspects AETP, POCP and EDP in lower net environmental benefits. Consequently there are some higher environmental loads of the recycling scenarios in the case of gasification. These differences however can hardly be detected (comparison of the results of figure 8.4.3 with those of figure 8.2.1).

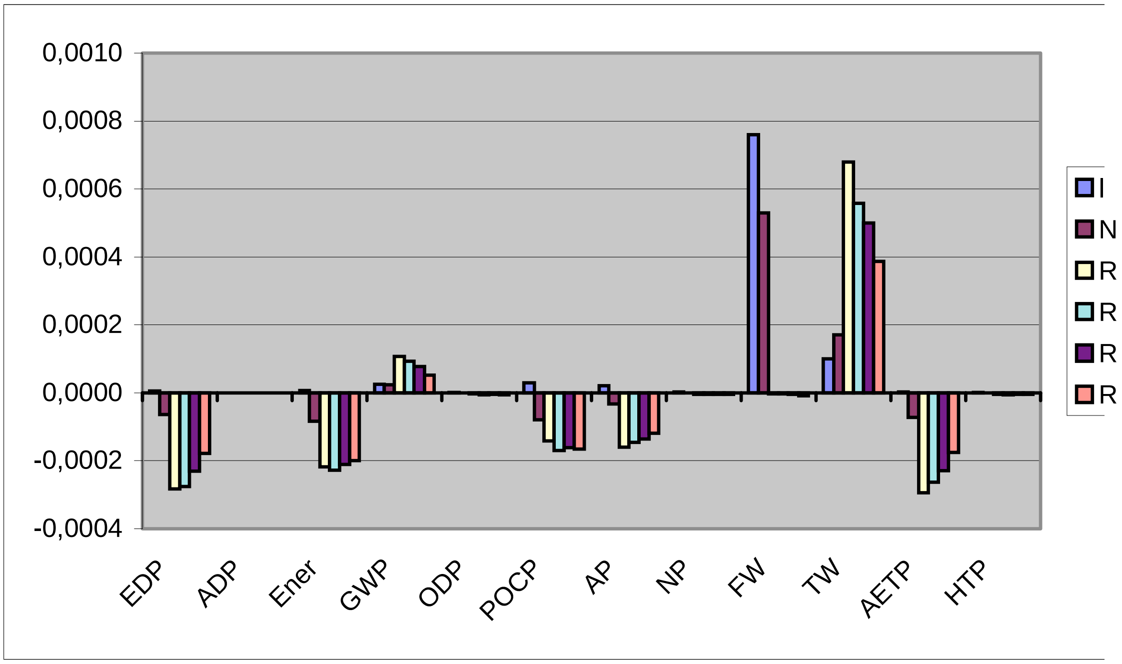


Figure 8.2.1 *Environmental impact assessment: Normalised scores of landf, NOW, R15, R25y, R35y and R50y (scenarios II, III and IV; collection with the yellow bag).*

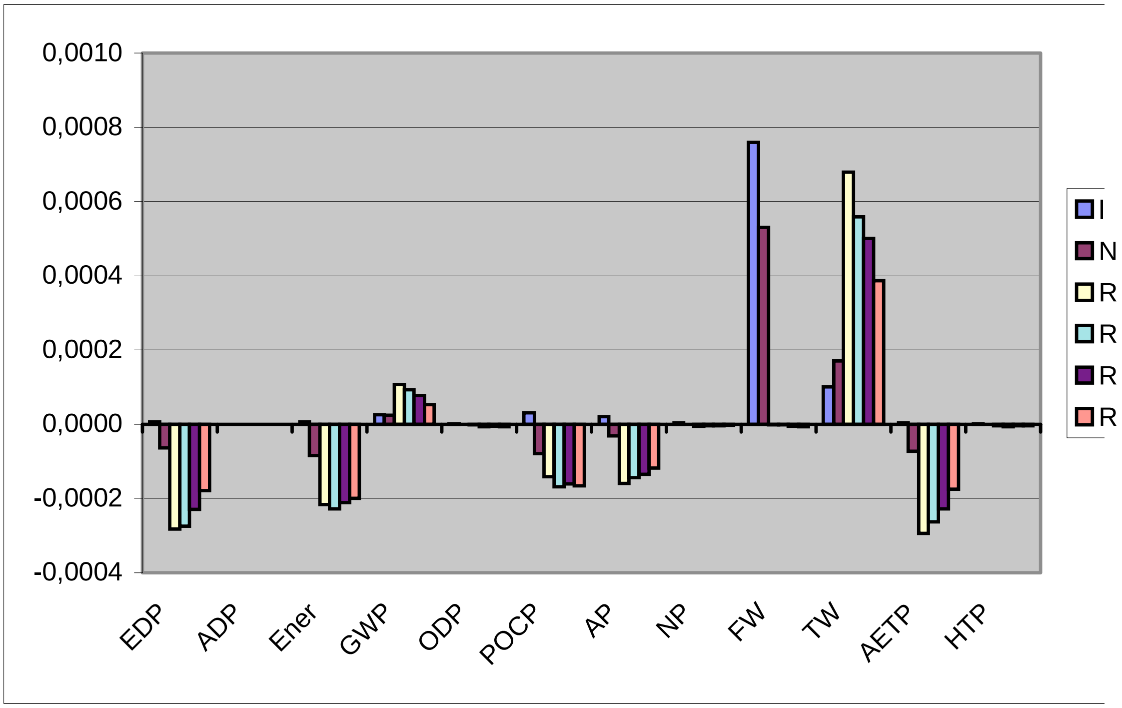


Figure 8.4.3 *Normalised environmental impacts yellow bag routes :*
Feedstock recycling by blast furnace process (FR = blast furnace) compared with Texaco gasification process)
(FR = gasification).

8.4.4 Sensitivity of normalisation factors

As discussed in paragraph 8.3 there is a considerable uncertainty about the values of normalisation factors. In part II of this study (see 10.3) some alternative normalisation sets (N2, N3) are presented considering the eco efficiency approach. In this paragraph the impacts of these alternative normalisation data sets are illustrated in the graphs of figure 8.4.4 a and figure 8.4.4b and compared with the results of the base case, see figure 8.2.1 (normalisation set N1).

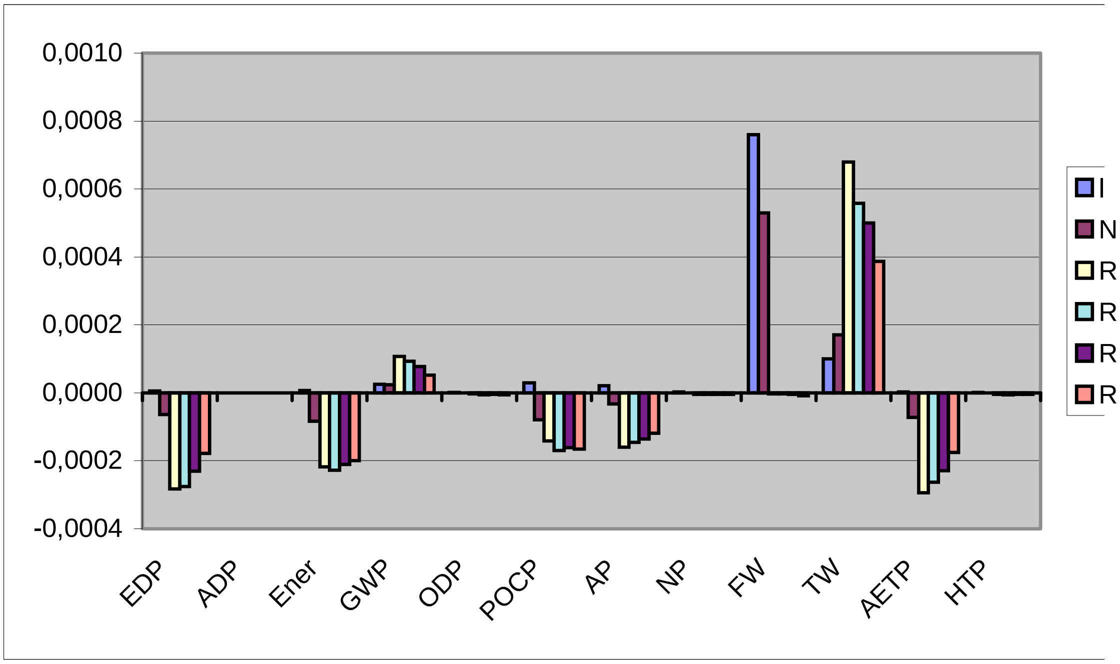


Figure 8.2.1 Environmental impact assessment: Normalised scores of landf, NOW, R15, R25y, R35y and R50y (scenarios II, III and IV; collection with the yellow bag).

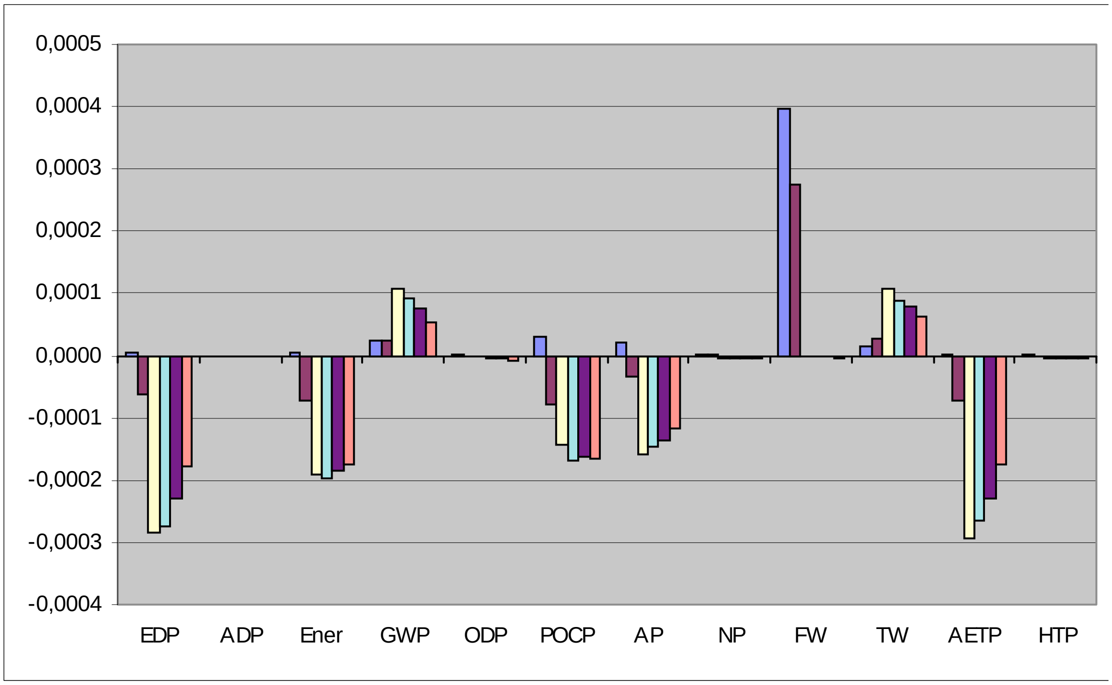
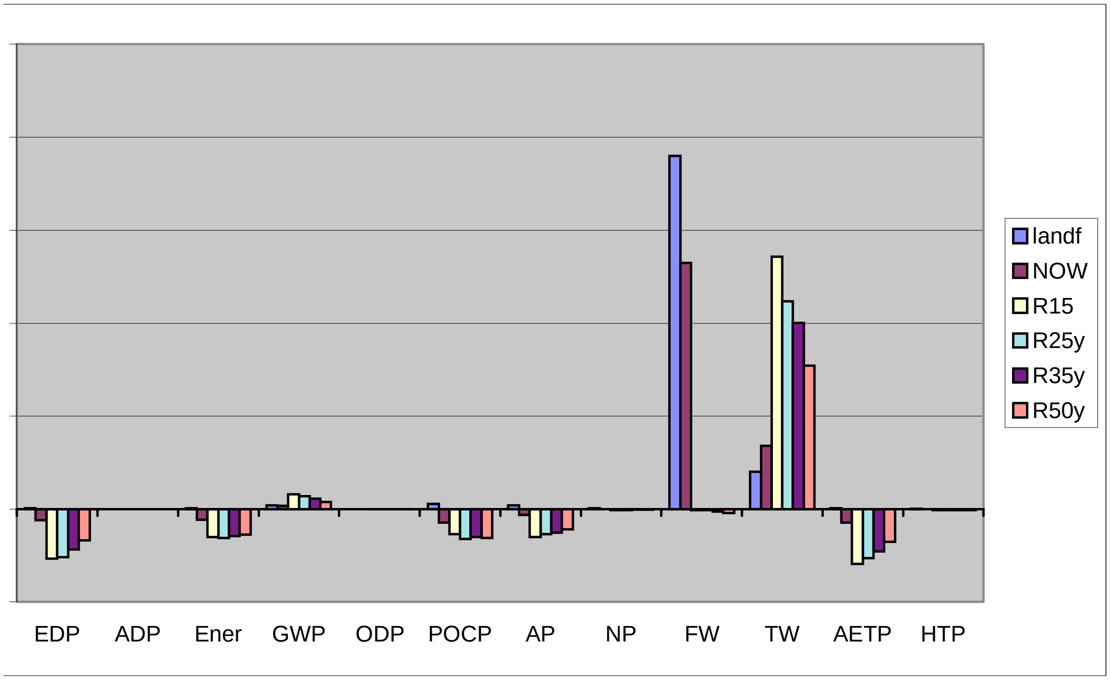


Figure 8.4.4a Normalised environmental impacts yellow bag routes : Normalisation by set N2 (see table 10.3.2).



.4b Normalised environmental impacts yellow bag routes :
Normalisation by set N3 (see table 10.3.2).

Such as in the base case (normalisation set N1, see figure 8.2.1) the relative contribution of the FW impact to the integral environmental impact for the scenarios “landfill”and “NOW”is also most dominant in figure 8.4.4a (application normalisation set N2) and figure 8.4.4b (application normalisation set N3).
The relative contributions to the normalised environmental impact of the other themes (EDP, ENER, GWP, POCP, etc.) varies considerably when different normalisation sets are applied.

9. Conclusions part I

Hereafter the conclusions of the analysis of costs and environmental impacts are summarised.

Costs inventory

Inventoried costs in this study are derived from literature as real costs, without subsidies, profits etc. The costs inventory leads to the following features:

- Total costs of the reference scenarios vary between 0.174 EURO per kg plastics (landfill) and 0.254 EURO per kg plastics (NOW). Total costs of recycling scenarios vary more then a factor 3 between 0.204 EURO per kg plastics (R15) and 0.669 EURO per kg plastics (R50y).
- The scenarios with an increasing recycling rate R[1] illustrate an increase of total costs. Increasing costs for collection, separation and treatment are only partly compensated by an increase of benefits.
- Increasing R rate by mixed plastics recycling as a concrete substitute (MPR) results in higher total costs compared with feedstock recycling (FR), because of the rather low benefits of the MPR products compared with those of feedstock.
- Yellow bag scenarios have higher total costs compared with grey bag scenarios. Especially the collection costs increase with increasing R rate in that case.

Environmental impact assessment

In this study environmental inventory items (emissions, resources and wastes) of scenarios are expressed as environmental impacts by the LCA method. Environmental impacts in this study are : mineral resources depletion (ADP), fuel resources depletion (EDP), global warming (GWP), ozone depletion (ODP), human toxicity (HTP), aquatic ecotoxicity (AETP), photochemical ozone creation (POCP), acidification potential (AP), nutrification potential (NP), final waste deposit (FW), specific final waste deposit (TW) and cumulative energy requirement (ENER). Environmental impacts scores are made dimensionless by means of normalisation with average European impacts.

Relative important impacts:

- The impacts FW and TW, followed by AETP, AP, EDP, ENER, POCP and GWP relatively have the highest part to the normalised European environmental impact.

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[1] $R = \Sigma \{MR + MPR + FR\}$

Consequences of increasing recycling rate R

- With an increasing recycling rate R of the scenarios there is an increase of AETP, AP, EDP and ENER, whereas there is a decrease of the impacts TW and GWP.

Comparison grey bag scenarios with yellow bag scenarios

- With an increasing recycling rate R of the scenarios there is a greater increase of some impacts for grey bag scenarios, especially with respect to AETP and EDP. The greater impact load is a consequence of the higher energy input for separation processes in the case of grey bag options.

Relative important processes in the comparison:

- The calculated FW impact is mainly a consequence of the landfill application, whereas most of TW impact is generated from fly ash and residues of MSWI.
- Generally the reduction of FW and the growth of TW and GWP is dominated by the final treatment (application) processes. Collection and separation processes have minor influence on these impacts, The same conclusion can be made for the substituted processes with respect to FW and TW. With respect to GWP there is a considerable contribution of the substituted processes.
- The reduction of the impacts AETP, AP, EDP, ENER and POCP is mainly a result of substituted processes. Collection, separation and application processes have minor influences on these impacts.

Sensitivity analysis with respect to substituted processes

Relevant selections with respect to substituted processes are subjected to a sensitivity analysis.

- Changing 100% MSWI energy recovery to a combination of partial MSWI and partial co-combustion in a cement kiln for both scenarios III and IV can not be realised by implementation of grey bag scenarios. The reason is the limited level of collection efficiency and separation efficiency in practise. In the case of yellow bag scenarios there is a reasonable potential for co-combustion in a cement kiln. Regarding these scenarios combined energy recovery results in a relative important decrease of the TW impact and in some decrease of the AETP impact.
- Increasing the energy recovery of a MSWI to 65% heat recovery (compared with 20% electricity plus 10% heat recovery) results in a slight decrease of the AP and AETP impacts, whereas there is an increase of EDP impact. This result is caused by differences with respect to substituted fuels.
- Change of the feedstock recycling process to Texaco gasification with substitution of the production of natural gas based syngas (compared with substitution of oil in a blast furnace) results in limited consequences of environmental impacts. Feedstock recycling by gasification gives higher environmental impacts especially considering AETP, POCP and EDP, because of differences between the substituted feedstock and the additional hydrogen supply needed in the case of gasification.

Application of normalisation factors

The choice of the set of normalisation factors (and their values) estimates the relative part of the normalised European impact to the several environmental themes.

General conclusion

Increase of the recycling rate R results in an increase of costs and in variation of the environmental impacts for the studied scenarios. The variation of impacts is mainly dependent of the substitution of primary products by the products (or output) of recycling processes and energy recovery processes.

Part II: Demonstration Eco-efficiency

10. Introduction Eco-efficiency

10.1 Weighting environmental impacts

In principle the environmental load calculations result in 12 separate scores per environmental aspect for each scenario (see part 1, table 2.6).
The relative environmental scores of the scenarios (normalised scores of the individual environmental themes,) are presented in “bar charts” (part I : chapter 8). Normalised scores show the relative contribution of the individual environmental themes, but do not give a comparison or a mutual impact judgement of the different themes. The normalisation results only indicate that 8 environmental themes have a relevant contribution to the total load (FW, TW, EDP, ENER, GWP, POCP, AP and AETP). This means that the residual themes (ADP, ODP, NP, HTP) have a relatively small influence.

For a condensed presentation of the LCA results there is a need to present the environmental load in one total score per scenario (*integral environmental impact score*). Lists with 12 different environmental scores give detailed information, but the presentations are less convenient.
To be able to calculate one integral environmental impact score a weighting of the different environmental aspects has to take place. The integral environmental impact calculation is based on a weighting or ranking of the relevance of the different environmental themes. Such a ranking gives rise to at least two important objections:

- The ranking is subjective. Different visions of society result in different ranking methods.
- Today no ranking method has a broad society support and there is no general consensus for this item.

For these reasons weighting is the most subjective element of the LCA methodology In the ISO guidelines for the LCA methodology (ISO FDIS14042) it is even recommended to execute no weighting for LCA studies with a “broad public impact”. In a number of LCA studies the weighting step is not incorporated.
On the other hand there are several LCA studies in which one or more weighting methods are carried out (for example (5), (12), (21), (22)) and the results are applied for different purposes.

A partial counter against the objections can be offered by the following:

1. To argue in a clear way the need of a weighting during describing the goal and scope definition of the LCA study
2. To make a distinction between the results with and without a weighting of the environmental aspects.
3. To apply different weighting methods and different weighting factors during the weighting of the environmental aspects.

The above mentioned aspects are also incorporated in the report of this study. In addition to the detailed impacts described in part 1, part 2 presents one total score per scenario for the environmental load.

10.2 Portfolio's

In addition to the environmental load, also the costs of the different ways to process plastic packaging waste have been estimated during the execution of this study. So the judgement of the different scenarios is related to "ecology" and "economy". The term "Eco" has a dual meaning in this situation.

The condensed presentation of the results of this study is based on two parameters, the total costs score and the integral environmental impact score. These parameters are estimated in the following way:

- During the costs calculations in part I (chapter 6 of this study) the different cost items are summarised in one total costs score per scenario.
- The weighting of the environmental aspects results in one integral environmental impact score per scenario.

The combined presentation of the integral environmental impact score and the total costs score can be realised in a graphic way with a two dimensional graph.
In literature different presentation ways are described (for instance (5), (12)).

The proposed option is the so-called " portfolio " presentation. This option has been developed and applied by BASF (12) in this framework. With this way of presentation both scores are reflected in a "portfolio square" divided in 4 "squares". Only the *differences* between the costs scores and the differences between the environmental impact scores are presented. In addition these differences are *standardised* (made dimensionless). The results of the two described operations are called the **"Costs Indicator"** and the **"Impacts Indicator"**.

Figure 10.1 gives a schematic example of the defined portfolio. The calculated portfolio costs and the calculated portfolio impacts estimate the position of each scenario in the portfolio.

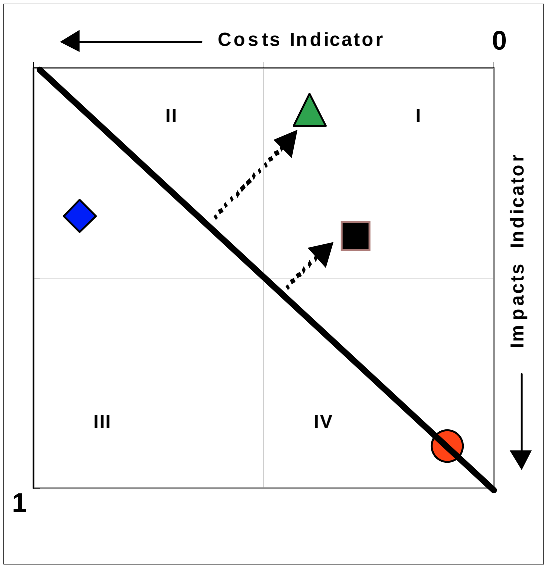

Figure 10.1 Example of portfolio for 4 scenarios (hypothetical)
(--------- ▸ = Eco-efficiency).

The portfolio “Costs Indicator” as well as the portfolio “Impacts Indicator” always have a value between 0 and 1. All separate values are a linear representation of the differences between the total costs scores and the differences between the integral environmental impacts scores of the scenarios to be compared.

The significance of the 4 squares in the portfolio is roughly as follows:

- square I = relatively low costs, relatively low environmental impact
- square II = relatively high costs, relatively low environmental impact
- square III = relatively high costs, relatively high environmental impact
- square IV = relatively low costs, relatively high environmental impact

In principle the diagonal is an important reference line in the portfolio. Points with a relatively great distance *above* the diagonal are *relatively* Eco efficient.

The advantage of the portfolio presentation is the clear positioning of the different scenarios with respect to the differences in costs and the differences in environmental impacts.

In this report the portfolio presentation is used for the judgement of the Eco-efficiency of the scenarios with the different recycling rates.

10.3 Calculation basis for Eco-efficiency

In part II of this study the portfolio presentation is applied for the judgement of the Eco-efficiency of the several scenarios with different recycling targets.

This way of presentation is important for *specific combinations (sets*) of scenarios to be compared. The differences of the separate scenarios of the set are “high-lighted” in the portfolio. In principle the Eco-efficiency calculations are carried out for the same combinations of scenarios, which are illustrated in the bar charts described in chapter 8, part 1.
The following sensitivity analyses are carried out in chapter 11 on a portfolio basis:

Weighting factors:
As already indicated in chapter 10.2 the selection of the different weighting methods (and weighting factors) to be applied is an important prior condition for the calculation of the environmental impact scores and so for the estimation of the Eco-efficiency.
Table 10.3.1 shows the different combinations of weighting factors related to different weighting methods applied in this study.

Normalisation factors:
As already described in chapter 8.3 the normalisation factors of several environmental aspects are relatively uncertain (for the calculation of the relative contribution to the environmental load). During calculations of these aspects people have to apply a range of values for the normalisation factor. A change of the normalisation factors value can result in a move of the point position in the portfolio.
Table 10.3.2 gives an overview of the several normalisation factors, which correspond with different frameworks (Europe, Germany, Netherlands).

List of environmental aspects:
The results of the LCA studies are not always achieved from the same combinations of environmental aspects as applied in this study (part I; table 2.6). During the execution of several LCA studies for instance people do not consider toxicity (HTP and AETP). The results of other LCA studies show the omission of the aspect final waste (FW and TW). Table 10.3.3 shows the different combinations of environmental aspects used for the sensitivity calculations.

Application processes:
As already indicated in part I chapter 8.3 the selection of the application processes and the specific output and efficiency of these processes determine the relevance of the environmental impacts to an important extent. The choice of the so called “back ground” processes has (indirectly) an important impact.
The same sensitivity analysis as performed in chapter 8.4 is executed on the basis of portfolio presentation.

Additional scenarios:
In the sensitivity analysis some additional scenarios are considered in addition to the main recycling scenarios as given in part I:

- Two additional scenarios with 10% mechanical recycling combined with 90% energy recovery, in order to illustrate the consequences of a decrease of mechanical recycling and an increase of energy recovery. One additional scenario is strictly focussed at mechanical recycling of IW plastic mono streams and one additional scenario is mainly focussed at mechanical recycling of MSW packaging plastics.
- Two additional scenarios with 10% mechanical recycling, in combination with a decreased energy recovery and an increased rate of landfill, in order to illustrate the consequences of landfill instead of energy recovery.

Table 10.3.1 Settings of weighting factors for environmental impacts
W_1 = base weighting factors APME, all impacts equal except toxicity (correction factor ½).
W_2 = weighting method conform Danish EDIP method (33)
W_3 = DTT weighting factors (Distance to target factors, Dutch government; reference (31)).

	W_1	**W_2**	**W_3**
EDP	9.1%	0.16% 1)	-
ADP	9.1%	0.16% 2)	-
ENER	9.1%	0.08% 3)	3.4% 6)
GWP	9.1%	10.36 %	4.2%
ODP	9.1%	-	22.8%
POCP	9.1%	9.56%	5.5%
AP	9.1%	10.36%	13.5%
NP	9.1%	9.56%	11.4%
FW	9.1%	8.76%	13.5%
TW	9.1%	8.76%	13.5%
AETP	4.5%	20.72% 4)	5.9%
HTP	4.5%	21.51% 5)	6.3%

1) average weighting factor for gas and oil

2) average weighting factor for lead, copper and nickel

3) average weighting factor for oil, coal, gas and brown coal

4) average weighting factor acute and chronic aquatic ecotoxicity

5) average weighting factor human toxicity (air, water and soil)

6) default weighting factor assumed by [31]

Table 10.3.2 Settings of normalisation factors for environmental impacts

N_1 = *base normalisation, conform table 2.7, derived from European totals.*

N_2 = *normalisation data derived from German totals*

N_3 = *normalisation data derived from Dutch totals.*

	N_1	**N_2**	**N_3**
EDP	0.0016	0.0016	0.0015
ADP	0.00043	0.00043	0.00043
ENER	0.0073	0.0063	0.0050
GWP	0.00009	0.00009	0.00006
ODP	11	11	3
POCP	0.11	0.11	0.10
AP	0.021	0.021	0.019
NP	0.019	0.019	0.019
FW	0.00080	0.00042	0.0020
TW	0.013	0.0020	0.025
AETP	0.000014	0.000014	0.000014
HTP	0.00010	0.00010	0.00010

Table 10.3.3 Settings of environmental impacts selections for calculation integral environmental impacts.

	M_1	**M_2**	**M_3**
EDP	Included	Included	Included
ADP	Included	Included	Included
Ener	Included	Included	Included
GWP	Included	Included	Included
ODP	Included	Included	Included
POCP	Included	Included	Included
AP	Included	Included	Included
NP	Included	Included	Included
FW	Included	Included	**Not Included**
TW	Included	Included	**Not Included**
AETP	Included	**Not Included**	**Not Included**
HTP	Included	**Not Included**	**Not Included**

11. Results Eco-efficiency

11.1 Comparison of grey bag and yellow bag system

The Eco-efficiency has been calculated for the scenario combinations, which are presented in part I chapter 8.2. The “base” weighting factors (table 10.3.1), the “base” normalisation factors (table 10.3.2) and the “base” impact assessment method (table 10.3.3) are starting points for the calculations.

Calculation example of a portfolio

Environmental impact indicator

The results of the normalisation of scenarios R15, R25y, R35y and R50y, including both reference scenarios, are the basis of the calculation of the value of the environmental impact indicator in this example. All normalised figures are presented in table 11.1. Multiplication with the corresponding weighting factors (factors W1 , table 10.3.1) totalises the individual theme scores per scenario.The total weighted scores per scenario (SUM) are presented in the second part of table 11.1

The landfill scenario shows the highest total impact (0.000087), scenario R15 has a negative total value (- 0.000016) whereas scenario R50y has the lowest total impact (- 0.000030). The difference (DELTA) between both extremes in this comparison is 0.000117. Consequently the environmental impact indicators are:

- scenario landfill: 0.9,
- scenario R50y: 0.1
- scenario R15: 0.9 - 0.8* (0.000087 + 0.000016)/0.0000117 = 0.20

Costs indicator

Costs figures per kg packaging plastics of scenarios R15, R25y, R35y and R50y including both reference scenarios, are the basis of the calculation of the value of the costs indicator in this example.

The landfill scenario shows the lowest total costs (0.174 euro), scenario R15 accounts for higher costs (0.204 euro) whereas scenario R50y has the highest costs in this comparison (0.669 euro); see table 11.2. The difference (DELTA) between both extremes in this comparison is 0.415 euro. Consequently the costs indicators are:

- scenario landfill: 0.1,
- scenario R50y: 0.9
- scenario R15: 0.9 - 0.8* (0,669 - 0.204)/0.495 = 0.15

Table 11.1 Base case calculation example impacts indicator.

	Landf	**NOW**	**R15**	**R25y**	**R35y**	**R50y**
normalised values (factors N1, table 10.3.2)						
EDP	6.1E-06	-6.4E-05	-2.8E-04	-2.7E-04	-2.3E-04	-1.8E-04
ADP	0.0E+00	-2.0E-09	3.0E-10	1.9E-10	-1.3E-08	-2.7E-08
Ener	6.7E-06	-8.4E-05	-2.2E-04	-2.3E-04	-2.1E-04	-2.0E-04
GWP	2.6E-05	2.4E-05	1.1E-04	9.3E-05	7.7E-05	5.2E-05
ODP	8.8E-07	-4.3E-07	-2.1E-06	-5.9E-06	-5.2E-06	-6.4E-06
POCP	3.0E-05	-7.9E-05	-1.4E-04	-1.7E-04	-1.6E-04	-1.7E-04
AP	2.0E-05	-3.2E-05	-1.6E-04	-1.4E-04	-1.4E-04	-1.2E-04
NP	3.3E-06	3.0E-07	-5.2E-06	-4.2E-06	-4.0E-06	-3.3E-06
FW	7.6E-04	5.3E-04	-2.5E-06	-2.5E-06	-5.2E-06	-7.8E-06
TW	1.0E-04	1.7E-04	6.8E-04	5.6E-04	5.0E-04	3.9E-04
AETP	2.9E-06	-7.3E-05	-2.9E-04	-2.6E-04	-2.3E-04	-1.8E-04
HTP	1.3E-06	2.1E-09	-4.0E-06	-5.9E-06	-4.7E-06	-4.3E-06
weighted values (factors W1, table 10.3.1)						
EDP	5.5E-07	-5.8E-06	-2.6E-05	-2.5E-05	-2.1E-05	-1.6E-05
ADP	0.0E+00	-1.9E-10	2.8E-11	1.7E-11	-1.2E-09	-2.4E-09
Ener	6.1E-07	-7.6E-06	-2.0E-05	-2.1E-05	-1.9E-05	-1.8E-05
GWP	2.3E-06	2.2E-06	9.8E-06	8.5E-06	7.0E-06	4.7E-06
ODP	8.0E-08	-3.9E-08	-1.9E-07	-5.4E-07	-4.8E-07	-5.8E-07
POCP	2.8E-06	-7.2E-06	-1.3E-05	-1.5E-05	-1.5E-05	-1.5E-05
AP	1.9E-06	-2.9E-06	-1.5E-05	-1.3E-05	-1.2E-05	-1.1E-05
NP	3.0E-07	2.7E-08	-4.8E-07	-3.8E-07	-3.6E-07	-3.0E-07
FW	6.9E-05	4.8E-05	-2.2E-07	-2.3E-07	-4.7E-07	-7.1E-07
TW	9.1E-06	1.5E-05	6.2E-05	5.1E-05	4.6E-05	3.5E-05
AETP	1.3E-07	-3.3E-06	-1.3E-05	-1.2E-05	-1.0E-05	-8.0E-06
HTP	5.8E-08	9.5E-11	-1.8E-07	-2.7E-07	-2.1E-07	-2.0E-07
SUM	*8.7E-05*	*3.9E-05*	*-1.6E-05*	*-2.8E-05*	*-2.6E-05*	*-3.0E-05*
DELTA	***0.00003 + 0.000087 = 0.000117***					
IMPACT INDICATOR	**0.90**	**0.57**	**0.20**	**0.11**	**0.13**	**0.10**

Table 11.2 Base case calculation example costs indicator.

	Landf	NOW	R15	R25y	R35y	R50y
Euro	0.174	0.254	0.204	0.354	0.480	0.669
DELTA			***0.669 - 0.174 = 0.495***			
COSTS INDICATOR	0.10	0.33	0.15	0.38	0.59	0.90

Figure 11.1.1 shows the results of the yellow bag scenarios R25y, R35y and R50y together with those of the both reference scenarios (landfill and NOW) and scenario R15. Figure 11.1.2 shows the results of the grey bag scenarios R25g, R35g and R50g together with those of the both reference scenarios (landfill and NOW) and scenario R15. The scenarios landfill and NOW show the greatest environmental load in all portfolios, but the costs are relatively low. Scenario R15 gives an obvious decrease of the environmental load without a significant costs increase. With increasing R value the scenarios R25, R35 and R50 show a growth in costs without an obvious reduction of the environmental impacts. For this reason scenario R15 followed by R25 is the most Eco efficient scenario regarding both comparisons.

Figure 11.1.1 and figure 11.1.2 cannot be compared with each other, because the scaling factors for both figures are different. Figure 11.1.3 is constructed in order to compare the results of the yellow bag scenarios with the results of the grey bag scenarios. Figure 11.1.3 contains the results of the grey bag scenarios R35g and R50g compared with the results of the yellow bag scenarios R35y and R50y, in combination with those of the both reference scenarios (landfill and NOW) and scenario R15.
The yellow bag systems are realised with more costs whereas the grey bag systems are characterised by more environmental load. An important reason for the difference in environmental load is the energy consumption of the mechanical separation of the grey bag volumes. But figure 11.1.3 also shows that overall less difference is observed with respect to the Eco-efficiency of yellow bag systems versus the Eco-efficiency of grey bag systems.

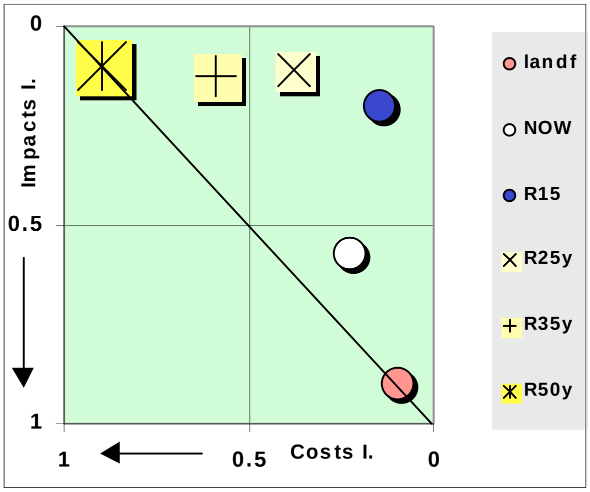

Figure 11.1.1 Eco-efficiency portfolio: Comparison of reference scenarios and R15 (scenario I), R25y, R35y and R50y (scenarios II, III and IV; collection with the yellow bag).

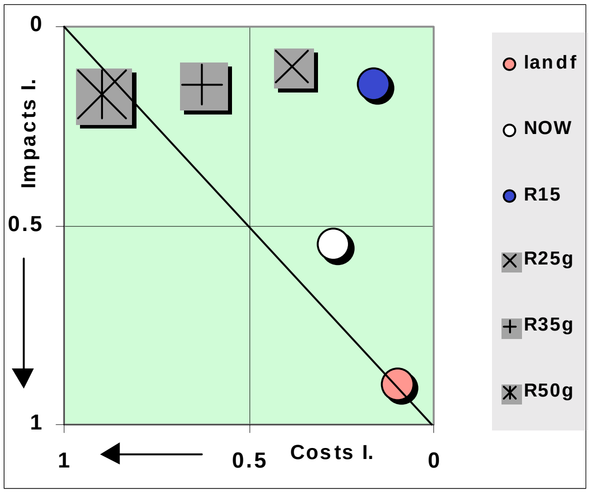

Figure 11.1.2 Eco-efficiency portfolio: Comparison of reference scenarios and R15 (scenario I), R25g, R35g and R50g (scenarios II, III and IV; collection with the grey bag).

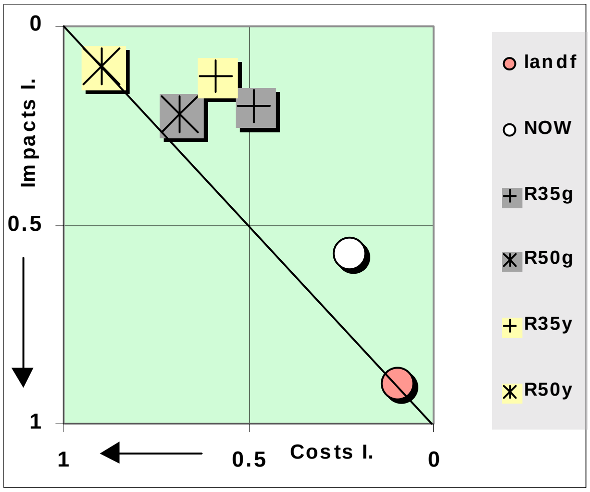

Figure 11.1.3 Eco-efficiency portfolio : Comparison of reference scenarios and R35g, R50g, R35y and R50y (scenarios III and IV with resp. yellow and grey bag).

11.2 Varying ER and FR

11.2.1 Energy recovery by a combination of MSWI and cement kiln

The sensitivity analysis in part I chapter 8.4 concerns energy recovery with a higher conversion efficiency in a cement kiln (ER_{high}). Yellow bag scenarios including ER_{high} have the following features of recycling rates:

- R35yHE with 35% R, 33.8% ER_{mswi} and 31.2% ER_{high}
- R50yHE with 50% R, 33.8% ER_{mswi} and 16.2% ER_{high}

In figure 11.2.1 the Eco-efficiency portfolio of both alternatives R35yHE and R50yHE is presented in combination with the Eco-efficiency of the both reference scenarios and the scenarios R25y and R15.
The processing of packaging plastics in a cement kiln concerning R35yHE and R50yHE results in a further going reduction of the environmental load compared with R25y and R15 (without processing of plastics in a cement kiln). This image does not agree with that of figure 11.1.1 Nevertheless scenario R15 (followed by R25) is the most Eco efficient scenario regarding this comparison. The reason for this are the relatively high costs of the scenarios R35yHE and R50yHE.

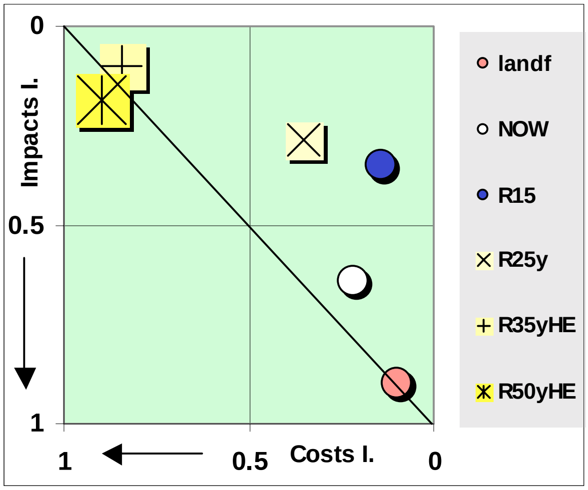

Figure 11.2.1 *Eco-efficiency portfolio :*
Energy recovery by combination of MSWI and cement kiln.

11.2.2 Energy recovery by a MSWI with 65% heat recovery

The energy yield of the MSWI (ER_{mswi}) is an important starting point of the calculations. For the standard calculations the energy yield corresponds with 0.2 MJ electricity output and 0.1 MJ heat output per MJ (LHV) input. The sensitivity analysis carried out in part I chapter 8.4 concerns also a yield of 0.65 MJ heat per MJ (LHV) input for the yellow bag scenarios.
Figure 11.2.2 shows the Eco-efficiency portfolio of these yellow bag alternatives in combination with the Eco-efficiency of both reference scenarios and R15.
Figure 11.2.2. is almost comparable with figure 11.1.1. Scenario R15 (followed by R25y) is also the most Eco efficient scenario in this context.

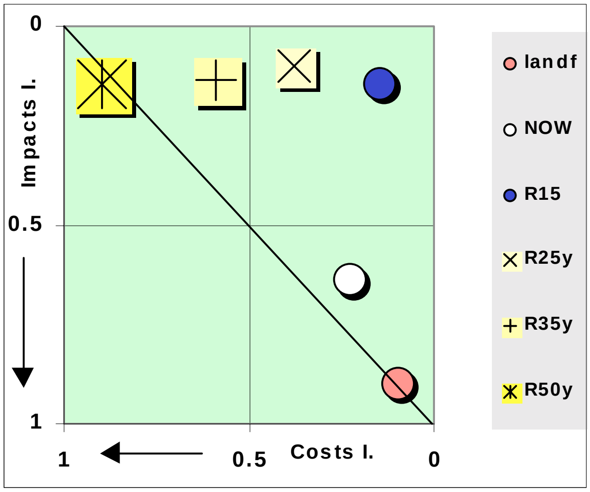

Figure 11.2.2 *Eco-efficiency portfolio :*
Energy recovery by MSWI with 65% heat recovery efficiency.

11.2.3 Feedstock recycling by the Texaco gasification process

In the sensitivity analysis FR mixed plastics fractions are processed as feedstock in the Texaco gasification plant as alternative for the application in the Blast Furnace, as described in chapter 8.4.

The changed selection of the feedstock recycling option has no relevant consequences for the portfolio comparison. Figure 11.2.3 is almost comparable with figure 11.1.1. Scenario R15 (followed by R25y) is the most Eco efficient scenario in this context.

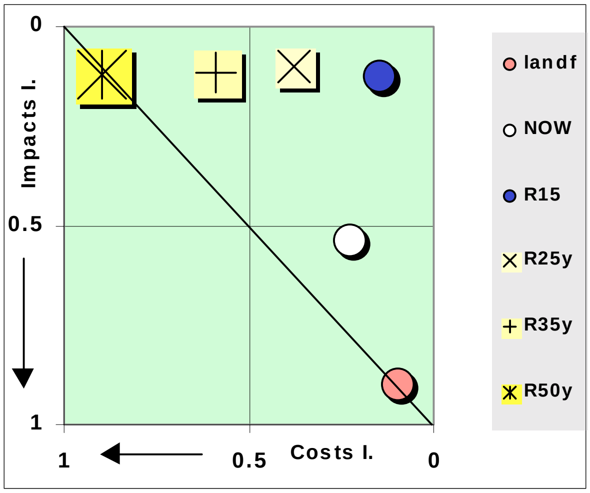

*Figure 11.2.3 Eco-efficiency portfolio:
Feedstock recycling by the Texaco gasification process.*

11.3 Varying weighting and normalisation factors

An important limiting condition when judging the Eco-efficiency is the calculation of an aggregated environmental impact score with “subjective” weighting factors, as already indicated in chapter 10. Some additional remarks can be made for the selection of the normalisation factors and the choice of impact assessment themes; see 2.7.

All Eco-efficiency portfolios presented in chapter 11.1 and chapter 11.2 are calculated with the “base” weighting factors (table 10.3.1), the “base” normalisation factors (table 10.3.2) and the “base” impact assessment method (table 10.3.3). Figure 11.3.1 up to figure 11.3.6 inclusive demonstrate the consequences of the change of the weighting factors, normalisation factors and of the consequences of other selections of impact assessment themes. All these examples are based on the comparison of the yellow bag scenarios R25y, R35y and R50y with the both reference scenarios (landfill and NOW) and with scenario R15.

The codes of the clusters of the weighting factors, normalisation factors and the code of the impact method are given in the tables 10.3.1 up to 10.3.3 inclusive and used in the figures 11.3.1 up to 11.3.6 inclusive. The examples illustrated in figure 11.3.1 up to figure 11.3.6 inclusive are comparable with the presentation in figure 11.1.1.

The presentations in figure 11.3.1 up to figure 11.3.6 inclusive illustrate that the change of weighting factors and normalisation factors and an other selection of impact assessment themes (within the restrictions as given in chapter 10.3) have a small influence on the Eco-efficiency profiles. In all portfolios scenario R15 (followed by R25y) is the most Eco efficient scenario.

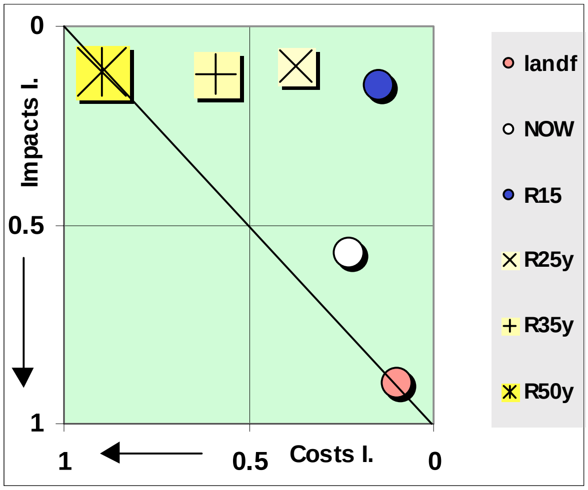

Figure 11.3.1 *Eco-efficiency portfolio:*
Weighting W2, normalisation Nbase, method Mbase.

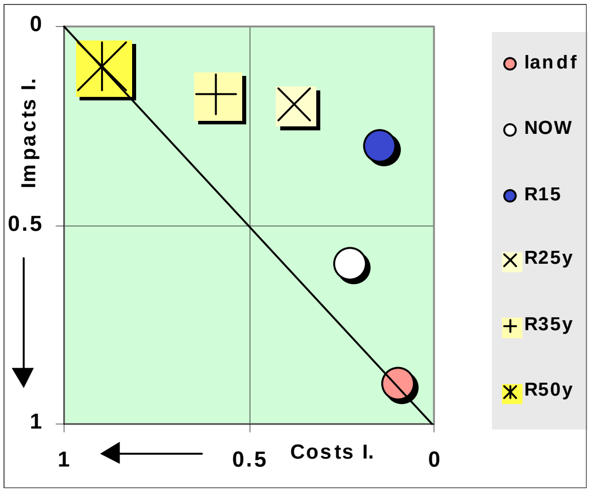

Figure 11.3.2 *Eco-efficiency portfolio:*
Weighting W3, normalisation Nbase, method Mbase.

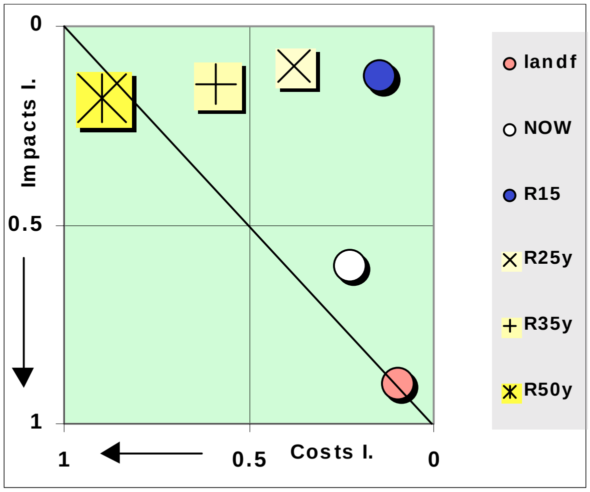

Figure 11.3.3 *Eco-efficiency portfolio:*
Weighting Wbase, normalisation N2, method Mbase.

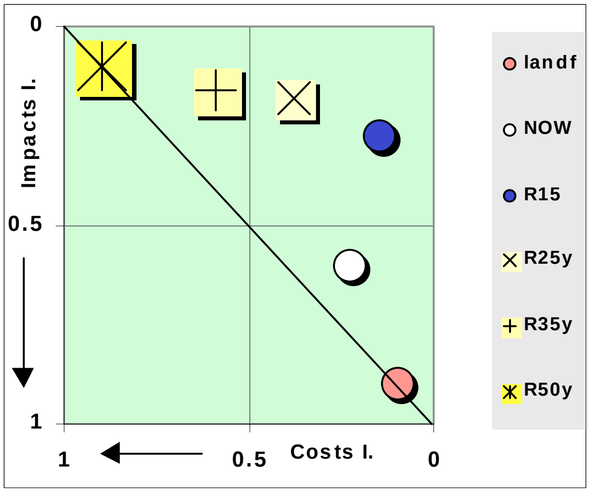

Figure 11.3.4 *Eco-efficiency portfolio:*
Weighting Wbase, normalisation N3, method Mbase.

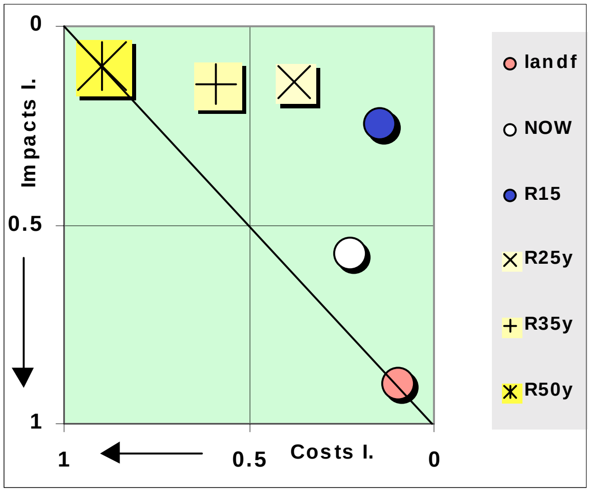

Figure 11.3.5 *Eco-efficiency portfolio:*
Weighting Wbase, normalisation Nbase, method M2.

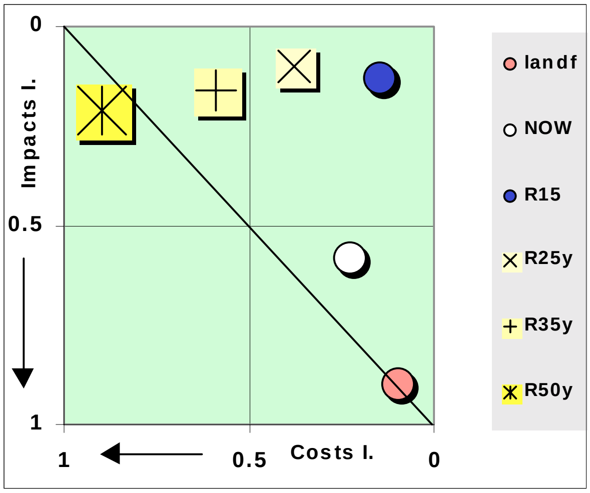

Figure 11.3.6 *Eco-efficiency portfolio:*
Weighting Wbase, normalisation Nbase, method M3.

11.4 Additional scenarios

In this paragraph, considering the sensitivity analysis, some additional scenarios are considered in addition to the main recycling scenarios as given in part I.

Decrease of mechanical recycling and increase of energy recovery
Two additional scenarios are defined with 10% mechanical recycling combined with 90% energy recovery, in order to illustrate the consequences of a decrease of mechanical recycling and an increase of energy recovery compared with scenario R15. In “additional scenario R10i” the 10% mechanical recycling is strictly focussed on IW mono streams, whereas in “additional scenario R10m” the mechanical

recycling is a combination of 6% MPR plus 2% MR from MSW plastics and 2% MR from IW plastic mono streams.

In figure 11.4.1 both additional scenarios are compared with the main recycling scenarios and the reference scenarios. The additional scenario with the mechanical recycling strictly focussed at mono streams (R10i) shows a “more or less” equal Eco-efficiency as the main recycling scenario R15 (15% mechanical recycling and 85% energy recovery). Obviously in this context a detailed analysis of replacing mechanical recycling by energy recovery cannot be illustrated with the “rough” comparison basis shown in figure 11.4.1.

The additional scenario R10m focussed on MR and MPR of MSW plastics results however in a considerable decrease of Eco-efficiency compared with the main recycling scenario R15. Most important reason is the relatively high costs of mechanical recycling or mixed plastics recycling of plastics out of MSW, compared with the costs of mechanical recycling of IW plastics mono streams.

Decrease of energy recovery and increase of landfill

Two additional scenario’s with 10% mechanical recycling of IW plastics mono streams in combination with a decreased share of energy recovery are defined, in order to illustrate the consequences of landfill instead of energy recovery. Additional scenario R10ia contains a combination of 10% MR, 50% ER plus 40% landfill, whereas additional scenario R10ib has a combination of 10% MR and 90% landfill. In figure 11.4.2 both additional scenarios are compared with the main recycling scenarios and the reference scenarios.

Figure 11.4.2 indicates that increasing levels of energy recovery compared to the NOW situation could be an attractive way forward in terms of Eco-efficiency.

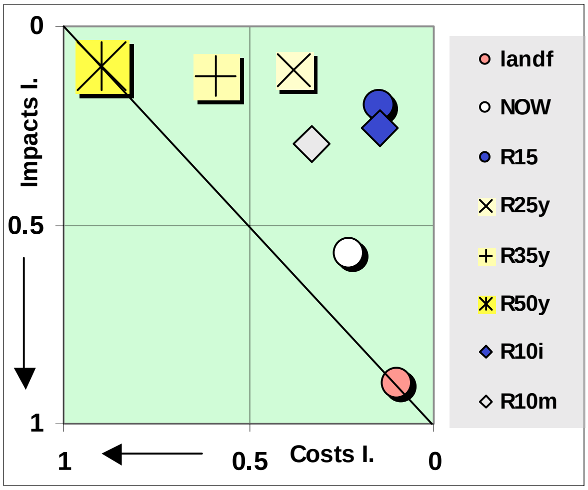

Figure 11.4.1 Eco-efficiency portfolio:
Comparison of alternative scenarios with 10 % mechanical recycling and 90% energy recovery (R10i, focussed at IW plastic mono streams and R10m, focussed at MSW plastics) with scenarios I, II, III and IV (R15, R25y, R35y and R50y) and reference scenarios (landfill and NOW).

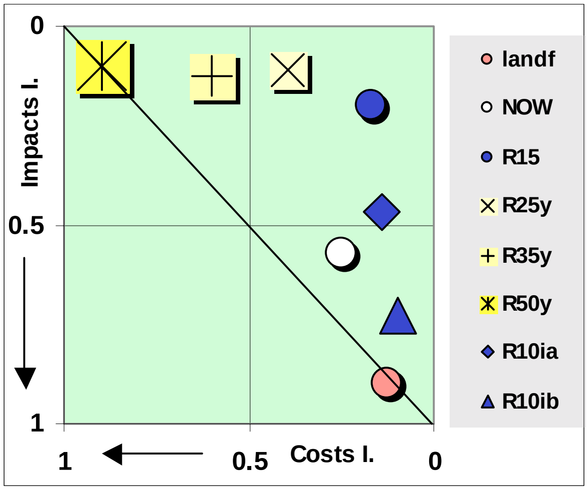

Figure 11.4.2 Eco-efficiency portfolio:
Comparison of alternative scenarios, 10% MR, 50% ER and 40% landfill (R10ia) and 10% MR, 0% ER and 90 % landfill (R10ib), with scenarios I, II, III and IV (R15, R25y, R35y and R50y) and reference scenarios (landfill and NOW).

11.5 Discussion

In the preceding paragraphs of this chapter the portfolio presentation is used for illustration of the sensitivities of relevant assumptions, starting points in the calculation procedure, etc. and the portfolio presentation is positioned as a powerful tool for the judgement of the Eco-efficiency of the recycling scenarios.

On the other hand there are still some specific restrictions in this presentation:
- The portfolio presentation is based on *dimensionless* figures. Different portfolios with different scenarios cannot be compared with each other directly.
- Critical environmental themes in each portfolio have to be analysed additionally
- Weighting factors are always subjective.

These restrictions will be elucidated in this paragraph.

11.5.1 Restrictions of dimensionless figures

The Eco-efficiency presentation is based on dimensionless costs differences and on dimensionless environmental impacts differences. Different portfolios with different scenarios cannot be compared with each other, because the scenarios compared and their scaling factors are different whereas the Eco-efficiency portfolios give no direct information about absolute figures.

As a consequence standardisation of portfolios by dimensionless figures results in some interpretation draw-backs. In this context in figure 11.5.1 identical scenarios as in figure 11.1.1 are presented in a “portfolio” with *absolute* figures.

Absolute **costs** figures per kg plastic are presented in figure 11.5.1. The costs difference between the recycling rates of 15% and 50% (R15 and R50y) is at least a factor 3 (about 0.2 Euro/ kg plastic vs. 0.67 Euro/kg plastic). On a European scale the total amount of plastic packaging waste is estimated at 9.8 million ton/y. This results in total costs of 2.0 billion Euro/y for R15 compared with the total costs of 6.7 billion Euro/y for R50y.

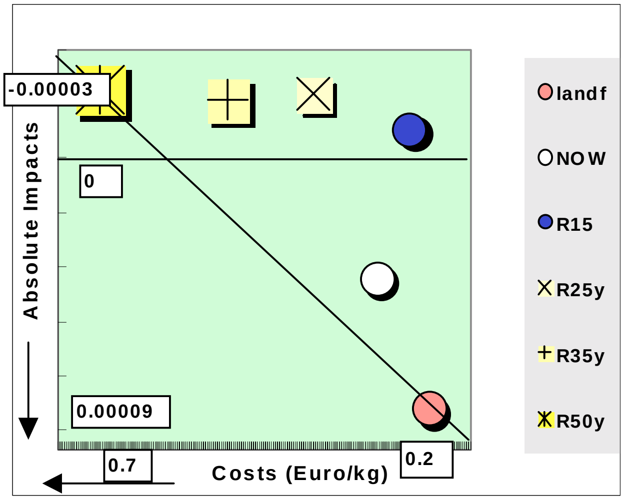

*Figure 11.5.1 Eco-efficiency “portfolio” with **absolute** figures: Comparison of the reference scenarios (landfill and NOW) with the recycling scenarios R15 (scenario I) and R25y, R35y, R50 y (scenarios II, III and IV with the yellow bag system).*

The *absolute* environmental impact scores indicated in figure 11.5.1 are the normalised plus weighted scores. These absolute scores correspond with an environmental credit (negative valued environmental impact) or an environmental load (positive valued environmental impact).
Scenario R15 scenario has an environmental credit of -0.000015 but in view of environmental impacts the best scoring scenario corresponds to 50% recycling (R50y). This recycling scenario corresponds with an environmental credit of -0.00003 whereas the landfill scenario corresponds with an environmental load of 0.00009.

To illustrate in this context the environmental impacts in figure 11.5.1 (or figure 11.1.1 etc.) a comparison is made with a familiar public activity, “driving a car”. Per kg plastic the difference in environmental impacts between scenarios R15 and R50y represents an average passenger car journey of 800 meters. On a European scale the difference between R50y and R15 corresponds with a car journey of

20 km per year per European inhabitant. Compared with the landfill scenario, the scenario R15 is equivalent with to the saving of a car journey of 160 km per year per European inhabitant.

11.5.2 Most sensitive environmental impacts

From the Eco-efficiency figures people cannot directly estimate the value of the individual contributions of the separate environmental impacts scores to the environmental impact indicator in the portfolio. This restriction is a consequence of the condensed presentation of the LCA results (as an “one value indicator” of integral environmental impacts).

The contributions of separate environmental impacts can differ enormously per scenario. Besides in some cases there is a difference of the uncertainty range per environmental impact. As a consequence there are several relevant sensitive (or “critical”) environmental themes for each portfolio. Hereafter an analysis of the base portfolio (comparison of landfill, NOW, R15, R25y, R35y and R50y) is given:

A: Final waste (FW) and specific final waste (TW).

The environmental impacts indicator score of both the reference scenarios (landfill and NOW) is determined by the FW score to a relevant extent. Regarding at the other hand the different recycling scenarios, the TW score has a relatively large contribution. In view of the normalisation a relative large uncertainty range is recognised for TW as well as FW normalisation factors. The resulting “bandwidth” of the Environmental Impacts Indicator probably can cause some shifted positions in the portfolios, especially for the individual recycling scenario positions to each other.

B: Aquatic ecotoxicity (AETP) and fuel resources depletion (EDP)

The MR, FR and ER options have a relatively important (positive) score for EDP and AETP. This results in a relatively attractive score of the Environmental Impact Indicator of the recycling and recovery alternatives. The mutual positions of the examined recycling scenarios are determined especially by the following factors to a relevant extent:

- For AETP the selection of the “background data” (data of the energy conversion and fuel production processes) play an important role. Another selection (in this study the BUWAL250 data are used) could give shifted positions of the recycling scenarios.
- The EDP judgement has been based on the worldwide technically available stocks of fuel types. When this classification basis will be changed (for instance geological stocks instead of technical stocks) this will have consequences to a greater or lesser extent for the mutual position of the recycling scenarios in the portfolio presentation.

11.5.3 Weighting factors

Any weighting is subjective and there is no general consensus on any weighting method. There are scientific, economic and political approaches with respect to the different weighting methods.
Different society views and options will result in the selection of different weighting factors for the environmental themes. In this study the three different weighting approaches, applied for the Eco-efficiency portfolio calculations, are related to the scientific approach. When sufficiently developed economic and political approaches are available, it is recommendable to apply them.
If weighting is restricted to one single theme the Eco-efficiency portfolios can change enormously. For instance when only the final specific waste theme (TW) would be weighted the landfill scenarios is the “best” scenario as can be seen in figure 8.6. Weighting methods with a high weighting of a specific theme show the same effect. For example the weighting with “shadow prices” results in a high weight for the global warming theme [39] as shown in figure 8.1.3. This weighting will give the best “environmental results” for the NOW scenario and the landfill scenario. These specific weighting methods are not considered in this study but their application would change the results considerably.

The weighting with shadow prices is not included for the following reasons:

- Broad range of the prices of a specific theme.
- For not all the themes shadow prices are defined or available.

When this method is developed further on it can become an attractive one.
The eco-indicator method is also not taken into account, because this method applies other defined environmental themes, for example biodiversity, and themes as toxicity and final waste are not included. For that reason this method is less suitable in the area of waste management.

12. Conclusions part II

Hereafter the conclusions of part II are summarised.

General

- The executed study is a first step with regard to the comparison of scenarios with different levels of material recycling and energy recovery.
- For this study (except the market evolution of recycled plastics) the approach is descriptive rather than change oriented. It is based on theoretical scenarios. As usual for such studies, results may vary according to the data used, the selected primary products and processes which are substituted by secondary products/energy resources, or by the weighting method selected to calculate the integrated environmental impact. Some variants around the basic scenarios I-IV illustrate the impact this can have on the conclusions.
- The calculations are related to the current situation with respect to the composition of plastics (the “average” European composition) and real “state of the art” processes (developed in Northern Europe). The data used are related to the second half of the nineties. This study does not present results of a dynamic approach with respect to composition changes of plastics and improvement of existing processes or introduction of new processes.
- Within the described limitations the study indicates trends for the next decade. The results of the study have to be used on an European level (or possibly country level) and are not applicable for any local/regional situation, because waste volumes, compositions and regional collection systems can vary enormously.
- The results of the study show:
    - The single most positive impact on eco-efficiency comes via diversion from landfill in favour of a combination of mechanical recycling of monomaterial relatively clean waste + energy recovery in moderately efficient modern MSWIs (30% energy recovery efficiency, complying with the new EU Incineration Directive).
    - Increasing the efficiency of energy recovery improves the eco-efficiency of the system.
    - Increasing recycling rates from 15 to 50% (with FR and/or MPR) and correspondingly decreasing the energy recovery rate increases costs by a factor 3 while environmental impact remain broadly similar.
    - With the choice of the recovery options mechanical recycling of monomaterial relatively clean waste + energy recovery in moderately efficient modern MSWIs, significant improvement in environmental impact could be achieved at similar costs compared to the current EU average.
- Further developments based on the results of this study can be:
    - The execution of prospective studies of selected routes for given countries.
    - The execution of a change-oriented approach including changes in plastics composition and innovations in technological processes.

  - An evaluation within 5 years to take into account the evolution of waste composition, waste processing techniques and to include the actual experience in the field of municipal solid waste management.
- The study has been critical reviewed by a panel of independent experts.

Comparison of reference scenarios and recycling scenarios

- The sensitivity analysis is only performed on environmental aspects and not on costs.
- Both reference scenarios (landfill and NOW) show the relatively highest environmental impacts, but costs are relatively low.
- With increasing recycling rate R scenarios don't result in an obvious difference in environmental impacts, but there is a significant cost increase.
- Scenario R15, followed by scenario R25y or R25g, are the most favourable scenarios with respect to the results of the Eco-efficiency analysis.
- Less difference is observed between the Eco-efficiency of the yellow bag systems compared with the Eco-efficiency of the grey bag systems.
- The process type energy recovery, the energy recovery level and the kind of feedstock recycling process are varied in this study. Variation of these options does not change the result of the comparison (scenario R15, followed by R25 are the most attractive ones from the Eco-efficiency point of view).
- Weighting factors, normalisation factors and the number of impact assessment themes are varied within defined restrictions or ranges. Varying these aspects does not change the results of the comparisons (scenario R15, followed by R25 are the most attractive ones from the Eco-efficiency point of view).
- Regarding the comparison of scenarios and the results of the sensitivity analysis (varying weighting factors, assumptions etc.) a more Eco efficient processing of end of life packaging plastics will result in a combination of 15-25% recycling and 85-75% (high efficiency) energy recovery. An increase of 15% to 25% recycling means an additional (feedstock and/or mixed plastics) recycling of more contaminated (mixed) plastics to the (mechanical) recycling of mono-streams is achieved.

Demonstration of the Eco-efficiency concept

- This type of presentation gives a clear overall overview of the different scenarios with respect to differences in costs and differences in environmental impacts. When the environmental impact does not differ more than 5% one has to be cautious when conclusions have to be drawn.
- Calculations in this study are based on defined assumptions and starting points. The consequences of changing underlying parameters are clearly demonstrated with the Eco-efficiency presentation.
- The results of this study demonstrate how a plastic packaging waste processing scenario could be improved in terms of Eco-efficiency.

13. Critical Review Report

CRITICAL REVIEW REPORT

Eco-efficiency of Recovery Scenarios of Plastic Packaging

ject was completed by TNO for the APME. It investigates the costs and environmental of different theoretical scenarios for the recovery of plastic packaging.

rt is divided into two parts:

the first part is dedicated to the LCA and the cost inventory of the recovery scenarios; and

the second part is dedicated to the analysis of the eco-efficiency of the scenarios.

cal review panel reviewed the entire document, although only the LCA part was considered in to the ISO 14040 standards.

of the Critical Review

uld be performed according ISO 14040 and following. According to the ISO-Standard a eview process is necessary if LCA results are used for comparative assertions which are to be disclosed. This is valid for LCA on hand.

g ISO 14040 the critical review process shall ensure that:

the methods used to carry out LCA are consistent with the International Standard,

the methods used to carry out LCA are scientifically and technically valid,

the data used are appropriate and reasonable in relation to the goal of the study,

the interpretations reflect the limitations and the goal of the study,

the study report is transparent and consistent.

International Standard does not specify requirements on the goals or uses of LCA, a critical an neither verify nor validate the goals that are chosen for an LCA, or the uses to which LCA re applied.

s of the critical review panel were Helene Teulon (chairperson), Roland Hischier, Geert and Till Nürrenbach.

Goal and Scope

The goal and scope of the project are clearly displayed in the report. It is clearly stated that this is a <u>first</u> step to identify <u>trends</u> in the recovery of plastic packaging for the five coming years. It clearly mentioned that the selected approach for this "first step" does not take into account the e tion of the collection and treatment techniques and the possible changes in the composition of p waste from packaging : it is a "descriptive approach", as opposed to a "dynamic" one.

Methodology and Data

The methodology and the assumptions made along the project are logical and scientifically vali are consistent with the goal and scope of the project.

The approach for the selection of data is a pragmatic approach: only the composition of plastic from packaging is based on average data in a set of European countries. For the collection and t ment of plastic waste, readily available "state-of-the-art" data have been selected from different tries. This is consistent with the goal and scope of the project as long as the related limitations a played with the conclusions, and it is the case in the report.

Limitations

The main limitations of the approach are displayed in the executive summary as well as in the c sion of the report.

In particular, it is clearly mentioned that the "results may vary according to the data used, the se primary products and processes which are substituted by secondary products, or by the weightin method selected to calculate the integrated environmental impact".

In the conclusion, it is also clearly stated that the trends identified in this study can only be used European level, and that they "are not applicable for any local/regional situation, because waste volumes, compositions and regional collection systems can vary enormously". The panel is reluctant to agree that the results could possibly us the country level, and recommends that specific data are collected for a country level use. However, the methodological framework could be fruitfully re-used in that case.

Besides, relevant possible extensions of the study are proposed in the conclusion, such as

- to conduct a similar study with a dynamic approach, making assumptions on the ev tion of both the packaging waste composition and the collection and treatment tech niques; or to reconsider the results within 5 years, to take into account the evolution of techniques, waste composition, and to take advantage of the new experiences in the field of municipal waste management.

hese limitations, the panelists are confident that the results are reliable. It has to be noticed ata related to the "substituted processes" dominate the results. However, the displayed ns demonstrate that the results are robust.
lts summarised in the executive summary and in the conclusion truly reflect the content of the

ciency Portfolio Presentation

120, it is said that "this type of presentation gives a clear overall overview of the different s with respect to differences in costs and differences in environmental impacts. When ental impact do not differ by more than 5%, one has to be cautious when conclusions are to ". The panel further insists that the eco-efficiency port-folio presentation can be misleading differences between the compared results are not significantly different. Indeed, whatever the e in percentage between the results, the portfolio will spread the dots apart on the graph, ill make the results appear as significantly different. This might lead to erroneous conclusions. he case in this project, but it is important to keep this risk in mind when using this type of tion.

CA/Compliance with ISO 14040ff

all report is consistent and transparent.
part complies in general with the recommendations of the ISO14040 and following g data, methodology and reporting. The detailed appendices allow to reproduce most of the ons if needed.
cond part of the report, a weighting method is used to combine the different environmental into a single note, which is not consistent with ISO 14040 recommendations. This choice is clearly stated and argued in section 10.
rt includes most of the sections specifically required in the case of a "comparative assertion to sed to the public". Only the treatment of missing data and the data quality assessment could n either added or developed.
be noticed that all the LCA calculations are based on existing LCA data, extracted from eliable sources. This implies that the calculation procedures might not be consistent in all owever, the data used are appropriate and reasonable in relation to the goal of the study.

Overall Conclusion

The report is transparant and it displays clear objectives with reasonable limited targets. The de ment of the methodology is logical and scientifically valid, the approach for the selection of dat pragmatic, their are both consistent with the goal and scope of the project.
The calculations are rigorous and clearly displayed. Relevant conclusions are drawn from the ca tions. The limitations are displayed at the same time as the conclusions, which helps make the r strong and consistent with the goal and scope of the project.

The LCA part of the project was in general conducted in compliance with the recommendations ISO 14040ff standards.
The critical review process was constructive, and significant efforts were successfully dedicated improvement of the project and the report.

14. References

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15. Abbreviations

energy recovery rate
energy recovery rate realised by high efficiency recovery (cement kiln)
energy recovery rate realised by MSWI
feedstock recycling rate
functional unit
high efficiency energy recovery
industrial waste
landfill of waste
low heating value
mixed plastics recycling rate
mechanical recycling rate
municipal solid waste
municipal solid waste incineration
poly ethylene
poly propylene
poly styrene
poly vinyl chloride
recycling rate (sum of MR, MPR en FR)
refuse derived fuel
substitution factor; ratio of primary products replaced (substituted) by secondary plastics

MENTAL IMPACTS, CATEGORIES

environmental impact	Mineral Resources Depletion Potential
environmental impact	Fuel Resources Depletion Potential
environmental impact	Global Warming Potential
environmental impact	Ozone Depletion Potential
environmental impact	Human Toxicity Potential
environmental impact	Aquatic Eco toxicity Potential
environmental impact	Photochemical Ozone Creation Potential
environmental impact	Acidification Potential
environmental impact	Nutrification Potential
environmental categorie	Final Waste
environmental categorie	Specific final Waste (hazardous waste)
environmental categorie	Cumulative energy requirement

ROUTES FOR COLLECTION AND SEPARATION

A1	route for MSW	integral collection (black bag), residues to MSW
A1L	route for MSW	integral collection (black bag), residues to landfi
A2	route for MSW	integral collection (black bag) + bottle bank, res
A2L	route for MSW	integral collection (black bag) + bottle bank, res
A3	route for MSW	dry/wet collection (grey bag), residues to MSWI
A4	route for MSW	dry/wet collection (grey bag) + bottle bank, resid
A4NOW	route for MSW	dry/wet collection (grey bag) + bottle bank (shif for NOW scenario), residues to MSWI
A4R35g	route for MSW	dry/wet collection (grey bag) + bottle bank (shif for R35g scenario), residues to MSWI
A4R50g	route for MSW	dry/wet collection (grey bag) + bottle bank (shif for R50g scenario), residues to MSWI
A5	route for MSW	separate collection (yellow bag), residues to MS
A5R25y	route for MSW	separate collection (yellow bag), (shifted separat scenario), residues to MSWI
A5R35y	route for MSW	separate collection (yellow bag), (shifted separat scenario), residues to MSWI
A5R35yHE	route for MSW	separate collection (yellow bag), (shifted separat scenario with optimised energy recovery), resid
A5R50y	route for MSW	separate collection (yellow bag), (shifted separat scenario), residues to MSWI
A5R50yHE	route for MSW	separate collection (yellow bag), (shifted separat scenario with optimised energy recovery), resid

B1	route for IW	integral collection (black bag), residues to MSW
B1L	route for IW	integral collection (black bag) + bottle bank, res
B2	route for IW	separate collection rigids and films, residues to M
B2L	route for IW	separate collection rigids and films, residues to l
B3	route for IW	separate collection rigids, films and mixed plasti MSWI

S OF PLASTIC PACKAGING PROCESSING

reference scenario	scenario I (landfill)
reference scenario	scenario II
scenario I	recycling rate R = 15 %
scenario II	recycling rate R = 25 %
scenario II with yellow bag route	recycling rate R = 25 %
scenario II with grey bag route	recycling rate R = 25 %
scenario III	recycling rate R = 35 %
scenario III with yellow bag route	recycling rate R = 35 %
scenario III with yellow bag route	recycling rate R = 35 %, optimised energy recovery
scenario III with grey bag route	recycling rate R = 35 %
scenario IV	recycling rate R = 50 %
scenario IV with yellow bag route	recycling rate R = 50 %
scenario IV with yellow bag route	recycling rate R = 50 %, optimised energy recovery
scenario IV with grey bag route	recycling rate R = 50 %
additional scenario	recycling rate R = 10%, by IW recycling and rest to MSWI (energy recovery 90%)
additional scenario	recycling rate R = 10%, mainly by MSW recycling and rest to MSWI (energy recovery 90%)
additional scenario	recycling rate R = 10%, by IW recycling and rest partially to MSWI (energy recovery 50%, landfill 40 %)
additional scenario	recycling rate R = 10%, by IW recycling and rest to landfill (energy recovery 0%, landfill 90 %)

16. Authentication

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Date upon which, or period in which, the research took place:

January 1999 - March 2000

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