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Institut für Energie-
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Heidelberg GmbH

Life Cycle Assessment of food packaging made of Ingeo^{TM} biopolymer and (r)PET

Addendum to the LCA study on food packaging made of NatureWorks® biopolymer and alternative materials [2006]

Final report

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1 Introduction

The underlying study is an addendum to the Life Cycle Assessment of Polylactide (Ingeo^{TM}) clamshells commissioned by NatureWorks LLC and finalized by IFEU Heidelberg in July 2006 [IFEU 2006].

In the 2006 study clamshells made from Ingeo^{TM} were compared to clamshells made from polypropylene (PP), oriented polystyrene (OPS) and polyethylene terephthalate (PET) with a German focus. The 2006 study included a critical review and achieved ISO-conformity.

In the addendum presented here, clamshells made from Ingeo^{TM} are compared to clamshells made partly or completely from recycled PET under a broader international perspective. The objective of this study is to compare the environmental performance of clamshells made from Ingeo^{TM} with clamshells made from virgin and recycled PET.

The aim of this exercise is to compare Ingeo^{TM} and PET clamshells under a European and US framework. Relevant settings within the given framework are the final waste treatment options, the supplied grid electricity and the regarding raw material transport.

The main difference between the two geographical frameworks – beside the differences in the energy grid - is that there is no Ingeo^{TM} production in Europe. In the latter case the required Ingeo^{TM} has to be transported overseas from the USA to Europe.

In this report Europe is understood to comprise the former EU 15 countries, as those widely cover NatureWorks´ European market for clamshells made from Ingeo^{TM}.

2 Examined packaging Systems

2.1 Weight of clamshells

The weight of the PET clamshells is assumed to be 19.9 g. It is assumed, that there is no difference between clamshells made from virgin PET and clamshells made with or from recycled PET.

The weight of the Ingeo^{TM} clamshells is assumed to be 15 g for the European and US base-scenarios. This optimised clamshell weight is possible due to the lower density and higher stiffness of Ingeo^{TM} as compared to PET.

In a variant scenario for Ingeo^{TM} clamshells the weight of Ingeo^{TM} clamshells and PET clamshells are the same (19.9 g). Clam shell weights are summarized in the following table 1.

Table 1: Overview of packaging weights for clamshells.

	Ingeo^{TM} clamshells (base)	Ingeo^{TM} clamshells (heavier variant)	PET clamshells
clamshell weight*	15 g	19.9 g	19.9 g
*: weight includes the clamshell lid			

Regarding weights of Ingeo^{TM} clam shells a wide range is found on the market, as weights strongly depend on the clam shell producer and the targeted application (e.g. clam shells for premium products often show higher weights). In order to examine the effect of heavier Ingeo^{TM,} clam shells, 19.9 g clam shells are included in the study as variants – in this case compared clam shells made of different polymers are assumed to have equal weights. The 19.9 g clam shells may be considered as an overdesigned clam shell, since the weight of Ingeo^{TM} clam shells, with an equivalent function to PET clam shells, can be 20-25% lower as a results of the lower density and higher stiffness. The 19.9 g Ingeo^{TM} clam shells may therefore be considered as a worst case scenario.

2.2 Polymer production data

Ingeo^{TM} – Polylactide biopolymers (*NatureWorks)*

Ingeo^{TM} is the trade name of polylactide biopolymers produced by NatureWorks LLC. All the results for Ingeo^{TM} biopolymer (Ingeo^{TM}) given in the underlying report are only valid for Ingeo^{TM} biopolymer produced by NatureWorks LLC and are not valid for PLA production in general.

Two different types of Ingeo^{TM} biopolymer are being used in this report.

Ingeo5[1]: represents the 2005 cradle-to-pellet Ingeo^{TM} production system operated by NatureWorks LLC.

IngeoNGT: represents the cradle-to-pellet Ingeo^{TM} production system operated by NatureWorks LLC which is based on new fermentation technology. All the electricity required is im-

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[1] Ingeo5 corresponds to the inventory labeled “PLA5” in [Vink et al, 2007]:

ported from the public grid. (NGT stands for next generation, only Technology part). This new technology has been implemented in December 2008.

PET - Polyethylene Terephthalate (Plastics*Europe*)

The present LCA study uses the ecoprofile data reviewed, updated and published by Plastics*Europe*[2] in 2005 [Plastics Europe 2005]. The dataset covers the production from the cradle to the polymer factory gate. The PET and upstream intermediates production data have been gathered directly from European producers and compiled by Dr. Ian Boustead. The PET production data are valid for the year 2004. The upstream olefin data are valid for the year 2000. The PET production data represents more than 80% of Western-Europe PET production [Boustead 2009]. The final results were approved by the participating companies organized in Plastics*Europe*.

2.3 The use of rPET in clamshells

PET clam shells can be equally produced from virgin PET or from recycled PET. In both cases the PET material has to provide the same properties. One of those is the so-called intrinsic viscosity (IV) which is around 0.65 dl/g for film applications and around 0.8 dl/g for bottles. There is a certain loss of IV during product lifetime and recovery treatment of PET bottles. However, as bottle PET has a higher IV recycled PET flakes usually comply with the IV requirements of foil PET.

Still food-grade applications require that the rPET is free of contaminants which could migrate into the food stuff. For this reason recovered PET flakes have to undergo a combined vacuum and heat treatment. This has been considered in the underlying process model.

RPET used in clam shells substitutes virgin PET which would have to be used otherwise. RPET available on the market to date is coming from recovered PET bottles exclusively. This means that there is a linkage of PET bottle systems and PET clam shell systems via recovery and recycling. In LCA language this is referred to as open loop recycling.

This open-loop recycling system is the pre-condition of the saving of virgin PET in the clam shell production. In this case, the accountancy of the benefit of saving virgin PET has to consider a number of criteria set in the LCA ISO standard and developed in practical LCA work.

In this study the so-called 50/50 procedure has been applied. Appendix A gives a detailed description of the possible procedures and an argumentation why the 50/50 procedure is a good compromise within the array of existing approaches.

3 Main assumptions regarding waste treatment

It is assumed that used clamshells are disposed of by the consumer with the residual waste fraction, which undergoes a final waste treatment. There are three different ways of waste treatment examined in the present study:

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[2] http://www.lca.plasticseurope.org/index.htm

- deposition of domestic wastes on a sanitary landfill[3] site
- domestic waste end up in a municipal solid waste incineration
- waste treatment in a composting plant (Ingeo^{TM} material only)

3.1 Landfill (Europe & US)

The landfill model accounts for the emissions and the consumption of resources for the deposition of domestic wastes on a sanitary landfill site. Although any anaerobic degradation of polylactide in a landfill environment has been postulated by some to be very slow, there has until now been any rigorous backup or quantification of this. To redress this concern, NatureWorks is conducting 3rd party measurement via OWS (Organic Waste Systems, Ghent, Belgium) using both accelerated testing (ASTM D5511) and longer term landfill simulation (ASTM D5526). Because of this uncertainty around the behavior of PLA in landfills the degradation rate of Ingeo^{TM} on a landfill has been assumed to be 0% as best case. IFEU will be updating the information in this LCA as soon as this better information is available.

3.2 Municipal solid waste incineration - MSWI (Europe)

It is assumed that from the energy content of the waste incinerated, 11% is recovered as electricity and 30% as thermal energy. Those numbers are derived from Eurostat data on amounts of waste incinerated, and electricity and thermal energy generated in MSWI plants. The numbers are also supported by a report of the European Waste Incineration Plant Operators [CEWEP 2006].

In the incineration model a technical standard (especially regarding flue gas cleaning) is assumed which complies with the requirements given by the EU incineration directive (Council Directive 2000/76/EC). The model calculation considers a grid-fired boiler system with steam turbine and flue gas cleaning.

The electric energy generated in MSWI plants is assumed to substitute European grid electricity (EU15 grid). Thermal energy recovered in MSWI plants is assumed to serve as process heat, replacing process heat generated by light fuel oil (50%) and natural gas (50%). The latter mix of energy sources is an assumption made by IFEU, as official data regarding this aspect are not available according to the knowledge of the authors of this study.

3.3 Industrial composting (Europe)

Composting of Ingeo^{TM} shows a two-step degradation process:

1. The polymer is broken down to its basic building blocks – the lactic acid – by hydrolysis
2. The lactic acid is metabolized by micro-organisms into CO_2.

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[3] sanitary landfill means a managed landfill where waste is isolated from the environment until it is safe. As a minimum, four basic conditions (full or partial hydrogeological isolation, formal engineering preparations, permanent control, and planned waste emplacement and covering) should be met by any site design and operation before it can be regarded as a sanitary landfill [Thurgood 1999].

The biogenic waste is treated in plants with improved techniques, especially to minimize the odour pollution and also to reduce the area demand [Detzel et al., 2006].

The composting model considered here refers to a medium-sized commercial composting standard having an encapsulated system (container composting) for the main degrading step. The second degrading step is split up – 50% of the fresh compost is treated in an encapsulated system, the other 50% is treated in an open system (IFEU assumption).

IFEU is still pointing to the fact that during composting methane and other volatile organic compounds (VOCs) are emitted. According to OWS this is not the case due to the surplus of air. This has to be solved, since these assumptions do have a significant impact on the final conclusions. In the underlying report the ifeu assumptions have been used.

3.4 Main assumptions regarding PET bottle-recycling

After being collected and (potentially) sorted into a bottle fraction the PET bottles are baled and sent to the recycling plant. The recycling process can be structured into two principle process steps:

1. Bottle-to-flake production
2. Flake conditioning and (often) pellet production

The inputs to and efficiency of the recycling process largely depend on the quality of the starting material, the target flake quality and the recycling technology used. The recycling plants currently used in Europe for PET bottles differ in age and their detailed specifications, but most comprise the following processing steps:

- Bale-opening and separation of the bottles with subsequent manual or automatic sorting (for separation of contaminant materials and metals)
- Grinding of the bottles into flakes, density separation (in particular separation of PE, PP and EVA)
- Washing process (usually hot with NaOH)
- Mechanical and thermal drying of the PET flakes (in some plants there is then automatic post-sorting to remove PVC contaminants and coloured PET)
- Solid stating, Vacuum treatment
- Bagging of the PET flakes or the granules

The process data implemented in the underlying LCA reflect an average of current Western European PET recycling operations.

4 Scenario overview

This study is focussing on the European as well as the US market. Overall three different sets of scenarios were determined.

Scenario Set 1 - European framework:

There are two different sets of base scenarios implemented in the European framework regarding alternative end of life settings:

- Base scenarios, group 1: all post-consumer clamshell waste end up in a landfill.
  For this group of base scenarios one variant was studied:
    - clamshell weight variant: means identical weight of Ingeo^{TM} and PET clamshells
- Base scenarios, group 2: all post-consumer clamshell waste ends up in an incineration plant.
  For this group of base scenarios two variants were studied:
    - clamshell weight variant: means identical weight of Ingeo^{TM} and PET clamshells
    - waste treatment variant: means as an alternative waste treatment option that all post-consumer clamshell waste of clamshells made from Ingeo^{TM} ends up in an industrial composting plant.

The scenario settings for the European framework are given in table 2.

Scenario Set 2 - US framework:

Base scenarios, group 3: There is one set of base scenarios implemented in the US framework:

- all post-consumer clamshell waste ends up in a landfill.
  For this group of base scenarios one variant aspects was studied:
    - clamshell weight variant: means identical weight of Ingeo^{TM} and PET clamshells

The scenario settings for the US framework are given in table 3.

Table 2: Scenario Set 1 - scenarios for clamshells made of Ingeo^{TM} and PET, Focus Europe

Base-scenario group 1: Waste treatment: landfill
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: Ingeo5, Focus: EU15 countries (production/ waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill (no degradation)**
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: IngeoNGT, Focus: EU15 countries (production /waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill (no degradation)**
19.9 g PET clamshell; made of 100% virgin PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: EU15 countries (production/waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill**
19.9 g PET clamshell; made of 50% virgin PET 50% recycled PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: EU15 countries (production/waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill**
19.9 g PET clamshell; made of 100% recycled PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: EU15 countries (production/waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill**
Clamshell weight variant: identical weight of Ingeo^{TM} and PET clamshells
19.9 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: Ingeo5, Focus: EU15 countries (production/ waste treatment of clamshells) ->end-of-life settings: 100% disposed of in a landfill (no degradation)
19.9 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: IngeoNGT, Focus: EU15 countries (production /waste treatment of clamshells) ->end-of-life settings: 100% disposed of in a landfill (no degradation)
Base-scenario group 2: Waste treatment: incineration
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: Ingeo5, Focus: EU15 countries (production/ waste treatment of clamshells) **->end-of-life settings: 100% incineration (MSWI) with energy recovery**
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: IngeoNGT, Focus: EU15 countries (production /waste treatment of clamshells) **->end-of-life settings: 100% incineration (MSWI) with energy recovery**
19.9 g PET clamshell; made of 100% virgin PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: EU15 countries (production/waste treatment of clamshells) **->end-of-life settings: 100% incineration (MSWI) with energy recovery**
19.9 g PET clamshell; made of 50% virgin PET 50% recycled PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: EU15 countries (production/waste treatment of clamshells) **->end-of-life settings: 100% incineration (MSWI) with energy recovery**
19.9 g PET clamshell; made of 100% recycled PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: EU15 countries (production/waste treatment of clamshells) **->end-of-life settings: 100% incineration (MSWI) with energy recovery**
Clamshell weight variant: identical weight of Ingeo^{TM} and PET clamshells
19.9 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: Ingeo5, Focus: EU15 countries (production/ waste treatment of clamshells) ->end-of-life settings: 100% incineration (MSWI) with energy recovery
19.9 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: IngeoNGT, Focus: EU15 countries (production /waste treatment of clamshells) ->end-of-life settings: 100% incineration (MSWI) with energy recovery
Waste treatment variant: alternative waste treatment option: industrial composting
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: Ingeo5, Focus: EU15 countries (production/ waste treatment of clamshells) **->end-of-life settings: 100% industrial composting**
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: IngeoNGT, Focus: EU15 countries (production /waste treatment of clamshells) **->end-of-life settings: 100% industrial composting**

MSWI: municipal solid waste incineration

Table 3: Scenario Set 2 - scenarios for clamshells made of Ingeo^{TM} and PET, Focus USA

Base-scenario group 3: Waste treatment: landfill
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: Ingeo5, Focus: USA (production/ waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill (no degradation)**
15 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: IngeoNGT, Focus: USA (production /waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill (no degradation)**
19.9 g PET clamshell; made of 100% virgin PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: USA (production/waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill**
19.9 g PET clamshell; made of 50% virgin PET 50% recycled PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: USA (production/waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill**
19.9 g PET clamshell; made of 100% recycled PET; PET inventory data: PET amorphous [PlasticsEurope 2005] Focus: USA (production/waste treatment of clamshells) **->end-of-life settings: 100% disposed of in a landfill**
Clamshell weight variant: identical weight of Ingeo^{TM} and PET clamshells
19.9 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: Ingeo5, Focus: USA (production/ waste treatment of clamshells) ->end-of-life settings: 100% disposed of in a landfill (no degradation)
19.9 g Ingeo^{TM} clamshell; Ingeo^{TM} inventory data: IngeoNGT, Focus: USA (production /waste treatment of clamshells) ->end-of-life settings: 100% disposed of in a landfill (no degradation)

The results of scenario set 1 and scenario set 2 will be displayed in stacked bar format in figure 1 to 3 (landfill scenarios Europe), figure 4 to 6 (incineration scenarios Europe) and figure 9 to 11 (landfill scenarios USA).

Figure 7 to 8 display the net results of waste treatment variant to scenario set 1 (alternative waste treatment option: industrial composting) and the net results of base scenario I and base scenario II.

5 Results

Environmental indicator results are shown in form of bar charts in figures 1 to 6 (-> Focus Europe) and figures 9 to 11 (-> Focus USA). The stacked bar format indicates the contributions of important life cycle steps to the packaging system results, which are:

- the PET-production from the preceding product life cycle allocated to the R-PET (only relevant for PET clamshells with R-PET content) (***"Environmental burden of PET-first life cycle"***)
- the production of primary Ingeo^{TM} and PET pellets (**"plastics production (virgin)"**)
- the transport of primary polymer pellets to the polymer processor (**"transport plastics"**)
- Production of clamshells by extrusion and thermoforming (**"clamshell production"**)
- the recycling of used packaging materials, including transports to recycling sites (**"recycling"**)
- the disposal of used packaging materials, including transports to disposal sites (**"disposal"**)

There are two other separate bars in the LCA result graphs:

- credit for energy recovery (replacing e.g. grid electricity or process heat) (**"credits energy")** and
- net results (grey bar) as a result of the subtraction of credits from overall environmental loads **"net results"**

All graphs shown refer to the functional unit of 1000 clamshells.

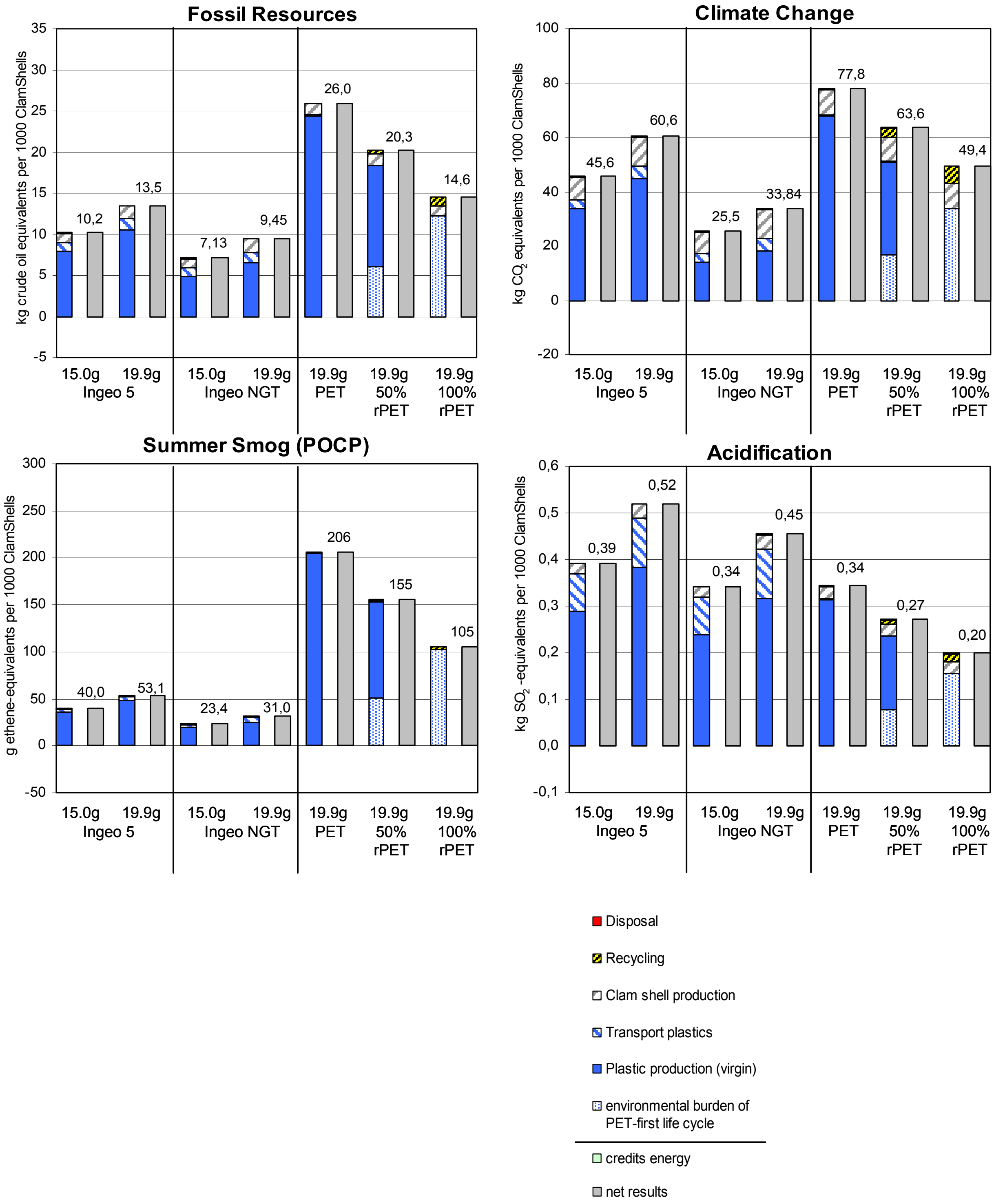

Figure 1 Scenario Set 1: Focus EU 15, Results of base scenario I (clamshell waste is 100% disposed of in a landfill) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

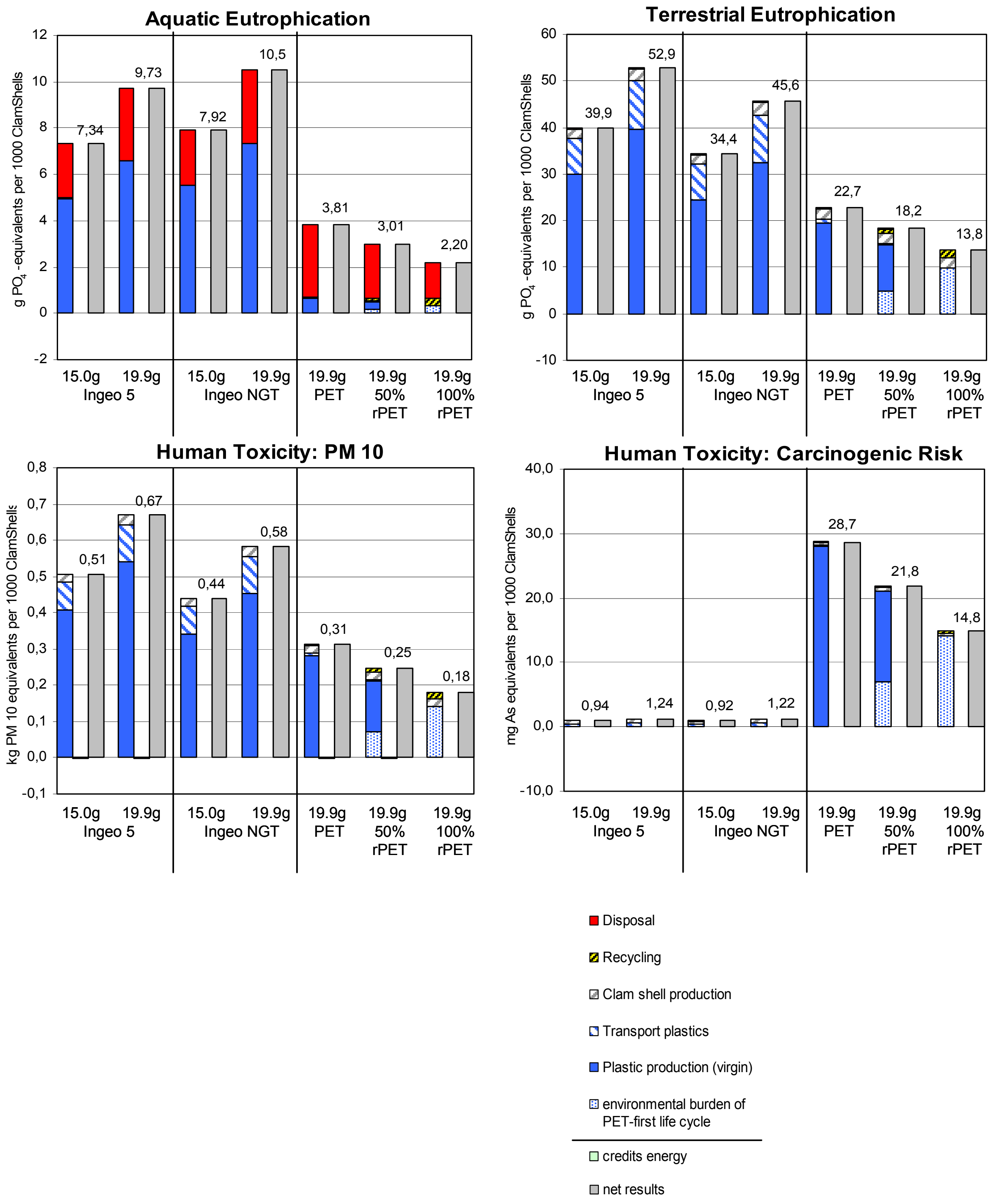

Figure 2 Scenario Set 1: Focus EU 15, Results of base scenario I (clamshell waste is 100% disposed of in a landfill) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

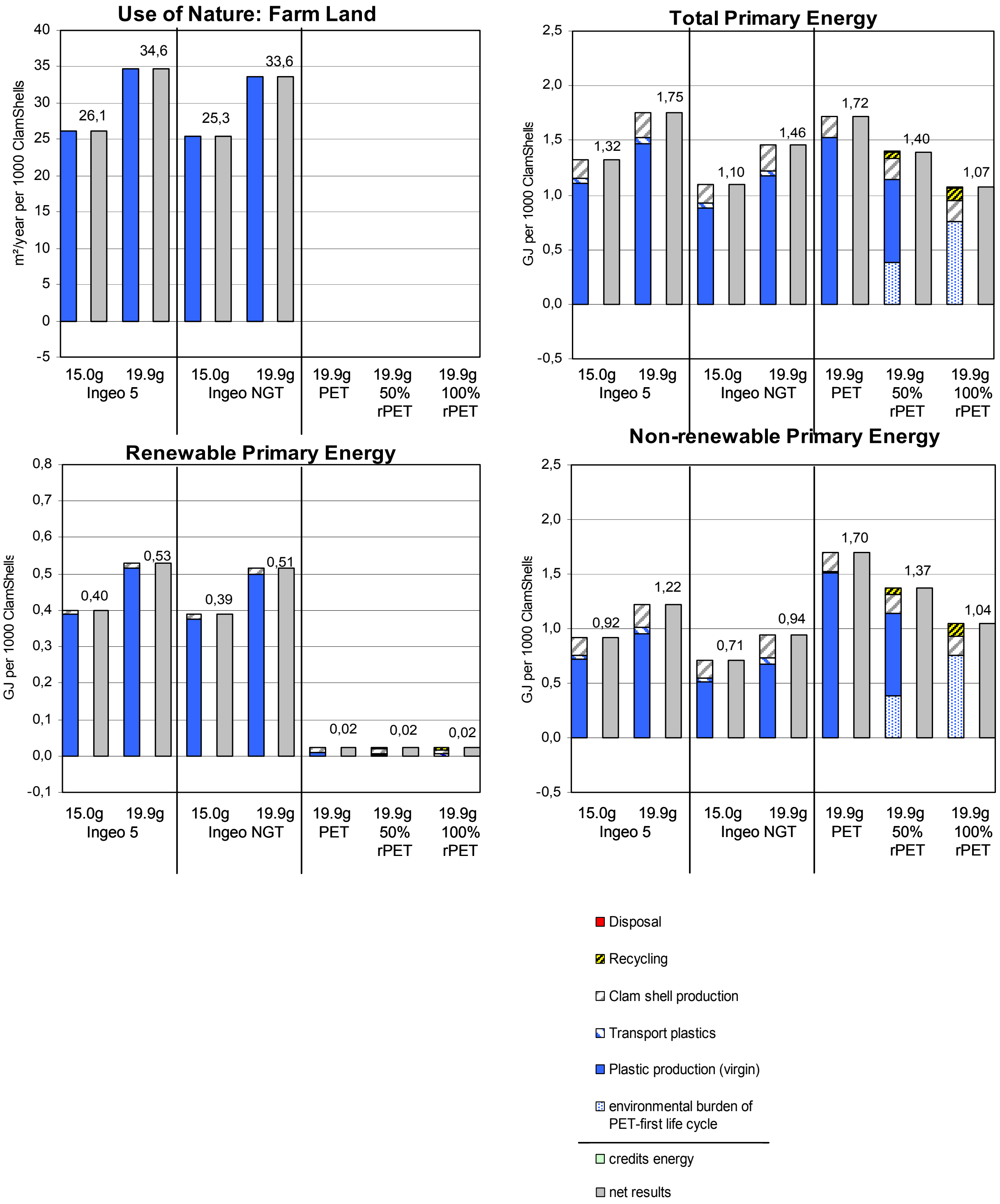

Figure 3 Scenario Set 1: Focus EU 15, Results of base scenario I (clamshell waste is 100% disposed of in a landfill) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

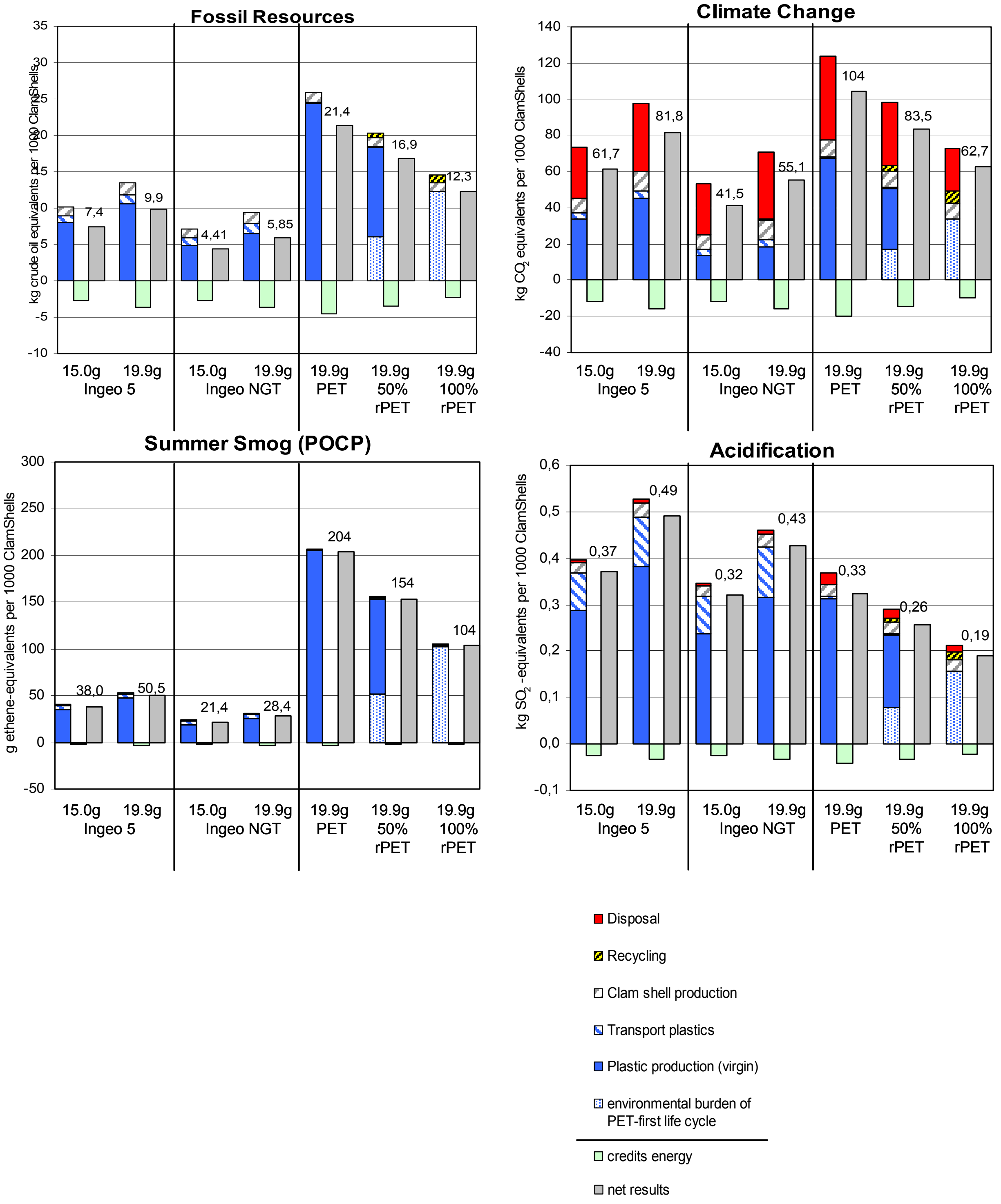

Figure 4 Scenario Set 1: Focus EU 15, Results of base scenario II (clamshell waste is 100% incinerated in a MSWI plant) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

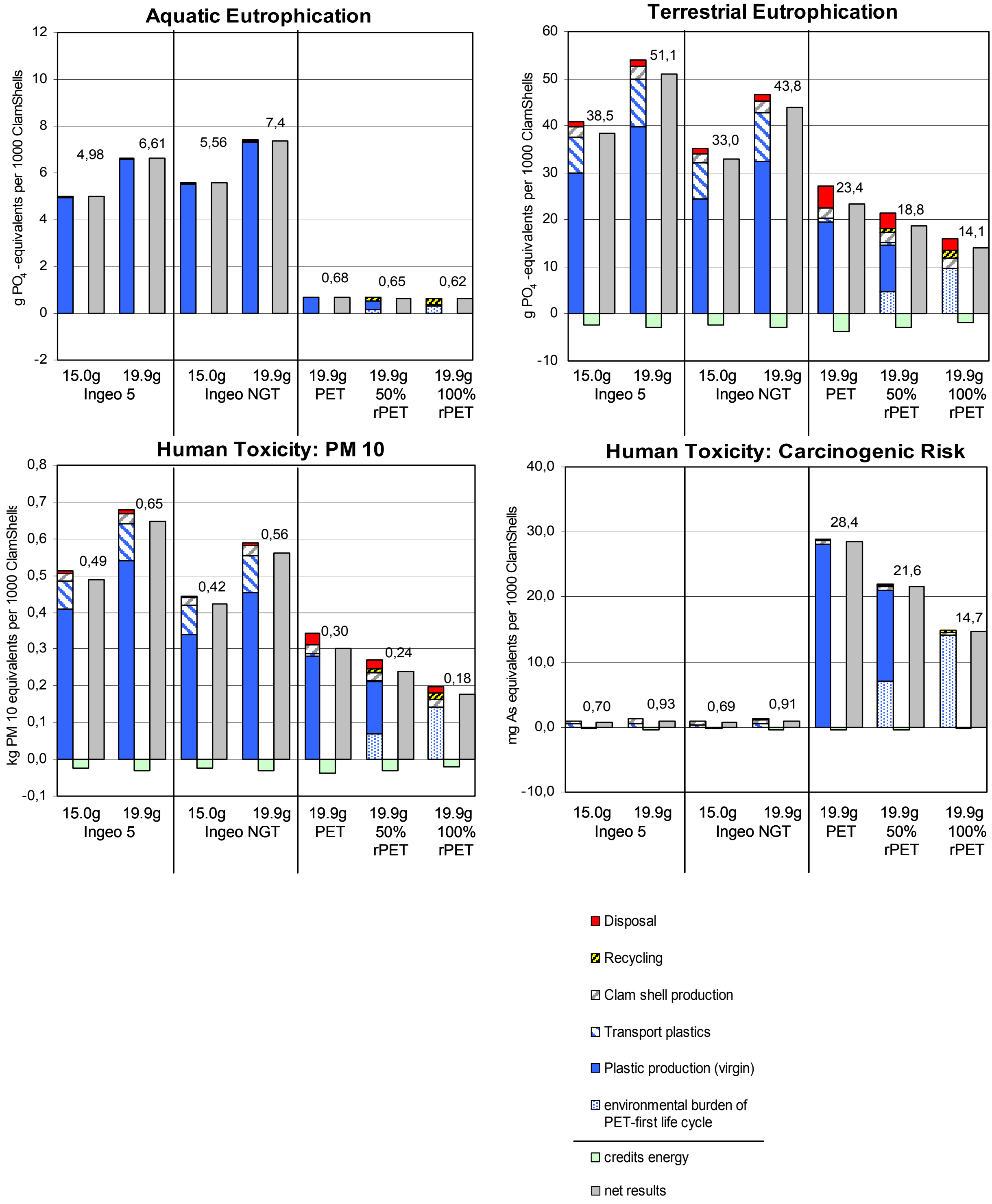

Figure 5 Scenario Set 1: Focus EU 15, Results of base scenario II (clamshell waste is 100% incinerated in a MSWI plant) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

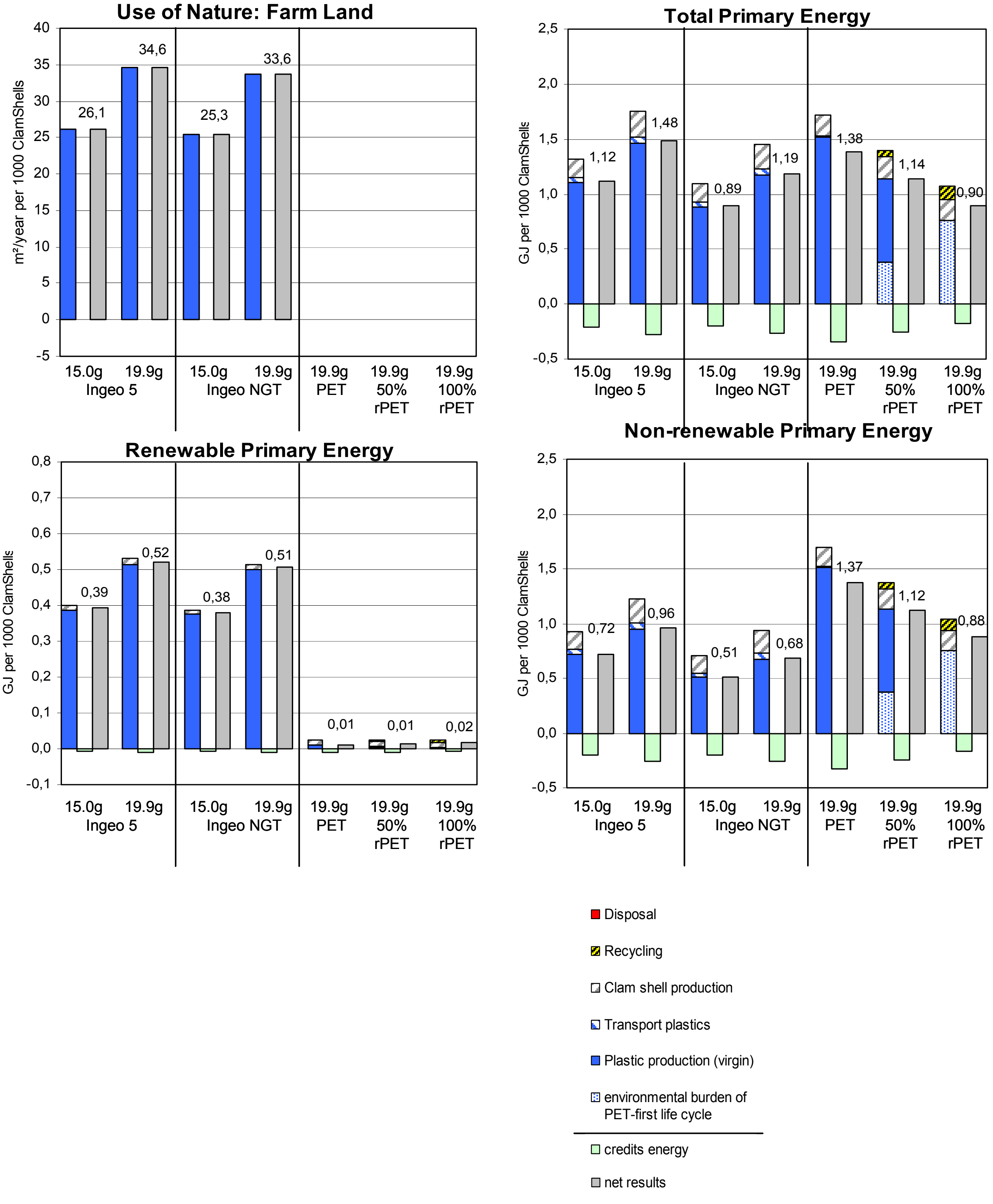

Figure 6 Scenario Set 1: Focus EU 15, Results of base scenario II (clamshell waste is 100% incinerated in a MSWI plant) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

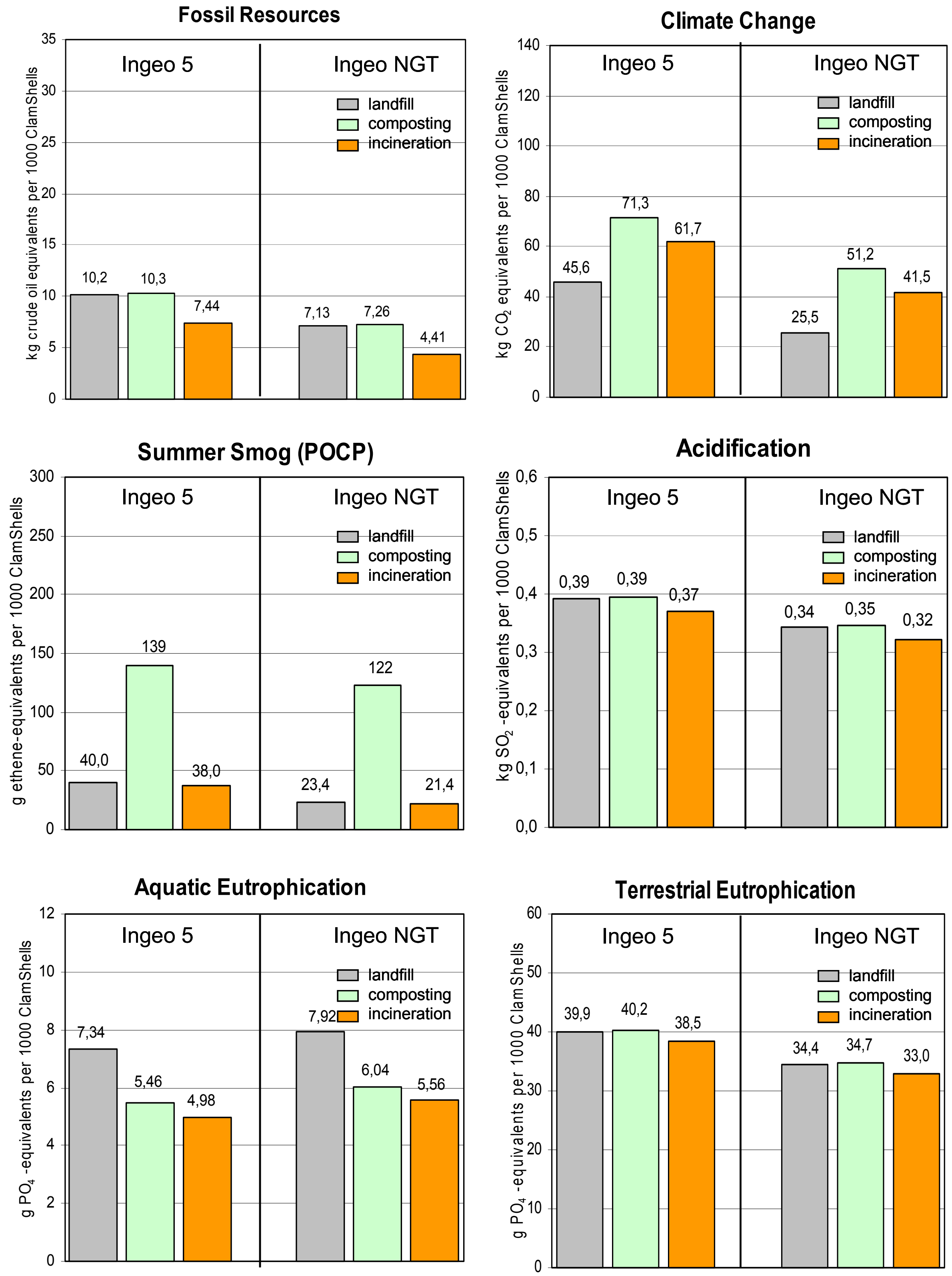

Figure 7 Scenario Set 1: Focus EU 15, Results of variant aspect: alternative waste treatment option: industrial composting

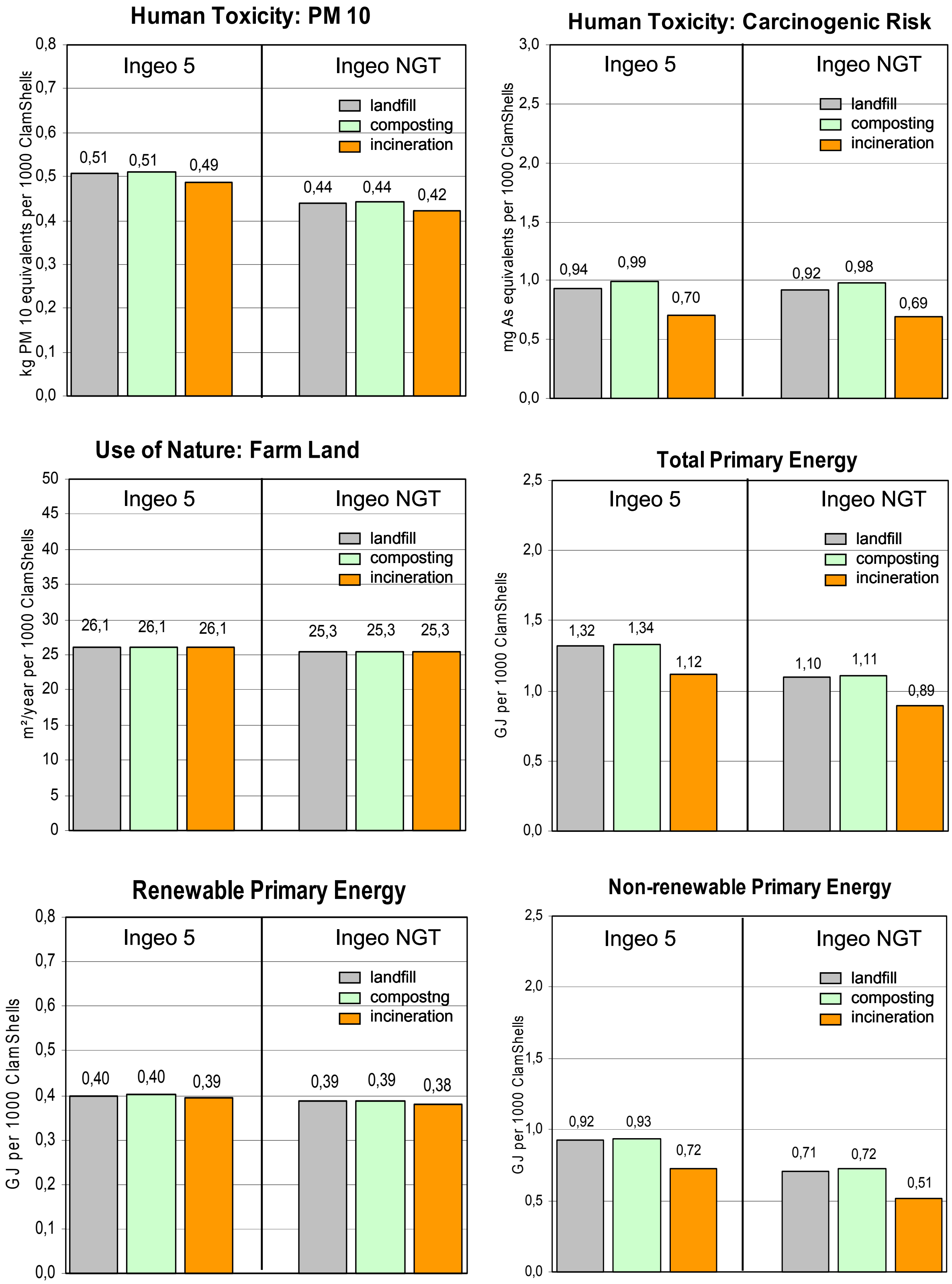

Figure 8 Scenario Set 1: Focus EU 15, Results of variant aspect: alternative waste treatment option: industrial composting

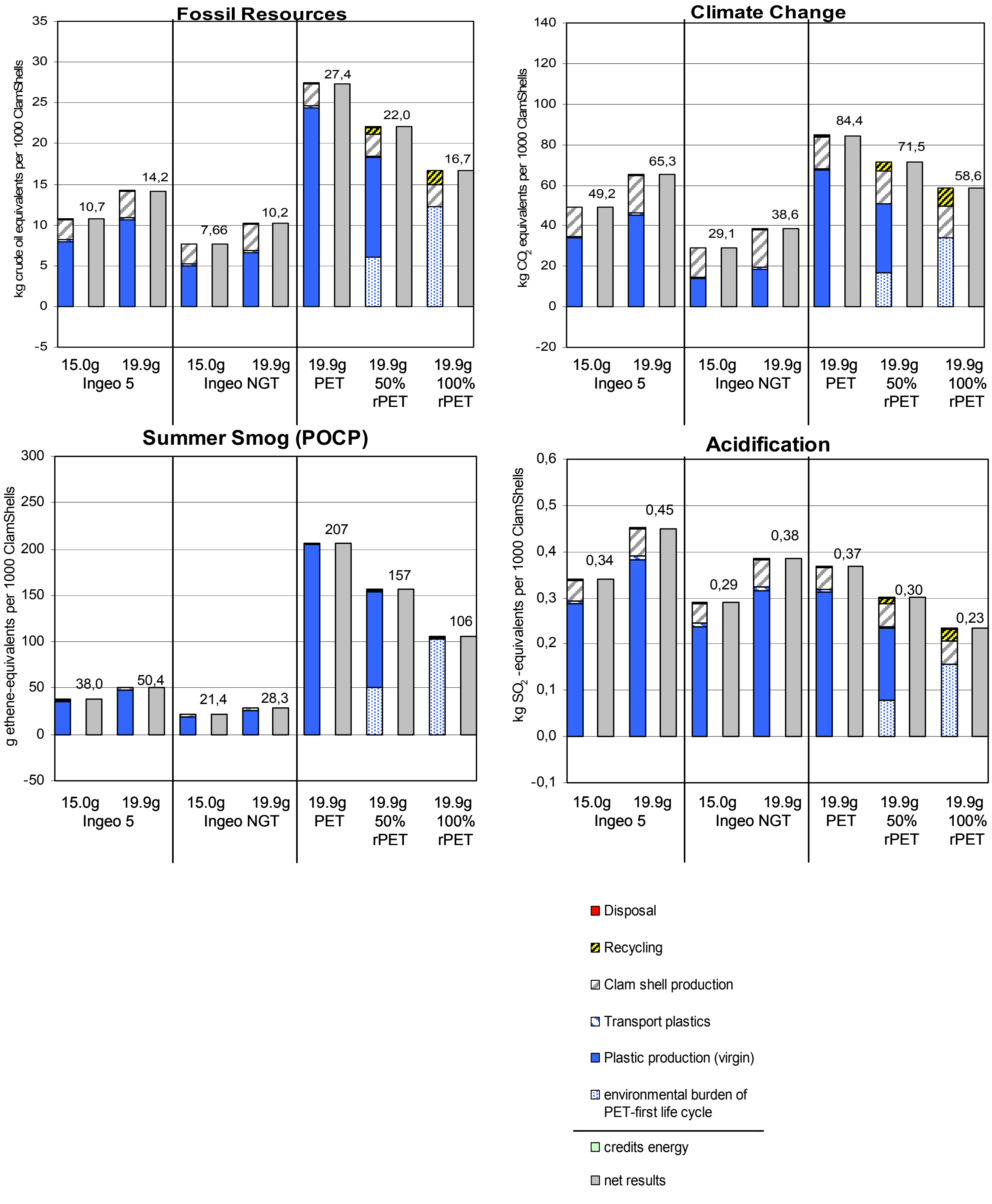

Figure 9 Scenario Set 2: Focus USA, Results of base scenario III (clamshell waste is 100% disposed of in a landfill) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

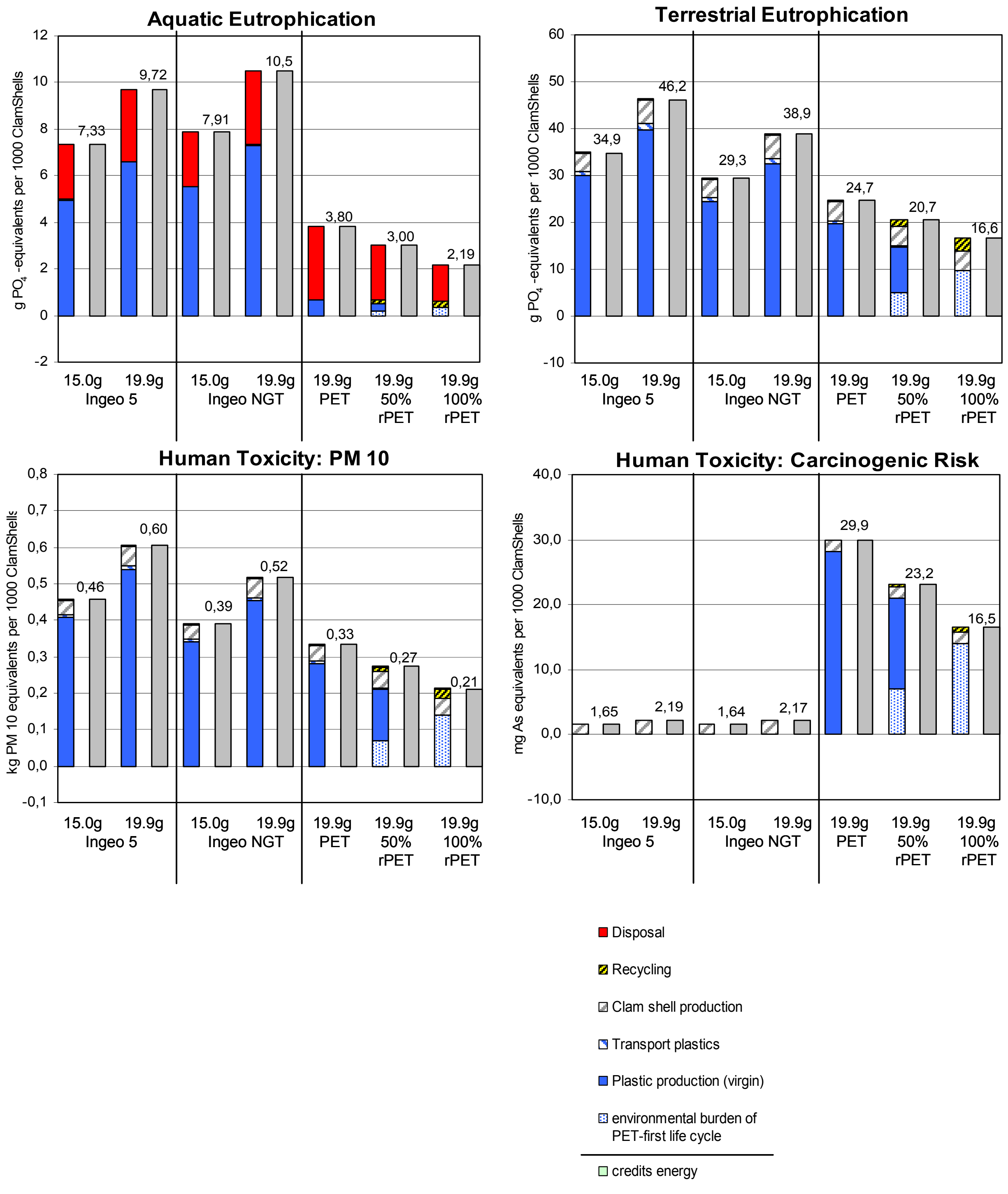

Figure 10 Scenario Set 2: Focus USA, Results of base sc ll waste is 100% disposed of in a landfill) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

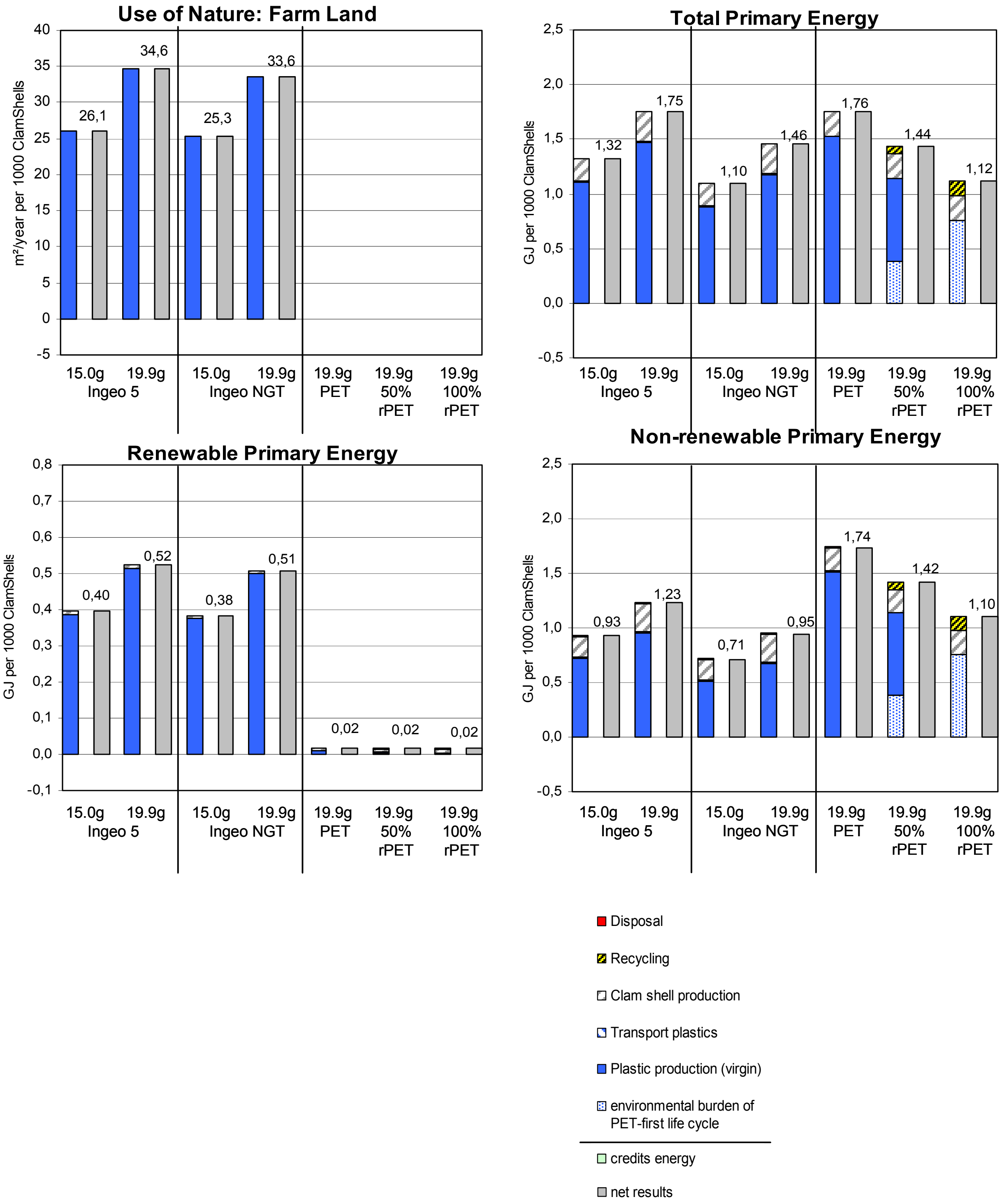

Figure 11 Scenario Set 2: Focus USA, Results of base scenario III (clamshell waste is 100% disposed of in a landfill) and variant aspect: clamshell weight variant (clamshell weight 19.9g)

6 Findings

Table 4 to 7 show the comparison of environmental indicator results:

- In Table 4 the results of clamshells made from Ingeo5 are compared with the environmental indicator results of clamshells made from virgin PET.
- In Table 5 the results of clamshells made from IngeoNGT are compared with the environmental indicator results of clamshells made from virgin PET.
- In Table 6 the results of clamshells made from Ingeo5 are compared with the environmental indicator results of clamshells made from 100% recycled PET.
- In Table 7 the results of clamshells made from IngeoNGT are compared with the environmental indicator results of clamshells made from 100% recycled PET.

The tables have to be read in the way, that the displayed system shows lower environmental indicator results than the compared system. For a better visualization the compared systems are marked with different colours. Clamshells made from Ingeo^{TM} material are displayed in light blue; clamshells made from PET are displayed in light orange.

6.1 General findings

PET-rPET Trends: Clamshells made from 50% recycled PET show lower environmental indicator results than clamshells made from virgin PET. Clamshells made from 100% recycled PET show the smallest environmental impacts of all clamshells made from PET under study. These patterns can be seen for all indicators (except renewable primary energy) and all scenarios.

Ingeo^{TM} Trends: Clamshells made from IngeoNGT show lower environmental indicator results than clamshells made from Ingeo5. These patterns can be seen for all indicators and all scenarios.

In all Ingeo^{TM} scenarios and all indicators used the 15.0 g Ingeo^{TM} clamshells show a lower environmental score than the 19.9g Ingeo^{TM} clamshells simply because less material is used

Table 4: comparison of environmental indicator results: clamshells made from Ingeo5 versus clamshells made from PET

	European framework					US framework	
Indicator	**Base Scenario I**	**clamshell weight variant**	**Base Scenario II**	**clamshell weight variant**	**waste treatment variant**	**Base Scenario III**	**clamshell weight variant**
End of life setting	*landfill*	*landfill*	*MSWI*	*MSWI*	*composting**	*landfill*	*landfill*
Fossil Resources	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Climate Change	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Summer Smog (POCP)	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Acidification	PET	PET	PET	PET	PET	Ingeo5	Ingeo5
Terrestrial Eutrophication	PET	PET	PET	PET	PET	PET	PET
Aquatic Eutrophication	PET	PET	PET	PET	PET	PET	PET
Human Tox: PM10	PET	PET	PET	PET	PET	PET	PET
Human Tox.: Carcinogenic Risk	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Use of Nature: Farm Land	PET	PET	PET	PET	PET	PET	PET
Renewable Primary Energy	PET	PET	PET	PET	PET	PET	PET
Non-renewable Primary Energy	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Total Primary Energy	Ingeo5	PET	Ingeo5	PET	Ingeo5	Ingeo5	Ingeo5

Note:the displayed system in the cell shows the smallest environmental impact to the environmental indicator in the row

* the waste treatment variant “composting” is compared with the results of clamhells made from PET from base scenario I (landfill)

Table 5: comparison of environmental indicator results: clamshells made from IngeoNGT versus clamshells made from PET

	European framework					US framework	
Indicator	**Base Scenario I**	**clamshell weight variant**	**Base Scenario II**	**clamshell weight variant**	**waste treatment variant**	**Base Scenario III**	**clamshell weight variant**
End of life setting	*landfill*	*landfill*	*MSWI*	*MSWI*	*composting**	*landfill*	*landfill*
Fossil Resources	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Climate Change	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Summer Smog (POCP)	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Acidification	IngeoNGT/ PET	PET	IngeoNGT	PET	PET	IngeoNGT	PET
Terrestrial Eutrophication	PET	PET	PET	PET	PET	PET	PET
Aquatic Eutrophication	PET	PET	PET	PET	PET	PET	PET
Human Tox: PM10	PET	PET	PET	PET	PET	PET	PET
Human Tox.: Carcinogenic Risk	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Use of Nature: Farm Land	PET	PET	PET	PET	PET	PET	PET
Renewable Primary Energy	PET	PET	PET	PET	PET	PET	PET
Non-renewable Primary Energy	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Total Primary Energy	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT

Note:the displayed system in the cell shows the smallest environmental impact to the environmental indicator in the row

* the waste treatment variant “composting” is compared with the results of clamhells made from PET from base scenario I (landfill)

Table 6: comparison of environmental indicator results: clamshells made from Ingeo5 versus clamshells made from 100% rPET

	European framework					**US framework**	
Indicator	**Base Scenario I**	**clamshell weight variant**	**Base Scenario II**	**clamshell weight variant**	**waste treatment variant**	**Base Scenario III**	**clamshell weight variant**
End of life setting	*landfill*	*landfill*	*MSWI*	*MSWI*	*composting**	*landfill*	*landfill*
Fossil Resources	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Climate Change	Ingeo5	100% rPET	Ingeo5	100% rPET	100% rPET	Ingeo5	Ingeo5
Summer Smog (POCP)	Ingeo5	Ingeo5	Ingeo5	Ingeo5	100% rPET	Ingeo5	Ingeo5
Acidification	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Terrestrial Eutrophication	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Aquatic Eutrophication	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Human Tox: PM10	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Human Tox.: Carcinogenic Risk	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Use of Nature: Farm Land	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Renewable Primary Energy	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Non-renewable Primary Energy	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5	Ingeo5
Total Primary Energy	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET

Note:the displayed system in the cell shows the smallest environmental impact to the environmental indicator in the row

* the waste treatment variant “composting” is compared with the results of clamhells made from PET from base scenario I (landfill)

Table 7: comparison of environmental indicator results: clamshells made from IngeoNGT versus clamshells made from 100%rPET

	European framework					**US framework**	
Indicator	**Base Scenario I**	**clamshell weight variant**	**Base Scenario II**	**clamshell weight variant**	**waste treatment variant**	**Base Scenario III**	**clamshell weight variant**
End of life setting	*landfill*	*landfill*	*MSWI*	*MSWI*	*composting**	*landfill*	*landfill*
Fossil Resources	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Climate Change	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	100% rPET	IngeoNGT	IngeoNGT
Summer Smog (POCP)	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	100% rPET	IngeoNGT	IngeoNGT
Acidification	100%rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Terrestrial Eutrophication	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Aquatic Eutrophication	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Human Tox: PM10	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Human Tox.: Carcinogenic Risk	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Use of Nature: Farm Land	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Renewable Primary Energy	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET	100% rPET
Non-renewable Primary Energy	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT	IngeoNGT
Total Primary Energy	100% rPET	100% rPET	IngeoNGT	100% rPET	100% rPET	IngeoNGT	100% rPET

Note:the displayed system in the cell shows the smallest environmental impact to the environmental indicator in the row

* the waste treatment variant “composting” is compared with the results of clamhells made from PET from base scenario I (landfill)

6.2 Findings for the European framework

The results for all the scenarios studied for the European framework are given in the Figures 1-8 and summarized in Table 4-7.

General: in many scenarios clamshells made from Ingeo^{TM} show lower potential environmental impacts than clamshells made from either PET or rPET for the indicators *fossil resources, climate change, summer smog, human toxicity: carcinogenic risk, non renewable and total primary energy.* On the other hand, PET (and rPET), has a better score for *use of nature: farmland, terrestrial and aquatic eutrophication, human toxicity: PM10, renewable energy,* and often a better score for *acidification*. In order to define the final preference for one or the other clamshell depends on the individual value judgement applied to these indicators.

From a climate change point of view: the best end of life (EOL) option for any clamshell is landfill (assuming 0% degradation), followed by incineration with energy recovery and composting.

From a non-renewable energy point of view: the best choice is incineration with energy recovery; both other options show an equal score.

Assuming landfill as EOL: Comparing the best option for Ingeo^{TM} (15.0 g - IngeoNGT) with the best option for PET (100% rPET), Ingeo^{TM} shows a lower score for *fossil resource use, climate change, summer smog, human toxicity: carcinogenic risk and non-renewable energy.* For others like *acidification, terrestrial and aquatic eutrophication and human toxicity: PM10* PET shows a lower score. Again, in order to define the final preference for one or the other clamshell depends on the individual value judgement applied to these indicators. The same conclusions are valid for incineration as the end of life option.

6.3 Findings for the US framework

The results for all the scenarios studied for the US framework are given in the Figures 9-11 and also summarized in Table 4-7.

General: the only waste treatment route examined under the US framework is landfill. So the results are similar to the results for clamshells which end up on European landfills; only for the indicator *acidification* the net results for clamshells made from Ingeo^{TM} material show now lower potential environmental impacts than clamshells made from virgin PET. This is due to the avoided oversea transport of Ingeo^{TM} pellets in the US framework.

The comparison of clamshells made from Ingeo^{TM} and clamshells made from 100% rPET shows a similar result pattern than the results for the European framework: lower environmental indicator results for clamshells made from Ingeo^{TM} for the indicators *fossil resources, climate change, summer smog, human toxicity: carcinogenic risk and renewable primary energy* and smaller environmental indicator results for clamshells made from 100% rPET for the indicators *acidification*, *terrestrial and aquatic eutrophication and human toxicity: PM10.*

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8 Appendix A

Allocation procedure for rPET clam shells

Background

The principles of allocation are addressed in ISO 14044 (§4.3.4). They apply to all allocation situations including allocation procedures in the context of open-loop recycling which is the subject to be dealt with in this appendix.

According to ISO 14044 it is a fundamental requirement that the sum of the allocated inputs and outputs shall be equal to the inputs and outputs before allocation [*Requirement 1*]. This requirement sort of transfers the physical law of mass and energy conservation into LCA thinking.

The additional requirements set by ISO 14044 on first sight read rather theoretical. It says that allocation procedures should use, as the basis for allocation, the following order, if feasible:

- physical properties (e.g. mass) [*Requirement 2*];
- economic value (e.g. market value of the scrap material or recycled material in relation to market value of primary material); or
- the number of subsequent uses of the recycled material .

In addition further aspects to be considered according to ISO 14044 are

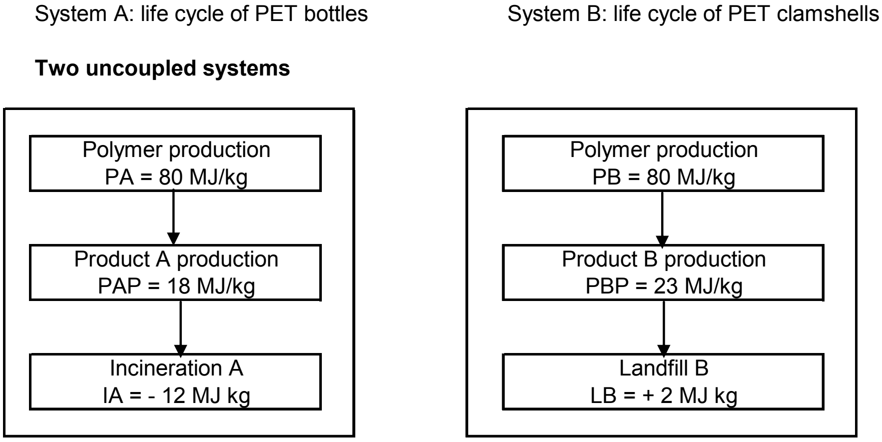
- regarding reuse and recycling an allocation procedure may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system [*Requirement 3*];
- reuse and recycling may change the inherent properties of materials in subsequent use;
- specific care should be taken when defining system boundary with regard to recovery processes. [*Requirement 4*]

The underlined requirements are the corner stones of the allocation procedure applied in this study.

Application in the current study

Figure 1 gives the simplified life cycles of two systems. In System A virgin PET polymer is produced, converted into a bottle and finally disposed of via incineration. In Systems B virgin PET polymer is produced, converted into a clam shell and finally disposed of via landfill[4]. Here, both systems are not coupled.

Figure 1. Uncoupled production system for PET bottles and clam shells.



The total energy consumption of system A is: PA + PAP + IA = 86 MJ/kg bottles. The total energy consumption of system B is: PB+PBP+LB = 105 MJ/kg. Thus, the total energy used in both systems together is 86 + 105 = 191 MJ.

Please take into consideration that all the numbers given are fictive numbers (though rather close to reality) to make the allocation procedure more transparent.

The underlying LCA presented in this report is assessing the life cycle of PET clam shells. PET clam shells can be made of virgin PET, as given in above System B of Figure 1, or partially or even completely from recycled PET (rPET). In reality only PET bottles are generating rPET and therefore the source of rPET used for clam shells are PET bottles. This situation implicates a certain need for allocation as will be explained in the following text with the example of System A and B.

In the case of the production of rPET-based clam shells both systems get coupled: PET coming from the bottle life cycle is flowing via the recovery process into the clam shell life cycle. Looking at overall material flows only the rPET generated from bottles gets connected to the life cycle of the clam shells. This connection is depicted in Figure 2.

In the present example of coupled Systems A and B it is – again for the purpose of simplification - assumed that all bottles of System A are recovered after use and supplied as a raw material to System B. This way, the polymer PA has two uses as it serves for the production of Product A and Product B. In addition, though produced in System A originally, its material properties affect the end-of-life treatment in System B.

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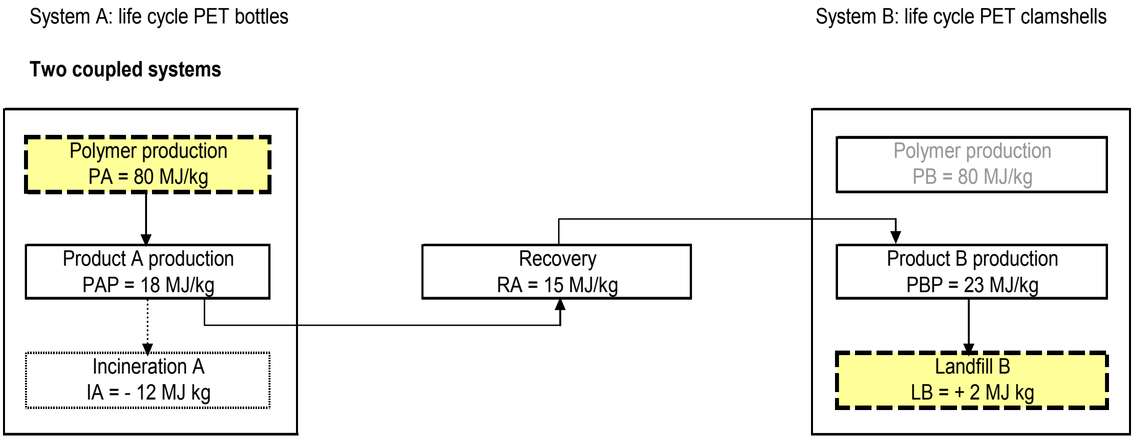
[4] Remark: Incineration (in system A) and landfill (in System B) are only one possible option in a mix of end-of-life pathways. They are used in the flow charts (as place holders) for the purpose of simplification.

In reality, a part of the bottles are recycled and another part (those bottles which are not source-separated after use) is landfill or incinerated. Again, for the purpose of simplification the assumption is that all bottles go into the recycling route.

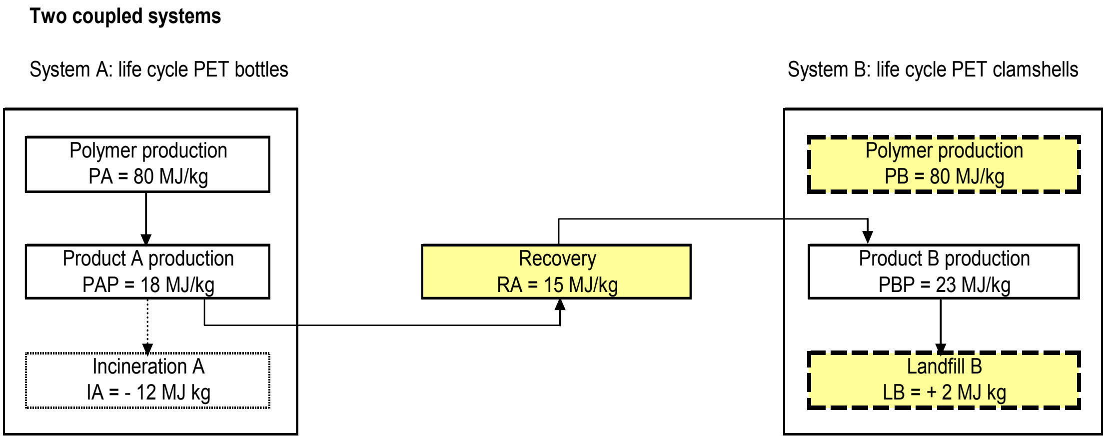
Figure 2: The coupling between both systems.



In a product LCA the task usually is to assess the environmental performance of a dedicated product system regardless its coupling to preceding or subsequent product systems. In the example presented here the system boundaries of the LCA are such that only product System B is examined (i.e. the rPET clam shell) and consequently it is necessary to allocate PA and LB between Systems A and B in order to comply with *requirement 3* (see above).

For reasons of practicability the approach usually implemented in LCAs is slightly different as is indicated in figure 3. It will be explained at more detail in the following.

Figure 3: Process steps included in the allocation procedure of coupled systems



The first step is to focus on the fact that by using rPET in System B the environmental loads related to an equivalents quantity (*requirement 2*) of virgin polymer production (PB) is avoided. The allocation procedure now has to decide how the possible environmental benefits of the PB saving are allocated (or credited) to System A and B. This approach is sometimes referred to as the "avoided burden approach" or "crediting approach".

The practical advantage of this procedure is twofold:

a) it also applies when the recycled material displaces other types of raw materials (e.g. rPET-Flakes used for PET fibres displacing cotton fibres; or recycled polyolefins used for park benches displacing wood benches)

b) the full contribution of the polymer production step (PA) in the environmental profile of product A is fully visible (and not cut-down by allocation of a part of the loads to system B) which is an important information for hot spot and improvement analysis. Furthermore, the relevance of the avoided burden credit assigned to system A can be easily shown separately which increases transparency of the LCA calculation significantly.

Requirement 4 (see above) demands the recovery process being considered in the allocation procedure too. Up to this point the allocation procedure has to consider the partitioning of

- the benefits of the avoided burden (e.g. by substitution of vPET related to an equal quantity of rPET as taken up in System B);
- the loads of the Recovery process (related to the quantity of rPET taken-up in System B).

This is where it seems that most on-going discussion on open-loop recycling seem to agree upon. However, there is no agreement so far as to which system (A or B) - and to which extent - should be assigned the benefit and which the loads (see sections below).

The methodology used at IFEU, beyond the two steps mentioned above, a third point included in the allocation procedure addresses

- the potential loads and benefits of the final treatment in System B (related to the quantity of rPET taken-up in System B).

This latter point seeks compliance with *requirements 3* of the ISO 14044 as mentioned in the background section of Appendix A.

As shown in the next section the implementation of the allocation procedure described still gives room to subjective choices. However, in all cases there is an important premise to comply with by any allocation method chosen: the mass (and energy) balance of all inputs and outputs of System A and B after allocation must be the same as the inputs and outputs calculated for the sum of System A and B before allocation (see *requirement 1*).

Allocation choices and their implication

Let's assume that for the production of 1 kg of 100% rPET-based clam shells one needs 1 kg rPET generated from bottles. In this case 1 kg PET flows from System A into System B. The total energy use of the overall system becomes:

PA + PAP + RA + PBP + LB = 80+18+15+23+2 = 138 MJ,

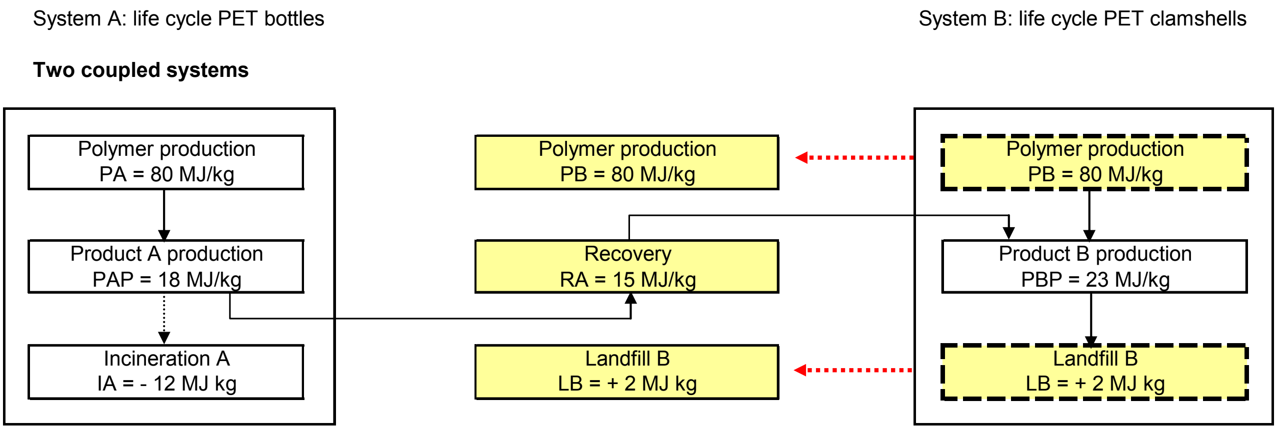
which is 53 MJ less than the uncoupled systems. It seems that recycling makes sense.

In this case we talk about open loop recycling: material flows from one system (System A) into another system (System B).

As a result of this material flow the virgin polymer production (PB) process is avoided while the recovery process is a new additional activity.

This has been highlighted by placing the processes subjected to allocation decisions in the space between system A and B as depicted in Figure 4.

Figure 4. Process steps to be shared by two coupled systems via an allocation rule



Eventually, the question raises how the environmental benefits and loads of the depicted processes are allocated to System A and B. In the following three different ways to allocate these are explained.

1. 100% allocation to System A.
2. 100% allocation to System B.
3. A compromise: both systems take 50% of the burdens and benefits.

Potentially there are more options but those presented show the margins as well as a way in between.

In following section the effects on Energy use on the bottles and clam shells, using the fictive numbers given in Figure 4, are calculated and discussed.

1. 100% allocation to System A.

According to this model System A takes all the benefits (= avoided virgin polymer production, PB) and the entire burden (= recovery, RA and Landfill, LB) of the processes in "the middle". Hence, System A does get a 100% credit for the virgin material production displaced in System B but on the other hand takes 100% of the recovery burden, and a 100% load for the landfill.

Consequently, System B is charged with 100% virgin material production (although it uses recycled material), in order to guarantee the sum of the two systems equals the real loads, and saves the incineration process.

What does this mean for the energy use of both systems?

The energy use system A is: PA + PAP - PB + RA + LB = 80+18-80+15+2 = 35 MJ.

The energy use system B is: PB + PBP = 23+80 = 103 MJ

The total energy use of System A + B is: 35 + 103 = 138 MJ (Energy use of total system should be constant.)

The result for System A is that the energy drops from 86 down to 35 MJ. The result for System B is that the energy increased from 91 up to 103 MJ.

System A has a typically high benefit from this approach (burdens for virgin material completely saved). On the other hand, System B, although it uses recycled material, has calculatively the same burden as if it used virgin material. In other words, for System B it hardly matters if virgin material or recycled material is used. But, again, System A needs System B - if there is no System B using the recycled material - there is no benefit from it in reality.

2. 100% allocation to System B [5]

** According to this model System B takes all the benefits (+avoided polymer production, PB) and all the burden (= recovery, RA and landfill LB) of the processes in "the middle". Hence, System B saves the production of virgin material, but on the other hand takes 100% of the recovery burden, and a 100% load for the landfill.

Consequently, System A now is charged with 100% virgin material production while it is not sharing any burden from the incineration process in System B.

What does that mean for the energy use of both systems?

- The energy use of the clam shells is RA+PBP+LB = 15+23+2 = 40 MJ.
- The energy use of the bottles is 80+18 = 98MJ.

Typically, at least in case of high quality recycling (means the recycled material goes to a high quality application - which is the case for clam shells), the advantage of system A only consists in having avoided final disposal of PET waste and not being charged with the recovery process. However, the credits for System A are clearly smaller than the savings obtained by avoided virgin material production (for System B).

System A can claim that it provides a valuable “waste” material, which may be converted into a high quality recycled material, but gets hardly any advantage out of that. In other words, the big advantage is located in the System B, which uses the recycled material. This approach kind of ignores the fact, that System B can only use the recycled material, if System A is able and willing to provide it, which will not happen under these conditions.

Trade-Off Situation

Both, approach 1 and approach 2 are associated with problems:

Approach 1 represents an unfair treatment of System A and approach 2 seems to contradict System's B internal logic - why worry with recyclate (and its potential problems), if the result is mathematically hardly different or even worse than if using virgin material?

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[5] A rather similar approach is sometimes referred to as “cut-off” approach. The difference is that in the cut-off approach the recovery process is not considered as being in the middle of two coupled systems but is considered being a component of system A. As a consequence both systems are perceived as separate systems.

For this reason, based on the finding that both systems are required: System A providing the recyclate and System B using the recyclate, in order to have a net (overall) benefit (of System A + System B), the 50/50 method has been developed. It is (amongst others) based on the following criteria:

1. shall be mathematically correct - no "double counting"

2. shall have internal logic ("if I am using recyclate, and there is an overall benefit, I should not be treated as if using virgin material")

3. fairness - if coupled systems lead to an overall benefit, both systems should participate in that benefit.

3. 50/50 Allocation to both systems

All benefits + burdens of the processes in "the middle" are allocated on a 50:50 basis to System A and B.

The energy use system of System A is: PA + PAP -0.5*PB + 0.5*RA + 0.5*LB = 80+18-40+7.5+1 = 66.5 MJ.

The energy use system of System B: PBP + 0.5*PB + 0.5*RA + 0.5*LB (here again you are violating Requirement 1. In case of PB you have a +0.5PB and a -0.5PB factor; in case of LB both are + = 23+40+7.5+1 = 71.5 MJ.

The total energy use System A + B: 66.5 + 71.5 = 138 MJ (Energy use of total system is constant).

Result for System A: energy dropped from 86 down to 66.5 MJ; advantage for bottles is -19.5 MJ or 23%.

Result for System B: energy dropped from 105 down to 71.5 MJ; advantage for clam shells is -33.5 MJ or 32%.

This seems to be an acceptable allocation procedure which divides the benefits of coupled systems equally over the “partners” and therefore is used in this study.