Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers

Polyamide 6 (PA6)
PlasticsEurope
February 2014

PlasticsEurope
Association of Plastics Manufacturers

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Environmental Product Declaration

Introduction

This Environmental Product Declaration (EPD) is based upon life cycle inventory (LCI) data from PlasticsEurope's Eco-profile programme. It has been prepared according to **PlasticsEurope's Eco-profiles and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors** (PCR version 2.0, April 2011). EPDs provide environmental performance data, but no information on the economic and social aspects which would be necessary for a complete sustainability assessment. Further, they do not imply a value judgment between environmental criteria.

This EPD describes the production of the Polyamide 6 (PA6) polymer from cradle to gate (from crude oil extraction to granules or resin at plant). **Please keep in mind that comparisons cannot be made on the level of the polymer material alone**: it is necessary to consider the full life cycle of an application in order to compare the performance of different materials and the effects of relevant life cycle parameters. This EPD is intended to be used by member companies, to support product-orientated environmental management; by users of plastics, as a building block of life cycle assessment (LCA) studies of individual products; and by other interested parties, as a source of life cycle information.

Meta Data

Data Owner	PlasticsEurope, Product Group Engineering Polymers
LCA Practitioner	PricewaterhouseCoopers
Programme Owner	PlasticsEurope aisbl
Programme Manager, Reviewer	DEKRA Consulting GmbH
Number of plants included in data collection	7
Representativeness	57%
Reference year	2010–2012
Year of data collection and calculation	2012–2013
Expected temporal validity	2016
Cut-offs	No significant cut-offs
Data Quality	Very good
Allocation method	No allocation; substitution method is used for co-products

Description of the Product and the Production Process

Polyamides are a group of polymers characterised by a carbon chain with –C=O–NH– groups interspersed at regular intervals along it. They are commonly referred to by the generic name Nylon and are usually identified by a numbering system that indicates the number of carbon atoms between successive nitrogen atoms in the main chain. This EPD is for Polyamide 6 (PA6), a polymer formed by ring-opening polymerisation of caprolactam, a cyclic monomer. Caprolactam has a peptide bond which is broken during polymerisation, after which new peptide bonds are formed at each end of the monomer. This leads to a backbone polymer.

Production Process

PA6 is formed by polymerisation of caprolactam. Caprolactam is produced from cyclohexanone, which reacts with hydroxylamine to form an oxime which undergoes a Beckmann rearrangement with an acid to form the bisulphate salt of caprolactam. The latter is neutralised with an alkali compound to form caprolactam. A byproduct of caprolactam production is ammonium sulphate. As for cyclohexanone, there are two ways to produce it using benzene as a starting chemical: one route is the hydrogenation of benzene to produce cyclohexane, which is then oxygenated to give cyclohexanone. The alternative route uses the reaction of benzene with propylene. This gives cumene that can be further oxygenated to phenol, giving acetone as by-product. Phenol can then be hydrogenated to form cyclohexanone.

The reference flow, to which all data given in this EPD refer, is 1 kg of PA6 in pellet form.

Data Sources and Allocation

The main data source was a data collection from European producers of polyamide 6 (PA6). Primary data on gate-to-gate PA6 production is derived from site-specific information for processes under operational control supplied by the participating companies of this study. Four different PA6 producers with plants in four European countries were participating in the primary data collection. They represent approximately 57% of European PA6 production (EU27) in 2012. Unless primary data were provided, data for the upstream supply chain until the precursors as well as relevant background data, such as energy and auxiliary material, are from the *DEAM,* PlasticsEurope and *Ecoinvent* databases. For caprolactam, three caprolactam producers with plants in three European countries participated in the primary data collection.

Use Phase and End-of-Life Management

PA6 can be extruded, granulated and moulded in a wide range of textile, packaging and engineering applications. The main uses include fibers, films and engineering plastics. Applications range from automotive and electrical to food packaging. It should be noted that PA6 (polycaprolactam or Nylon 6) and PA6.6 (Nylon 6.6) are used for similar purposes. PA6 can be recycled mechanically or for feedstock; chemical recycling back to the monomer is commercially exploited.

Environmental Performance

The tables below show the environmental performance indicators associated with the production of 1 kg of PA6.

Input Parameters

Indicator	Unit	Value
Non-renewable energy resources[1]	MJ	128.8
• Fuel energy	MJ	90.3
• Feedstock energy	MJ	38.5
Renewable energy resources (biomass)[1]	MJ	0.36
• Fuel energy	MJ	0.35
• Feedstock energy	MJ	0.01
Abiotic Depletion Potential		
• Elements	kg Sb eq	1.7E-08
•Fossil fuels	MJ	115.9
Renewable materials (biomass)	kg	8.3E-03
Water use	kg	1647
• for process	kg	10
• for cooling	kg	1637
[1] Calculated as upper heating value (UHV)		

Output Parameters

Indicator	Unit	Value
GWP	kg CO_2 eq	6.7
ODP	g CFC-11 eq	1.2E-04
AP	g SO_2 eq	12.0
POCP	g Ethene eq	0.6
EP	g PO_4 eq	4.2
Dust/particulate matter[2]	g PM10	1.2
Total particulate matter[2]	g	1.2
Waste		
• Non-hazardous	kg	0.06
• Hazardous	kg	0.03
[2] Including secondary PM10		

Additional Environmental and Health Information

PA6 is not classified as dangerous according to CLP legislation (EC 1272/2008). It does not require a hazard label in accordance with EC Directives. Under certain circumstances (temperature >300°C), thermal degradation can give rise to toxicologically relevant HCN and CO emissions. The manufacturers of polyamides are working through PlasticsEurope, the American Chemistry Council (ACC) and other industry groups to foster product safety and to actively engage with stakeholders.

Additional Technical Information

Among the intrinsic properties of PA6 are: high tensile strength, good abrasion resistance, elasticity, barrier properties of films, durability, flexible design, and easy processing. It is also resistant to acid and alkali chemicals as well as to hydrocarbons, solvents, fuels, waxes, and oils. In addition, PA6 is an electrical isolator.

Additional Economic Information

Weight reduction in automobiles and increased shelf life of fresh food are examples where PA6 applications contribute to reduction of carbon footprint and costs in the use phase compared with standard solutions.

Information

Data Owner

PlasticsEurope, Product Group Engineering Polymers
Avenue E van Nieuwenhuyse 4, Box 3
B-1160 Brussels, Belgium
Tel.: +32 (2) 675 32 97, Fax: +32 (2) 675 39 35
E-mail: info@plasticseurope.org.

Programme Manager & Reviewer
DEKRA Consulting GmbH
This Environmental Product Declaration has been reviewed by DEKRA Consulting GmbH. It was approved according to the Product Category Rules PCR version 1.2 (2010-06) and ISO 14025:2006. Registration number: PlasticsEurope 2013-003, validation expires on 31 December 2016 (date of next revalidation review).

Programme Owner

PlasticsEurope
Avenue E van Nieuwenhuyse 4, Box 3
B-1160 Brussels, Belgium
Tel.: +32 (2) 675 32 97, Fax: +32 (2) 675 39 35
E-mail: info@plasticseurope.org.

For copies of this EPD, for the underlying LCI data (Eco-profile); and for additional information, please refer to http://www.plasticseurope.org/.

References

- PlasticsEurope: Eco-profiles and environmental declarations – LCI methodology and PCR for uncompounded polymer resins and reactive polymer precursors (version 2.0, April 2011)
- Cover image with kind permission by DSM.

Plastics
The Material for the 21st Century

Goal & Scope

Intended Use & Target Audience

➢ *Eco-profiles (LCIs) and EPDs from this programme are intended to be used as »cradle-to-gate« building blocks of life cycle assessment (LCA) studies of defined applications or products. LCA studies considering the full life cycle (»cradle-to-grave«) of an application or product allow for comparative assertions to be derived. It is essential to note that comparisons cannot be made at the level of the polymer or its precursors. In order to compare the performance of different materials, the whole life cycle and the effects of relevant life cycle parameters must be considered.*

PlasticsEurope Eco-profiles and EPDs represent polymer production systems with a defined output. They can be used as modular building blocks in LCA studies. However, these integrated industrial systems cannot be disaggregated further into single unit processes, such as polymerisation, because this would neglect the interdependence of the elements, e.g. the internal recycling of feedstocks and precursors between different parts of the integrated production sites.

PlasticsEurope Eco-profiles and EPDs are prepared in accordance with the stringent ISO 14040–44 requirements. Since the system boundary is »cradle-to-gate«, however, their respective reference flows are disparate, namely referring to a broad variety of polymers and precursors. This implies that, in accordance with ISO 14040–44, a direct comparison of Eco-profiles is impossible. While ISO 14025, Clause 5.2.2 does allow EPDs to be used in comparison, PlasticsEurope EPDs are derived from Eco-profiles, i.e. with the same »cradle-to-gate« system boundaries.

As a consequence, a direct comparison of Eco-profiles or EPDs makes no sense because 1 kg of different polymers are not functionally equivalent.

Once a full life cycle model for a defined polymer application among several functionally equivalent systems is established, and only then, can comparative assertions be derived. The same goes for EPDs, for instance, of building product where PlasticsEurope EPDs can serve as building blocks.

Eco-profiles and EPDs are intended for use by the following target audiences:

- member companies, to support product-orientated environmental management and continuous improvement of production processes (benchmarking);
- downstream users of plastics, as a building block of life cycle assessment (LCA) studies of plastics applications and products; and
- other interested parties, as a source of life cycle information.

Product Category and Declared Unit

Product Category

The core product category is defined as **uncompounded polymer resins, or reactive polymer precursors**. This product category is defined "at gate" of the polymer or precursor production and is thus fully within the scope of PlasticsEurope as a federation. In some cases, it may be necessary to include one or several additives in the Eco-profile to represent the polymer or precursor "at gate". For instance, some polymers may require a heat stabiliser, or a reactive precursor may require a flame retardant. This special case is distinguished from a subsequent compounding step conducted by a third-party downstream user (outside PlasticsEurope's core scope).

Functional Unit and Declared Unit

The default Functional Unit and Declared Unit of PlasticsEurope Eco-profiles and EPDs are (unless otherwise specified[1]):

1 kg of primary PA6 "at gate" (production site output) representing a European industry production average, in pellet form.

Product and Producer Description

Product Description

Polycaprolactam (PA6) is a thermoplastic polymer.

- IUPAC name: Polycaprolactam
- CAS no. 25038-54-4
- Chemical formula: $–[C_6H_{11}NO]–_n$
- Density: 1.084 g/cm^3

First synthesised in 1938, PA6 is among the earliest synthetic plastics ever made and belongs to the family of polyamides, also called "nylons". Its base structure is a six-carbon amide function created through the opening of the caprolactam cycle. Hydrogen bonds between nylon chains provide PA6 with favourable mechanical and physical properties, such as high tensile strength, elasticity, and durability. It is noteworthy that the relative number of amide groups – expressed, for example, as methylene to amide group ratio – is identical for PA6 and PA6.6 polymers (equal to 5).

For the industrial production of PA6, ring-opening polymerisation of caprolactam is used.

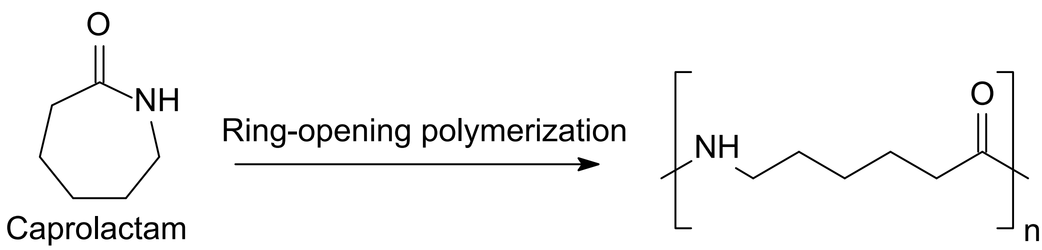

Figure 1: Synthesis of PA6 through ring-opening polymerisation of caprolactam

Caprolactam is synthesised from cyclohexanone though the following process:

[1] Exceptions can occur when reporting Eco-profiles of, for instance, process energy, such as on-site steam, or conversion processes, such as extrusion.

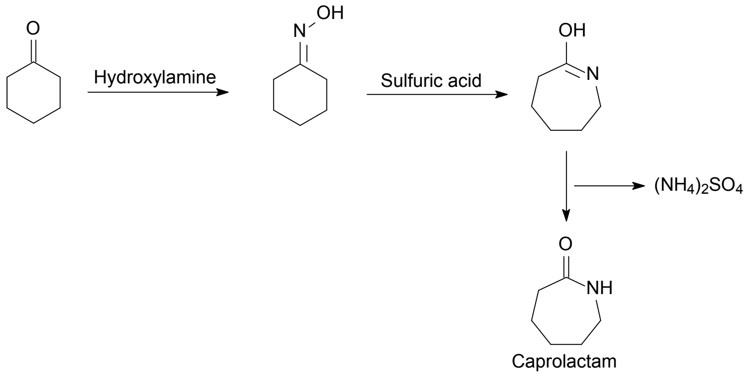

Figure 2: Overview of Caprolactam synthesis

It should be noted that ammonium sulphate is a major by-product of caprolactam production. Ammonium sulphate has a limited economic importance as a feedstock for fertilisers and efforts are being made to limit the quantity of ammonium sulphate produced as a by-product of caprolactam production. Process data show that the production of ammonium sulphate ranges between 2 and 5 kg per kg of caprolactam. In addition, processes involved in caprolactam production generate emissions of nitrous oxide (N_2O), a potent greenhouse gas (GHG). Abatement of N_2O emissions is a major interest of caprolactam producers.

Cyclohexanone is generally produced through the oxidation of cyclohexane, synthesised from benzene. This oxidation generates a mix of cyclohexanol and cyclohexanone ("ketone-alcohol mixture" or "KA oil") which is also the main feedstock for adipic acid, one of the monomers used to produce PA6.6. Alternatively, cyclohexanone may be produced through the hydrogenation of phenol, which in turn is derived from benzene.

The processes described here, including supplementary materials (catalysts for instance), energy and utilities, are referred to as "foreground processes" as they are under direct management control. Related upstream processes (raw materials or chemicals production, fuels production etc) are referred to as "background processes".

Producer Description

PlasticsEurope Eco-profiles and EPDs represent European industry averages within the scope of PlasticsEurope as the issuing trade federation. Hence they are not attributed to any single producer, but rather to the European plastics industry as represented by PlasticsEurope's membership and the production sites participating in the Eco-profile data collection. The following companies contributed data to this Eco-profile:

- BASF
- DSM
- Lanxess
- Radici

Eco-profile – Life Cycle Inventory

System Boundaries

PlasticsEurope Eco-profiles and EPDs refer to the production of polymers as a cradle-to-gate system (Figure 3).

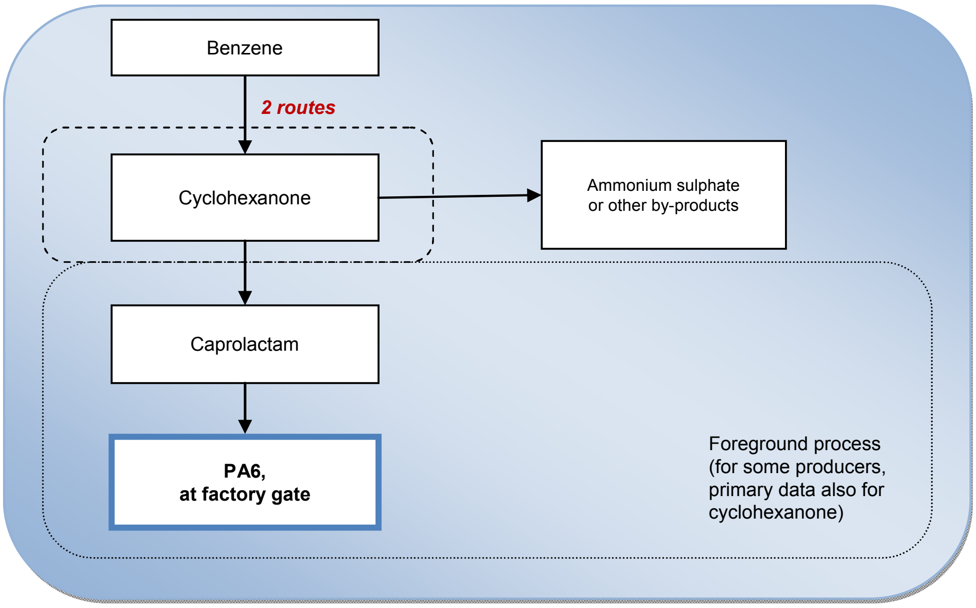

Figure 3: Cradle-to-gate system boundaries

Technological Reference

The production processes were modelled using specific values from primary data collection at site, representing the specific technology for the four companies. The LCI data represent technology in use in the defined production region employed by participating producers. The considered participants cover all producers in Europe, so the technological coverage is understood as representative. Primary data were used for all foreground processes (under operational control) complemented with secondary data from background processes (under indirect management control). In the EU27+2 region relevant here, the total PA6 production volume is between 650kt (Western Europe) and 969kt (Greater Europe, source: PCI Nylon GmbH, respectively); an estimate by Radici of 913kt (EU+EFTA) was assumed as a basis, resulting in a coverage of 57% represented by the participants of this study.

Temporal Reference

The LCI data for production were collected as 12-month averages representing the years 2010–2012, to compensate seasonal influences of data. The overall reference year for this Eco-profile is 2010–2012 with a maximal temporal validity until 2016.

Geographical Reference

Primary production data for PA6 production is from four different suppliers in the EU. Fuel and energy inputs in the system reflect average European conditions and whenever applicable, site-specific conditions were applied, to reflect representative situations. Therefore, the study results are intended to be applicable within EU27+2 boundaries – in order to be applied in other regions, adjustments might be required. Caprolactam imported into Europe was not considered in this Eco-profile.

Cut-off Rules

In the foreground processes all relevant flows were considered, trying to avoid any cut-off of material and energy flows. At least 95 % of mass and energy of the input and output flows were covered and 98 % of their environmental relevance (according to expert judgment) was considered, hence an influence of cut-offs less than 2 % on the total is expected.

Data Quality Requirements

Data Sources

Eco-profile developed by PlasticsEurope use average data representative of the respective foreground production process, both in terms of technology and market share. The primary data are derived from site-specific information for processes under operational control supplied by the participating member companies of PlasticsEurope (see Producer Description).

All relevant background data, such as energy and auxiliary materials, are taken from the *DEAM*, PlasticsEurope and *Ecoinvent 2.2* databases. Most of the background data and the pertinent documentation are publicly available. The dominance analysis (Table 19) showed that the contribution of these background datasets on impact indicators is lower than 10% (except for abiotic depletion, see Table 18).

Relevance

With regard to the goal and scope of this Eco-profile, the collected primary data of foreground processes are of high relevance.

Representativeness

The participanting companies represent about 57% of PA6 production in Europe in 2010–2012. The selected background data can be regarded as representative for the intended purpose.

Consistency

To ensure consistency only primary data of the same level of detail and background data from the *DEAM*, PlasticsEurope and *Ecoinvent* databases were used. While building up the model, cross-checks concerning the plausibility of mass and energy flows were continuously conducted. The methodological framework is consistent throughout the whole model as the same methodological principles are used both in foreground and background system.

Reliability

Data reliability ranges from measured to estimated data. Data of foreground processes provided directly by producers were predominantly measured. Data of relevant background processes were measured or derived from literature; qualified estimates were used for some flows.

Completeness

Primary data used for the gate-to-gate production of PA6 covers all related flows in accordance with the cut-off criteria. In this way all relevant flows were quantified and data is considered complete.

Precision and Accuracy

As the relevant foreground data is primary data or modelled based on primary information, precision is considered sufficient within this goal and scope. Despite the relevance of N_2O emissions – and their variation – for the final GWP results (see Table 20), the European average reported here seems robust.

Reproducibility

All data and information used are either documented in this report or they are available from the processes and process plans designed within the *TEAM®* software. The reproducibility is given for internal use since the owners of the technology provided the data and the models are stored and available in a database. Sub-systems are modelled by ´state of art´ technology using data from a publicly available and internationally used database. It is worth noting that for external audiences, it may be the case that full reproducibility in any degree of detail will not be available for confidentiality reasons. However, experienced experts would easily be able to recalculate and reproduce suitable parts of the system as well as key indicators.

Data Validation

Primary data collected from project partners was validated by the data providers in an iterative process several times, using existing data from published sources and expert knowledge. In particular, the data for N_2O emissions have been assessed to be based on recent measurements and dedicated reports; their plausibility has been checked. The background information from the databases is updated regularly and validated through regular feedback by users worldwide.

Life Cycle Model

The study has been performed with the LCA software *TEAM®*. The associated database complies with ISO 14040/44 requirements. Due to confidentiality reasons details on software modelling and methods used cannot be shown here.

Calculation Rules

Vertical Averaging

When modelling and calculating average Eco-profiles from the collected individual LCI datasets, vertical averages were calculated (Figure 5).

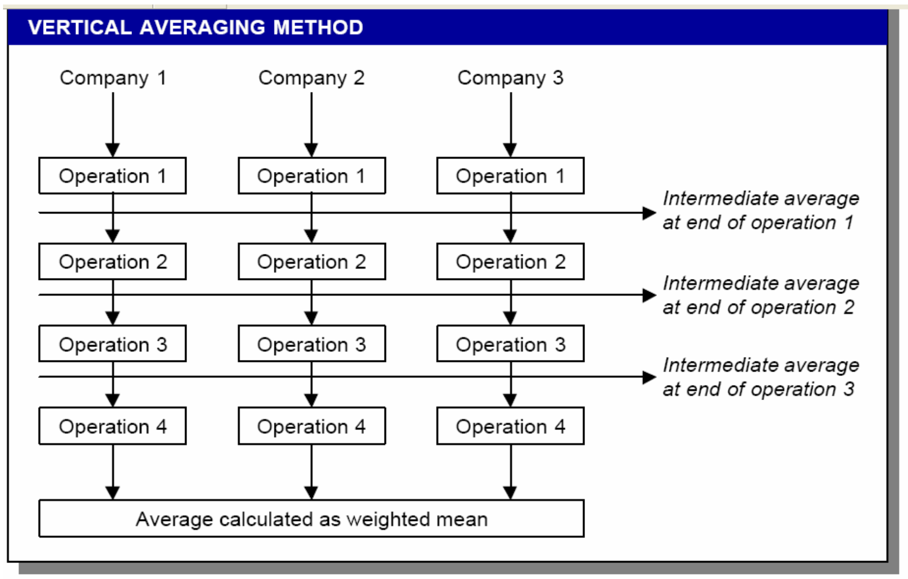

Figure 5: *Vertical Averaging (source: Eco-profile of high volume commodity phthalate esters, ECPI European Council for Plasticisers and Intermediates, 2001)*

Allocation Rules

Production processes in chemical and plastics industry are usually multi-functional systems, i.e. they have not one, but several valuable product and co-product outputs. Wherever possible, allocation should be avoided by expanding the system to include the additional functions related to the co-products. Often, however, avoiding allocation is not feasible in technical reality; as alternative stand-alone processes do not exist in reality or alternative technologies show different technical performance and product quality output. In such cases, the aim of allocation is to find a suitable partitioning parameter so that the inputs and outputs of the system can be assigned to the specific product sub-system under consideration. Within the scope of this Eco-profile, allocation was avoided, using the substitution method for the co-product ammonium sulphate. Due to the system boundary at gate this approach rendered negative values for some flows and impacts (see results).

Due to the relevance of the allocation decision on the results, a sensitivity analysis (Table 1) was conducted:

- The recommended solution, in terms of the best representation of industrial/economic systems, is the use of system expansion and substitution to account for ammonium sulphate (AMS) and, in some cases, sulphuric acid (H_2SO_4) co-production alongside caprolactam. This solution reflects an emerging consensus among industry experts (*WBCSD* working group[2]).

- While allocation should be avoided, where possible, an alternative solutiuon is an economic allocation for AMS (i.e. no credits from substitution).

While it is apparent that the economic allocation renders more conservative results, the project group adhered to the *WBCSD* working group consensus and implemented the substitution (see results below for details). Among the primary reasons for this decision is that economic allocation introduces another uncertain element, i.e. fluctuating market prices. The LCI of substituted AMS was prepared from *ecoinvent* datasets for ammonia and sulphuric acid (based on stoechiometric equations).

[2] Global chemical companies, members of the World Business Council for Sustainable Development (WCSD), formed a working group on life cycle metrics for assessing and reporting in the chemical sector.

Table 1: Sensitivity analysis of substitution vs. allocation

Impact Results	Substitution	Economic Allocation	Unit
Abiotic Depletion Potential (ADP), elements	1.7E-08	4.5E-06	kg Sb eq
Abiotic Depletion Potential (ADP), fossil fuels	115.9	125.5	MJ
Global Warming Potential (GWP)	6.7	7.3	kg CO_2 eq.
Acidification Potential (AP)	12.0	42.5	g SO_2 eq.
Eutrophication Potential (EP), total	4.2	4.5	g PO_4^{3-} eq.
Ozone Depletion Potential (ODP)	1.2E-04	1.2E-04	g CFC-11 eq.
Photochemical Ozone Creation Potential (POCP)	0.6	1.8	g Ethene eq.

Life Cycle Inventory (LCI) Results

Formats of LCI Dataset

The Eco-profile is provided in three electronic formats:

- As input/output table in Excel®
- As XML document in EcoSpold format (www.ecoinvent.org)
- As XML document in ILCD format (http://lct.jrc.ec.europa.eu)

Key results are summarised below.

Energy Demand

As a key indicator on the inventory level, the **primary energy demand** (system input) of 129.1 MJ/kg indicates the cumulative energy requirements at the resource level, accrued along the entire process chain (system boundaries), quantified as gross calorific value (upper heating value, UHV).

As a measure of the share of primary energy incorporated in the product, and hence indicating a recovery potential, the **energy content in the polymer** (system output), quantified as the gross calorific value (UHV), is 35.0 MJ/kg.

Table 2: Primary energy demand (system boundary level) per 1kg PA6

Primary Energy Demand	Value [MJ]
Energy content in polymer (energy recovery potential, quantified as gross calorific value of polymer)	38.5
Process energy (quantified as difference between primary energy demand and energy content of polymer)	90.6
Total primary energy demand	**129.1**

Consequently, the difference (Δ) between primary energy input and energy content in polymer output is a measure of **process energy** which may be either dissipated as waste heat or recovered for use within the system boundaries. Useful energy flows leaving the system boundaries were removed during allocation.

Table 3 shows how the total energy input (primary energy demand) is used as fuel or feedstock. Fuel use means generating process energy, whereas feedstock use means incorporating hydrocarbon resources into the polymer. Note that some feedstock input may still be valorised as energy; furthermore, process energy requirements may also be affected by exothermal or endothermal reactions of intermediate products. Hence, there is a difference between the feedstock energy input and the energy content of the polymer (measurable as its gross calorific value). Considering this uncertainty of the exact division of the process energy as originating from either fuels or feedstocks, as well as the use of average data (secondary data) in the modelling with different country-specific grades of crude oil and natural gas, the feedstock energy has a 20% error margin.

Table 4 shows that nearly all of the primary energy demand is from non-renewable resources. Since the scope of PlasticsEurope and their member companies is the polymer production, Table 5 analyses the types of useful energy inputs in the polymerisation: electricity has a minor contribution, whereas the majority is thermal energy (heat). This represents the share of the energy requirement that is under operational control of the polymer producer. Accordingly, Table 6 shows that the majority (91%) of the primary energy demand is accounted for by precursors. Finally, Table 7 provides a more detailed overview of the key processes along the production system, their contribution to primary energy demand and how this is sourced from the respective energy resources. This puts the predomimant contribution of the production into perspective with the precursor caprolactam. In order to analyse these upstream operations more closely, please refer to the Eco-profiles of the respective precursors. It should be noted, however, that the LCI tables in the annex account for the entire cradle-to-gate primary energy demand of the PA6 system.

Table 3: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1kg PA6

Primary energy resource input	**Total Energy Input [MJ]**	**Total Mass Input [kg]**	**Feedstock Energy Input [MJ]**	**Fuel Energy Input [MJ]**
Coal	5.5	0.20	0.0	5.5
Oil	34.7	0.77	18.4*	16.3
Natural gas	77.2	1.4	20.0*	57.2
Lignite	0.9	0.06	0.0	0.95
Nuclear	10.4	1.9E-05	0.0	10.4
Biomass	0.15	7.9E-03	0.0	0.15
Hydro	0.17	0.0	0.0	0.17
Solar	4.7E-03	0.0	0.0	4.7E-03
Geothermics	9.6E-07	0.0	0.0	9.6E-07
Waves	0.00	0.0	0.0	0.00
Wood	5.9E-03	3.2E-04	5.9E-03	0.0
Wind	2.7E-02	0.0	0.0	2.7E-02
Other renewable fuels	0.0	0.0	0.0	0.0
Sub-total renew-able	**0.36**	**0.01**	**0.01**	**0.35**
Sub-total non-renewable	**128.8**	**2.5**	**38.5**	**90.3**
Total	**129.1**	**2.5**	**38.5**	**90.7**

*) Based on expert judgment.

Table 4: Primary energy demand by renewability per 1kg PA6

Fuel/energy input type	**Value [MJ]**	**%**
Renewable energy resources	0.4	0.2%
Non-renewable energy resources	128.8	99.8%
Total	**129.1**	**100%**

Table 5: Analysis by type of useful energy (PA6 production – foreground process) per 1kg PA6

Type of useful energy in process input	**Value [MJ]**
Electricity	2.8
Heat, thermal energy	5.8
Other types of useful energy	0
Total (for selected key process)	8.6

Table 6: Contribution to primary energy demand (dominance analysis) per 1kg PA6

Contribution to Primary Energy per segment	Value [MJ]	%
Caprolactam	117.4	91%
Key foreground processes (polymerisation, see Figure 3) – of which: natural gas use	11.7 (6.6)	9%
Total	**129.1**	**100%**

Table 7: Contribution of life cycle stages to total primary energy demand (gross calorific values) per 1kg PA6

Total Primary Energy [MJ]	Caprolactam	Other	Utilities	Electricity	Thermal	Transport (for PA6)
Coal	3.7	5.7E-03	0.40	1.27	0.10	0.03
Oil	34.2	0.02	0.14	0.19	0.03	0.12
Natural gas	69.8	0.03	0.27	0.93	6.19	0.02
Lignite	0.63	3.5E-03	0.29	0.00	1.5E-05	0.02
Nuclear	8.89	9.4E-03	0.44	0.71	0.31	0.04
Biomass	0.11	4.5E-03	0.02	1.6E-10	0.01	1.5E-03
Hydro	0.09	7.0E-04	0.08	0.0E+00	0.0	5.4E-03
Solar	0.00	6.6E-06	1.1E-04	0.0E+00	0.0	1.0E-05
Geothermics	7.1E-07	0.0	0.0	0.0	0.0	0.0
Waves	0.0	0.0	0.0	0.0	0.0	0.0
Wood	-0.02	1.0E-03	0.02	3.2E-06	9.3E-07	1.7E-03
Wind	0.02	1.0E-04	7.8E-03	0.0E+00	0.0	6.6E-04
Other renew. fuels	0.0	0.0	0.0	0.0	0.0	0.0
Total	**117.4**	**0.08**	**1.7**	**3.1**	**6.6**	**0.25**

Water Consumption

In the scope of this project, it was not feasible anymore to implement the emerging methodology for water inventory. Therefore, only a differentiation by source is provided (Table 8). Note that this gross water consumption data cannot be used for purposes of water footprinting.

Table 8: Gross water resources table per 1kg PA6

Source	Process water [kg]	Cooling water [kg]	Total [kg]
Public supply	2	0	2
River/canal	3	209	212
Sea	0.8	0	0.8
Unspecified	2	--163*	--161*
Lake	0	0	0
Well	2	5	6
Totals	**10**	**1637**	**1647**
Turbined water (unspecified source, directly released to environment)			**1587**

*) Negative values due to substitution approach (see page 12).

Air Emission Data

Table 9 shows a few selected air emissions which are commonly reported and used as key performance indicators; for a full inventory of air emissions, please refer to the complete LCI table in the annex of this report.

Table 9: Selected air emissions per 1kg PA6

Air emissions	kg
Carbon dioxide, fossil (CO_2, fossil)	4.0
Carbon monoxide (CO)	3.5E-03
Sulphur dioxide (SO_2)	5.3E-03
Nitrogen oxides (NO_x)	1.1E-02
Nitrous Oxide (N_2O)	7.4E-03
Particulate matter ≤ 10 µm (PM 10)	1.2E-03

Wastewater Emissions

Table 10 shows a few selected wastewater emissions which are commonly reported and used as key performance indicators; for a full inventory of wastewater emissions, please refer to the complete LCI table in the annex of this report.

Table 10: Selected water emissions per 1kg PA6

Water emissions	**kg**
Biological oxygen demand after 5 days (BOD 5)	3.1E-04
Chemical oxygen demand (COD)	1.5E-03
Total organic carbon (TOC)	5.4E-03

Solid Waste

Table 11: Solid waste generation per 1kg PA6 (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	7.0E-03	5.5E-04	2.1E-03	4.7E-02	**5.7E-02**
Hazardous	2.0E-02	2.4E-04	8.1E-04	5.3E-03	**2.6E-02**
Unspecified	7.6E-04	1.4E-04	0	6.0E-02	**6.1E-02**
Total	**0.03**	**9.3E-04**	**2.9E-03**	**0.11**	**0.14**

Life Cycle Impact Assessment

The reported impact categories were calculated with the CML method; please refer to the Methodology document (PLASTICSEUROPE 2011) for details.

Input

Natural Resources

The ADP, fossil fuels, is based on the lower heating value. The ADP, elements, is based on ultimate reserve scenario from CML.

Table 12: Abiotic Depletion Potential per 1kg PA6

Natural resources	Value
Abiotic Depletion Potential (ADP), elements [kg Sb eq], ultimate reserves	1.7E-08
Abiotic Depletion Potential (ADP), fossil fuels [MJ], lower heating value	115.9

Output

Climate Change

Table 13: Global Warming Potential (100 years) per 1kg PA6

Climate change	kg CO_2 eq.
Global Warming Potential (GWP)	6.7

Acidification

Table 14: Acidification Potential per 1kg PA6

Acidification of soils and water bodies	g SO_2 eq.
Acidification Potential (AP)	12.0

Eutrophication

Table 15: Eutrophication Potential per 1kg PA6

Eutrophication of soils and water bodies	g PO_4^{3-} eq.
Eutrophication Potential (EP), total	4.2

Ozone Depletion

Table 16: Ozone Depletion Potential per 1kg PA6

	g CFC-11 eq.
Ozone Depletion Potential (ODP)	1.2E-04

Summer Smog

Table 17: Photochemical Ozone Creation Potential per 1kg PA6

	g Ethene eq.
Photochemical Ozone Creation Potential (POCP)	0.6

Dust & Particulate Matter

Table 18: PM10 emissions per 1kg PA6

Particulate matter	g PM10 eq.
Particulate matter ≤ 10 µm, total	1.2
Particulate matter ≤ 10 µm (direct emissions)	1.4E-03
Particulate matter ≤ 10 µm, secondary	1.2

Dominance Analysis

Table 19 shows the main contributions to the results presented above. An average based on the weighted mean from the different technologies of the participating producers is used. In all analysed environmental impact categories, intermediates contribute more than 80% of the total impact (except for ADP, elements). Utilities have a high impact on ADP, elements. Hence the use of high-quality data is critical to the environmental profile of PA6.

Table 19: Dominance analysis of impacts per 1kg PA6

	Total Primary Energy [MJ]	ADP Elements [kg Sb eq.]	ADP Fossil [MJ]	GWP [kg CO_2 eq.]	AP [g SO_2 eq.]	EP [g PO_4^{3-} eq]	POCP [g Ethene eq.]
Caprolactam	91%	50%	91%	92%	86%	90%	84%
Other chemicals	0%	0%	0%	0%	0%	0%	0%
Utilities	1%	48%	1%	1%	4%	8%	3%
Electricity	2%	2%	2%	2%	8%	1%	9%
Thermal Energy	5%	0%	5%	5%	2%	0%	4%
Transport (for PA6)	0%	0%	0%	0%	1%	1%	0%
Total	100%	100%	100%	100%	100%	100%	100%

Comparison of the Present Eco-profile with its Previous Version

Table 20 compares the present results with the previous version of the Eco-profile, showing a significant improvement in the environmental profile of PA6 between the two data collections. Note that for the purposes of this comparison, updated impact assessment models (2013) were applied to the LCI data for 2005 – due to updated characterisation factors, this results in some small differences compared to impact indicators as reported in 2005.

Table 20: Comparison of the present Eco-profile with its previous version (2005/2013)

Environmental Impact Categories	Eco-profile PA6 (2005)	Eco-profile PA6 (2013)	Difference
Gross primary energy from resources [MJ]	121.9	129.1	6%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	6.5E-05	1.7E-08	--99.9%
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	122.4	115.9	–5%
Global Warming Potential (GWP) [kg CO_2 eq.]	9.2	6.7	–29%
Acidification Potential (AP) [g SO_2 eq.]	29.5	12.0	–59%
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	6.0	4.2	–29%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	n/a	1.2E-04	n/a
Photochemical Ozone Creation Pot. (POCP) [g Ethene eq.]	1.4	0.6	–55%

The gross primary energy and – correlated – the ADP, fossil fuels, are approximately stable. The reduction in GWP is, to a greater extent, due to an optimisation of energy efficiency and, to a lesser extent, due to the progress industry has made in greenhouse gas abatement, eliminating nitrous oxide (N_2O, laughing gas) emissions. This is substantiated by the reductions in CO_2 emissions by –26% and N_2O emissions by –14%, quantified in CO_2 equivalents, respectively. While further N_2O emission reductions seem possible, this is impeded by high avoidance costs (due to low concentrations) and current market conditions. It should also be noted that the previous version of the Eco-profile provided a less detailed life cycle inventory (LCI) so that comparisons of some indicators, in particular ODP and POCP, are limited or even impossible. Further, the 2005 study used mass allocation rather than the system expansion implemented here (see Table 1); this likely explains the larger differences observed for AP and EP.

Review

Review Details

The project included regular milestone meetings with representatives of all participating producers and PlasticsEurope as system operator. The reviewer participated in these meetings. In addition, a review meeting between the LCA practitioner and the reviewer was held, including a model and database review, and spot checks of data and calculations.

Specific comments on the results include:

- The nitrous oxide (laughing gas, N_2O) emission abatement in terms of technologies used, their elimination efficiency, and degree of use was subject to review and received due attention. It became apparent that adoption of such technologies is at quite different stages across industry, in some cases being very recent developments, which may partly explain the disparities in reported N_2O levels. Further, the monitoring of N_2O levels varied from continuous to intermittent, adding some uncertainty to reported levels in a few cases. An effort was made to confirm the reported N_2O emission with reports under the ETS scheme.

- The use of system expansion and substitution to account for ammonium sulphate (AMS) and, in some cases, sulphuric acid (H2SO4) co-production alongside caprolactam reflects an emerging consensus among industry experts (*WBCSD* working group), but is still debatable and by no means unanimous. As with all allocation decisions, it remains a subjective decision with pros and cons. Its effects on final results are, in fact, quite substantial, as shown by the sensitivity analysis (Table 1) of this aspect.

- The differentiation of the water inventory by source and destination (allowing for a water balance and supporting water footprints) should be included in future updates.

Compliance with ILCD Entry-level Requirements

Table 21: General review reporting items (reproduced with kind permission of JRC)

REVIEW REPORTING			
General information			
Data set name	**Polycaprolactam (PA6)**		
Data set UUID and version number	n/a		
Data set locator (e.g. Permanent URI, URL, contact point, or database name and version, etc.)	n/a		
Data set owner	PlasticsEurope aisbl		
Review commissioner(s)	PlasticsEurope aisbl		
Reviewer name(s) and affiliation(s), contact	Dr.-Ing. Ivo Mersiowsky, DEKRA Consulting GmbH		
Review type applied	Independent external		
Date of review completion (DD/MM/YYYY)	13/12/2013		
Reviewed against / Compliance system name	ILCD Data Network – Entry-level requirements		
Reviewer assessment:			
Aspect	**Yes**	**No**	**Comments**
Quality compliance (ISO 14040 & 14044) fulfilled (see Table 22)	X		
Method compliance (ISO 14040 & 14044) fulfilled and documented in data set	X		
Nomenclature compliance (see Table 23) fulfilled	X		
Documentation compliance (see Table 23) fulfilled	X		
Review compliance (Independent external review report) fulfilled	X		
Compliant with ISO 14040 & 14044	X		
Overall compliant with compliance system	X		
Date, location, reviewer signature	13 December 2013, Stuttgart, Germany		

Table 22: Specific/detailed review reporting items for LCI data set: quality compliance (ISO 14040 & 14044; reproduced with kind permission of JRC)

ITEMs	Comments
Time-related coverage/representativeness: “age of data and the minimum length of time over which data should be collected” “qualitative assessment of the degree to which the data set reflects the true population of interest”	**Very Good** Foreground: 12 month averages representing the years 2010–2012. Background: 2010—2012 (tbc based on list of secondary datasets). Maximum temporal validity until 2016. (p.9)
Geographical coverage/representativeness: “geographical area from which data for unit processes should be collected to satisfy the goal of the study” “qualitative assessment of the degree to which the data set reflects the true population of interest”	**Very Good** European production average (data from four producers with seven sites in four different European countries; supplemented by average from literature). (p.9)
Technology coverage/representativeness: “specific technology or technology mix” “qualitative assessment of the degree to which the data set reflects the true population of interest”	**Very Good** Technology mix representing European production (see above). 57 % of the European production capacity (EU-27) in 2010–2012. (p.9)
Precision: “measure of the variability of the data values for each data expressed (e.g. variance)”	**n/a** Relevant foreground data is primary data, or modelled based on primary information sources of the owners of the technologies. See Uncertainty below for explanation of “n/a” rating. (p. 10)
Completeness: “percentage of flow that is measured or estimated”; assessed on level of process	**Very good** Primary data used for the gate-to-gate production covered all relevant flows in accordance with the cut-off criteria, i.e. at least 95 % of mass and energy of the input and output flows, and 98 % of their environmental relevance (according to expert judgment) were considered. (p.10)
Consistency: “qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis”	**Very Good** Primary data of the same level of detail and background data from DEAM and other databases were used. While building up the model, cross-checks ensured the plausibility of mass and energy flows. Due to the relevance of background datasets from different databases and the inclusion of literature data, the overall consistency rating is reduced. Allocation was solved as follows: • AMS as co-product of caprolactam: system expansion, credits were awarded for substitution of AMS from alternative production. • Phenol/acetone co-production from cumene: mass allocation. (p.10)
Sources of the data; Appropriateness of use primary/secondary data source	The main data source was a primary data collection from European producers, providing site-specific gate-to-gate production data for processes under operational control of the participating companies. Data for the upstream supply chain until the precursors are taken from several databases (DEAM, PlasticsEurope, GaBi, ecoinvent). (p.10)

ITEMs	Comments
Uncertainty of the information (e.g. data, models and assumptions).	Variation of single data was not recorded. Variation of the model/dataset not applicable due to vertical average of production lines and technologies. Hence, Precision above was rated "n/a". Critical elements within the model include: • level of N_2O emissions (based on effectiveness and use of abatement technologies as well as completeness of monitoring) • allocations for phenol/acetone and capro/AMS (p.10—11)

Table 23: Specific/detailed review reporting items for LCI data set: nomenclature and documentation (reproduced with kind permission of JRC)

ITEMs	Comments
Nomenclature	
Correctness and consistency of applied nomenclature	Yes
Documentation	
Appropriateness of documentation extent (see document "Documentation of LCA data sets")	Yes
Appropriateness of documentation form (ILCD Format)	Yes

Review Summary

This Eco-profile is considered a representative, reliable and high-quality quality representation of PA6 production in Europe. The allocation decision affects energy and GWP indicators with approximately 10%. The critical review confirms that this Eco-profile adheres to the rules set forth in the PlasticsEurope's Eco-profiles and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors (PCR version 2.0, April 2011).

Reviewer Name and Institution

Dr.-Ing. Ivo Mersiowsky, Business Line Manager Sustainability Leadership, DEKRA Consulting GmbH, Stuttgart, Germany

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PlasticsEurope AISBL

Avenue E. van Nieuwenhuyse 4/3
B-1160 Brussels · Belgium

Phone +32 (0)2 675 3297
Fax +32 (0)2 675 3935

info@plasticseurope.org
www.plasticseurope.org