Eco-profile of

Polyamide 6

September 2022

Important warning

This eco-profile is only representative of participating companies: Basf, Fibrant, Lanxess, Radici.

For PA6 from other sources it is recommended to use values specific of supply chain and check that the methodology used for their calculation is the same.

TABLE OF CONTENTS

1 SUMMARY

This Eco-profile has been prepared according to **Eco-profiles program and methodology –PlasticsEurope – V3.0 (2019)**.

It provides environmental performance data representative for a section of the European production of polyamide 6 (PA6), covering the main production routes of ε- caprolactam being the main monomer and its polymerization to the final product within the scope of this study - from cradle to gate (from crude oil extraction to the polymer granulate at plant).

Please keep in mind that comparisons cannot be made on the level of the polymer granulate 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. It 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.

1.1 META DATA

Data Owner	PlasticsEurope
LCA Practitioner	Sphera Solutions GmbH
Programme Owner	PlasticsEurope
Reviewer	Angela Schindler
Number of plants included in data collection	3 for polymer production and 3 for the monomer production
Representativeness	Primary data used for system modelling cover about 21% of the EU polyamide 6 installed production capacity
Reference year	2019/2020
Year of data collection and calculation	2022
Expected temporal validity	Revision should be considered in 2027
Cut-offs	No significant cut-offs
Data Quality	Good to very good
Allocation method	Combined elemental + mass allocation (in ε- caprolactam production)

1.2 DESCRIPTION OF THE PRODUCT AND THE PRODUCTION PROCESS

Polyamides are a group of polymers characterised by the functional group of secondary amides [–(C=O)–NH–] interspersed at regular intervals along it. They are commonly referred to by the brand 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 Eco-profile is for Polyamide 6 (PA6), a polymer formed by ring-opening polymerization of caprolactam, a cyclic monomer.

Caprolactam has an amide bond which is opened during polymerisation, after which new amide bonds are formed at each end of the monomer. This leads to a backbone polymer.

Caprolactam is produced from cyclohexanone, which reacts with hydroxylamine to form an oxime which undergoes a Beckmann rearrangement with an acid to form the bisulfate salt of caprolactam. The latter is neutralised with an alkali compound to form caprolactam.

A co-product of caprolactam production is ammonium sulfate.

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 subsequently 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 study refer to, is 1 kg of PA6 in pellet form.

1.3 DATA SOURCES AND ALLOCATION

Although this Eco-profile deals primarily with the polymerisation step of PA6, input/output data has been also collected for the production of its monomer caprolactam, due to high relevance to overall results.

The main data source was a data collection from a set of European producers of caprolactam and PA6. Primary data on gate-to-gate system boundaries is derived from site-specific information for processes under operational control supplied by the participating companies of this study.

For the data collection of caprolactam, three different caprolactam producers contributed by providing data for one plant each. These plants are located in two European countries. The involved companies run in total four European sites for caprolactam production.

For the data collection of the polymerisation step to PA6, three different producers contributed by providing data for one plant each. These plants are located in two European countries. The involved companies run in total five European sites for PA6 production.

The data for the upstream supply chain until the main precursors (such as Cyclohexane/Phenol, Ammonia, Sulfur) as well as all relevant background data such as energy and auxiliary material are taken from the GaBi 2022 LCI database [SPHERA 2022]. Most of the background data used is publicly available and public documentation exists.

A combined elemental and mass based approach has been chosen for the allocation of the environmental burden in the production of caprolactam, which delivers solid ammonium sulfate (AS) as co-product, being globally used as fertilizing ingredient. The choice of this allocation procedure is explained in detail in chapter 2.11

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 fibres, films and engineering plastics. Applications range from automotive and electrical to food packaging. PA6 can be recycled mechanically (via shredding and re-melting) and chemically (via depolymerization back to its monomer).

PA6 End of Life treatment options depend on its concrete end application and the related material specific characteristics.

1.4 ENVIRONMENTAL PERFORMANCE

The tables below show the environmental performance indicators associated with the production of 1 kg of PA6 (system boundary: cradle-to-gate)

1.4.1 Input Parameters

Indicator	Unit	Value	Impact method ref.
Non-renewable energy resources[1)]			
• Fuel energy	MJ	57.84	-
• Feedstock energy	MJ	34.20	Gross calorific value
Renewable energy resources (biomass)[1)]			
• Fuel energy	MJ	3.85	-
• Feedstock energy	MJ	0.00	Gross calorific value-
Resource use			
• Minerals and Metals	kg Sb eq	3.16E-07	EF 3.0
• Energy Carriers	MJ	84.55	EF 3.0
Renewable materials (biomass)	kg	not relevant	-
Water scarcity	m^3 world eq	1.68E-01	EF 3.0
[1)] Calculated as upper heating value (UHV)			

1.4.2 Output Parameters

Indicator	Unit	Value	Impact method ref.
Climate change, total	kg CO_2 eq.	4.52	EF 3.0
Ozone depletion	kg CFC-11 eq.	7.17E-12	EF 3.0
Acidification	Mole of H+ eq	3.63E-03	EF 3.0
Photochemical ozone formation	kg NMVOC eq	4.42E-03	EF 3.0
Eutrophication, freshwater	kg P eq	3.95E-06	EF 3.0
Respiratory Inorganics	Disease incidences	2.63E-08	EF 3.0
Waste			
• Non-hazardous*	kg	0.0219	*Deposited waste
• Hazardous	kg	1.06E-03	

Please see chapter 3 for all other EF3.0 impact indicator results.

1.5 Programme Owner

PlasticsEurope

Rue Belliard 40

B-1040 Brussels, Belgium

E-mail: info@plasticseurope.org

For copies of this EPD, for the underlying LCI data (Eco-profile); and for additional information, please refer to https://plasticseurope.org/sustainability/circularity/life-cycle-thinking/eco-profiles-set/

1.6 Data Owner

PlasticsEurope

Rue Belliard 40

B-1040 Brussels, Belgium

E-mail: info@plasticseurope.org

1.7 LCA Practitioner

Sphera Solutions GmbH

Hauptstraße 111-113

70771 Leinfelden-Echterdingen, Germany

Phone: +49 711 3418170

1.8 Reviewer

Angela Schindler

Tüfinger Str. 12

88682 Salem, Germany

E-mail: angela@schindler-umwelt.de

2 Eco-profile Report

2.1 Functional Unit and Declared Unit

1 kg of unpacked primary PA6 "at gate" in pellet form, representative for about 21% of the European industry production capacity

2.2 Product Description

Polycaprolactam (PA6) is a thermoplastic polymer.

- IUPAC name: Polycaprolactam
- CAS no. 25038-54-4
- Chemical formula: $–[C_6H_{11}NO]–_n$
- Density: 1.14 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.

2.3 Manufacturing Description

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

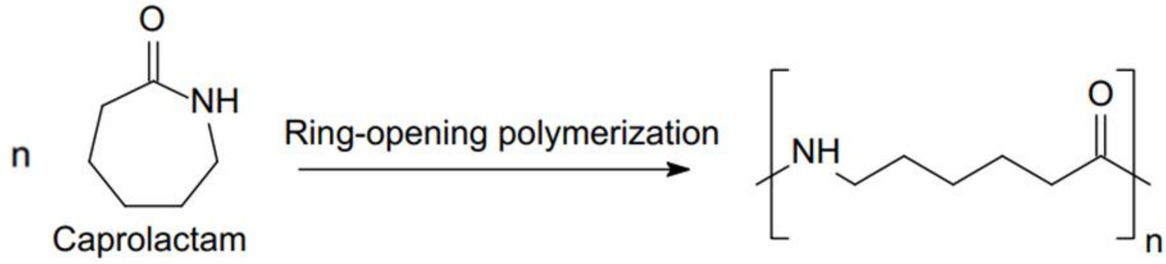


Figure 1 : Synthesis of PA6 through ring-opening polymerisation of caprolactam

Caprolactam is synthesised from cyclohexanone though the following process (simplified depiction):

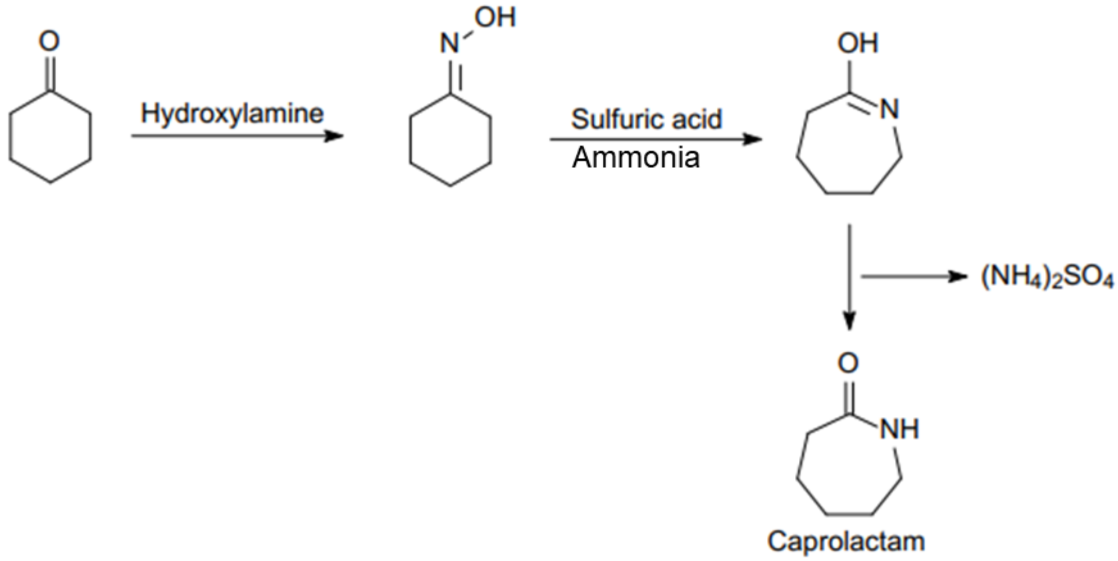


Figure 2 : Overview of Caprolactam synthesis

Ammonium sulfate is a major co-product of caprolactam production. Ammonium sulfate has an economic importance as fertiliser. Process data show that the production of ammonium sulfate ranges between 2 and 5 kg per kg of caprolactam. In addition, some 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 and has been developed further in the previous years.

In Europe, cyclohexanone is 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 is produced through the hydrogenation of phenol, which in turn is derived from benzene. Both routes presented above are covered within this Eco-profile and their representation is determined by the weighting of the participating caprolactam producers.

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 (please also see *Figure 3*)

2.4 PRODUCER DESCRIPTION

The following companies have provided primary data for the production of the ε – caprolactam monomer:

- BASF SE
- Fibrant BV
- Lanxess Performance Materials GmbH

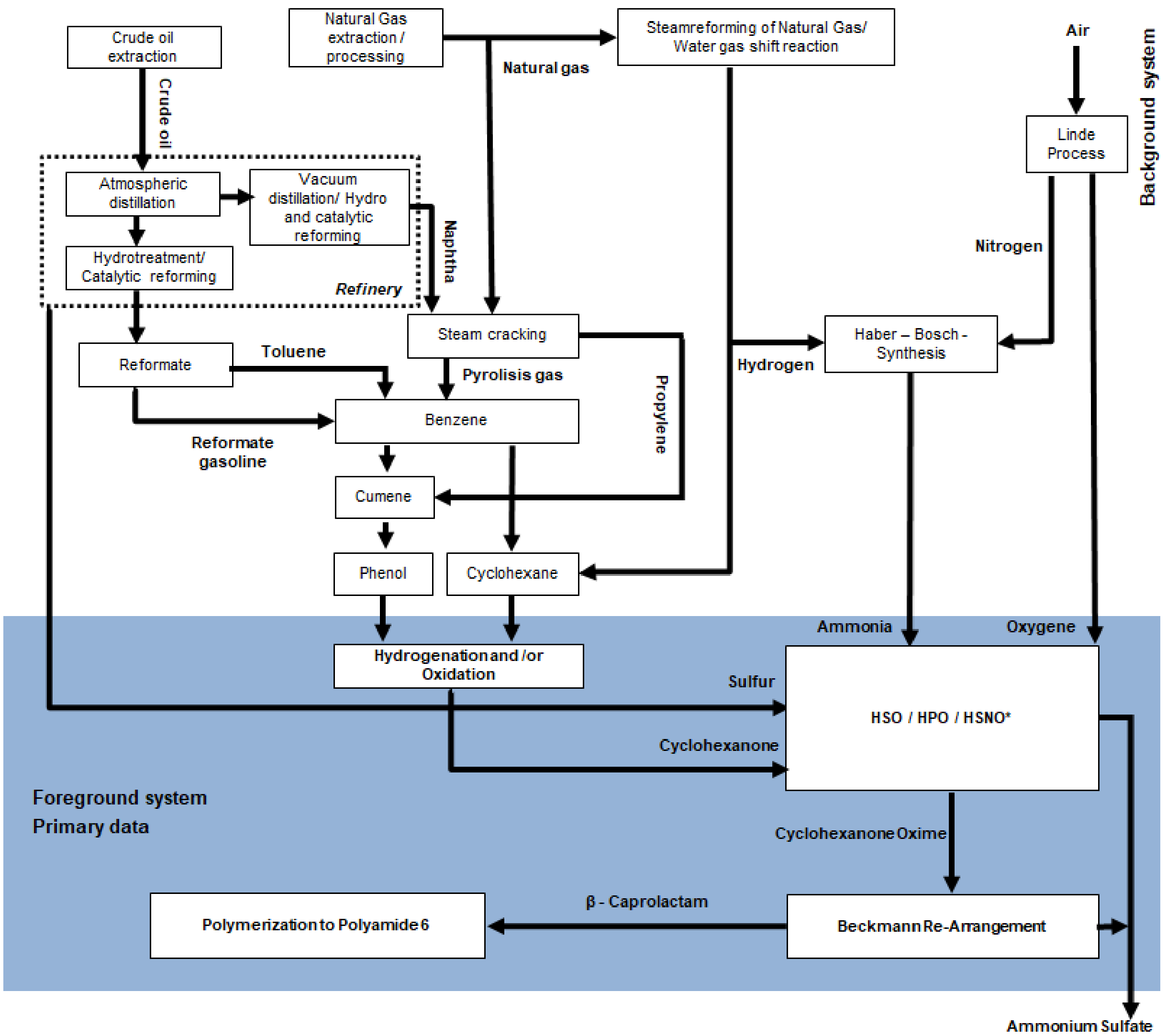
The following companies provided primary data for the relevant, most contributing input/output flows of the polymerization of caprolactam into PA6

- BASF SE
- Lanxess Performance Materials GmbH
- Radici Group S.p.A.

The total production capacities of these companies represent ~60% of the caprolactam production capacity (equals 4 sites) and ~40% of the PA6 production capacity (equals 5 sites) in Europe.

2.5 SYSTEM BOUNDARIES

PlasticsEurope Eco-profiles and EPDs refer to the production of polymers as a cradle-to-gate system:



*HSO = Raschig process / HPO =Hydroxylamine phosphate oxime process / HSNO = NO hydrogenation in sulfuric acid process

Figure 3: Cradle-to-gate system boundaries (PA 6 via caprolactam)

As *Figure 3* already indicates, benzene is one of the major indirect upstream precursors of caprolactam/PA6. It can be produced by several technologies with significantly different environmental burdens.

The GaBi dataset used for benzene in the upstream background is composed of an average mix (for the reference year 2019) of all routes and based on the most current information given by [PETROCHEM 2019]:

- Reformate based: 40%
- Pyrolysis Gas based: 50%
- Toluene based: 10%

The GaBi datasets used for the modelling of ethylene and propylene are both based on steam cracker models being by far the most used technology to produce these raw materials.

2.6 TECHNOLOGICAL REFERENCE

The production processes were modelled using specific values from primary data collection at site, representing the specific technology for the three companies producing monomer and polymer. The LCI data represent technology in use in the defined production region employed by participating producers. The considered production covers about 21% of the European capacities of PA6 in 2019. [HDIN 2019]

Primary data were used for all foreground processes (under operational control) complemented with secondary data from background processes (under indirect management control).

These secondary data are mainly based on a mix of data related from market studies, complemented by necessary calculations and estimations based on expert knowledge.

In general, all GaBi background datasets are reviewed internally before adding them to the GaBi dataset pool und undergo annual updates, which not only includes refreshment of background energy mixes, but also import mixes of raw materials and process technology and efficiencies once these become known.

2.7 TEMPORAL REFERENCE

The LCI data for production was collected as 12-month averages representing the year 2019 or 2020, to compensate for seasonal influence of data.

Both, foreground and background datasets used from the GaBi database refer to the year 2021 (in case of raw materials) and 2018 (in case of energy datasets).

The dataset is considered to be valid until substantial technological changes in the production chain occur. The overall reference year for this Eco-profile is 2019/2020 with a recommended temporal validity until 2027 to which the relevance of the revision should be considered.

2.8 GEOGRAPHICAL REFERENCE

Raw materials, 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 EU boundaries and in order to be applied in other regions adjustments might be required. PA6 and caprolactam imported into Europe was not considered in this Eco-profile.

2.9 CUT-OFF RULES

No foreground data has been cut off.

According to the GaBi 2021 LCI database [SPHERA 2021], used for the background processes, 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 1% on the total is expected. Transportation has not been considered relevant. Including production, the contribution of all transports is expected to be less than 1%.

2.10 DATA QUALITY REQUIREMENTS

Data Sources

Eco-profiles developed by PlasticsEurope use primary data representative of the respective foreground production process, both in terms of technology and the reported market share.

The primary data are derived from site specific information for processes under operational control supplied by the participating member companies (see 2.4)

All relevant background data such as precursor materials, energy and auxiliary materials are taken from the GaBi 2022 LCI database [SPHERA 2022]. Most of the background data used is publicly available and public documentation of the data sources exists.

These secondary data are mainly based on a mix of data related from market studies, industry information, publicly available statistics and complemented by necessary calculations and estimations based on expert knowledge.

In general, all GaBi background datasets are reviewed internally before adding them to the GaBi dataset pool und undergo annual updates, which not only includes refreshment of background energy mixes but also import mixes of raw materials and process technology and efficiencies once these become known.

Relevance and Representativeness

Regarding the goal and scope of this Eco-profile, the collected primary data of foreground processes (for both polymer and monomer) are of high relevance, i.e., data was sourced from key PA6 and caprolactam producers in Europe in order to generate an average over the participating companies and sites.

Therefore, the selected foreground and background data can be regarded as representative for the intended purpose and the stated share of industry/ contributing companies considered. The environmental contributions of each process to the overall LCI results are included in the Chapter 'Dominance Analysis'.

Nonetheless it should be also mentioned that the representativeness in terms of percentage of the total European PA6 production capacity is relatively low (21%) and that the variability of especially the caprolactam production (being the biggest contributor to the PA6 environmental footprint) process is high.

Therefore, the representativeness of the reported LCA results– and GWP especially (due to potential N_2O emissions) – with regards to the total European production (capacity) is considered moderate to low.

Consistency

To ensure consistency only foreground data of the same level of detail and background data from the GaBi 2022 LCI database [SPHERA 2022] 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 (such as monomer production) processes were measured at several sites or determined by literature data or estimated for some flows, which usually have been reviewed and checked for its quality.

Completeness

Foreground and background data used for the gate-to-gate production of PA6 and its monomer caprolactam cover all relevant 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 sources of the owner of the technology, better precision is not reachable within this goal and scope. All background data is consistently GaBi professional data with related public documentation.

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 GaBi 10 software. The reproducibility is given for internal use since 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 in a certain confidence range.

Data Validation

The data on production collected from the project partners and the data providing companies was validated in an iterative process. The collected data was validated using existing data from published sources or expert knowledge. The data itself has been checked with regards to mass, water and elemental balance performing stoichiometric checks. The background information from the GaBi 2021 LCI database [SPHERA 2021] is updated and validated regularly.
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Life Cycle Model

The study has been performed with the LCA software GaBi 10. The associated database integrates ISO 14040/44 requirements. Due to confidentiality reasons details on software modelling and methods used cannot be shown here. However, in principle the model can be reviewed in detail if the data owners agree; an independent external review has been conducted to this aim. The calculation follows the vertical calculation methodology as far as possible, i.e. that the averaging is done after modelling the specific processes (see below).

A final data quality rating based on the criteria and calculation rules described in the guide to develop EF (environmental footprint) compliant datasets [JRC 2020] led to the following weighted average result:

Table 1: Data quality rating (DQR) of PA6 Eco-profile dataset

Tech	Time	Geo	Precision	DQR of created dataset
1.89	1.00	1.81	1.00	1.42

2.11 CALCULATION RULES

Vertical Averaging

According to the Plastics Europe methodology [PlasticsEurope 2019], vertical averaging (see Figure 4) should be applied wherever possible. As far as known and available, route specific precursor datasets matching the real supply chain conditions have been used for modelling accordingly.

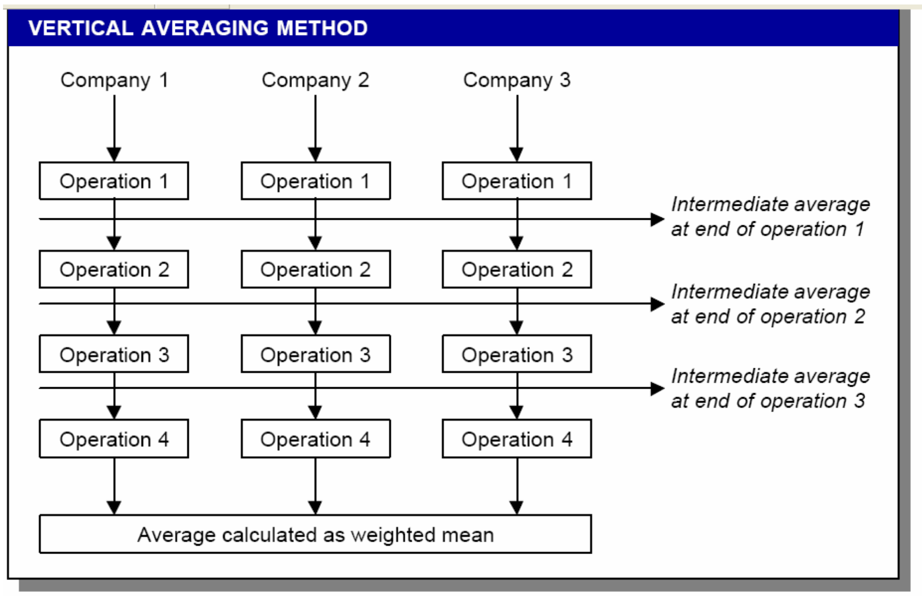

Figure 4: Vertical Averaging

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, or alternative technologies show completely 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.

For most of the commonly used technologies (and in each of the sites considered in this Eco-profile) of producing caprolactam the fertilizer material ammonium sulfate (AS) is co-produced.

For the considered caprolactam production technology applied by the participants of this Eco-profile, ammonium sulfate (AS) is gained as co-product. When deciding on the most suitable way of allocation the following aspects should be kept in mind:

• Although the primary purpose of the plants is to produce caprolactam as the monomer of PA6, these processes have been specifically designed not only to produce the main product in the required quality, but also to produce AS in a quality that can be marketed, i.e., AS is a desired co-product. Therefore, the quality of the AS is a critical aspect and influences the process design.

- Despite the fact that both products are sold as valuable substances, prices do not reach the same level for both cases, with higher absolute values for caprolactam (assumed price ratio about 14:1).

- The ratio in terms of product volume between main product and co-product depends on the process technology and operational control and can range from 1,5 to 5 kg of AS in relation to 1 kg of caprolactam.

- Furthermore, market values are volatile and differs with respect to regions and market demand, amplified by the fact that the materials are applied in different sectors.

As a consequence of this, in a first step a physical allocation has been considered - however, a pure mass allocation of all consumed materials would distribute the related burden equally (and lead to an equal result per 1 kg of both products). This approach would neither reflect the initial intention of the caprolactam production system, nor consider the different value of the products.

Hence an allocation approach has been designed for the base case, which directly relates the upstream inputs to the products based on their chemical composition and structure.

Furthermore, it also reflects and considers intermediate process steps within the complex production chain for caprolactam/AS system, as shown in *Figure 3*. This approach includes the allocation of resource consumptions and emissions in various production steps per intermediate: e.g. resources for cyclohexanone via KA oil, hydroxylamine, SO_3, etc emissions of N_2O caused by undesired side reactions in the hydroxylamine production can be related to caprolactam molecule only, as well as energy generated by exothermic reaction parts.

The following overview shows the rationale and specific application of the allocation approach applied:

Table 2 : Allocation of material inputs and outputs to co-product system caprolactam/AS applying within the elemental allocation approach

Burden (resources and emissions for the production of…)	Purpose/fate	Allocation to Caprolactam	Allocation to AS
Phenol /Cyclohexane	Carbon ending up in Caprolactam (and potential other related co-products from cyclohexanone production)	up to 100% *	0%
Hydrogen	Necessary for the production of cyclohexanone and hydroxylamine	100%	0%
N containing inputs (Ammonia)	Nitrogen ends up in hydroxylamine (and potential other related co-products) as well as in AS	Depending on N content in co-products (1 kg Caprolactam contains 0.12 kg N, 1 kg AS contains 0.21 kg N)	
Emissions (N_2O + CO_2) of Hydroxylamine production	Originating from Hydroxylamine (pre-cursor) production	100%	0%
S containing inputs and emissions	Ending up in AS molecule only	0%	100%

* Carbon from phenol / cyclohexane ending up in cyclohexanone is 100% allocated to Caprolactam, carbon from phenol / cyclohexane ending up in potential co-products of cyclohexanone production is allocated according their C content

All further materials, as well as energy, electricity and further auxiliary inputs which cannot be assigned product-specifically are allocated by mass to both co-products.

For that reason, the developed approach can be called a combined “elemental+mass” allocation approach.

The following table shows the sensitivity of the allocation decision with regards to the overall PA6 environmental footprint (here expressed by the GWP):

Table 3: Carbon footprint results (EF 3.0) for alternative allocation procedures per 1kg of average polyamide 6

Environmental Impact Category	Elemental + Mass allocation (base case)	Economic allocation	Mass allocation
Global Warming Potential (GWP) [kg CO_2 eq]	4.52	6.05	1.68

The analysis shows that when applying economic allocation and using the price ratio mentioned above, the PA6 result would increase in a relevant magnitude (33%). Different market demands could change that picture completely though into both directions.

Compared with the mass allocation approach both alternative allocation approaches show significant (>50%) higher results. However, as discussed above, mass allocation is not considered a suitable allocation approach for the product system under study.

In the refinery operations (production chain until cyclohexane, phenol, ammonia, sulfur, see *Figure 3*), co-production was addressed by applying allocation based on mass and net calorific value [SPHERA 2022]. The chosen allocation in refinery is based on several sensitivity analyses, which was accompanied by petrochemical experts. The relevance and influence of possible other allocation keys in this context is small. In steam cracking, allocation according to net calorific value is applied. Relevance of other allocation rules (mass) is below 2 %.

2.12 LIFE CYCLE INVENTORY (LCI) RESULTS

Delivery and Formats of LCI Dataset

This eco-profile comprises

- A dataset in ILCD/EF 3.0 format (.xml) (http://lct.jrc.ec.europa.eu) according to the last version at the date of publication of the eco-profile and including the reviewer (internal and external) input.
- A dataset in GaBi format (.GaBiDB)
- This report in pdf format.

Energy Demand

The **primary energy demand** (system input) of 95.89 MJ/kg PA6 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).

The **energy content in PA6** indicates a measure of the share of primary energy incorporated in the product, and hence a recovery potential (system output), quantified as the gross calorific value (UHV), is 34.2 MJ/kg PA6.

The difference (Δ) between primary energy input and energy content in the polyamide 6 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 (production wastes used as fuels) leaving the system boundaries were treated with system expansion (credits associated to main product system).

Table 4 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 monomer)	34.20
Process energy (quantified as difference between primary energy demand and energy content of monomer)	61.69
Total primary energy demand	**95.89**

Water cradle to gate Use and Consumption

The cradle-to-gate water **use** is 1569 kg per 1 kg of PA6. The corresponding water **consumption** in the same system boundary is 10.6 kg.

Water foreground (gate to gate) Use and Consumption

The following table shows the average values for water use of the considered PA6 production process (gate-to-gate level). For each of the typical water applications the water sources are shown:

Table 5 Water use and source per 1kg of PA6

Source	Process water [kg]	Cooling water [kg]	Steam Water [kg]	Water in Raw Materials [kg]	Total [kg]
From Tap	0.12	0.00	0.00	0.00	0.12
Deionized / Softened	0.26	0.32	0.58	0.00	1.17
Untreated (from river/lake)	0.00	27.17	0.00	0.00	27.17
Untreated (from sea)	0.00	20.67	0.00	0.00	20.67
Relooped	0.00	0.00	0.27	0.00	0.27
Totals	**0.38**	**48.17**	**0.85**	**0.00**	**49.40**

The following table shows the further handling/processing of the water output of the average production process of PA6:

Table 6 Treatment of Water Output per 1kg of PA6

Treatment	Water Output [kg]
To WWTP	0.24
Untreated (to river/lake)	27.17
Untreated (to sea)	20.67
Relooped	0.44
Water leaving with products	0.00
Water Vapour	0.88
Formed in reaction (to WWTP)	0.00
Totals	**49.40**

Based on the water use and output figures above the **water consumption** can be calculated as:

Consumption = (water vapour + water lost to the sea) – (water generated by using water containing raw materials + water generated by the reaction + seawater used)

= **0.88 kg**

Dominance Analysis

Table 5 shows a clear dominance of the main raw material and monomer caprolactam to the production of PA6.

It reaches a minimum contribution of 76% in all considered impact categories while other used material inputs not even cross the 1% line of contribution.

Some contribution can be assigned to thermal energy and electricity used. The latter showing relevant contribution with regards to ozone depletion.

Table 7 Dominance analysis of impacts per 1kg PA6

	Total Primary Energy	Resource use, energy carriers	Resource use, minerals and metals	Climate change, total	Acidi-fication	Eutro-phication, freshwater	Photo-chemical ozone formation	Ozone depletion
Caprolactam	94%	95%	91%	94%	95%	85%	95%	76%
Production Process	0%	0%	0%	0%	0%	0%	0%	0%
Other Chemicals	0%	0%	0%	0%	0%	0%	0%	0%
Thermal Energy	3%	3%	1%	4%	2%	1%	3%	0%
Electricity	3%	2%	7%	2%	3%	8%	2%	21%
Utilities	0%	0%	1%	0%	0%	2%	0%	2%
Process Waste Treatment	0%	0%	0%	0%	0%	4%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Comparison of the present Eco-profile with its previous version

Table 8 Comparison of the present Eco-profile with its previous version for 1 kg of PA6 (Economic allocation)

Environmental Impact Categories (CML 2013)	Previous (2014)	New (2022)	Difference (%)
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	4.50E-06	1.32E-06	-70.67%
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	125.5	119	-5.18%
Global Warming Potential (GWP) [kg CO_2 eq.]	7.3	5.92	-18.90%
Acidification Potential (AP) [g SO_2 eq.]	42.5	4.86	-88.56%
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	4.5	1.66	-63.11%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	1.20E-04	1.74E-08	-99.99%
Photochemical Ozone Creation Potential [g Ethene eq.]	1.8	0.83	-53.89%

Please note: The results as presented in table above have been calculated with CML 2013 impact methodology and are therefore not to be compared with any other result table in this report.

Furthermore, in order to allow comparability of this study with the previous report the results of the 2014-study based on economic allocation are selected. (The base case for the previous Eco-profile included system expansion, the report nonetheless provided the results applying economic allocation as a scenario, which are used in the table above)

When interpreting the results, it should be also kept in mind that the previous results have been calculated using the Ecoinvent v2.2 database and are based on an unknown (probably different) price ratio for caprolactam and AS, which adds further uncertainty into the conclusions of a direct result comparison.

Nonetheless it can be stated, that for every impact category considered lower impacts are calculated, while the contribution of foreground and background data to this improvement is unknown.

The global warming potential result for example has improved by almost 19%, which can be partly related to continued industry efforts in abatement of laughing gas emissions on the one hand and further heat integration measurements on the other.

The general “greening” of European electricity grid mixes over the past years has contributed to the overall advancement as well.

3 EF 3.0 INDICATOR RESULTS

The following table shows the LCA results for 1 kg of considered PA6 when applying the EF3.0 impact assessment methodology.

Please note: when importing the delivered LCI dataset in ILCD/EF3.0 (.xml) format only these results can be recovered in the LCA software tool!

Table 9 : LCA results for 1 kg of average PA6 applying EF3.0 impact assessment methodology

Indicator	**Unit**	PA6
Climate change, total	kg CO_2 eq.	4.52
Climate Change, biogenic	kg CO_2 eq.	9.43E-03
Climate Change, fossil	kg CO_2 eq.	4.51
Climate Change, land use and land use change	kg CO_2 eq.	1.84E-04
Ozone depletion	kg CFC-11 eq.	7.17E-12
Acidification	Mole of H+ eq	3.63E-03
Photochemical ozone formation	kg NMVOC eq	4.42E-03
Eutrophication, freshwater	kg P eq	3.95E-06
Eutrophication, marine	kg N eq.	1.15E-03
Eutrophication, terrestrial	Mole of N eq.	1.22E-02
Respiratory Inorganics	Disease incidences	2.63E-08
Ionising radiation, human health	kBq U235 eq.	0.12
Human toxicity, cancer – total	CTUh	8.24E-10
Human toxicity, cancer inorganics	CTUh	1.46E-19
Human toxicity, cancer metals	CTUh	5.99E-10
Human toxicity, cancer organics	CTUh	2.25E-10
Human toxicity, noncancer – total	CTUh	3.30E-08
Human toxicity, noncancer inorganics	CTUh	6.42E-09
Human toxicity, noncancer metals	CTUh	2.64E-08
Human toxicity, noncancer organics	CTUh	5.35E-10
Ecotoxicity, freshwater – total	CTUe	3.10E+01
Ecotoxicity, freshwater inorganics	CTUe	2.87E+01
Ecotoxicity, freshwater metals	CTUe	2.10E+00
Ecotoxicity, freshwater organics	CTUe	2.67E-01
Land Use	Pt	2.96E+00
Resource use, energy carriers	MJ	84.55

Resource use, minerals and metals	kg Sb eq.	3.16E-07
Water scarcity	m^3 world equiv.	1.68E-01

4 REVIEW

4.1 EXTERNAL INDEPENDENT REVIEW SUMMARY

External independent review summary

The present Eco-Profile is an update of an Eco-profile published in 2014 for the polymer Polyamide 6. The collection of primary data, the applied background data, the allocation procedure as well as the assessment indicators have changed and follow the developments in LCA methodology of the last years.

The study started in 2021 and was finally reviewed in August/September 2022. The reviewer has been involved in the process of developing a suitable allocation approach and thus accompanied the project process.

The compliance of the documents was reviewed according to the current requirements of the Eco-profiles program and methodology, version 3.0 (Oct 2019) of PlasticsEurope and the accompanying template for Eco-profile reports. The study is assessed according to the European Comission's PEF Guide by EF 3.0 defined impact categories. Further detailed methodological aspects of the PEF Guide are not fully taken on.

The primary data collection covers a wide range of the supply chain; at the same time, the participating companies/sites represent only 21% of the production volume in Europe. The delivered data show high precision and detailed information in respect to specific process steps, cover the current variety of technological differences at the considered sites and thus can be assumed to display an industry average.

Beside the documents submitted to the reviewer, the LCA practitioner (Sphera) showed confidential information on primary data, the supporting software model and explained details of the implementation of the applied allocation approach in a webmeeting.

The production for PA 6 is embedded in a complex structure for producing a relative high number of various products and co-products. For assessing the single product PA 6 a methodological approach for the assignments of environmental burdens is required.
In the first phase of the project the members discussed various possibilities on system expansion and allocation criteria. Under consideration of aspects like process intention and product/co-product value a fair and generally acceptable approach has been developed, explained thoroughly in the Eco-profile document. The reviewer was invited and also took part in these discussions leading to the combined elemental and mass allocation criteria. The indicator GWP is also displayed for the calculation, when applying an economic allocation instead; in the review process also further relevant indicators were checked, justifying the selected allocation approach.

Due to the change of assessment indicators, the Eco-profile is supplemented also by an evaluation applying the impact categories of the preliminary Eco-profile. This principally allows a relative comparison of the results. Both background data and foreground data are updated and previous confidential foreground data are not available to the LCA-practitioner. This enables only a limited statement of the actual improvement in respect to sustainable development.

The software model applied has undergone a Sphera internal quality check to avoid mistakes of data transfer. The plausibility checks were also topic of the review process. The detailed process information delivered by the participating companies allowed the very specific allocation approach, which even made it possible to allocate energy flows generated via different production residues by internal incineration.

Overall, the project is carried out very thoroughly. During the review process following aspects have been discussed and adapted:

- Editorial corrections and adaptations for unambiguous und clear understanding in texts, figures and tables
- Clarification of the number of participating sites delivering data
- Declaration of waste according to definition in EN 15804

For future optimisation of the data, the reviewer strongly recommends, that further companies producing caprolactam and/or PA 6 are convinced to participate by delivering data for ideally all production sites in order to increase the representativity of this publication.

The structure and description of the Eco-profile is clear and transparent, thus displaying a reliable source of information.

Despite all necessary due diligence performed during the critical review process by the reviewer, the commissioner of the LCA study remains liable for the underlying information and data.

Salem, September 2022

Angela Schindler

Angela Schindler, Umweltberatung
Salem, Germany
angela@schindler-umwelt.de

Angela Schindler
Umweltberatung

4.2 Reviewer Contact Details

Angela Schindler

Tüfinger Str. 12

88682 Salem, Germany

E-mail: angela@schindler-umwelt.de

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