



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

Polypropylene (PP)

PlasticsEurope

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# Environmental Product Declaration

## Introduction

This Environmental Product Declaration (EPD) is based upon life cycle inventory (LCI) data from PlasticsEurope's member companies. It has been prepared according to the rules of **PlasticsEurope's Eco-profiles and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors** (version 2.0, April 2011). EPDs provide environmental performance data, but no information on the economic and social aspects that 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 following polyolefin from cradle to gate (i.e. from raw material extraction to polymer resin at plant): Polypropylene (PP). **Please keep in mind that comparisons cannot be made on the level of the polymer 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 polymers, 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, Polyolefins Group
LCA Practitioner	IFEU Heidelberg
Programme Owner	PlasticsEurope aisbl
Programme Manager, Reviewer	DEKRA Consulting GmbH
Number of plants included in data collection	35
Representativeness	77 %
Reference year	2011
Year of data collection and calculation	2013
Expected temporal validity	2016
Cut-offs	None
Data Quality	Good
Allocation method	Physical allocation

## Description of the Product and the Production Process

This EPD represents the average industrial production of PP resin.

### Production Process

PP is produced by polymerisation of propylene, often with other co-monomers, chiefly ethylene. In Europe, most of the ethylene and a large share of propylene are produced by steam cracking of naphtha. About 23 % of the used propylene is produced in refineries by fluid catalytic cracking (FCC) of heavy feedstocks like gas oils and other distillation residues. This Eco-profile comprises extraction and refinery of crude oil and natural gas, the FCC process, steam cracking of hydrocarbons into lower olefins and polymerisation of the monomers into PP (and polyethylene). The model of the polymer production process represents commercial PP production technologies. Impacts related to accidents and other irregular conditions are not considered in this study.

### Data Sources and Allocation

The monomer production including all upstream processes was modelled based on the Eco-profile for ethylene and propylene [PlasticsEurope 2012]. For the share of propylene feedstock produced by FCC however, an IFEU proprietary model of petroleum refinery was used. The polyolefin production processes themselves were based on confidential process and emission data collected from polymer production sites (primary data). Country-specific electricity grid mixes were used. On-site production of electricity and steam were partially modelled using primary data from the polymer producers; data gaps in on-site energy production were closed using European average data of power plants and steam boilers. Representative literature data has been used to fill gaps where no primary data was available and for cross-checks. Allocation within

the foreground system was avoided; where necessary, processes have been allocated by physical properties, such as mass, exergy, or enthalpy.

#### Use Phase and End-of-Life Management

The use phase and end-of-life processes of the investigated polymers are outside the system boundaries of this cradle-to-gate system: since PP resin has a wide range of application, even a qualitative discussion of these aspects was deemed inappropriate. However, the disposal of waste from production processes is considered within the system boundaries of this Eco-Profile.

### Environmental Performance

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

#### Input Parameters

Indicator	Unit	Value
Non-renewable energy resources <sup>1)</sup>		
Fuel energy	MJ	29.7
Feedstock energy	MJ	47.4
Renewable energy resources (biomass) <sup>1)</sup>		
Fuel energy	MJ	0.7
Feedstock energy	MJ	0.0
Abiotic Depletion Potential (ADP)		
Elements	kg Sb eq.	1.4E-07
Fossil fuels	MJ	70.2
Water "cradle to gate"		
- use = withdrawal	kg	58.5
- consumption	kg	27.6

1) Calculated as upper heating value (UHV)

#### Output Parameters

Indicator	Unit	Value
Global Warming Potential (GWP)	kg CO <sub>2</sub> eq.	1.63
Ozone Depletion Potential (ODP)	g CFC-11 eq.	5.5E-04
Acidification Potential (AP)	g SO <sub>2</sub> eq.	4.32
Photochemical Ozone Creation Potential (POCP)	g Ethene eq.	3.7E-01
Eutrophication Potential (EP)	g PO <sub>4</sub> eq.	1.18
Dust/particulate matter <sup>1)</sup>	g PM10	3.97
Total particulate matter <sup>1)</sup>	g	4.28
Waste (only from polyolefin production, before treatment)		
Non-hazardous	kg	1.84E-03
Hazardous	kg	2.28E-03

<sup>1)</sup> Including secondary PM10

### Additional Environmental and Health Information

The monomer propylene is a short chain olefin and is therefore categorised as a Volatile Organic Compound (VOC). Propylene possesses a Photochemical Ozone Creation Potential (POCP, 1 kg propylene is equivalent to 1.12 kg ethylene, in terms of summer smog formation). As with the majority of polymers, polyolefin materials do not biodegrade in the natural environment. While particles which may result from long-term UV ageing and mechanical fragmentation of polyolefins are non-toxic, their presence in the environment should be prevented through responsible waste management and anti-littering initiatives.

### Additional Technical Information

PP has a rather high melting point, low density, good stiffness, and toughness. PP is used in an extremely wide range of applications, either transparent or pigmented, such as food packaging, textiles, automotive components, medical devices, and consumer goods.

### Additional Economic Information

PP is the second most important thermoplastic with an annual production volume of more than eight million tons in Europe. While production volumes of polyolefins are slightly decreasing within Europe, global demand and production of polyolefins are still growing, especially in the Middle and Far East.

## Information

### Data Owner

#### **PlasticsEurope, Polyolefins Group**

Avenue E van Nieuwenhuysse 4, Box 3

B-1160 Brussels, Belgium

Tel.: +32 (2) 675 32 97, Fax: +32 (2) 675 39 35

E-mail: [info@plasticseurope.org](mailto: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 2.0 (2010-06) and ISO 14025:2006. Registration number: PlasticsEurope 2014-002, validation expires on 31 December 2016 (date of next revalidation review).

### Programme Owner

#### **PlasticsEurope**

Avenue E van Nieuwenhuysse 4, Box 3

B-1160 Brussels, Belgium

Tel.: +32 (2) 675 32 97, Fax: +32 (2) 675 39 35

E-mail: [info@plasticseurope.org](mailto: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 2011: Eco-profiles and environmental declarations – LCI methodology and PCR for uncompounded polymer resins and reactive polymer precursor (version 2.0, April 2011).
- PlasticsEurope 2012: Eco-profile Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), Ethylene Glycols (MEG, DEG, TEG), November 2012.

# 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, since 1 kg of a specific polymer is not functionally equivalent to 1 kg of any other polymer.*

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 instance, for EPDs of products, 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 production site and is thus fully within the scope of PlasticsEurope as a federation. During the production process, polyolefins often are upgraded with additives to achieve the desired quality of the polymer granulate. These processes are by definition within the

scope and have to be clearly distinguished from a subsequent compounding step (often) conducted by a third-party company, which is outside the scope of PlasticsEurope.

### Functional Unit and Declared Unit

The Functional Unit and Declared Unit of the present Eco-profile and EPD are:

*1 kg of Polypropylene (PP) »at gate« (production site output) representing a European industry production average.*

## Product and Producer Description

### Product Description

The main characteristics of polypropylene are presented in Table 1.

Table 1: Characteristics of PP

Name of polymer	CAS number	Chemical formula of repeating unit	Density g/cm <sup>3</sup>	Melting Point	Gross calorific value MJ/kg <sup>a)</sup>
PP	9003-07-0	C <sub>3</sub> H <sub>6</sub>	0.89–0.92	130–171 °C	46.4

<sup>a)</sup> Values taken from BABRAUSKAS 1992

Polypropylene is produced all over Europe; the plants are usually in the vicinity of refineries which supply the monomers. In many cases PE and PP are produced on the same sites and by the same companies. PP is among the so called commodity polymers, which are used in large quantities and which can be produced commercially at relatively low costs for major applications [BREF 2007]. Commodity polymers as a whole account for about 80% of the overall plastic demand in Europe, led by PE with 29% market share and PP with 19% [PLASTICSEUROPE 2012A]. In the years 2011/2012 the European demand for PP is indicated with more than 8,500 kt/year [PLASTICSEUROPE 2012A]. The main applications for polyolefins are packaging products (see Figure 1). PP itself is mainly used for packaging, either as film, in expanded form as thermo insulation, or as solid container. Another important application for PP is the automotive sector, where it is used, for example, for battery cases. Other applications of polyolefins include various sectors such as consumer and household appliances, furniture, agriculture, sport, health and safety [PLASTICSEUROPE 2012A].

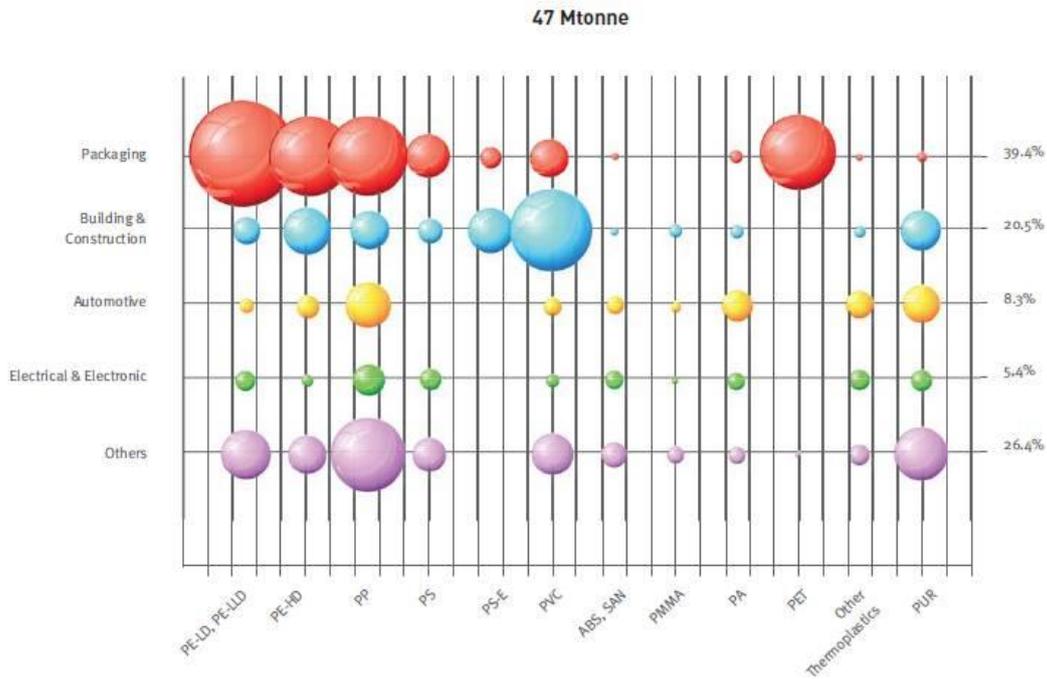
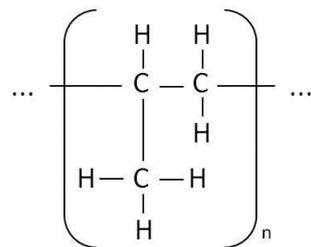


Figure 1: European (EU27+NO+CH) plastics demand by segment and resin type 2011. Source: PlasticsEurope Market Research Group [PEMRG]. Quoted from: [PLASTICSEUROPE 2012].

### Structure of PP

Polyolefins are based on crude oil. The raw material is propylene as monomer and, to a certain amount, ethylene which is used as a co-monomer. Polymers consist of many thousand units of a monomer that have reacted and built a molecular chain. A chain polymerisation can take place due to the double bond of the olefin molecules. With various techniques (described below) the double bond is forced to open, forming a radical and attach itself to another monomer molecule. Figure 2 illustrates the resulting repeat unit [Dominghaus 2012; BOUSTEAD 2005A, BOUSTEAD 2005B, BOUSTEAD 2005C, BOUSTEAD 2005D, SCHWARZ 2007, KAISER 2011].



Polypropylene

Figure 2: Repeat unit for polypropylene

During the polymerisation, the monomer units of propylene form a carbon backbone. The methyl side groups (CH<sub>3</sub>) of polypropylene can be arranged in three different ways in relation to the carbon backbone, which influences the properties of the end material. As Figure 3 shows, all methyl side groups can either be arranged at the same side of the carbon chain (isotactic polypropylene), or arranged regularly on alternate

sides of the carbon backbone (syndiotactic polypropylene), both forming a helix structure. As a third variation, the methyl group can be formed randomly on either side of the polymer chain (atactic polypropylene), resulting in an amorphous structure.

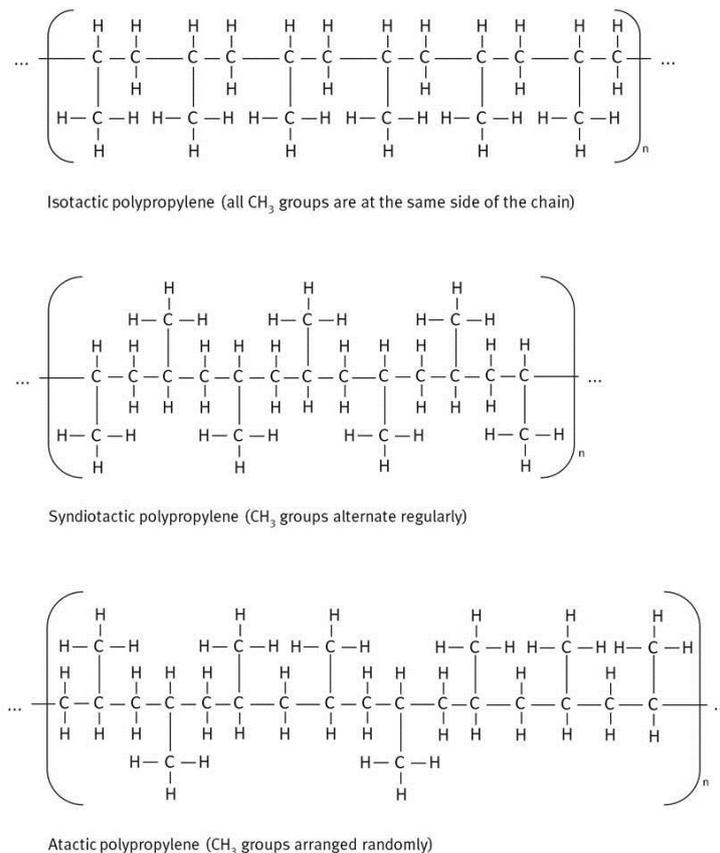


Figure 3: Different types of polypropylene depending on the arrangement of the methyl side group

The variations in the structure of polypropylene – and hence the properties of the resulting material – is basically conditioned by the manufacturing technique.

### Characteristics of PP

Polypropylene has a rather high melting point, low density, good stiffness, and toughness. These properties depend upon the degree of crystallinity and type and level of co-monomer incorporated within the product. As shown in Figure 2, the base unit of PP consists of three carbon and six hydrogen atoms, and the methyl (CH<sub>3</sub>) group is characteristic [BREF 2007; Dominghaus 2012; Boustead 2005a, Boustead 2005b, Boustead 2005c, Boustead 2005d, Schwarz 2007, Kaiser 2011].

Isotactic PP has a density of 0.936 g/cm<sup>3</sup>. Syndiotactic PP has a density of less than 0.910 g/cm<sup>3</sup>. In atactic PP, the methyl side groups are randomly arranged on either side of the chain. Of the three forms, isotactic PP has the superior properties. Increasing the tacticity (regularity of the CH<sub>3</sub> arrangement) leads to an increase in the degree of crystallinity, fluxing temperature, tensile strength, rigidity and hardness.

## Technology description

In the plastics industry, chain polymerisation is the most important reaction process (compared to step-growth polymerisation) and is used to produce polyethylene (PE) and PP [BREF 2007]. The polymer grade and its properties are particularly influenced by the choice of reactor type, catalytic system, initiator, and any co-monomers. Further, the chosen additives and auxiliaries play an important role, but will not be further addressed in this description. The following description summarises the main commercially used technologies, which were surveyed in this study.

## Overview of Technology

For the polymer production, a monomer of very high purity is needed. The requirement for very high purity is moreover important for all raw materials, like co-monomers, catalysts, initiators, solvents, etc. Ethylene and propylene produced by modern crackers are usually of sufficient purity to be used without further purification. Impurities in other raw materials, like from storage containers or stabilisers, have to be removed [BREF 2007, Kaiser 2011, Whiteley 2000]. For the polymerisation of PP, different technologies and processes are used, which are described below. After the reaction phase, most of the residual (unreacted) monomers (which are mostly present as gases) are separated from the polymer and are either recycled back into the process or flared off. Depending on the purity of the separated monomers, the gas can either be fed directly back into the production line or the monomers are returned to a purification unit. To limit the accumulation of impurities in the process, usually a small side-stream (purge) of the unreacted gas is sent back to the cracker or to a dedicated purification unit. After polymerisation, the polymer is usually fed directly into a hot melt extruder, where additives can be added to the melted polymer if required. The polymer is then pelletised in an underwater pelletiser. The pelletised product is dried, blended where required and degassed.

For the processing of polyolefins and to determine their properties, different processes and technologies are applied. The main differences can be found in the choice of process technology, reactor type and choice of catalyst or initiator. Figure 4 illustrates the technologies mainly used with their processes and catalyst types, whereas the following section generally describes those individual production processes of PP.

**Possible combinations of main process technologies, reactor types and catalysts**

PP	PROCESSTECHNOLOGY	REACTORTYPE	(Co-)CATALYST/INITIATOR
	gas phase	CSTR	2nd, 3rd, 4th, 5th generation
	slurry suspension	loop	metallocene
	bulk suspension	fluidised bed (FB)	organic peroxides
		dry powder bed	Ziegler-Natta

*Figure 4: Most important process technologies, reactor types, and catalysts applied in polypropylene production*

## Manufacturing of PP

PP is usually manufactured with the gas phase or the suspension process [BREF 2007, Kaiser 2011, Whiteley 2000]. The production processes that are applied are very similar to the manufacturing of HDPE. The process traditionally known as "suspension process" is called "slurry process" in the PP producers' nomenclature. Modern suspension processes, however, use liquid monomers instead of a solvent and are termed "bulk" process.

The catalysts used for the production of polypropylene have an important influence on the properties of the polymer as well as on the process conditions. The development of the catalysts had far-reaching consequences for the process development of PP production. The catalysts used are classified into “generations”. Where 1<sup>st</sup> generation catalysts were first introduced in the 1960s in the slurry process, 2<sup>nd</sup> generation catalysts were used in suspension and gas phase processes until the 1970s. The 2<sup>nd</sup> generation catalysts were followed by the 3<sup>rd</sup> generation catalysts in the 1980s for the same purpose. [BREF 2007] defined the 4<sup>th</sup> generation catalysts as current industry standard (state 2007), whereas the 5<sup>th</sup> generation catalysts would extend the performance of this standard. The 4<sup>th</sup> generation catalysts consist of phthalate/silicon donors and a spherical support which is used for a fluid monomer in a homopolymer reactor. The catalysts of the 5<sup>th</sup> generation, however, are based on a new diether and succinate donor technology. This leads to an increased activity and improved product performance. Thus, higher yields, lower catalyst residues, and lower specific catalyst per consumption per ton of polymer are the result. Metallocene catalyst types play a minor role – less than 5% of PP is produced using this catalyst type.

### **Description of Process Technology**

The polymerisation technologies can be classified according to their reaction conditions into high and low pressure processes [BREF 2007, Kaiser 2011, Whiteley 2000]. For low pressure, three main subcategories can be distinguished based on the reaction phase:

- Slurry suspension polymerisation
- Bulk suspension polymerisation
- Gas phase polymerization

As opposed to high-pressure polymerisation, where process parameters like pressure and temperature, play a major role, in the low-pressure processes, which are used for PP production, product properties are mainly defined by the catalyst type and co-monomers used. The processes can as well be used in combination, e.g. suspension and gas phase process. Regarding the reaction mechanism of polymerisation, radical polymerisation takes place under high pressure conditions whereas at low pressure chain growth is induced by insertion. The insertion mechanism, where monomers are inserted into the polymer chain at the reactive center of the catalyst (instead of at the opposite end of the chain as is the case in radical polymerisation), allows the highly defined structure of PP to be created.

#### *Slurry Suspension Polymerisation*

The suspension polymerisation can be described as precipitation process. The formation of the polymer takes place in a hydrocarbon diluent and under conditions, where the monomer is soluble in the solution. The precipitated polymer, however, is insoluble and forms a fine suspension. The polymer can be separated by centrifugation.

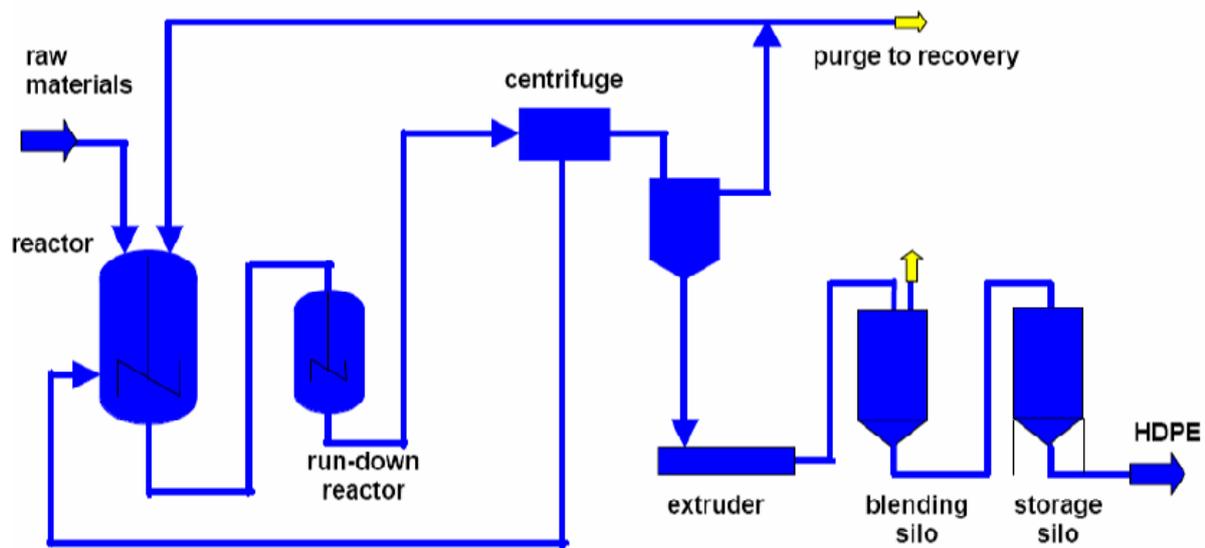


Figure 5: Flow diagram of the the suspension process with stirred tank reactors [BREF 2007]<sup>1</sup>

#### Bulk Suspension Polymerisation

The bulk suspension process describes the slurry suspension process used for the production of PP where the monomer propylene is used as solvent instead of other hydrocarbons. Modern suspension processes for the production of PP use liquid monomers instead of gaseous.

#### Gas Phase Polymerisation

Gas phase processes are used for both polyethylene and polypropylene production. A fluidised bed of polymer particles and catalyst is maintained by a steady gaseous monomer feed from the bottom of the reactor. Polymer powder is continuously extracted at the bottom of the fluidised bed reactor. Unreacted monomer gas from the top is compressed and recycled to the reactor inlet. Catalyst, and co-catalyst if necessary, is also continuously fed to the reactor. Modern, highly active catalysts can be used in low amounts, so that a subsequent separation is not necessary. In this process, no additional solvents are needed. The newest generation of gas phase processes can be operated in the condensing mode. Thus, heat removal and reactor productivity can be improved. Gas phase processes are often used, e.g. in Ziegler-Natta-type polymerisations, where the catalyst is supported on inert silica particles so that the reaction takes place at the catalyst surface. This helps controlling the stereochemistry (especially for isotactic polypropylene). The set-up of the gas phase process technology is more generic than the solution polymerisation process. The proprietary and protected information of this process are condensing mode, dual reactor operation, catalyst system etc.

<sup>1</sup> In [BREF 2007] the example refers to HDPE production process. The graphik can also be applied for the illustration of PP polymerisation.

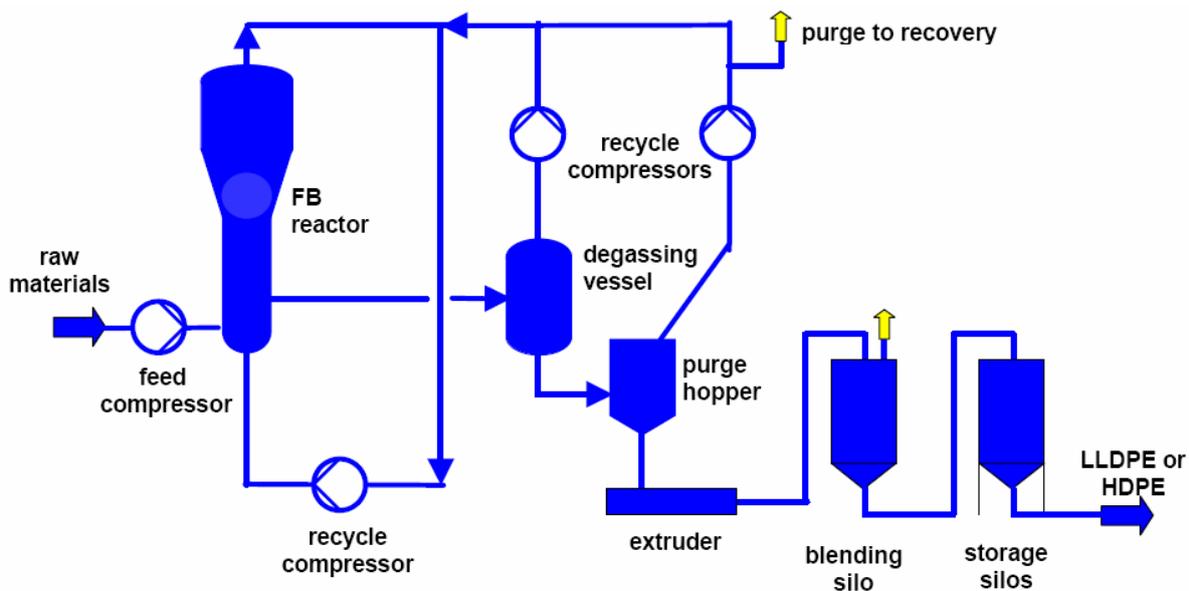


Figure 6: Flow diagram of the gas phase process [BREF 2007]<sup>2</sup>

### Description of Catalytic Systems

As mentioned above, the product properties can be influenced not only by the process technology, but also by the choice of the catalytic system. Catalysts allow producing polymers with more controlled structures. As catalytic systems, usually titanium- and aluminium compounds are chosen. To improve the polymerisation process, catalytic systems are under constant development to increase their performance [BREF 2007, Kaiser 2011, Whiteley 2000]. For the polypropylene production two three types of catalysts are used: Ziegler-Natta-type (titanium-based), Phillips-type (chromium-based), and metallocene catalysts.

**Ziegler-Natta-type catalyst** — In the year 1953, A. Ziegler and his team found, that ethene and triethylaluminium (TEA) react with catalysts that contain titanium halides and alkylaluminium at atmospheric pressure and low temperatures (about 50 – 100°C) to high-molecular polyethylene. Depending on the precise composition of the catalyst it is possible to create different types of polyethylene with a variation of product properties. G. Natta modified this catalytic system in 1954, so that isotactic (unbranched) polypropylene could be produced with this catalyst as well (isotactic PP see Figure 3). The commercial production of Polyethylene and polypropylene started in 1957. The catalyst systems that are mainly used are  $\text{TiCl}_3$ ,  $\text{Et}_2\text{AlCl}$ ,  $\text{AlR}_3$ ,  $\text{TiCl}_4$ ,  $\text{AlR}_3$ , and  $\text{TiCl}_4$ . Commercial Ziegler-Natta catalysts are typically supported on porous silica, titania or  $\text{MgCl}_2$  and are therefore insoluble leading to a heterogeneous catalyst system. Therefore, a targeted regulation of the product properties like temperature or impact resistance, hardness and transparency, is not possible, but Ziegler-Natta catalysts lead to a heterogeneous polymer structure.

**Phillips-type catalyst** — Another catalytic system of controlled polymerisation is the Phillips-type catalyst, which contains chromium trioxide on a silica carrier. Ethene and hydrogen reduce the chromium trioxide and thus create the active catalyst. The polymerisation can take place at pressures of about 3–4 MPa and similar low temperatures (70 – 100°C) and can be used for polyethylene products. The first HDPE polymer was produced using the Phillips-type catalyst.

<sup>2</sup> In [BREF 2007] the example refers to HDPE production process. The graphik can also be applied for the illustration of PP polymerisation.

**Metallocene-type catalyst** — As explained above, Ziegler-Natta-type catalysts do not allow a targeted influence of specific product properties due to their insolubility. Metallocene-type catalysts, however, consisting of two hydrocarbon (mostly cyclopentadienyl anions) rings surrounding a metal cation (usually titanium or zirconium), are soluble in organic solvents. For industrial polymerisation applications, metallocene catalysts are supported on silica. Metallocene-type catalysts are used to design specific product ranges with a particular resin design.

## Upstream Processes

**Monomer Production** — Propylene for polymerisation is produced by steam cracking, fluid catalytic cracking (FCC) and to a minor extent by propane metathesis (with shares of 72 % steam cracking, 24 % FCC, and 4 % propane metathesis). For the calculation of the current Eco-profile, only the major production routes for propylene, steam cracking and FCC, were considered. The production capacity for propylene was 12,502 kt solely on steam crackers. The propylene production on steam crackers and by other production routes amounted to a total of 14,665 kt in 2011 (source: APPE 2012). In the steam cracking process, lower olefins are produced by thermal cracking of up longer, saturated hydrocarbons into shorter, unsaturated compounds. The chemical reaction for the cracking process is a dehydrogenation carried out in the presence of steam (to minimise coke formation) and at temperatures of up to 875 °C. Steam cracking accounts for the majority of the ethylene, propylene, and butadiene production. In the European Union crackers are basically fed with naphtha (from petroleum refineries) and condensates, also called natural gas liquids (NGL). Both sorts of feedstock are very similar mixtures of hydrocarbons. Naphtha is an important product of the oil refinery, with a boiling range in between 50 and 190 °C. Liquid feedstocks have a high share as they are transported easily. Other important feedstocks for crackers in the EU are gas oil, butane, propane, refinery gas, and ethane (see Table 2). Ethane mainly comes from North Sea gas fields, whereas other feedstock gases come from refineries. The main products of steam cracking are ethylene, propylene, and methane, and their shares are depending on the feedstock. Important minor products are butadiene and, in case of naphtha or gas-oil feedstock, pyrolysis gasoline with a high aromatic content.

Table 2: *Feedstock for crackers in the European Union 2008–2010 (Source: APPE)*

Feedstock	Share [%]
Ethane / Refinery gases	4 %
Propane / Butane / LPG	12 %
Naphtha / Condensates (NGL)	74 %
Gas oil	6 %
Others (incl. C4)	4 %

**Fluid Catalytic Cracking (FCC)** — The FCC process is used to convert higher-molecular-weight hydrocarbons to lighter, more valuable products through contact with a powdered zeolite catalyst at 500–550 °C. Historically, the primary purpose of the FCC process has been to produce gasoline, distillate, and C3/C4 olefins from low-value excess refinery gas oils and heavier refinery streams. FCC is often the heart of a modern refinery because of its adaptability to changing feedstocks and product demands and because of high margins that exist between the FCC feedstocks and converted FCC products. The cracking reactions are carried out in an up-flowing vertical reactor-riser in which a liquid oil stream contacts hot powdered catalyst. The oil vapourises and cracks to lighter products as it moves up the riser and carries the catalyst along with it. The reactions are rapid, requiring only a few seconds of contact time. Simultaneously with the de-

sired reactions, coke, a material having a low ratio of hydrogen to carbon, deposits on the catalyst and renders it less catalytically active. Catalyst and product vapours separate in a disengaging vessel with the catalyst continuing first through a stripping stage and second through a regeneration stage where coke is combusted to rejuvenate the catalyst and provide heat for operation of the process. The regenerated catalyst then passes to the bottom of the reactor-riser, where the cycle starts again. Hydrocarbon product vapours flow downstream for separation into individual products. The FCC unit can accept a broad range of feedstocks, such as straight-run atmospheric gas oils, vacuum gas oils, certain atmospheric residues, and heavy stocks recovered from other refinery operations. The main products of FCC are high-octane gasoline, light fuel oils, and olefin-rich light gases. Since the FCC unit is fully integrated into a typical oil refinery, it is necessary to take all the relevant processes into account for a proper calculation of the burdens of propylene produced by FCC. Therefore, a model of an average European refinery was set up, which is described in the following paragraph.

**Petroleum refinery** — As the feedstock and its pre-processing significantly influence the LCI results of the polymer precursors under consideration in this Eco-profile, the adequate modelling of the petroleum refinery as part of the upstream chain is a key issue for this Eco-profile of polymer precursors. In spite of the large variety of possible and actual refinery configurations, the Draft Reference Document on Best Available Techniques for Mineral Oil and Gas Refineries [BREF 2012] describes in its Annex II four typical refinery configurations – from a simple hydroskimming unit up to a complex refinery with hydroconversion and a hydrocracker and/or an Integrated Gasification Combined Cycle Unit (IGCC). The refinery model used for the calculation of the current Eco-profile is a model that represents all typical processes of the different refinery configurations. It considers the capacity-weighted mixture of refinery configurations in Europe according to BREF 2012 and Eurostat, taking the changed product mix in recent years in account. This detailed model comprises the single processes of a petroleum refinery and makes up an average model of the European refinery (see Figure 7). As BREF 2010 does not only contain aggregated numbers or weighted averages of emission and energy/water consumption data, but also primary data of the majority of refineries in Europe in anonymous form, the data quality for this model is very good. This data has been complemented by various specific confidential refinery data, by numbers from Eurostat, e.g. for the mix of energy sources for process energy, and by literature data from widely acknowledged sources such as Meyers 2003 and others. In the cases mentioned by BREF 2010, a range of values for process parameters the arithmetic averages were applied. After adopting the model to the up-to-date mass and energy flows within European refineries, it has been validated by comparing its results to the data of BREF 2010, Eurostat, and EPER.

**Process Technology:** The process within the refinery that is of high relevance for the subsequent steam cracking is the atmospheric distillation of crude oil since naphtha is directly obtained as distillation fraction. FCC feedstock is obtained from vacuum distillation and from hydrocracking of vacuum residue. In the following, only the processes relevant for steam cracker and FCC feedstock production are described in detail.

**Desalting:** Crude oil and heavy residues contain varying quantities of inorganic compounds such as water, soluble salts, sand, silt, rust, and other solids, together characterized as bottoms sediment. Those impurities, especially salts could lead to fouling and corrosion of heat exchangers and especially the crude distillation unit overhead system. Therefore desalting of the incoming crude is generally applied before separating it into fractions. The principle of desalting is to wash the crude oil or heavy residues with water at high temperature and pressure to dissolve, separate, and remove the salts and solids. After preheating to 115 – 150 °C, the oil feedstock is mixed with water in order to dissolve and wash out the salts. The water must then be separated from the oil feedstock in a separating vessel by applying a high potential electric field across the

settling vessel to coalesce the polar salt water droplets or by adding demulsifier chemicals to assist in breaking up the emulsion. Many refineries have more than one desalter.

**Atmospheric Distillation:** The next step after desalting – and the most important in regard of cracker feedstock – is atmospheric distillation, which is the first and fundamental separation process in a refinery. In the atmospheric distillation unit crude oil is heated to temperatures of 300 to 400 °C and then subjected to distillation under atmospheric pressure separating the various fractions according to their boiling range. Heavier fractions from the bottom of the atmospheric distillation unit can be further separated by subsequent vacuum distillation.

The products from the crude distillation unit, ranging from the lightest to the heaviest cut are: naphtha and light components (boiling < 180 °C), kerosene (boiling range: 180 – 240 °C), light gasoil (240 – 300 °C), heavy gasoil (300 – 360 °C) and atmospheric residue (boiling > 360 °C). These fractions are separated by condensing on 30 to 50 fractionation trays. The lighter fractions condense and are collected towards the top of the vertical distillation column. The overhead of this column is the light fraction, non-condensable refinery fuel gas. Most of the fractions resulting from atmospheric distillation can be sold directly for use in the petrochemical industry (the route which naphtha and atmospheric gas oil take), as finished products after hydrotreatment, or be blended with products from downstream processes, e.g. heavy gas oil being mixed into diesel. So leaving the atmospheric distillation unit the straight-run unstabilised naphtha is passed to a naphtha splitter, separating the share for the petrochemical industry (industrial spirit) which is already in condition to be fed to the steam cracker, from the stream that is fed to the hydrotreater. During hydrotreatment, unsaturated light hydrocarbons in the straight-run naphtha are saturated and sulfur is removed by reaction with hydrogen. Saturated light hydrocarbons are separated from naphtha and either sold to the market or used as feedstock for the steam cracker (propane, butane or a propane/butane mix as liquefied petroleum gas). The third relevant feedstock for steam cracking from the petroleum refinery is atmospheric gas oil which can be taken directly from the atmospheric distillation unit and be used as a feed.

**Vacuum distillation [BREF 2012]:** The main feed stream to the vacuum distillation unit is the bottom stream of the atmospheric distillation unit, referred to as atmospheric residue. The products from the vacuum distillation unit are light vacuum gasoil, heavy vacuum gasoil, and vacuum residue. Light vacuum gasoil is normally sent to the gasoil hydrotreater, heavy gasoil is normally routed to a FCC and/or hydrocracker unit. The vacuum residue can have many destinations such as visbreaking, flexicoking or delayed coking, residue hydroprocessing, residue hydrocracking, bitumen blowing or it may go to the heavy fuel oil pool. Atmospheric residue is heated up to 400 °C, partially vaporised and flashed into the base of the vacuum column at a pressure between 40 and 100 mbar. The vacuum inside the fractionator is maintained with steam ejectors, vacuum pumps, barometric condensers, or surface condensers. The injection of superheated steam at the base of the vacuum fractionator column further reduces the partial pressure of the hydrocarbons in the tower, facilitating vaporisation and separation. The unvaporised part of the feed forms the bottom product and its temperature is controlled at about 355 °C to minimise coking. The flashed vapour rising through the column is contacted with wash oil (vacuum distillate) to wash out entrained liquid, coke, and metals. The washed vapour is condensed in two or three main spray sections. In the lower sections of the column, the heavy vacuum distillate and optional medium vacuum gasoil are condensed. In the upper section of the vacuum column the light vacuum distillate is condensed. Light (non-condensable) components and steam from the top of the column are condensed and accumulated in an overhead drum for separating the light non-condensables, the heavier condensed gasoil, and the water phase.

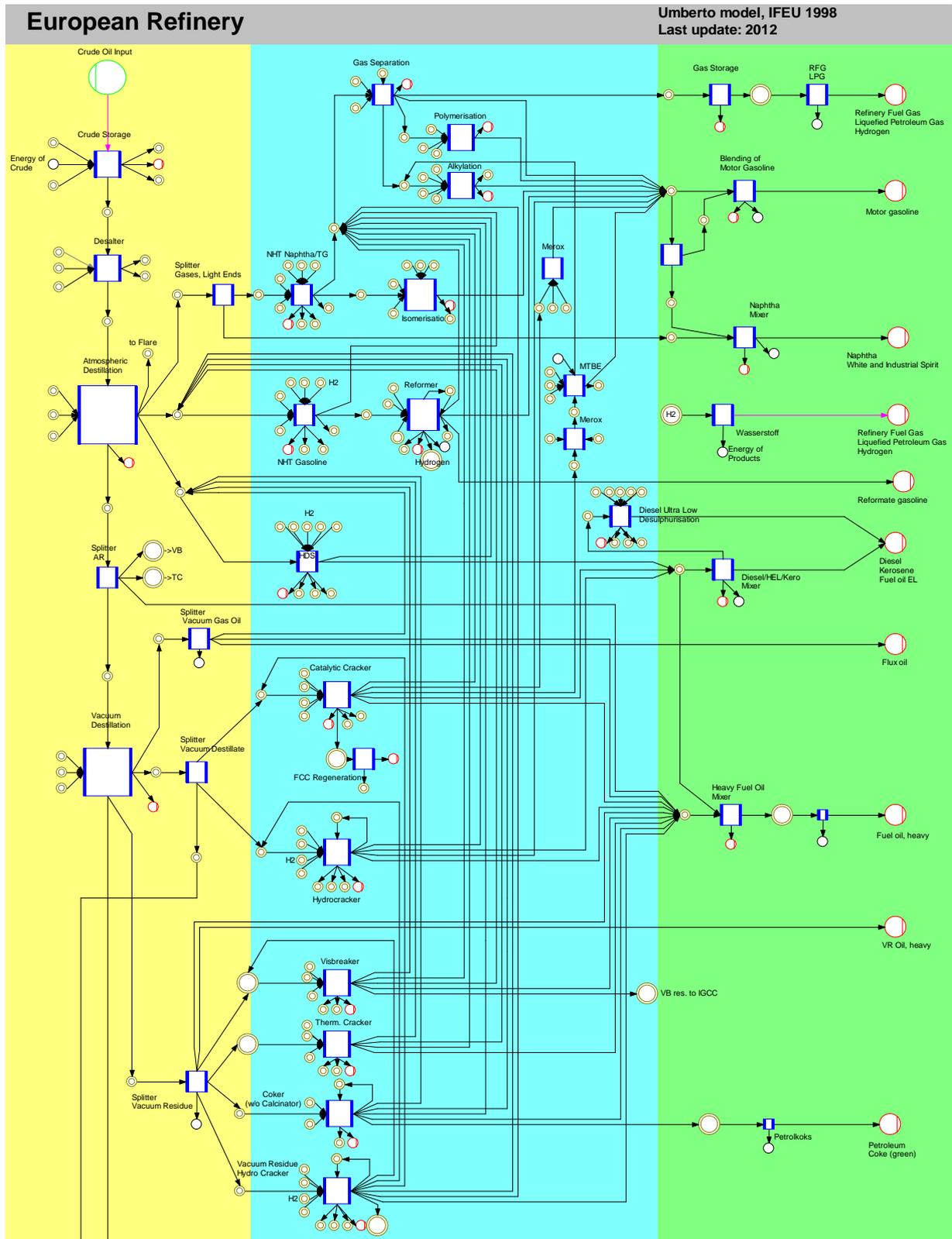


Figure 7: Screenshot of the petroleum refinery model in UMBERTO (Source: IFEU 2012)

**Hydrocracking of vacuum residue** [BREF 2012]: Residue hydrocracking is a type of hydrocracking applied to convert low-value vacuum residue and other heavy residue streams into lighter low-boiling hydrocarbons by reacting them with hydrogen. The hydrocracking reactions occur under high hydrogen partial

pressure in the presence of a catalyst with a two-fold function: hydrogenation and cracking. The type of catalyst maximises the production of naphtha, mid-distillates, or lube production. The presence of hydrogen suppresses the formation of heavy residual material and increases the yield of gasoline by reacting with the cracked products, giving net products, which are a mixture of pure paraffins, naphthenes, and aromatics. Hydrocracking produces mid-distillates (kerosene, diesel fuels, light and heavy naphtha) and heavy products that are hydrogen-rich for feed FCC units, or lube oil dewaxing and finishing facilities. When hydrocracking is applied to heavy residues, a pre-treatment is needed to remove high metal content before the hydrocracking reaction is produced. Hydrocracking normally uses a fixed-bed catalytic reactor with cracking occurring under substantial pressure in the presence of hydrogen at temperatures between 280 and 475 °C. This process also breaks the heavy, sulphur-, nitrogen- and oxygen-bearing hydrocarbons and releases these impurities to where they could potentially foul the catalyst. For this reason, the feedstock is often first hydrotreated and dewatered to remove impurities (H<sub>2</sub>S, NH<sub>3</sub>, H<sub>2</sub>O) before being sent to the hydrocracker.

### Crude Oil and Natural Gas

To achieve appropriate LCI results in this study, especially concerning air emissions, it was not only necessary to integrate the petroleum refineries into the model, but also to adequately represent the upstream chains of crude oil, natural gas, natural gas liquids, and refinery gas. Their contributions to the overall LCI results are significant. To illustrate the relevance of an up-to-date upstream chain, some characteristics of the pre-chains of crude oil and natural gas are shown in Table 3 and Table 4. For the compilation of this Eco-profile, using up-to-date data of the steam cracker's the upstream chain was a key issue. To achieve this aim, the upstream chains of crude oil and natural gas from Ecoinvent v2.2 were used and updated with current primary data from the oil and gas producing industry. Furthermore, upstream chains for NGL and ethane from North Sea fields were derived subsequently. For each location of refineries and crackers, the respective country specific electricity mix (including the respective pre-chains) was used instead of an average EU27 electricity mix. The processes of monomer production described above, including all upstream processes, were modelled based on the Eco-profile of Steam Cracker Products [PlasticsEurope 2012B].

Table 3: Key figures for the upstream chain of crude oil according to provenance (Ref. year: 2010)

Countries of origin	Share [wt.-%]	Crude oil in ground req'd per kg crude oil at refinery [kg]	Efficiency [%]	CO <sub>2</sub> emission per kg crude oil at re- finery [kg]
Libya, Algeria, Angola	11.1%	1.0282	97.26	0.2890
Middle East, Azerbaijan, Kazakhstan	22.9%	1.0491	95.32	0.2906
Netherlands	0.3%	1.0018	99.82	0.0304
Nigeria	4.3%	1.0123	98.78	0.4468
Norway, Denmark	15.7%	1.0038	99.63	0.0692
Russia	32.8%	1.0333	96.78	0.2014
United Kingdom	10.1%	1.0082	99.19	0.1980
Venezuela	2.8%	1.0947	91.35	0.4580
<b>Average according to cracker capacity mix</b>		<b>1.0299</b>	<b>97.13</b>	<b>0.2278</b>

Table 4: Key figures for the upstream chain of natural gas according to provenance (Ref. year: 2010)

<b>Countries of origin</b>	<b>Share</b> [vol.-%]	<b>Natural gas in ground</b> req'd per kg gas feedstock [kg]	<b>Efficiency</b> [%]	<b>CO<sub>2</sub> emission</b> per kg gas feedstock [kg]
Algeria, Qatar	16.5%	1.1307	88.44	0.2888
Germany	6.4%	1.0513	95.12	0.1462
Netherlands	23.2%	1.0126	98.76	0.0274
Norway	23.6%	1.0337	96.74	0.0779
Russia	22.7%	1.1708	85.41	0.3487
United Kingdom	7.6%	1.0598	94.36	0.1533
<b>Average according to cracker capacity mix</b>		<b>1.0791</b>	<b>92.98</b>	<b>0.1727</b>

### Grid Electricity Supply

Amongst other energy sources, the operation of a polyolefin production plant depends on the availability of electric power, which is usually obtained from the national electricity grid in the form of alternating current (AC) power. A national grid electricity mix represents a typical mix of electric power from different types of power plants. Those include hard coal, lignite, oil and gas power plants among the fossil-fuel-fired plants, biomass, geothermal, photovoltaic and hydropower plants as well as wind farms among renewable energies power generators, nuclear power plants, and waste incineration plants. Power supply implies the generation of electricity from the respective energy carrier by using the according electricity-generating technology, the extraction or production of the fuel in the case of fuel-based energy carriers, e.g. coal, natural gas or biomass, as well as the distribution of electricity within the grid, which comes along with losses due to transformation and transportation. Table 5 shows the Global Warming Potential (GWP 100) of the country specific electricity supply mixes for the European countries (EU27+NO+CH) as well as averages weighted by electricity production and by the polyolefin production capacity covered in this study.

Table 5: Global Warming Potential (GWP 100) of country specific electricity supply mixes (2011)

<b>Country</b>	<b>GWP</b> kg CO <sub>2</sub> eq./kWh
Austria	0.210
Belgium	0.142
Finland	0.292
France	0.060
Germany	0.605
Italy	0.419
Norway	0.016
Portugal	0.394
Spain	0.383
Sweden	0.033
Netherlands	0.467
United Kingdom	0.454
Mix EU27+NO+CH, weighted by <b>electricity production</b>	0.414
Mix EU27+NO+CH, weighted by <b>PP production covered in this study</b>	0.278

### **On-site Energy Production / Process Steam Generation**

Besides the power supply from the electricity grid, thermal energy (i.e. heat) and electric energy are often generated on-site. On-site energy plants produce either heat only or both heat and electricity (combined heat and power, CHP plants). Fuel oil, natural gas, hard coal, and lignite are the most commonly used fuels for on-site energy generating plants.

### **Producer Description**

PlasticsEurope Eco-profiles 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 companies contributing data to this Eco-profile are:

- Ineos Olefins and Polymers Europe, Switzerland
- Repsol S.A., Spain
- SABIC Europe, Netherlands
- ExxonMobil Chemical, Belgium
- Borealis AG, Austria
- Total S.A., France
- LyondellBasell Polyolefins, United Kingdom

Data was collected from the European polyolefin production units of the above-mentioned companies. The data collection aimed at information on all energy and material inputs and outputs of one of the specified polyolefin resins, on distances and means of transportation of each material input, on emissions to air and water, and on the type, amount, destination, and transport distances of wastes produced inside the battery limits. Furthermore, the same set of data was collected concerning the on-site production of electricity and steam by either power plants or steam boilers delivering energy directly (i.e. not via the national electricity grid) to the polyolefin production unit. Total amounts for one year (the reference year 2011) have been asked for.

# Eco-profile – Life Cycle Inventory

## System Boundaries

PlasticsEurope Eco-profiles and EPDs refer to the production of polyolefins as a cradle-to-gate system (Figure 8).

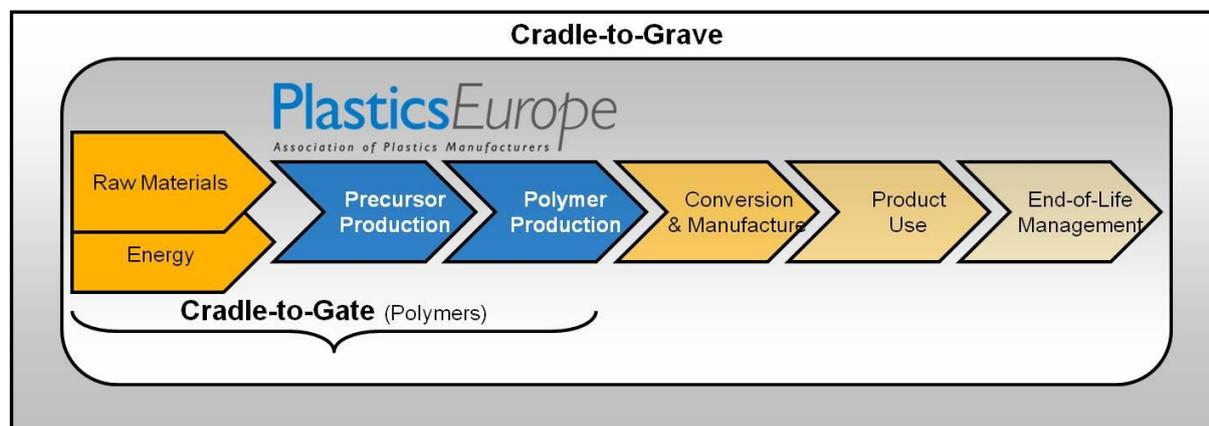


Figure 8: Cradle-to-gate system boundaries

## Cradle-to-Gate System Boundaries for Production

The following processes are included in the cradle-to-gate LCI system boundaries (see also Figure 9):

- Extraction of non-renewable resources (e.g. of oil and natural gas)
- Growing and harvesting of renewable resources (e.g. biomass production)
- Beneficiation or refining, transfer and storage of extracted or harvested resources into feedstock for production;
- Recycling of waste or secondary materials for use in production
- Converting of non-renewable or renewable resources or waste into energy
- Production processes
- All relevant transportation processes (transport of materials, fuels and intermediate products at all stages)
- Management of production waste streams and related emissions generated by processes within the system boundaries.

According to the methodology of Eco-profiles (PlasticsEurope v 2.0, April 2011), capital goods, i.e. the construction of plants and equipment as well as the maintenance of plants, vehicles, and machinery is outside the LCI system boundaries. The end-of-life treatment of the products of the polyolefin production and their resulting products is also outside the LCI system boundaries of this Eco-profile. Inputs and outputs of secondary materials and wastes for recovery or disposal are noted as crossing the system boundaries. An exception is low-radioactive waste from electricity generation for which a final storage has not been found yet; it is declared as output.

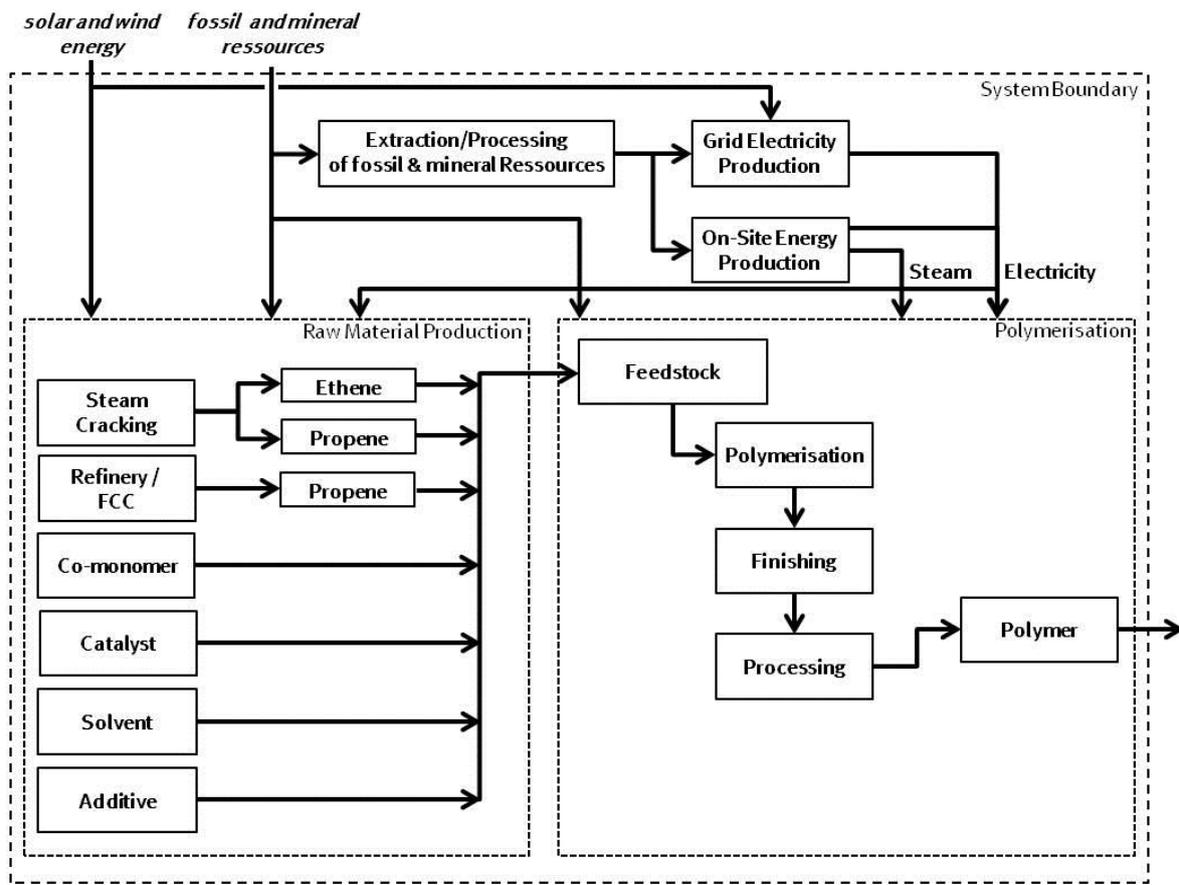


Figure 9: Schematic flow chart of the processes under consideration in this study

### Technological Reference

The production processes were modelled using specific values from primary data collection at site, representing the specific technologies of the polyolefin production of the companies, (i.e. different reactor types, reaction phases, or catalysts) as well as the water treatment that is applied on-site. The LCI data represents the production mix of technology in use in the defined production region employed by participating producers. For the on-site energy supply, primary data was collected as well. Thus, primary data were used for all foreground processes (under operational control) as well as for the provision of on-site-energy, if applicable. This input data is complemented with secondary data from background processes, e.g. grid electricity supply. From the total number of 43 polypropylene plants in Europe, 38 were selected for participation in this study, which represent the plants of members of PlasticsEurope. Of those plants, 35 were able to provide data. The remaining 3 polymer plants did not participate in the data collection due to internal reasons. In the year 2011, the 35 participating plants represented 77% of the European nameplate capacity for PP (Figure 10).

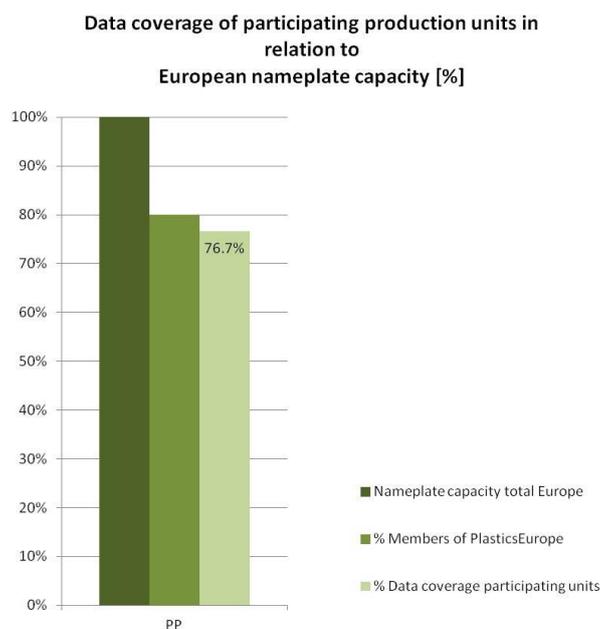


Figure 10: *Participating PP production units and their share of European PP production capacity (nameplate capacity, 2011)*

### Temporal Reference

The LCI data for production was collected as 12 month averages representing the year, to compensate seasonal influence of data. The overall reference year for this Eco-profile is 2011 with a maximal temporal validity until 2016. It seems adequate to refer to the 5-year interval that is proposed in the product category rules for polymers [PLASTICSEUROPE 2010]. Thus, the dataset can be adjusted to current process improvements or changes in the European electricity production mix.

### Geographical Reference

Primary production data for polyolefin production were provided from 35 different production units in the EU27 member states, Norway, and Switzerland (EU27+NO+CH). For most of the considered countries, the data coverage is 100% (related to production capacity of the participating companies). The data coverage of France reaches 88%. One of two units in Great Britain provided data, which lead to a data coverage slightly lower than 50%, whereas the only production site in Poland could not provide data (Table 6). In total, the geographical reference can be assessed as good.

Table 6: *Data coverage per country, related to production capacity of the participating countries*

Country	Data coverage
Austria	100%
Belgium	100%
Finland	100%
France	88%
Germany	100%
Italy	100%
Netherlands	100%
Poland	0%
Portugal	100%
Spain	100%
United Kingdom	48%

Fuel and energy inputs in the system reflect average country-specific conditions and whenever applicable, site-specific conditions were applied to reflect representative situations. Therefore, the study results are intended to be applicable within EU27+NO+CH boundaries. In order to be applied in other regions adjustments might be required. Polyolefin products imported into Europe were not considered in this Eco-profile.

## Cut-off Rules

To achieve completeness, i.e. a closed mass and energy balance, any cut-off of material and energy flows has been avoided in this Eco-profile. For commodities with a total input of less than 4 wt.-% (solvents, catalysts, initiators, additives) generic datasets from the Ecoinvent v 2.2 database [ECOINVENT 2010] have been used. In Ecoinvent datasets, waste for recycling is generally cut off. Furthermore, expenses for capital equipment were not considered in this Eco-profile.

## Data Quality Requirements

### Data Sources

This Eco-profile and EPD uses average data representative of the respective foreground production process, both in terms of technology and market share. These processes consist of the polyolefin production unit including water treatment, and on-site energy production. The primary data for the polyolefin production unit and the on-site energy production are derived from site-specific information for processes under operational control supplied by the participating member companies of PlasticsEurope (see Producer Description).

Data concerning the monomer feedstock, i.e. ethene and propylene, was taken from the recently published EPD and Eco-profile of steam cracker products [PLASTICSEUROPE 2012], of which the full dataset is known to the LCA practitioner. In this publication, the modelling of the steam cracking processes is based on confidential data provided by plant operators as well as on representative literature data such as data from the following databases and publications:

- Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry [BREF 2003]
- Life cycle inventory database Ecoinvent v2.2 [Ecoinvent 2010]

- Ullmann's Encyclopedia of Industrial Chemistry [ULLMANN 2010]
- Furthermore, the Association of Petrochemicals Producers in Europe (APPE) provided recent data for energy consumption, feedstock mix, and CO<sub>2</sub> emissions for the majority of European plants.

For the share of propylene feedstock produced by fluid catalytic cracking (FCC) a proprietary model by IFEU model of a petroleum refinery was used, based on confidential process and emission data from several sites as well as on representative literature data from the following publications:

- Draft Reference Document on Best Available Techniques for Mineral Oil and Gas Refineries [BREF 2012]
- R. A. Meyers: Handbook of Petroleum Refining Processes [MEYERS 2003]

Statistical data for product mix and energy demand have been taken from the Eurostat database for the year 2007 – 2009. As fuel oil and natural gas are commonly used as fuels for the production of heat, i.e. in the form of process steam, or power on-site, it was necessary to represent their upstream chains adequately to achieve appropriate LCI results in this study, especially concerning the air emissions. For the compilation of this Eco-profile, up-to-date data of the upstream chains of fuel oil and natural gas, which had been collected and implemented recently, could be used. They are based on the database Ecoinvent v2.2 [Ecoinvent 2010]. A regional provenance mix according to the respective polymer production site was considered using statistical data from Eurostat for the year 2011. The upstream chains for crude oil and natural gas were updated for the main production countries/regions with primary data, notably in view of its inputs and outputs. The primary data derives from the environmental/annual reports either of associations of the oil and gas producing industry or directly from important producers representing specific regions (e.g. the North Sea region, Russia, OPEC countries). Furthermore, data from scientific studies was used for the update of the upstream chain of natural gas. Hard coal and light fuel oil are less important fuels for on-site energy generation, which are used mostly in combined heat and power plants. The datasets for those fuels representing a European average were taken directly from the database Ecoinvent v2.2 [Ecoinvent 2010]. For transport processes the main data sources are –

- Rail: TREMOD (2009) and EcoTransIT (2008)
- Road HBEFA 2.1 and TREMOD (2009)
- Ship: Borken 1999 and Ecoinvent v2.2 [ECOINVENT 2010]
- Pipeline: Ecoinvent v2.2 [ECOINVENT 2010]

Datasets for other relevant inputs, e.g. solvents, co-monomers, or auxiliary materials used in waste management or water preparation are also taken from the database Ecoinvent v2.2 [Ecoinvent 2010]. Electric power supply was modelled using country specific grid electricity mixes, since the environmental burdens of power production varies strongly depending on the electricity generation technology. The country-specific electricity mixes are obtained from a master network for grid power modelling maintained and annually updated at IFEU as described in IFEU 2011. This network considers the basic power plant types and their respective raw material processes. Using network parameters, the fuel mix and essential technical characteristics of the energy systems are freely adjustable. Thus, the national grid electricity mix for each European country has been calculated. It is based on national electricity mix data by EUROSTAT [2013] for the reference year, which is 2011 for all countries.

The system boundary of the electricity module includes –

- power plant processes for electricity generation using coal and lignite, fuel oil, natural gas, bio-mass and waste as well as nuclear, hydroelectric, geothermal, solar and wind power;
- upstream fuel chains in the case of coal, lignite, fuel oil, natural gas, biomass and nuclear power;
- distribution of electricity to the consumer with appropriate management and transformer losses.

The network also includes combined heat and power generation. The share of district heat produced in coupled form is adjustable according to the power plant type. An allocation of the burdens to electricity and district heating is performed through allocation based on exergetic values of products. Additional information concerning the applied electricity grid model can be found on the website of IFEU.

### **Relevance**

With regard to the goal and scope of this Eco-profile, the collected primary data of foreground processes are of high relevance, i.e. data from the most important producers in Europe in order to generate a European industry average production. The environmental contributions of each process to the overall LCI results can be found in Chapter 'Life Cycle Impact Assessment'.

### **Representativeness**

The data used for this study covers 77 % of the installed PP nameplate capacity in Europe (EU27 + Norway + Switzerland) in 2011. The background data used can be regarded as representative for the intended purpose, as it is average data and not in the focus of the analysis.

### **Consistency**

To ensure consistency only primary data of the same level of detail and background data from the databases mentioned under 'data sources' 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**

In the questionnaires, the site managers were encouraged to classify their data into one of the following reliability grades: measured, calculated, or estimated. According to these statements, the data of foreground processes provided directly by producers were almost completely measured. Data of relevant background processes, e.g. grid electricity, is based on IFEU models that are regularly updated with statistical data, with available primary data, and with data derived from literature after it has been reviewed and checked for its quality. Thus, the overall reliability of data for this Eco-profile is considered very high.

### **Completeness**

The data collection took place in two phases: In phase one, the participating companies provided data on the relevant inputs (e.g. amount of raw materials, energy, or water) and main output products (e.g. polyolefins, recovered energy). In phase 2, additional relevant output data was collected, concerning emissions to

air and water, amounts of waste, and transport information. In general, the collected and applied data is held to be complete, because no flows are omitted or substituted. However, for some production sites it was not possible to obtain detailed emission data due to site-specific measurement and recording practices. In order to compensate missing information on certain important inputs and outputs, average values (calculated based on the data reported by other production sites of the same polyolefin type and weighted by product output) were used in cases where no data was given. This procedure avoids missing information to be treated as "zero" in the calculation of average values. This procedure was applied to the following substances/process flows:

- emissions of propylene to air
- the total amount of flue gas from process
- the total amount of waste water
- all emissions to air and water in cases where no information on emissions was given
- process water and non-contact cooling water input
- waste output

In case of missing information on the fuel mix (natural gas, fuel oil, coal, etc.) used for on-site energy production, the average fuel mix of all participating polyolefin plants was assumed. The method was applied for thermal or electrical efficiencies of on-site energy installations, as well as for means and distances of raw materials and waste transport.

### **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 was not feasible within this goal and scope.

### **Reproducibility**

All data and information used either are documented in this report or are available from the mathematical model of the processes and process plans designed within the Umberto 5.6 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**

Data on polyolefin production were collected from PlasticsEurope members in an iterative process with several feedback steps if necessary. The collected data was validated using existing data from published sources or expert knowledge. The relevant background information are validated and updated regularly by the LCA practitioner.

## Life Cycle Model

The life cycle system is modelled in Umberto 5.6, a standard software tool for LCA (see for Figure 11 a simplified model). The associated database integrates ISO 14040/44 requirements [ISO 14040: 2006, ISO 14044: 2006]. Due to confidentiality reasons, details on software modelling and methods used cannot be shown here. Data for production processes have been transferred to the model after a successful data validation. The calculation follows the vertical calculation methodology, i.e. that the averaging is done after modelling the specific processes.

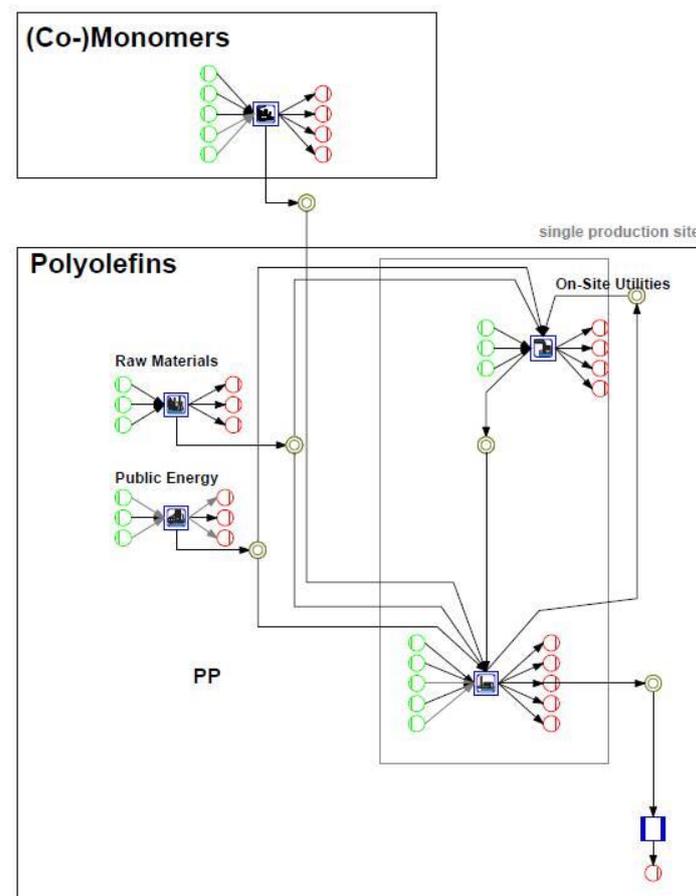


Figure 11: A simplified flow chart of the Life cycle model for the European production of PP in Umberto. Here, only one production site is shown (inside the dashed box), connected to the prechains of public energy, (co)-monomers and other raw materials. For the complete model, additional production sites were inserted in parallel.

## Calculation Rules

### Vertical Averaging

When modelling and calculating average Eco-profiles from the collected individual LCI datasets, vertical averages were calculated (Figure 12). These vertical averages comprise the polyolefin production unit itself (for the production process of PP), the on-site energy supply (electricity and steam if produced on-site), on-site production of supply materials like pressurised air, nitrogen, or process water, transport of input materials and waste, waste treatment, and wastewater treatment. National electricity mixes were used to calculate the grid electricity supply, and horizontal averages were used for ethene and propylene monomers and

other raw materials.

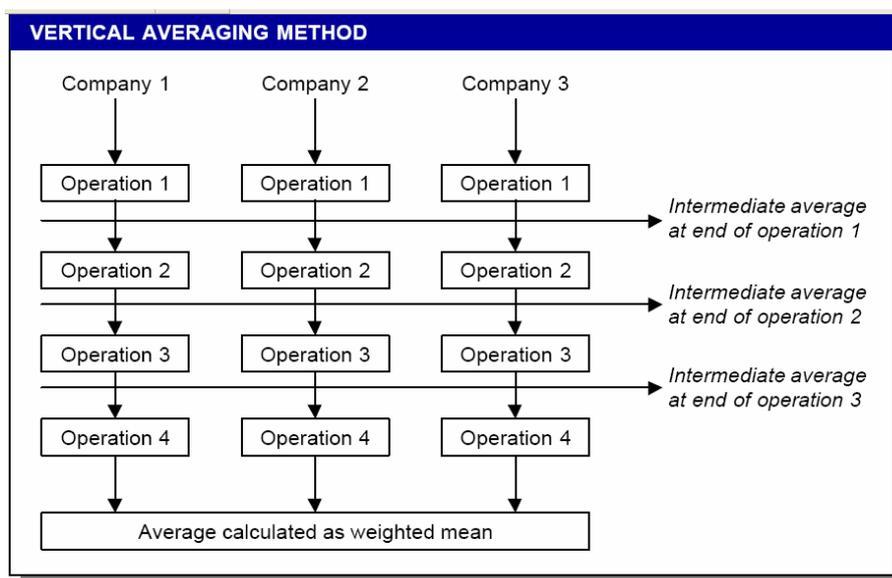


Figure 12: Vertical Averaging (source: Eco-profile of high volume commodity phthalate esters, ECPI European Council for Plasticisers and Intermediates, 2001)

### 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 complete 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.

The polyolefin production itself is regarded as a single-output process since only one polymer type is produced by one installation. All other products of this installation, e.g. monomers being recycled to the cracker or distillation, or hydrocarbons being used thermally, are treated as internal flows replacing the respective input materials (i.e. monomers or energy carriers). Hence, no allocation is needed for the polyolefin production process. For some production sites where different polymer types are produced on the same installation, the companies allocated expenses and emissions by mass to the different polymer types.

Other processes in the pre-chain of the polyolefin production are treated as follows regarding allocation:

- Steam cracking of liquid or gaseous feeds yields several products, which in part are internally used as fuel or feedstock. This internal recycling is modelled as closed-loop and does not lead to additional products of the considered sub-system. Diverse hydrocarbons are generated as co-products next to ethene, propylene, hydrogen, butadiene, and pyrolysis gas. The shares of the co-products can vary significantly depending on plant configuration, market values of products and feedstock composition – ethene and propylene are the dominating products if naphtha is used as feedstock. The feedstock input is allocated by mass to all products leaving the cracking plant. All the other inputs and outputs, i.e. energy input, emissions and solid wastes, are allocated by mass to the High Value Chemicals (HVC) products, i.e. ethene, propylene, butadiene, benzene, toluene, xylenes, and purified hydrogen. APPE applied this

allocation procedure in the European Emission Trading System (EU ETS) and recommends its application also in this study to keep consistency.

- An oil refinery is a complex production sub-system with many multi-output processes and products. The basic allocation criterion is the energy of products on a detailed process level. Since the majority of the products of the petroleum refinery are used for energy application the calorific value is the preferable coefficient. For this reason and as the EU Renewable Energy Directive recommends energy allocation for biofuels, bioliquids, and their fossil fuel comparators, refinery processes have been allocated by energy. The intention of every process has been considered defining the allocation keys between expenses and revenues, e.g. the catalytic cracking process (in refineries) is a conversion process to upgrade heavier hydrocarbons into more valuable lower boiling hydrocarbons. The feed stream, which is usually heavy vacuum distillate, is allocated to all product streams by energy. But other expenses, such as energy and catalysts input or emissions, are allocated by energy only to the desired lighter products; the cracker residue does not receive any energy or emission burdens besides the material feed demand.
- The emissions that crude oil extraction and natural gas processing cause within a specific supply region were basically allocated by mass. This is especially relevant for regions where a combined gas and oil production takes place.
- For Combined Heat and Power (CHP) plants, burdens for electricity and heat were allocated by exergy.

The allocation rule for end-of-life management is the following: process waste with a recycling potential (e.g. catalysts) leaving the system (<0.5 wt.-%) does not receive any burdens or credits (cut-off). Other process waste is treated within the system.

## 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](http://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), shown in Table 7, 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 net calorific value (lower heating value, LHV) is also presented in Table 7 for information purposes. 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), is quantified as the gross calorific value (UHV).

Table 7: Primary energy demand (system boundary level) per 1 kg of PP

Primary Energy Demand	Value [MJ]
Energy content in polymer (energy recovery potential, quantified as gross calorific value of polymer)	46.4
Process energy (quantified as difference between primary energy demand and energy content of polymer)	31.5
<b>Total primary energy demand (upper heating value)</b>	<b>77.9</b>
Total primary energy demand (lower heating value)	73.1

Consequently, the difference ( $\Delta$ ) 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 8 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).

Table 8: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg PP

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	0.98	0.048		0.98
Oil	59.66	1.303	41.52	18.13
Natural gas	13.61	0.295	5.88	7.73
Lignite	0.62	0.058		0.62
Nuclear	2.25	0.000		2.25
Hydro	0.00			0.00
Solar	0.35			0.35
Geothermic	0.27			0.27
Waves	0.03			0.03
Wood	0.00			0.00
Wind	0.10			0.10
Other renewable fuels	0.00			0.00
<b>Sub-total renewable</b>	<b>0.7</b>	<b>0.0</b>	<b>0.0</b>	<b>0.7</b>
<b>Sub-total Non-renewable</b>	<b>77.1</b>	<b>1.7</b>	<b>47.4</b>	<b>29.7</b>
<b>Total</b>	<b>77.9</b>	<b>1.7</b>	<b>47.4</b>	<b>30.4</b>

Table 9 shows the distribution of the primary energy demand between renewable and non-renewable resources. Since the polymerisation plants within the scope of this study are exclusively using monomers produced from fossil resources (crude oil and natural gas), the share of non-renewable energy resources is close to 100 %. The small share of renewables is mainly caused by the national electricity mixes.

Table 9: Primary energy demand by renewability

Fuel/energy input type	%
Renewable energy resources	1.0%
Non-renewable energy resources	99.0%
<b>Total</b>	<b>100.0%</b>

In Table 10 the types of useful energy inputs into the polymerisation process are analysed. This represents the share of the energy requirement that is under operational control of the polymer producer. Both electric and thermal energy inputs play a significant role.

Table 10: Analysis by type of useful energy for the PP production process per 1 kg of product

Type of useful energy in process input	Value [MJ]
Electricity	1.27
Heat, thermal energy	0.84
<b>Total (for selected key processes)</b>	<b>2.11</b>

Same as Table 10, the following tables are related to the foreground processes only. This means that in contrast to the other tables in this section, only direct inputs and outputs of the polyolefin production process were analysed. An exception was made in Table 13, where on-site utilities are taken into account as well.

### Water Balance

Table 11 shows the water withdrawal and consumption of the polyolefin “gate to gate” production process considering only the water household of production site, while Table 12 depicts the same figure in the case of the “cradle to gate” system. It includes the water inputs and outputs of the background system, as well.

Table 11 Gross water resources used in of the PP production process (“gate to gate”) per 1 kg of product

Source	PP
Process water [kg]	0.4
Boiler feed water [kg]	0.18
Non-contact cooling water [kg]	19.3
<b>Water use (= total withdrawal)</b>	<b>19.8</b>
Water output to same water body	16.3
<b>Water consumption</b>	<b>3.6</b>

Water withdrawal is the amount removed directly from natural resources. Water consumption shows how much water dissipated during the process namely did not return into the original source (e.g. evaporates).

Table 12 Gross water resources used in polyolefin “cradle to gate” production process per 1 kg of product

Source	PP
Process water [kg]	1.5
Non-contact cooling water [kg]	57.0
<b>Water use (= total withdrawal)</b>	<b>58.5</b>
Water output to same water body	30.9
<b>Water consumption</b>	<b>27.6</b>

### Air Emission Data

Table 13 shows a few selected air emissions which are commonly reported and used as key performance indicators for the polyolefin production process, including the on-site energy production. For a full inventory of air emissions, please refer to the complete LCI table in the annex of this report.

Table 13: Selected air emissions of the foreground processes (PP production plus including on-site utilities) per 1 kg of product

Air emissions	kg
Carbon dioxide, fossil (CO <sub>2</sub> , fossil)	1.30E-01
Carbon monoxide (CO)	2.65E-05
Sulphur dioxide (SO <sub>2</sub> )	1.54E-04
Nitrogen oxides (NO <sub>x</sub> )	1.18E-04
Particulate matter ≤ 10 µm (PM 10)	7.62E-06

## Wastewater Emissions

Table 14 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 14: *Selected water emissions of the PP production process per 1 kg of product*

<b>Water emissions</b>	<b>kg</b>
Biological oxygen demand after 5 days (BOD <sub>5</sub> )	2.38E-06
Chemical oxygen demand (COD)	2.79E-05
Total organic carbon (TOC)	6.01E-06

## Solid Waste

Table 15: Solid waste generation of the PP production process per 1 kg of product

<b>Waste for –</b>	<b>Incineration</b>	<b>Landfill</b>	<b>Recovery</b>	<b>Unspecified</b>	<b>Total</b>
	kg	kg	kg	kg	kg
Hazardous	1.94E-03	5.96E-06	2.55E-04	8.00E-05	2.28E-03
Non-hazardous	8.38E-05	2.43E-04	1.49E-03	2.24E-05	1.84E-03

# Life Cycle Impact Assessment

## Input

### Natural Resources

The Abiotic Depletion Potential (ADP) measures the extraction of natural resources such as iron ore, scarce minerals, and fossil fuels such as crude oil. This indicator is based on ultimate reserves and extraction rates. It is distinguished into the two subcategories 'ADP, elements' and 'ADP, fossil fuels'. For 'ADP, elements' Antimony (Sb) is used as a reference for the depletion of minerals and metal ores and for 'ADP, fossil fuels' the lower heating value (LHV) of extracted fossil fuels is considered. It is calculated according to updated characterisation factors of CML [CML 2010]. 'ADP, fossil fuels' is not identical with the 'Primary Energy Resource Input' since the latter is based on upper heating values and ADP is based on lower heating values. Furthermore, 'ADP, fossil fuels' does neither include renewable resources nor uranium.

Table 16: Abiotic Depletion Potential per 1 kg PP

Natural resources	Value
Abiotic Depletion Potential (ADP), elements [Sb eq.]	1.4E-07
Abiotic Depletion Potential (ADP), fossil fuels [MJ], ultimate reserves	70.2

## Output

### Climate Change

The impact category climate change is represented by the Global Warming Potential (GWP) with a time horizon of 100 years. The applied characterisation factors are basing on the last report of the Intergovernmental Panel on Climate Change [IPCC 2007].

Table 17: Global Warming Potential (100 years) per 1 kg PP

Climate change	kg CO <sub>2</sub> eq.
Global Warming Potential (GWP)	1.63

### Acidification

The Acidification Potential (AP) is quantified according to HAUSCHILD 1998 with updated characterisation factors of CML [CML 2012].

Table 18: Acidification Potential per 1 kg PP

Acidification of soils and water bodies	g SO <sub>2</sub> eq.
Acidification Potential (AP)	4.32

### Eutrophication

The Eutrophication Potential (EP) is calculated according to HEIJUNGS 1992 with updated characterisation factors of CML [CML 2012].

Table 19: *Eutrophication Potential per 1 kg PP*

<b>Eutrophication of soils and water bodies</b>	<b>g PO<sub>4</sub><sup>3-</sup> eq.</b>
Eutrophication Potential (EP), terrestrial	0.38
Eutrophication Potential (EP), aquatic [g PO <sub>4</sub> <sup>3-</sup> eq.]	0.80
Eutrophication Potential (EP), total [g PO <sub>4</sub> <sup>3-</sup> eq.]	1.18

### Ozone Depletion

The calculation of Ozone Depletion Potential (ODP) is based on characterisation factors of the World Meteorological Organisation [WMO 2011]. This implies also the consideration of dinitrogen monoxide (N<sub>2</sub>O) as ozone depleting substance with an ODP of 0.017 kg CFC-11 eq. per kg of N<sub>2</sub>O. This emission plays a relevant role for the overall ODP result of the considered products in this study with 62 % to 85 %.

Table 20: *Ozone Depletion Potential per 1 kg PP*

<b>Ozone Depletion</b>	<b>g CFC-11 eq.</b>
Ozone Depletion Potential (ODP)	5.5E-04

### Summer Smog

The Photochemical Ozone Creation Potential (POCP) is quantified according to JENKIN 1999 and DERWENT 1998 with updated characterisation factors of CML [CML 2012].

Table 21: *Photochemical Ozone Creation Potential per 1 kg PP*

<b>Summersmog</b>	<b>g Ethene eq.</b>
Photochemical Ozone Creation Potential (POCP)	3.7E-01

### Dust & Particulate Matter

Particulate matter with an aerodynamic diameter of less than 10 µm (PM10) is suspected to cause heart and circulatory diseases. Studies from internationally recognised organisations (e.g. WHO 2006) confirm a high mortality risk from fine dust. Large scale air pollution of PM10 is caused by direct emissions of particulate matter and secondary particles that are formed by precursors such as nitrogen dioxide (NO<sub>2</sub>), sulphur dioxide (SO<sub>2</sub>), ammonia (NH<sub>3</sub>) and Non-Methane Volatile Organic Compounds (NMVOC). The characterisation factors shown in Table 22 are based on works of DE LEEUW 2002 and HELDSTAB 2003 for NMVOC.

Table 22: *PM10 characterisation factors of air emissions according to DE LEEUW (2002) and HELDSTAB (2003)*

<b>PM10 and precursors</b>	<b>kg PM10 eq. / kg air emission</b>
Particulate matter PM10	1
Secondary aerosol formers (precursors)	
NO <sub>x</sub> (as NO <sub>2</sub> )	0.88
SO <sub>2</sub>	0.54
NH <sub>3</sub>	0.64
NMVOC	0.012

Table 23: *PM10 emissions per 1 kg PP*

<b>Particulate matter</b>	<b>g PM10 eq.</b>
PM10, direct emissions	0.25
PM10, secondary	3.71
PM10, total	3.97

## Dominance Analysis

Table 24 shows the main contributions to the results presented above. In this context, foreground process refers to the polyolefin production itself, including monomer purification, polymerisation reactors, extrusion, pelletising, heat exchangers, compressors, flares, as well as on-site utilities like water preparation and wastewater treatment. Expenses and emissions concerning electric and thermal (including on-site generation of compressed air and nitrogen) energy production for the foreground process are treated separately. The section (co-) monomer production refers to the monomer ethylene but also to co-monomers like propylene, 1-butene, and others including their pre-chain from the extraction of fossil resources to gate. Other raw materials include initiators, catalysts, solvents or additives and their pre-chain. Transport includes the transport of all the materials directly fed to the foreground process (i.e. (co-)monomers and raw materials). Disposal refers to the waste treatment and the transport of wastes to the respective treatment facility. It is shown in Table 24, that the monomer (and and co-monomer) production is dominating the impact factors 'Total Primary Energy', 'ADP, fossil', AP, EP, and PM10 with shares of more than 80 %, respectively. Electricity needed for the polymerisation processes also has a significant impact, especially on GWP. Concerning 'ADP, elements', the second important contribution is caused by 'Other Raw Materials', mainly by catalysts and pigments. The comparably high share of polymer production on POCP impact is mainly caused by venting of propylene directly to the atmosphere.

Table 24: Dominance analysis of impacts per 1 kg PP

	Total Primary Energy [MJ]	ADP Elements [kg Sb eq.]	ADP Fossil [MJ]	GWP [kg CO <sub>2</sub> eq.]	AP [g SO <sub>2</sub> eq.]	EP [g PO <sub>4</sub> <sup>3-</sup> eq.]	POCP [g C <sub>2</sub> H <sub>4</sub> eq.]	PM10 [g PM10 eq.]
<b>Foreground process</b> (polyolefin production)	0.0%	0.0%	0.0%	3.1%	2.7%	1.0%	13.1%	2.1%
<b>Electricity</b> for foreground processes	3.8%	1.8%	1.7%	8.6%	6.5%	3.0%	2.2%	6.6%
<b>Thermal energy and utilities</b> for foreground processes	1.9%	0.4%	1.9%	2.9%	2.7%	1.7%	1.4%	2.4%
<b>Monomer production</b>	93.7%	77.4%	95.8%	84.0%	86.1%	92.6%	81.3%	87.0%
<b>Other raw materials</b>	0.6%	20.4%	0.5%	1.0%	1.5%	1.6%	1.8%	1.5%
<b>Transport of monomers and other raw materials</b>	0.0%	0.0%	0.0%	0.1%	0.3%	0.1%	0.1%	0.3%
<b>Disposal</b>	0.0%	0.0%	0.0%	0.3%	0.1%	0.1%	0.0%	0.1%
<b>Total</b>	100%	100%	100%	100%	100%	100%	100%	100%

### Comparison of the present Eco-profile with its previous version of EPD (2008)

Table 25 compares the present results with the previous version of the EPD from 2008, which is based on the Eco-profile from 2005 [BOUSTEAD 2005D]. As shown in Table 24, the results are dominated by the monomer production, i.e. crude oil and natural gas extraction and transport, the refinery, and the steam cracking and FCC processes. Furthermore, the previous versions of the Eco-profiles of both propylene [PLASTICSEUROPE 2012B] and polypropylene [BOUSTEAD 2005D] are based on data collected for the reference year 1999. These facts should be kept in mind when comparing the two Eco-profiles. Additionally, the documentations of the EPDs from 2008 and of the Eco-profiles from 2005 do not contain comprehensive details of the calculation background. Thus, while a comparison between previous and current results is fundamentally possible, the analysis of the differences is based on assumptions instead of documented facts.

Concerning the consumption of energy resources, a slight increase is reported. This increase is almost the same as the increase in energy resources consumption reported for the propylene monomer production [PLASTICSEUROPE 2012B]. As shown there, the consumption of energy resources for propylene production is dominated by crude oil and natural gas extraction. Therefore, the observed increase is partly due to the increasing effort for the extraction of fossil fuels during the last decade. Another important cause for the increase in the energy demand for propylene production is the fact that the allocation of ecological burdens has been handled differently between the current report on steam cracker products and its previous version: formerly, the burdens of steam cracking were allocated evenly to all output products (mass allocation). In the recent approach, a distinction is made between high value chemicals (HVC) and low value products, transferring the main ecological burdens to HVCs like propylene.

For the Global Warming Potential (GWP) significantly lower values are reported compared to the previous report on polypropylene. GWP is also dominated by monomer production, but also by electricity for both monomer production and polymerisation. In addition, while the previous version of the Eco-profile for polypropylene only considered propylene from steam cracker, this updated Eco-profile for PP also takes into

account propylene from FCC (with a share of 23 % of total propylene input). Propylene from FCC has a Cumulated Energy Demand (CED) of about 10 % less than the CED of propylene from steam cracking; moreover, the GWP of propylene from FCC is about 40% less than the GWP of propylene from steam cracking. Therefore, the newly introduced share of propylene from FCC contributes substantially to the reduction in GWP. Additionally, the improved efficiency in polymerisation processes during the last years (larger facilities, improved energy efficiency, and increased yields due to improved catalysts) is likely to further contribute to the GWP reduction.

Concerning the Acidification Potential (AP) and the Photochemical Ozone Creation Potential (POCP), improvements related to flue gas treatment especially in refineries and steam cracking units, but also concerning the extraction of fossil fuels are most likely responsible for the positive change in these impact categories during the last decade. The Eutrophication Potential (EP) is a parameter summarising a lot of substances emitted into water bodies. A large share of these substances was not considered in the data collection in 1999, so that the EP in the previous report can be considered as systematically too low; a comparison is thus not appropriate.

Table 25: Comparison of the present Eco-profile of PP with its previous version (2008)

<b>Environmental Impact Categories</b>	<b>Eco-profile PP (2008)</b>	<b>Eco-profile PP (2013)</b>	<b>Difference</b>
Gross primary energy from non-renewable resources [MJ]	73.00	77.10	+5.6%
Gross primary energy from renewable resources [MJ]	0.40	0.75	+87.2%
Global Warming Potential (GWP) [kg CO <sub>2</sub> eq.]	2.00	1.63	-18.7%
Acidification Potential (AP) [g SO <sub>2</sub> eq.]	6.13	4.32	-29.6%
Eutrophication Potential (EP) [g PO <sub>4</sub> <sup>3-</sup> eq.]	0.74	1.18	+59.7%
Photochemical Ozone Creation Potential [g Ethene eq.]	0.92	0.37	-59.7%

# Review

## Review Summary

As part of the PlasticsEurope Polyolefins Group programme management and quality assurance, DEKRA Consulting GmbH conducted an external independent critical review of this work. The outcome of the critical review is reproduced below. The subject of this critical review was the development of the Eco-profile for Polypropylene (PP).

The project included milestone meetings with representatives of participating producers, the LCA practitioner, and the reviewer. Furthermore, various review meetings between the LCA practitioner and the reviewer were held, which included a model and database review and spot checks of data and calculations. The final Eco-profile report was also reviewed by members of the Polyolefins Group and the reviewer. All questions and recommendations were discussed with the LCA practitioner, and the report was adapted and revised accordingly.

Original industry data were collected for all foreground processes taking into account the specific technologies in place for PP production. The monomer production including all upstream processes until raw material extraction was modelled based on the Eco-profile for Steam Cracker Products [PlasticsEurope 2012]. For the share of propylene feedstock produced by catalytic cracking (FCC) however, an IFEU-internal model of petroleum refinery was used. Primary industry data was collected from 35 production sites of 7 companies which led to an overall representativeness of 76.7% of the European polypropylene production capacity.

The potential environmental impacts for PP are dominated by monomer (and co-monomer) production across most impact categories. Electricity needed for the polymerisation processes also has a significant impact (e.g. 8.6% for GWP). The results for ADP elements are driven by the use of pigments and catalysts, POCP scores are dominated by venting of propylene directly to atmosphere.

During this review, great attention was paid to the comparison of the results with the previous version of the polypropylene Eco-profile. Hence, this report contains a detailed justification for the observed changes that is to the best knowledge and expert judgment of the LCA practitioner and reviewers.

The LCA practitioner has demonstrated very good competence and experience, with a track record of LCA projects in the chemical and plastics industry. 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). As a result, this dataset is assessed to be a reliable and high quality representation of PP produced in Europe.

## Reviewers Names and Institution

Matthias Schulz, Product Line Manager, Sustainable Products & Strategy, DEKRA Consulting GmbH, Stuttgart, Germany

Dr.-Ing. Ivo Mersiowsky, Business Line Manager, Sustainable Products & Strategy, DEKRA Consulting GmbH, Stuttgart, Germany

Guy Castelan, December 2016: Modifications to water Balance pages 4 and 33 to differentiate water use and water consumption.

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**PlasticsEurope AISBL**

*Avenue E. van Nieuwenhuysse  
4/3*

*B-1160 Brussels † Belgium*

*Phone +32 (0)2 675 3297*

*Fax +32 (0)2 675 3935*

*info@plasticseurope.org*

*www.plasticseurope.org*