



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

High-density Polyethylene (HDPE),  
Low-density Polyethylene (LDPE),  
Linear Low-density Polyethylene (LLDPE)

PlasticsEurope

April 2014

December 2016: update water balance



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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 polyolefins from cradle to gate (i.e. from raw material extraction to polymer resin at plant): High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), and Linear Low-density Polyethylene (LLDPE). **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	52
Representativeness	HDPE 68%; LDPE 72%; LLDPE 86%
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 HDPE, LDPE, and LLDPE resins.

### Production Process

PE is produced by polymerisation of ethylene. In Europe, most of the ethylene is produced by steam cracking of naphtha. This Eco-profile comprises extraction and refinery of crude oil and natural gas, steam cracking of hydrocarbons into lower olefins, and polymerisation of the monomers into PE. The model represents commercial PE 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 [PlasticsEurope 2012]. 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 was 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 PE resins have a wide range of applications, even a qualitative discussion of these aspects was deemed inap-

appropriate. 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 each PE grade; abbreviated as follows: High-density (HDPE), Low-density (LDPE), and Linear Low-density Polyethylene (LLDPE).

## Additional Environmental and Health Information

The monomer ethylene is a short chain olefin and is therefore categorised as a Volatile Organic Compound (VOC). It possesses a Photochemical Ozone Creation Potential (POCP, ethylene or ethene is the reference substance 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

Soft, flexible and tough, LDPE is mainly used in films, e.g. plastic bags, packaging, and agricultural films. It is also used for electrical cable coating, the main application for LDPE in the past. More rigid and less bendable, HDPE is used to make stable plastic containers, crates, bottles, containers, pipes, and industrial wrapping and films. Very tough and flexible, LLDPE is used for stretch films, industrial packaging, thin-walled containers, and multilayer films.

## Additional Economic Information

PE is one of the economically most important thermoplastics with an annual production volume of more than 11 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.

### Input Parameters

Indicator	Unit	HDPE	LDPE	LLDPE
Non-renewable energy resources <sup>1)</sup>				
• Fuel energy	MJ	31.5	33.7	30.5
• Feedstock energy	MJ	47.8	47.8	47.8
Renewable energy resources (biomass) <sup>1)</sup>				
• Fuel energy	MJ	0.8	1.4	0.9
• Feedstock energy	MJ	0.0	0.0	0.0
Abiotic Depletion Potential (ADP)				
• Elements	kg Sb eq.	4.4E-08	5.2E-08	6.5E-08
• Fossil fuels	MJ	72.0	72.8	71.3
Water "cradle to gate"				
• use = withdrawal	kg	73.6	116.5	130.8
• consumption	kg	31.9	55.2	49.2

<sup>1)</sup> Calculated as upper heating value (UHV)

### Output Parameters

Indicator	Unit	HDPE	LDPE	LLDPE
Global Warming Potential (GWP)	kg CO <sub>2</sub> eq.	1.80	1.87	1.79
Ozone Depletion Potential (ODP)	g CFC-11 eq.	6.4E-04	8.2E-04	5.7E-04
Acidification Potential (AP)	g SO <sub>2</sub> eq.	4.28	4.36	4.33
Photochemical Ozone Creation Potential (POCP)	g Ethene eq.	6.3E-01	1.3E+00	4.7E-01
Eutrophication Potential (EP)	g PO <sub>4</sub> eq.	1.20	1.25	1.15
Dust/particulate matter ( $\leq 10 \mu\text{m}$ ) <sup>2)</sup>	g PM <sub>10</sub>	3.97	4.09	4.01
Total particulate matter <sup>2)</sup>	g	4.31	4.45	4.31

Waste (only from polyolefin production, before treatment)				
• Non-hazardous	kg	1.28E-03	2.38E-03	8.35E-04
• Hazardous	kg	9.30E-04	3.06E-03	5.61E-04

<sup>2)</sup> Including secondary PM10

## Information

### Data Owner

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

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### 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 2014-001, validation expires on 31 December 2016 (date of next revalidation review).

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

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### 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: Ecoprofiles and Environmental Product Declarations of the European Plastics Manufacturers - 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 Low-density Polyethylene (LDPE); 1 kg of Linear Low-density Polyethylene (LLDPE); 1 kg of High-density Polyethylene (HDPE), each »at gate« (production site output) representing a European industry production average.*

## Product and Producer Description

### Product Description

The products considered in this Eco-profile and EPD are the polyolefins High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), and Linear Low-density Polyethylene (LLDPE). This Eco-profile represents the average industrial production of each of these products. Main characteristics of the polyolefins under investigation are presented in Table 1.

Table 1: Characteristics of PE

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>
HDPE	9002-88-4	C <sub>2</sub> H <sub>4</sub>	0.94–0.97	130–145 °C	46.2
LDPE	9002-88-4	C <sub>2</sub> H <sub>4</sub>	0.91–0.93	130–145 °C	46.2
LLDPE	9002-88-4	C <sub>2</sub> H <sub>4</sub>	0.87–0.94	45–125 °C	46.2

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

Polyethylene 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. PE 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 of PE is indicated with more than 8,000 kt/year [PLASTICSEUROPE 2012A]. The main applications for polyolefins are packaging products (see Figure 1). LDPE and LLDPE are mainly used as films, e.g. for the production of plastic bags, packaging material, and agricultural films. It is also used for electrical cable coating. HDPE is mainly used to make stable plastic containers, crates, bottles, containers, and pipes (in the building and construction sector), as well as for industrial wrapping and films. Other applications of the polyolefins include various sectors such as consumer and household appliances, furniture, agriculture, sport, health and safety [PLASTICSEUROPE 2012A].

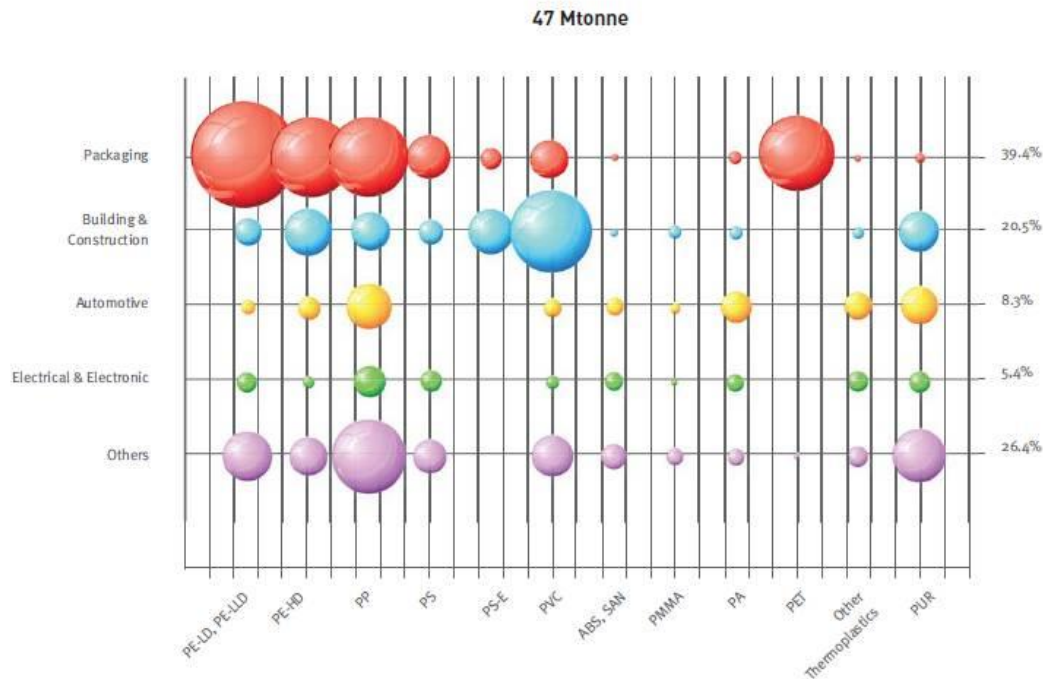


Figure 1: European (EU27+NO+CH) plastics demand by segment and resin type 2011. Source: PlasticsEurope Market Research Group [PEMRG]. Quoted from: [PlasticsEurope 2012].

## Structure of PE

Polyolefins are based on crude oil. The raw materials are ethene and propene as monomer for HDPE, LDPE, and LLDPE. 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, therewith form a radical and attach itself to another monomer molecule (see Figure 2). By constantly repeating this process, long polymer chains can be created [Domininghaus 2012; Boustead 2005a, Boustead 2005b, Boustead 2005c, Boustead 2005d, Schwarz 2007, Kaiser 2011].

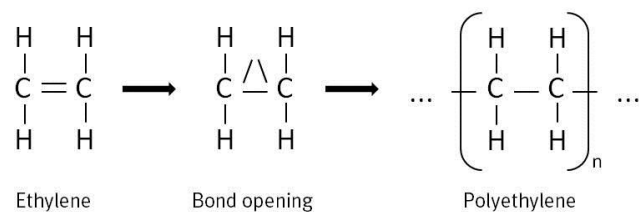


Figure 2: Schematic diagram of the formation of polyethylene

The described process is referred to as addition polymerisation, as the monomer units are continually added. Thus, polymerised ethene and propene form an unbroken carbon backbone. The structure of the different PE resins, however, varies. As the name suggests, e.g. linear polyethylene generates a highly linear structure (see Figure 3).

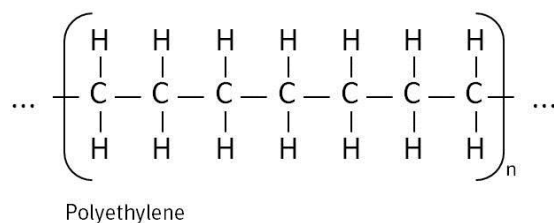


Figure 3: Schematic structure of linear polyethylene

Depending on the polymerisation process and technique, variations of this structure can be achieved. Therefore, the product properties can be influenced, e.g. by the variation of branching and by the polymerisation factor. Products may differ by density, molar mass, or flexibility. Further, the addition of co-monomers like C<sub>4</sub> to C<sub>8</sub> olefins influence the polymerisation and can also change the properties of the final resin. By changing the structure of the polymer chains, product variations can be achieved. For example see Figure 4, where co-monomers were added and form LDPE.

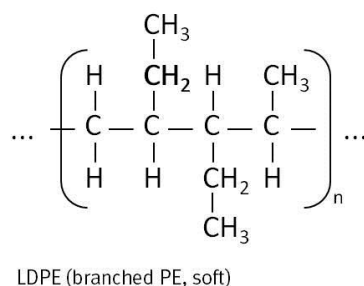


Figure 4: Schematic diagram of the formation of LDPE

### Characteristics of HDPE

HDPE is the most rigid and least flexible of the different grades of polyethylene [BREF 2007; Domininghaus 2012; Boustead 2005a, Boustead 2005b, Boustead 2005c, Boustead 2005d, Schwarz 2007, Kaiser 2011]. This is due to the amount of side branches: whereas HDPE has the same repeat unit as LDPE (see Figure 4), with 3 to 5 methyl side groups per 1000 carbon atoms on the backbone, it shows much fewer branches, which are usually short. Long side branches are very rare. This leads to a density that is always higher than 0.940 g/cm<sup>3</sup> and is referred to as up to 0.960 g/cm<sup>3</sup>. The molecular weight is similar to LDPE, but crystallinity is usually high (50–85%).

### Characteristics of LDPE

LDPE is the oldest type of polyethylene [BREF 2007; Domininghaus 2012; Boustead 2005a, Boustead 2005b, Boustead 2005c, Boustead 2005d, Schwarz 2007, Kaiser 2011]. Unlike HDPE, Low-density Polyethylene is soft, tough, and flexible, which is due to its highly branched molecular structure. At the repeat unit of LDPE (see Figure 4), 20 to 40 methyl side groups (CH<sub>3</sub>) as well as 0.5 to 5 long chain branches per 1000 carbon atoms can occur. Those long branches can reach the length of the carbon chain itself. The produced chain length ranging from 50,000 to 100,000 repeat units, with crystallinities in the range 35–75%. This leads to a loosely packed molecular structure. Due to that, this resin shows a low density. LDPE is defined by a density of less than 0.940 g/cm<sup>3</sup> – the typical density is referred to as between 0.915 g/cm<sup>3</sup> up to 0.935 g/cm<sup>3</sup>.

## Characteristics of LLDPE

LLDPE is the youngest of the polyethylene types [BREF 2007; Domininghaus 2012; Boustead 2005a, Boustead 2005b, Boustead 2005c, Boustead 2005d, Schwarz 2007, Kaiser 2011]. It is very tough and can keep its shape, and it can be used to make flexible as well as rigid products. LLDPE is a copolymer of ethene with another short chain olefin ( $C_4$ – $C_8$ ). The most common co-monomers are 1-butene, 1-hexene, 4-methyl-1-pentene, and 1-octene. The co-monomer is usually present in concentrations of 2.5–3.5 wt.%. The molecular structure is similar to HDPE, with a linear structure, but lower crystallinity (30–45 %), due to a larger number of short chain branches. Due to that structure, the density ranges between 0.915 g/cm<sup>3</sup> and 0.925 g/cm<sup>3</sup>, whereas the density decreases with increasing share of short chain olefins.

## Technology description

In the plastics industry, chain polymerisation is the most important reaction process (compared to step-growth polymerisation) and is used to produce PE and polypropylene (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 [BREF 2007, Kaiser 2011, Whiteley 2000] 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. Ethene and propene produced of 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 HDPE, LDPE, and LLDPE, 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 specific types of polyolefins as well as their product properties, different processes and technologies are applied. The main differences can be found in the choice of process technology, reactor type and catalyst types resp. initiators. Figure 5 illustrates the mainly used variety of technologies, processes and catalyst types within the PO production (including polypropylene production) whereas the following section generally describes those individual production processes of the polyolefins HDPE, LDPE, LLDPE.

Possible combinations of main process technologies, reactor types and catalysts			
<b>HDPE</b>	<b>PROCESS TECHNOLOGY</b> slurry suspension gas phase slurry suspension/gas phase solution	<b>REACTOR TYPE</b> stirred tank (CSTR) loop reactor (recycle) fluidised bed (FB) loop + FB in series	<b>(Co-)CATALYST</b> Ziegler-Natta Phillips metallocene
<b>LDPE</b>	<b>PROCESS TECHNOLOGY</b> high pressure	<b>REACTOR TYPE</b> autoclave tubular	<b>INITIATOR</b> organic peroxides oxygen oxygen/peroxides mixture
<b>LLDPE</b>	<b>PROCESS TECHNOLOGY</b> gas phase solution	<b>REACTOR TYPE</b> stirred tank (CSTR) fluidised bed (FB)	<b>(Co-)CATALYST</b> Ziegler-Natta metallocene

Figure 5: Most important process technologies, reactor types, and catalysts applied in polyethylene production by polymer type

## Manufacturing of Polyolefins

**HDPE** is mainly produced with the slurry suspension, solution or the gas phase process, which belong to the low-pressure technologies. As mentioned above, the suspension process can be combined with a stirred tank reactor or a loop reactor. For the suspension process, different diluents can be chosen, like C5 to C9 hydrocarbons, hexane, or isobutane. For the gas phase process, usually fluidised bed reactors are used. Furthermore, a combination of suspension and gas phase process is possible, with propane as the diluent in a series with a fluidised bed reactor. As catalysts, usually Ziegler-Natta or Phillips-type catalysts are applied, but metallocene-type catalysts can also be used. Due to this wide range of choice of process technology, reactor type, or catalyst type, a typical process for HDPE production cannot be defined. Additionally to the different types of technology, the product properties can be influenced by the choice of the co-monomers (1-butene or 1-hexene), which are able to control the polymer density, as well as by the use of hydrogen, which influences the molecular weight. Thus, HDPE can be produced with a wide range of specified properties.

**LDPE** is produced through high-pressure polymerisation, which is actually a very generic process. The individual process parameters, however, are proprietary information of each producer, as the properties of the products are controlled by those process parameters. As typical initiators to start the polymerisation process, organic peroxides and oxygen are used. Furthermore, polar modifiers (aldehydes, ketones, or alcohols) or aliphatic hydrocarbons are fed into the monomer stream to control the molecular weight distribution.

**LLDPE** is either produced in the gas phase process in a fluidised bed reactor or in the solution process. Depending of the kind of co-monomer chosen, the kind of used technology has to be adapted. If 1-butene is used as co-monomer, usually the gas phase process is chosen, for 1-octene as co-monomer, the solution



process is preferable. For a polymerisation process with 1-hexene as co-monomer, however, both technologies can be applied. The gas phase process designed for the LLDPE production is also used for the production of HDPE.

### **Description of Process Technology**

The polymerisation technologies can be classified according to their reaction conditions into high and low pressure processes. For low pressure, three main subcategories can be distinguished based on the reaction phase:

- Slurry suspension polymerisation
- Solution polymerisation
- Gas phase polymerisation

In high pressure polymerisation, which is exclusively used for LDPE production, the product properties are defined mainly by process parameters, like pressure and temperature, and by the choice of co-monomers. In the low pressure processes, however, which are used for HDPE and LLDPE production, product properties are mainly defined by the used catalyst type and co-monomers. 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 it is the case in radical polymerisation), allows the highly defined structure of HDPE and LLDPE 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.

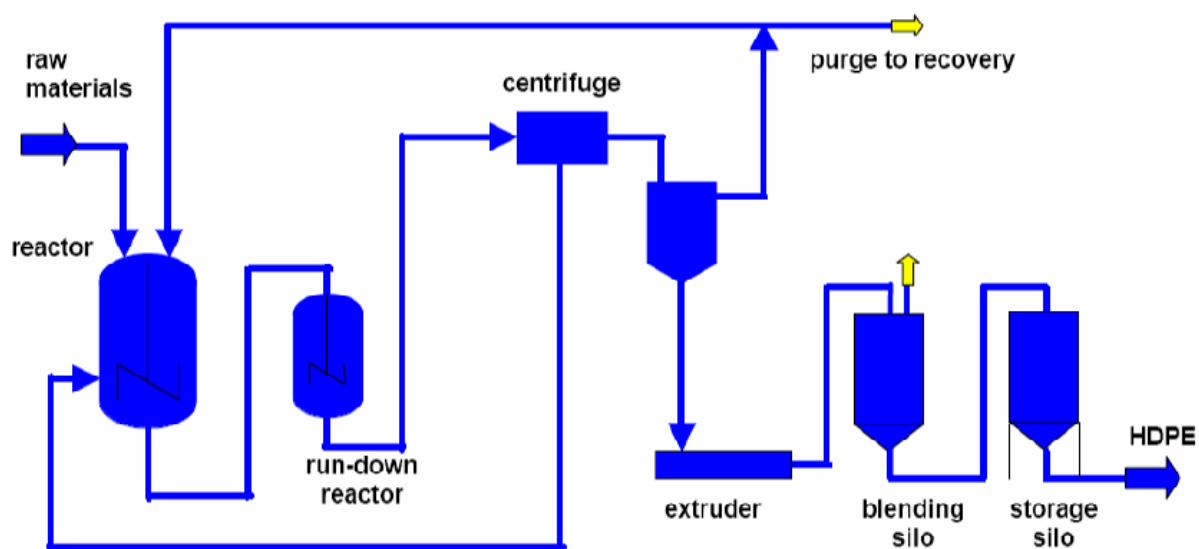


Figure 6: Flow diagram of HDPE production as an example of the suspension process with stirred tank reactors [BREF 2007]

#### Solution Polymerisation

For solution polymerisation, the hydrocarbon solvent (C<sub>9</sub>-C<sub>6</sub>) is kept at high temperature (>130 °C) to ensure that the formed polymer stays dissolved after production. In a subsequent step, the solvent is evaporated and recycled, and the liquid polymer can directly be sent to the extruder. The solution process technology is much specified. Individual process set-up and operating conditions of manufacturers are considered as proprietary information.

#### 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.

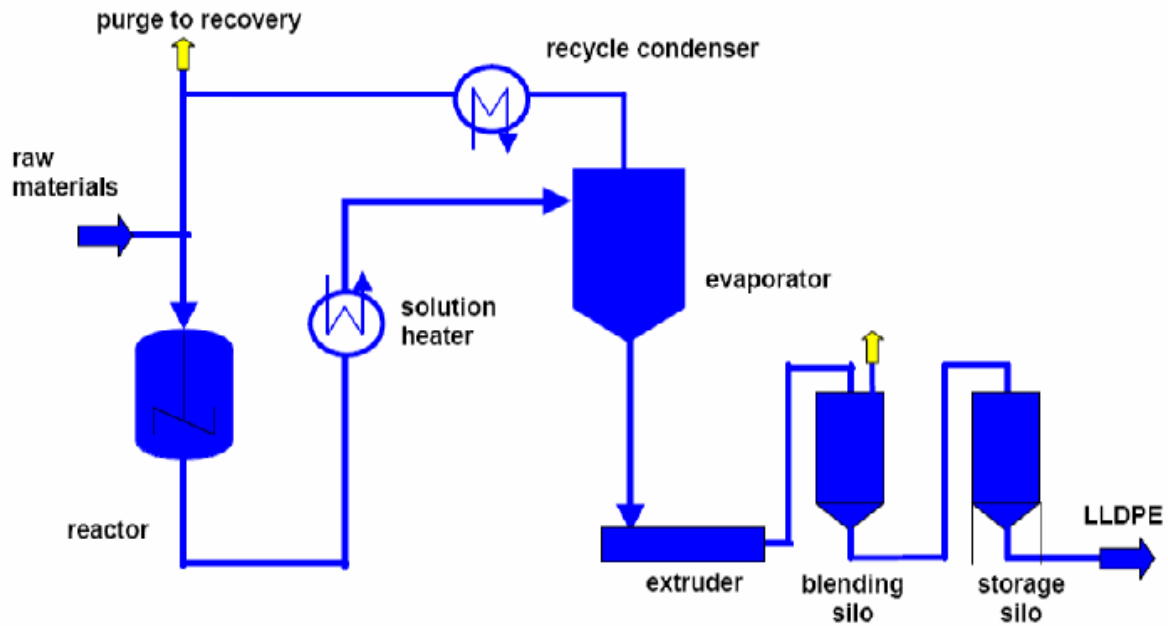


Figure 7: Flow diagram of LLDPE production as an example of the solution process [BREF 2007]

#### High-pressure Polymerisation

With this technology, ethylene is polymerised to polyethylene at pressures of 1500 to 3500 bar and temperatures of about 200°C. Under those conditions, oxygen or peroxides work as initiators to start the radical polymerisation process. The reaction may take place either in an autoclave or a tubular reactor. Both techniques, however, work with two pressure ranges, whereas the (second) compressor used for the high pressure process is sometimes called a hyper compressor. Due to the high operating pressures, special equipment is required for the whole polymerisation process. The polymerisation is an exothermic reaction. The ethylene gas is used as a heat sink for the resulting heat, which means that the ethylene gas cannot be totally converted to polymer. The unreacted gas is directly recycled back into the process and combined with fresh ethylene. Losses due to leaking gas of the compressor are usually recycled the same way within the LDPE closed-loop-recycling process. Furthermore, the heat of the exothermic reaction can be recuperated to generate low pressure steam. The key operating characteristics of this process are usually proprietary information. This is due to the fact that the high-pressure process is described as very generic, whereas the individual product properties, though, are to be designed by specific process conditions and initiator mixtures.

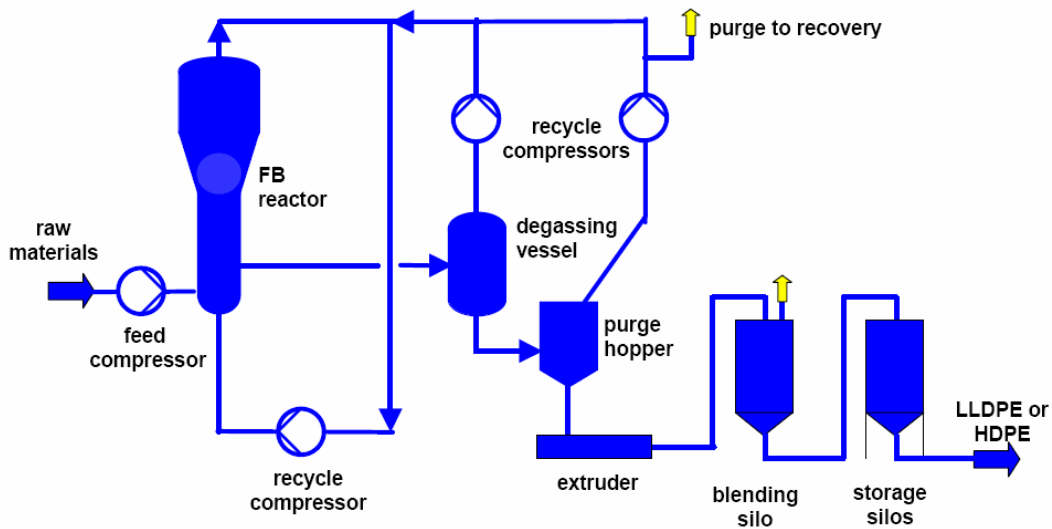


Figure 8: Flow diagram of HDPE production as an example of the gas phase process [BREF 2007]

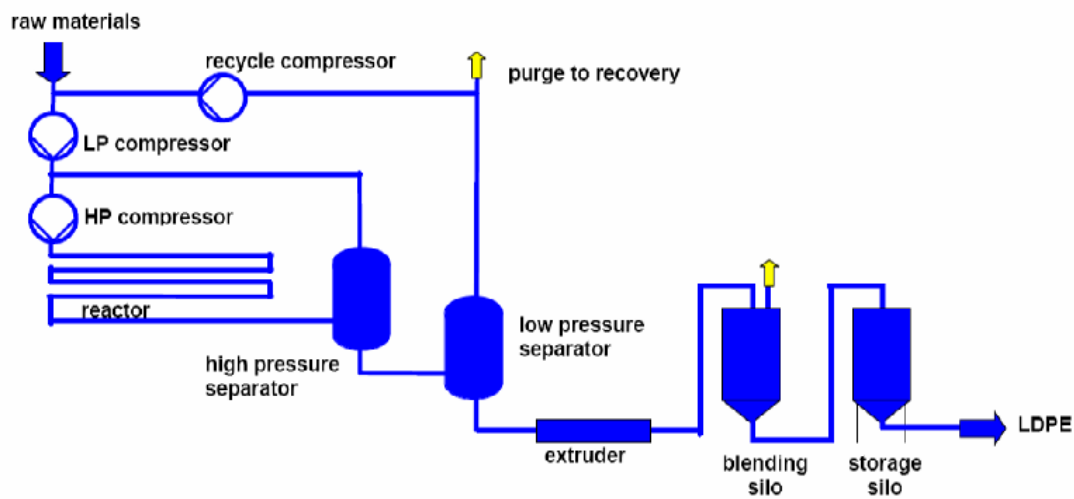


Figure 9: Flow Diagram of LDPE production as an example of the high pressure process [BREF 2007]

### 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 polyolefin production mainly 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 com-

position 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 **Erreur ! Source du renvoi introuvable.**). 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.

**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.

**Initiator systems** — For the polymerisation of LDPE, instead of catalytic systems, initiator systems are required. Typical initiators are oxygen or organic peroxides. The initiator concentrations usually vary between 0.1 and 0.5 wt.-%. Decomposed metal alkyl residues of the initiator remain in the product and sometimes have an influence on end-use properties. Dissociation products of the radical initiator are removed from the polymer or built in.

## Upstream Processes

**Monomer production** — Ethylene for polymerisation is almost exclusively produced by steam cracking. The annual production of ethylene in Europe was 19,559 kt in 2011, the production capacity being 24,212 kt in the same year (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 lion's share 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 ethene, propene, 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 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 %

**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. Despite 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 10). 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. In the following, only the processes relevant for steam cracker feedstock production are described in detail.

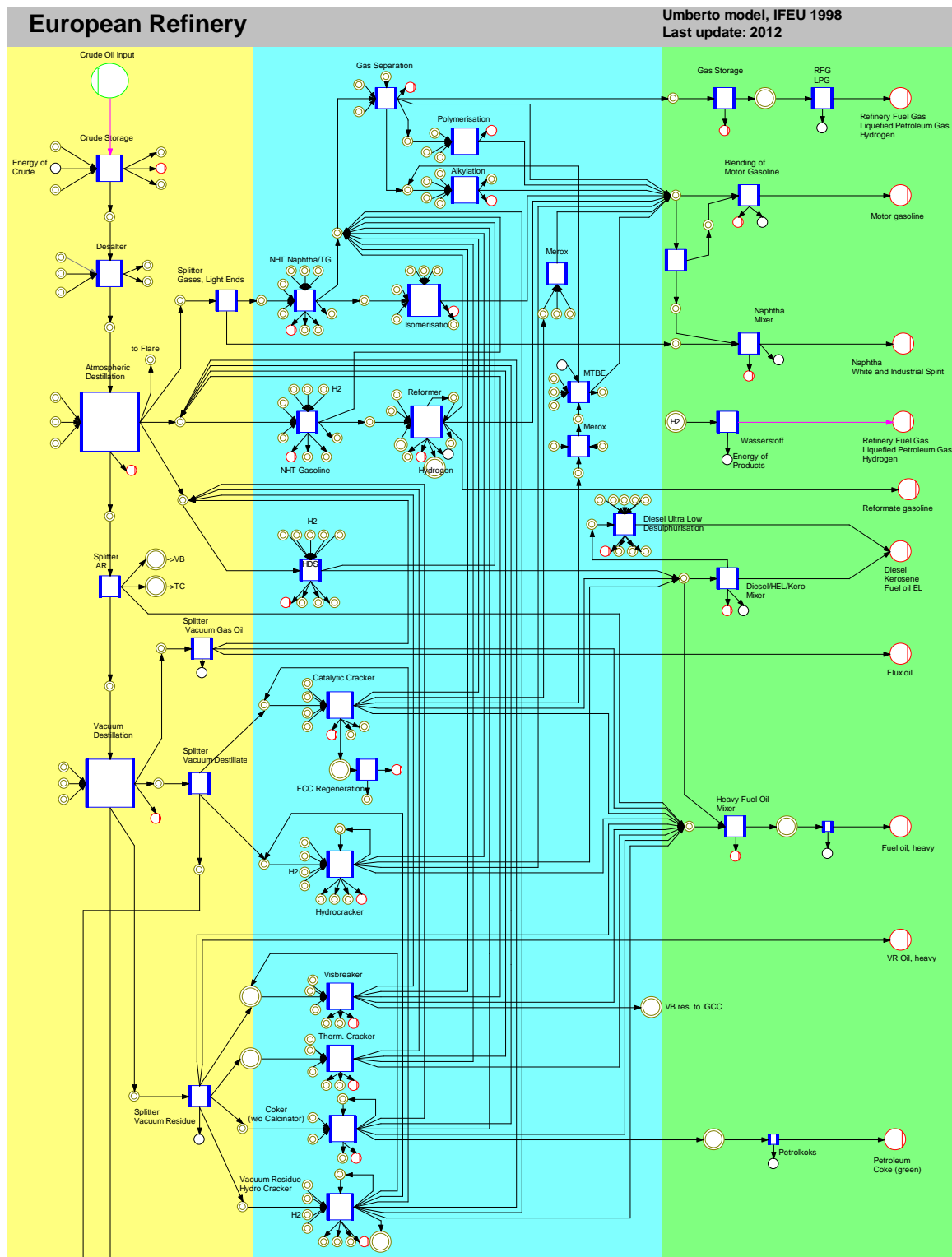


Figure 10: Screenshot of the petroleum refinery model in UMBERTO (Source: IFEU 2012)

**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.

### **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 the Ecoinvent database 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 in-

stead of an average EU27 electricity mix. The described processes of monomer production including all upstream processes until raw material extraction were modelled based on the Eco-profile and EPD 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 refinery [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)

Countries of origin	Share [vol.-%]	Natural gas in ground req'd per kg gas feedstock [kg]	Efficiency [%]	CO <sub>2</sub> emission 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 weighed, by polyolefin production capacity, and by the polyolefin production capacity covered in this study.



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

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

- Versalis S.p.A., Italy
- Dow Europe GmbH, Switzerland
- 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 11).

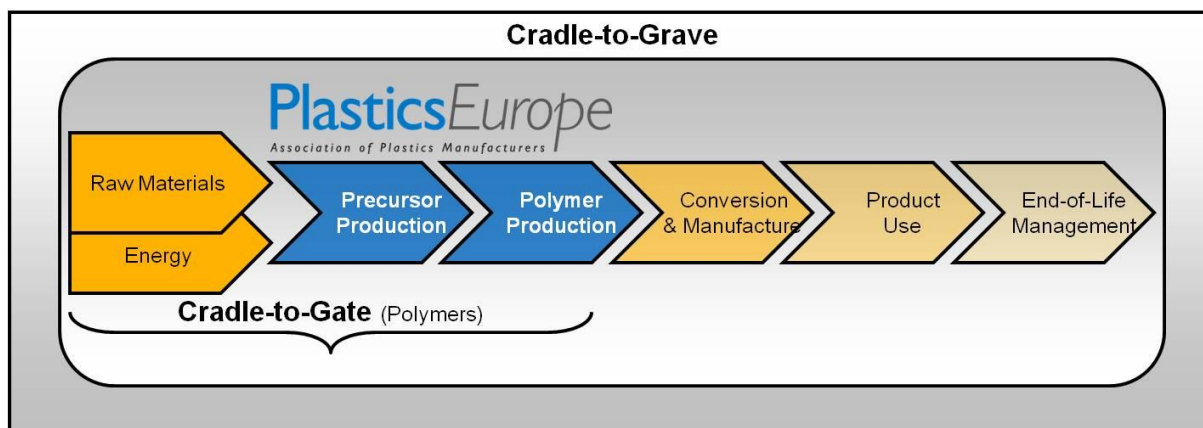


Figure 11: Cradle-to-gate system boundaries

## Cradle-to-Gate System Boundaries for Production

The following processes are included in the cradle-to-gate LCI system boundaries (see also Figure 12):

- 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.

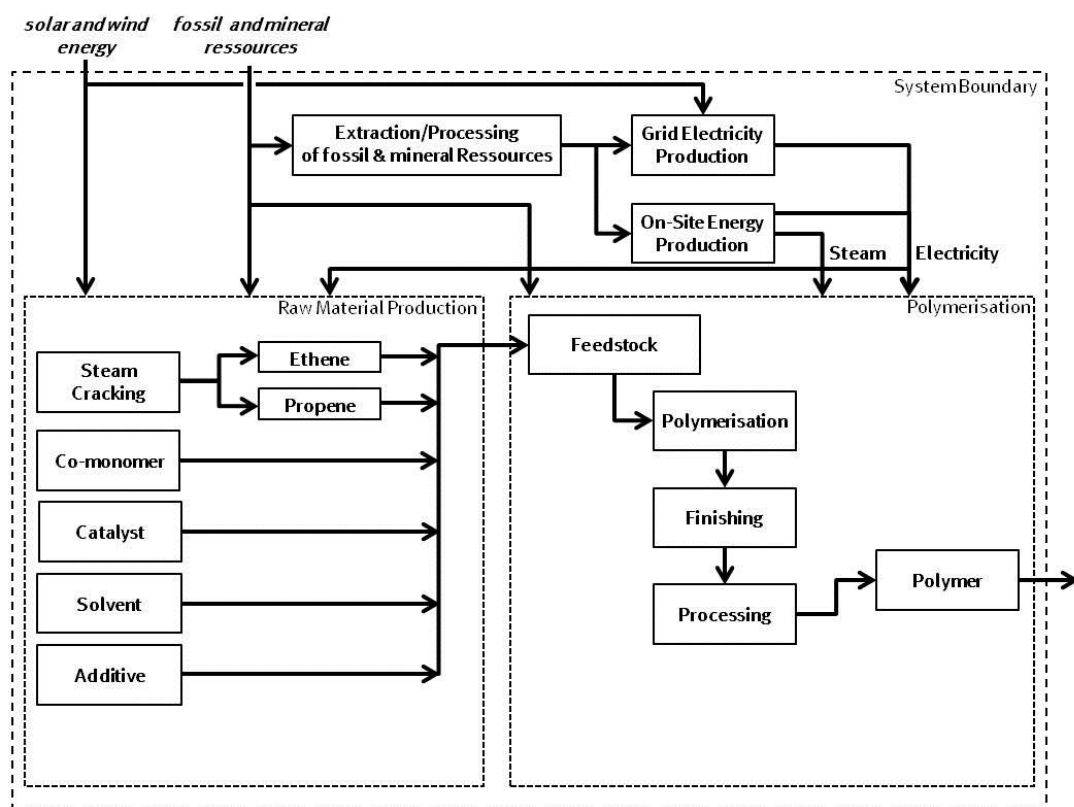


Figure 12: Schematic flow chart of the processes under consideration in this study

## 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 90 polyethylene producing plants in Europe, 64 were selected for participation in this study, representing the plants of PlasticsEurope members. Of those plants, 52 were able to provide data. The remaining 12 polymer plants did not participate in the data collection due to several reasons:

- being in a startup-phase in the year 2011 (1)
- production of other polymers than polyolefins to a proportion higher than 90% (1)
- being in a shut-down phase (2)
- other internal reasons (8)

In the year 2011, the 52 participating represented 74% of the European nameplate capacity for PE production. Relating to the individual polyolefin products, the data coverage can be differentiated as shown in Table 6. Figure 13 illustrates those shares.

Table 6: Participating polyolefin production units and their share in European polyolefin production capacity (nameplate capacity) by product

	Selected units	Participating units	Coverage by nameplate capacity <sup>1)</sup>
HDPE	24	21	68.3 %
LDPE	26	22	72.3 %
LLDPE	14	9	86.4 %
<b>Total</b>	<b>64</b>	<b>52</b>	<b>73.8 %</b>

<sup>1)</sup> Based on installed European nameplate capacity; Source: PlasticsEurope, 2014

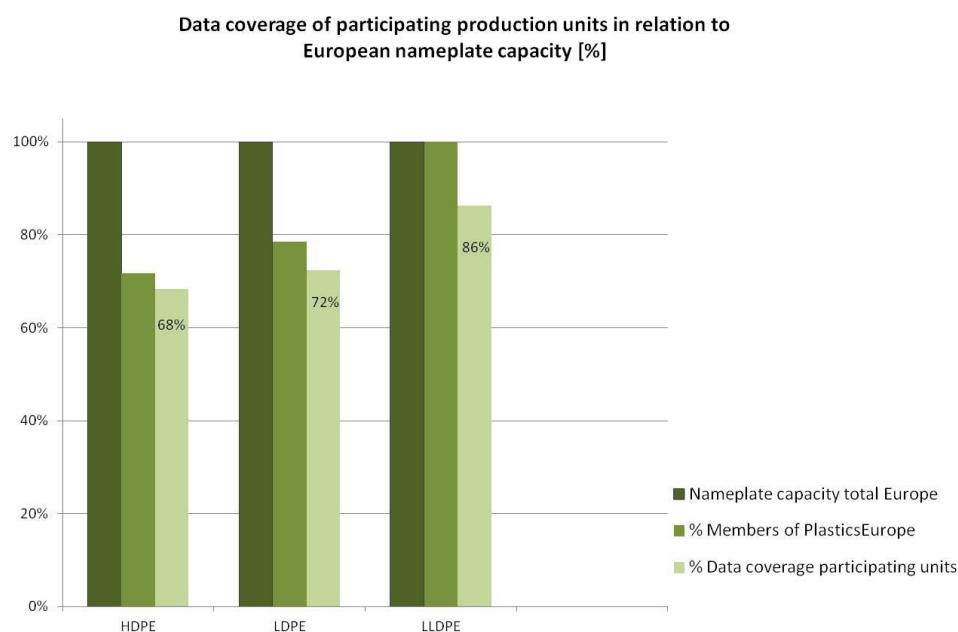


Figure 13: Participating polyolefin production units and their share of European PE production capacity (nameplate capacity) by product (2011)

## 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 52 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 and Germany reach a coverage of 80% and higher. One of two units in Great Britain provided data, which leads to a data coverage just above 50%, whereas the only production site in Poland did not provide data (see Table 7). In total, the geographical reference can be assessed as good.

Table 7: *Data coverage per country, related to production capacity of the participating countries*

Country	Data coverage
Austria	100%
Belgium	100%
Finland	100%
France	84%
Germany	80%
Italy	100%
Netherlands	100%
Norway	100%
Poland	0 %
Portugal	100%
Spain	100%
Sweden	100%
United Kingdom	55%

Fuel and energy inputs into 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, 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.

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 2011.

### **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 74% of the installed polyolefin nameplate capacity in Europe (EU27 + Norway + Switzerland) in 2011. Related to the individual polyolefin products, the coverage is 68% for HDPE, 72% for LDPE, and 86% for LLDPE. 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 can be stated as 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 ethene 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 Figure 14 for 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.



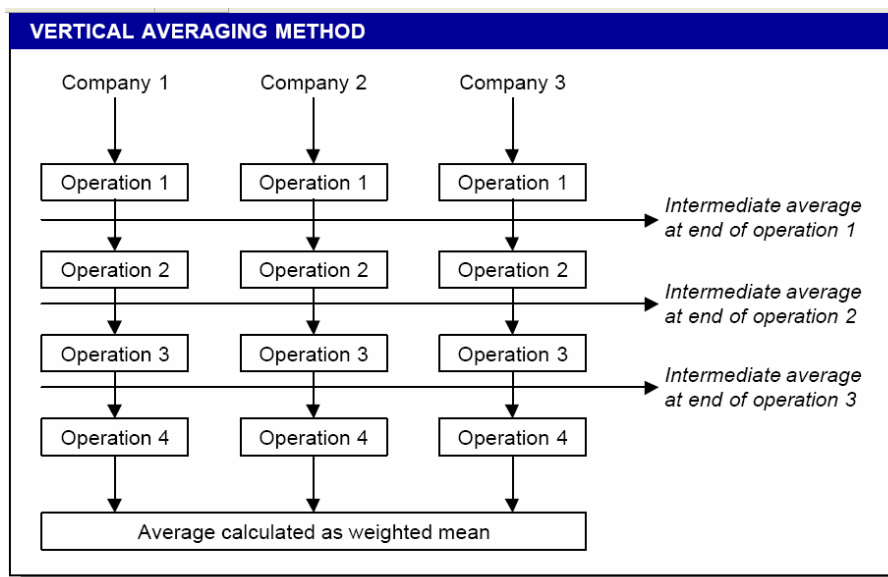


Figure 15: Vertical Averaging (source: *Eco-profile of high volume commodity phthalate esters*, ECPI European Council for Plasticisers and Intermediates, 2001)

### 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 completely different technical performance and product quality output. In such cases, the aim of allocation is to find a suitable partitioning parameter so that the inputs and outputs of the system can be assigned to the specific product sub-system under consideration.

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, propene, hydrogen, and 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 propene 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, propene, 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://lci.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 8, 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 8 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 8: Primary energy demand (system boundary level) per 1 kg of PE

Primary Energy Demand	HDPE	LDPE	LLDPE
Energy content in polymer [MJ] (energy recovery potential, quantified as gross calorific value of polymer)	46.2	46.2	46.2
Process energy [MJ] (quantified as difference between primary energy demand and energy content of polymer)	34.0	36.7	33.0
<b>Total primary energy demand (Upper heating value) [MJ]</b>	<b>80.2</b>	<b>82.9</b>	<b>79.2</b>
Total primary energy demand (Lower heating value) [MJ]	75.3	77.9	74.4

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 9 to Table 11 show 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 9: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg HDPE

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	1.25	0.063		1.25
Oil	59.28	1.294	40.27	19.01
Natural gas	15.65	0.339	7.57	8.08
Lignite	0.64	0.060		0.64
Nuclear	2.57	0.000		2.57
Hydro	0.00			0.00
Solar	0.37			0.37
Geothermal	0.26			0.26
Waves	0.03			0.03
Wood	0.00			0.00
Wind	0.11			0.11
Other renewable fuels	0.00			0.00
<b>Sub-total renewable</b>	<b>0.8</b>	<b>0.0</b>	<b>0.0</b>	<b>0.8</b>
<b>Sub-total Non-renewable</b>	<b>79.4</b>	<b>1.8</b>	<b>47.8</b>	<b>31.5</b>
<b>Total</b>	<b>80.2</b>	<b>1.8</b>	<b>47.8</b>	<b>32.3</b>

Table 10: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg LDPE

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	1.74	0.087		1.74
Oil	58.67	1.281	40.27	18.40
Natural gas	16.70	0.361	7.57	9.13
Lignite	0.62	0.058		0.62
Nuclear	3.79	0.000		3.79
Hydro	0.00			0.00
Solar	0.60			0.60
Geothermal	0.54			0.54
Waves	0.03			0.03
Wood	0.00			0.00
Wind	0.17			0.17
Other renewable fuels	0.00			0.00
<b>Sub-total renewable</b>	<b>1.4</b>	<b>0.0</b>	<b>0.0</b>	<b>1.4</b>
<b>Sub-total Non-renewable</b>	<b>81.5</b>	<b>1.8</b>	<b>47.8</b>	<b>33.7</b>
<b>Total</b>	<b>82.9</b>	<b>1.8</b>	<b>47.8</b>	<b>35.0</b>



Table 11: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg LLDPE

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	1.08	0.054		1.08
Oil	58.26	1.272	40.27	17.99
Natural gas	16.09	0.350	7.57	8.51
Lignite	0.63	0.060		0.63
Nuclear	2.24	0.000		2.24
Hydro	0.00			0.00
Solar	0.38			0.38
Geothermal	0.40			0.40
Waves	0.02			0.02
Wood	0.00			0.00
Wind	0.11			0.11
Other renewable fuels	0.00			0.00
<b>Sub-total renewable</b>	<b>0.9</b>	<b>0.0</b>	<b>0.0</b>	<b>0.9</b>
<b>Sub-total Non-renewable</b>	<b>78.3</b>	<b>1.7</b>	<b>47.8</b>	<b>30.5</b>
<b>Total</b>	<b>79.2</b>	<b>1.7</b>	<b>47.8</b>	<b>31.4</b>

Table 12 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 12: Primary energy demand by renewability

Fuel/energy input type	HDPE	LDPE	LLDPE
Renewable energy resources	1.0%	1.6%	1.1%
Non-renewable energy resources	99.0%	98.4%	98.9%
<b>Total</b>	<b>100.0%</b>	<b>100.0%</b>	<b>100.0%</b>

In Table 13, the types of useful energy inputs into the polymerisation process are analysed. For HDPE and LLDPE both electric and thermal energy inputs play a major role, whereas the LDPE production is a net steam exporting process.

Table 13: Analysis by type of useful energy for polyolefin production process per 1 kg of product

Type of useful energy in process input	HDPE	LDPE	LLDPE
Electricity [MJ]	1.56	3.43	1.27
Heat, thermal energy [MJ]	1.32	-0.25	0.69
<b>Total (for selected key processes) [MJ]</b>	<b>2.88</b>	<b>3.18</b>	<b>1.96</b>

Same as Table 13, 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.

### Water Balance

Table 14 shows the water withdrawal and consumption of the polyolefin “gate to gate” production process considering only the water household of production site, while Table 15 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 14: Gross water resources used in polyolefin “gate to gate” production process per 1 kg of product

Source	HDPE	LDPE	LLDPE
Process water [kg]	0.7	1.2	0.4
Boiler feed water [kg]	0.07	0.36	0.07
Non-contact cooling water [kg]	23.0	41.3	88.7
<b>Water use (= total withdrawal) [kg]</b>	<b>23.7</b>	<b>42.9</b>	<b>89.1</b>
Water output to same water body [kg]	18.4	30.7	67.8
<b>Water consumption [kg]</b>	<b>5.3</b>	<b>12.2</b>	<b>21.4</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 15 Gross water resources used in polyolefin “cradle to gate” production process per 1 kg of product

Source	HDPE	LDPE	LLDPE
Process water [kg]	1.6	4.7	1.2
Non-contact cooling water [kg]	72.1	111.8	129.6
<b>Water use (= total withdrawal) [kg]</b>	<b>73.6</b>	<b>116.5</b>	<b>130.8</b>
Water output to same water body [kg]	41.7	61.3	81.6
<b>Water consumption [kg]</b>	<b>31.9</b>	<b>55.2</b>	<b>49.2</b>

### Air Emission Data

Table 16 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 16: *Selected air emissions of the foreground processes (polyolefin production including on-site utilities) per 1 kg of product*

Air emissions	HDPE	LDPE	LLDPE
Carbon dioxide, fossil (CO <sub>2</sub> , fossil) [kg]	1.90E-01	2.02E-01	1.61E-01
Carbon monoxide (CO) [kg]	8.31E-05	3.14E-05	9.22E-05
Sulphur dioxide (SO <sub>2</sub> ) [kg]	1.68E-04	9.32E-05	1.10E-04
Nitrogen oxides (NO <sub>x</sub> ) [kg]	1.62E-04	1.75E-04	1.31E-04
Particulate matter ≤ 10 µm (PM 10) [kg]	6.86E-06	3.70E-06	3.22E-06

## Wastewater Emissions

Table 17 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 17: *Selected water emissions of the polyolefin production process per 1 kg of product*

Water emissions	HDPE	LDPE	LLDPE
Biological oxygen demand after 5 days (BOD <sub>5</sub> ) [kg]	3.58E-06	3.48E-06	1.58E-07
Chemical oxygen demand (COD) [kg]	3.51E-05	8.88E-05	2.67E-05
Total organic carbon (TOC) [kg]	6.48E-06	1.77E-05	1.58E-07

## Solid Waste

Table 18: *Solid waste generation of the polyolefin production process by type and destination per 1 kg of product*

	Waste for –	Incineration	Landfill	Recovery	Unspecified	Total
Product		kg	kg	kg	kg	kg
HDPE	Hazardous	4.26E-04	1.50E-05	3.68E-04	1.21E-04	9.30E-04
	Non-hazardous	5.49E-06	1.48E-04	7.95E-04	3.34E-04	1.28E-03
LDPE	Hazardous	1.59E-03	9.94E-05	1.18E-03	1.93E-04	3.06E-03
	Non-hazardous	1.29E-04	1.12E-04	2.04E-03	9.65E-05	2.38E-03
LLDPE	Hazardous	9.00E-05	2.86E-06	3.05E-04	1.64E-04	5.61E-04
	Non-hazardous	7.38E-05	2.24E-04	5.33E-04	4.00E-06	8.35E-04

# 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 19: Abiotic Depletion Potential per 1 kg product

Natural resources	HDPE	LDPE	LLDPE
Abiotic Depletion Potential (ADP), elements [Sb eq.]	4.4E-08	5.2E-08	6.5E-08
Abiotic Depletion Potential (ADP), fossil fuels [MJ], ultimate reserves	72.0	72.8	71.3

## 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 based on the last report of the Intergovernmental Panel on Climate Change [IPCC 2007].

Table 20: Global Warming Potential (100 years) per 1 kg product

Climate change	HDPE	LDPE	LLDPE
Global Warming Potential (GWP) [kg CO <sub>2</sub> eq.]	1.80	1.87	1.79

### Acidification

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

Table 21: Acidification Potential per 1 kg product

Acidification of soils and water bodies	HDPE	LDPE	LLDPE
Acidification Potential (AP) [g SO <sub>2</sub> eq.]	4.28	4.36	4.33

### Eutrophication

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

Table 22: *Eutrophication Potential per 1 kg product*

<b>Eutrophication of soils and water bodies</b>	<b>HDPE</b>	<b>LDPE</b>	<b>LLDPE</b>
Eutrophication Potential (EP), terrestrial [g PO <sub>4</sub> <sup>3-</sup> eq.]	0.40	0.42	0.39
Eutrophication Potential (EP), aquatic [g PO <sub>4</sub> <sup>3-</sup> eq.]	0.80	0.84	0.76
Eutrophication Potential (EP), total [g PO <sub>4</sub> <sup>3-</sup> eq.]	1.20	1.25	1.15

### 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 23: *Ozone Depletion Potential per 1 kg product*

<b>Ozone Depletion</b>	<b>HDPE</b>	<b>LDPE</b>	<b>LLDPE</b>
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	6.4E-04	8.2E-04	5.7E-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 24: *Photochemical Ozone Creation Potential per 1 kg product*

<b>Summersmog</b>	<b>HDPE</b>	<b>LDPE</b>	<b>LLDPE</b>
POCP [g Ethene eq.]	6.3E-01	1.3E+00	4.7E-01

### Dust & Particulate Matter

Particulate matter with an aerodynamic diameter of less than 10 µm (PM<sub>10</sub>) 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 PM<sub>10</sub> 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 25 are based on works of DE LEEUW 2002 and HELDSTAB 2003 for NMVOC.

Table 25: *PM10 characterisation factors of air emissions according to De Leeuw 2002 and Heldstab 2003*

PM10 and precursors	kg PM10 eq. / kg air emission
Particulate matter PM10	1.00
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 26: *PM10 emissions per 1 kg product*

Particulate matter ≤ 10 µm	HDPE	LDPE	LLDPE
PM10, direct emissions [g PM10 eq.]	0.25	0.25	0.27
PM10, secondary [g PM10 eq.]	3.73	3.84	3.74
PM10, total [g PM10 eq.]	3.97	4.09	4.01

## Dominance Analysis

Table 27 to Table 29 show 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 ethene but also to co-monomers like propene, 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 27 to Table 29, that for all polyethylene types 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 and 'ADP, elements'. The higher impact of electricity for LDPE is a result of the higher energy requirements in this process. Concerning 'ADP, elements', the second important contribution is caused by 'Other Raw Materials', mainly by pigments and catalysts. POCP is dominated by both monomer and polymer production. The high share of polymer production on POCP impact is mainly caused by venting of ethene directly to the atmosphere.

Table 27: Dominance analysis of impacts per 1 kg HDPE

	Total Pri- mary En- ergy [MJ]	ADP Ele- ments [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%	2.6%	3.0%	0.9%	43.2%	2.3%
<b>Electricity</b> for foreground processes	4.0%	6.7%	1.6%	9.4%	6.9%	3.1%	1.3%	7.0%
<b>Thermal energy and utili- ties</b> for foreground processes	3.3%	0.9%	3.4%	5.2%	3.8%	4.0%	1.2%	3.4%
<b>(Co-)Monomer production</b>	91.3%	62.5%	93.7%	81.3%	83.3%	90.0%	52.1%	84.6%
<b>Other raw materials</b>	1.3%	29.9%	1.3%	1.5%	2.7%	1.8%	2.1%	2.4%
<b>Transport of monomers and other raw materials</b>	0.0%	0.1%	0.0%	0.1%	0.4%	0.1%	0.1%	0.3%
<b>Disposal</b>	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
<b>Total</b>	100%	100%	100%	100%	100%	100%	100%	100%

Table 28: Dominance analysis of impacts per 1 kg LDPE

	Total Pri- mary En- ergy [MJ]	ADP Ele- ments [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%	1.3%	1.8%	1.3%	72.3%	1.8%
<b>Electricity</b> for foreground processes	7.0%	11.0%	2.7%	16.9%	12.5%	5.5%	1.1%	12.4%
<b>Thermal energy and utili- ties</b> for foreground processes	4.0%	0.1%	4.1%	1.9%	1.8%	4.5%	0.4%	1.7%
<b>(Co-)Monomer production</b>	88.3%	54.2%	92.6%	78.0%	82.1%	87.4%	25.5%	82.4%
<b>Other raw materials</b>	0.7%	34.7%	0.7%	1.6%	1.7%	1.3%	0.7%	1.6%
<b>Transport of monomers and other raw materials</b>	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%
<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%

Table 29: Dominance analysis of impacts per 1 kg LLDPE

	Total Pri- mary En- ergy [MJ]	ADP Ele- ments [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%	5.1%	2.7%	1.2%	23.6%	2.4%
<b>Electricity</b> for foreground processes	3.7%	4.2%	1.6%	8.2%	6.3%	3.0%	1.7%	6.3%
<b>Thermal energy and utilities</b> for foreground processes	2.2%	0.2%	2.2%	2.0%	1.6%	1.5%	0.9%	1.5%
<b>(Co-)Monomer production</b>	92.0%	41.6%	94.1%	82.0%	82.8%	89.5%	68.8%	84.0%
<b>Other raw materials</b>	2.1%	54.1%	2.1%	2.7%	6.0%	4.7%	4.9%	5.4%
<b>Transport of monomers and other raw materials</b>	0.0%	0.0%	0.0%	0.1%	0.5%	0.2%	0.1%	0.5%
<b>Disposal</b>	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
<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 30 to Table 32 compare the present results with the previous version of the EPDs from 2008, which are based on the Eco-profiles from 2005 [BOUSTEAD 2005A, BOUSTEAD 2005B, BOUSTEAD 2005C]. As shown above, the results are dominated by the monomer production, i.e. crude oil and natural gas extraction and transport, and the refinery. Furthermore, the previous versions of the Eco-profiles of both ethene [PLASTICSEUROPE 2012B] and polyethylene products [BOUSTEAD 2005A, BOUSTEAD 2005B, BOUSTEAD 2005C] are based on collected data from 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 ethene monomer production [PLASTICSEUROPE 2012B]. As shown there, the consumption of energy resources for ethene production is mainly 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 which was necessary in the last decade. Another important cause for the increase in the energy demand for ethene production is the fact that the distribution of the ecological burdens has been handled differently in the recent report on steam cracker products and its preceding version: in previous calculations, 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 ethene.

For the Global Warming Potential (GWP) significantly lower values are reported compared to the previous reports on polyethylene products. GWP is also dominated by monomer production, but also by electricity for both monomer production and polymerisation. Since the GWP for ethene monomer was reported to have



increased by 5 % compared to 1999 [PLASTICSEUROPE 2012B], which can be explained by different allocation approaches (see above), the overall reduction in GWP is most likely caused by (1) the improved GWP of electricity in general, and (2) improved efficiency in polymerisation processes during the last years: larger facilities, improved energy efficiency and increased yields (due to improved catalysts).

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. As an exception to this, a higher POCP for LDPE was reported. This is mainly caused by venting high amounts of ethene directly to the atmosphere. An analysis showed that average ethene emissions from LDPE plants are by a factor of 4-10 higher than average ethene emissions from other polyolefin plants. A more widespread application of ethene flaring would be highly beneficial for POCP reduction.

The Eutrophication Potential (EP) is a parameter summarising a lot of substances emitted into the 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 30: Comparison of the present Eco-profile of HDPE with its previous version (2008)*

<b>Environmental Impact Categories</b>	<b>Eco-profile HDPE (2008)</b>	<b>Eco-profile HDPE (2013)</b>	<b>Difference</b>
Gross primary energy from non-renewable resources [MJ]	76.00	79.39	+4.5%
Gross primary energy from renewable resources [MJ]	0.80	0.77	−4.0%
Global Warming Potential (GWP) [kg CO <sub>2</sub> eq.]	1.96	1.80	−8.4%
Acidification Potential (AP) [g SO <sub>2</sub> eq.]	6.39	4.28	−33.1%
Eutrophication Potential (EP) [g PO <sub>4</sub> <sup>3-</sup> eq.]	0.43	1.20	+178.2%
Photochemical Ozone Creation Potential [g Ethene eq.]	1.23	0.63	−48.6%

Table 31: Comparison of the present Eco-profile of LDPE with its previous version (2008)

Environmental Impact Categories	Eco-profile LDPE (2008)	Eco-profile LDPE (2013)	Difference
Gross primary energy from non-renewable resources [MJ]	76.90	81.52	+6.0%
Gross primary energy from renewable resources [MJ]	1.20	1.35	+12.6%
Global Warming Potential (GWP) [kg CO <sub>2</sub> eq.]	2.13	1.87	-12.1%
Acidification Potential (AP) [g SO <sub>2</sub> eq.]	7.74	4.36	-43.7%
Eutrophication Potential (EP) [g PO <sub>4</sub> <sup>3-</sup> eq.]	0.50	1.25	+150.7%
Photochemical Ozone Creation Potential [g Ethene eq.]	1.19	1.33	+11.7%

Table 32: Comparison of the present Eco-profile of LLDPE with its previous version (2008)

Environmental Impact Categories	Eco-profile LLDPE (2008)	Eco-profile LLDPE (2013)	Difference
Gross primary energy from non-renewable resources [MJ]	72.30	78.30	+8.3%
Gross primary energy from renewable resources [MJ]	0.40	0.91	+126.4%
Global Warming Potential (GWP) [kg CO <sub>2</sub> eq.]	1.89	1.79	-5.4%
Acidification Potential (AP) [g SO <sub>2</sub> eq.]	5.62	4.33	-23.0%
Eutrophication Potential (EP) [g PO <sub>4</sub> <sup>3-</sup> eq.]	0.40	1.15	+187.7%
Photochemical Ozone Creation Potential [g Ethene eq.]	0.76	0.47	-37.8%

# 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 High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), and Linear Low-density Polyethylene (LLDPE).

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 HDPE, LDPE, and LLDPE production. The monomer production including all upstream processes until raw material extraction was modelled based on the Eco-profile and EPD for Steam Cracker Products [PlasticsEurope 2012]. Primary industry data was collected from 52 production sites of 9 companies which lead to an overall representativeness of 73.8% (HDPE: 68.3%; LDPE: 72.3%; LLDPE: 86.4%) of the European polyethylene production capacity.

The potential environmental impacts for HDPE, LDPE, and LLDPE are dominated by monomer (and comonomer) production across most impact categories. Electricity needed for the polymerisation processes also has a significant impact (e.g. between 8 and 17% for GWP). The results for ADP elements are driven by the use of pigments and catalysts, POCP scores are dominated by venting of ethene directly to atmosphere. During this review, great attention was paid to the comparison of the results with the previous version of the polyethylene 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 HDPE, LDPE and LLDPE produced in Europe.

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Guy Castelan, December 2016: Modifications to water Balance pages 5 and 38 to differentiate water use and water consumption.



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