



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

Ethylene, Propylene, Butadiene,
Pyrolysis Gasoline, Ethylene Oxide (EO),
Ethylene Glycols (MEG, DEG, TEG)
PlasticsEurope
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PlasticsEurope
Association of Plastics Manufacturers

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Environmental Product Declaration

This Environmental Product Declaration (EPD) is based upon life cycle inventory (LCI) data from PlasticsEurope's Eco-profile programme. It has been prepared according to **PlasticsEurope's Eco-profiles and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors** (PCR version 2.0, April 2011). EPDs provide environmental performance data, but no information on the economic and social aspects which would be necessary for a complete sustainability assessment. Further, they do not imply a value judgment between environmental criteria. This EPD describes the production of the polymer precursors Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO) and Ethylene Glycols (EG) from cradle to gate (from crude oil extraction to product at plant). **Please keep in mind that comparisons cannot be made on the level of the precursors:** it is necessary to consider the full life cycle of an application in order to compare the performance of different materials and the effects of relevant life cycle parameters. This EPD is intended to be used by member companies, to support product-orientated environmental management; by users of plastics, as a building block of life cycle assessment (LCA) studies of individual products; and by other interested parties, as a source of life cycle information.

Meta Data

Data Owner	PlasticsEurope & CEFIC/APPE
LCA Practitioner	IFEU – Institut für Energie- und Umweltforschung Heidelberg
Programme Owner	PlasticsEurope aisbl
Programme Manager, Reviewer	DEKRA Consulting GmbH
Number of plants included in data collection	50 steam cracker units; complemented by desktop study of subsequent steps.
Representativeness	Production in EU27 countries + Norway
Reference year	2009
Year of data collection and calculation	2007–2010
Expected temporal validity	2014
Cut-offs	None
Data Quality	Good
Allocation method	mass allocation, except for: stoichiometric allocation for glycol process, energy allocation for refinery

Description of the Product and the Production Process

This Eco-Profile and EPD represents the average industrial production of several petrochemical polymer precursors from cradle to gate.

Production Process

The model for this Eco-profile comprises extraction and refinery of crude oil and natural gas, steam cracking of longer, saturated hydrocarbons into lower olefins, ethylene oxidation, and ethylene glycol production. Impacts related to abnormal process conditions (like accidents) are not considered in this study.

Data Sources and Allocation

The modelling of steam cracking and petroleum refinery is based on confidential process and emission data from several sites. Additionally, recent data for energy consumption, feedstock mix and CO₂ emissions have been provided by APPE for the majority of European (EU27+CH+NOR) steam crackers. Representative literature data has been used to fill gaps where no primary data were available and to cross-check primary data. The glycol process has been allocated by stoichiometric principles; the petroleum refinery has been allocated by energy; other processes have been allocated by mass as a default.

Use Phase and End-of-Life Management

The disposal of waste from production processes is considered within the system boundaries this Eco-profile. However, the use phase and end-of-life processes are outside the system boundaries of this cradle-to-gate system: since the objects of this study are polymer precursors with a broad range of applications, even a qualitative discussion of these aspects was deemed inappropriate.

Environmental Performance

The tables below show the environmental performance indicators associated with the production of 1 kg of each respective polymer precursor (the follow-

ing abbreviations are used – EO: Ethylene oxide; MEG: Monoethyleneglycol; DEG: Diethyleneglycol; TEG: Triethyleneglycol; Pygas: pyrolysis gasoline).

Input Parameters

Indicator	Unit	Ethyl-ene	Propyl-ene	Buta-diene	Pygas	EO	MEG	DEG	TEG
Non-renewable energy resources ¹⁾									
• Fuel energy	MJ	24.4	24.4	34.2	14.8	33.7	27.1	32.2	34.2
• Feedstock energy	MJ	47.8	47.8	49.6	50.2	30.4	21.6	25.3	26.8
Renewable energy resources (biomass) ¹⁾									
• Fuel energy	MJ	0.3	0.3	0.6	0.2	1.2	1.3	1.5	1.6
• Feedstock energy	MJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Abiotic Depletion Potential									
• Elements	kg Sb eq	2.7x10 ⁻⁸	2.7x10 ⁻⁸	3.5x10 ⁻⁸	2.2x10 ⁻⁸	2.8x10 ⁻⁸	2.2x10 ⁻⁸	2.6x10 ⁻⁸	2.8x10 ⁻⁸
• Fossil fuels	MJ	66.9	66.9	76.7	60.4	56.8	42.1	49.7	52.7
Renewable materials (biomass)	kg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water use	kg	19.1	19.1	78.4	14.2	38.5	43.2	51.0	54.1
• for process	kg	1.9	1.9	2.5	1.6	2.3	7.8	9.2	9.8
• for cooling	kg	14.4	14.4	73.2	10.1	34.0	33.8	39.9	42.3
• unspecified	kg	2.8	2.8	2.8	2.5	2.2	1.6	1.9	2.0

¹⁾ Calculated as upper heating value (UHV)

Output Parameters

Indicator	Unit	Ethyl-ene	Propyl-ene	Buta-diene	Pygas	EO	MEG	DEG	TEG
GWP	kg CO ₂ eq	1.44	1.44	1.98	1.02	2.00	1.58	1.86	1.97
ODP	g CFC-11 eq	2.7x10 ⁻⁴	2.7x10 ⁻⁴	4.8x10 ⁻⁴	2.2x10 ⁻⁴	5.0x10 ⁻⁴	4.9x10 ⁻⁴	5.7x10 ⁻⁴	6.1x10 ⁻⁴
AP	g SO ₂ eq	3.52	3.52	4.14	3.00	3.76	3.10	3.67	3.89
POCP	g Ethene eq	0.33	0.33	0.36	0.24	0.53	0.40	0.47	0.50
EP	g PO ₄ eq	1.08	1.08	1.16	0.95	0.94	0.72	0.85	0.90
Dust/particulate matter	g PM10	0.21	0.21	0.24	0.18	0.23	0.19	0.23	0.24
Total particulate matter ²⁾	g PM10 eq	3.33	3.33	3.91	2.81	3.45	2.81	3.32	3.52
Waste	kg	0.0053	0.0053	0.0055	0.0031	0.0042	0.0030	0.0036	0.0038
• Non-hazardous	kg	0.0024	0.0024	0.0025	0.0014	0.0019	0.0014	0.0016	0.0017
• Hazardous	kg	0.00028	0.00028	0.00038	0.00017	0.00022	0.00016	0.00019	0.00020
• Unspecified	kg	0.0026	0.0026	0.0026	0.0015	0.0021	0.0015	0.0017	0.0018

²⁾ Including secondary PM10

Additional Environmental and Health Information

At the end of 1998, the International Council of Chemical Associations (ICCA) launched a voluntary global initiative to accelerate the process of data collection and hazard assessment for High Produc-

tion Volume (HPV) chemicals in the frame of the OECD SIDS (Screening Information Data Set) programme. On the ICCA/HPV list (1,325 chemicals), the percentage of commitment for APPE-related products reached 91.5 %, the general chemical industry percentage of commitment being 70.3 %.

Additional Technical Information

Lower olefins are petrochemical derivatives produced by cracking feedstocks from raw materials such as natural gas and crude oil. The main olefin products are ethylene, propylene, butadiene and C₄ derivatives. These petrochemical derivatives are used to produce plastics, as chemical intermediates, and, in some cases, as industrial solvents. Ethylene oxide alone or in combination with other inert gases such as carbon dioxide and nitrogen is used to sterilise instruments for the healthcare, publication and wood products sectors. Ethylene oxide is also used in other industries where heat-sensitive goods are sterilised and in the manufacture of choline chloride, glycol ethers and polyglycols. Other minor uses world-wide include its application in the manufacture of rocket propellant and petroleum demulsifiers.

The major use of ethylene oxide is in the manufacture of ethylene glycol, which is used as a chemical intermediate in the manufacture of polyesters for fibres, films, bottles etc. with a further 25% used as antifreeze in engine coolants. Ethylene glycol is also used as a plasticiser for adhesives, as a softener for cellulose film, and as solvents in paint, printing inks and adhesives. Ethylene glycol has also specialised applications as glycoborates in electrolytic condensers, glycol dinitrate in explosives, various heat transfer applications, hydraulic brake fluids, humectant in inks, antifreeze and plasticiser in paints and to reduce gelling of medium oil alkyds based on pentaerythritol.

Additional Economic Information

The chemical industry is an energy-intensive industry in a highly competitive global environment. On average, about 9% of total production costs are due to energy use. For some petrochemicals, this ratio can rise up to 75%. Because of this, the chemical industry has already invested over many decades in energy efficiency improvement. Whilst energy saving has been primarily economically motivated, the EU chemical industry is increasingly recognising the implications of potential actions to reduce green-

house gas (GHG) emissions and the effects that these might have on their operations. In line with its Responsible Care approach to environment, health and safety, the EU chemical industry has taken early actions through innovation and better management to improve the energy efficiency of its processes. These actions have achieved an improvement in specific energy consumption of 30% since 1990.

Information

Data Owner

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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 (2011-04) and ISO 14025:2006.
Registration number: PlasticsEurope 2012-003, valid until 30 November 2015 (date of next revalidation review).

Programme Owner

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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/>.

References

- PlasticsEurope: Eco-profiles and environmental declarations – LCI methodology and PCR for uncompounded polymer resins and reactive polymer precursor (version 2.0, April 2011).

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

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

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

Once a full life cycle model for a defined polymer application among several functionally equivalent systems is established, and only then, can comparative assertions be derived. The same goes for EPDs, for instance, of building 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 and polymer precursors**. This product category is defined »at gate« of the polymer or precursor production and is thus within the scope of PlasticsEurope as a federation. For instance, the monomers ethylene and propylene are used for the production of polyethylene (PE) or polypropylene (PP); pyrolysis gasoline is used for the production of aromatic hydrocarbons, which in turn are also used for the production of polymers.

Functional Unit and Declared Unit

The Functional Unit and Declared Unit of this Eco-profile is:

1 kg of primary polymer precursor »at gate« (production site output) representing a European industry production average.

Product and Producer Description

Product Description

This Eco-profile represents the average industrial production of polymer precursors as presented in Table 1. Hence it is not attributed to any single producer, but rather to the European petrochemical industry, which is represented by the Association of Petrochemicals Producers in Europe (APPE).

Table 1: Characteristics of the polymer precursors under consideration in this Eco-profile

Precursor name		IUPAC name (for mixtures systematic name)	CAS number	Chemical formula
Ethylene (HVC)		Ethene	74-85-1	C ₂ H ₄
Propylene (HVC)		Propene	115-07-1	C ₃ H ₆
(1,3-)Butadiene (HVC)		Buta-1,3-diene	106-99-0	C ₄ H ₆
Pyrolysis Gasoline containing:		n/a	77097-78-0 68606-10-0	n/a
- Benzene (HVC)	32.1 %	Benzene	71-43-2	C ₆ H ₆
- Toluene (HVC)	13.9 %	Methylbenzene	108-88-3	C ₆ H ₅ CH ₃
- Xylenes (HVC)	5.0 %	Dimethylbenzenes	1330-20-7	C ₆ H ₄ (CH ₃) ₂
- Ethylbenzene (HVC)	2.8 %	Ethylbenzene	100-41-4	C ₈ H ₁₀
- Styrene (HVC)	5.2 %	Phenylethene	100-42-5	C ₈ H ₈
- Other compounds	40.9 %	n/a	n/a	n/a
Ethylene Oxide		Oxirane	75-21-8	C ₂ H ₄ O
Monoethylene Glycol		Ethane-1,2-diol	107-21-1	C ₂ H ₆ O ₂
Diethylene Glycol		(2-Hydroxyethoxy)ethan-2-ol	111-46-6	C ₄ H ₁₀ O ₃
Triethylene Glycol		2-[2-(2-Hydroxyethoxy)ethoxy] ethanol	112-27-6	C ₆ H ₁₄ O ₄

Upstream Chains of Crude Oil, Natural Gas, and Electricity

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 and natural gas liquids. 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 2 and Table 3.

For the compilation of this Eco-profile, using up-to-date data of the steam cracker's the upstream chains 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.

Table 2: Key figures for the upstream chain of crude oil according to provenance

Countries of origin	Share [wt.-%]	Crude oil in ground req'd per kg crude oil at refinery [kg]	Efficiency [%]	CO ₂ 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
Average according to cracker capacity mix		1.0299	97.13	0.2278

Table 3: Key figures for the upstream chain of natural gas according to provenance

Countries of origin	Share [vol.-%]	Natural gas in ground req'd per kg gas feedstock [kg]	Efficiency [%]	CO ₂ emission per kg gas feed- stock [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
Average according to cracker capacity mix		1.0791	92.98	0.1727

Petroleum Refinery

Petroleum refineries are complex plants in which the combination and sequence of processes are usually very specific to the characteristics of the raw materials, i.e. the composition of the crude oil, and the products to be produced. Refineries are not only different regarding their configuration, process integration, feedstock, product mix, unit size design and control systems. Differences in market situation, location and age of the refinery environmental regulation are amongst other reasons for a wide variety of refinery concepts.

Model Development for European Refineries: As the cracker feedstock and its pre-processing significantly influence the LCI results of the polymer precursors under consideration in this Eco-profile, the adequate modelling of the petroleum refinery as part of the upstream chain is a key issue for this Eco-profile of polymer precursors. In spite of the large variety of possible and actual refinery configurations, the Draft Reference Document on Best Available Techniques for Mineral Oil and Gas Refineries (BREF 2010) 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 2010 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 1).

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 BREF 2010 mentioned 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 European Pollutant Release and Transfer Register (E-PRTR).

Process Technology: The process within the refinery that is of high relevance for the subsequent steam cracking is the atmospheric distillation of crude oil. Most other energy and emission intensive processes of a refinery are more relevant for products, which are usually not used as a steam cracker feedstock. Therefore, only the processes for pre-treatment of crude oil feedstock and atmospheric distillation are described in detail.

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

Atmospheric Distillation: The next step after desalting – and the most important in regard of cracker feedstock – is atmospheric distillation, which is the first and fundamental separation process in a refinery. In the atmospheric distillation unit crude oil is heated to temperatures of 300 to 400 °C and then subjected to distillation under atmospheric pressure separating the various fractions according to their boiling range. Heavier fractions from the bottom of the atmospheric distillation unit can be further separated by subsequent vacuum distillation. The products from the crude distillation unit, ranging from the lightest to the heaviest cut are: naphtha and light components (boiling < 180 °C), kerosene (boiling range: 180 – 240 °C), light gasoil (240 – 300 °C), heavy gasoil (300 – 360 °C) and atmospheric residue (boiling > 360 °C). These fractions are separated by condensing on 30 to 50 fractionation trays. The lighter fractions condense and are collected towards the top of the vertical distillation column. The overhead of this column is the light fraction, non-condensable refinery fuel gas. Most of the fractions resulting from atmospheric distillation can be sold directly for use in the petrochemical industry (the route which naphtha and atmospheric gas oil take), as finished products after hydrotreatment, or be blended with products from downstream processes, e.g. heavy gas oil being mixed into diesel. So leaving the atmospheric distillation unit the straight-run unstabilised naphtha is passed to a naphtha splitter, separating the share for the petrochemical industry (industrial spirit), 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.

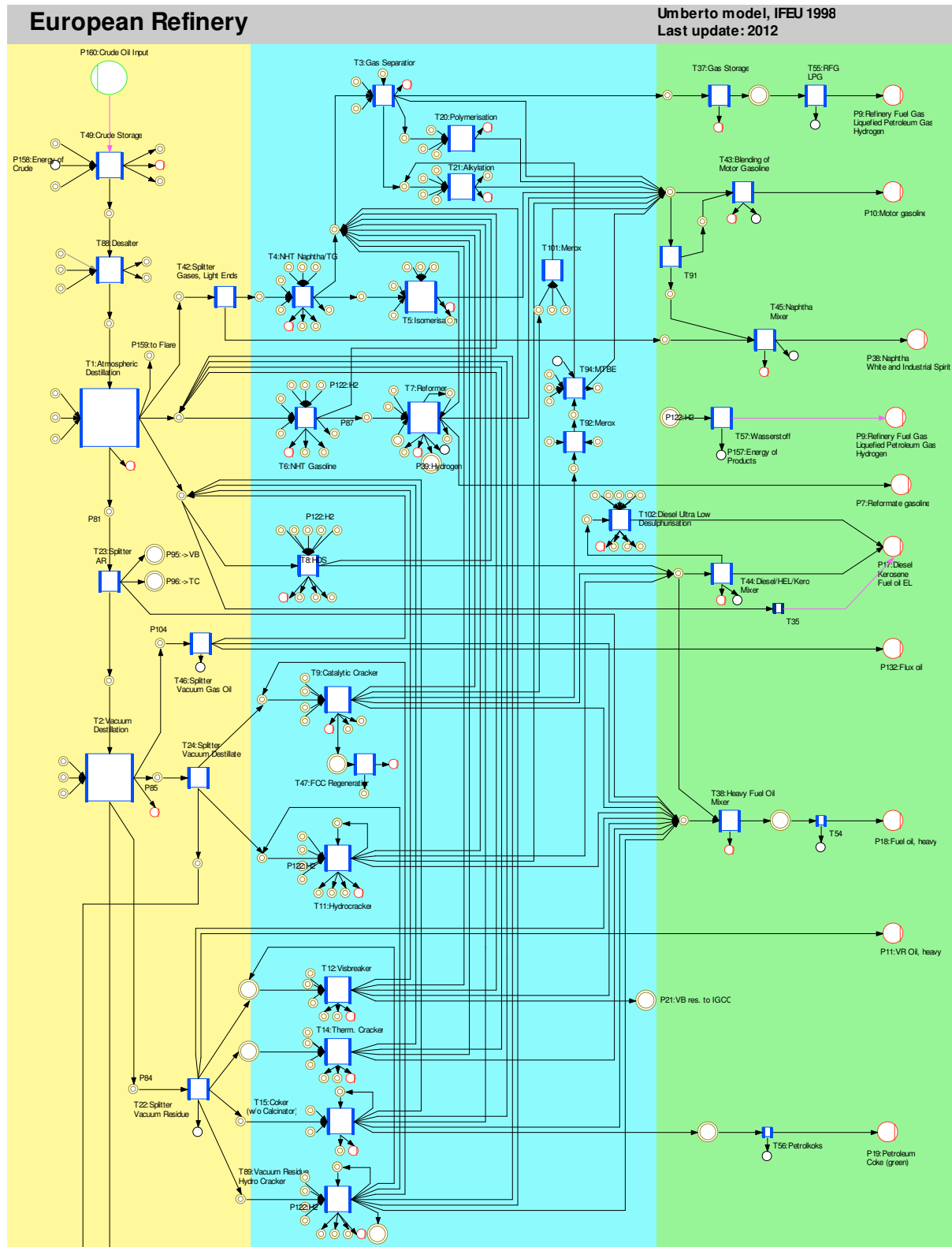


Figure 1: Screenshot of the petroleum refinery model in UMBERTO (Source: IFEU 2012)

Steam Cracking for the Production of Lower Olefins

The worldwide demand for lower olefins, i.e. ethylene, propylene, and butadienes is higher than for any other chemical as they form the primary feedstock for most plastics, polymers and man-made fibres. But lower olefins

are only found in very low concentrations in crude oil due to their high reactivity. It is thus necessary to split up longer, saturated hydrocarbons into shorter, unsaturated compounds using large-scale cracking processes. The chemical reaction for the cracking process is a dehydrogenation and can be affected either catalytically or thermally. In the European Union the steam cracking process, where the reaction is carried out in the presence of steam and at temperatures of up to 875 °C, accounts for the lion's share of the ethylene, propylene, and butadiene production. Due to the rising demand for ethylene and propylene as precursors for the polymer production not only naphtha, but also gas fractions are used as feedstock for steam cracking. In the European Union they play a minor role, whereas in the USA most crackers use gaseous feedstock.

Process Technology: Only a limited number of international technology contractors licenses the equipment used for crackers. The generic design of the cracking units is quite similar. Little modifications help optimize the plant performance according to local conditions. Besides differences in furnace design, pressure and temperature of the fractionation columns and refrigeration systems may vary or turbo expanders may be in use. Regardless of feedstock or contractor a cracker complex may be separated into three sections namely pyrolysis, primary fractionation/compression and product fractionation as shown in Figure 2.

In the **pyrolysis section** the hydrocarbon feedstock is preheated and then vaporised with superheated steam before passing into long and narrow tubes arranged in a cracking furnace. In this reactor, the hydrocarbon feedstock is cracked into smaller molecules. The product distribution of the product can be controlled through variation of residence time, temperature profile, and partial pressure. This process is highly endothermic and therefore requires high energy input. Therefore the tubes of the furnace are heated to 750 – 875 °C by oil or gas fire burners. To reduce the partial pressure of the hydrocarbon mixture and to minimise coke formation high-pressure steam is injected which gives the process the name steam cracking. To quickly quench the product gases to 550 – 650°C and to recover heat for internal use, transfer line exchangers (TLEs) may be used.

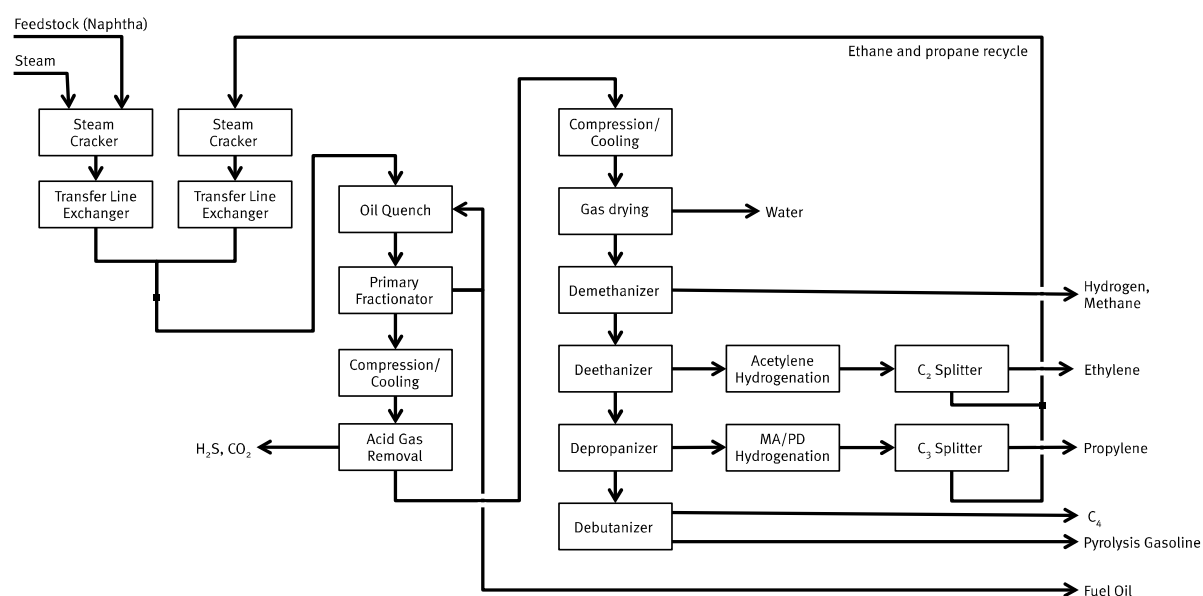


Figure 2: Schematic flow diagram showing the lower olefin production in a naphtha-based front-end de-methanising steam cracker

The **primary fractionation and compression section** consists of the primary fractionator (naphtha and gas oil feed only), quench tower, gas compressor and gas clean-up facilities. The primary fractionator is used to condense and fractionate fuel oil streams produced from naphtha and gas oil fed crackers. The gases are de-superheated

in the quench tower by a circulating oil or water stream. The circulating oil or water stream is used as a medium level heat source for the rest of the plant. Product gases from the quench tower are condensed by four or five stages of gas compression. The gas is cooled after each stage and passed through a liquid knock-out drum. Finally, acid gases and carbon dioxide are removed from the cracked gas.

In the **product fractionation section** products are cooled down and subsequently fractionated. The chilling train usually consists of four or five successive stages of chilling, incorporating ethylene and propylene refrigeration as well as an elaborate self-refrigeration system. This produces hydrogen, which is used for downstream hydrogenation or hydrotreating of the heavier products or sold as a product. The exact process flow sequence varies according to the feedstock and the design arrangement, but various fractionation towers are used to separate the desired products. This may include a sequence of de-methaniser, followed by a de-ethaniser. Bottoms from the de-ethaniser are directed to the de-propaniser and the de-butaniser. The lighter the feedstock, the fewer fractions need to be separated and the separation system may be constructed simpler. After separation the ethylene still contains undesirable acetylene and ethane. Acetylene is removed either by selective catalytic hydrogenation or by extractive distillation. After separation from ethylene ethane is recycled back to the cracker. Similarly the C₃ fraction contains methyl acetylene and propadiene after separation. Selective hydrogenation is used to convert this into propylene and propane prior to separation in a C₃ splitter.

Feedstock: In the European Union crackers are basically fed with naphtha 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 4). Ethane mainly comes from North Sea gas fields whereas other feedstock gases come from refineries.

Table 4: 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 %

Products: The main products of steam cracking are ethylene, propylene, and methane, their shares depending on the feedstock. Important minor products are butadiene and, in case of naphtha or gas-oil feedstock, pyrolysis gasoline with high aromatic content.

Ethylene is an important precursor for the organic chemical industry and it has a wide range of derivatives. More than 50 % of ethylene is used in the production of polyethylene, but it is also very important for the production of polystyrene (via ethylbenzene and styrene), glycols, vinyl acetate and PVC. Propylene is mostly used to produce polypropylene (more than 50 %) but also for the production of acetonitrile, a precursor of acrylic esters, and propylene oxide. About half of butadiene is used to produce styrene/butadiene rubbers and latexes. A further quarter is used for polybutadiene rubber, most notably ethylene-propylene-diene monomer (EPDM) rubber. It is also used for the production of adiponitrile – a precursor for nylon production. From pyrolysis gasoline (pygas), benzene, toluene, and xylenes (BTX-aromatics) are extracted, all of them being used as precursors in the polymer industry.

The annual production of ethylene in Europe was 20,280 kt in 2010, the production capacity being 24,463 kt in the same year. The production capacity for propylene was 12,885 kt solely on steam crackers. The propylene production on steam crackers and by other production routes amounted to a total of 15,167 kt in 2010. Table 5 shows capacities and production data for polymer precursors and their most common derivatives.

Table 5: Capacities and production data for petrochemicals in Europe (Source: APPE)

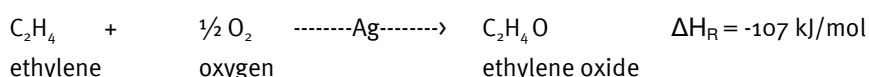
Precursor / polymer	Production capacity 2010 [kt]	Production 2010 [kt]
Ethylene	24,463	20,280
Low-density polyethylene (LDPE)	5,615	4,290
Linear low-density polyethylene (LLDPE)	3,663	2,855
High-density polyethylene (HDPE)	4,586	4,550
Ethylbenzene	6,456	5,315
Styrene	5,719	4,977
Ethylene oxide	2,936	2,575
Monoethylene glycol	1,227	926
Propylene	12,885*	15,167
Polypropylene (PP)	9,580	8,535
Butadiene	2,490	2,079

* capacity on steam crackers only

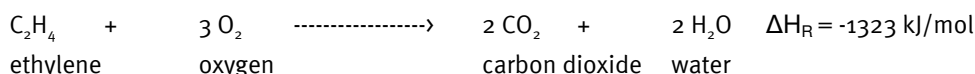
Production of Ethylene Oxide and Ethylene Glycol

Ethylene oxide (EO) is a key chemical intermediate to the manufacture of many products. Since about 40 % of the EO production in Europe and about 70 % of the worldwide EO production is converted into ethylene glycols, EO and ethylene glycols are mostly produced together at integrated plants. The main product of the hydrolysis of EO is mono ethylene glycol (MEG), but further reaction of MEG with EO leads to diethylene glycol (DEG) and triethylene glycol (TEG). MEG is mainly used for the manufacture of polyester fibres and polyethylene terephthalate (PET); smaller quantities are used as anti-freezing agent in cooling systems. DEG is used in the fibre industry and as tobacco humectant and TEG is used in the manufacture of cellophane for food packaging. DEG and TEG are both used for gas drying.

The commercial production of ethylene oxide started in 1937 with a Union Carbide process based on ethylene and air. In 1958, oxygen (rather than air) processes were introduced by Shell Development Company, and most European EO plants are now based on pure oxygen feedstock. The most common way of producing ethylene oxide is by reacting gaseous ethylene and oxygen over an aluminium oxide supported silver catalyst. The exothermic reaction is carried out at elevated temperature (200 to 300 °C) and pressure (15 to 25 bar) with very short residence times (around 1 second).

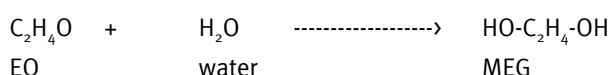


The main by-products are carbon dioxide and water, which result from the highly exothermic total oxidation of ethylene. The consecutive oxidation of the main product EO to carbon dioxide and water is a possible but unwanted side-reaction.

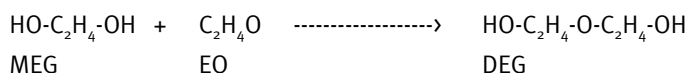


The ratio between the above-mentioned reactions defines the selectivity of the process, defined as the amount of EO produced per amount of ethylene consumed. Selectivity is mainly determined by the type of catalyst used and during the lifetime of the catalyst (2-5 years) selectivity decreases due to catalyst aging. Applied process technologies achieve a selectivity of approximately 80 % at ethylene conversions of 8-10 %.

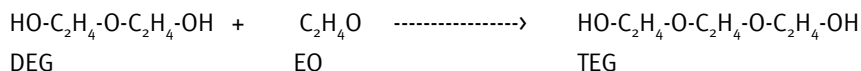
Monoethylene glycol is formed by the hydrolysis of EO with water at elevated temperature and pressure (150 to 250 °C, 30 to 40 bar). In commercial units the resulting mixture of crude glycols typically contains between 70 and 95 % w/w of MEG.



The main co-product in the MEG manufacturing process is diethylene glycol, which is formed by the reaction of MEG with EO.



DEG can again react with another molecule of EO to form triethylene glycol and further on to heavier glycols (ethoxylation).



Ethylene Oxide and Ethylene Glycol Production Technology: In practice most EO / EG plants are designed as integrated plants for a production mix of high purity ethylene oxide and glycols. Although there is a number of different EO / EG manufacturing process licensors, the process technologies are similar in their basic process steps. Figure 3 shows a typical production sequence for an oxygen-fed EO / EG process. Feedstock ethylene is typically received by pipeline from a steam cracker. Oxygen is usually provided in pure form by pipeline from an air separation unit. The reaction between ethylene and oxygen is carried out in a multi-tubular fixed bed type reactor containing the catalyst particles (spheres or rings with 3–8 mm diameter) inside the tubes and a coolant on the shell side. The heat generated by the exothermic reactions is removed by the coolant, and is recovered by means of steam production. The steam is used as a heating medium in various sections of the plant. Due to various reasons (e.g. flammability of EO and ethylene, temperature control of the reactor, high EO selectivity only achievable at low ethylene conversion), low ethylene feed concentrations (15–40% vol) and low ethylene conversions (7–15 %) are reasonable. Thus, a large gas flow is circulated continuously through the EO reactor. The reaction products ethylene oxide, carbon dioxide and water are removed from the circulating gas while unconverted oxygen and ethylene are recycled back to the reactor.

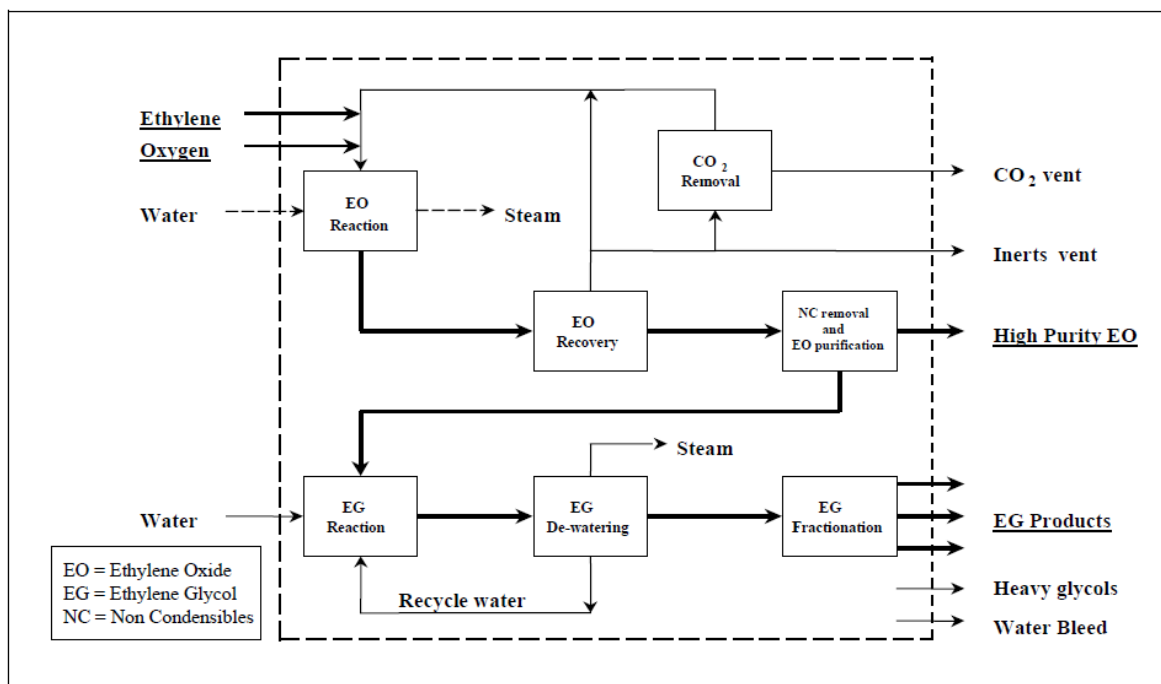
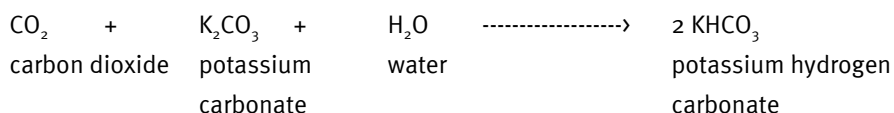


Figure 3: Schematic flow diagram showing the typical production route of ethylene oxide (EO) and ethylene glycol (EG) process with pure oxygen feed (Source: BREF 2003, originally CEFIC, please check copyrights)

Ethylene oxide recovery and purification: After cooling the reactor effluent, EO is recovered by absorption in water. The resulting aqueous solution is fed to a desorber where an EO-rich water stream is received as head product. Since during absorption also small amounts of CO₂ and other by-products were dissolved, EO has to be stripped off the low-boiling components. The bottom stream of the EO desorber is an EO free water stream that is cooled and recycled to the EO absorber unit. The EO/water mixture received overhead from the EO desorber is partly condensed and routed to a unit for removing traces of carbon dioxide, ethylene and other non-condensables. The non-condensables are routed back to the recycle gas loop while the purified EO/water mixture is routed to a unit for high purity EO recovery and/or to the glycols reactor. Most plants in Europe have a EO purification unit in which high purity EO is recovered via distillation from the EO/water mixture. This product typically is chilled (10 °C) and routed to storage or shipped in railroad tank cars (under a nitrogen blanket for safety reasons).

Carbon dioxide recovery: The gaseous stream leaving the EO absorber overhead contains mostly unconverted ethylene and oxygen but also 5–10 % CO₂ and other side products. To reduce the CO₂ content in the recycle stream, a part of the recycle gas is sent to a column where CO₂ is removed by absorption in a hot aqueous potassium carbonate solution.



The potassium carbonate solution is sent to a CO₂ desorption unit. The carbon dioxide vent from the top of the desorber is either routed to atmosphere or recovered for further use. The regenerated carbonate solution from the desorber bottom is cooled and recycled to the carbon dioxide absorber. The carbon dioxide free overheads stream from the CO₂ absorber unit is recombined with the recycle gas stream and routed to the EO reactor.

Glycols production: A mixture of EO and water is fed to the glycol reactor which is operated at typical temperatures between 150 and 250 °C. Under these conditions reaction rates are fast and no catalyst is required. Residence time is adjusted to provide total conversion of EO. At a reactor pressure of 30 to 40 bar vaporisation of EO is avoided. The reactor feed contains an excess of water in order to limit the adiabatic temperature rise and to enhance the selectivity to MEG. Typically the produced glycol mixture consist of 70 to 95 % w/w MEG; the rest consists mostly of DEG and small quantities of TEG. Usually the unit is operated at total conversion of EO to glycols. The excess water is removed by multiple effect evaporation with subsequent vacuum distillation and is recycled back to the glycols reactor after heat exchange. Low pressure steam generated in this section is used as heating medium at various locations in the plant. The water-free crude glycol stream is fractionated in a number of vacuum columns to recover the individual glycol products at high purity level. The glycol products are cooled and routed to storage. The bottom stream from the last vacuum column contains the heavier glycols, which are used for further glycols recovery or sent to disposal.

Eco-profile – Life Cycle Inventory

System Boundaries

This Eco-profile refers to the **production of polymer precursors** and is based on a **cradle-to-gate system** (Figure 4). The production stage covers all life cycle processes from extraction of natural resources, up to the point where the product is ready for transportation to the customer (e.g. by pipeline or ship). In this cradle-to-gate information module, the subsequent steps of polymer production, conversion, use phase and end-of-life management are not included.

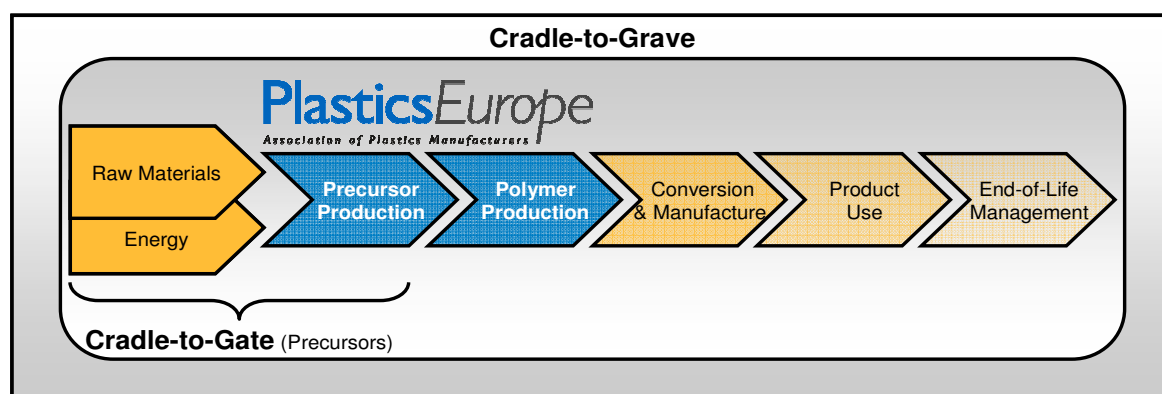


Figure 4: Cradle-to-gate system boundaries (Source: PlasticsEurope)

Cradle-to-Gate System Boundaries for Production

The following processes are included in the cradle-to-gate LCI system boundaries (see also Figure 5):

- 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 energyware¹
- 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 Eco-profile methodology (PlasticsEurope 2011), capital goods, i.e. the construction of plant 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 monomers 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.

1 Energyware: Tradable commodity used mainly to produce mechanical work or heat, or to operate chemical or physical processes, and which is listed in Annex A of ISO 13600 (1999).

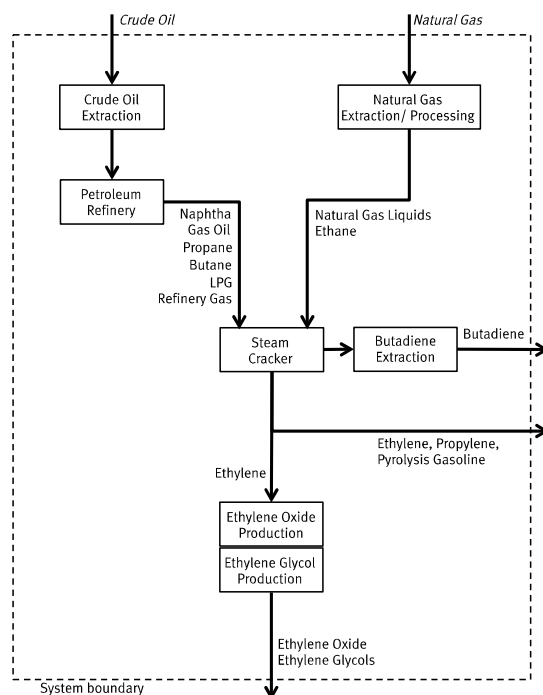


Figure 5: Schematic flow chart of the production processes for the polymer precursors under consideration

Technological Reference

The LCI data in this Eco-profile represents the average applied technology for the production of polymer precursors in Europe as shown in Figure 5. It is based on confidential data by some producers as well as on representative literature data. As the production processes are not under control of PlasticsEurope's member companies primary data could not be obtained systematically. Thus, the coverage as percentage of the total production volume cannot be stated. However, the data of the core process steam cracking was reviewed by APPE, the Association of Petrochemicals Producers in Europe, which represents the European petrochemical industry. Based on a survey of APPE for the European Emission Trading System (EU ETS), covering 50 steam cracker units in Europe, the Eco-profile model for steam cracking was verified and amended with actual industry data from 2008–2010. Due to this fact, the technological coverage of this Eco-profile is assessed to be at least 90 %. Crackers using gas feedstock, such as ethane, propane or butane are hardly in use within the EU27. They are, however, represented in the data set in an adequate proportion. *It should be carefully noted that, for the production of ethylene and propylene, the study considered only steam cracking, whereas the Fluid Catalytic Cracking (FCC) process will be a subject of a separate study.*

According to the PlasticsEurope LCI methodology and product category rules for uncompounded polymer resins and reactive polymer precursors v.2.0, Eco-profiles shall differentiate –

- primary data from **foreground processes**, i.e. those that are under operational control, and
- secondary data from **background processes**, i.e. those operated by third parties where only indirect management control or no control exists.

Thus, all processes under consideration in the present Eco-profile are background processes according to the above-mentioned methodology as they are not under operational control of PlasticsEurope. However, due to their relevance for the results of this Eco-profile (and subsequent Eco-profiles for polymers) all processes within

the system boundaries have been treated like foreground processes as far as research on and validation of the underlying data are concerned.

According to the PlasticsEurope LCI methodology and product category rules inputs of secondary materials (recyclate) and outputs of waste for recovery shall be noted as crossing the system boundaries. While there is no input of recyclates at all, outputs of wastes for recovery or disposal only contribute very little to the total proceedings under consideration in this Eco-profile. The largest fraction is non-hazardous waste from petroleum refining which accounts for 2 g/kg ethylene. As the last enquiry towards these in- and output streams within CEFIC was published in 1993 data quality is considered to be less reliable. Due to lack of more recent data, the treatment of wastes for disposal has been modelled in this Eco-profile according to this CEFIC information.

Temporal Reference

The LCI data for this Eco-profile represents the most recent available data and therefore represents the average technology in Europe. For the petroleum refinery the collected data is from the time period 2007–2010, mostly from 2009. Data on steam cracking originates from the years 2008–2010. For the ethylene oxide and ethylene glycol production data was collected during the years 1999–2010. In spite of its age, this data is considered to be still valid since the production facilities have high investment costs and since therefore the data underlies only small changes. For the upstream chains of the feedstock most data was collected for the year 2009; a few exceptions of the data originate from the years 2007–2008. The reference year for this Eco-profile is 2009, with a maximum temporal validity until 2014.

Geographical Reference

This Eco-profile refers to the average production of polymers precursors in the EU27 member states and Norway. The LCI data describing direct inputs and outputs of the production processes is representative of the defined production region. In order to be applied in other regions adjustments might be required.

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 an input < 1 % of the respective polymer precursor's output, e.g. NaOH and HCl, generic datasets from the LCA database ecoinvent v.2.2 (2010) have been used. Simplified generic processes were assumed for catalysts and a few commodities (input < 0.1 % of the precursor's output) with missing secondary production data. The process input/output relation has been determined by reaction equations from literature. The upstream production of the used metals (antimony, cobalt, manganese, and palladium) and chemicals were implemented using ecoinvent v.2.2 data. Thus the potential environmental relevant metal extraction and refinement processes are included in the LCI data.

Data Quality Requirements

Data Sources

The LCI data used in this Eco-profile is representative of the production processes of polymer precursors in Europe, both in terms of technology and market share. The modelling of the petroleum refinery is based on confidential process and emission data from several sites as well as on representative literature data from the following publications:

- Draft Reference Document on Best Available Techniques for Mineral Oil and Gas Refineries (2010)
- R. A. Meyers: Handbook of Petroleum Refining Processes (2003)

Statistical data for product mix and energy demand have been taken from the Eurostat database for the year 2007–2009 (Eurostat 2011).

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 (2003)
- Life cycle inventory database ecoinvent v2.2 (2010)
- Ullmann's Encyclopedia of Industrial Chemistry (2005)

Furthermore the Association of Petrochemicals Producers in Europe (APPE) provided recent data for energy consumption, feedstock mix, product yields, and CO₂ emissions for the majority of European plants (50 units, APPE 2010), which for reasons of confidentiality appears in form of an aggregated average in the final model.

The modelling of the EO/EG production process is based 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 (2003)
- Life cycle inventory database ecoinvent v2.2 (2010)
- Ullmann's Encyclopedia of Industrial Chemistry (2005)
- Ethylene Oxide Reactor System (JEO, 1999)

The upstream chains for the relevant feedstock, i.e. crude oil, natural gas, natural gas liquids (NGL) and ethane from the North Sea are based on the database ecoinvent v2.2 (2010). The regional provenance mix has been updated with statistical data from Eurostat for the year 2009. The upstream chain has been updated, notably in view of its inputs and outputs, with primary data from the following environmental/annual reports:

- BP North Sea Region Environmental Statement 2010
- ENI Sustainability Performance 2010
- Gazprom Environmental Report 2009
- Lukoil Sustainability Report Russian Federation 2007-2008
- NOGEPa Annual Report 2009
- OLF Environmental Report 2010
- Shell U.K. Annual Environmental Statement for Upstream Operations 2010
- WEG Annual Report 2009 Facts & Figures

Besides data from these publications has been used for the update of the upstream chains:

- Greenhouse Gas Emissions from the Russian Natural Gas Export Pipeline (WUPI 2005)
- Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands (TNO 2011)

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 ecoinvent2.2
- Pipeline: ecoinvent 2.2

Data sources of on-site energy and utilities:

- Steam and electricity:
 - Data from several IFEU projects and ecoinvent2.2
 - For the electricity supply of steam crackers the national production mixes have been applied; the distribution of crackers and their electricity consumption in EU27 countries + Norway is based on cracker production capacities in Europe of 2011 (APPE 2012)
- Compressed air (low and high pressure):
Several data from IFEU projects, ecoinvent2.2 and BREF (2008)
- Industrial gases: oxygen and nitrogen according to ecoinvent2.2 and IFEU internal database
- Process water: ecoinvent 2.2

Relevance

With regard to the goal and scope of this Eco-profile, the collected process data, i.e. data for steam cracking, the EO/EG process and refinery processes, are the essential processes for production of polymer precursors in Europe. The environmental contributions of each process to the overall LCI results are shown below.

Representativeness

Data was collected or updated according to goal and scope of this Eco-profile. The used data reflect the current technology in Europe and the current upstream chains of feedstock relevant for production in EU27 member countries. One data basis used is the APPE Cracker Rule Book (APPE 2010), reflecting the most recent data applied for the benchmarking of crackers in the European Emission Trading Scheme (ETS). As the model of the core process steam cracking was reviewed by APPE, the representativeness of the process data is assumed to be at least 80 % in terms of production volume.

Consistency

Relevant process and upstream chain data have been validated to comply with goal and scope of this Eco-profile. Thus an overall consistency of the applied data can be stated. 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 throughout the whole system. Although all parts of the model are defined as background systems according to the PlasticsEurope methodology v.2.0, all parts of the model have been treated with the same thoroughness as if they were foreground systems.

Reliability

In this Eco-profile process data presents a hybrid model of confidential operator data, confidential data from the Association of Petrochemicals Producers in Europe (APPE) and additional literature data as described in the section 'data sources'. Data of the upstream chains of the feedstock are based on the LCI database ecoinvent v.2.2

and have been updated by data from primary and secondary sources as described in the section 'data sources'. The confidential data from operators and from the association APPE is considered to be reliable; data from literature sources was cross-checked by the LCI practitioners. Furthermore, data contained in the APPE Cracker Rule Book (APPE 2010) was thoroughly reviewed during the ETS benchmarking process.

Completeness

In general the collected and applied data are complete, in that no flows were omitted or substituted. However, some minor processes at individual plants with potential emissions are unknown. Thus the data is considered as complete for all relevant flows.

Precision and Accuracy

The assessment of data precision is generally a difficult topic for LCA practitioners. It is desirable to calculate a confidence range for the LCI (and LCIA) results. Technically this confidence interval of the results could be calculated with the help of Monte-Carlo simulation (in Umberto5). For this, standard deviations (or distribution functions) of every flow and every unit process would have to be known that are not available in reality due to insufficient independent data points. An alternative option to determine the uncertainty could be an estimation of the standard deviations basing on a pedigree matrix, as practised e.g. in ecoinvent 2.2. The disadvantage of this method would be that incorrect estimates of relevant flows would lead to wrong confidence intervals and basic misinterpretations of results. Hence a quantitative uncertainty assessment cannot be provided. The overall qualitative assessment of data accuracy is as follows:

- There is a high accuracy of relevant material flows, especially of intermediate products within the production system;
- There is good accuracy for energy flows and combustion related air emissions (CO_2 , SO_2 , NO_x , CH_4);
- There is satisfactory accuracy for other air emissions and emissions to water bodies.

Reproducibility

All data and information used are either documented in this report or they are available from the processes and process plans designed within the Umberto5 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

The data of the core process steam cracking was reviewed by APPE, and based on a survey of APPE, the Eco-profile model for steam cracking could be verified and amended with industry data from 2008 – 2010. Furthermore, data contained in the APPE Cracker Rule Book (APPE 2010) was intensely reviewed during the ETS benchmarking process. The production data from the other sources mentioned above has been cross-checked with literature data. This literature as the Reference Documents on Best Available Techniques, ecoinvent v.2.2 and Ullmann's Encyclopaedia are considered to contain highly representative data. The upstream chains of the feedstock have been validated after their update by comparing the emissions with different references, i.e. Gemis

4.6, ecoinvent v.2.2, internal reference from IFEU. The changes of emissions along the upstream chains of the feedstock are in accordance with the respective primary data and well to explain. The consistency of the overall input data is thus confirmed.

Life Cycle Model

The life cycle system is modelled in UMBERTO5, a standard software tool for LCA (see Figure 6). The associated database integrates ISO 14040/44 requirements. Data for production processes have been transferred to the model after a successful data validation.

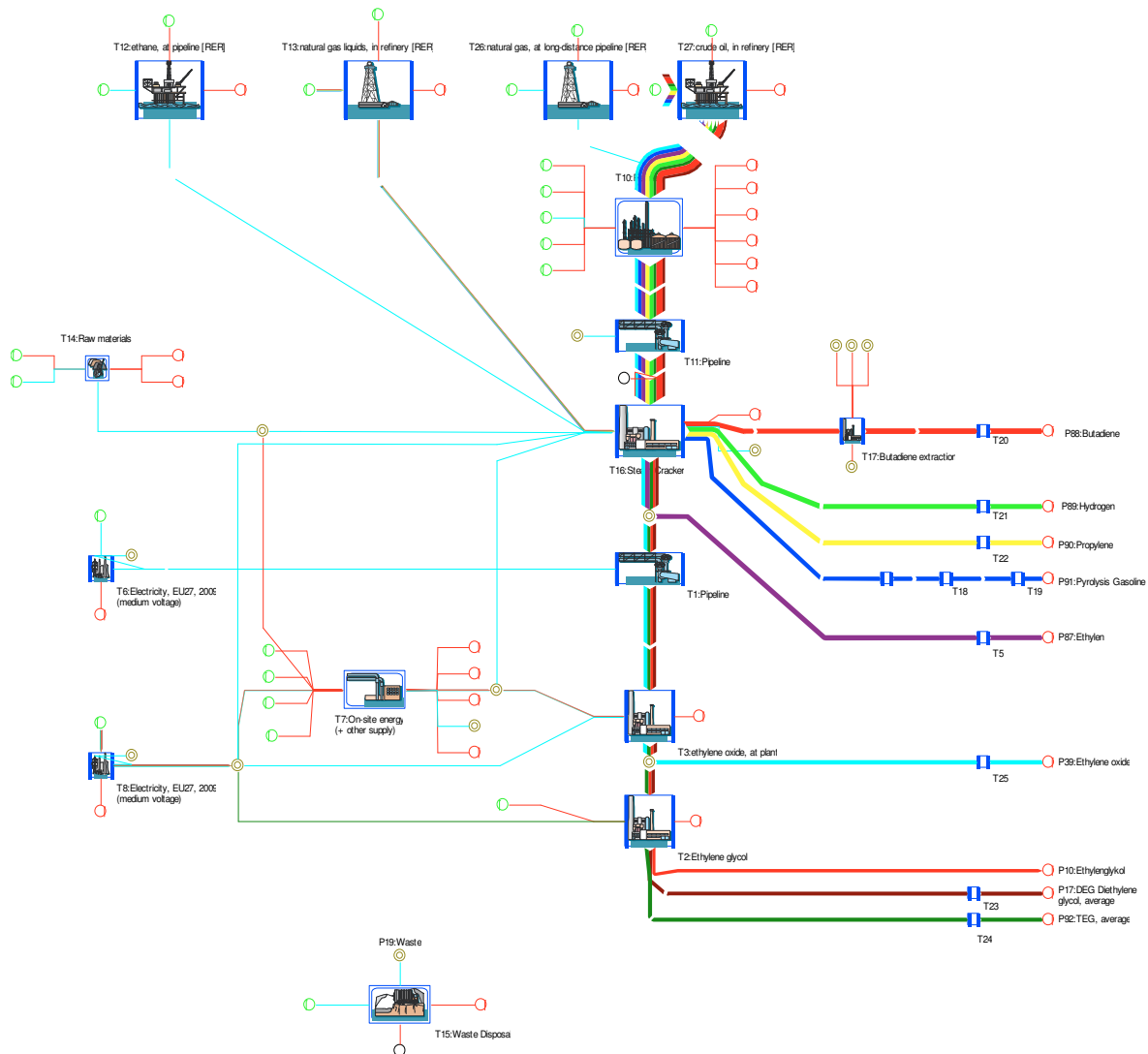


Figure 6: Life cycle model for the production of polymer precursors in Europe in UMBERTO5

Due to confidentiality reasons details on software modelling and methods used cannot be shown here. The calculation follows the horizontal calculation methodology, i.e. processes are aggregated each supplying the same reference flow.

Calculation Rules

Vertical/Horizontal Averaging

When modelling and calculating average Eco-profiles, horizontal averaging was applied (Figure 7). As the production of polymer precursors is not under operational control of PlasticsEurope no company specific supply chain was available; thus average European processes had to be used for the model. It is assumed that the averages are highly consistent anyway as the core process data for steam cracking was verified with data from and by the Association of Petrochemicals Producers in Europe (APPE). The data for processes in the upstream of the steam cracker, i.e. petroleum refinery and pre-chains of the steam cracker's feedstock, are assumed to be highly consistent as well as operators' data was cross-check with well-respected literature sources.

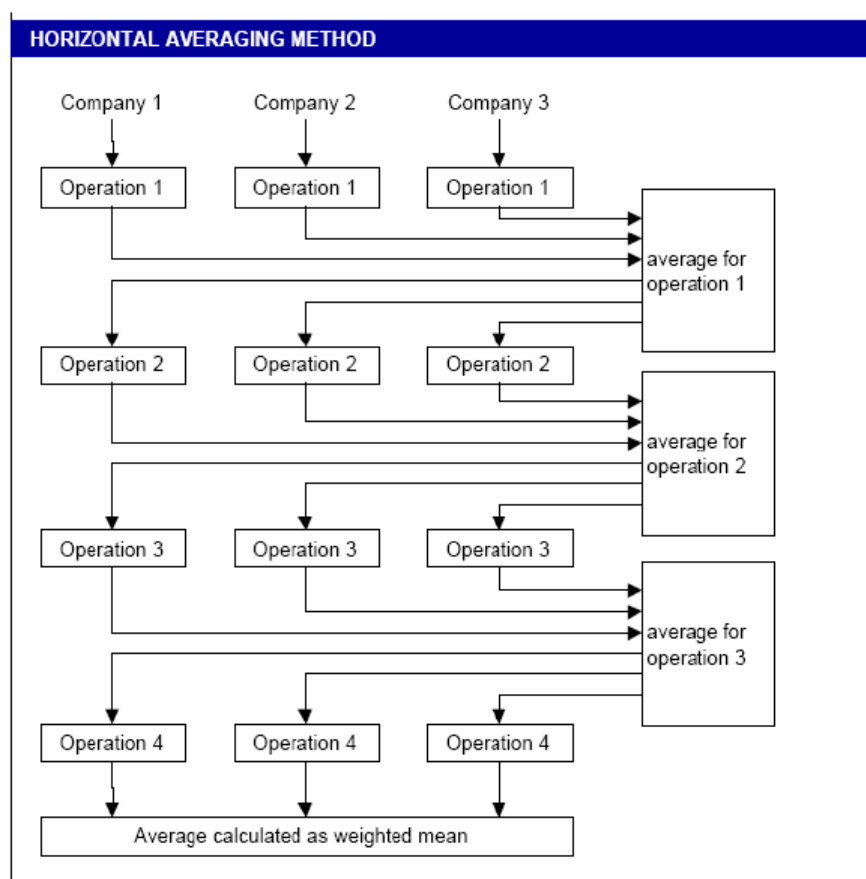


Figure 7: Horizontal Averaging (source: Eco-profile of high volume commodity phthalate esters, ECPI European Council for Plasticisers and Intermediates, 2001)

Allocation Rules

Production processes in chemical and plastics industry are often multi-functional systems, i.e. they have not one, but several valuable product and co-product outputs. According to PlasticsEurope's LCI methodology and product category rules for uncompounded polymer resins and reactive polymer precursors v.2.0, allocation should be avoided by expanding the system to include the additional functions related to the co-products, wherever possible. Therefore, a generic process with the same function (product) can be introduced, and the examined system receives credits for the associated burdens avoided elsewhere (»avoidance allocation«). System expansion should only be used where there is a dominant, identifiable displaced product, and if there is a dominant, identifiable production path for the displaced product.

In this Eco-profile, where the main production technologies for specific polymer precursors are considered, avoiding allocation is not feasible. 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. In principle, allocation rules should reflect the goal of the production process. If allocation cannot be avoided, physical allocation is applied in general in this Eco-profile. The production of ethylene oxide has no relevant co-product. Heat from the highly exothermic process of ethylene oxidation is internally used at plant sites. For the processes of steam cracking, ethylene glycol production, oil refining and the upstream chains of crude oil and natural gas allocations are necessary, and the following allocation rules were applied:

- The emissions caused by **crude oil extraction** and **natural gas processing** within a specific supply region were allocated by mass. This is especially relevant for regions where a combined gas and oil production takes place.
- An **oil refinery** is a complex production sub-system with many multi-output processes and products. The basic allocation criterion is the energy content 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 since the EU Renewable Energy Directive (RED) 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; to the cracker residues (looped back), no energy or emission burdens besides the material feed demand were assigned.
- **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 sub-system under consideration. Diverse hydrocarbons are formed as co-products besides ethylene, propylene, hydrogen, butadiene and pyrolysis gas. The shares of the co-products can vary significantly depending on plant configuration, market values of products and feedstock composition. Ethylene and propylene are the dominating products if naphtha is used as feedstock. The feedstock input is allocated by mass to all products leaving the cracking plant. All the other inputs and outputs, i.e. energy input, emissions and solid wastes, are allocated by mass to the High Value Chemicals (HVC) products, i.e. ethylene, propylene, butadiene, acetylene, benzene, toluene, xylenes, ethyl benzene, styrene 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.
- **Ethylene glycols** production generates monoethylene glycol as main output and lower shares of diethylene glycol and triethylene glycol as co-products. Inputs and outputs of the ethylene glycol-process are allocated to the products by stoichiometric principles.

As a sensitivity analysis, an alternative economic allocation could be desirable for the above-mentioned processes. However, uncertainties were found to be too large; the market prices for the considered products fluctuate greatly and some prices for intermediate products (e.g. of refineries) cannot be determined at all. For steam cracking, it is also possible to choose the energy content of the products as criterion for physical allocation. This method renders results similar to those of mass-based allocation, since the calorific values of the main products ethylene, propylene and butadiene are very similar. This applies also to the glycols production and the petro-

leum refinery. However, mass allocation for refinery processes would lead to higher burdens for heavy fractions and residues compared to low-boiling products, due to their higher density. Thus, Eco-profiles for high-boiling products would be over-estimated if mass allocation were applied.

In the previous Eco-Profile (BOUSTEAD 2005), all material and energy inputs and emissions had been allocated by mass to all cracker products, regardless of the value of these products. In contrast to this, in the current study energy inputs and emissions were allocated only to High Value Chemicals (HVC). The remaining products (non-HVC) are usually fed back to the refineries and are used in refinery products (e.g. for gasoline and diesel). The economic value of these back-flowing non-HVC products is similar to that of cracker feedstock from refineries (e.g. of naphtha). Thus, only the feedstock of the cracker was allocated to the non-HVC products. According to this allocation method, the backflows (non-HVC) have a similar ecologic burden as the feedstock, e.g. naphtha. This is in accordance with the allocation method described in the APPE Cracker Rule Book (APPE 2010) which was used in the cracker benchmark for the European Emission Trading Scheme (ETS). The influence of the different allocation methods is shown by way of example in a sensitivity analysis for the impact category "Global warming potential (GWP)" in Table 29 on page 37.

The following allocation rule for end-of-life management was employed: 'waste for reuse' with a recycling potential leaving the system, i.e. slags and ashes, does not receive any burdens or credits (cut-off). Process waste for disposal is treated within the system.

Life Cycle Inventory (LCI) Results

Formats of LCI Dataset

The Eco-profiles is provided in three electronic formats:

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

Key results are summarised below.

Energy Demand

As a key indicator on the inventory level, the **primary energy demand** (system input) 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 values (lower heating value, LHV) are also presented in Table 6 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), quantified as the gross calorific value (UHV).

Table 6: Primary energy demand (system boundary level) per 1 kg of product

Primary Energy Demand	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
Energy content in polymer [MJ] (energy recovery potential, quantified as gross calorific value of polymer)	50.2	48.8	47.0	42.4	29.6	19.0	22.3	25.3
Process energy [MJ] (quantified as difference between primary energy demand and energy content of polymer)	22.4	23.8	37.5	22.8	35.7	31.0	36.7	37.3
Total primary energy demand (Upper heating value) [MJ]	72.6	72.6	84.4	65.2	65.4	50.0	59.0	62.6
Total primary energy demand (Lower heating value) [MJ]	68.2	68.2	79.0	61.2	61.5	47.0	55.5	58.9

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

Table 7 to Table 14 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 carbon backbone of the polymer precursors –all feedstocks used contain more hydrogen than needed for the polymer precursors considered. The remaining hydrogen is used for process energy generation. Note that some

feedstock input may still be valorised as energy; furthermore, process energy requirements may also be affected by exothermic or endothermic 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 7: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg ethylene

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	0.49	0.024		0.49
Oil	57.99	1.266	40.27	17.72
Natural gas	12.39	0.268	7.57	4.81
Lignite	0.41	0.038		0.41
Nuclear	1.02	0.000		1.02
Other non-renewable fuels	0.00			0.00
Biomass	0.13			0.13
Hydro	0.14			0.14
Solar	0.00			0.00
Geothermics	0.00			0.00
Wind	0.04			0.04
Other renewable fuels	0.00			0.00
Sub-total renewable	0.3	0.0	0.0	0.3
Sub-total non-renewable	72.3	1.6	47.8	24.4
Total	72.6	1.6	47.8	24.8

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	0.49	0.024		0.49
Oil	57.99	1.266	40.27	17.72
Natural gas	12.39	0.268	7.57	4.81
Lignite	0.41	0.038		0.41
Nuclear	1.02	0.000		1.02
Other non-renewable fuels	0.00			0.00
Biomass	0.13			0.13
Hydro	0.14			0.14
Solar	0.00			0.00
Geothermics	0.00			0.00
Wind	0.04			0.04
Other renewable fuels	0.00			0.00
Sub-total renewable	0.3	0.0	0.0	0.3
Sub-total non-renewable	72.3	1.6	47.8	24.4
Total	72.6	1.6	47.8	24.8

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	0.85	0.042		0.85
Oil	59.29	1.295	41.76	17.53
Natural gas	21.26	0.460	7.86	13.41
Lignite	0.69	0.064		0.69
Nuclear	1.76	0.000		1.76
Other non-renewable fuels	0.00			0.00
Biomass	0.26			0.26
Hydro	0.25			0.25
Solar	0.01			0.01
Geothermics	0.00			0.00
Wind	0.07			0.07
Other renewable fuels	0.00			0.00
Sub-total renewable	0.6	0.0	0.0	0.6
Sub-total Non-renewable	83.8	1.9	49.6	34.2
Total	84.4	1.9	49.6	34.8

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	0.34	0.017		0.34
Oil	52.52	1.147	42.22	10.31
Natural gas	11.11	0.240	7.94	3.17
Lignite	0.29	0.027		0.29
Nuclear	0.71	0.000		0.71
Other non-renewable fuels	0.00			0.00
Biomass	0.08			0.08
Hydro	0.10			0.10
Solar	0.00			0.00
Geothermics	0.00			0.00
Wind	0.03			0.03
Other renewable fuels	0.00			0.00
Sub-total renewable	0.2	0.0	0.0	0.2
Sub-total Non-renewable	65.0	1.4	50.2	14.8
Total	65.2	1.4	50.2	15.0

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	1.69	0.082		1.69
Oil	46.57	1.017	25.63	20.94
Natural gas	11.05	0.239	4.82	6.23
Lignite	1.34	0.123		1.34
Nuclear	3.50	0.000		3.50
Other non-renewable fuels	0.00			0.00
Biomass	0.57			0.57
Hydro	0.47			0.47
Solar	0.02			0.02
Geothermics	0.00			0.00
Wind	0.16			0.16
Other renewable fuels	0.00			0.00
Sub-total renewable	1.2	0.0	0.0	1.2
Sub-total non-renewable	64.1	1.5	30.4	33.7
Total	65.4	1.5	30.4	34.9

Table 12: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg monoethylene glycol

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	1.79	0.086		1.79
Oil	33.41	0.729	18.19	15.22
Natural gas	8.41	0.182	3.42	4.99
Lignite	1.41	0.129		1.41
Nuclear	3.69	0.000		3.69
Other non-renewable fuels	0.00			0.00
Biomass	0.62			0.62
Hydro	0.49			0.49
Solar	0.02			0.02
Geothermics	0.00			0.00
Wind	0.17			0.17
Other renewable fuels	0.00			0.00
Sub-total renewable	1.3	0.0	0.0	1.3
Sub-total non-renewable	48.7	1.1	21.6	27.1
Total	50.0	1.1	21.6	28.4

Table 13: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg diethylene glycol

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	2.11	0.102		2.11
Oil	39.44	0.861	21.28	18.17
Natural gas	9.93	0.215	4.00	5.93
Lignite	1.66	0.152		1.66
Nuclear	4.36	0.000		4.36
Other non-renewable fuels	0.00			0.00
Biomass	0.73			0.73
Hydro	0.58			0.58
Solar	0.02			0.02
Geothermics	0.00			0.00
Wind	0.20			0.20
Other renewable fuels	0.00			0.00
Sub-total renewable	1.5	0.0	0.0	1.5
Sub-total non-renewable	57.5	1.3	25.3	32.2
Total	59.0	1.3	25.3	33.8

Table 14: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg triethylene glycol

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	2.24	0.108		2.24
Oil	41.82	0.913	22.55	19.27
Natural gas	10.53	0.227	4.24	6.28
Lignite	1.76	0.162		1.76
Nuclear	4.62	0.000		4.62
Other non-renewable fuels	0.00			0.00
Biomass	0.77			0.77
Hydro	0.61			0.61
Solar	0.02			0.02
Geothermics	0.00			0.00
Wind	0.22			0.22
Other renewable fuels	0.00			0.00
Sub-total renewable	1.6	0.0	0.0	1.6
Sub-total non-renewable	61.0	1.4	26.8	34.2
Total	62.6	1.4	26.8	35.8

Table 15 shows that nearly all of the primary energy demand is from non-renewable resources. Table 16 analyses the types of useful energy inputs in the polymerisation: electricity has a minor contribution, whereas the majority is thermal energy (heat). It should be noted, however, that the LCI tables in the annex account for the entire cradle-to-gate primary energy demand of the considered production system.

Table 15: Primary energy demand by renewability

Fuel/energy input type	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
Renewable energy resources	0.4%	0.4%	0.7%	0.3%	1.9%	2.6%	2.6%	2.6%
Non-renewable energy resources	99.6%	99.6%	99.3%	99.7%	98.1%	97.4%	97.4%	97.4%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 16: Analysis by type of useful energy for foreground processes (steam cracking, butadiene extraction, ethylene oxide and ethylene glycol production) per 1 kg of product

Type of useful energy in process input	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
Electricity [MJ]	0.76	0.76	1.5	0.46	1.0	2.1	2.4	2.6
Heat, thermal energy [MJ]	12.6	12.6	19.1	7.4	10.0	7.1	8.4	8.9
Total (for selected key process) [MJ]	13.4	13.4	20.6	7.9	11.1	9.2	10.9	11.5

Water Consumption

Table 17: Gross water resources per 1 kg of product

Water use	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
Process water [kg]	1.9	1.9	2.5	1.6	2.3	7.8	9.2	9.8
Cooling water [kg]	14.4	14.4	73.2	10.1	34.0	33.8	39.9	42.3
Unspecified [kg]	2.8	2.8	2.8	2.5	2.2	1.6	1.9	2.0
Total [kg]	19.1	19.1	78.4	14.2	38.5	43.2	51.0	54.1

Air Emission Data

Table 18 shows a few selected air emissions, which are commonly reported and used as key performance indicators; for a full inventory of air emissions, please refer to the complete LCI table in the annex of this report.

Table 18: Selected air emissions per 1 kg of product

Air emissions	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
Carbon dioxide, fossil [kg]	1.37	1.37	1.89	0.96	1.91	1.50	1.77	1.88
Carbon monoxide (CO) [kg]	0.0009	0.0009	0.0010	0.0007	0.0010	0.0008	0.0009	0.0009
Sulphur dioxide (SO ₂) [kg]	0.0017	0.0017	0.0020	0.0015	0.0019	0.0016	0.0019	0.0020
Nitrogen oxides (NO _x) [kg]	0.0025	0.0025	0.0030	0.0021	0.0026	0.0021	0.0025	0.0026
Particulate matter ≤ 10 µm [kg]	0.00021	0.00021	0.00024	0.00018	0.00023	0.00019	0.00023	0.00024

Wastewater Emissions

Table 19 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 19: Selected wastewater emissions per 1 kg of product

Wastewater emissions	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
Biological oxygen demand after 5 days (BOD 5) [kg]	0.028	0.028	0.028	0.025	0.022	0.016	0.019	0.020
Chemical oxygen demand (COD) [kg]	0.028	0.028	0.029	0.025	0.022	0.016	0.019	0.020
Total organic carbon (TOC) [kg]	0.0081	0.0081	0.0083	0.0074	0.0065	0.0047	0.0056	0.0059

Solid Waste

Table 20: Solid waste generation per 1 kg ethylene (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0024	0.0024
Hazardous	0.000042	0.0	0.0	0.00024	0.00028
Unspecified	0.00018	0.0	0.0011	0.0013	0.0026
Total	0.00022	0.0	0.0011	0.0040	0.0053

Table 21: Solid waste generation per 1 kg propylene (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0024	0.0024
Hazardous	0.000042	0.0	0.0	0.00024	0.00028
Unspecified	0.00018	0.0	0.0011	0.0013	0.0026
Total	0.00022	0.0	0.0011	0.0040	0.0053

Table 22: Solid waste generation per 1 kg butadiene (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0025	0.0025
Hazardous	0.000133	0.0	0.0	0.00024	0.00038
Unspecified	0.00018	0.0	0.0011	0.0013	0.0026
Total	0.00032	0.0	0.0011	0.0041	0.0055

Table 23: Solid waste generation per 1 kg pyrolysis gasoline (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0014	0.0014
Hazardous	0.000025	0.0	0.0	0.00014	0.00017
Unspecified	0.00011	0.0	0.00064	0.0008	0.0015
Total	0.00013	0.0	0.00064	0.0024	0.0031

Table 24: Solid waste generation per 1 kg ethylene oxide (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0019	0.0019
Hazardous	0.000033	0.0	0.0	0.00019	0.00022
Unspecified	0.00014	0.0	0.0009	0.0011	0.0021
Total	0.00018	0.0	0.0009	0.0032	0.0042

Table 25: Solid waste generation per 1 kg monoethylene glycol (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0014	0.0014
Hazardous	0.000024	0.0	0.0	0.00014	0.00016
Unspecified	0.00010	0.0	0.0006	0.0007	0.0015
Total	0.00013	0.0	0.0006	0.0023	0.0030

Table 26: Solid waste generation per 1 kg diethylene glycol (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0016	0.0016
Hazardous	0.000028	0.0	0.0	0.00016	0.00019
Unspecified	0.00012	0.0	0.0007	0.0009	0.0017
Total	0.00015	0.0	0.0007	0.0027	0.0036

Table 27: Solid waste generation per 1 kg triethylene glycol (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.0	0.0	0.0	0.0017	0.0017
Hazardous	0.000030	0.0	0.0	0.00017	0.00020
Unspecified	0.00013	0.0	0.0008	0.0009	0.0018
Total	0.00016	0.0	0.0008	0.0028	0.0038

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 (2002, 2012).

Table 28: Abiotic Depletion Potential (ADP) per 1 kg of product

Natural resources	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
ADP, elements [kg Sb eq]	2.7×10^{-8}	2.7×10^{-8}	3.5×10^{-8}	2.2×10^{-8}	2.8×10^{-8}	2.2×10^{-8}	2.6×10^{-8}	2.8×10^{-8}
ADP, fossil fuels (LHV) [MJ]	66.9	66.9	76.7	60.4	56.8	42.1	49.7	52.7

Output

Climate Change

The impact category climate change is represented by the Global Warming Potential (GWP) with a time horizon of 100 years. The applied characterisation factors are basing on the last report of the Intergovernmental Panel on Climate Change (IPCC 2007). In the previous version of this Eco-Profile (BOUSTEAD 2005), all material and energy inputs and emissions had been allocated by mass to **all** cracker products, regardless of the value of these products. In contrast to this, in the current study energy input and emissions were allocated only to High Value Chemicals (HVC), which is in accordance with the allocation method described in the APPE Cracker Rule Book (APPE 2010). The influence of the different allocation methods is shown in a sensitivity analysis for "Global warming potential (GWP)" in Table 29.

Table 29: Global Warming Potential (GWP, 100 years) per 1 kg of product

Climate change	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
GWP [kg CO ₂ eq.] (standard allocation to HVC only)	1.44	1.44	1.98	1.02	2.00	1.58	1.86	1.97
GWP [kg CO ₂ eq.] (sensitivity analysis: mass allocation to HVC <u>and</u> non-HVC)	1.21	1.21	1.75	1.21	1.82	1.45	1.71	1.81
Difference	-16%	-16%	-12%	+20%	-9%	-8%	-8%	-8%

Acidification

The Acidification Potential (AP) is quantified according to Hauschild (1998) with updated characterisation factors of CML (2010).

Table 30: Acidification Potential per 1 kg of product

Acidification of soils and water bodies	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
AP [g SO ₂ eq.]	3.52	3.52	4.14	3.00	3.76	3.10	3.67	3.89

Eutrophication

The Eutrophication Potential (EP) is calculated according to Heijungs (1992) with updated characterisation factors of CML (2010).

Table 31: Eutrophication Potential per 1 kg of product

Eutrophication of soils and water bodies	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
EP, terrestrial [g PO ₄ ³⁻ eq.]	0.33	0.33	0.40	0.27	0.35	0.28	0.33	0.35
EP, aquatic [g PO ₄ ³⁻ eq.]	0.75	0.75	0.77	0.68	0.60	0.43	0.51	0.54
EP, total [g PO ₄ ³⁻ eq.]	1.08	1.08	1.16	0.95	0.94	0.72	0.85	0.90

Ozone Depletion

The calculation of Ozone Depletion Potential (ODP) is basing on characterisation factors of the World Meteorological Organisation (WMO 2011). This implies also the consideration of dinitrogen monoxide (N₂O) as ozone depleting substance with an ODP of 0.017 kg CFC-11 eq. per kg of N₂O. This emission plays a relevant role for the overall ODP result of the considered products in this study with 23 % to 48 %.

Table 32: Ozone Depletion Potential per 1 kg of product

Ozone Depletion Potential	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
ODP [g CFC-11 eq.]	2.7x10 ⁻⁴	2.7x10 ⁻⁴	4.8x10 ⁻⁴	2.2x10 ⁻⁴	5.0x10 ⁻⁴	4.9x10 ⁻⁴	5.7x10 ⁻⁴	6.1x10 ⁻⁴

Summer Smog

The Photochemical Ozone Creation Potential (POCP) is quantified according to Jenkin (1999) and Derwent (1998) with updated characterisation factors of CML (2009).

Table 33: Photochemical Ozone Creation Potential per 1 kg of product

Photochemical Ozone Creation Potential	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
POCP [g Ethene eq.]	0.33	0.33	0.36	0.24	0.53	0.40	0.47	0.50

Dust & Particulate Matter

Particulate matter with an aerodynamic diameter of less than 10 µm (PM₁₀) is suspected to cause heart and circulatory diseases. New studies from internationally recognised organisations (e.g. WHO 2006) confirm a high mortality risk from fine dust. Large scale air pollution of PM₁₀ is caused by direct emissions of particulate matter and secondary particles that are formed by precursors such as nitrogen dioxide (NO₂), sulphur dioxide (SO₂), ammonia (NH₃) and Non-Methane Volatile Organic Compounds (NMVOC). The characterisation factors shown in Table 34 are based on works of De Leeuw (2002) and Heldstab (2003) for NMVOC.

Table 34: PM₁₀ characterisation factors of air emissions

PM ₁₀ and precursors	kg PM ₁₀ eq. / kg
Particulate matter PM ₁₀	1
Secondary aerosol formers (precursors)	
NO _x (as NO ₂)	0.88
SO ₂	0.54
NH ₃	0.64
NMVOC	0.012

Table 35: PM₁₀ emissions per 1kg precursor

Particulate matter ≤ 10 µm	Ethylene	Propylene	Butadiene	Pyrolysis Gasoline	Ethylene Oxide	Monoethylene Glycol	Diethylene Glycol	Triethylene Glycol
PM ₁₀ , direct emissions [PM ₁₀ eq.]	0.21	0.21	0.24	0.18	0.23	0.19	0.23	0.24
PM ₁₀ , secondary [PM ₁₀ eq.]	3.12	3.12	3.67	2.63	3.22	2.62	3.10	3.28
PM ₁₀ , total [PM ₁₀ eq.]	3.33	3.33	3.91	2.81	3.45	2.81	3.32	3.52

Dominance Analysis

Table 36 until Table 43 show the main contributions to the results presented above.

Table 36: Dominance analysis of impacts per 1 kg ethylene

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.0%	0.0%	57.9%	10.4%	6.3%	55.8%	13.6%
Electricity for foreground processes	2.7%	5.6%	1.4%	5.9%	6.9%	1.9%	2.5%	6.1%
Raw materials for foreground processes	0.1%	26.6%	0.1%	0.1%	0.1%	0.2%	0.1%	0.1%
Refinery	0.0%	61.5%	0.0%	9.5%	15.2%	2.1%	10.7%	11.3%
Crude oil & Natural gas extraction and transport	97.2%	5.7%	98.5%	26.4%	67.3%	89.4%	30.8%	68.8%
Process waste treatment	0.0%	0.5%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 37: Dominance analysis of impacts per 1 kg propylene

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.0%	0.0%	57.9%	10.4%	6.3%	55.8%	13.6%
Electricity for foreground processes	2.7%	5.6%	1.4%	5.9%	6.9%	1.9%	2.5%	6.1%
Raw materials for foreground processes	0.1%	26.6%	0.1%	0.1%	0.1%	0.2%	0.1%	0.1%
Refinery	0.0%	61.5%	0.0%	9.5%	15.2%	2.1%	10.7%	11.3%
Crude oil & Natural gas extraction and transport	97.2%	5.7%	98.5%	26.4%	67.3%	89.4%	30.8%	68.8%
Process waste treatment	0.0%	0.5%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 38: Dominance analysis of impacts per 1 kg 1,3-butadiene

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.2%	0.0%	64.2%	16.1%	9.2%	56.2%	19.4%
Electricity for foreground processes	4.7%	8.9%	2.4%	8.9%	12.1%	3.7%	4.8%	10.7%
Raw materials for foreground processes	0.1%	37.6%	0.1%	0.1%	0.2%	0.6%	0.2%	0.1%
Refinery	0.0%	48.3%	0.0%	7.0%	13.2%	2.0%	10.0%	9.8%
Crude oil & Natural gas extraction and transport	95.1%	4.5%	97.5%	19.6%	58.4%	84.4%	28.9%	59.8%
Process waste treatment	0.0%	0.4%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 39: Dominance analysis of impacts per 1 kg pyrolysis gasoline

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.0%	0.0%	48.6%	7.2%	4.2%	45.7%	9.5%
Electricity for foreground processes	1.8%	4.2%	0.9%	5.0%	4.8%	1.3%	2.1%	4.3%
Raw materials for foreground processes	0.1%	19.6%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Refinery	0.0%	69.5%	0.0%	12.2%	16.2%	2.2%	13.4%	12.1%
Crude oil & Natural gas extraction and transport	98.1%	6.4%	99.0%	34.0%	71.6%	92.1%	38.7%	73.9%
Process waste treatment	0.0%	0.4%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 40: Dominance analysis of impacts per 1 kg ethylene oxide

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.0%	0.0%	59.1%	7.8%	6.1%	72.1%	10.5%
Electricity for foreground processes	13.9%	26.1%	7.5%	20.1%	30.5%	10.5%	7.4%	27.8%
Raw materials for foreground processes	0.1%	20.8%	0.1%	0.1%	0.1%	0.2%	0.1%	0.1%
Refinery	0.0%	48.2%	0.0%	5.4%	11.4%	1.9%	5.3%	8.7%
Crude oil & Natural gas extraction and transport	85.9%	4.5%	92.4%	15.2%	50.2%	81.2%	15.2%	52.8%
Process waste treatment	0.0%	0.4%	0.0%	0.1%	0.1%	0.1%	0.0%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 41: Dominance analysis of impacts per 1 kg monoethylene glycol

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.0%	0.0%	53.5%	6.7%	6.6%	70.0%	9.2%
Electricity for foreground processes	19.7%	34.9%	11.0%	27.6%	39.9%	14.9%	10.6%	36.8%
Raw materials for foreground processes	0.1%	18.3%	0.1%	0.1%	0.1%	0.2%	0.1%	0.1%
Refinery	0.0%	42.4%	0.0%	4.9%	9.8%	1.8%	5.0%	7.6%
Crude oil & Natural gas extraction and transport	80.2%	3.9%	88.9%	13.7%	43.4%	76.4%	14.4%	46.2%
Process waste treatment	0.0%	0.3%	0.0%	0.1%	0.1%	0.1%	0.0%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 42: Dominance analysis of impacts per 1 kg diethylene glycol

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.0%	0.0%	53.5%	6.7%	6.6%	70.0%	9.2%
Electricity for foreground processes	19.7%	34.9%	11.0%	27.6%	39.9%	14.9%	10.6%	36.8%
Raw materials for foreground processes	0.1%	18.3%	0.1%	0.1%	0.1%	0.2%	0.1%	0.1%
Refinery	0.0%	42.4%	0.0%	4.9%	9.8%	1.8%	5.0%	7.6%
Crude oil & Natural gas extraction and transport	80.2%	3.9%	88.9%	13.7%	43.4%	76.4%	14.4%	46.2%
Process waste treatment	0.0%	0.3%	0.0%	0.1%	0.1%	0.1%	0.0%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 43: Dominance analysis of impacts per 1 kg triethylene glycol

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g Ethene eq.]	[g PM10 eq.]
Foreground processes (steam cracking, ethylene oxide, glycol production) incl. thermal energy	0.0%	0.0%	0.0%	53.5%	6.7%	6.6%	70.0%	9.2%
Electricity for foreground processes	19.7%	34.9%	11.0%	27.6%	39.9%	14.9%	10.6%	36.8%
Raw materials for foreground processes	0.1%	18.3%	0.1%	0.1%	0.1%	0.2%	0.1%	0.1%
Refinery	0.0%	42.4%	0.0%	4.9%	9.8%	1.8%	5.0%	7.6%
Crude oil & Natural gas extraction and transport	80.2%	3.9%	88.9%	13.7%	43.4%	76.4%	14.4%	46.2%
Process waste treatment	0.0%	0.3%	0.0%	0.1%	0.1%	0.1%	0.0%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Comparison of the Present Eco-profile with its Previous Version

Table 44 to Table 47 compare the present results with the previous version of the Eco-profile of 2005. In the previous Eco-profile, the available LCI did not comprise all the substances necessary for the calculation of Eutrophication potential (EP) and Ozone Depletion Potential (ODP). Therefore, it is not recommended to compare the results of these impact categories with the current Eco-Profile.

Table 44: Comparison of the present Eco-profile of ethylene with its previous version (1999/2005)

Environmental Impact Categories	Ethylene Eco-profile Process data 1999 Calculated 2005	Ethylene Eco-profile 2012	Difference
Gross primary energy from resources [MJ]	66.0	72.6	10%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.] ^(a)	3.0E-08	2.7 x10 ⁻⁸	-10%
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	66.3	66.9	1%
Global Warming Potential (GWP) [kg CO ₂ eq.]	1.38	1.44	5%
Acidification Potential (AP) [g SO ₂ eq.] ^(a)	3.9	3.5	-9%
Eutrophication Potential (EP) [g PO ₄ ³⁻ eq.] ^(a)	0.34	1.1	213%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	n/a ^(b)	2.7 x10 ⁻⁴	n/a ^(b)
Photochemical Ozone Creation Potential [g Ethene eq.] ^(a)	0.23	0.33	44%

a) Results are not included in previous Eco-profile; values have been extracted from implemented dataset in ecoinvent2.2

b) not applicable: relevant substances for impact category are not listed in previous Eco-profile

Table 45: Comparison of the present Eco-profile of propylene with its previous version (1999/2005)

Environmental Impact Categories	Propylene Eco-profile Process data 1999 Calculated 2005	Propylene Eco-profile 2012	Difference
Gross primary energy from resources [MJ]	67.4	72.6	8%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.] ^(a)	2.0E-08	2.7x10 ⁻⁸	33%
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	67.8	66.9	-1%
Global Warming Potential (GWP) [kg CO ₂ eq.]	1.42	1.44	2%
Acidification Potential (AP) [g SO ₂ eq.] ^(a)	4.0	3.5	-11%
Eutrophication Potential (EP) [g PO ₄ ³⁻ eq.] ^(a)	0.33	1.1	223%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	n/a ^(b)	2.7 x10 ⁻⁴	n/a ^(b)
Photochemical Ozone Creation Potential [g Ethene eq.] ^(a)	0.24	0.33	37%

a) Results are not included in previous Eco-profile; values have been extracted from implemented dataset in ecoinvent2.2

b) not applicable: relevant substances for impact category are not listed in previous Eco-profile

Table 46: Comparison of the present Eco-profile of butadiene with its previous version (1999/2005)

Environmental Impact Categories	Butadiene Eco-profile Process data 1999 Calculated 2005	Butadiene Eco-profile 2012	Difference
Gross primary energy from resources [MJ]	64.9	84.4	30%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.] ^(a)	1.8E-08	3.5x10 ⁻⁸	94%
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	65.1	76.7	18%
Global Warming Potential (GWP) [kg CO ₂ eq.]	1.16	1.98	70%
Acidification Potential (AP) [g SO ₂ eq.] ^(a)	3.8	4.1	10%
Eutrophication Potential (EP) [g PO ₄ ³⁻ eq.] ^(a)	0.30	1.2	292%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	n/a ^(b)	4.8 x10 ⁻⁴	n/a ^(b)
Photochemical Ozone Creation Potential [g Ethene eq.] ^(a)	0.19	0.36	84%

a) Results are not included in previous Eco-profile; values have been extracted from implemented dataset in ecoinvent2.2

b) not applicable: relevant substances for impact category are not listed in previous Eco-profile

Table 47: Comparison of the present Eco-profile of pyrolysis gasoline with its previous version (1999/2005)

Environmental Impact Categories	Pyrolysis gaso- line Eco-profile Process data 1999 Calculated 2005	Pyrolysis gaso- line Eco-profile 2012	Difference
Gross primary energy from resources [MJ]	63.9	65.2	2%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.] ^(a)	n/a ^(b)	2.2x10 ⁻⁸	n/a ^(b)
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	64.5	60.4	-6%
Global Warming Potential (GWP) [kg CO ₂ eq.]	1.41	1.02	-28%
Acidification Potential (AP) [g SO ₂ eq.] ^(a)	n/a ^(b)	3.0	n/a ^(b)
Eutrophication Potential (EP) [g PO ₄ ³⁻ eq.] ^(a)	n/a ^(b)	0.9	n/a ^(b)
Ozone Depletion Potential (ODP) [g CFC-11 eq.] ^(a)	n/a ^(b)	2.2x10 ⁻⁴	n/a ^(b)
Photochemical Ozone Creation Potential [g Ethene eq.] ^(a)	n/a ^(b)	0.24	n/a ^(b)

^{a)} Results are not included in previous Eco-profile

Review

Review Details

The goal and scope of this Eco-profile study was confirmed to be a European production average of the following polymer precursors: Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), and Ethylene Glycols (MEG, DEG, TEG). The geographical scope includes the EU 27 member states and Norway, with a coverage of 50 plants (approx. 90% of European production volume). One important limitation of the technological scope is that the study considered only steam cracking, the most important process to produce ethylene and propylene, whereas the Fluid Catalytic Cracking (FCC) process is not included here. This technological scope is in line with earlier Eco-profiles published by PlasticsEurope which were also limited to steam crackers as a source of olefins and their derivatives. Further, since naphtha is the most common feedstock in Europe, the examined population of cracker units comprised predominantly naphtha crackers (only 2 gas crackers using ethane, while all others use a mix of feeds, with naphtha being predominant).

The main data source used for this study was a validated confidential report by the petrochemical industry (APPE) under the European Emission Trading Scheme (ETS) on energy use and CO₂ emissions of European steamcracking operations. In addition, publicly available literature was used. Other processes, including refinery, ethylene oxidation, and ethylene glycol production, were derived from a proprietary refinery model (developed by the practitioner IFEU through various petrochemical industry projects), and further literature data. The review confirmed that, despite no primary data collection was conducted, the data used are applicable, up-to-date, and modelled with a view to internal consistency. The temporal scope was confirmed to be 2009 reference year and valid at least until 2014 in view of the slow technological changes.

The following aspects were subject to particular scrutiny by the review panel:

- The product range of the steam cracker, especially the designation as high value compounds (HVC) for the purposes of allocation;
- the input/output balance of hydrocarbon feedstocks, also accounting for internal loops or further processing of some intermediate products (such as hydrogen and pyrolysis gas);
- specifically, the modelling of non-HVC refinery/fuel gases which are valorised either for thermal energy or for secondary cracking or other post-processing steps – while these will not be burdened with process energy requirements and emissions of the steam cracker itself, they do bear a share of the upstream burdens;
- the use of electric and thermal energy, and the consistent accounting for the associated emissions;
- the consistent and justifiable use of allocation methods;
- plausibility checks of calculations along the productions chains.

A review meeting between the LCA practitioner and the reviewers was held, including a model and database review, and spot checks of data and calculations. The results are thus held to be representative and reliable for the specified production routes. It is noteworthy that, compared with previous studies under the PlasticsEurope Eco-profiles programme, the results for butadiene and pyrolysis gasoline (pygas) have changed notably:

- According to recent industry data (APPE), the thermal energy (steam) required for the steam cracking process is rather high compared with the previous version of this Eco-profile.
- The previous edition of the Eco-profiles for olefins apparently used a mass allocation of energy demand and emissions of the steam cracking process to all cracker output streams (thus lowering specific burdens), not

only to the HVC as in the present version; from today's perspective, also to ensure consistency with current industry practice (APPE), the allocation used here is deemed more appropriate.

- It is noteworthy that fuel-grade by-products which are returned to the refinery (looped back) were calculated with their calorific value and with their upstream burdens (oil extraction, transport and refining), but no process-related environmental impacts were assigned to them.
- Specifically, the impact indicators for butadiene have increased substantially because butadiene is extracted in a separate facility following the steam cracker, and this additional processing requires thermal energy, electricity, and solvents.
- The impact indicators for pygas (including benzene, toluene and xylene, BTX, and other components) have decreased because of the adjusted allocation.
- The overall levels of greenhouse gas emissions of the steam cracker units were confirmed to be in line with APPE's ETS reporting and corroborated by bottom-up calculations based on the internal use of low-value by-products as process fuels (mainly methane). For greenhouse gas emissions, the results of this new version of the Eco-profile are hardly higher than those published in the previous version of 2005.
- Other impact categories changed somewhat in proportion with the process energy requirements. It should be noted, however, that some indicators apparently changed substantially due to life cycle inventory items in the previous version not being specific enough to allow an accurate *a posteriori* calculation (average characterisation factors applied to unspecified substance flows). In these cases, a comparison with the previous version is strictly speaking not valid.

Further, the review verified that the model and calculations comply with the rules of the PlasticsEurope Eco-profiles methodology and with ISO 14040–14044: the resulting life cycle inventory datasets for Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), and Ethylene Glycols (MEG, DEG, TEG) and are thus compatible building blocks for use in other Eco-profile calculations.

Review Summary

The Eco-profile of Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), and Ethylene Glycols (MEG, DEG, TEG) has been validated to appropriately represent current European production of these polymer precursors. The underlying emission data for the steam cracking process are consistent with reports of the petrochemical industry under the European Emission Trading Scheme (ETS). Other processes, including refinery, ethylene oxidation, and ethylene glycol production, were derived from project and literature data and modelled with a view to internal consistency. The results are thus held to be representative and reliable for the specified production routes.

Reviewer Names and Institutions

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References

- APPE 2010 Association of Petrochemicals Producers in Europe (APPE) and The European Chemical Industry Council (CEFIC): Cracker Rule Book, March 2010
- APPE 2012 Association of Petrochemicals Producers in Europe (APPE): Cracker Capacities 2011
→ <http://www.petrochemistry.net/crackers-capacities-in-europe.html>
- BOUSTEAD 2005 Boustead, I., Eco-profiles of the European Plastics Industry, Plastics Europe, March 2005
- BP 2010 BP North Sea Region Environmental Statement 2010. BP Exploration Operating Company Ltd, Aberdeen, 2010
- BREF 2003 Integrated Pollution Prevention and Control (IPPC): Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry, February 2003
- BREF 2010 Integrated Pollution Prevention and Control (IPPC): Draft Reference Document on Best Available Techniques for Mineral Oil and Gas Refineries, July 2010
- CML 2002 Guinée, J. B. (Ed.): Handbook on Life Cycle Assessment – Operational Guide to the ISO Standards. Springer, 2002
- CML 2010 CML - Institute of Environmental Sciences: Impact assessment characterisation factors, version 3.9. CML, Leiden, November, 2010
→ <http://www.leidenuniv.nl/interfac/cml/ssp/index.html>
- ecoinvent2.2 Life cycle inventory database ecoinvent v2.2. ecoinvent Centre, St. Gallen, 2010. → <http://www.ecoinvent.org>
- ENI 2010 Sustainability Performance 2010. ENI spa, Rome
- EUROSTAT 2011 Energy – Yearly statistics 2009. Eurostat, Luxembourg, 2011
→ <http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home>
- EYERER 1996 Ganzheitliche Bilanzierung – Werkzeug zum Planen und Wirtschaften in Kreisläufen, 1996
- GAZPROM 2009 Environmental Report 2009. OAO Gazprom, Moscow
- GEMIS4.6 Global Emission Model for Integrated Systems v4.6. Ökoinstitut, Institute for Applied Ecology, Freiburg, August 2010. → <http://www.gemis.de>
- GUINÉE ET AL. 2001 Guinée, J. et. al. Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards. Centre of Environmental Science, Leiden University (CML); The Netherlands, 2001.
- GUINÉE ET AL. 2002 Handbook on Life Cycle Assessment: An operational Guide to the ISO Standards; Dordrecht: Kluwer Academic Publishers, 2002.
- HAUSCHILD 1998 Hauschild, M, Wenzel, H.: Environmental Assessment of products. Volume 2: Scientific background. Chapman & Hall, London, 1998
- HEIJUNGS 1992 Heijungs, R., J. Guinée, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin, H.P. de Goede, 1992: Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Science (CML), Leiden University, Leiden.

HUIJBREGTS 1999	Huijbregts, M., 1999b: Life cycle impact assessment of acidifying and eutrophying air pollutants. Calculation of equivalency factors with RAINS-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science, University of Amsterdam, The Netherlands. Forthcoming.
HUIJBREGTS 2000	Huijbregts, M.A.J., 2000. Priority Assessment of Toxic Substances in the frame of LCA. Time horizon dependency of toxicity potentials calculated with the multi-media fate, exposure and effects model USES-LCA. Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands. (http://www.leidenuniv.nl/interfac/cml/lca2/).
IPCC 2007	IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change. [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
ISO 14025: 2006	ISO 14025 Environmental labels and declarations – Type III environmental declarations. Geneva, 2006
ISO 14040: 2006	ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework. Geneva, 2006
ISO 14044: 2006	ISO 14044 Environmental management -- Life cycle assessment -- Requirements and guidelines. Geneva, 2006
ILCD 2010	European Commission (2010): ILCD Handbook – General guide for Life Cycle Assessment (LCA) – Detailed guidance
JEO 1999	Huang, J.: Ethylene Oxide Reactor System. jEO & Associates, October 1999. → http://www.owl.net.rice.edu/~ceng403/gr1599/finalreport3.html
LUKOIL 2008	Sustainability Report Russian Federation 2007-2008. OAO Lukoil, Moscow
MEYERS 2003	Robert A. Meyers (ed.): Handbook of Petroleum Refining Processes, 3 rd edition. 2003
NOGEPA 2009	Annual Report 2009. Highlights of the E&P industry in the Netherlands. NO-GEPA Netherlands Oil and Gas Exploration and Production Association, The Hague
OLF 2010	Environmental Report 2010. The environmental efforts of the oil and gas industry. Facts and trends. OLF - The Norwegian Oil Industry Association, Sandnes, June 2010
PLASTICSEUROPE 2010	Life Cycle Inventory (LCI) Methodology and Product Category Rules (PCR) for Uncompounded Polymer Resins and Reactive Polymer Precursors. Version 2.0, April 2011.
REBSDAT 2005A	Rebsdats, S, Mayer, D.: Ethylene Oxide. In Ullmann's Encyclopedia of Industrial Chemistry, WILEY-VCH Verlag, Weinheim, 2005
REBSDAT 2005B	Rebsdats, S, Mayer, D.: Ethylene Glycol. In Ullmann's Encyclopedia of Industrial Chemistry, WILEY-VCH Verlag, Weinheim, 2005
ROSNEFT 2009	Rosneft Sustainability Report 2009. OJSC Rosneft, Moscow
SHELL 2010	2010 Annual Environmental Statement for Upstream Operations. Shell U.K. Limited, Aberdeen, May 2011

TNO 2011	Verbeek R., Kadijk G., van Mensch P., Wulffers C., van den Beemt B., Fraga F.: Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands. TNO, Delft, March 2011
ULLMANN 2010	Ullmann's Encyclopedia of Industrial Chemistry, John Wiley & Sons, Inc. , Hoboken / USA, 2010
WEG 2009	Jahresbericht Zahlen & Fakten. WEG Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V., Hannover
WMO 2011	WMO (World Meteorological Organization), Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project – Report No. 52, 516 pp., Geneva, Switzerland, 2011.
WUPI 2005	Lechtenböhmer S., Dienst C., Fishedick M., Hanke T., Langrock T.: Greenhouse Gas Emissions from the Russian Natural Gas Export Pipeline. Results and Extrapolation of Measurements and Surveys in Russia. A Project on behalf of E.ON Ruhrgas AG. Wuppertal Institute for Climate, Environment and Energy in cooperation with Max-Planck-Institute for Chemistry, Mainz, Wuppertal and Mainz, February 2005

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