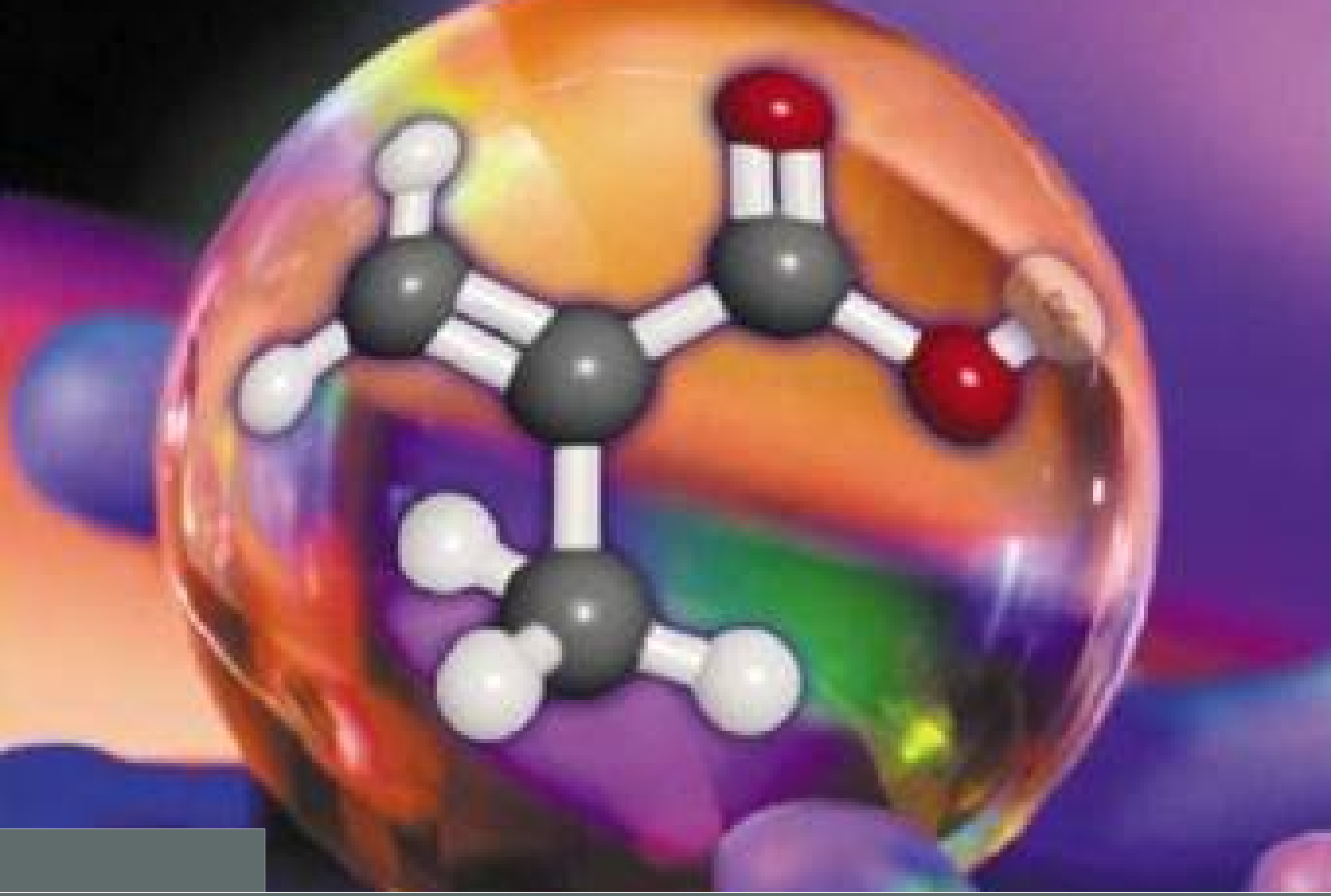


Methyl methacrylate (MMA)

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

March 2014

Environmental Product Declaration

Introduction

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

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

Meta Data

Data Owner	Cefic, MSG
LCA Practitioner	BIO Intelligence Service
Programme Owner	PlasticsEurope aisbl
Programme Manager, Reviewer	DEKRA Consulting GmbH
Number of plants included in data collection	5
Representativeness	European production (92%)
Reference year	2010 – 2011
Year of data collection and calculation	2012 – 2013
Expected temporal validity	2016
Cut-offs	No significant cut-offs
Data Quality	Good
Allocation method	Price allocation or 50/50 allocation (functional approach)

Description of the Product and the Production Process

This Eco-profile represents the European average production of methyl methacrylate (MMA) monomer from cradle to gate. MMA is an organic compound with the formula $C_5H_8O_2$. It is a key intermediate chemical, due to its ability to undergo polymerization and copolymerization. MMA is mainly used for the production of polymethyl methacrylate (PMMA).

Production Process

Several methods exist for the production of MMA. The main route, which is used by the European producers participating in this Eco-profile, is the "acetone cyanohydrin route".

This route is based on three steps.

The first step of the process is intended to produce hydrogen cyanide (HCN). Hydrogen cyanide is usually produced from methane and ammonia according to the Andrussow process or the Degussa process. These processes produce ammonium sulfate as a co-product. Hydrogen cyanide may also be obtained as a co-product from the acrylonitrile production process (Sohio process).

In the second step, hydrogen cyanide and acetone are used as reagents for the production of Acetone cyanohydrin (ACH).

In the third step, MMA is produced from acetone cyanohydrin, sulfuric acid and methanol. Firstly, acetone cyanohydrin undergoes sulfuric acid assisted hydrolysis and is converted into a sulfate ester of methacrylamide. Secondly, an esterification with methanol gives MMA. During the third step, sulfuric acid is used as an intermediate reagent. After the reactions, the spent sulfuric acid may be recycled and reused for the MMA production or may be neutralised with ammonia, producing ammonium sulfate as a co-product.

Data Sources and Allocation

This Eco-profile is based on 3 individual LCA studies performed independently by the 3 main European producers of MMA: Altuglas, Evonik and Lucite. The primary data used in these 3 studies and then in this Eco-profile comes from 5 plants located in 3 different European countries and is site-specific gate-to-gate production data.

The 3 producers participating to this Eco-profile cover 92 % of the European MMA production capacity in 2012.

Data for the upstream supply chain until the precursors and all relevant background data (such as energy and auxiliary materials) are taken from the ecoivent 2.2 database, except for acetone which is taken from the GaBi 5 database.

In this Eco-profile, allocation was applied in the first step and in the third step of the MMA production process. In the first step of the process, when it was possible, the process was subdivided into sub-processes and only a few flows intrinsically shared by the co-products were allocated. In this case, these specific flows were fully allocated to the most valuable co-product. Otherwise, when the available data did not allow any subdivision, economic allocation was applied in order to partition all the input and output flows of the process between hydrogen cyanide and its co-product (ammonium sulfate or acrylonitrile). In the third step of the process, where the spent sulfuric is used to produce ammonium sulfate as a co-product, the amount of sulfuric acid consumed in the process is equally allocated between MMA and ammonium sulfate (50/50 by mass). This approach is based on the functions fulfilled by sulfuric acid, which is required for the production of the two co-products.

Use Phase and End-of-Life Management

The disposal of waste from production processes is considered within the system boundaries of this Eco-profile. The use phase and end-of-life processes are outside the system boundaries of this cradle-to-gate system.

Environmental Performance

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

Input Parameters

Indicator	Unit	Value
Non-renewable energy resources[1)]	MJ	100.3
• Fuel energy	MJ	64.8
• Feedstock energy	MJ	35.5
Renewable energy resources (biomass)[1)]	MJ	0.66
• Fuel energy	MJ	0.66
• Feedstock energy	MJ	—
Abiotic Depletion Potential		
• Elements	kg Sb eq	2.58E-06
• Fossil fuels	MJ	93.8
Renewable materials (biomass)	kg	—
Water use (including cooling water)[2)]	kg	500

[1)] Calculated as upper heating value (UHV)
[2)] With available data, it was not possible to calculate the water use without cooling water and net freshwater consumption.

Output Parameters

Indicator	Unit	Value
GWP	kg CO_2 eq	3.47
ODP	g CFC-11 eq	3.24E-04
AP	g SO_2 eq	19
POCP	g Ethene eq	1.07
EP	g PO_4 eq	1.97
Dust, particulate matter	g PM10	4.54E-01
Waste sent to landfill[1)]		
• Non-hazardous	kg	1.55E-01
• Hazardous	kg	1.30E-03

[1)] With available data, it was not possible to assess the amount of waste sent to incineration.

Additional Environmental and Health Information

Methacrylate monomers are reactive products which must be handled in appropriate ways. In order to manage hazards please refer to the Safe Handling Manuals MSG and MPA. These documents provide product stewardship advice for the safe storage, handling and use of these products. Along with the Safety Datasheets provided by each supplier, they should be read and understood before ordering, storing and using methacrylates. Because methacrylate esters are contact allergens, the use of unreacted liquid monomers in mixtures which are intended to come into contact with skin or nails, e.g. nail sculpting, is not recommended. More information on methacrylates and human health can be found on the MPA website.

Additional Technical Information

The polymer PMMA, made from monomer MMA, is characterized by its robust properties and by the fact that it is easy to process. Thanks to its properties (light reflexion and transmission, mechanical resistance, low-density, capacity to be thermoformed etc.), PMMA can be used for a wide range of fields and applications (automobile industry, medical technologies, decoration, anti-noise walls, bathtubs and showers, advertising signs etc.).

Additional Economic Information

MMA is produced for use as monomer for production of polymers and as intermediate for synthesis of other methacrylate esters. The substance is manufactured in industrial settings in closed systems and used by industry for manufacture of polymers in closed and semi-closed systems. Downstream use of MMA is almost exclusively in the form of polymer although some products used by professionals and hobbyists may contain significant quantities of the liquid monomer.

Information

Data Owner

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

Programme Manager & Reviewer
DEKRA Consulting GmbH
This Environmental Product Declaration has been reviewed by DEKRA Consulting GmbH.
It was approved according to the Product Category Rules PCR version 2.0 (2011-04) and ISO 14025:2006.
Registration number: PlasticsEurope 2013-005 validation expires on 31 December 2016 (date of next revalidation review).

Programme Owner

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

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

References

PlasticsEurope: Eco-profiles and environmental declarations – LCI methodology and PCR for uncompounded polymer resins and reactive polymer 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 monomer or polymer production systems with a defined output. They can be used as modular building blocks in LCA studies. However, these integrated industrial systems cannot be disaggregated further into single unit processes, such as polymerisation, because this would neglect the interdependence of the elements, e.g. the internal recycling of feedstocks and precursors between different parts of the integrated production sites.

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

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

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

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

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

Product Category and Declared Unit

Product Category

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

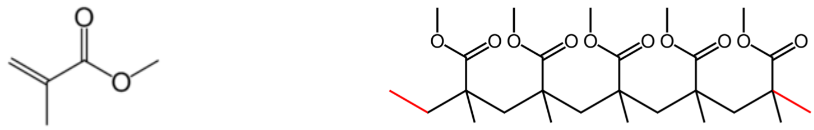
Functional Unit and Declared Unit

The Functional Unit (or Declared Unit) of this Eco-profile is:
1 kg of primary methyl methacrylate (MMA) "at gate" (production site output) representing a European industry production average.

Product and Producer Description

Product Description

Methyl methacrylate (MMA) is an organic compound with the formula $C_5H_8O_2$.
It is a key intermediate chemical, due to its ability to undergo polymerization and copolymerization.
MMA is mainly used for the production of polymethylmethacrylate (PMMA).



MMA PMMA

Figure 1: MMA and PMMA formulas

- IUPAC name: Methyl 2-methylprop-2-enoate
- Molar mass: 100.12 g/mol
- CAS no. 80-62-6
- Chemical formula: $C_5H_8O_2$
- Gross calorific value: 27.0 MJ/kg.

Production process Description

Several methods exist for the production of MMA. The main route, which is used by the European producers participating in this Eco-profile, is the "acetone Cyanohydrin route".
This route is based on three steps described in the following paragraphs and in Figure 2.
The first step of the process is intended to produce hydrogen cyanide (HCN). Hydrogen cyanide is usually produced from methane and ammonia according to the Andrussow process or the Degussa process. The Andrussow process is a catalytic oxidative dehydrogenation of methane and ammonia. This process is exothermic and hydrogen cyanide yields of 60 to 70% can be expected. The Degussa process is a dehydrogenation of methane and ammonia, in absence of air. The reaction is endothermic and then heat must be supplied to the reactor. However, up to 90% of the ammonia can be converted to hydrogen cyanide. Within these two processes, ammonia in excess is neutralised with sulfuric acid, producing ammonium sulfate as a co-product. Hydrogen cyanide may also be obtained as a co-product from the acrylonitrile production process (Sohio process). In this case, the first step of the process is different than the first step indicated in Figure 2.
In the second step, hydrogen cyanide and acetone are used as reagents for the production of acetone cyanohydrin (ACH).
In the third step, MMA is produced from acetone cyanohydrin, sulfuric acid and methanol. Firstly, acetone cyanohydrin undergoes sulfuric acid assisted hydrolysis and is converted into a sulfate ester of methacrylamide. Secondly, an esterification with methanol gives MMA. During the third step, sulfuric acid is

used as an intermediate reagent. After the reactions, the spent sulfuric acid may be recycled and reused for the MMA production or may be neutralised with ammonia, producing ammonium sulfate as a co-product.

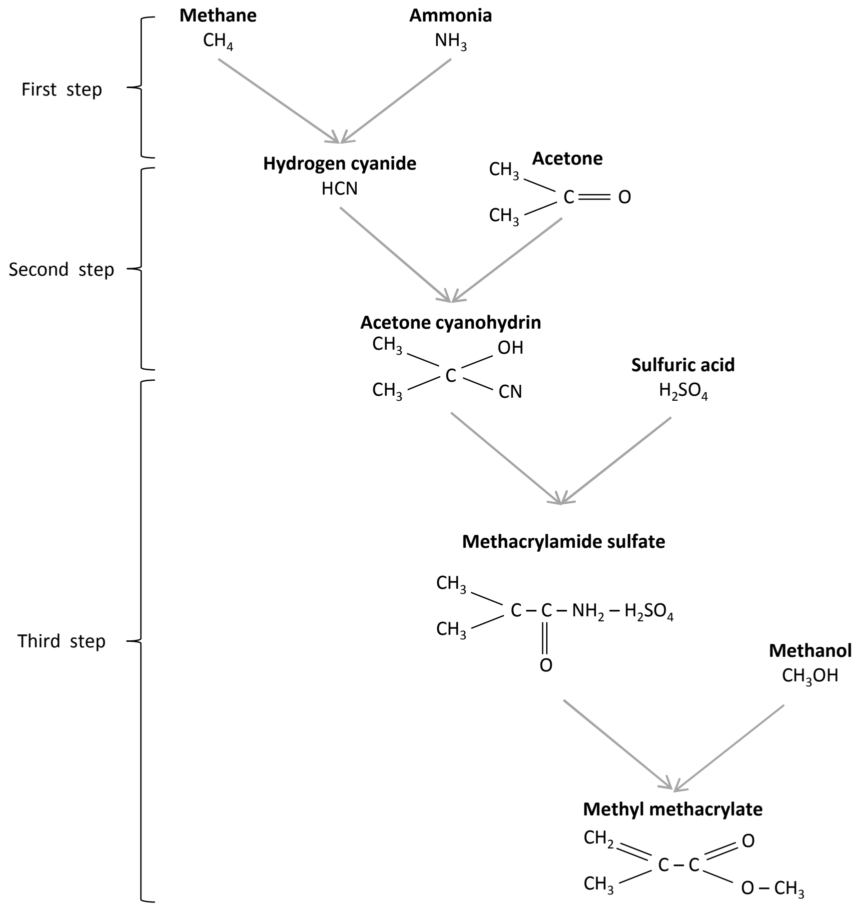


Figure 2: MMA production process

Producer Description

PlasticsEurope Eco-profiles and EPDs represent European industry averages within the scope of Cefic and PlasticsEurope as the issuing trade federations. Hence they are not attributed to any single producer, but rather to the European plastics industry as represented by Cefic's membership and the production sites participating in the Eco-profile data collection. The 3 following companies, which are the 3 main European producers of MMA, contributed data to this Eco-profile and EPD:

- **Arkema Group**

  420 rue d'Estienne d'Orves

  92705 Colombes Cedex

  http://www.arkema.com/

- **Evonik Industries**

  Kirschenallee

  64293 Darmstadt

  Germany

  http://www.evonik.com

- **Lucite International**

  Cumberland House

  15-17 Cumberland Place,

  Southampton, SO15 2BG

  United Kingdom

  http://www.luciteinternational.com/

Eco-profile – Life Cycle Inventory

Special feature of this Eco-profile

This Eco-profile is based on 3 individual LCA studies performed independently by the 3 participating companies. These LCA studies are based on primary data collected separately by each company and they were all critically reviewed according to ISO 14040-44 standards. Hence, contrary to what is usually done, the data collection process was not carried out during the elaboration of this Eco-profile. The main tasks performed for the elaboration of this Eco-profile were to harmonise the underlying methodology of the 3 studies and to consolidate the results in order to obtain a life cycle inventory representative of MMA production in Europe.

System Boundaries

This Eco-profile refers to the production of MMA monomer as a cradle-to-gate system.

Two different systems are considered depending on how the sulfuric acid used in the third step of the production process is managed. After the reactions, the spent sulfuric acid may be recycled and reused for the MMA production or may be neutralised with ammonia, producing ammonium sulfate as a co-product (Figure 3 and Figure 4).

Besides, it should be noticed that hydrogen cyanide is sometimes obtained as a co-product from the acrylonitrile production process. In this case, the first step of the process (production of hygrogen cyanide) is different.

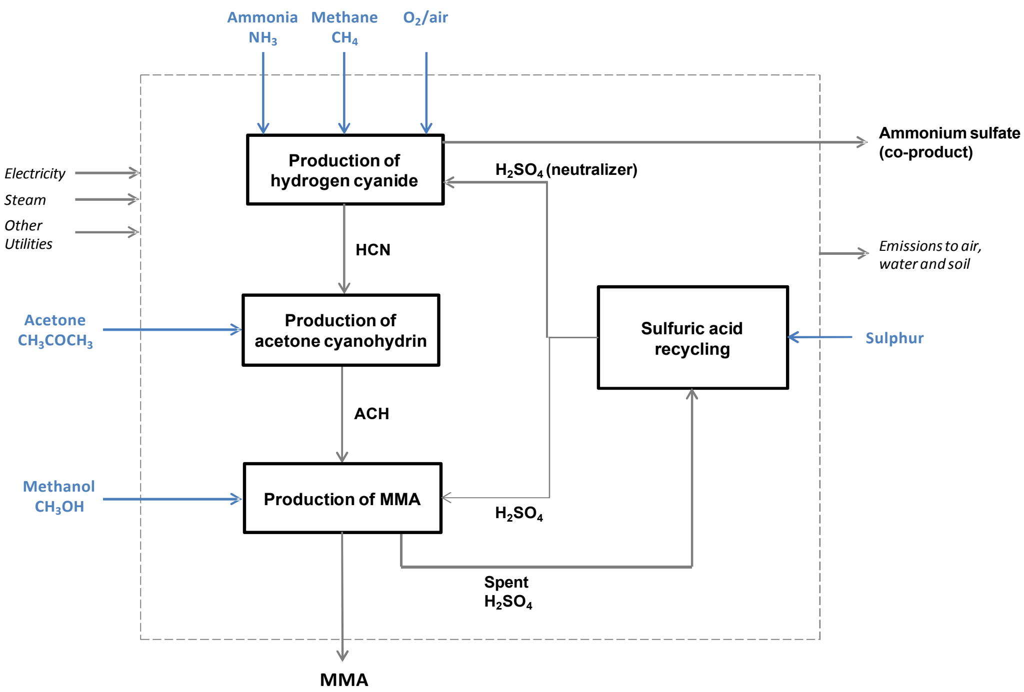


Figure 3: Cradle-to-gate system boundaries with sulfuric acid recycling

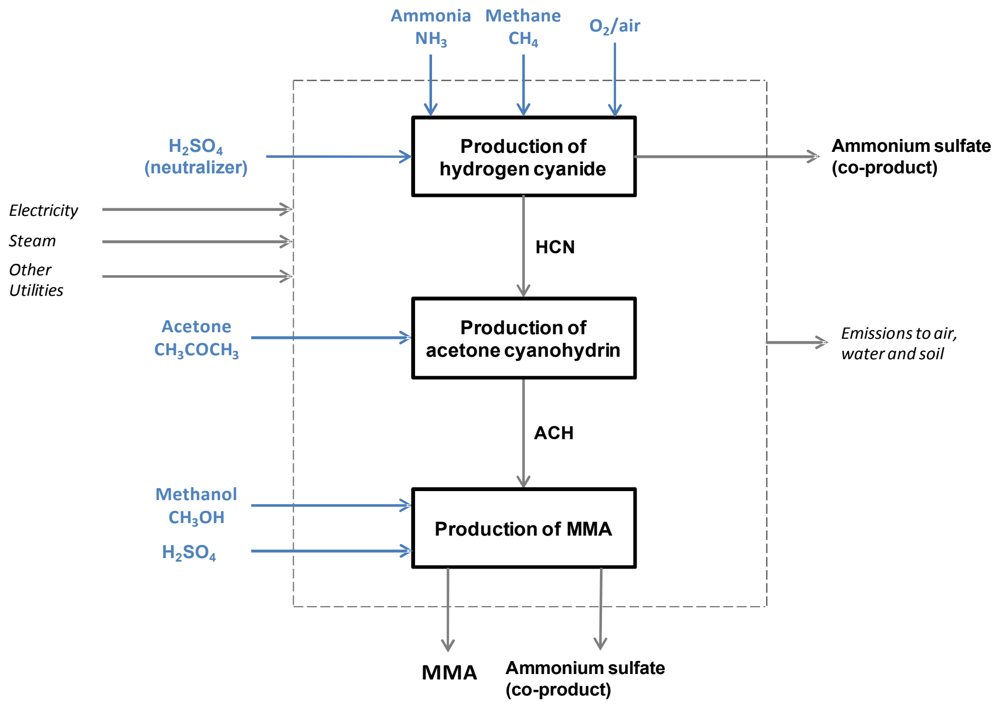


Figure 4: Cradle-to-gate system boundaries without sulfuric acid recycling

Technological Reference

This Eco-profile represents the European average technology for the production of MMA monomer.

The production process considered, which is used by the European producers participating to this Eco-profile, is the "Acetone Cyanohydrin route". This process is described in paragraph Production process description.

For the first step of the process, which aims at producing hydrogen cyanide, 3 routes used by the participating companies are considered: the Andrussow process, the Degussa process and the production of hydrogen cyanide as a co-product of acrylonitrile (Sohio process).

For the last step of the process, which aims at producing MMA out of acetone cyanohydrin, sulfuric acid and methanol, 2 technologies are implemented by the participating companies and are considered: recycling and internal reuse of spent sulfuric acid or neutralisation of spent sulfuric acid with ammonia, producing ammonium sulfate as a co-product.

This Eco-profile is based on data coming from the 3 main European producers of MMA. These 3 producers cover 92 % of the European MMA production capacity in 2012 (100% capacity production is around 634 000 t, CEFIC, 2012). Consequently, the technological coverage is understood as representative.

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

Temporal Reference

The primary data used for this Eco-profile is representative of the year 2010 or 2011, depending on the participating companies. The primary data was collected as 12 month averages to compensate seasonal influence of data. The overall reference year for this Eco-profile is 2010 - 2011 with a maximal temporal validity until 2016.

Geographical Reference

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

Cut-off Rules

The cut-off rules applied in the 3 individuals LCA studies used for this Eco-profile were different. In order to harmonise the scope of the inputs and outputs taken into account, an additional data collection was performed for some specific flows. For example, complementary data such as transportation distances (for key inputs of the production processes), masses of specific auxiliary substances, air emissions of MMA as well as amount of wastewater were collected in some participating companies. After this harmonisation, one can state that all relevant flows of the foreground process are considered, trying to avoid any cut-off of material or energy flows. However, for catalysts and a few commodities (input <0.2% in mass of product output), generic datasets have been used.

Note that capital, i.e. the construction of plant and equipment as well as the maintenance of plants, vehicles and machinery is outside the LCI system boundaries of Eco-profiles.

Regarding potential cut-off in background data, please refer to the ecoinvent documentation.

Data Quality Requirements

Data Sources

This Eco-profile is based on 3 individual LCA studies performed independently by the 3 main European producers of MMA. The primary data used in these studies and then in this Eco-profile comes from 5 plants located in 3 different European countries and is site-specific gate-to-gate production data.

Hence, this Eco-profile uses average data representative of the respective foreground production process, both in terms of technology and market share.

Concerning the upstream supply chain until the precursors and all relevant background data (such as energy and auxiliary materials), the 3 individual LCA studies used for this Eco-profile were based on datasets coming from different databases. For consistency reasons, datasets used in the 3 studies were harmonised. Thus, for this Eco-profile, all the datasets are taken from the ecoinvent database 2.2 with the exception of acetone production dataset, which is taken from the GaBi 5 database. Reasons for this choice are: the significant influence of acetone production on the LCA results, the fact that the Gabi dataset for acetone was considered more relevant (cross-check with other sources on acetone production such as emission trading reports), the fact that the Gabi dataset for acetone was used in other Eco-profiles such as the Eco-profile of polycarbonate.

Relevance

With regard to the goal and scope of this Eco-profile, the collected primary data of foreground processes are of high relevance, i.e. data from the most important producers in Europe in order to generate a European industry average production.

Representativeness

The considered participants covered 92% of the MMA European production capacity in 2012. The selected background data can be regarded as representative for the intended purpose, as it is average data and not in the focus of the analysis.

Consistency

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

Reliability

Data reliability ranges from measured to estimated data. Data of foreground processes provided directly by producers were predominantly measured. Data of relevant background processes were measured at several sites as far as accessible. For a limited number of flows with less significance data have been taken from literature. Only in very few cases data have been estimated. Literature based data and estimated data have been reviewed and checked for its quality.

Completeness

Thanks to primary data collected by the 3 participating companies to perform the 3 individual LCA studies and thanks to additional data collected for the elaboration of this Eco-profile, one may consider that all relevant flows were quantified and data is complete.

Precision and Accuracy

As the relevant foreground data is primary data or modelled based on primary information sources of the owner of the technology, better precision is not reachable within this goal and scope.

Reproducibility

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.

Data Validation

The 3 individual LCA studies used for the elaboration of this Eco-profile were critically reviewed by independent experts according to ISO 14040-44 standards.
The background information from the ecoinvent database is updated regularly and validated in principle daily by the various users worldwide.

Life Cycle Model

The study was performed with the LCA Software Simapro and the ecoinvent database. This database integrates ISO 14040/44 requirements. The life cycle models of the 3 participating companies were integrated in Simapro by using import/export functions of the different softwares used by the companies. Then, a harmonisation process was applied to each model and a consolidated dataset representative of MMA production in Europe was elaborated.

Calculation Rules

Vertical Averaging

The calculation follows the vertical calculation methodology, i.e. that the averaging is done after modelling the specific processes of each participating company (Figure 5).

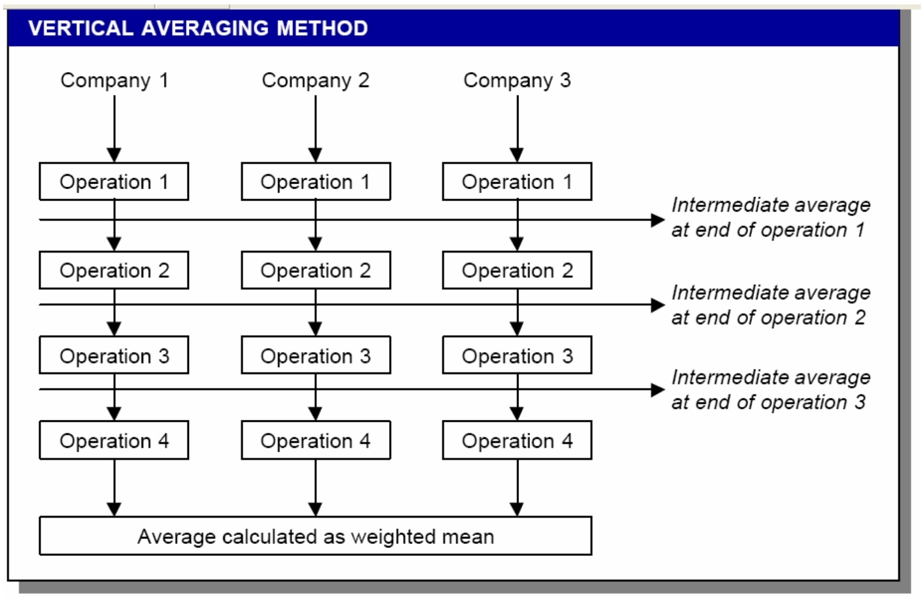


Figure 5: Vertical Averaging (source: Eco-profile of high volume commodity phthalate esters, ECPI European Council for Plasticisers and Intermediates, 2001)

Allocation Rules

Production processes in chemical and plastics industry are usually multi-functional systems, i.e. they have not one, but several valuable product and co-product outputs. Wherever possible, allocation should be avoided by expanding the system to include the additional functions related to the co-products. Often, however, avoiding allocation is not feasible in technical reality, as alternative stand-alone processes do not exist in reality or alternative technologies show completely different technical performance and product quality output. In such cases, the aim of allocation is to find a suitable partitioning parameter so that the inputs and outputs of the system can be assigned to the specific product sub-system under consideration.

In this Eco-profile, allocation was applied in the first step and in the third step of the MMA production process.

The first step of the MMA production process is intended to produce hydrogen cyanide. The 3 routes used by the participating companies and considered in this Eco-profile generate co-products: the Andrussow process and the Degussa process produce hydrogen cyanide and ammonium sulfate, the Sohio process (acrylonitrile production) produce hydrogen cyanide and acrylonitrile.

For the Andrussow and the Degussa process, when it was possible, the process was subdivided into sub-processes and only a few flows intrinsically shared by the co-products were allocated. In this case, these specific flows were fully allocated to hydrogen cyanide which is the most valuable co-product. Otherwise, when the available data did not allow any subdivision, economic allocation was applied to all the input and output flows of the whole process.

For the Sohio process, economic allocation was also applied to the whole process.

Prices taken into account for the economic allocations come from ICIS and Fertecon and are representative of 2012. For hydrogen cyanide, price is estimated based on prices of acetone, methanol and MMA.

In the third step of the MMA production process, sulfuric acid is used as an intermediate reagent in order to convert acetone cyanohydrin into MMA. After the reaction, the spent sulfuric acid can be either recycled and reused internally or used to produce ammonium sulfate as a co-product. In the latter case, sulfuric acid is required for the production of the two co-products MMA and ammonium sulfate and allocation is needed. Several methods were considered in order to partition the consumption of sulfuric acid between the co-products (mass allocation, economic allocation, full allocation to the most valuable product…). After discussion with the CEFIC and the participating companies, the following approach was selected as the best option: the amount of sulfuric acid consumed in the third step of the process was equally allocated between MMA and ammonium sulfate (50/50 by mass). This approach is based on the functions fulfilled by sulfuric acid.

Life Cycle Inventory (LCI) Results

Formats of LCI Dataset

The Eco-profile is provided in three electronic formats:

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

Key results are summarised below.

Energy Demand

As a key indicator on the inventory level, the **primary energy demand** (system input) of 101.0 MJ/kg indicates the cumulative energy requirements at the resource level, accrued along the entire process chain (system boundaries), quantified as gross calorific value (upper heating value, UHV).

As a measure of the share of primary energy incorporated in the product, and hence indicating a recovery potential, the **energy content in the monomer** (system output), quantified as the gross calorific value (UHV), is 27.0 MJ/kg.

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

Primary Energy Demand	Value [MJ]
Energy content in monomer (energy recovery potential, quantified as gross calorific value of monomer)	27.0
Process energy (quantified as difference between primary energy demand and energy content of monomer)	74.0
Total primary energy demand	**101.0**

Consequently, the difference (Δ) between primary energy input and energy content in monomer 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 2 shows how the total energy input (primary energy demand) is used as fuel or feedstock. Fuel use means generating process energy, whereas feedstock use means incorporating hydrocarbon resources into the monomer. Note that some feedstock input may still be valorised as energy; furthermore, process energy requirements may also be affected by exothermal or endothermal reactions of intermediate products. Hence, there is a difference between the feedstock energy input and the energy content of the monomer (measurable as its gross calorific value). Considering the uncertainty of the exact division of the process energy as originating from either fuels or feedstocks, as well as the use of average data (secondary data) in the modelling with different country-specific grades of crude oil and natural gas, there are uncertainties on the feedstock energy and fuel energy results presented in Table 2.

Table 2: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1kg MMA

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	5.49	0.169		5.49
Oil	34.89	0.762	19.2	15.69
Natural gas	54.72	1.072	16.3	38.42
Lignite	1.87	0.124		1.87
Nuclear	3.36	6.00E-06		3.36
Biomass	0.14			0.14
Hydro	0.39			0.39
Solar	0.05			0.05
Geothermics				
Waves				
Wood				
Wind	0.09			0.09
Other renewable fuels				
Sub-total renewable	**0.66**		**0.0**	**0.66**
Sub-total Non-renewable	**100.3**	**2.13**	**35.5**	**64.8**
Total	**101.0**		**35.5**	**65.5**

Table 3 shows that nearly all of the primary energy demand is from non-renewable resources.

Table 3: Primary energy demand by renewability per 1kg MMA

Fuel/energy input type	Value [MJ]	%
Renewable energy resources	0.66	0.7%
Non-renewable energy resources	100.3	99.3%
Total	**101.0**	**100.0%**

Table 4 analyses the types of useful energy inputs in the production process. This represents the share of the energy requirement that is under operational control of the MMA producers.

Table 4: Analysis by type of energy consumed during process per 1kg MMA (in the foreground system)

Type of useful energy in process input	Value [MJ]
Electricity	3.05
Heat, thermal energy	8.86
Total (for process)	11.9

Finally, Table 5 presents the contribution of the raw materials and the other inputs of the process to primary energy demand and presents the type of energy resources used.

Raw materials refer to precursors or necessary chemicals for the production of MMA: ammonia and methane used for hydrogen cyanide production, acetone used for acetone cyanohydrin production and sulfuric acid and methanol used in the last step of the MMA production process.

Others refer for example to catalysts, electricity, heat or other utilities (compressed air, nitrogen, water…).

Table 5 highlights the predominant contribution of the raw materials. In order to analyse the upstream operations more closely, please refer to the Eco-profiles of the respective chemicals.

Table 5: Contribution of the raw materials to total primary energy demand (gross calorific values) per 1kg MMA

Primary energy resource input	Raw materials [MJ] (NH_3, CH_4, CH_3COCH_3, H_2SO_4, CH_3OH)	Others [MJ] (catalysts, electricity, heat and other utilities)	Total [MJ]
Coal	1.57	3.92	5.49
Oil	33.7	1.24	34.89
Natural gas	43.1	11.7	54.72
Lignite	1.24	0.63	1.87
Nuclear	1.90	1.46	3.36
Biomass	0.062	0.078	0.14
Hydro	0.263	0.127	0.39
Solar	0.049	2.25E-04	0.05
Geothermics			
Waves			
Wood			
Wind	0.067	0.019	0.09
Other renewable fuels			
Total	**81.9**	**19.1**	**101.0**

Water Consumption

Table 6 shows the gross water resources used at cradle-to-gate level. It should be noticed that cooling water is taken into account. Considering available data, it was neither possible to calculate the water use without cooling water nor the net freshwater consumption.

Table 6: Gross water resources use per 1kg MMA (including cooling water)

Water use	Value [kg]
River/canal/lake	444
Sea	3
Unspecified	38
Well	16
Totals	**500**

Air Emission Data

Table 7 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 7: Selected air emissions per 1kg MMA

Air emissions	Value [kg]
Carbon dioxide, fossil (CO_2, fossil)	3.21
Carbon monoxide (CO)	8.02E-04
Sulfur dioxide (SO_2)	1.37E-02
Nitrogen oxides (NO_x)	5.05E-03
Particulate matter ≤ 10 µm (PM 10)	4.54E-04

Wastewater Emissions

Table 8 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 8: Selected water emissions per 1kg MMA

Water emissions	Value [kg]
Biological oxygen demand after 5 days (BOD 5)	3.97E-03
Chemical oxygen demand (COD)	4.51E-03
Total organic carbon (TOC)	1.38E-03

Solid Waste

Table 9 shows the solid waste generation at cradle-to-gate level. Only the amount of waste which are sent to landfill are reported here because the available data did not allow the calculation of another indicator.

Table 9: Solid waste generation per 1kg MMA (Waste sent to landfill)

Waste sent to landfill	Value [kg]
Non-hazardous	**1.55E-01**
Hazardous	**1.30E-03**
Total	**1.56E-01**

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 [OERS2002] with updated characterisation factors of CML (CML 2001, April 2013, version 4.2).

Table 10: Abiotic Depletion Potential per 1kg MMA

Natural resources	Value
Abiotic Depletion Potential (ADP). elements [kg Sb eq]	2.58E-06
Abiotic Depletion Potential (ADP). fossil fuels [MJ]	93.8

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 come from the last report of the Intergovernmental Panel on Climate Change [IPCC 2007].

Table 11: Global Warming Potential (100 years) per 1kg MMA

Climate change	Value [kg CO_2 eq.]
Global Warming Potential (GWP)	3.47

Acidification

The Acidification Potential (AP) is quantified according to [HUIJBREGTS1999] (model including fate) with updated characterisation factors of CML (CML 2001, April 2013, version 4.2).

Table 12: Acidification Potential per 1kg MMA

Acidification of soils and water bodies	Value [g SO_2 eq.]
Acidification Potential (AP)	19.0

Eutrophication

The Eutrophication Potential (EP) is calculated according to [HEIJUNGS1992] with updated characterisation factors of CML (CML 2001, April 2013, version 4.2).

Table 13: Eutrophication Potential per 1kg MMA

Eutrophication of soils and water bodies	Value [g PO_4^{3-} eq.]
Eutrophication Potential (EP), total	1.97

Ozone Depletion

The Ozone Depletion Potential (ODP) is calculated according to [WMO 2003] (ODP steady state) with updated characterisation factors of CML (CML 2001, April 2013, version 4.2).

Table 14: Ozone Depletion Potential per 1kg MMA

Ozone Depletion Potential	Value [g CFC-11 eq.]
Ozone Depletion Potential (ODP)	3.24E-04

Summer Smog

The Photochemical Ozone Creation Potential (POCP) is quantified according to [JENKIN1999] and [DERWENT1998] with updated characterisation factors of CML (CML 2001, April 2013, version 4.2).

Table 15: Photochemical Ozone Creation Potential per 1kg MMA

	Value [g Ethene eq.]
Photochemical Ozone Creation Potential	1.07

Dust & Particulate Matter

Dust and particulate matter are reported as PM10 (particulate ≤ 10 µm).

Table 16: PM10 emissions per 1kg MMA

Particulate matter	Value [g PM10 eq.]
Particulate matter ≤ 10 µm. total	4.54E-01

Dominance Analysis

Table 17 presents the contribution of the raw materials and the other inputs and outputs of the process to the results presented above.

As for Table 5, raw materials refer to precursors or necessary chemicals for the production of MMA: ammonia and methane used for hydrogen cyanide production, acetone used for acetone cyanohydrin production and sulfuric acid and methanol used in the last step of the MMA production process. Others refer for example to catalysts, electricity, heat or other utilities (compressed air, nitrogen, water…).

In all analysed environmental impact categories, raw materials contribute to more than 40% of the total impacts. In particular, acetone is a significant contributor to the impacts of raw materials. Besides, it should be noted that the management of the sulfuric acid used in the third step of the process has a notable influence on the results. Indeed, companies which recycle sulfuric acid use less raw materials but more process energy (included in “Others”). To the contrary, companies which do not recycle sulfuric acid have higher contributions in the “Raw materials” category and lower contributions in the “Others” category.

Table 17: Dominance analysis of impacts per 1kg MMA

	Total Primary Energy [MJ]	ADP Elements [kg Sb eq.]	ADP Fossil [MJ]	GWP [kg CO_2 eq.]	AP [g SO_2 eq.]	EP [g PO_4^{3-} eq]	POCP [g Ethene eq.]
Raw materials **(NH_3, CH_4, CH_3COCH_3, H_2SO_4, CH_3OH)**	81.5%	41.6%	82.1%	60.9%	46.1%	59.7%	48.8%
Others **(catalysts, electricity, heat and other utilities)**	18.5%	58.4%	17.9%	39.1%	53.9%	40.3%	51.2%
Total	100%	100%	100%	100%	100%	100%	100%

Comparison of the present Eco-profile with its previous version (2005)

Table 18 compares the present results with the previous version of the MMA Eco-profile [BOUSTEAD 2005]. Only the more robust indicators are presented.

Table 18: Comparison of the present Eco-profile with its previous version (2005)

Environmental Impact Categories	Eco-profile MMA (2005)[1]	Eco-profile MMA (2013)	Difference
Gross primary energy from resources [MJ]	1.25E+02	1.01E+02	-19%
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	1.13E+02	9.38E+01	-17%
Global Warming Potential (GWP) [kg CO_2 eq.]	6.69E+00	3.47E+00	-48%
Acidification Potential (AP) [g SO_2 eq.]	3.44E+01	1.90E+01	-45%
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	3.66E+00	1.97E+00	-46%
Photochemical Ozone Creation Potential [g Ethene eq.]	1.65E+00	1.07E+00	-35%

One can notice that the environmental impacts of MMA production assessed in the 2013 Eco-profile are lower than in the 2005 Eco-profile.

However, care has to be taken when deriving interpretation of this comparison. Indeed, two main factors may explain these differences: production process improvements and LCA methodological changes such as scope of data collection, databases used for the upstream supply chain and all background process, allocation between co-products…

Regarding production process improvements, participating companies have implemented several changes that have led to environmental impact reductions such as process yield improvements, energy efficiency progresses and changes in energy mixes. For example, during the last years, participating companies mentioned an average decrease of 1% per year of energy consumption in their plants.

Regarding LCA methodological aspects, the 2005 Eco-profile does not provide detailed and transparent information. This lack of information does not allow for identifying and quantifying the importance of methodological changes in the overall environmental impact reduction.

1 Differences with the report from 2005 might be observed due to the update of the characterisation factors of the environmental impact methods, or different heating values of resources in case of Primary Energy. The impact method used here is CML 2001 – April 2013 (Version 4.2)

As a consequence, it is not possible to assess the share of environmental impact reduction of MMA production due to real production process improvements and the share due to LCA methodological changes.

Besides, it has to be noted that the methodological aspects of the 2013 Eco-profile have been deeply analysed and discussed with all stakeholders involved in order to define the most suitable approaches in a concerted manner. They are transparently reported in this Eco-profile in order to allow an easier monitoring of MMA production environmental impacts in the future.

Review

Review Summary

As part of the CEFIC / Product Group MSG programme management and quality assurance, DEKRA Consulting GmbH conducted an external independent critical review of this work. The outcome of the critical review is reproduced below.

The subject of this critical review was the development of the Eco-profile for Methyl methacrylate (MMA). In contrast to many other Eco-profile projects, the basis for this European average MMA Eco-profile were three individual LCA studies which had been performed by the three participating MMA producers. Consequently, the main challenges in this project included the adoption of a harmonised method, the respective adaptations to the individual studies and the consolidation into one life cycle model.

The project included milestone meetings with representatives of participating producers, the LCA practitioner and the reviewer. In addition, various review meetings between the LCA practitioner and the reviewer were held, which featured intensive discussions regarding the methodological harmonisation of three individual LCA studies and the construction of one consolidated life cycle model, amongst others. The final Eco-profile report was also reviewed by representatives of the participating organisations and the reviewer. All questions and recommendations were discussed with the LCA practitioner, and the report was adapted and revised accordingly.

The individual LCA studies are based on primary data collected separately by each company and were each critically reviewed according to ISO 14040-44 standards. In order to consolidate the three individual studies into one MMA Eco-profile, the individual studies were analysed and methodological differences identified. Then, a best practice methodological approach was defined that aligns with the PlasticsEurope's Eco-profiles and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors (PCR version 2.0, April 2011). The main methodological harmonisation issues related to allocation, the inclusion of cut-off flows and emissions and the selection of background datasets. During a stakeholder meeting, these harmonisation issues were discussed in great detail with the participating industry representatives. In the following, additional data was collected and in the end, well-informed decisions were taken reflecting LCA best-practice. As a result, both the data quality and methodological consistency can be rated to be very high. In addition and in contrast to the previous version of the MMA Eco-profile (2005), all methodological choices taken are transparently documented in this report.

The 3 producers participating to this Eco-profile cover 92 % of the European MMA production capacity in 2012. Data for the upstream supply chain until the precursors and all relevant background data (such as energy and auxiliary materials) are taken from the ecoivent 2.2 database, except for acetone which is taken from the GaBi 5 database.

The LCA practitioner has demonstrated very good competence and great project management skills. The critical review confirms that this Eco-profile adheres to the rules set forth in the PlasticsEurope's Eco-profiles and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors (PCR version 2.0, April 2011). As a result, this dataset is assessed to be a reliable and high quality representation of MMA produced in Europe.

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