



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

Glacial acrylic acid (GAA), Methyl acrylate (MA), Ethyl acrylate (EA), n-Butyl acrylate (BA) and 2-Ethylhexyl acrylate (2-EHA)

EBAM

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EBAM
European Basic Acrylic Monomer Group

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Environmental Product Declaration

Introduction

This Environmental Product Declaration (EPD) is based upon life cycle inventory (LCI) data from the GaBi database 2013 fulfilling the requirements on 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) [PLASTICSEUROPE 2011]. EPDs provide environmental performance data, but no information on the economic and social aspects which would be necessary for a complete sustainability assessment. EPDs do not imply a value judgment between environmental criteria.

This EPD describes the production from cradle to gate of Acrylic Monomers, namely Glacial acrylic acid (GAA) and its basic esters, Methyl acrylate (MA), Ethyl acrylate (EA), n-Butyl acrylate (BA) as well as 2-Ethylhexyl acrylate (2-EHA). **Please keep in mind that comparisons <u>cannot</u> be made on the level of the monomer 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 European Basic Acrylic Monomers Sector group (EBAM) Avenue E. Van Nieuwenhuyse, 4 box 2 B - 1160 Brussels Belgium
LCA Practitioner	thinkstep AG
Programme Owner	PlasticsEurope aisbl
Programme Manager, Reviewer	DEKRA Assurance Services GmbH

Number of plants included in data collection	6 (GAA) 3 (MA) 3 (EA) 4 (BA) 3 (2-EHA)
Representativeness	100%
Reference year	2012
Year of data collection and calculation	2013-2014
Expected temporal validity	2022
Cut-offs	No significant cut-offs
Data Quality	Good
Allocation method[1)]	Price allocation
[1)] for further information see 'Allocation Rules'	

Description of the Product and the Production Process

Glacial acrylic acid **(GAA)** is a clear, colorless liquid. The odor is very similar to acetic acid. It is highly reactive. Methyl acrylate **(MA)** is a clear, colorless liquid which is completely soluble in alcohols, ethers and many other organic solvents. It is very volatile, highly flammable and has a strong odor. As well as methyl acrylate, also ethyl acrylate **(EA)** is a colorless liquid. It is very volatile and highly flammable. It is soluble in most organic solvents and it stands out in the series of acrylic esters by its pungent odor. n-butyl acrylate **(BA)** is a liquid organic substance which is flammable and volatile and can easily be recognised by its odor. It is soluble in most organic substances. 2-Ethylhexyl acrylate **(2-EHA)** is a clear, colorless liquid with negligible solubility in water.

All esters as well as glacial acid itself have in common, that they are highly reactive. Therefore they have the tendency to polymerise very easily in a highly exothermic reaction in case that some kind of initiation is provided. Hence a polymerisation inhibitor is required for their storage.

Production Process

Glacial acrylic acid **(GAA)** is produced by the catalysed oxidation of propene. Yields are above 90%. The reaction is highly exothermic. The **lower alkyl acrylates** (like MA and EA) are mainly produced by an acid-catalysed esterification reaction of acrylic acid and alcohol, respectively. In the reaction process either a strong acid, such as sulphuric acid or a solid catalyst is used. For the production of the **higher alkyl acrylates** (like BA and 2-EHA) also the corresponding alcohol reacts with acrylic acid. As the esterification rate declines with the increasing length of the alkyl chain of the alcohol the reaction temperatures are higher and residence times longer.

Data Sources and Allocation

The main data source is a primary data collection from European producers of GAA and its four corresponding esters, providing site-specific gate-to-gate production data for processes under operational control of the participating companies of five producers overall with 19 plants in four different European countries (BE, CZ, DE, FR). The table below illustrates the number of delivering producers and plants broken down for each product in detail.

Indicator	producers	plants
GAA	5	6
MA	3	3
EA	3	3
BA	4	4
2-EHA	3	3

The provided data covers 100% of the European GAA and alkyl acrylate production capacity (EU-27) in 2012, respectively. The data for the upstream supply chain until the precursors are taken from the database of the software system GaBi 6 [GaBi 6 2014]. For propene the dataset has been adapted according to information from an existing Eco-profile [PLASTICSEUROPE 2014]. All relevant background data, such as energy and auxiliary materials, is from the GaBi 6 databases, which is also documented [GaBi 6 2014].

Use Phase and End-of-Life Management

GAA is used as a chemical intermediate in the manufacture of chemicals and chemical products, primarily acrylate esters, acrylate salts, and as a building block to produce homo- and co-polymers. The resulting materials are used in coatings, elastomers, water treatment, leather finishing, detergents, hygiene products, adhesives/sealants, thickeners, surfactants, fibres, plastics, textiles and inks. **Lower alkyl acrylates** are mostly used as co-monomers with acrylic acid, acrylates, methacrylates, olefins, etc.. They are also used as a chemical intermediate to produce other monomers by transesterification and molecules through chemical synthesis, because of their high affinity for addition reactions with many inorganic and organic compounds. The resulting materials are ingredients used in coatings, elastomers, water treatment, leather finishing, adhesives/sealants, thickeners, surfactants, fibers, plastics, textiles, inks and pharmaceutical intermediates. **Higher alkyl acrylates** are mostly used as monomers and co-monomers with acrylic acid, acrylates, methacrylates, olefins, etc.. The resulting materials are ingredients used in water-based paints and coatings; coatings for textiles, wood and paper; leather finishing, particularly for nubuck and suede; construction adhesives and pressure-sensitive adhesives; and the manufacture of various plastics. 2-EHA is used for the production of homo- and co-polymers. The production of co-polymers follows the same reactants and conditions as the manufacture of butyl acrylate with the exception that 2-ethylhexanol is used. It is also used in pressure-sensitive adhesives.

Environmental Performance

The tables below show the environmental performance indicators associated with the production of 1 kg for each product: GAA, MA, EA, BA and 2-EHA.

Input Parameters

Indicator	Unit	Value				
		GAA	MA	EA	BA	2-EHA
Non-renewable energy resources[1)]	MJ	44.63	58.31	57.77	75.43	101.93
• Fuel energy	MJ	23.64	33.56	29.75	43.11	64.80
• Feedstock energy	MJ	20.99	24.75	28.02	32.32	37.13
Renewable energy resources (biomass)[1)]	MJ	0.61	0.92	27.00	0.65	1.59
• Fuel energy	MJ	0.61	0.92	ca. 19	0.65	1.59
• Feedstock energy	MJ	0.00	0.00	ca. 8	0.00	0.00
Abiotic Depletion Potential						
• Elements	kg Sb eq	4.64E-06	5.83E-06	2.41E-06	4.14E-06	3.31E-06
• Fossil fuels	MJ	39.53	49.98	49.69	68.41	90.55
Renewable materials (biomass) (key foreground process level)	kg	-	-	0.42	-	-
Water use (key foreground process level)[2)]	kg	35.60	104.48	17.70	1.71	61.56
• for process	kg	n/a	n/a	n/a	n/a	n/a
• for cooling	kg	n/a	n/a	n/a	n/a	n/a

[1)] Calculated as upper heating value (UHV)
[2)] For details see table 25

Output Parameters

Indicator	Unit	Value				
		GAA	MA	EA	BA	2-EHA
GWP, incl. biogenic Carbon	kg CO_2 eq	1.21	1.68	1.54	2.20	3.30
GWP, excl. biogenic Carbon	kg CO_2 eq	1.18	1.66	2.33	2.16	3.28
ODP	g CFC-11 eq	5,98E-07	6.66E-07	4.29E-04	4.01E-07	1.71E-07
AP	g SO_2 eq	2.54	4.08	10.44	5.10	7.65
POCP	g Ethene eq	0.43	0.92	2.21	0.75	1.28
EP	g PO_4 eq	0.24	0.38	5.24	0.42	0.53
Dust/particulate matter (2.5 – 10 µm)	g PM10	5.07E-02	6.56E-02	8.28E+00	6.24E-02	6.12E-02
Total particulate matter	g	8.44E-02	1.30E-01	1.08E+01	1.17E-01	1.51E-01
Waste						
• Radioactive waste	kg	7.82E-04	1.56E-03	1.44E-03	5.77E-04	1.13E-03
• Non-radioactive waste[1)]	kg	6.03E-02	6.19E-02	1.51E-01	4.80E-02	4.92E-02

[1)] Non-radioactive wastes include: spoil, tailings, and waste, deposited

Additional Environmental and Health Information

All five substances are industrially manufactured and used in closed systems, or consumed by polymerisation. This minimises their releases to the environment. 2-EHA is also used by professionals (non-industrial settings), but in very low volumes. Any release biodegrades rapidly in waste water treatment plants, or photodegrades in the atmosphere. They are not expected to bio-accumulate significantly along the food chain or to bind significantly to soil or sediment.

Consumers are not directly exposed to any of these substances: they are transformed into other substances present in consumer products. Indirect exposure is prevented by the biodegradability. For GAA, water is the main release compartment due to the high water solubility and low volatility. With a logarithmic acid dissociation constant (pKa) value of 4.0, its anionic form predominates in the environment.

Acrylic acid is very toxic to algae while invertebrates and fish are much less sensitive to it. For its esters, the main expected release compartment is the atmosphere due to the volatility. The latter decreases with increasing ester molecular weight. These esters are acutely toxic to fish, invertebrates and algae. They are harmful to invertebrates and algae (no data on fish) upon long-term exposure.

Additional Technical Information

In water-based paints and coatings, acrylate-based co-polymers provide good water resistance, low temperature flexibility, and excellent weathering and sunlight resistance. For construction products, acrylate chemicals offer properties such as strong adhesion, improved water resistance, ease of use, and increased durability. Some acrylate polymers also enable superabsorbency and flocculation. Finally, when used as molecular building blocks, acrylate-based monomers impart properties such as adhesion, flexibility, weather ability, internal plasticisation, hardness control, abrasion protection, and resistance to oils and greases.

Additional Economic Information

Due to the unique chemical (polarity) and physical (UV-resistance and moisture absorption) properties, it is almost impossible to substitute acrylic monomers while keeping the properties of the polymer. Substitution may only be possible for some marginal application.

Information

Data Owner

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Programme Manager & Reviewer
DEKRA Assurance Service GmbH
This Environmental Product Declaration has been reviewed by DEKRA Assurance Services GmbH. It was approved according to the Product Category Rules PCR version 2.0 (2011-04) and ISO 14025:2006.
Registration number: PlasticsEurope 2015-006, validation expires on 30 July 2017 (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 precursors (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 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 and 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«. For instance, some polymers may require a heat stabiliser, or a reactive precursor may require a flame retardant. 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 and Declared Unit of this Eco-profile and EPD is:

1 kg of the Acrylic Monomer Glacial acrylic acid (GAA) – or – 1 kg of its basic esters, respectively, »at gate« (production site output) representing a European industry production average.

Product and Producer Description

Product Description

Acrylic acid and its esters are used in many applications. The product description for acrylic acid as well as for each ester in detail is listed below.

Acrylic acid

Acrylic acid is used in the production of homopolymers of sodium acrylate so called superabsorbents, co-polymers for waste water treatment plants, acrylic esters, elastomers, coatings, thickeners, adhesives, and fiber sizing.

- CAS: 79-10-7
- $C_3H_4O_2$
- gross calorific value 19080 kJ/kg

Methyl acrylate

Methyl acrylate is used in many applications as in the production of acrylic fibers, coatings, elastomers or in chemical synthesis.

- CAS: 96-33-3
- $C_4H_6O_2$
- gross calorific value 22504 kJ/kg

Ethyl acrylate

Ethyl acrylate is used in the production of other acrylic esters, homo- as well as co-polymers which find their applications in many fields.

- CAS: 140-88-5
- $C_5H_8O_2$
- gross calorific value 25476 kJ/kg

n-Butyl acrylate

n-Butyl acrylate is also used in the production of many homo- and co-polymers which have a variety of applications.

- CAS: 141-32-2
- $C_7H_{12}O_2$
- gross calorific value 29385 kJ/kg

2-Ethylhexyl acrylate

2-Ethylhexyl acrylate is used to produce homo- and co-polymers that find many applications.

- CAS: 103-11-7
- $C_{11}H_{20}O_2$
- gross calorific value 33755 kJ/kg

Production Process Description

GAA is produced by the catalysed oxidation of propene in a single- or two-step process. Because of higher yields of the two-step process, it is preferred over the single-step process and results in yields of about 90%. Both production routes are highly exothermic. The reaction conditions of the two steps, in particular the reaction temperature and catalysts, are different to produce optimum conversion and selectivity in each step. The resulting crude acrylic acid is either purified by a distillation or a crystallisation process.
Although acrylic acid can be esterified in the vapour phase, the liquid phase esterification is industrially more important.

To synthesise lower alkyl acrylates (MA or EA), acrylic acid and a small excess (10 – 30%) of an alcohol are fed into a reactor packed with a cation-exchange resin and operated at a temperature of 60 to 80°C. In the case of Ethyl acrylate the alcohol used can be petro-based or bio-based Ethanol. In this Eco-profile both Ethanol sources are included.

$$CH_2{=}CH\text{-}CO_2H + CH_3\text{-}OH \rightarrow CH_2{=}CH\text{-}CO_2\text{-}CH_3 + H_2O$$

(Acrylic acid + Methanol → Methyl acrylate + Water)

$$CH_2{=}CH\text{-}CO_2H + CH_3\text{-}CH_2\text{-}OH \rightarrow CH_2{=}CH\text{-}CO_2\text{-}CH_2\text{-}CH_3 + H_2O$$

(Acrylic acid + Ethanol → Ethyl acrylate + Water)

The reaction liquid is then stripped to remove unreacted acid which is recycled as well as high boiling materials. Then water is separated and alcohol is extracted and recovered for reuse. Polymerisation inhibitors, such as hydroquinone or phenothiazine, are added to each column. Crude ester remaining is distilled to obtain acrylate of high purity.

For higher alkyl acrylates (BA and 2-EHA), the esterification reaction is preferably carried out batchwise in the presence of an organic solvent as entrainer and sulphuric acid as catalyst.

$$CH_2{=}CH\text{-}CO_2H + CH_3\text{-}(CH_2)_3\text{-}OH \rightarrow CH_2{=}CH\text{-}CO_2\text{-}(CH_2)_3\text{-}CH_3 + H_2O$$

(Acrylic acid + Butanol → n-Butyl acrylate + Water)

$$CH_2{=}CH\text{-}CO_2H + CH_3\text{-}(CH_2)_3\text{-}CH(C_2H_5)\text{-}CH_2\text{-}OH \rightarrow CH_2{=}CH\text{-}CO_2\text{-}\ CH_2\text{-}CH(C_2H_5)\text{-}(CH_2)_3\text{-}CH_3 + H_2O$$

(Acrylic acid + 2-Ethylhexanol → 2-Ethylhexyl acrylate + Water)

The reaction conditions are: atmospheric pressure, temperature 85 - 95°C, reaction time 3 - 5 h, molar ratio (alcohol to acid) 1.0 – 1.1. The oil and water layers are separated and stored separately; the solvent and alcohol are recovered overhead and reused in the reaction.

Purified acrylic ester is obtained by distillation of the crude ester.
For lower as for higher acrylate esters, the yield reaches 95% based on acrylic acid. The purity of the product exceeds 99.5 wt%. [ULLMANN 2010]

Producer Description

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

Arkema France

420, rue d'Estienne d'Orves
F-92705 Colombes Cedex
France
http://www.arkema.com/en/

BASF SE

Carl-Bosch-Strasse 38
D-67056 Ludwigshafen
Germany
http://www.basf.com

DOW Europe

Bachtobelstrasse 3
CH-8810 Horgen
Switzerland
http://www.dow.com/

Evonik Industries AG

Paul-Baumann-Straße 1
45772 Marl
Germany
http://www.evonik.com

Momentive Speciality Chemicals a.s.

Tovarni 2093
356 01 Sokolov
Czech Republic
http://www.momentive.com/

Eco-profile – Life Cycle Inventory

System Boundaries

PlasticsEurope Eco-profiles and EPDs refer to the production of polymers and their precursors as a cradle-to-gate system (see Figure 1 for GAA and Figure 2 for esters (MA, EA, BA, 2-EHA).

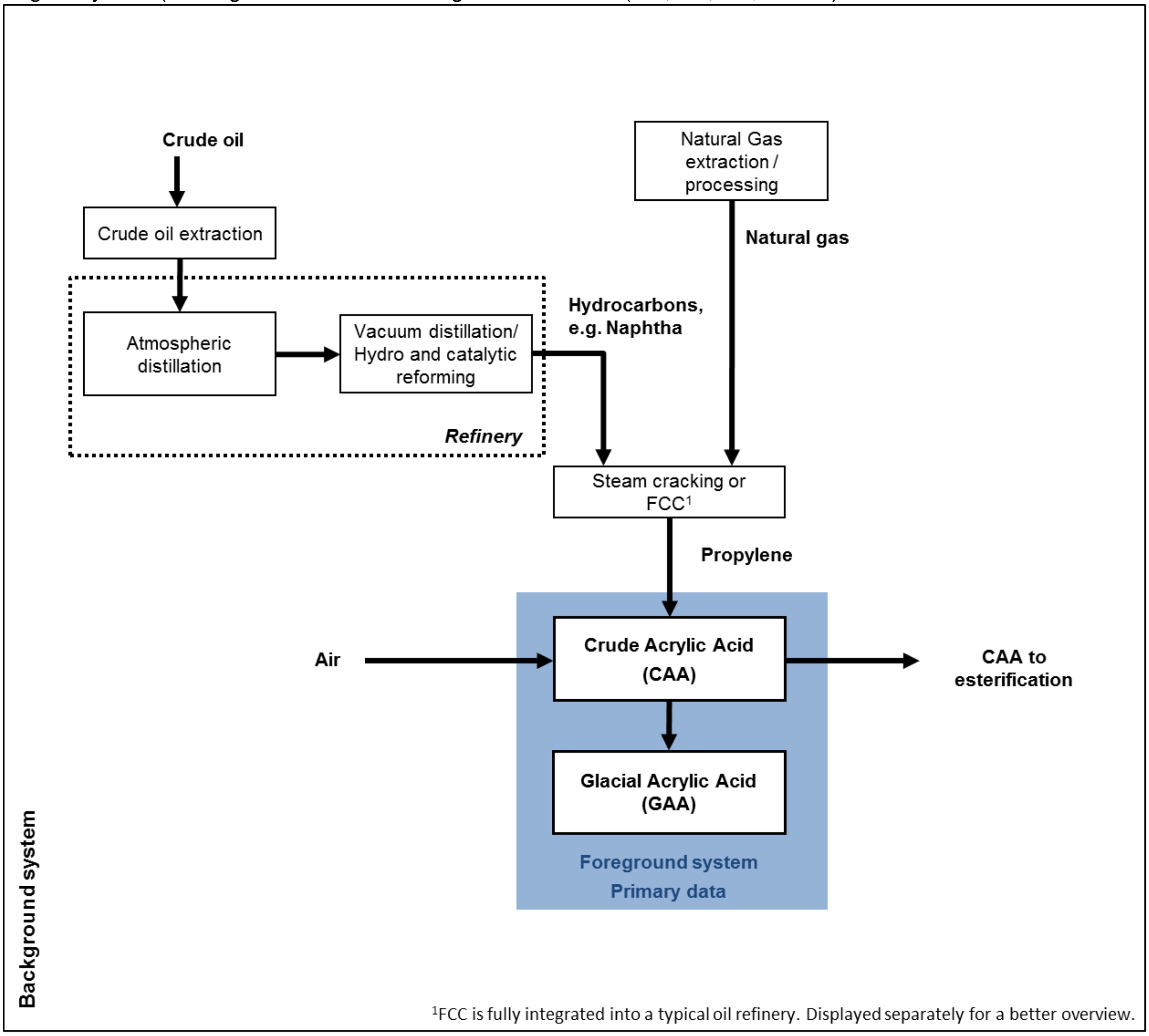


Figure 1: Cradle-to-gate system boundaries (GAA)

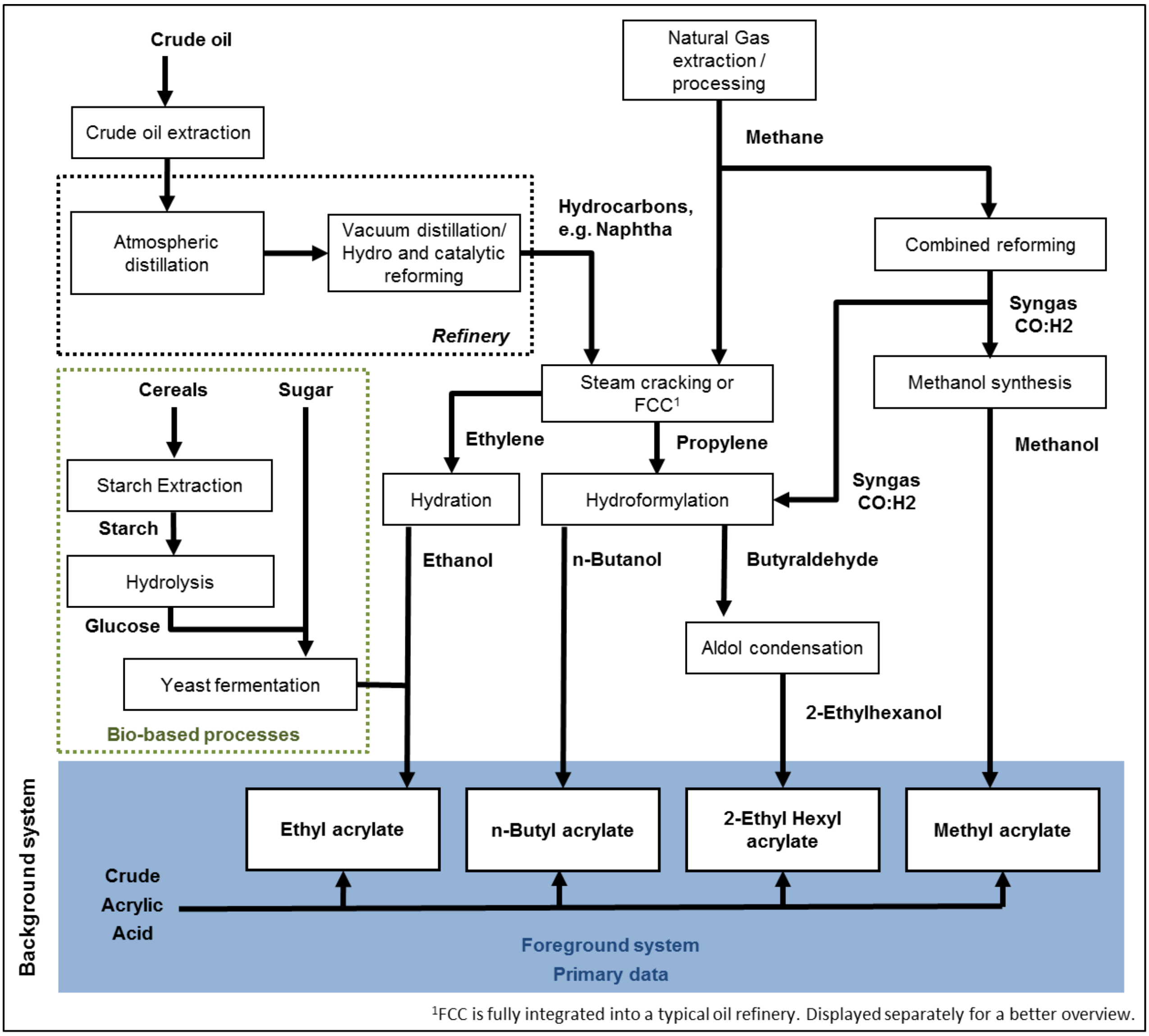


Figure 2: *Cradle-to-gate system boundaries (esters)*

Technological Reference

The production processes are modelled using specific values from primary data collection at site. The main data source is a primary data collection from European producers of GAA, MA, EA, BA and 2-EHA, providing site-specific gate-to-gate production data for processes under operational control of the participating companies: five producers with nineteen plants (GAA: 5 producers and 6 plants; MA: 3 producers and 3 plants; EA: 3 producers and 3 plants; BA: 4 producers and 4 plants; 2-EHA: 3 producers and 3 plants) in four different European countries (BE, CZ, DE, FR). This covers 100% of the European GAA and ester production capacity (EU-27) in 2012, respectively [EBAM 2015]. Primary data are used for all foreground processes (under operational control) complemented with secondary data for background processes (under indirect management control). The data for the upstream supply chain until the precursors are taken from the database of the software system GaBi 6 [GaBi 6 2014]. For propene two different production technologies have been considered (steam cracking and fluid catalytic cracking (FCC)). The share of the two technologies has been modelled according to information from the Eco-profile for Polypropylene (72% steam cracking, 24% FCC and 4% propane metathesis) [PLASTICSEUROPE 2014]. The steam cracking process uses thermal cracking to produce shorter, unsaturated compounds from longer, saturated hydrocarbons. This dehydrogenation process is carried out at temperatures of up to 875°C. The main feedstock for steam cracking is naphtha from oil refineries. The FCC process is fed with higher-molecular-weight hydrocarbons and produces lighter, more valuable products. The cracking is carried out by the contact of liquid oil stream with a hot powdered catalyst, which is a rapid reaction in an up-flowing vertical reactor-riser at temperatures of 500-550°C. The FCC unit is fully integrated into a typical oil refinery [PLASTICSEUROPE 2014].

Temporal Reference

The LCI data for production is collected as 12 month averages representing the year 2012, to compensate seasonal influence of data. Background data have reference years between 2013 and 2011 for electricity and thermal energy processes. The dataset is considered to be valid until substantial technological changes in the production chain occur. In view of the latest technology development, the overall reference year for this Eco-profile is 2012, with a maximum temporal validity until 2022 for the foreground system.

Geographical Reference

Primary production data for GAA, MA, EA, BA and 2-EHA production are from up to five different European suppliers (see 'Technological Reference'). Whenever applicable (in the majority of the cases), site specific conditions are applied. Only in cases where no further information or region-specific dataset is available, average European conditions are used for fuel, energy and material inputs in the system. Therefore, the study results are intended to be applicable within EU boundaries: adjustments might be required if the results are applied to other regions. GAA and corresponding esters imported into Europe are not considered in this Eco-profile.

Cut-off Rules

In the foreground processes all relevant flows are considered, trying to avoid any cut-off of material and energy flows. According to the GaBi database [GaBi 6 2014], used in the background processes, at least 95 % of mass and energy of the input and output flows are covered and 98 % of their environmental relevance (according to expert judgment) is considered, hence an influence of cut-offs less than 2 % on the total is expected.

Data Quality Requirements

Data Sources

Eco-profiles and EPDs developed by PlasticsEurope use average data representative of the respective foreground production process, both in terms of technology and market share. The primary data are derived from site specific information for processes under operational control supplied by the participating member companies of EBAM (see Producer Description).

The data for the upstream supply chain as well as relevant background data such as energy and auxiliary materials are sourced from the life cycle database of the software system GaBi 6 [GaBi 6 2014]. Most of the background datasets used are documented (http://www.gabi-software.com/support/gabi/gabi-database-2014-lci-documentation/professional-database-2014/). For propene the dataset has been adapted according to information from an existing Eco-profile [PLASTICSEUROPE 2014]. So both production routes (steam cracking and FCC) are represented in the background system (see chapter Technological Reference).

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 was sourced from the most important GAA and ester producers in Europe in order to generate a European production average. The environmental contributions of each process to the overall LCI results are included in the Chapter 'Life Cycle Impact Assessment'.

Representativeness

The participating companies represent 100% of the European GAA and ester production volume in 2012 [EBAM 2015]. The selected background data can be regarded as representative for the intended purpose.

Consistency

To ensure consistency, only primary data of the same level of detail and background data from the GaBi 6 databases [GaBi 6 2014] are used. While building up the model, cross-checks ensures the plausibility of mass and energy flows. The methodological framework is consistent throughout the whole model as the same methodological principles are used both in the foreground and background system. In addition to the external review, an internal independent quality check was performed (see 'Internal Independent Quality Assurance Statement').

Reliability

Data of foreground processes provided directly by producers are predominantly measured. Data of relevant background processes are measured at several sites – alternatively, they are determined from literature data, or estimated for some flows, which usually have been reviewed and quality checked.

Completeness

Primary data used for the gate-to-gate production of GAA, MA, EA, BA and 2-EHA covers all related flows in accordance with the above cut-off criteria. In this way all relevant flows are quantified and data is considered complete. The elementary flows covered in the model enable the impact assessment of all selected impact categories. Waste treatment is included in the model, so that only elementary flows cross the system boundaries.

Precision and Accuracy

As the relevant foreground data is primary data, or modelled based on primary information sources of the owners of the technologies, precision is deemed appropriate to the goal and scope.

Reproducibility

Reproducibility is given for internal use since the owners of the technologies provided the data under confidentiality agreements. Key information is documented in this report, and data and models are stored in the GaBi 6 software database. Sub-systems are modelled by ´state of art´ technology using data from a internationally used database. It is worth noting that for external audiences, full and detailed reproducibility will not be possible for confidentiality reasons. However, experienced practitioners could reproduce suitable parts of the system as well as key indicators in a certain confidence range.

Data Validation

The data on production collected from the project partners and the data providing companies are validated in an iterative process several times. The collected data are validated using existing data from published sources or expert knowledge. The background information from the GaBi database is updated regularly and continuously validated.

Life Cycle Model

The study is performed with the LCA software GaBi 6 [GaBi 6 2014]. The associated database integrates ISO 14040/44 requirements. Due to confidentiality reasons details on software modelling and methods used cannot be shown here. However, provided that appropriate confidentiality agreements are in place the model can be reviewed in detail; an external independent review has been conducted to this aim. The calculation follows the vertical calculation methodology (see below).

Calculation Rules

Vertical Averaging

When modelling and calculating average Eco-profiles from the collected individual LCI datasets, vertical averages are calculated (Figure 3).

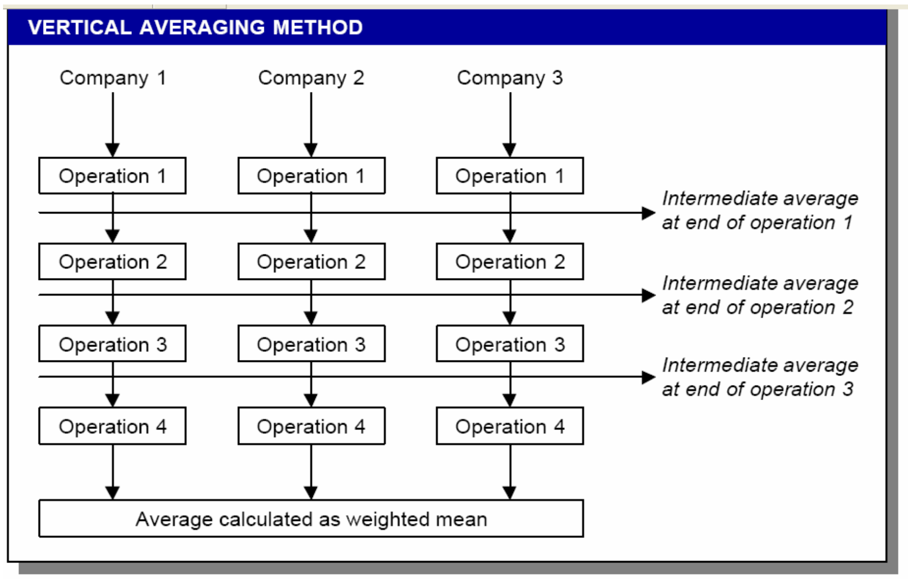


Figure 3: Vertical Averaging (source: PlasticsEurope 2011)

Allocation Rules

Production processes in chemical and plastics industry are usually multi-functional systems, i.e. they have not one, but several valuable product and co-product outputs. Wherever possible, allocation should be avoided by expanding the system to include the additional functions related to the co-products. Often, however, avoiding allocation is not feasible in technical reality, as alternative stand-alone processes do not exist or even 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.

Foreground system

For the production of crude acrylic acid (CAA) in some cases price allocation is applied, as the by-products are marketed as well. These products have much lower assignments compared to the main product of this production step (CAA). Due to the significantly lower amount of by-product and a lower market value, the influence of the allocation is negligible. For the production of GAA, MA, EA, BA and 2-EHA no allocation has been applied in the foreground system.

Background system

In the refinery operations, co-production is addressed by applying allocation based on mass and net calorific value [GaBi 6 2014]. The chosen allocation in downstream petrochemicals is based on several sensitivity analyses, which were reviewed by petrochemical experts. Materials and chemicals needed are modelled using the allocation rule most suitable for the respective product (mass, energy, exergy, economic). For further information on specific product see documentation (gabi-software.com).

Life Cycle Inventory (LCI) Results

Formats of LCI Dataset

The Eco-profile is provided in four 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)
- As LCI in GaBi format (www.gabi-software.com)

Key results are summarised below.

Energy Demand

As a key indicator on the inventory level, the **primary energy demand** (system input) of 45.23 MJ/kg GAA, 59.23 MJ/kg MA, 84.78 MJ/kg EA, 76.08 MJ/kg BA and 103.52 MJ/kg 2-EHA 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 product** (system output), quantified as the gross calorific value (UHV), is 19.08 MJ/kg (GAA), 22.50 MJ/kg (MA), 25.48 MJ/kg (EA), 29.39 MJ/kg (BA) and 33.76 MJ/kg (2-EHA).

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

Primary Energy Demand	GAA Value [MJ]	MA Value [MJ]	EA Value [MJ]	BA Value [MJ]	2-EHA Value [MJ]
Energy content in product (energy recovery potential, quantified as gross calorific value of product)	19.08	22.50	25.48	29.39	33.76
Process energy (quantified as difference between primary energy demand and energy content of product)	26.15	36.72	59.30	46.70	69.77
Total primary energy demand	**45.23**	**59.23**	**84.78**	**76.08**	**103.52**

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

Table 2 to Table 6 show how the total energy input (primary energy demand) is used as fuel or feedstock. Fuel use means generating process energy, whereas feedstock use means incorporating hydrocarbon resources into the polymer or precursor. Note that some feedstock input may still be valorised as energy; furthermore, process energy requirements may also be affected by exothermal or endothermal reactions of intermediate products. Hence, there is a difference between the feedstock energy input and the energy content of the polymer or precursor (measurable as its gross calorific value). Considering this 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, the feedstock energy is presented as approximate data.

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	1.25	0.05		1.25
Oil	30.61	0.68	15.67	14.93
Natural gas	10.38	0.21	5.32	5.07
Lignite	0.42	0.03		0.42
Nuclear	1.97	4.38E-06		1.97
Biomass	0.00			0.00
Hydro	0.11			0.11
Solar	0.35			0.35
Geothermics	8.78E-04			8.78E-04
Waves	2.82E-13			2.82E-13
Wood	3.06E-11			3.06E-11
Wind	0.15			0.15
Other renewable fuels	0.00			0.00
Sub-total renewable	**0.61**	**0.00**	**0.00**	**0.61**
Sub-total Non-renewable	**44.63**	**0.97**	**20.99**	**23.64**
Total	**45.23**	**0.97**	**20.99**	**24.25**

Table 3: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1kg MA

Primary energy resource input	**Total Energy Input [MJ]**	**Total Mass Input [kg]**	**Feedstock Energy Input [MJ]**	**Fuel Energy Input [MJ]**
Coal	0.72	0.03		0.72
Oil	28.24	0.62	13.26	14.98
Natural gas	24.48	0.50	11.49	12.98
Lignite	0.93	0.07		0.93
Nuclear	3.94	8.74E-06		3.94
Biomass	0.00			0.00
Hydro	0.20			0.20
Solar	0.51			0.51
Geothermics	2.34E-03			2.34E-03
Waves	4.40E-13			4.40E-13
Wood	4.06E-11			4.06E-11
Wind	0.20			0.20
Other renewable fuels	0.00			0.00
Sub-total renewable	**0.92**	**0.00**	**0.00**	**0.92**
Sub-total Non-renewable	**58.31**	**1.22**	**24.75**	**33.56**
Total	**59.22**	**1.22**	**24.75**	**34.47**

Table 4: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1kg EA

Primary energy resource input	**Total Energy Input [MJ]**	**Total Mass Input [kg]**	**Feedstock Energy Input [MJ]**	**Fuel Energy Input [MJ]**
Coal	0.69	0.03		0.69
Oil	26.37	0.58	14.18	12.19
Natural gas	25.73	0.53	13.84	11.89
Lignite	1.34	0.10		1.34
Nuclear	3.64	8.08E-06		3.64
Biomass	0.00			0.00
Hydro	0.04			0.04
Solar	26.79		ca. 8	ca. 19
Geothermics	1.78E-03			1.78E-03
Waves	2.90E-13			2.90E-13
Wood	2.67E-11			2.67E-11
Wind	0.17			0.17
Other renewable fuels	0.00			0.00
Sub-total renewable	**27.00**	**0.00**	**0.00**	**27.00**
Sub-total Non-renewable	**57.77**	**1.23**	**28.02**	**29.75**
Total	**84.77**	**1.23**	**28.02**	**56.75**

Table 5: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1kg BA

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	0.69	0.03		0.69
Oil	51.19	1.13	22.83	28.36
Natural gas	21.29	0.44	9.49	11.80
Lignite	0.80	0.06		0.80
Nuclear	1.45	3.22E-06		1.45
Biomass	0.00			0.00
Hydro	0.14			0.14
Solar	0.32			0.32
Geothermics	1.66E-03			1.66E-03
Waves	2.92E-13			2.92E-13
Wood	2.71E-11			2.71E-11
Wind	0.18			0.18
Other renewable fuels	0.00			0.00
Sub-total renewable	**0.65**	**0.00**	**0.00**	**0.65**
Sub-total Non-renewable	**75.43**	**1.65**	**32.32**	**43.11**
Total	**76.08**	**1.65**	**32.32**	**43.76**

Table 6: Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1kg 2-EHA

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	1.83	0.07		1.83
Oil	35.02	0.78	13.75	21.27
Natural gas	59.58	1.22	23.38	36.19
Lignite	2.65	0.20		2.65
Nuclear	2.85	6.32E-06		2.85
Biomass	0.00			0.00
Hydro	0.26			0.26
Solar	0.86			0.86
Geothermics	1.10E-03			1.10E-03
Waves	7.81E-13			7.81E-13
Wood	7.22E-11			7.22E-11
Wind	0.47			0.47
Other renewable fuels	0.00			0.00
Sub-total renewable	**1.59**	**0.00**	**0.00**	**1.59**
Sub-total Non-renewable	**101.93**	**2.26**	**37.13**	**64.80**
Total	**103.52**	**2.26**	**37.13**	**66.39**

Table 7 to Table 11 show that nearly all of the primary energy demand is from non-renewable resources for most of the products. Only for EA a significant share of the energy input is based on renewable energy due to renewable-based ethanol used in the production of EA. Since the focus scope of EBAM and their member companies is the polymer precursor production, Table 12 analyses the types of useful energy inputs in the production process: Electricity has a minor contribution here, whereas the majority is thermal energy (heat). This represents the share of the energy requirement that is under operational control of the monomer producer (Figure 4). Accordingly, Table 13 to Table 17 show that the majority (79 % - 99%) of the primary energy demand is accounted for by upstream processes. Finally, Table 18 to Table 22 provide a more detailed overview of the key processes along the production system, their contribution to primary energy demand and how this is sourced from the respective energy resources. This puts the predominant contribution of the precursors into perspective with energy, utilities, additives (»other chemicals«), transportation and waste treatment. It should be noted, however, that the LCI tables in the annex account for the entire cradle-to-gate primary energy demand of GAA, MA, EA, BA and 2-EHA systems.

Table 7: Primary energy demand by renewability per 1kg GAA

Fuel/energy input type	Value [MJ]	%
Renewable energy resources	0.61	1%
Non-renewable energy resources	44.63	99%
Total	**45.23**	**100%**

Table 8: Primary energy demand by renewability per 1kg MA

Fuel/energy input type	Value [MJ]	%
Renewable energy resources	0.92	3%
Non-renewable energy resources	58.31	98%
Total	**59.23**	**100%**

Table 9: Primary energy demand by renewability per 1kg EA

Fuel/energy input type	Value [MJ]	%
Renewable energy resources	27.00	32%
Non-renewable energy resources	57.77	68%
Total	**84.78**	**100%**

Table 10: Primary energy demand by renewability per 1kg BA

Fuel/energy input type	Value [MJ]	%
Renewable energy resources	0.65	1%
Non-renewable energy resources	75.43	99%
Total	**76.08**	**100%**

Table 11: Primary energy demand by renewability per 1kg 2-EHA

Fuel/energy input type	Value [MJ]	%
Renewable energy resources	1.59	2%
Non-renewable energy resources	101.93	98%
Total	**103.52**	**100%**

Table 12: Analysis by type of useful energy (unit process level) per 1kg product

Type of useful energy in process input	GAA Value [MJ]	MA Value [MJ]	EA Value [MJ]	BA Value [MJ]	2-EHA Value [MJ]
Electricity	1.80	0.30	0.54	0.21	0.48
Heat, thermal energy	-6.89	6.34	13.03	4.44	4.11
Other types of useful energy (relevant contributions to be specified)	0.00	0.00	0.00	0.00	0.00
Total (for selected key process)	**-5.09**	**6.64**	**13.57**	**4.66**	**4.59**

In Table 12 a negative value for thermal energy is given for GAA as the production process for acrylic acid is highly exothermic. The generated thermal energy is used for the production of corresponding esters. Therefore process steam has been given as credit in the GAA system. This is also reflected in the negative values for primary energy demand in the production step in Table 13.

Table 13: Contribution to primary energy demand (dominance analysis) per 1kg GAA

Contribution to Primary Energy per segment	Value [MJ]	%
Production (electricity, steam, unit process, utilities, waste treatment)	-2.23	-5%
Pre-chain	47.47	105%
Total	**45.23**	**100%**

Table 14: Contribution to primary energy demand (dominance analysis) per 1kg MA

Contribution to Primary Energy per segment	Value [MJ]	%
Production (electricity, steam, unit process, utilities, waste treatment)	9.47	16%
Pre-chain	49.76	84%
Total	**59.22**	**100%**

Table 15: Contribution to primary energy demand (dominance analysis) per 1kg EA

Contribution to Primary Energy per segment	Value [MJ]	%
Production (electricity, steam, unit process, utilities, waste treatment)	17.70	21%
Pre-chain	67.07	79%
Total	**84.77**	**100%**

Table 16: Contribution to primary energy demand (dominance analysis) per 1kg BA

Contribution to Primary Energy per segment	Value [MJ]	%
Production (electricity, steam, unit process, utilities, waste treatment)	5.50	7%
Pre-chain	70.58	93%
Total	**76.08**	**100%**

Table 17: Contribution to primary energy demand (dominance analysis) per 1kg 2-EHA

Contribution to Primary Energy per segment	Value [MJ]	%
Production (electricity, steam, unit process, utilities, waste treatment)	6.02	6%
Pre-chain	97.50	94%
Total	**103.52**	**100%**

Table 18: Contribution of life cycle stages to total primary energy demand (gross calorific values) per 1kg GAA, see Figure 4

Total Primary Energy [MJ]	Precursors	Other Chemicals	Utilities[1)]	Electricity	Thermal Energy	Transport	Process Waste Treatment
Coal	1.86E-01	2.39E-02	4.14E-01	3.79E-01	2.45E-01	2.81E-03	-2.27E-03
Oil	2.98E+01	7.15E-01	5.97E-02	5.30E-02	-7.89E-04	8.20E-03	8.86E-03
Natural gas	1.56E+01	4.56E-01	3.01E-01	1.80E+00	-7.70E+00	4.64E-03	-7.12E-02
Lignite	1.76E-01	1.81E-02	4.72E-02	1.70E-01	1.15E-02	2.13E-03	-7.26E-03
Nuclear	3.14E-01	2.37E-02	7.30E-02	1.56E+00	-5.75E-03	1.47E-02	-8.10E-03
Biomass	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	3.67E-02	2.84E-03	1.00E-02	5.71E-02	6.20E-04	1.20E-03	-7.61E-04
Solar	8.36E-02	2.44E-02	2.28E-02	2.16E-01	8.89E-04	1.36E-03	-4.05E-03
Geothermics	4.04E-04	5.90E-05	2.27E-04	9.84E-05	5.26E-05	3.61E-05	1.30E-06
Waves	8.41E-14	7.01E-15	2.02E-14	1.74E-13	9.22E-16	1.03E-15	-5.13E-15
Wood	7.77E-12	6.47E-13	1.87E-12	2.05E-11	1.16E-13	9.52E-14	-4.74E-13
Wind	4.78E-02	4.44E-03	1.28E-02	8.69E-02	1.17E-03	9.59E-04	-2.47E-03
Other renewable fuels	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	**4.62E+01**	**1.27E+00**	**9.40E-01**	**4.33E+00**	**-7.45E+00**	**3.60E-02**	**-8.73E-02**

[1)] Including water, catalyst, nitrogen, compressed air

Table 19: Contribution of life cycle stages to total primary energy demand (gross calorific values) per 1kg MA, see Figure 4

Total Primary Energy [MJ]	Precursors	Other Chemicals	Utilities[1)]	Electricity	Thermal Energy	Transport	Process Waste Treatment
Coal	5.93E-01	4.25E-03	2.39E-02	7.42E-02	1.59E-02	2.78E-03	4.76E-03
Oil	2.79E+01	1.16E-01	2.69E-02	1.13E-02	3.31E-02	1.51E-01	6.20E-03
Natural gas	1.65E+01	6.26E-02	4.13E-02	1.29E-01	7.77E+00	9.15E-03	2.01E-03
Lignite	4.30E-01	4.22E-03	2.39E-02	1.59E-01	3.02E-01	6.25E-03	4.88E-03
Nuclear	3.40E+00	8.72E-03	2.98E-02	4.49E-01	4.77E-02	6.68E-03	1.98E-03
Biomass	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	1.78E-01	8.84E-04	4.24E-03	1.50E-02	3.35E-03	3.99E-04	3.85E-04
Solar	4.23E-01	1.82E-03	1.11E-02	5.98E-02	8.09E-03	1.07E-03	1.73E-03
Geothermics	2.07E-03	1.65E-05	1.62E-04	2.49E-05	4.97E-05	2.46E-06	1.57E-05
Waves	3.59E-13	1.74E-15	1.13E-14	5.77E-14	7.65E-15	1.09E-15	1.75E-15
Wood	3.31E-11	1.60E-13	1.04E-12	5.31E-12	7.06E-13	1.01E-13	1.61E-13
Wind	1.74E-01	1.16E-03	7.00E-03	1.65E-02	3.98E-03	2.16E-04	9.80E-04
Other renewable fuels	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	**4.96E+01**	**2.00E-01**	**1.68E-01**	**9.14E-01**	**8.19E+00**	**1.77E-01**	**2.29E-02**

[1)] Including water, catalyst, nitrogen, compressed air

Table 20: Contribution of life cycle stages to total primary energy demand (gross calorific values) per 1kg EA, see Figure 4

Total Primary Energy [MJ]	Precursors	Other Chemicals	Utilities[1)]	Electricity	Thermal Energy	Transport	Process Waste Treatment
Coal	4.98E-01	8.44E-03	5.04E-02	7.55E-02	4.68E-02	1.34E-03	1.02E-02
Oil	2.58E+01	1.76E-01	8.65E-02	1.43E-02	8.18E-02	1.79E-01	1.16E-02
Natural gas	1.03E+01	1.29E-01	1.04E-01	5.31E-01	1.46E+01	1.59E-02	-7.37E-03
Lignite	4.89E-01	7.34E-03	5.11E-02	2.18E-01	5.62E-01	1.85E-04	1.11E-02
Nuclear	2.78E+00	2.23E-02	5.99E-02	6.05E-01	1.51E-01	2.71E-02	1.42E-03
Biomass	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	-1.41E-02	1.99E-03	8.29E-03	3.01E-02	1.13E-02	1.68E-03	5.22E-04
Solar	2.67E+01	3.10E-03	2.38E-02	4.46E-02	2.22E-02	3.14E-03	3.81E-03
Geothermics	1.23E-03	3.58E-05	2.89E-04	4.49E-05	1.70E-04	2.52E-06	1.55E-05
Waves	1.85E-13	2.57E-15	2.45E-14	5.05E-14	2.20E-14	6.63E-16	3.99E-15
Wood	1.71E-11	2.38E-13	2.26E-12	4.67E-12	2.02E-12	6.11E-14	3.68E-13
Wind	1.24E-01	2.08E-03	1.47E-02	1.57E-02	1.30E-02	7.44E-04	2.05E-03
Other renewable fuels	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	**6.67E+01**	**3.51E-01**	**3.99E-01**	**1.53E+00**	**1.55E+01**	**2.29E-01**	**3.34E-02**

[1)] Including water, catalyst, nitrogen, compressed air

Table 21: Contribution of life cycle stages to total primary energy demand (gross calorific values) per 1kg BA, see Figure 4

Total Primary Energy [MJ]	Precursors	Other Chemicals	Utilities[1)]	Electricity	Thermal Energy	Transport	Process Waste Treatment
Coal	5.74E-01	3.42E-02	2.30E-02	4.53E-02	1.28E-02	1.66E-03	1.90E-03
Oil	5.09E+01	1.46E-01	1.61E-02	6.97E-03	1.86E-02	8.19E-02	5.11E-03
Natural gas	1.64E+01	1.18E-01	3.51E-02	2.66E-01	4.52E+00	8.80E-03	-1.49E-02
Lignite	6.19E-01	3.50E-02	2.24E-02	7.83E-02	4.43E-02	2.36E-03	1.26E-03
Nuclear	1.14E+00	7.80E-02	3.12E-02	1.57E-01	2.36E-02	2.19E-02	-6.13E-04
Biomass	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	1.18E-01	5.90E-03	4.57E-03	9.88E-03	2.08E-03	1.14E-03	-1.55E-05
Solar	2.58E-01	1.73E-02	1.05E-02	2.75E-02	6.09E-03	3.39E-03	1.53E-04
Geothermics	1.40E-03	2.49E-05	1.94E-04	1.57E-05	2.16E-05	1.86E-06	5.21E-06
Waves	2.25E-13	1.90E-14	1.03E-14	3.16E-14	6.00E-15	9.43E-16	1.18E-17
Wood	2.08E-11	1.75E-12	9.50E-13	2.92E-12	5.53E-13	8.69E-14	1.09E-15
Wind	1.46E-01	1.05E-02	6.79E-03	1.49E-02	3.45E-03	6.24E-04	3.57E-05
Other renewable fuels	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	**7.01E+01**	**4.45E-01**	**1.50E-01**	**6.06E-01**	**4.63E+00**	**1.22E-01**	**-7.08E-03**

1) Including water, catalyst, nitrogen, compressed air

Table 22: Contribution of life cycle stages to total primary energy demand (gross calorific values) per 1kg 2-EHA, see Figure 4

Total Primary Energy [MJ]	Precursors	Other Chemicals	Utilities[1)]	Electricity	Thermal Energy	Transport	Process Waste Treatment
Coal	1.70E+00	1.10E-02	2.15E-02	7.24E-02	1.87E-02	4.54E-03	6.92E-03
Oil	3.45E+01	3.29E-01	2.19E-02	9.26E-03	2.65E-02	9.54E-02	7.95E-03
Natural gas	5.46E+01	2.60E-01	3.46E-02	6.33E-01	4.00E+00	1.25E-02	6.28E-03
Lignite	2.16E+00	8.35E-03	2.17E-02	2.51E-01	1.89E-01	1.24E-02	7.56E-03
Nuclear	2.40E+00	1.21E-02	2.96E-02	3.38E-01	3.28E-02	3.39E-02	3.96E-03
Biomass	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	2.37E-01	1.41E-03	4.31E-03	1.66E-02	3.18E-03	1.73E-03	4.72E-04
Solar	7.84E-01	3.70E-03	1.01E-02	4.39E-02	8.85E-03	9.22E-03	2.67E-03
Geothermics	7.86E-04	3.16E-05	1.79E-04	2.66E-05	6.73E-05	3.02E-06	1.05E-05
Waves	7.03E-13	3.69E-15	1.00E-14	5.00E-14	8.72E-15	2.96E-15	2.82E-15
Wood	6.50E-11	3.40E-13	9.25E-13	4.63E-12	8.05E-13	2.72E-13	2.60E-13
Wind	4.40E-01	2.25E-03	6.53E-03	8.59E-03	4.89E-03	9.41E-04	1.49E-03
Other renewable fuels	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	**9.69E+01**	**6.29E-01**	**1.50E-01**	**1.37E+00**	**4.29E+00**	**1.71E-01**	**3.73E-02**

1) Including water, catalyst, nitrogen, compressed air

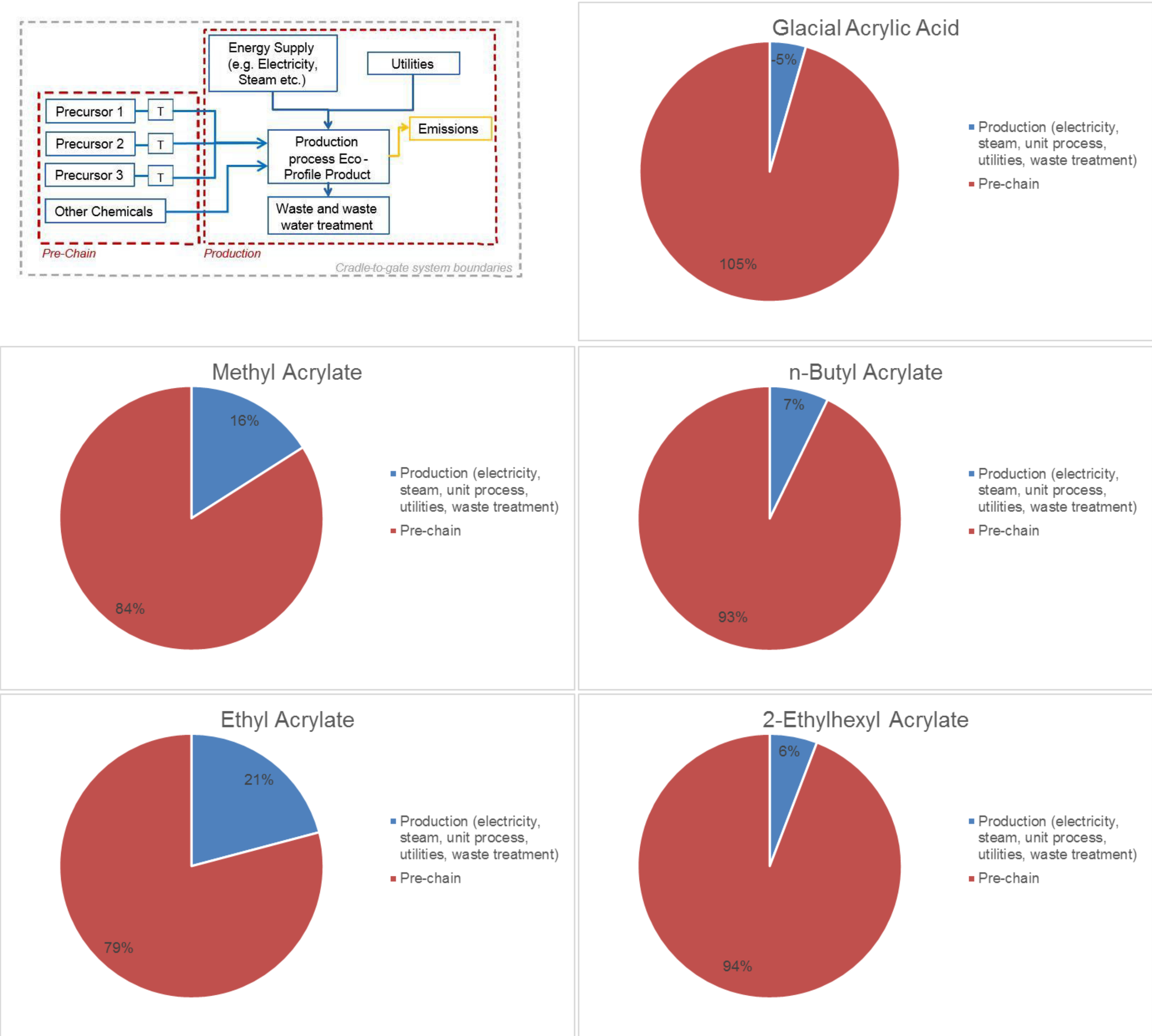


Figure 4: *Contribution to primary energy demand per segment*

Water Consumption

Table 23 shows the water use at cradle-to-gate level. Water use (incl. fresh- and seawater; blue- and green water) equals the measured water input into a product system or process. Water use is determined by total water withdrawal (water abstraction). The negative value for the water use of lake water for EA is due to Bioethanol used as feedstock for the EA production. In the production of Bioethanol energy credits are given for the internal energy generation by burning by-products. The credited energy contains a high share of hydro power, which requires lake water as an input. The high input values for river water result from energy supply (also in the background system) partly based on hydro power.

Table 23: Water use (fresh- and seawater; blue- and greenwater) table per 1kg product (cradle-to-gate)

Input	GAA Value [kg]	MA Value [kg]	EA Value [kg]	BA Value [kg]	2-EHA Value [kg]
Water (ground water)	9.12	13.78	45.37	10.51	21.47
Water (lake water)	12.82	27.99	-26.87	17.73	22.68
Water (rain water)	1.11	1.13	497.06	1.25	2.50
Water (river water)	472.49	855.65	1006.20	644.33	1493.99
Water (sea water)	2.63	4.21	8.94	2.97	3.49
Water (fossil groundwater)	0.00	0.00	0.00	0.00	0.00
Overall water use [kg]	**498.18**	**902.75**	**1530.70**	**676.79**	**1544.12**

Table 24 provides the corresponding freshwater part in the water balance. Freshwater is naturally occurring water on the Earth's surface in ponds, lakes, rivers and streams, as ice, and underground as groundwater in aquifers and underground streams. The term specifically excludes seawater and brackish water. Blue water refers to surface and groundwater used.

Table 24: Freshwater (blue water not including rain water) use table per 1kg product (cradle-to-gate), see Figure 5 to Figure 9

Input	GAA Value [kg]	MA Value [kg]	EA Value [kg]	BA Value [kg]	2-EHA Value [kg]
Water (ground water)	9.12	13.78	45.37	10.51	21.47
Water (lake water)	12.82	27.99	-26.87	17.73	22.68
Water (river water)	472.49	855.65	1006.20	644.33	1493.99
Water (fossil groundwater)	0.00	0.00	0.00	0.00	0.00
Total fresh water use [kg]	**494.44**	**897.41**	**1024.70**	**672.57**	**1538.13**

Output	GAA Value [kg]	MA Value [kg]	EA Value [kg]	BA Value [kg]	2-EHA Value [kg]
Water (river water from technosphere, cooling water)	43.20	192.82	36.88	24.76	100.45
Water (river water from technosphere, turbined)	439.45	687.46	938.89	634.72	1412.42
Water (river water from technosphere, waste water)	5.14	7.77	11.01	5.66	8.01
Water (lake water from technosphere, cooling water)	0.00	0.00	0.00	0.00	0.00
Water (lake water from technosphere, turbined)	0.00	0.00	0.00	0.00	0.00
Water (lake water from technosphere, waste water)	0.00	0.00	0.00	0.00	0.00
Total fresh water release from technosphere (degradative use) [kg]	**487.79**	**888.05**	**986.78**	**665.13**	**1520.87**
Total fresh water consumption (blue water)	**6.65**	**9.36**	**37.92**	**7.44**	**17.26**

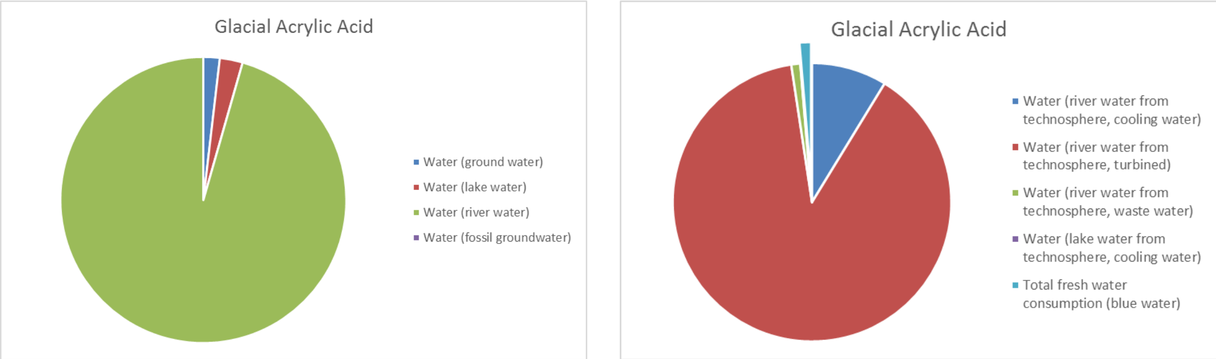


Figure 5: Total fresh water use (input) / water release (output) and water consumption (GAA)

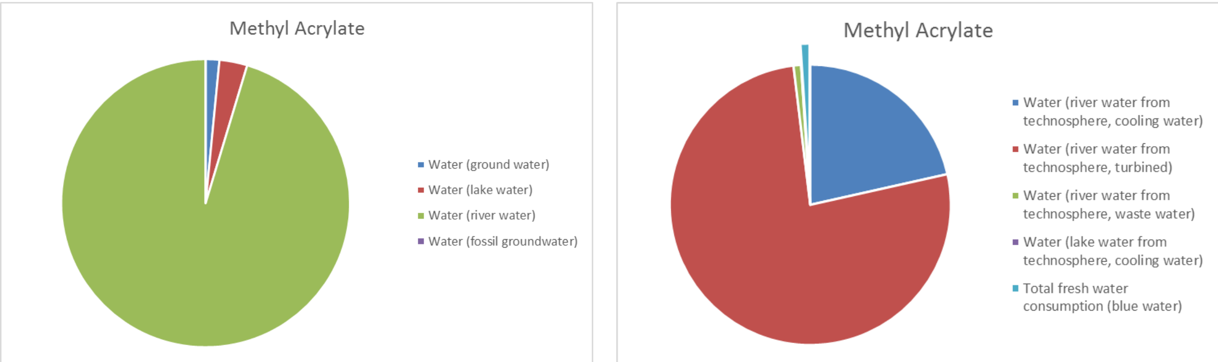


Figure 6: Total fresh water use (input) / water release (output) and water consumption (MA)

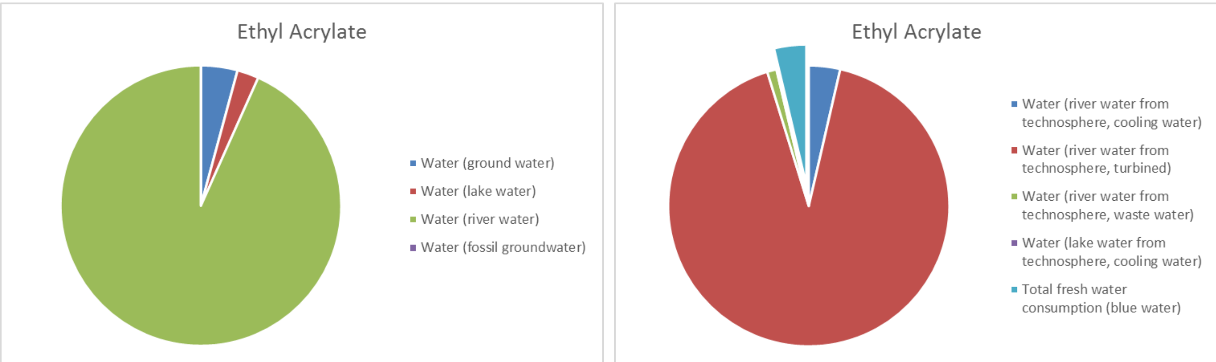


Figure 7: Total fresh water use (input) / water release (output) and water consumption (EA)

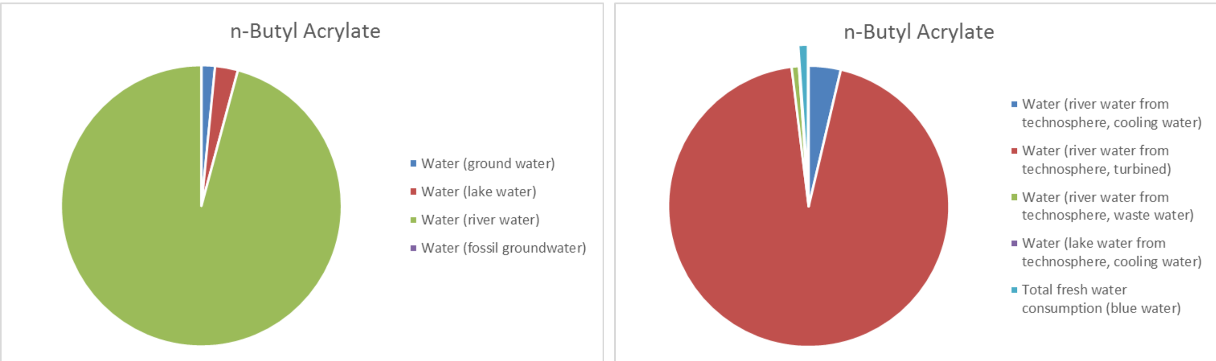


Figure 8: Total fresh water use (input) / water release (output) and water consumption (BA)

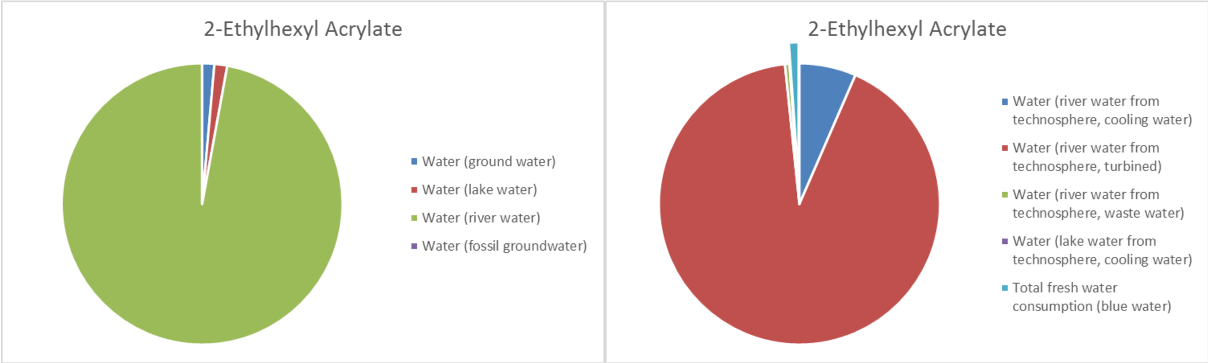


Figure 9: Total fresh water use (input) / water release (output) and water consumption (2-EHA)

Table 25 shows the water balance at unit process level. In some cases the water balance does not completely close. This can be due to inputs that are released into waste water, water, which is generated in the chemical reaction, or due to lack of exactly measured primary data.

Table 25: Water balance table per 1kg product (unit process level)

Input	GAA Value [kg]	MA Value [kg]	EA Value [kg]	BA Value [kg]	2-EHA Value [kg]
Water (cooling water)[1]	29.25	103.25	13.97	0.65	60.27
Water (process water)	2.67	0.84	3.19	0.56	1.18
Water (deionised)	3.63	0.34	0.40	0.36	0.08
Water (tap)	0.04	0.05	0.14	0.03	0.03
Water (ground water)	0.01	0.00	0.00	0.00	0.00
Water (river water)	0.00	0.00	0.00	0.11	0.00
Water (sea water)	0.00	0.00	0.00	0.00	0.00
Total water input [kg]	**35.60**	**104.48**	**17.70**	**1.71**	**61.56**

Output	GAA Value [kg]	MA Value [kg]	EA Value [kg]	BA Value [kg]	2-EHA Value [kg]
Water vapour	3.73	0.53	1.47	0.32	0.42
Water (waste water, untreated) to WWTP	3.18	1.64	4.46	1.41	1.59
Water direct released to the environment without WWTP					
Water (river water from technosphere, cooling water)	28.70	102.03	10.11	0.00	59.46
Water (river water from technosphere, turbined)	0.00	0.00	0.00	0.00	0.00
Water (river water from technosphere, waste water)	0.00	0.00	0.00	0.00	0.00
Water (sea water from technosphere, cooling water)	0.00	0.00	0.00	0.00	0.00
Water (sea water from technosphere, turbined)	0.00	0.00	0.00	0.00	0.00
Water (sea water from technosphere, waste water)	0.00	0.00	0.00	0.00	0.00
Water (lake water from technosphere, cooling water)	0.00	0.00	0.00	0.00	0.00
Water (lake water from technosphere, turbined)	0.00	0.00	0.00	0.00	0.00
Total water output [kg]	**35.62**	**104.20**	**16.04**	**1.73**	**61.48**

Air Emission Data

Table 26 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.

The fossil CO_2 emissions for EA are higher than the absolute value for GWP. This is due to biogenic CO_2, which is incorporated into the bio-based ethanol (partly used for the production of EA) and therefore reduces the GWP for EA.

[1] Cooling water can be processed (softened), deionised, tap, ground, river or sea water, dependent on the location, applied technology and necessary temperature level and site specific frame conditions. Data for differentiation of water amounts used for cooling and processing due to lack of specific meters only partly available.

Table 26: Selected air emissions per 1kg product

Air emissions	GAA Value [kg]	MA Value [kg]	EA Value [kg]	BA Value [kg]	2-EHA Value [kg]
Carbon dioxide, fossil (CO_2, fossil)	1.07E+00	1.54E+00	2.01E+00	1.98E+00	2.96E+00
Carbon dioxide, biogenic (CO_2, biogenic)	3.28E-02	2.51E-02	-7.92E-01	4.09E-02	2.25E-02
Carbon monoxide (CO)	2.20E-03	1.42E-02	3.53E-02	3.33E-03	9.51E-03
Methane (CH_4)	4.12E-03	4.35E-03	8.03E-03	6.81E-03	1.22E-02
Sulphur dioxide (SO_2)	1.51E-03	2.41E-03	3.99E-03	3.14E-03	4.97E-03
Nitrogen oxides (NO_x)	1.02E-03	2.10E-03	6.02E-03	2.44E-03	3.02E-03
Particulate matter ≤ 10 µm (PM 10)	8.44E-05	1.30E-04	1.08E-02	1.17E-04	1.51E-04

Wastewater Emissions

Table 27 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 27: Selected water emissions per 1kg product

Water emissions	GAA Value [kg]	MA Value [kg]	EA Value [kg]	BA Value [kg]	2-EHA Value [kg]
Biological oxygen demand after 5 days (BOD 5)	3.76E-05	6.55E-05	7.96E-05	4.55E-05	6.29E-05
Chemical oxygen demand (COD)	4.18E-04	4.39E-04	7.12E-02	6.85E-04	9.35E-04
Total organic carbon (TOC)	1.39E-05	1.53E-05	1.37E-05	1.95E-05	1.94E-05

Solid Waste

Table 28 to Table 32 below list the solid wastes at unit process level before treatment.

Table 28: Solid waste generation per 1kg GAA (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.00	0.00	0.00	0.00	0.00
Hazardous	0.00	0.00	0.00	0.00	0.00
Unspecified	1.69E-02	9.09E-04	1.25E-04	0.00	1.79E-02
Total	**1.69E-02**	**9.09E-04**	**1.25E-04**	**0.00**	**1.79E-02**

Table 29: Solid waste generation per 1kg MA (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.00	0.00	0.00	0.00	0.00
Hazardous	0.00	0.00	0.00	0.00	0.00
Unspecified	3.11E-02	0.00	0.00	0.00	3.11E-02
Total	**3.11E-02**	**0.00**	**0.00**	**0.00**	**3.11E-02**

Table 30: Solid waste generation per 1kg EA (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.00	0.00	0.00	0.00	0.00
Hazardous	0.00	0.00	0.00	0.00	0.00
Unspecified	3.93E-02	0.00	0.00	0.00	3.93E-02
Total	**3.93E-02**	**0.00**	**0.00**	**0.00**	**3.93E-02**

Table 31: Solid waste generation per 1kg BA (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.00	0.00	0.00	0.00	0.00
Hazardous	0.00	0.00	0.00	0.00	0.00
Unspecified	2.72E-02	0.00	0.00	0.00	2.72E-02
Total	**2.72E-02**	**0.00**	**0.00**	**0.00**	**2.72E-02**

Table 32: Solid waste generation per 1kg 2-EHA (key foreground process level)

Waste for –	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Non-hazardous	0.00	0.00	0.00	0.00	0.00
Hazardous	0.00	0.00	0.00	0.00	0.00
Unspecified	4.14E-02	0.00	0.00	0.00	4.14E-02
Total	**4.14E-02**	**0.00**	**0.00**	**0.00**	**4.14E-02**

The End-of-life scenarios for different waste fractions is considered in partial stream calculations; i.e. the resource depletion and emissions referring to incineration and the respective credits for energy gain depend on calorific value and actual elementary composition, which is relevant for the life cycle assessment. This is independent from the official attribution into hazardous/non-hazardous categories not consistently provided in the data collection.

Land Use

Additionally to the LCI results evaluated according to the PCR [PLASTICSEUROPE 2011] the evaluation of land use indicators are chosen for this Eco-profile.

LANCA® (land use indicator value calculation tool) enables the calculation of indicator values which describe the environmental impacts of land-intensive processes on various ecosystem services. The LANCA® calculations are based on geo-ecological classification systems. The environmental impacts are expressed by using different soil quality indicators. These are erosion resistance, mechanical filtration, physicochemical filtration, groundwater replenishment and biotic production.

Land use indicators are always given for “transformation” and “occupation”.

“Transformation” reflects permanent impacts that prevail after regeneration of the land (after t_4).

Occupation describes the altered soil quality during the use of the land. This is calculated by the difference between the soil qualities during use and after regeneration (after t_4) multiplied by the area and time of use.

The calculation scheme is demonstrated in Figure 11. In general, for occupation impacts the land quality after the regeneration of the land is compared to the quality during land use whereas for transformation impacts calculation, the quality before the regarded land use and after land regeneration is compared. [LANCA 2010]

For more detailed information see [LANCA 2010].

For this Eco-profile the land use indicators are only based on the background data. No data has been collected for the production sites as the impact caused by the production site is negligible due to very high throughput per area. In the background data the most relevant production processes (mining, production of renewable resources, forestry) are taken into account for calculating land use indicators. The land use indicators are displayed in Table 33 (land occupation indicators) and Table 34 (land transformation indicators).

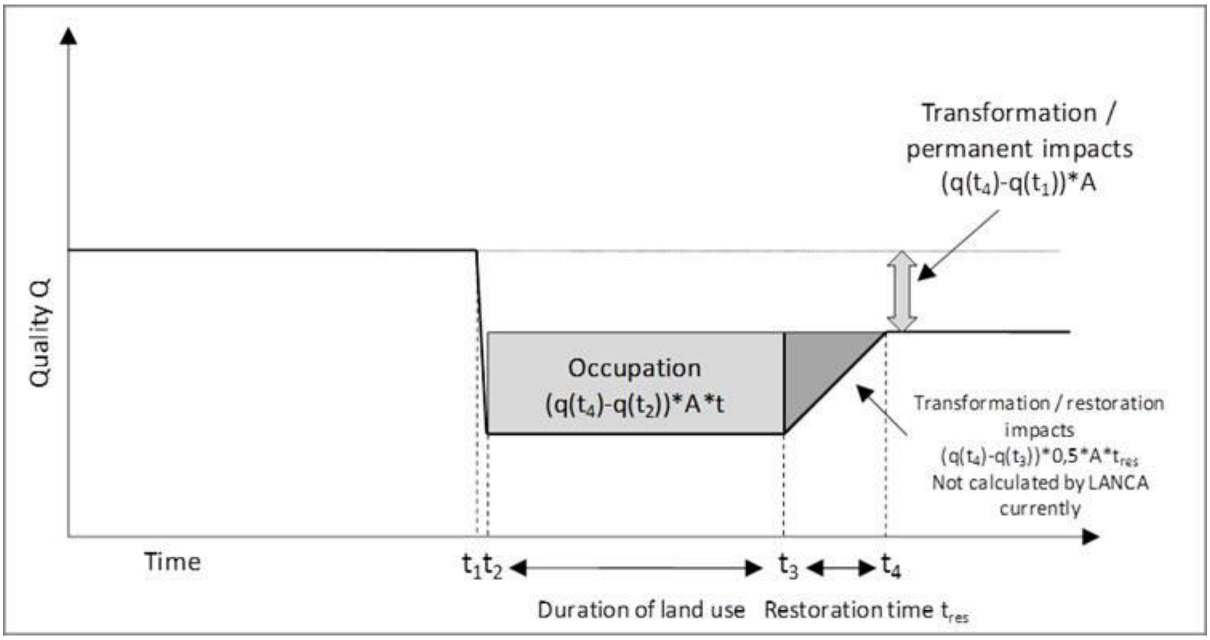


Figure 11: Land use calculation scheme (LANCA®) *[LANCA 2010]*

Table 33: Land Use Indicators per 1kg product (Occupation) (cradle-to-gate without foreground system)

Land Use - Occupation	GAA	MA	EA	BA	2-EHA
Erosion Resistance [kg]	3,82E-04	5,23E-04	5,18E-02	5,60E-04	1,30E-03
Mechanical Filtration [cm*m²]	1,62E+00	1,76E+00	6,49E+02	2,05E+00	4,66E+00
Physicochemical Filtration [cmol*m²*a)/kg]	2,19E-03	3,19E-03	3,50E-01	1,07E-02	6,35E-03
Groundwater Replenishment [mm*m²]	3,99E-01	4,66E-01	8,79E+01	5,79E-01	1,42E+00
Biotic Production [kg]	2,24E-03	3,12E-03	3,57E-01	2,88E-03	7,22E-03

Table 34: Land Use Indicators per 1kg product (Transformation) (cradle-to-gate without foreground system)

Land Use - Transformation	GAA	MA	EA	BA	2-EHA
Erosion Resistance [kg/a]	8,07E-07	-6,18E-07	-2,10E-06	6,59E-08	-7,11E-07
Mechanical Filtration [cm*m²/d]	-1,48E-05	-1,30E-05	-5,70E-05	-2,70E-05	-8,11E-05
Physicochemical Filtration [cmol*m²/kg]	-3,89E-06	-7,94E-06	-2,62E-05	-7,27E-06	-2,07E-05
Groundwater Replenishment [mm*m²/a]	7,05E-04	5,91E-04	1,12E-03	1,65E-03	2.97E-03
Biotic Production [kg/a]	8,34E-06	5,56E-06	3,77E-05	7,76E-06	1,40E-05

The values for EA are significantly higher than for all other products due to the share of ethanol based on renewable resources used in the production of EA. This is most obvious for occupation indicators as the productivity per area, which has a high relevance for occupation, is much lower for renewable resources compared to petro-based materials.

Life Cycle Impact Assessment

For the calculation of the LCIA the CML methods (CML 2001 – April 2013 (Version 4.2), see http://www.gabi-soft-ware.com/support/gabi/gabi-lcia-documentation) are used.

Input

Natural Resources

Table 35: Abiotic Depletion Potential per 1kg product

Natural resources	GAA Value	MA Value	EA Value	BA Value	2-EHA Value
Abiotic Depletion Potential (ADP), elements [kg Sb eq]	4.64E-06	5.83E-06	2.41E-06	4.14E-06	3.31E-06
Abiotic Depletion Potential (ADP), fossil fuels [MJ]	39.53	49.98	49.69	68.41	90.55

Output

Climate Change

Table 36: Global Warming Potential (100 years) per 1kg product

Climate change	GAA kg CO_2 eq.	MA kg CO_2 eq.	EA kg CO_2 eq.	BA kg CO_2 eq.	2-EHA kg CO_2 eq.
Global Warming Potential (GWP), incl. biogenic Carbon	1.21	1.68	1.54	2.20	3.30
Global Warming Potential (GWP), excl. biogenic Carbon	1.18	1.66	2.33	2.16	3.28

Acidification

Table 37: Acidification Potential per 1kg product

Acidification of soils and water bodies	GAA g SO2 eq.	MA g SO2 eq.	EA g SO2 eq.	BA g SO2 eq.	2-EHA g SO2 eq.
Acidification Potential (AP)	2.54	4.08	10.44	5.10	7.65

Eutrophication

Table 38: Eutrophication Potential per 1kg product

Eutrophication of soils and water bodies	GAA g PO_4^{3-} eq.	MA g PO_4^{3-} eq.	EA g PO_4^{3-} eq.	BA g PO_4^{3-} eq.	2-EHA g PO_4^{3-} eq.
Eutrophication Potential (EP), total	0.24	0.38	5.24	0.42	0.53

Ozone Depletion

Table 39: Ozone Depletion Potential per 1kg product

	GAA g CFC-11 eq.	MA g CFC-11 eq.	EA g CFC-11 eq.	BA g CFC-11 eq.	2-EHA g CFC-11 eq.
Ozone Depletion Potential (ODP)	5,98E-07	6.66E-07	4.29E-04	4.01E-07	1.71E-07

Summer Smog

Table 40: Photochemical Ozone Creation Potential per 1kg product

	GAA g Ethene eq.	MA g Ethene eq.	EA g Ethene eq.	BA g Ethene eq.	2-EHA g Ethene eq.
Photochemical Ozone Creation Potential	0.43	0.92	2.21	0.75	1.28

Dust & Particulate Matter

Table 41: PM10 emissions per 1kg product

Particulate matter	GAA g PM10 eq.	MA g PM10 eq.	EA g PM10 eq.	BA g PM10 eq.	2-EHA g PM10 eq.
Particulate matter ≤ 2.5 µm	3.36E-02	6.44E-02	2.56E+00	5.49E-02	9.00E-02
Particulate matter 2.5 - 10 µm	5.07E-02	6.56E-02	8.28E+00	6.24E-02	6.12E-02
Particulate matter > 10 µm	2.50E-05	3.11E-05	3.52E-05	3.01E-05	7.91E-05
Particulate matter total	8.44E-02	1.30E-01	1.08E+01	1.17E-01	1.51E-01

Dominance Analysis

Table 42 to Table 46 show the main contributions to the results presented above. A weighted average of the different technologies represented by the participating producers is used. In all analysed environmental impact categories (the only exception being the indicator ADP Elements for GAA), precursors and direct process emissions contribute with the highest share of the total impact, with precursors being the dominant contributor. Process emissions only have a significant share for GAA as there are higher direct process emissions due to the combustion of fuels.

The negative values due to thermal energy for GAA result from the highly exothermic reaction to produce GAA. The excess energy is used for the production of acrylates.
A significant share to GWP results from thermal energy, especially for MA and EA.
In the case of ADP Elements for GAA, the different distribution results mainly from the use of catalysts with a metal content in production or along the supply chain.
The comparatively high share of EP and AP for transportation in MA results from long transport distances for methanol in some cases.
For EA the high value for ODP (in absolute values, see Table 39) are due to the use of bio-based ethanol.

Table 42: *Dominance analysis of impacts per 1kg GAA*

	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.]
Precursors and Process[1)]	102.13%	5.00%	106.76%	112.56%	90.97%	84.65%	100.55%
Other chemicals	2.80%	0.75%	2.83%	3.29%	3.26%	5.52%	3.12%
Utilities[2)]	2.08%	158.99%	1.94%	5.59%	6.14%	7.78%	2.35%
Electricity	9.56%	0.64%	5.54%	13.16%	9.61%	11.95%	5.36%
Thermal Energy	-16.47%	0.58%	-16.95%	-39.11%	-11.56%	-21.53%	-11.89%
Transport	0.08%	0.01%	0.04%	0.11%	0.28%	0.46%	0.08%
Process waste treatment	-0.19%	-65.96%	-0.16%	4.40%	1.29%	11.17%	0.43%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

[1)] Process = direct process emissions
[2)] Including water, catalyst, nitrogen, compressed air

Table 43: *Dominance analysis of impacts per 1kg MA*

	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.]
Precursors and Process[1)]	83.68%	97.77%	83.77%	66.88%	72.53%	65.78%	87.93%
Other chemicals	0.34%	0.19%	0.35%	0.41%	0.85%	0.42%	0.31%
Utilities[2)]	0.28%	1.06%	0.21%	0.50%	0.62%	0.93%	0.22%
Electricity	1.54%	0.12%	0.68%	1.79%	3.89%	2.51%	1.06%
Thermal Energy	13.82%	0.79%	14.65%	26.82%	12.25%	16.27%	7.94%
Transport	0.30%	0.00%	0.31%	0.77%	9.21%	10.00%	2.38%
Process waste treatment	0.04%	0.07%	0.03%	2.83%	0.65%	4.10%	0.16%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

[1)] Process = direct process emissions
[2)] Including water, catalyst, nitrogen, compressed air

Table 44: *Dominance analysis of impacts per 1kg EA*

	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 Eth-ene eq.]
Precursors and Process[1)]	78.70%	85.40%	69.15%	31.78%	84.05%	95.72%	90.99%
Other chemicals	0.41%	1.32%	0.60%	0.86%	0.29%	0.06%	0.18%
Utilities[2)]	0.47%	6.51%	0.54%	1.26%	0.52%	0.16%	0.22%
Electricity	1.81%	0.35%	1.52%	3.76%	2.18%	0.26%	0.69%
Thermal Energy	18.29%	5.97%	27.77%	56.80%	9.93%	2.47%	7.43%
Transport	0.27%	0.03%	0.37%	0.89%	2.55%	0.59%	0.38%
Process waste treatment	0.04%	0.42%	0.05%	4.65%	0.46%	0.74%	0.12%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

[1)] Process = direct process emissions
[2)] Including water, catalyst, nitrogen, compressed air

Table 45: Dominance analysis of impacts per 1kg BA

	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.]
Precursors and Process[1)]	92.19%	84.93%	92.72%	83.91%	89.02%	82.21%	92.66%
Other chemicals	0.58%	12.93%	0.45%	0.76%	1.68%	1.38%	0.87%
Utilities[2)]	0.20%	1.16%	0.13%	0.34%	0.49%	0.71%	0.24%
Electricity	0.80%	0.10%	0.53%	1.25%	1.17%	1.24%	0.63%
Thermal Energy	6.08%	0.77%	6.05%	11.66%	4.74%	7.67%	5.03%
Transport	0.16%	0.01%	0.13%	0.32%	2.50%	3.62%	0.43%
Process waste treatment	-0.01%	0.10%	-0.01%	1.76%	0.40%	3.17%	0.15%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

[1)] Process = direct process emissions
[2)] Including water, catalyst, nitrogen, compressed air

Table 46: Dominance analysis of impacts per 1kg 2-EHA

	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.]
Precursors and Process[1)]	93.58%	96.46%	93.94%	87.88%	90.35%	84.06%	93.22%
Other chemicals	0.61%	0.29%	0.62%	0.57%	0.60%	0.73%	1.15%
Utilities[2)]	0.15%	1.07%	0.10%	0.22%	0.31%	0.49%	0.14%
Electricity	1.33%	0.22%	0.96%	1.99%	3.32%	2.76%	1.33%
Thermal Energy	4.14%	1.72%	4.22%	7.24%	4.21%	6.34%	3.39%
Transport	0.16%	0.02%	0.13%	0.27%	0.81%	2.61%	0.62%
Process waste treatment	0.04%	0.21%	0.03%	1.84%	0.40%	3.01%	0.14%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

[1)] Process = direct process emissions
[2)] Including water, catalyst, nitrogen, compressed air

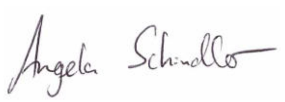
This Eco-profile is the first one for GAA, MA, EA, BA and 2-EHA. Therefore a comparison to previous Eco-Profile information was not possible. During the quality assurance of the life cycle models for GAA, MA, EA; BA and 2-EHA a comparison with existing life cycle inventories in the GaBi database [GABI 6 2014] was performed. The comparison has shown no significant differences for all considered life cycle impact categories.

Reviews

Internal Independent Quality Assurance Statement

As part of the overall quality assurance during the preparation of this Eco-profile, *thinkstep AG* conducted an internal review of this work. The resulting quality assurance statement is reproduced in the Internal Independent Quality Assurance Statement:

On behalf of thinkstep AG and its subsidiaries

Document prepared by	Anja Lehmann
Title	Project Manager
Signature	
Quality assurance by	Angela Schindler
Title	Quality Manager Central Europe
Signature	
Approved by	Hannes Partl
Title	Regional Director Central Europe, Service
Signature	

This report has been prepared by thinkstep with all reasonable skill and diligence within the terms and conditions of the contract between thinkstep and the client. thinkstep is not accountable to the client, or any others, with respect to any matters outside the scope agreed upon for this project.
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External Independent Review Summary

The subject of this critical review is the development of the Eco-profiles for Acrylic Monomers, namely Glacial acrylic acid (GAA) and its basic esters, Methyl acrylate (MA), Ethyl acrylate (EA), n-Butyl acrylate (BA) as well as 2-Ethylhexyl acrylate (2-EHA).

The review process included various meetings/web-conferences between the LCA practitioner and the reviewer, which encompassed a model and database review and spot checks of data and calculations. Furthermore, the final Eco-profile report was reviewed by the reviewer as well as industry participants involved in this project. All questions and recommendations were discussed with the LCA practitioner, and the report was adapted and revised accordingly.

Primary industry data were collected for the foreground processes comprising the production of Crude Acrylic Acid (CAA) – a precursor of GAA, MA, EA, BA and 2-EHA and taking into account the specific production processes of the participating companies. Background data representing the main precursors as well as all other material and energy inputs were taken from the GaBi database. An exception is the dataset for propene for which information and data from an existing Eco-profile [PlasticsEurope 2014] was used. Primary industry data was collected from 5 producer of GAA (6 plants), 4 producers of BA (4 plants) and 3 producers of MA, EA and 2-EHA (3 plants), which lead to an estimated overall representativeness of 100% of the installed EU27 production capacity in 2012.

The potential environmental impacts for GAA and the Acrylic Monomer Esters are dominated by the precursors across all impact categories (except ADPe). Also thermal energy needed for Acrylic Monomer Ester production has a significant impact on the results. For further details, please refer to the main report.

Since this was the first time an Eco-profile for this group of products was developed, a comparison with a previous version of Eco-profiles was not possible.

The LCA practitioners have demonstrated very good competence and experience, with a track record of LCA projects in the chemical and plastics industry. The critical review confirms that this Eco-profile adheres to the rules set forth in the PlasticsEurope's Eco-profiles and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors (PCR version 2.0, April 2011). As a result, this dataset is assessed to be a reliable and high quality representation of GAA, MA, EA, BA and 2-EHA produced in Europe.

Name and affiliation of reviewer:

Reviewer: Matthias Schulz, *DEKRA Assurance Services GmbH*, Stuttgart, Germany

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