Eco-profile of

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

EBAM

May 2024

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2 SUMMARY

This Eco-profile report has been prepared according to the **Eco-profiles program and methodology –PlasticsEurope – V3.1 (2022)** with regards to the report layout, general structure and the chapters covered. As it is mentioned on several occasions later within chapter 3.10, the rules of the underlying LCA model are defined by and according to the **Guide for EF compliant data sets – V2.0 (2020)**

It provides average environmental performance data of a representative European market mix of each 1 kg of the following five acrylic monomers.

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

analysed from cradle to gate (from crude oil (and other, potentially biobased feedstock) extraction to the final monomer production at plant).

Please keep in mind that comparisons cannot be made on the level of the acrylic 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.

It is intended to be used by the member companies, to support product-orientated environmental management; by users of acrylic monomers, 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.

The underlying developed, aggregated LCI datasets are compiled following the EF 3.1 standard [JRC 2020] and therefore can be used for the creation and modelling for future (product) environmental footprint (EF) studies/profiles according the official (P)EF guidance document [PEF GUIDE 2013)].

2.1 META DATA

Data Owner	Cefic European Basic Acrylic Monomers Sector group (EBAM)
LCA Practitioner	Sphera Solutions GmbH
Programme Owner	PlasticsEurope
Reviewer	Angela Schindler, Umweltberatung
Number of plants included in data collection	5 (GAA) 4 (MA) 3 (EA) 4 (BA) 3 (2-EHA)
Representativeness	> 50% coverage in terms of European industry market
Reference year	2021
Year of data collection and calculation	2023/24
Expected temporal validity	2029
Cut-offs	No significant cut-offs
Data Quality	Very good
Allocation method	Not applicable

2.2 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.

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.

With regards to the End-of-Life (EoL) treatment of the acrylic monomers, of course, no general statements can be made as it is clearly depending on their specific application.

2.3 Data Sources and Allocation

The main data source is a primary data collection from the main 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 17 plants (production units) 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	4	5
MA	2	2 (4[1])
EA	3	3
BA	4	4
2-EHA	3	3

The provided data cover (based on association information) more than 50% of the European GAA and alkyl acrylate industry market (EU-27) in 2021, respectively.

The data for the upstream supply chain until the precursors, as well as all relevant background data such as energy and auxiliary material are taken (upon availability) from the existing data stock of EF 3.1 compliant background datasets [EF DATABASE 2022], and (in case of background data gaps) from Sphera´s LCI database ("MLC" database, previously known as "GaBi" database)[2]

Most of the background data used is publicly available and public documentation exists [SPHERA 2023]

No allocation had to be applied in the foreground systems of the products in scope.

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[1] In order to ensure data confidentiality two additional datapoints referring to MA imported from outside of Europe (China and the US) have been included with their estimated import share to the European market (<10%). The corresponding foreground data was modelled based on primary data verified information from Sphera´s MLC database (previously known as GaBi database)

[2] These secondary data are mainly based on a mix of data related from market studies, complemented by necessary calculations and estimations based on expert knowledge.

In general, all Sphera MLC background datasets are reviewed internally before adding them to the MLC dataset pool und undergo annual updates, which not only includes refreshment of background energy mixes but also import mixes of raw materials and process technology and efficiencies once these become known.

2.4 Environmental Performance

The tables below show the environmental performance indicators associated with the production of 1 kg of each acrylic monomer (group):

2.4.1 Input Parameters

Indicator	**Unit**	**Products**					**Impact method ref.**
		GAA	**MA**	**EA**	**BA**	**2-EHA**	
Non-renewable energy resources[1)]							
• Fuel energy	MJ	22.91	33.56	36.46	48.81	61.55	-
• Feedstock energy	MJ	19.08	22.50	18.05	29.39	33.76	-
Renewable energy resources (biomass)[1)]							
• Fuel energy	MJ	1.37	1.30	11.22	1.47	3.32	-
• Feedstock energy	MJ	0.00	0.00	7.42	0.00	0.00	-
Resource use							
• Minerals and Metals	kg Sb eq	4.66E-06	3.84E-06	5.41E-06	3.75E-06	3.09E-06	EF 3.1
• Energy Carriers	MJ	39.05	51.69	50.36	72.10	87.52	EF 3.1
Renewable materials (biomass)	kg	-	-	0.28	-	-	-
Water scarcity	m^3 world eq	6.57E-02	1.23E-01	1.25E-01	6.98E-02	2.88E-01	EF 3.1
[1)] Calculated as upper heating value (UHV)							

2.4.2 Output Parameters

Indicator	**Unit**	**Products**					**Impact method ref.**
		GAA	**MA**	**EA**	**BA**	**2-EHA**	
Climate change, total	kg CO_2 eq.	0.87	1.22	1.97	2.39	2.90	EF 3.1
Ozone depletion	kg CFC-11 eq.	1.10E-08	4.83E-09	7.75E-09	2.18E-08	8.83E-09	EF 3.1
Acidification	Mole of H+ eq	2.01E-03	2.99E-03	6.23E-03	3.78E-03	4.83E-03	EF 3.1
Photochemical ozone formation	kg NMVOC eq	1.71E-03	2.89E-03	5.31E-03	2.98E-03	4.27E-03	EF 3.1
Eutrophication, freshwater	kg P eq	9.52E-06	3.10E-05	1.15E-04	1.32E-05	1.21E-05	EF 3.1

Respiratory Inorganics	Disease incidences	1.41E-08	2.17E-08	1.62E-07	2.67E-08	3.64E-08	EF 3.1
Waste							
• Non-hazardous	kg	0.81	0.55	0.86	1.16	2.52	-
• Hazardous	kg	8.42E-04	9.30E-04	1.01E-03	5.69E-04	6.68E-04	-

Please refer to chapter 5 for a complete overview of all EF 3.1 indicator results of the products in scope.

2.5 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 inverte-brates 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.

2.6 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.

2.7 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.

2.8 PROGRAMME OWNER

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3 ECO-PROFILE REPORT

3.1 FUNCTIONAL UNIT AND DECLARED UNIT

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

3.2 PRODUCT DESCRIPTION

Glacial 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 19,08 MJ/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 22,50 MJ/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 25,48 MJ/kg
- With regards to the average ethyl acrylate declared within the scope of this Eco-profile the biogenic carbon content is 0,16 kg per 1 kg of product or, in other words, 26% of the carbon included in the ethyl acrylate considered origins from a biogenic resource

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 29,39 MJ/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 33,76 MJ/kg

3.3 Manufacturing Description

GAA is produced by the catalysed oxidation of propene in a single- or two-step process.

$$CH_2{=}CH{-}CH_3 + 3\ O_2 \rightarrow 2\ CH_2{=}CH{-}CO_2H + 2\ H_2O$$

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 biobased Ethanol. In this Eco-profile both Ethanol sources are included.

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

(Acrylic acid + Methanol → Methyl acrylate + Water)

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

(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.

CH2=CH-CO2H + CH3-(CH2)3-OH → CH2=CH-CO2-(CH2)3-CH3 + H2O

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

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

(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]

3.4 PRODUCER DESCRIPTION

Eco-profiles 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 producers of basic acrylic monomers as represented by EBAM's membership and the production sites participating in the Eco-profile data collection. The following companies contributed data to this Eco-profile:

Company	Address	Contribution to				
		GAA	MA	EA	BA	2 - EHA
Arkema France	420, rue d'Estienne d'Orves F-92705 Colombes Cedex France http://www.arkema.com/en/	X		X	X	X
BASF SE	Carl-Bosch-Strasse 38 D-67056 Ludwigshafen Germany http://www.basf.com	X	X	X	X	X
DOW Europe	Bachtobelstrasse 3 CH-8810 Horgen Switzerland http://www.dow.com/				X	
Evonik Industries AG	Paul-Baumann-Straße 1 45772 Marl Germany http://www.evonik.com	X				
Synthomer	Tovarni 2093 356 01 Sokolov Czech Republic http://www.synthomer.com/	X	X	X	X	X

3.5 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 esters (MA, EA, BA, 2-EHA).

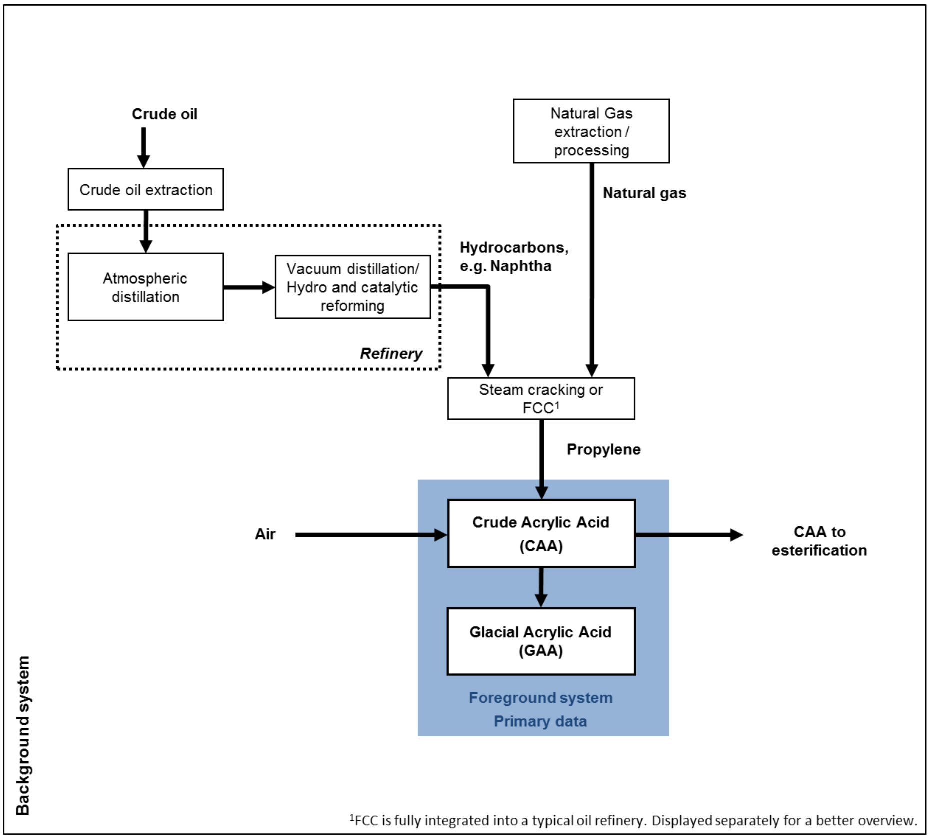

Figure 1:´Cradle-to-gate system boundaries (GAA)

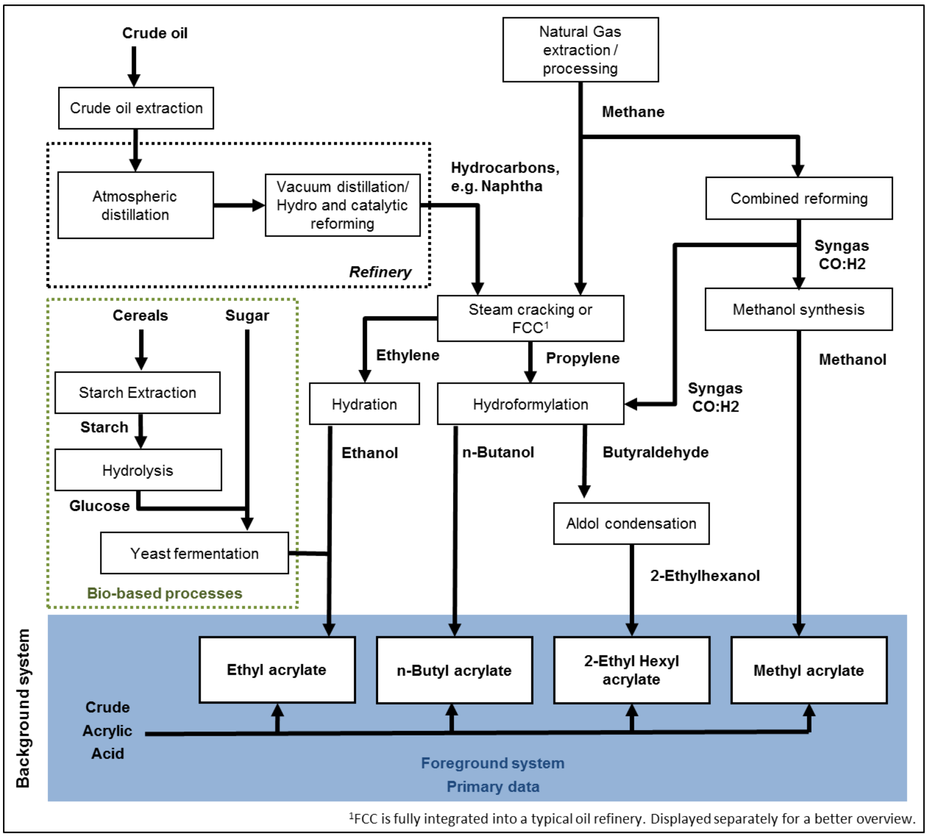

Figure 2: Cradle-to-gate system boundaries (Acrylic Esters)

3.6 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 seventeen plants (GAA: 5 producers and 6 plants; MA: 2 producers and 2 plants[3]; 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). It is assumed (based on association information) that the considered participants cover at least 50% of the European industry market in the reference year mentioned above.

Primary data are used for all foreground processes (under operational control) complemented with secondary data for background processes (under indirect management control). For the main precursor 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).

3.7 TEMPORAL REFERENCE

The LCI data for production was collected as 12-month averages representing the year 2021, to compensate for seasonal influence of data.

Background data have reference year from 2022 (Sphera data), and 2012/2015 regarding EF3.1 energy/auxiliary datasets respectively 2017/18 regarding EF3.1 raw material datasets (see chapter Data Sources for an overview of source and reference year of the main raw material datasets used for modelling)

The average datasets are considered to be valid until substantial technological changes in the production chain occur. Having the latest technology development in mind, the companies participating in this Eco-profile define as temporal reference: the overall reference year for this Eco-profile is 2021 with a temporal validity until 2029 for the foreground system.

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[3] In order to ensure data confidentiality two additional datapoints referring to MA imported from outside of Europe (China and the US) have been included with their estimated import share to the European market (<10%). The corresponding foreground data was modelled based on primary data verified information from Sphera´s MLC database (previously known as GaBi database)

3.8 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 (with the exception of MA) are not considered in this Eco-profile.

3.9 CUT-OFF RULES

In the foreground processes all reported flows were considered.

According to the Sphera´s MLC 2022 LCI database [SPHERA 2023], and [EF DATABASE 2022] used in the background processes, at least 95% of mass and energy of the input and output flows were covered and 98% of their environmental relevance (according to expert judgment) was considered, hence an influence of cut-offs less than 1% on the total is expected

3.10 DATA QUALITY REQUIREMENTS

Data Sources

Eco-profiles developed for EBAM use weighted 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 3.4).

The data for the upstream supply chain is taken from the Sphera´s MLC 2022 LCI database [SPHERA 2023] of the software system LCA for Experts (previously known as "GaBi" software) and the publicly available EF 3.1 datasets [EF DATABASE 2022], if applicable[4].

The source and reference years of the main upstream raw material datasets are:

- Propylene: Sphera MLC, 2022
- Methanol: EF3.1 datastock, 2017

[4] Due to the project goal of developing EF 3.1 compliant datasets, the related background datasets need to be taken from the current version of the EF Reference Package (v3.1) (with the reference year 2012 for energy datasets).

- Ethanol (fossil based): EF3.1 datastock, 2017
- Ethanol (bio-based): Sphera MLC, 2022
- n - Butanol: EF3.1 datastock, 2018
- 2 - Ethylhexanol: Sphera MLC, 2022

Background data for energy and auxiliaries are exclusively taken from the EF3.1 datastock. Most of the background data used is publicly available and public documentation exists.

Relevance

Regarding 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 acrylic monomers producers in Europe in order to generate a European industry average. The environmental contributions of each process to the overall LCI results are included in the Chapter 'Dominance Analysis'.

Representativeness

The considered participants covered at least 50% of the European industry market (2021) regarding the acrylic monomers in scope of this assessment. The selected background data can be regarded as representative for the intended purpose, as it is average data

Consistency

To ensure consistency only primary data of the same level of detail and background data from the Sphera´s MLC 2022 LCI database [SPHERA 2023] and the publicly available EF 3.1 datasets [EF DATABASE 2022], if applicable 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 or determined by literature data or estimated for some flows, which have been reviewed and checked for its quality.

Completeness

Primary data used for the gate-to-gate production of the acrylic monomers in scope of this assessment all related flows in accordance with the cut off criteria. In this way all relevant flows were quantified, and data is considered 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. All background data is consistently either Sphera´s MLC 2022 data or publicly available EF 3.1 data – both with related public documentation.

Reproducibility

All data and information used are either documented in this report or they are available from the processes and process plans designed within the LCA for experts software (v10.7). The reproducibility is given for internal use since the owners of the technology provided the data and the models are stored and available in a database. Sub-systems are modelled by ´state of art´ technology using data from a publicly available and internationally used database. It is worth noting that for external audiences, it may be the case that full reproducibility in any degree of detail will not be available for confidentiality reasons. However, experienced experts would easily be able to recalculate and reproduce suitable parts of the system as well as key indicators in a certain confidence range.

Data Validation

The data on production collected from the project partners and the data providing companies was validated in an iterative process several times. The collected data was validated using existing data from published sources or expert knowledge.

The background information from the Sphera MLC 2022 LCI database [SPHERA 2023] is updated regularly and validated and benchmarked daily by its various users worldwide.

Life Cycle Model

The study has been performed with the LCA software LCA for Experts (v 10.7). The associated database integrates ISO 14040/44 requirements. LCA modelling has been carried out following the rules of EF 3.1 compliant dataset modelling [JRC 2020]

Due to confidentiality reasons details on software modelling and methods used cannot be shown here. However, in principle the model can be reviewed in detail if the data owners agree. The calculation follows the vertical calculation methodology, i.e. that the averaging is done after modelling the specific processes.

3.11 CALCULATION RULES

Vertical Averaging

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

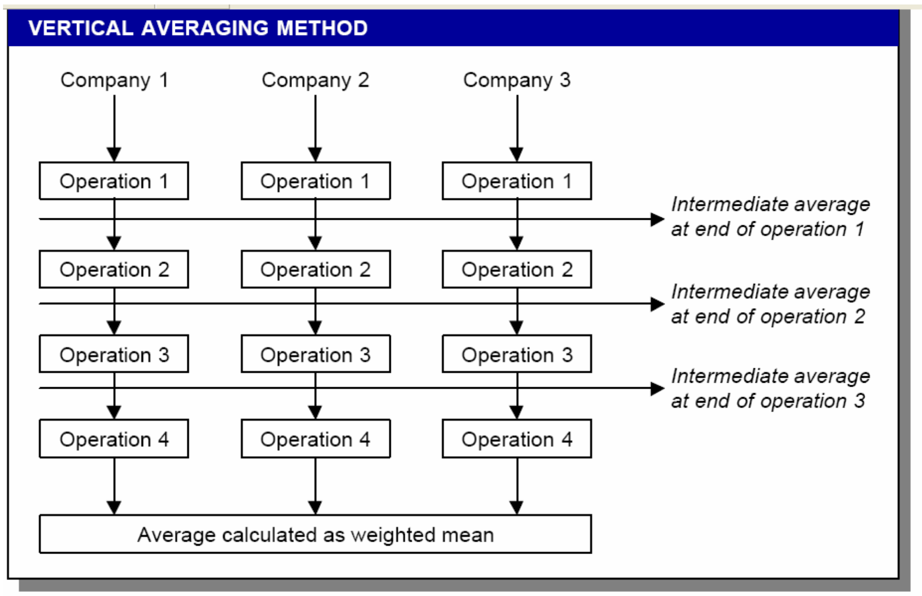

Figure 3: Vertical Averaging

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 are not existing, or alternative technologies show completely different technical performance and product quality output or no clear dominant route is available for credit generation. 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:

No allocation had to be applied in the foreground systems of the products in scope.

Background system:

Mass allocation has been applied as the method of choice reflecting the physical relationships between inputs and outputs in the very rare case of reported (only for the GAA product system and only in very minor amounts) valuable by-products - following the hierarchy suggested in [JRC 2020].

In the refinery operations, co-production was addressed by applying allocation based on mass and net calorific value [SPHERA 2023]. The chosen allocation in refinery is based on several sensitivity analyses, which was accompanied by petrochemical experts. The relevance and influence of possible other allocation keys in this context is small. In steam cracking, allocation according to net calorific value is applied. Relevance of other allocation rules (mass) is below 2 %.

3.12 Life Cycle Inventory (LCI) Results

Delivery and Formats of LCI Dataset

This eco-profile comprises

- One EF 3.1 compliant dataset per average acrylic monomer in ILCD/EF 3.1 format (https://eplca.jrc.ec.europa.eu/LCDN/developer.xhtml) according to the last version at the date of publication of the Eco-profile and including the reviewer (internal and external) input.
- LCA for experts format (.GabiDB)
- This report in pdf format.

Energy Demand

The **primary energy demand** (system input) indicates the cumulative energy requirements at the resource level, accrued along the entire process chain (system boundaries), quantified as gross calorific value (upper heating value, UHV).

The **energy content in the acrylic monomers** indicates a measure of the share of primary energy incorporated in the product, and hence a recovery potential (system output), quantified as the gross calorific value (UHV).

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

Table 1 Primary energy demand (system boundary level) per 1kg Glacial Acrylic Acid

Primary Energy Demand	Value [MJ]
Energy content in acrylic monomer (energy recovery potential, quantified as gross calorific value of acrylic monomer)	19.08
Process energy (quantified as difference between primary energy demand and energy content of acrylic monomer)	24.28
Total primary energy demand	**43.36**

Table 2 Primary energy demand (system boundary level) per 1kg Methyl Acrylate

Primary Energy Demand	Value [MJ]
Energy content in acrylic monomer (energy recovery potential, quantified as gross calorific value of acrylic monomer)	22.50
Process energy (quantified as difference between primary energy demand and energy content of acrylic monomer)	34.86
Total primary energy demand	**57.37**

Table 3 Primary energy demand (system boundary level) per 1kg Ethyl Acrylate

Primary Energy Demand	Value [MJ]
Energy content in acrylic monomer (energy recovery potential, quantified as gross calorific value of acrylic monomer)	25.48
Process energy (quantified as difference between primary energy demand and energy content of acrylic monomer)	47.67
Total primary energy demand	**73.15**

Table 4 Primary energy demand (system boundary level) per 1kg Butyl Acrylate

Primary Energy Demand	Value [MJ]
Energy content in acrylic monomer (energy recovery potential, quantified as gross calorific value of acrylic monomer)	29.39
Process energy (quantified as difference between primary energy demand and energy content of acrylic monomer)	50.28
Total primary energy demand	**79.67**

Table 5 Primary energy demand (system boundary level) per 1kg 2 – Ethylhexyl Acrylate

Primary Energy Demand	Value [MJ]
Energy content in acrylic monomer (energy recovery potential, quantified as gross calorific value of acrylic monomer)	33.76
Process energy (quantified as difference between primary energy demand and energy content of acrylic monomer)	64.87
Total primary energy demand	**98.63**

Water cradle to gate Use and Consumption

The cradle-to-gate[5] blue water [ISO 14064] **use** accounts for

- Glacial Acrylic Acid: 940 kg
- Methyl Acrylate: 753 kg
- Ethyl Acrylate: 1118 kg
- Butyl Acrylate: 1019 kg
- 2 – Ethylhexyl Acrylate: 1393 kg

The corresponding blue water **consumption** in the same system boundary shows as

- Glacial Acrylic Acid: 6.1 kg
- Methyl Acrylate: 6.1 kg
- Ethyl Acrylate: 13.8 kg
- Butyl Acrylate: 8.9 kg
- 2 – Ethylhexyl Acrylate: 16.7 kg

Water foreground (gate to gate) Use and Consumption

The following tables show the weighted average values for water use of the acrylic monomers production process (gate-to-gate level). For each of the typical water applications the water sources are shown.

[5] This includes water use in the total upstream supply chain

Table 6 Water use and source per 1kg of Glacial Acrylic Acid

Source	Process water [kg]	Cooling water [kg]	Steam Water [kg]	Water in Raw Materials [kg]	Total [kg]
From Tap	0.00	0.00	0.00	0.00	0.00
Deionized / Softened	0.05	0.00	2.81	0.00	2.86
Untreated (from river/lake)	0.00	96.03	0,00	0.00	96.03
Untreated (from sea)	0.00	0,00	0,00	0.00	0,00
Relooped	0.00	0,00	0.10	0.00	0.10
Totals	**0.05**	**96.03**	**2.91**	**0.00**	**98.99**

Table 7 Water use and source per 1kg of Methyl Acrylate

Source	Process water [kg]	Cooling water [kg]	Steam Water [kg]	Water in Raw Materials [kg]	Total [kg]
From Tap	0.02	0.00	0.00	0.00	0.02
Deionized / Softened	0.42	0.33	1.46	0.00	2.21
Untreated (from river/lake)	0.00	0.00	0.00	0.00	0.00
Untreated (from sea)	0.00	0.00	0.00	0.00	0.00
Relooped	0.00	0.00	0.00	0.00	0.00
Totals	**0.43**	**0.33**	**1.46**	**0.00**	**2.23**

Table 8 Water use and source per 1kg of Ethyl Acrylate

Source	Process water [kg]	Cooling water [kg]	Steam Water [kg]	Water in Raw Materials [kg]	Total [kg]
From Tap	0.00	0.00	0.00	0.00	0.00
Deionized / Softened	0.63	0.03	2.88	0.01	3.56
Untreated (from river/lake)	0.00	32.24	0.00	0.00	32.24
Untreated (from sea)	0.00	0.00	0.00	0.00	0.00
Relooped	0.00	225.69	1.89	0,00	227.57
Totals	**0.63**	**257.96**	**4.77**	**0.01**	**263.37**

Table 9 Water use and source per 1kg of Butyl Acrylate

Source	Process water [kg]	Cooling water [kg]	Steam Water [kg]	Water in Raw Materials [kg]	Total [kg]
From Tap	0.00	0.00	0.00	0.00	0.00
Deionized / Softened	0.14	0.22	1.53	0.03	1.91
Untreated (from river/lake)	0.09	0.40	0.00	0.00	0.48
Untreated (from sea)	0.00	0.00	0.00	0.00	0.00
Relooped	0.00	10.38	0.48	0.00	10.85
Totals	**0.22**	**10.99**	**2.01**	**0.03**	**13.25**

Table 10 Water use and source per 1kg of 2-Ethylhexyl Acrylate

Source	**Process water [kg]**	**Cooling water [kg]**	**Steam Water [kg]**	**Water in Raw Materials [kg]**	**Total [kg]**
From Tap	0.00	0.00	0.00	0.00	0.00
Deionized / Softened	0.04	0.04	1.13	0.00	1.22
Untreated (from river/lake)	0.00	55.20	0.00	0.00	55.20
Untreated (from sea)	0.00	0.00	0.00	0.00	0.00
Relooped	0.00	0.00	0.29	0.00	0.29
Totals	**0.04**	**55.25**	**1.43**	**0.00**	**56.71**

The following tables show the further handling/processing of the water output of the production processes of the acrylic monomers:

Table 11 Treatment of Water Output per 1kg of Glacial Acrylic Acid

Treatment	**Water Output [kg]**
To WWTP	0.22
Untreated (to river/lake)	95.94
Untreated (to sea)	0.00
Relooped	0.24
Water leaving with products	2.20
Water Vapour	0.39
Formed in reaction (to WWTP)	0.08
Totals	**99.07**

Table 12 Treatment of Water Output per 1kg of Methyl Acrylate

Treatment	**Water Output [kg]**
To WWTP	0.60
Untreated (to river/lake)	0.00
Untreated (to sea)	0.00
Relooped	1.20
Water leaving with products	0.00
Water Vapour	0.43
Formed in reaction (to WWTP)	0.21
Totals	**2.44**

Table 13 Treatment of Water Output per 1kg of Ethyl Acrylate

Treatment	**Water Output [kg]**
To WWTP	2.92
Untreated (to river/lake)	29.96
Untreated (to sea)	0.00
Relooped	228.18
Water leaving with products	0.00
Water Vapour	2.31
Formed in reaction (to WWTP)	0.18
Totals	**263.55**

Table 14 Treatment of Water Output per 1kg of Butyl Acrylate

Treatment	Water Output [kg]
To WWTP	1.26
Untreated (to river/lake)	0.00
Untreated (to sea)	0.00
Relooped	10.88
Water leaving with products	0.00
Water Vapour	1.12
Formed in reaction (to WWTP)	0.14
Totals	**13.39**

Table 15 Treatment of Water Output per 1kg of 2-Ethylhexyl Acrylate

Treatment	Water Output [kg]
To WWTP	1.26
Untreated (to river/lake)	54.80
Untreated (to sea)	0.00
Relooped	0.30
Water leaving with products	0.00
Water Vapour	0.36
Formed in reaction (to WWTP)	0.10
Totals	**56.81**

Based on the water use and output figures above the **gate-to-gate water consumption** can be calculated as:

Consumption = (water vapour + water lost to the sea) – (water generated by using water containing raw materials + water generated by the reaction + seawater used)

- Glacial Acrylic Acid: 0.3 kg
- Methyl Acrylate: 0.2 kg
- Ethyl Acrylate: 2.1 kg
- Butyl Acrylate: 1 kg
- 2 – Ethylhexyl Acrylate: 0.3 kg

Dominance Analysis

The following tables show for each 1 kg of the products in scope of this study the contribution analysis to those LCI and LCIA indicators which were considered most relevant (see chapter 2.4).

Table 16 to Table 20 reveal the main contributions and drivers to the results presented above: In all product systems as well as in all analysed environmental impact categories the precursors and the direct process emissions contribute with the highest share to the total impact. For most of the products/impacts even significantly with more than 50% contribution (often more than even 70%).

Exceptions from this general finding can be identified with regards to:

- Climate change:
  Some (between 10% to 25%), up to relevant (between 25% and 50%) contribution can be also observed from the emissions associated with the thermal energy demand. For the GAA product system, the related contribution is negative due to thermal energy/steam credits given for recovered process heat from the exothermic reaction. For the crediting of recovered thermal energy the local conditions have been considered which means that a suitable dataset for thermal energy/steam produced via natural gas was selected.

- Resource use, minerals and metals:
  Depending on the individual product system, there is some (up to relevant) contribution associated with the input group of "other chemicals". More precisely this is due to the metal catalysts used in the processes.

- Eutrophication, freshwater:
  Depending on the individual product system, there is some (up to relevant) contribution associated with the input group of "other chemicals". More precisely this is due to the stabilizer material used for acrylic acid. Some further contribution can be also observed related to process waste (water) treatment.

- Ozone depletion:
  Depending on the individual product system, either the main pre-cursors or the input group of "other chemicals" are responsible for most of the contribution.

Other processes like utilities, infrastructure, transportation only show minor (mostly even less) contribution in any of the categories selected.

- Glacial Acrylic Acid:

Table 16 Dominance analysis of impacts per 1kg Glacial Acrylic Acid

	Total Primary Energy	**Resource use, energy carriers**	**Resource use, minerals and metals**	**Climate change, total**	**Acidification**	**Eutrophication, freshwater**	**Photochemical ozone formation**	**Ozone depletion**
Precursors and Process	107%	108%	51%	126%	100%	61%	107%	63%
Other Chemicals	1%	1%	49%	2%	5%	32%	4%	37%
Thermal Energy	-17%	-17%	0%	-47%	-16%	-2%	-21%	0%
Electricity	9%	8%	1%	17%	10%	3%	10%	1%
Utilities	0%	0%	0%	1%	1%	2%	1%	0%
Process Waste Treatment	0%	0%	0%	0%	0%	4%	0%	0%
Infrastructure	0%	0%	0%	0%	0%	0%	0%	0%
Transports	0%	0%	0%	0%	0%	0%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

- Methyl Acrylate:

Table 17 Dominance analysis of impacts per 1kg Methyl Acrylate

	Total Primary Energy	**Resource use, energy carriers**	**Resource use, minerals and metals**	**Climate change, total**	**Acidification**	**Eutrophication, freshwater**	**Photochemical ozone formation**	**Ozone depletion**
Precursors and Process	89%	89%	97%	72%	87%	95%	87%	94%
Other Chemicals	0%	0%	2%	0%	2%	1%	1%	6%
Thermal Energy	10%	10%	1%	26%	9%	0%	11%	0%
Electricity	1%	1%	0%	1%	1%	0%	1%	0%
Utilities	0%	0%	0%	0%	0%	0%	0%	0%
Process Waste Treatment	0%	0%	0%	0%	0%	3%	0%	0%
Infrastructure	0%	0%	0%	0%	0%	0%	0%	0%
Transports	0%	0%	0%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

- Ethyl Acrylate:

Table 18 Dominance analysis of impacts per 1kg Ethyl Acrylate

	Total Primary Energy	Resource use, energy carriers	Resource use, minerals and metals	Climate change, total	Acidification	Eutrophication, freshwater	Photochemical ozone formation	Ozone depletion
Precursors and Process	79%	73%	72%	62%	78%	95%	81%	82%
Other Chemicals	3%	4%	28%	3%	11%	1%	4%	18%
Thermal Energy	16%	20%	0%	32%	8%	0%	11%	0%
Electricity	1%	2%	0%	1%	1%	0%	1%	1%
Utilities	0%	0%	0%	0%	0%	0%	0%	0%
Process Waste Treatment	-1%	-1%	0%	0%	0%	4%	0%	0%
Infrastructure	0%	0%	0%	0%	0%	0%	0%	0%
Transports	1%	1%	0%	2%	2%	0%	4%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

- Butyl Acrylate:

Table 19 Dominance analysis of impacts per 1kg Butyl Acrylate

	Total Primary Energy	Resource use, energy carriers	Resource use, minerals and metals	Climate change, total	Acidification	Eutrophication, freshwater	Photochemical ozone formation	Ozone depletion
Precursors and Process	91%	91%	88%	84%	85%	46%	86%	24%
Other Chemicals	1%	1%	11%	1%	7%	38%	3%	76%
Thermal Energy	8%	8%	0%	14%	7%	1%	10%	0%
Electricity	1%	1%	0%	1%	1%	0%	1%	0%
Utilities	0%	0%	0%	0%	0%	0%	0%	0%
Process Waste Treatment	0%	0%	0%	0%	0%	14%	0%	0%
Infrastructure	0%	0%	0%	0%	0%	0%	0%	0%
Transports	0%	0%	0%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

- 2-Ethylhexyl Acrylate:

Table 20 Dominance analysis of impacts per 1kg 2-Ethylhexyl Acrylate

	Total Primary Energy	**Resource use, energy carriers**	**Resource use, minerals and metals**	**Climate change, total**	**Acidification**	**Eutrophication, freshwater**	**Photochemical ozone formation**	**Ozone depletion**
Precursors and Process	94%	94%	75%	88%	89%	53%	90%	38%
Other Chemicals	1%	1%	25%	1%	6%	31%	3%	62%
Thermal Energy	5%	5%	0%	9%	4%	1%	6%	0%
Electricity	1%	1%	0%	1%	1%	0%	1%	0%
Utilities	0%	0%	0%	0%	0%	0%	0%	0%
Process Waste Treatment	-2%	-2%	0%	0%	-1%	14%	-1%	0%
Infrastructure	0%	0%	0%	0%	0%	0%	0%	0%
Transports	0%	0%	0%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Carbon footprint comparison of the present Eco-profile with its previous version

The following table shows a comparison of the Global Warming Potential (GWP) result (excluding biogenic carbon and excl. Land Use Change (LUC)) of the current vs the previous EBAM Eco-profile applying the CML 2013 methodology:

Table 21 Carbon Footprint Comparison of the present Eco-profile with its previous version referring to each 1 kg of Acrylic Monomers

Acrylic Monomer	**Previous (2015) kg CO_2 eq.**	**New (2024) kg CO_2 eq.**	**Difference (%)**
Glacial Acrylic Acid (GAA)	1.18	0.84	- 28%
Methyl Acrylate (MA)	1.66	1.09	- 34%
Ethyl Acrylate (EA)	2.33	1.56	- 33%
Butyl Acrylate (BA)	2.16	2.35	9%
2- Ethylhexyl Acrylate (2-EHA)	3.28	2.86	-13%

When contrasting the outcome of the present study with the previous one (published in 2015) the following factors have to be taken into consideration:

- Partly different modelling approach than in the previous study, defined by the guide on creating EF3.1 compliant datasets: Specific calculation and modelling principles were followed (such as adding infrastructure/capital goods, CFF formula to account for secondary fuel inputs and waste for recovery)
- Partly (mostly) different database applied for the background modelling of upstream materials (EF3.1 instead of Sphera MLC (previously GaBi)). This point is especially relevant for the directly consumed electricity (from national grid mixes) as the reference year for the corresponding EF3.1 datasets is fixed to 2012 which means that any "greening" of electricity production over the past decade is not reflected in the current results.

Nonetheless some relevant changes with regards to the carbon footprint (excl. biogenic carbon and LUC) can be observed and explained by the following findings:

- GAA: The average GWP result is lowered by 28% mostly due to a more efficient use of the propylene input (and also lower emissions from the corresponding waste treatment), decreased thermal energy consumption and in increased heat recovery
- MA: The average GWP result is lowered by 34% due to a shift in the production mix in favour of producers having relevantly increased (in comparison to the previous study) their material and energy resource efficiency in the upstream acrylic acid production. Another reason is furthermore an average reduction of the thermal energy consumption in the foreground.
- EA: The average GWP result is lowered by 33% due to a shift in the production mix in favour of producers having relevantly increased (in comparison to the previous study) their material and energy resource efficiency in the upstream acrylic acid production. The main reason though is an average reduction of the thermal energy consumption in the foreground.
- BA: The average GWP result is increased by 9%. This is mostly caused by the usage of the available primary data based EF3.1 compliant dataset for Butanol [ESIG 2021]
- 2-EHA: The average GWP result is lowered by 13%. This is related to the lower footprint of the 2-ethylhexanol dataset (from Sphera MLC database, with updated energy/electricity in the background) applied, while differences in the foreground system are neglectable and cancel each other out.

4 REVIEW

4.1 EXTERNAL INDEPENDENT REVIEW SUMMARY

External independent review summary

This Eco-profile covers the declaration of the environmental performance of glacial acrylic acid and four acrylates (MA, EA, BA, 2-EHA) based on GAA. The present Eco-profile is an update of an Eco-profile published in 2015. The review process was performed in accordance with ISO/TS 14071 and coordinated between EBAM/Sphera and the reviewer. The Eco-profile document and respective files was reviewed in the time frame of February to April 2024.

The compliance of the document was reviewed according to the current requirements of the Eco-profile program and methodology, version 3.1 (Sept. 2022) of PlasticsEurope and the accompanying template for Eco-profile reports. Besides, the substantial intention of this Eco-profile is the generation of life cycle inventories for the considered products, according to the Guide for EF compliant data sets, version 2.0 (2020), to be used as background data for environmental footprint studies, according to the European Commission's PEF Guide (2013).

Main producers have taken part in this study. The market coverage is estimated by > 50%. The data can be seen representative for a substantial proportion of the European market.

The review process covered the annotation of the Eco-profile by commenting the submitted Eco-profile report. In an extensive webmeeting the confidential data collection and the calculation principles were shown to the reviewer; the comments on the documents were discussed and questions clarified by explanations of the LCA practitioner.

For the update of the Eco-profile new and complete foreground data were delivered by the participants of the study complemented with upstream process inventories from the current available EF databases, supplemented by datasets from the MLC database of Sphera.

For all relevant material and energy flows specific LCIs could be selected from the background databases.

Data sources are explicitly shown. This provides a transparent picture of data quality in respect to temporal representativeness. With the requirement of declaring EF 3.1 conform LCIs, the existing database has to be used; unfortunately, this database is not up-to-date any more. Data not (yet) included in the EF-database are to be used from other sources. Main input flows of the supply chain are from external sources and more current than the EF-database. This leads to the situation, that high contributing material flows originate from more recent data sources. With this background information and according to the explanations given in the additional chapter comparing the current calculation assessment with the previous one, the dataset can be recommended as displaying best state-of-the-art technology by concurrently meeting the requirements of the Guide for EF compliant datasets.

So far the participating companies do not use green electricity for their production of the considered products. According to the EF-guide, the national consumption grid mix is applied in the software model.
For each LCI a respective and specific data quality rating scheme according to the EF-guide is generated and delivered to the reviewer.

The process chain does not involve products/production residues from or for recycling. This means, that the specific rules for EoL considering the circular footprint formula are not relevant for this assessment.

Although not included in the assessment according EF 3.1, the inventory considers elementary flows for carbon uptake and biogenic emissions. This enables the user to apply the LCIs also for studies requiring the assessment of the indicator GWP biogenic.

The elementary flows of the inventory are checked for EF- and ILCD compliance by the respective tools; evidence is shown to the reviewer.

Overall, the project is carried out very thoroughly. During the review process some aspects have been discussed:

The indicator renewable materials (biomass) is not defined in the methodological protocol. It is interpreted by the practitioner and reviewer as non-elementary flow of renewable resources (specifically bio-ethanol for EA) used in the processing as material flow and with this contained as renewable feedstock energy in the product.

Due to exothermic reaction, the production of GAA leads to additional thermal energy. Methodologically, this is solved via system expansion of avoided energy generation, which reduces the total environmental impact of GAA. The system expansion included in the GAA LCI does not follow completely the rules defined by EN 15804+A2, often relevant for downstream users of the Eco-profile. The alternative methodological approach of co-product allocation would also reduce the environmental impact for the main product GAA. The difference in result depends on the selected allocation criterion (e.g. economic value). Having said this, the effect of the applied system expansion is estimated to be acceptable, also for projects following EN 15804+A2.

All editorial recommendations of the reviewer were implemented by the practitioner.

The Eco-profile is supplemented by an evaluation applying the indicator GWP (CML 2013) applied ub the preliminary Eco-profile. This allows a relative comparison of the results. Both background data and foreground data are updated. This enables some statement of the changes, mainly referring to the optimization of heat recovery in the foreground process.

The products declared are based on fossil resources. So far, this Eco-profile does not reflect company strategies for the development of substituting the resources by renewable materials and/or focusing the application on long living or specific product application only. Additionally, innovations for potential recycling processes are essential for all kinds of polymers, due to many unknown effects when spread uncontrolled into environment. As ecological crisis become urgent, all stakeholders are asked to take action.

The structure and description of the Eco-profile is clear and transparent, thus displaying a reliable source of information.

Despite all necessary due diligence performed during the critical review process by the reviewer, the commissioner of the LCA study remains liable for the underlying information and data.

Salem, April 2024

Angela Schindler

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5 EF 3.1 INDICATOR RESULTS

The following table shows the full list of EF 3.1 indicator results for each of the product groups :

Table 22 : EF 3.1 indicator results for GAA and the corresponding basic esters

Indicator	Unit	GAA	MA	EA	BA	2-EHA
Climate change (total)	kg CO_2 eq.	0.87	1.22	1.97	2.39	2.90
Climate Change, biogenic	kg CO_2 eq.	4.47E-03	3.35E-03	1.33E-02	8.21E-03	1.06E-02
Climate Change, fossil	kg CO_2 eq.	0.862	1.219	1.720	2.381	2.892
Climate Change, land use and land use change	kg CO_2 eq.	3.38E-04	2.58E-04	2.41E-01	4.55E-04	2.69E-04
Ozone depletion	kg CFC-11 eq.	1.10E-08	4.83E-09	7.75E-09	2.18E-08	8.83E-09
Acidification	Mole of H+ eq	2.01E-03	2.99E-03	6.23E-03	3.78E-03	4.83E-03
Photochemical ozone formation	kg NMVOC eq	1.71E-03	2.89E-03	5.31E-03	2.98E-03	4.27E-03
Eutrophication, freshwater	kg P eq	9.52E-06	3.10E-05	1.15E-04	1.32E-05	1.21E-05
Eutrophication, marine	kg N eq.	5.19E-04	7.93E-04	5.49E-03	8.29E-04	1.12E-03
Eutrophication, terrestrial	Mole of N eq.	5.34E-03	8.43E-03	1.70E-02	8.67E-03	1.18E-02
Respiratory Inorganics	Disease incidences	1.41E-08	2.17E-08	1.62E-07	2.67E-08	3.64E-08
Ionising radiation, human health	kBq U235 eq.	0.12	0.10	0.23	0.12	0.11
Human toxicity, cancer - total	CTUh	5.33E-10	5.37E-10	1.63E-09	7.77E-10	8.95E-10
Human toxicity, cancer inorganics	CTUh	4.55E-10	4.30E-10	5.13E-10	6.19E-10	6.50E-10
Human toxicity, cancer organics	CTUh	7.77E-11	1.07E-10	1.12E-09	1.59E-10	2.45E-10
Human toxicity, non-cancer - total	CTUh	1.72E-08	1.30E-08	3.04E-08	3.12E-08	3.25E-08
Human toxicity, non-cancer inorganics	CTUh	1.70E-08	1.26E-08	2.99E-08	3.07E-08	3.20E-08
Human toxicity, non-cancer organics	CTUh	2.20E-10	4.46E-10	4.47E-10	4.43E-10	5.37E-10
Ecotoxicity, freshwater - total	CTUe	2.44E+01	2.02E+01	2.17E+01	3.70E+01	3.08E+01
Ecotoxicity, freshwater inorganics	CTUe	2.40E+01	1.96E+01	2.13E+01	3.66E+01	3.04E+01
Ecotoxicity, freshwater organics	CTUe	3.71E-01	5.64E-01	4.35E-01	4.12E-01	4.09E-01
Land Use	Pt	2.74E+00	2.85E+00	4.73E+01	2.30E+00	3.15E+00
Resource use, energy carriers	MJ	39.05	51.69	50.36	72.10	87.52

Resource use, minerals and metals	kg Sb eq.	4.66E-06	3.84E-06	5.41E-06	3.75E-06	3.09E-06
Water use	m^3 world equiv.	6.57E-02	1.23E-01	1.25E-01	6.98E-02	2.88E-01

6 REFERENCES

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