



Eco-profile of  
Styrene  
February 2022

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# 1 SUMMARY

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This Eco-profile has been prepared according to **Eco-profiles program and methodology – PlasticsEurope – V3.0 (2019)**.

It provides environmental performance data representative of the average European production of styrene, covering the two main production technologies via ethylbenzene styrene monomer (EBSM) and propylene oxide styrene monomer (POSM) production route, from cradle to gate (from crude oil extraction to the liquid monomer at plant).

**Please keep in mind that comparisons cannot be made on the level of the styrene substance 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 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.

## 1.1 META DATA

|  |  |
|--|--|
| Data Owner                                   | PlasticsEurope   |
| LCA Practitioner                             | Sphera Solutions GmbH  |
| Programme Owner                              | PlasticsEurope   |
| Reviewer                                     | Matthias Schulz, Schulz Sustainability Consulting, Germany   |
| Number of plants included in data collection | <ul style="list-style-type: none"><li>2 average route-specific secondary datasets for each EBSM and POSM have been validated with in total 3 primary data collections (1 EBSM, 2 POSM). Both resulting inventories have been weighted according to current total production capacities for each route.</li></ul> |
| Representativeness                           | Primary data used for validation represent about 37% of the EU styrene production volume in 2018. Due to the fact that both routes are well and efficiently established it is assumed that the primary data is also representative for the majority of the styrene monomer production.                           |
| Reference year                               | 2010/2020  |
| Year of data collection and calculation      | 2021   |

|                            |  |
|----------------------------|--|
| Expected temporal validity | 2025<br><br>Revision should be considered in 2023                    |
| Cut-offs                   | No significant cut-offs  |
| Data Quality (DQ)          | Overall: good<br>Confirmed by assessment of individual DQ indicators |
| Allocation method          | Economic (in POSM route)   |

## 1.2 DESCRIPTION OF THE PRODUCT AND THE PRODUCTION PROCESS

This Eco-profile covers the production styrene, an oily-liquid organic compound also called ethenylbenzene (IUPAC nomenclature) or vinylbenzene.

Within Europe the production capacity of styrene in 2018 was estimated up to 5,5 million metric tonnes. [HDIN 2019]

The main purpose of styrene is to serve as monomer being processed into the following (co-) polymers:

- General purpose polystyrene (GPPS)
- High impact polystyrene (HIPS)
- Expandable polystyrene (EPS)
- Styrene butadiene rubber (SBR)
- Styrene acrylonitrile rubber (SAN)
- Acrylonitrile butadiene styrene (ABS)
- Styrene butadiene (SB)
- Etc.

Styrene is mainly produced via two alternative routes:

- Via dehydrogenation of ethylbenzene (EBSM)
- Via co-production together with propylene oxide, based on ethylbenzene, propylene and oxygen (POSM)

In 2018 the ratio of available styrene production capacity via EBSM vs POSM route was about 60:40.

Further possible production routes (and also secondary processing of secondary feedstock via so called “chemcycling” of plastic wastes) are not considered within this study as these technologies do not have reached relevant market shares yet.

As a consequence of this, the functional unit and also reference flow of this study, to which all data and results given in this Eco-profile refer, is:

**1 kg of styrene, reflecting the weighted average of the current (2018) European production capacities via EBSM and POSM (60:40) production technologies**

## 1.3 DATA SOURCES AND ALLOCATION

For both routes existing and current GaBi datasets have formed the basis for the main gate-to-gate data source for this study. For those input/output flows contributing most to the overall results alignment and validation with existing primary, industry data has been carried out and consolidation done based on expert knowledge.

- EBSM route:

The data refers to the production year of 2020 and the data providing company is representative for about 20% of the European EBSM production capacity in 2018

- POSM route:

The industry data which has been consulted and used to align and verify together with the information given from the GaBi database is referring to the production year of 2010, while the related companies' share in the European POSM production capacity in 2018 was about 35%

Although the representativeness in terms of percentage of production capacity is low, as the variability of performance of POSM and EBSM mature optimized production process is equally low, it is considered that the representativeness for the European production is good.

As the POSM route delivers, next to styrene, propylene oxide as valuable co-product a suitable allocation approach needs to be applied.

As base case, economic allocation has been used, being in line with the current ISOPA Eco-profile [**Error! Reference source not found.**], where propylene oxide is consumed in the polyols upstream value chain. Also, in the current version of the POSM GaBi dataset, the economic allocation approach has been conducted.

A scenario analysis includes alternative allocation approaches, such as mass allocation and stoichiometric/elemental allocation in order to show the sensitivity of the allocation decision with regards to the overall styrene environmental footprint.

### Use Phase and End-of-Life Management

Styrene is an intermediate product used in the production of a variety of plastics, resins, rubbers and latexes, with key end applications in areas such as packaging, electronics and appliances, construction (primarily insulation) and automotive components:

- General purpose polystyrene (GPPS). GPPS is a clear, hard, usually colourless thermoplastic resin utilized in packaging, foamed containers, foam insulation, cutlery, medical lab-ware, clear cups and containers.
- High-impact polystyrene (HIPS). HIPS products are used in refrigerator liners and parts, vending cups and lids, dairy containers, appliance components, cosmetics cases, toys and various consumer products.
- Expandable polystyrene (EPS). EPS is polystyrene that, when heated, forms a lightweight foam (due to an added blowing agent such as pentane) used for packaging and insulation purposes.

- Acrylonitrile butadiene styrene (ABS). The main applications of ABS include electrical appliances such as vacuum cleaner components, washing machine panels and control devices, information technology devices such as computer and printer housings and automotive parts such as dashboard components, air vents, centre consoles and glove boxes.
- Styrene-butadiene block copolymers (SBCs). SBCs are a class of block copolymers of styrene and butadiene produced either as an elastomer or as a rigid product. Rigid products have a high transparency and are often used to “toughen” GPPS. The other type of SBCs, elastomers such as styrene-butadiene-styrene (“SBS”), are frequently used for injection-moulded parts as a hot-melt adhesive or as additives to improve the properties of bitumen.
- Etc.

As basically all styrene produced is processed into a polymer the corresponding End of Life treatment depends on its concrete application and the polymer specific characteristics.

## 1.4 ENVIRONMENTAL PERFORMANCE

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

### 1.4.1 Input Parameters

| Indicator   | Unit                    | Value                  | Impact method ref.     |
|---|-------------------------|------------------------|------------------------|
| Non-renewable energy resources <sup>1)</sup>          |                         |                        |                        |
| • Fuel energy   | MJ                      | 39.03                  | -                      |
| • Feedstock energy                                    | MJ                      | 42.20                  | Gross calorific value  |
| Renewable energy resources (biomass) <sup>1)</sup>    |                         |                        |                        |
| • Fuel energy   | MJ                      | 0.69                   | -                      |
| • Feedstock energy                                    | MJ                      | 0.00                   | Gross calorific value- |
| Resource use  |                         |                        |                        |
| • Minerals and Metals                                 | kg Sb eq                | 2.11E-07               | EF 3.0                 |
| • Energy Carriers                                     | MJ                      | 74.78                  | EF 3.0                 |
| Renewable materials (biomass)                         | kg                      | -2.97E-14 <sup>1</sup> | -                      |
| Water scarcity  | m <sup>3</sup> world eq | 2.26E-01               | EF 3.0                 |
| <sup>1)</sup> Calculated as upper heating value (UHV) |                         |                        |                        |

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<sup>1</sup> Neglectable negative result originating from a credit dataset used in upstream infrastructure modelling

## 1.4.2 Output Parameters

| Indicator                     | Unit                      | Value    | Impact method ref. |
|-------------------------------|---------------------------|----------|--------------------|
| Climate change, total         | kg CO <sub>2</sub> eq.    | 2.09     | EF 3.0             |
| Ozone depletion               | kg CFC-11 eq.             | 1.86E-15 | EF 3.0             |
| Acidification                 | Mole of H <sup>+</sup> eq | 3.29E-03 | EF 3.0             |
| Photochemical ozone formation | kg NMVOC eq               | 4.02E-03 | EF 3.0             |
| Eutrophication, freshwater    | kg P eq                   | 2.70E-06 | EF 3.0             |
| Respiratory Inorganics        | Disease incidences        | 2.38E-08 | EF 3.0             |
| Waste                         |                           |          |                    |
| • Non-hazardous               | kg                        | 0.53     |                    |
| • Hazardous                   | kg                        | 2.01E-04 |                    |

## 1.5 ADDITIONAL ENVIRONMENTAL AND HEALTH INFORMATION

This part has been written under the responsibility of the data owner only and is not part of the LCA practitioner and reviewer work.

Will be updated later by PlasticsEurope

## 1.6 ADDITIONAL TECHNICAL INFORMATION

This part has been written under the responsibility of the data owner only and is not part of the LCA practitioner and reviewer work.

## 1.7 ADDITIONAL ECONOMIC INFORMATION

This part has been written under the responsibility of the data owner only and is not part of the LCA practitioner and reviewer work.

## 1.8 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/>.

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## 2 ECO-PROFILE REPORT

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### 2.1 FUNCTIONAL UNIT AND DECLARED UNIT

**1 kg of styrene, reflecting the weighted average of the current (2018) European production capacities via EBSM and POSM (60:40) production technologies**

### 2.2 PRODUCT DESCRIPTION

Styrene (also called vinylbenzene) is an oily-liquid organic intermediate, mainly used as monomer in the production of plastics, resins, rubbers and latexes, with key end applications in areas such as packaging, electronics and appliances, construction (primarily insulation) and automotive components.

#### **Styrene (or styrene monomer = SM)**

- IUPAC name: ethenylbenzene
- CAS number: 100-42-5
- chemical formula:  $C_8H_8$
- gross calorific value: 42.2 MJ/kg

### 2.3 MANUFACTURING DESCRIPTION

Styrene is a liquid hydrocarbon produced from ethylene and benzene, using either the ethylbenzene dehydrogenation ("EBSM") process or the POSM process.

EBSM is the more traditional method for producing styrene, where ethylene is alkylated with benzene to produce ethylbenzene, which is dehydrogenated to produce styrene. This basic method has been used commercially for over 50 years, during which time it has been adapted and refined to improve the quality of the end product and to minimize the amount of energy and other resources, such as electricity, fuel, steam and cooling water, used in its production.

POSM is an alternative process whereby propylene oxide is produced, and styrene is generated as a co-product. POSM may decline in the future as new methods of producing propylene oxide have been designed, which do not yield any SM as a by-product. Both the EBSM and POSM processes are large-scale and capital intensive.

## EBSM process

Ethylbenzene is mixed with superheated steam at about 600 °C, where it is dehydrogenated to styrene. The stream from this reactor is separated into a vapour phase, an organic and a water phase. Water is used for boiler feed. The crude ethylbenzene/styrene product is then purified by distillation. As the difference in boiling points between the two compounds is only 9 °C at ambient pressure this necessitates the use of a series of distillation columns, unreacted ethyl benzene is recycled.

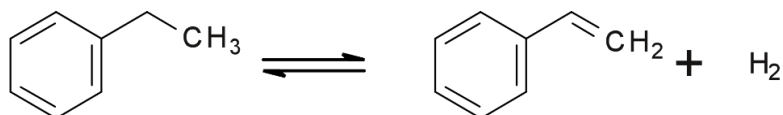


Figure 1 : Reaction equation EBSM process

## POSM process

In this process, ethylbenzene is treated with oxygen to form the ethylbenzene hydroperoxide. This hydroperoxide is then used to oxidize propylene to propylene oxide, which is also recovered as a co-product. The remaining 1-phenylethanol is dehydrated to give styrene.

In the first step, ethylbenzene is oxidized with air at 130°C and 0,2 MPa, ethyl benzene hydroperoxide (EBHP), methyl benzyl alcohol (MBA) and acetophenone (ACP) are formed.

In the next reaction step, EBHP is reacted with propylene by using a metallic catalyst. Propylene oxide and more MBA are formed. ACP formed by the first reaction step is hydrogenated at 90- 150°C and 8 MPa in liquid phase to yield more MBA.

In the last step, MBA is dehydrated to styrene at low pressures and temperatures around 250°C where a metal oxide catalyst is used.

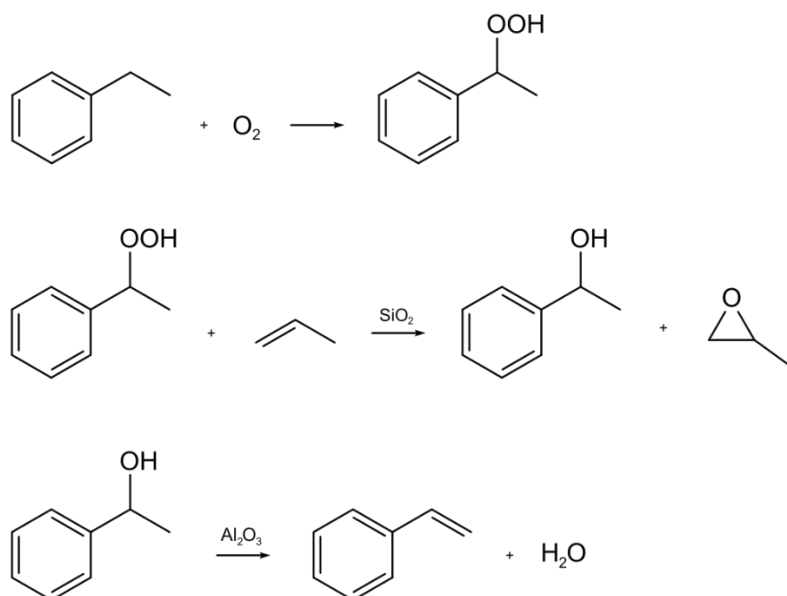


Figure 2 : Reaction equation POSM process

## 2.4 PRODUCER DESCRIPTION

The following companies currently run production facilities for styrene in Europe:

- BASF (EBSM)
- Ellba (POSM)
- Ineos Styrolution (EBSM)
- LyondellBasell (POSM)
- Trinseo (EBSM)
- Repsol (POSM)
- Shell (POSM)
- Synthos (EBSM)
- Total Petrochemicals (EBSM)
- Versalis (EBSM)

## 2.5 SYSTEM BOUNDARIES

PlasticsEurope Eco-profiles and EPDs refer to the production of polymers as a cradle-to-gate system:

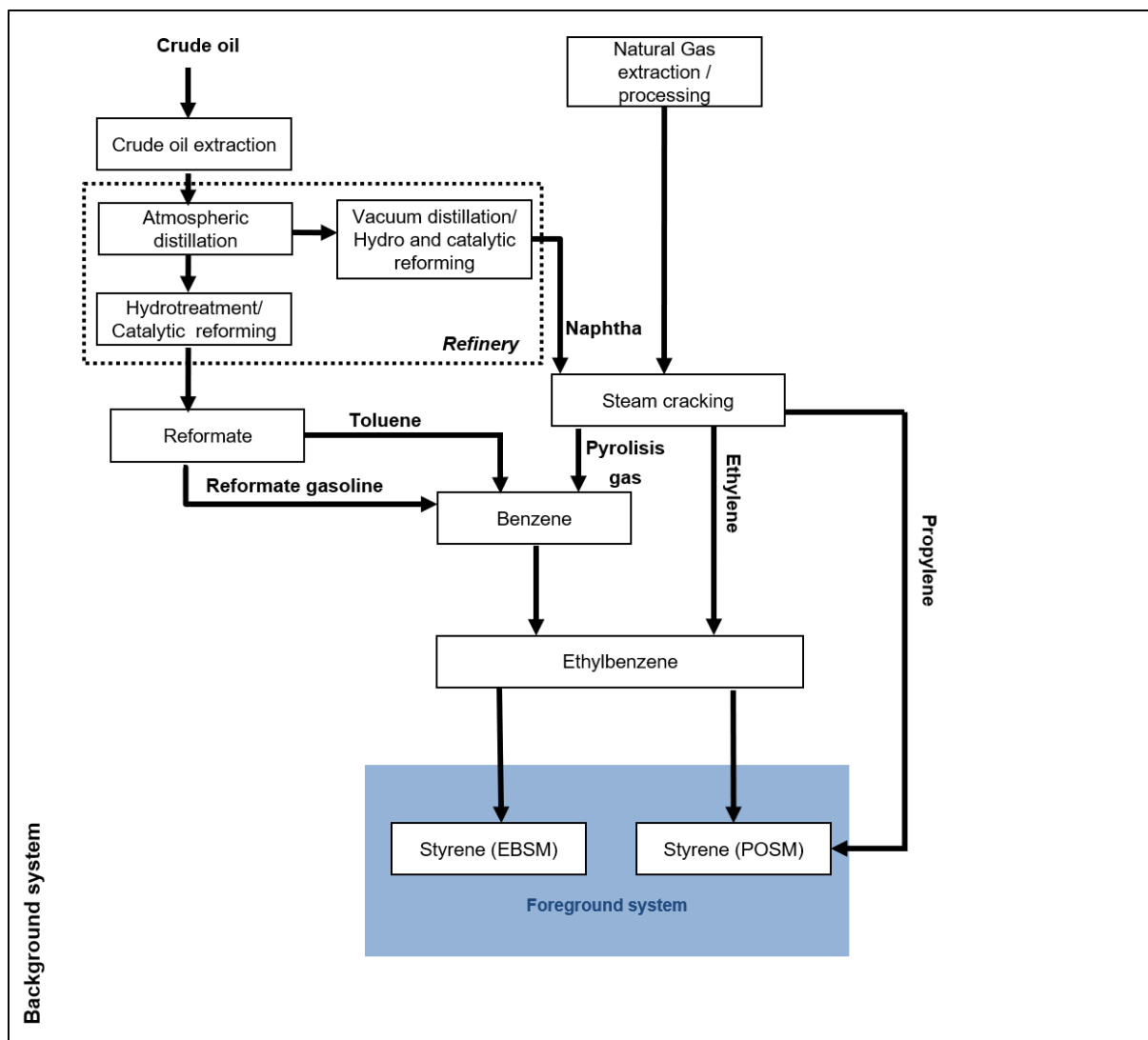


Figure 3: Cradle-to-gate system boundaries (Styrene)

As Figure 3 already indicates, benzene is one of the major upstream pre-cursors of styrene. It can be produced by several technologies with significantly different environmental burdens.

The GaBi dataset used for benzene in the upstream background is composed of an average mix (for the reference year 2019) of all routes and based on the most current information given by [PETROCHEM 2019]:

- Reformate based: 40%
- Pyrolysis Gas based: 50%
- Toluene based: 10%

The GaBi datasets used for the modelling of ethylene and propylene are both based on steam cracker models being by far the most used technology to produce these raw materials.

## **2.7 TECHNOLOGICAL REFERENCE**

The production processes were modelled using secondary foreground data derived from the dedicated EBSM and POSM unit processes available in the latest version (2021) of the GaBi database [SPHERA 2021]. The given values have been verified and aligned with available, route specific industry data for both routes for the most contributing input and output flows, further adaptations have been made based on expert knowledge.

These foreground datasets have been complemented with further technology specific secondary datasets for the pre-cursors applicable.

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 GaBi background datasets are reviewed internally before adding them to the GaBi dataset pool and 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.

## **2.8 TEMPORAL REFERENCE**

Both, foreground and background datasets used from the GaBi database refer to the year 2020 (in case of raw materials) and 2017 (in case of energy datasets). Available industry data used for the verification of the GaBi datasets refer to the years of 2020 (EBSM) and 2010 (POSM).

The dataset is considered to be valid until substantial technological changes in the production chain occur. The overall reference year for this Eco-profile is 2020 with a recommended temporal validity until 2025. According to the PlasticsEurope LCI methodology [PlasticsEurope 2019] updates of eco-profiles must at least be considered every 3 years.

## **2.9 GEOGRAPHICAL REFERENCE**

Raw materials, fuel and energy inputs related datasets used for the modelling of the production system reflect average European conditions, meaning European average background datasets have been selected for the intermediary input and output flows whenever possible.

Therefore, the study results are intended to be applicable within EU boundaries and in order to be applied in other regions adjustments might be required. Styrene imported into Europe was not considered in this Eco-profile.

## **2.10 CUT-OFF RULES**

According to the GaBi 2021 LCI database [SPHERA 2021] used for the foreground and 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.

Transportation has not been considered relevant. Including production, the contribution of all transports is expected to be less than 1%.

## 2.11 DATA QUALITY REQUIREMENTS

### Data Sources

Eco-profiles developed by PlasticsEurope use data representative of the respective foreground production process, both in terms of technology and market share.

Although the representativeness in terms of percentage of production capacity is low, as the variability of performance of POSM and EBSM mature optimized production process is equally low, it is considered that the representativeness for the average European production is good.

The foreground data are from derived technology-specific GaBi datasets for EBSM and POSM, aligned and validated with available industry data. Also, the data for the upstream supply chain are taken from the GaBi 2021 LCI database **[Error! Reference source not found. Error! Reference source not found.**SPHERA 2021], of the software system GaBi 10.

All relevant background data such as pre-cursor materials, energy and auxiliary materials are also taken from the GaBi 2021 LCI database [SPHERA 2021]. Most of the background data used is publicly available and public documentation of the data sources exists.

These secondary data are mainly based on a mix of data related from market studies, industry information, publicly available statistics and complemented by necessary calculations and estimations based on expert knowledge.

In general, all GaBi background datasets are reviewed internally before adding them to the GaBi dataset pool and 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.

### Relevance and Representativeness

Regarding the goal and scope of this Eco-profile, the foreground processes are of high relevance, defining the inputs and outputs of the styrene unit process. Although being based on secondary data, it has been derived from the existing average GaBi processes for EBSM and POSM technology and additionally verified and aligned based on expert knowledge, where necessary. Therefore, the selected foreground and background data can be regarded as representative for the intended purpose. The environmental contributions of each process to the overall LCI results are included in the Chapter 'Dominance Analysis'.

### Consistency

To ensure consistency only foreground data of the same level of detail and background data from the GaBi 2021 LCI database [SPHERA 2021] 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 of foreground and background processes were measured at several sites or determined by literature data or estimated for some flows, which usually have been reviewed and checked for its quality (see chapter Data Sources).

## **Completeness**

Foreground and background data used for the gate-to-gate production of styrene covers 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 secondary data yet validated with available information from the route specific industries a good data precision is assumed to fulfil the goal of the study. All background data is consistently GaBi professional data 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 GaBi 10 software. The reproducibility is given for internal use since 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 secondary foreground data on production derived from the latest version of the route specific GaBi datasets was validated with available industry data in an iterative process several times based on expert knowledge.

The background information from the GaBi 2021 LCI database [SPHERA 2021] 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 GaBi 10. The associated database integrates ISO 14040/44 requirements. 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 as far as possible, i.e. that the averaging is done after modelling the specific processes.

A data quality rating based on the criteria and calculation rules described in the guide to develop EF (environmental footprint) compliant datasets [JRC 2020] led to the following weighted average result:



| Weighted DQRs |      |     |           |                        |
|---------------|------|-----|-----------|------------------------|
| Tech          | Time | Geo | Precision | DQR of created dataset |
| 2             | 2.1  | 1   | 2         | 1.8                    |

## 2.12 CALCULATION RULES

### Vertical Averaging

According to the Plastics Europe methodology [PlasticsEurope 2019], vertical averaging should be applied wherever possible. As far as known and available, route specific pre-cursor datasets matching the real supply chain conditions have been used for modelling accordingly.

However, for some pre-cursor materials, information with regards to the specific technology applied was not available, so that average datasets have been selected, which follows the principle of horizontal averaging (see Figure 4).

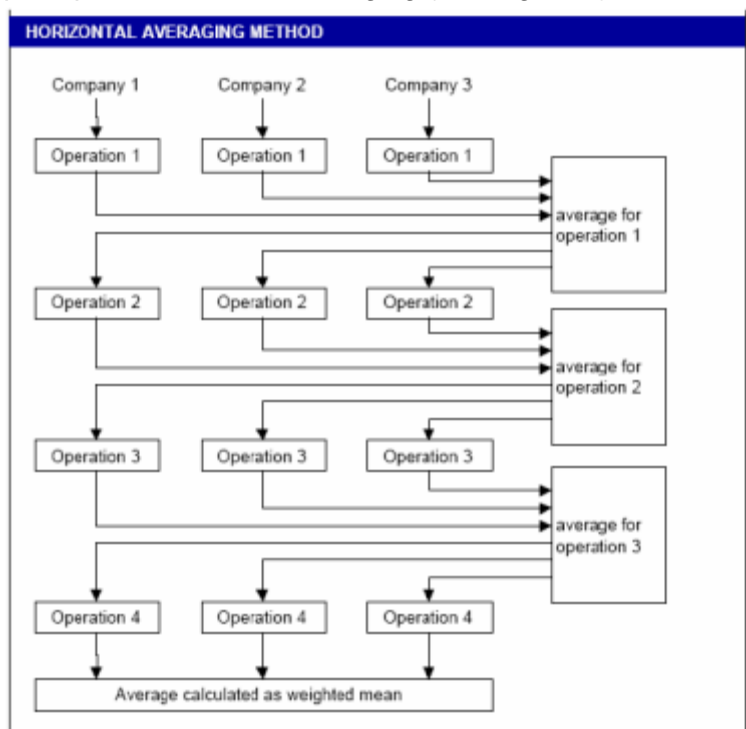


Figure 4: Horizontal Averaging

### 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. 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.

As the POSM route delivers, next to styrene, propylene oxide as valuable co-product a suitable allocation approach needs to be applied.

As base case, economic allocation has been used, being in line with the current ISOPA Eco-profile [**Error! Reference source not found.**], where propylene oxide is consumed in the polyols upstream value chain. Also, in the current version of the POSM GaBi dataset, the economic allocation approach has been applied. With both products being globally traded commodities and pre-cursor for many applications, they have defined markets and sales prices.

Nonetheless, a scenario analysis will include alternative allocation approaches, such as

- mass allocation
- combination of stoichiometric (elemental) allocation regarding main upstream inputs ethylbenzene (allocated to styrene only) and propylene (allocated to propylene oxide only) and mass allocation regarding all other process burden

in order to show the sensitivity of the allocation decision with regards to the overall styrene environmental footprint (here expressed by the GWP and the total primary energy demand).

As shown in Table 1, depending on the allocation procedure adopted and taking the economic allocation as a base case, GWP results for average styrene might increase by 5% with mass allocation respectively by 9%, if allocating all ethylbenzene upstream to styrene only and neglecting any propylene input (which is processed to propylene oxide).

Similar observation can be made regarding the total (gross) primary energy demand with a potential increase of 4% (mass allocation) respectively 9% (stoichiometric allocation).

All in all, the application of alternative co-product allocation approaches in the POSM process would not change the LCA results of the average styrene relevantly, which is also due to the fact that POSM route is only accounted for about 40% in the average.

Table 1: LCA results for alternative allocation procedures per 1kg of average styrene

| Environmental Impact Category                          | Price allocation | Mass allocation | Stoichiometric allocation |
|--|------------------|-----------------|---------------------------|
| Global Warming Potential (GWP) [kg CO <sub>2</sub> eq] | 2.09             | 2.19            | 2.27                      |
| Gross primary energy from resources [MJ]               | 81.92            | 85.49           | 88.9                      |

In the refinery operations, co-production was addressed by applying allocation based on mass and net calorific value [SPHERA 2021]. 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 %.

## 2.13 LIFE CYCLE INVENTORY (LCI) RESULTS

### Delivery and Formats of LCI Dataset

This eco-profile comprises

- A dataset in ILCD/EF 3.0 format (.xml) (<http://lct.jrc.ec.europa.eu>) according to the last version at the date of publication of the eco-profile and including the reviewer (internal and external) input.
- A dataset in GaBi format (.GaBiDB)
- This report in pdf format.

### Energy Demand

The **primary energy demand** (system input) of 81.92 MJ/kg styrene 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 styrene** 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), is 42.2 MJ/kg styrene.

The difference ( $\Delta$ ) between primary energy input and energy content in the isocyanate output is a measure of **process energy** which may be either dissipated as waste heat or recovered for use within the system boundaries. Useful energy flows leaving the system boundaries were treated according to the cut-off approach (no credits associated to main product system).

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

| Primary Energy Demand   | Value [MJ]   |
|---|--------------|
| Energy content in polymer (energy recovery potential, quantified as gross calorific value of monomer) | 42.20        |
| Process energy (quantified as difference between primary energy demand and energy content of monomer) | 39.72        |
| <b>Total primary energy demand</b>  | <b>81.92</b> |

### Water cradle to gate Use and Consumption

The cradle-to-gate water **use** is 473.5 kg per 1 kg of styrene. The corresponding water **consumption** in the same system boundary is 7.8 kg.

### Water foreground (gate to gate) Use and Consumption

The following table shows the average values for water use of the average styrene production process (gate-to-gate level). For each of the typical water applications the water sources are shown:

Table 3 Water use and source per 1kg of Styrene

| 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        | 0.30               | 0.03               | 2.52             | 0.00                        | 2.85         |
| Untreated (from river/lake) | 0.00               | 17.02              | 0.00             | 0.00                        | 17.02        |
| Untreated (from sea)        | 0.00               | 0.00               | 0.00             | 0.00                        | 0.00         |
| Relooped                    | 0.00               | 0.00               | 0.00             | 0.00                        | 0.00         |
| <b>Totals</b>               | <b>0.30</b>        | <b>17.04</b>       | <b>2.52</b>      | <b>0.00</b>                 | <b>19.86</b> |

The following table shows the further handling/processing of the water output of the average production process of styrene:

Table 4 Treatment of Water Output per 1kg of styrene

| Treatment                    | Water Output [kg] |
|------------------------------|-------------------|
| To WWTP                      | 1.64              |
| Untreated (to river/lake)    | 16.97             |
| Untreated (to sea)           | 0.00              |
| Relooped                     | 0.99              |
| Water leaving with products  | 0.00              |
| Water Vapour                 | 0.26              |
| Formed in reaction (to WWTP) | 0.05              |
| <b>Totals</b>                | <b>19.91</b>      |

Based on the water use and output figures above the **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)

- Styrene = 0.21 kg

## Dominance Analysis

Table 5 shows a clear dominance of the main raw materials to the production of styrene, ethylbenzene (to both routes) and propylene (only to POSM). In every impact category considered they both together exceed the 50% limit.

With regards to GWP they almost amount to 70% contribution, followed by the thermal energy consumption which is also the second largest contributor to all other categories except Eutrophication, freshwater and Ozone depletion.

While Eutrophication shows relevant contribution from process waste (water) treatment, the ozone depletion potential is relevantly influenced by the consumed electricity and its related environmental burden caused in this impact category.

With regards to all other impact categories studied, electricity is only playing a minor role (not exceeding 5%).

The latter also goes for the consumption of utilities and process waste treatment

*Table 5 Dominance analysis of impacts per 1kg Styrene*

|                            | <b>Total<br/>Primary<br/>Energy</b> | <b>Resource<br/>use, energy<br/>carriers</b> | <b>Resource<br/>use,<br/>minerals<br/>and metals</b> | <b>Climate<br/>change,<br/>total</b> | <b>Acidi-<br/>fication</b> | <b>Eutro-<br/>pication,<br/>freshwater</b> | <b>Photo-<br/>chemical ozone<br/>formation</b> | <b>Ozone<br/>depletion</b> |
|----------------------------|-------------------------------------|--|--|--------------------------------------|----------------------------|--|--|----------------------------|
| Ethylbenzene               | 73%                                 | 74%  | 70%  | 61%                                  | 76%                        | 47%  | 77%  | 53%                        |
| Propylene                  | 7%                                  | 7%   | 7%   | 5%                                   | 7%                         | 4%   | 7%   | 6%                         |
| Other Chemicals            | 0%                                  | 0%   | 1%   | 0%                                   | 1%                         | 1%   | 0%   | 7%                         |
| Thermal Energy             | 13%                                 | 13%  | 14%  | 28%                                  | 11%                        | 6%   | 11%  | 5%                         |
| Electricity                | 2%                                  | 1%   | 3%   | 4%                                   | 4%                         | 2%   | 3%   | 28%                        |
| Utilities                  | 0%                                  | 0%   | 0%   | 0%                                   | 0%                         | 1%   | 0%   | 1%                         |
| Process Waste<br>Treatment | 5%                                  | 5%   | 5%   | 2%                                   | 2%                         | 38%  | 2%   | 1%                         |
| <b>Total</b>               | 100%                                | 100%   | 100%   | 100%                                 | 100%                       | 100%                                       | 100%   | 100%                       |

## Comparison of the present Eco-profile with its previous version

Table 6

Comparison of the present Eco-profile with its previous version for 1 kg of Styrene

|   | Previous<br>(2005) | New<br>(2021) | Difference<br>(%)  |
|---|--------------------|---------------|--|
| Environmental Impact Categories                         | Unknown LCIA Meth. | CML 2016      |  |
| Gross primary energy from resources [MJ]                | 82.6               | 81.92         | Results not directly comparable due to the application of different LCIA methodologies |
| Global Warming Potential (GWP) [kg CO <sub>2</sub> eq.] | 3.06               | 2.03          |  |

The previous styrene Eco-profile is from 2005 and based on primary data that is even older. As no information is given on certain methodological aspects and e.g. how (based on which impact model and characterization factors) the results stated above have been calculated, a direct comparison is not possible. Also, no further indicator results have been published at that time.

Nonetheless, as can be expected given the long time period in-between (and the related “greening” of electricity grid mixes over the years as well as increasing process efficiencies), an improvement can be observed which is plausible.

Whereas the total primary energy demand has lowered only slightly a relevant improvement with regards to the carbon footprint can be asserted.

### 3 EF 3.0 INDICATOR RESULTS

The following table shows the LCA results for 1 kg of average styrene when applying the EF3.0 impact assessment methodology.

Please note: when importing the delivered LCI dataset in ILCD/EF3.0 (.xml) format only these results can be recovered in the LCA software tool!

*Table 7 : LCA results for 1 kg of average Styrene applying EF3.0 impact assessment methodology*

| Indicator                                    | Unit                      | Styrene  |
|--|---------------------------|----------|
| Climate change, total                        | kg CO <sub>2</sub> eq.    | 2.09     |
| Climate Change, biogenic                     | kg CO <sub>2</sub> eq.    | 7.62E-03 |
| Climate Change, fossil                       | kg CO <sub>2</sub> eq.    | 2.09     |
| Climate Change, land use and land use change | kg CO <sub>2</sub> eq.    | 2.40E-04 |
| Ozone depletion                              | kg CFC-11 eq.             | 1.86E-15 |
| Acidification                                | Mole of H <sup>+</sup> eq | 3.29E-03 |
| Photochemical ozone formation                | kg NMVOC eq               | 4.02E-03 |
| Eutrophication, freshwater                   | kg P eq                   | 2.70E-06 |
| Eutrophication, marine                       | kg N eq.                  | 9.16E-04 |
| Eutrophication, terrestrial                  | Mole of N eq.             | 9.88E-03 |
| Respiratory Inorganics                       | Disease incidences        | 2.38E-08 |
| Ionising radiation, human health             | kBq U235 eq.              | 0.03     |
| Human toxicity, cancer – total               | CTUh                      | 8.16E-10 |
| Human toxicity, cancer inorganics            | CTUh                      | 4.82E-20 |
| Human toxicity, cancer metals                | CTUh                      | 6.91E-10 |
| Human toxicity, cancer organics              | CTUh                      | 1.25E-10 |
| Human toxicity, noncancer – total            | CTUh                      | 3.50E-08 |
| Human toxicity, noncancer inorganics         | CTUh                      | 6.35E-09 |
| Human toxicity, noncancer metals             | CTUh                      | 2.85E-08 |
| Human toxicity, noncancer organics           | CTUh                      | 4.56E-10 |
| Ecotoxicity, freshwater – total              | CTUe                      | 4.01E+02 |
| Ecotoxicity, freshwater inorganics           | CTUe                      | 3.31E+01 |
| Ecotoxicity, freshwater metals               | CTUe                      | 3.67E+02 |
| Ecotoxicity, freshwater organics             | CTUe                      | 2.85E-01 |
| Land Use                                     | Pt                        | 5.05E-01 |
| Resource use, energy carriers                | MJ                        | 74.78    |

|                                   |                             |          |
|-----------------------------------|-----------------------------|----------|
| Resource use, minerals and metals | kg Sb eq.                   | 2.11E-07 |
| Water scarcity                    | m <sup>3</sup> world equiv. | 2.26E-01 |



## 4 REVIEW

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### 4.1 REVIEW DETAILS

|                  |   |
|------------------|---|
| Commissioned by: | PlasticsEurope  |
| Prepared by:     | Yannick Bernard<br>Sphera Solutions GmbH  |
| Reviewed by:     | Matthias Schulz<br>Schulz Sustainability Consulting   |
| References:      | <ul style="list-style-type: none"><li>• PlasticsEurope (2019): Eco-profiles program and methodology –PlasticsEurope – V3.0 (2019).</li><li>• ISO 14040 (2018): Environmental Management – Life Cycle Assessment – Principles and Framework</li><li>• ISO 14044 (2018): Environmental Management – Life Cycle Assessment – Requirements and Guidelines</li></ul> |

### 4.2 REVIEW STATEMENT

According to the PlasticsEurope methodology version 3.0 (2019), a critical review of the Eco-profile report by independent experts should be conducted before publication of the dataset. The outcome of the critical review is reproduced below.

The subject of this critical review was the development of the Eco-profile for styrene.

The critical review included two iterations of final Eco-profile report review (January and February 2022) in which the reviewer provided comments for clarification by the LCA practitioner. On 11.02.2022, a web-based review meeting was held in which open issues were discussed and spot checks of data, modelling and calculations were carried out. The final version of the report was provided to the reviewer on 13.02.2022. The reviewer checked the implementation of the comments and agreed to conclude the critical review process. The reviewer acknowledges the unrestricted access to all requested information, the dedicated efforts of the practitioner to address comments, as well as the open and constructive dialogue during the entire critical review process. All versions of the documentation (reports and data), including the reviewer's comments, questions and associated answers, are archived and can be made available upon request.

Primary data was collected for 3 styrene plants, 2 producing styrene via the EBSM and one via POSM route. The primary data was used to validate existing background datasets for both routes. This validation process was explained to the reviewer during the review meeting, and the reviewer found the respective procedure to be appropriate and valid.

Representativeness purely based on collected primary data is 37% of the 2018 European production volume of styrene. Due to the fact that both routes can be considered to be based on established technology, it is assumed that the representativeness of the resulting Eco-profile dataset for styrene is significantly higher.

The mix of both dominant production routes for styrene was considered in this Eco-profile, i.e. via dehydrogenation of ethylbenzene (EBSM) and via the propylene oxide styrene monomer (POSM) process which involves the co-production of propylene oxide. The assumed split of both production routes was 60:40 (EBSM : POSM) which is based on literature data and industry expert judgement.

Allocation is relevant for styrene produced via the POSM route. As a base case economic allocation was applied which corresponds with the approach taken for another relevant Eco-profile (ISOPA 2021) in which propylene oxide is consumed in the polyols upstream value chain. The allocation approach is suitably justified in the report. In addition, two sensitivity analyses were performed investigating the potential environmental impacts for styrene if mass or stoichiometric/elemental allocation were applied. Relevant results are discussed and evaluated in the report.

All background datasets used for this Eco-profile are described in the report and are considered appropriate for the goal and scope of this study. For example, benzene is a key precursor of styrene and its specific production routes were modelled according to recent Petrochem (2019) data. All background datasets including benzene stem from the GaBi database. Due to the fact that little primary data from individual styrene production plants were available, background data with a European geographical scope were chosen.

The reviewer carried out various plausibility checks of the data and results. In the end, all raised questions were clarified, and the reviewer found the data to be credible and without perceivable errors or shortcomings.

The potential environmental impacts for styrene are quantified using the EF v3.0 methodology, as recommended in the current PlasticsEurope methodology. The contribution analysis shows the predominant influence of key precursor materials, i.e. ethylbenzene and propylene for the majority of environmental indicators.

Since the last Eco-profile for styrene is very old (published in 2005, based on data from 1999) and methodological aspects are unknown, a comparison of results with this Eco-profile are not possible. Nevertheless, primary energy and carbon footprint results are provided in the report.

The LCA practitioner has demonstrated high levels of 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 methodology version 3.0 (2019) and represents best available data for styrene production in Europe.

## 5 REFERENCES

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