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

# Vinyl chloride (VCM) and Polyvinyl chloride (PVC) PlasticsEurope / The European Council of Vinyl Manufacturers (ECVM)

December 2022
Water update March 2023
Revised June 2023

# Environmental Product Declaration

## Introduction

This Environmental Product Declaration (EPD) is based upon life cycle inventory (LCI) data from PlasticsEurope's Eco-profile programme. It has been prepared according to **Eco-profiles program and methodology – PlasticsEurope – V3.1 (2021)** (PlasticsEurope 2021a).

EPDs provide environmental performance data, but no information on the economic and social aspects which would be necessary for a complete sustainability assessment. Further, they do not imply a value judgment between environmental criteria.

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

## Meta Data

| | |
|---|---|
| Data Owner | PlasticsEurope, ECVM |
| LCA Practitioner | ifeu Heidelberg GmbH, Germany |
| Programme Owner | PlasticsEurope, ECVM |
| Reviewer | Matthias Schulz<br>Schulz Sustainability Consulting |
| Number of plants included in data collection | 39 |
| Representativeness | VCM 68%<br>S-PVC 73% - E-PVC 81% |
| Reference year | 2021 |
| Year of data collection and calculation | 2022 |
| Expected temporal validity | 2026 |
| Cut-offs | none |
| Data Quality | Overall good quality (DQ rating 2, Confirmed by assessment of each single DQ indicator) |
| Allocation method | physical and economic |

## Description of the Product and the Production Process

This Eco-profile and EPD represents the average industrial production of both vinyl chloride monomer (VCM) and polyvinyl chloride (PVC) from cradle to gate. The Eco-profile treats the two main production processes for PVC separately: S-PVC from suspension polymerisation and E-PVC from emulsion polymerisation.

### Production Process

Polyvinyl chloride (PVC) is manufactured by polymerisation of vinyl chloride monomer (VCM), which in Europe is produced by the thermal cracking of ethylene dichloride (EDC).

In Europe (EU27+NO+CH+UK), most ethylene used in the manufacture of EDC is produced by steam cracking of naphtha. Chlorine is produced by electrolysis of sodium chloride (NaCl) according to the latest EuroChlor Eco-profile.

The model of this Eco-profile includes the refinery of crude oil for the ethylene production as well as production of EDC and the final polymerisation of VCM into PVC. The model of the polymer production process represents the major commercial PVC production technologies, which are suspension process (S-PVC) and emulsion process (E-PVC).

Impacts related to abnormal process conditions (e.g. accidents) are not considered in this study.

### Data Sources and Allocation

Ethylene production is modelled based on the reviewed but presently unpublished Eco-profile and EPD for ethylene and steam cracker products of PlasticsEurope (PlasticsEurope 2021d), and chlorine production is based on the Eco-profile and EPD for chlorine (EuroChlor 2022). For the production of those raw materials all upstream processes until raw material extraction were considered.

The production of the precursor ethylene dichloride (EDC), of the monomer vinyl chloride (VCM) and the polymer production processes themselves are based on confidential process and emission data collected from participating production sites (primary data).

Country-specific electricity mixes are used for grid electricity supply. On-site production of electricity and steam is partially modelled using primary data from the polymer producers; data gaps in on-site energy production are closed using European average data of power plants and steam boilers.

Representative literature data is used to fill gaps wherever primary data is unavailable, and in order to cross-check primary data. Allocation within the foreground system is intended to be avoided; where necessary, processes are allocated by physical properties, such as mass, exergy or enthalpy. Products with different economic values are allocated using the known relative prices (see Eco-profile for details).

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

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

## Environmental Performance

The tables below show the environmental performance indicators associated with the production of 1 kg of VCM and each PVC type.

**Input Parameters**

| Indicator | Unit | Vinyl chloride (VCM) | Suspension PVC (S-PVC) | Emulsion PVC (E-PVC) |
|---|---|---|---|---|
| Non-renewable energy resources (UHV) | MJ | 50.5 | 56.1 | 59.0 |
| Renewable energy resources (UHV) | MJ | 1.45 | 1.75 | 2.10 |
| Resource Use (or Abiotic Depletion Potential) | | | | |
| Elements (minerals and metals) | kg Sb eq. | 3.9E-06 | 4.7E-06 | 5.4E-06 |
| Fossil fuels | MJ | 48.0 | 53.3 | 56.4 |
| Water use | kg | 161.3 | 175.6 | 244.7 |
| for process | kg | 22.0 | 31.2 | 43.6 |
| for cooling | kg | 139.3 | 144.4 | 201.1 |
| Water consumption (w/o sea water) | kg | 47.1 | 42.1 | 86.3 |
| for process | kg | 19.3 | 24.8 | 36.8 |
| for cooling | kg | 27.8 | 17.4 | 49.5 |

**Output Parameters, LCIA Results**

| Impact Category | Unit | Vinyl chloride (VCM) | Suspension PVC (S-PVC) | Emulsion PVC (E-PVC) |
|---|---|---|---|---|
| Climate change | kg $CO_2$ eq. | 1.72 | 2.03 | 2.18 |
| Acidification | mol $H^+$ eq. | 8.7E-03 | 9.7E-03 | 1.1E-02 |
| Eutrophication, freshwater | kg P eq. | 4.3E-04 | 5.0E-04 | 6.4E-04 |
| Eutrophication marine | kg N eq. | 1.1E-03 | 1.3E-03 | 1.4E-03 |
| Eutrophication, terrestrial | mol N eq. | 1.2E-02 | 1.4E-02 | 1.9E-02 |
| Ozone depletion | kg CFC-11 eq. | 1.4E-06 | 1.6E-06 | 1.1E-06 |
| Photochemical ozone formation | kg NMVOC eq. | 4.9E-03 | 5.5E-03 | 5.6E-03 |
| Particulate Matter | disease incidents | 3.6E-08 | 4.2E-08 | 5.6E-08 |
| Human toxicity, cancer | CTUh | 4.9E-09 | 5.0E-09 | 5.7E-09 |
| Human toxicity, non-cancer | CTUh | 1.4E-08 | 1.5E-08 | 1.7E-08 |
| Ecotoxicity, freshwater | CTUe | 43.0 | 46.8 | 48.0 |
| Ionising radiation | kg U235 eq. | 2.1E-01 | 2.5E-01 | 3.0E-01 |
| Water use | $m^3$ world eq. | 2.02 | 1.81 | 3.71 |
| Land Use | - | 4.72 | 5.18 | 5.79 |

An evaluation of how the results have changed in comparison to the previous Eco-profile can be found in the main report (p. 42ff.).

## Additional Environmental and Health Information – PVC

Like many other materials, the manufacture of PVC involves the use of some hazardous chemicals. Such manufacturing processes are very tightly regulated and the risks are adequately controlled. Regulations are completed since the 1990s by voluntary commitments (ECVM Charters). PVC is probably the world's most researched plastic/polymer.

A substantial volume of research and over 50 years of experience support the fact that PVC can be safely used even in the most sensitive of applications (such as medical devices).

PVC is one of the most recyclable of polymers but can be disposed of, if required, quite safely.

Building upon the achievements of the VinylPlus sustainability programme, the European PVC industry launched VinylPlus 2030 in 2021, the new ten-year voluntary commitment of the European PVC industry. It addresses three sustainability pathways, including Scaling up PVC Value Chain Circularity, Advancing towards Carbon Neutrality and Minimising our Environmental Footprint and Building Global Coalitions and Partnering for the SDGs (more information can be found here[1]). Recycling and more generally end-of-life treatment of PVC is described in the "PVC recycling technologies brochure available for download from (VinylPlus 2017). Due to the low thermal stability of PVC, heat stabilisers have to be added. Furthermore, plasticisers are necessary to ensure the flexibility required by some applications. To meet the product requirements various further substances are added to the PVC resin (more information can be found here[2]).

The current Eco-profile includes only those additives which are used and added within the declared boundaries of the model system. Further additives that may be applied during later processing are thus not considered within the current study.

[1] https://www.vinylplus.eu/about-us/vinylplus-2030-commitment/

[2] https://pvc.org/

## Additional Technical Information – PVC

The chemistry of PVC has been understood since the end of the last century. PVC was first commercially produced in Europe in the 1930´s and has since then undergone continuous development and improvement. PVC's adaptability comes from its molecular structure. This makes possible many different blends of ingredients providing a range of properties, enabling the PVC industry to respond to the commercial and technical needs of many market sectors.

PVC can be found in an extremely wide range of applications whether transparent or pigmented, such as construction products like window frames, pipes and facade elements, or as products for mechanical or electrical engineering like cable insulation. PVC also has applications in food packaging or consumer goods.

PVC products are characterised by low natural flammability and high chemical and biological inertness.

## Additional Economic Information

Together with polyolefins, PVC is one of the economically most prominent thermoplastics. The PVC production in Europe sums up to about 5 million tons/year.

The production volumes of PVC have been slightly decreasing within Europe in recent years due to a depression of the construction sector in the Covid pandemic; from a global point of view, however, demand and production of PVC are still growing.

## Information

**Data Owner**

**The European Council of Vinyl Manufacturers (ECVM); PVC sector group of PlasticsEurope**

Avenue de Cortenbergh 71

B-1000 Brussels, Belgium

Tel.: +32 (2) 329 51 03

E-mail: info@pvc.org.

**LCA practitioner**

ifeu - Institute for Energy and Environmental Research

Wilckensstr. 3, D-69120 Heidelberg

Tel.: +49 (0) 6221 4767 0

E-mail: ifeu@ifeu.de

**Reviewer**

**Matthias Schulz**

Schulz Sustainability Consulting

Baldernstr. 2, D-70469 Stuttgart

E-mail: matthias@schulz-sustainability-consulting.de

**Programme Owner**

**PlasticsEurope AISBL**

Rue Belliard 40, Box 16

B-1040 Brussels, Belgium

Tel.: +32 (0)2 792 30 99

E-mail: info@plasticseurope.org

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

**References**


- EuroChlor (2022): An Eco-profile and Environmental Product Declaration of the European Chlor-Alkali Industry. Chlorine (The Chlor-Alkali Process). Euro Chlor. https://www.eurochlor.org/wp-content/uploads/2022/02/2022-Euro-Chlor-Eco-profile.pdf (26.09.2022).
- PlasticsEurope (2021a): Eco-profiles program and methodology, version 3.1 (September 2021) https://plasticseurope.org/wp-content/uploads/2022/11/Ecoprofiles-Methodology-V3.1.zip
- PlasticsEurope (2021d): Eco-profile of Steam Cracker Products: Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), Ethylene Glycols (MEG, DEG, TEG), not yet published.

# Eco-profile Report

## Functional Unit and Declared Unit

The Functional Unit and Declared Unit of this PlasticsEurope Eco-profile and EPD are:

- *1 kg of vinyl chloride (VCM),*
- *1 kg of polyvinyl chloride from suspension polymerisation (S-PVC) and*
- *1 kg of polyvinyl chloride from emulsion polymerisation (E-PVC).*

Each product »at gate« (production site output), representing a European industry production average.

## Product Description

The products considered in this Eco-profile and EPD are vinyl chloride (VCM), polyvinyl chloride from suspension polymerisation process (S-PVC) and polyvinyl chloride from emulsion polymerisation process (E-PVC). This Eco-profile represents the average European industrial production of each product. Main characteristics of the products under investigation are presented in Table 1. Hence, it is not attributed to any single producer, but rather to the European PVC industry, which is represented by ECVM.

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

| Common name | IUPAC name | CAS no. | Chemical formula | Density g/cm$^3$ | Melting Point | Gross calorific value MJ/kg[b)] |
|---|---|---|---|---|---|---|
| Vinyl chloride | Chloroethene | 75-01-4 | $C_2H_3Cl$ | 0.003 | -154°C | 17.5[a)] |
| Polyvinyl chloride | Poly(1-chloroethene) | 9002-86-2 | $(C_2H_3Cl)_n$ | 1.38-1.40 | > 180°C | 20.0[b)] |

[a)] calculated using the heats of formation of the reactants („NIST" 2022)
[b)] communications with ECVM, value for PVC resin

Vinyl chloride (VCM) is a colourless, toxic, flammable, and carcinogenic gas with a sweet odour. It is almost exclusively used for the production of polyvinyl chloride.

Polyvinyl chloride (PVC) is one of the most important commodity polymers. After polyethylene (PE) and polypropylene (PP), polyvinyl chloride (PVC) is among the top 3 resin types. European (EU27+NO+CH+UK) demand has a share of 9.6 % on the polymer market (PlasticsEurope 2021b). In the years 2019 – 2020 the European demand of polyvinyl chloride is indicated with about 4.7 – 5 Mt/year (PlasticsEurope 2021b).

The main application for PVC is in the building and construction sector (see Figure 1). The applied products include window frames, pipes and fittings, other profiles, e.g. rolling shutters as well as flooring, roofing, electrical insulation etc.  Furthermore, PVC is used for packaging products like blisters or films, and for other products such as toys, signs, or credit cards (PlasticsEurope 2021b).

The applications for S-PVC and E-PVC differ due to different material characteristics. S-PVC is better suited for the large volume production of a limited number of grades. Thus, S-PVC is the general-purpose grade and is used for most rigid PVC applications such as pipes, profiles, other building materials and hard foils. It is also plasticised and used for flexible applications such as cable insulation, soft foils and medical products. A number of specific applications require E-PVC or gain advantages from the use of E-PVC. It is primarily used for coating applications such as PVC coated fabrics. Due to the different applications it is necessary to produce an adequate proportion of PVC via the emulsion process in order to supply specific markets for which E-PVC is technically more suitable than S-PVC.

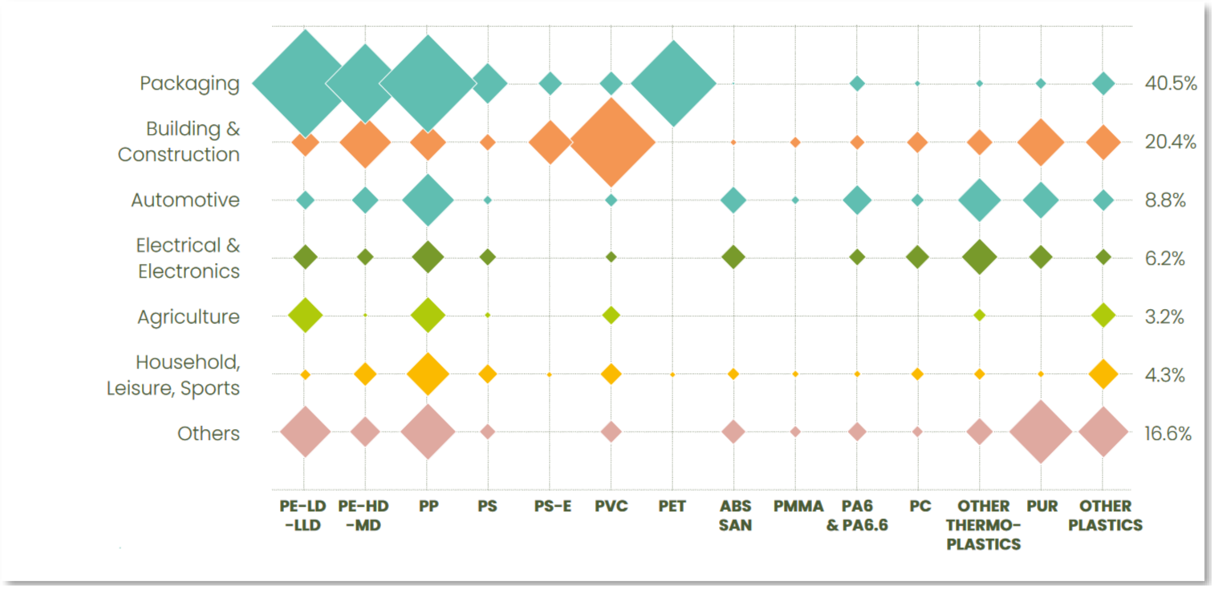


*Figure 1: European (EU27+3) plastics demand by segment and resin type 2020 (Total 49.1 Mt). Source: PlasticsEurope Market Research Group (PEMRG) and Conversio Market & Strategy GmbH. Quoted from: (PlasticsEurope 2021b)*

Polyvinyl chloride is a chlorinated hydrocarbon polymer, based on the raw materials chloride and ethylene. PVC is mainly produced as a homopolymer. About 90 % of the PVC consumed worldwide is polymerised using the suspension process. The structure of polyvinyl chloride is shown in Figure 2.

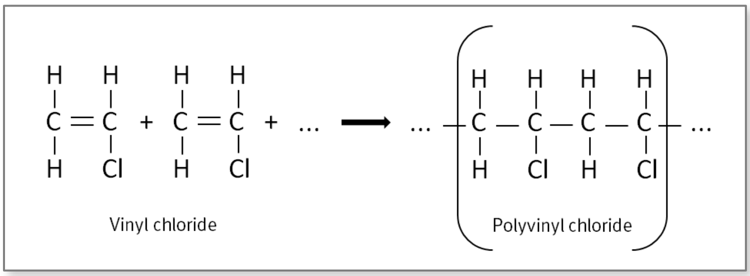


*Figure 2: Polymerisation of vinyl chloride yields polyvinyl chloride*

PVC, especially when produced by suspension process, is a very pure product with e.g. high stiffness and toughness, low natural flammability and with chemical and biological inertness. PVC, however, is never used in its pure form. To make the processing of the resin possible and to meet later product requirements, it is always mixed with heat stabilisers and lubricants, and sometimes with plasticisers, fillers and other additives.

## Manufacturing Description

(Fischer et al. 2014; LVOC BREF 2017)

Polyvinyl chloride (PVC) is manufactured by polymerisation of vinyl chloride monomer (VCM), which is produced by the thermal cracking of ethylene dichloride (EDC). In Europe (EU27+NO+CH+UK) most of the ethylene used in the manufacture of ethylene dichloride is produced by steam cracking of naphtha. The chlorine is derived from common salt (NaCl) by electrolysis.

For a technological description of the raw materials ethylene and chlorine please refer to the corresponding EPDs and Eco-profiles, in particular the Eco-profile and EPD of steam cracker products (ethylene, presently awaiting publication by PlasticsEurope), and the Eco-profile and EPD for chlorine (chlor-alkali process) (EuroChlor 2022). The manufacturing of the precursors EDC and VCM will be described in the following section.

**Production of ethylene dichloride (EDC) and vinyl chloride monomer (VCM)**

EDC, also known as 1,2-dichloroethane, is the precursor of VCM. It is mainly used for the purpose of VCM production, which is schematically illustrated in Figure 3. Originally, VCM was produced by the gas-phase hydrochlorination of acetylene (ethyne) with hydrochloric acid (HCl) over a mercuric chloride-based catalyst. Due to the high cost of acetylene and the emergence of large steam-crackers providing abundant ethylene the acetylene route has been replaced by chlorination of ethylene within the European industrial EDC production. Today, the original acetylene route is still widely used in Chinese production due to the availability of coal as a feedstock for acetylene production from calcium carbide.

The chlorination of ethylene can either be carried out by using chlorine (direct chlorination) or by using hydrogen chloride and oxygen (oxychlorination). Thermal cracking of dry, pure EDC then produces VCM and HCl. When all the HCl generated in EDC cracking is re-used in an oxychlorination section, and when no EDC or HCl is imported or exported, then the VCM unit is called a ‘balanced unit’. By using both, direct chlorination and oxychlorination, for EDC production, balanced units achieve a high level of chlorine utilisation without producing HCl as a by-product. Assuming a complete incorporation of chlorine input into EDC within a balanced unit, half of the produced EDC originates from each of the applied processes, direct chlorination and oxychlorination.

Additionally, the heat gain from both highly exothermic chlorination processes may be used in the associated VCM production, optimising the overall energy demand of the EDC/VCM/PVC production.

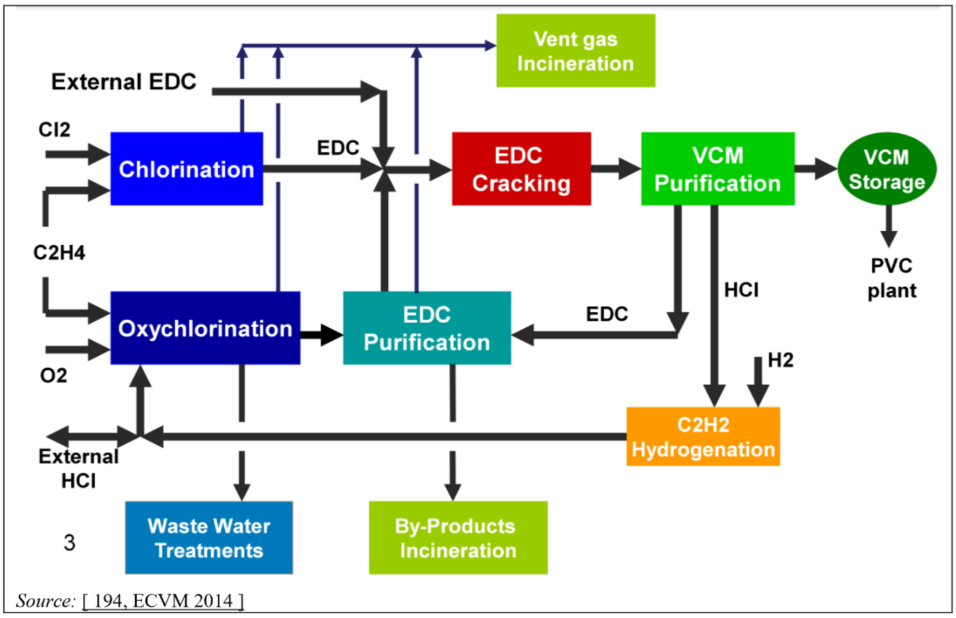


*Figure 3: Flow diagram of EDC and VCM manufacturing process (taken from LVOC BREF 2017)*

The reactions are represented by the formulae:

Direct chlorination: $C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (EDC)}$ ; $\Delta H_{R,0} = -220 \text{ kJ/mol}$

Cracking: $C_2H_4Cl_2 \rightarrow C_2H_3Cl \text{ (VCM)} + HCl$ ; $\Delta H_{R,0} = +\ 97 \text{ kJ/mol}$

Oxychlorination: $C_2H_4 + \frac{1}{2}\, O_2 + 2\ HCl \rightarrow C_2H_4Cl_2 \text{ (EDC)} + H_2O$ ; $\Delta H_{R,0} = -320 \text{ kJ/mol}$

For the production of EDC in a balanced unit the raw material requirement comprises ethylene and chlorine, which are generally supplied by pipeline from nearby production facilities. Chlorine and EDC production sites are often found in close proximity in order to reduce chlorine transportation distances to the EDC process, the single largest chlorine consumer.

**Polymerisation**

Polyvinyl chloride (PVC) is manufactured by polymerisation of vinyl chloride monomer (VCM). In the past, three main polymerisation processes were used for the commercial production of PVC: suspension polymerisation, yielding the majority of the global production, emulsion polymerisation with about a 10$^{th}$ of the production volume and mass or bulk polymerisation with only a few percent. This Eco-profile is omitting bulk polymerisation PVC due to its low significance. Accordingly, PVC processed by suspension polymerisation (S-PVC) and emulsion polymerisation (E-PVC) are analysed within the scope of this Eco-profile.

Polymerisation of PVC is an exothermic reaction. The pressure in the reactor is usually in the range of 0.4 – 1.2 MPa and the reaction temperature is between 35 – 70 °C. During the polymerisation reaction 85 – 97 % of the VCM is converted into PVC. Residual VCM is removed by stripping the polymer suspension or latex. The unreacted monomer is recovered, liquefied, and returned to polymerisation.

For the polymerisation process certain process chemicals are required. Surfactants, emulsifiers and protective colloids are used to prepare and stabilize the dispersion of monomer and PVC in process water (typically around 1 kg/t VCM in suspension and around 10 – 20 kg/t in emulsion). Organic peroxides or peresters are used as initiators (typically < 1 kg/t VCM) for the production of suspension and micro-suspension PVC, while e.g. hindered phenols are used to stop the reaction (typically < 1 kg/t VCM). For the production of emulsion PVC inorganic peroxides are common.

PVC suspension or latex can be concentrated before drying. For PVC suspension this is usually achieved by dewatering via centrifugation. The PVC is then dried using a combination of temperature and airflow in dryers of various designs. E-PVC is usually spray dried.

## Producer Description

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

- *Cires, Shin-Etsu Group (Companhia Industrial de Resinas Sintéticas, Cires, LDA)*
- *ERCROS, SA*
- *INOVYN EUROPE Ltd.*
- *Shin-Etsu Chemical Co., Ltd.*
- *VESTOLIT GmbH*
- *Vinnolit GmbH & Co. KG*
- *VYNOVA Group NV*

Data was collected from the European vinyl chloride and polyvinyl chloride production units of the above-mentioned companies. The data collection aimed at information on all energy and material inputs and outputs of the production of ethylene dichloride (EDC), vinyl chloride monomer (VCM) and polyvinyl chloride (PVC). Data for S-PVC and E-PVC as well as EDC/VCM were requested separately. In addition to production input and output information, the requested data also included information on distances and means of transportation of each material input, emissions to air and water, and the type, amount, destination, and transport distances of wastes produced inside the system boundaries. Furthermore, the same sets of data were collected regarding the on-site production of electricity and steam by either power plants or steam, delivering energy directly (i.e. not via the national electricity grid) to the polyvinyl chloride production unit. Total amounts for one year (the reference year 2021) were requested from a number of ECVM plants volunteering for this data collection; these plants were found to exhibit significant changes; for plants with no significant changes the latest available primary data were used: data from the previous Eco-profile (2013 data) were used wherever more recent information was not available; a small group of plants is represented by data from 2017 – 2020, since the practitioner has gained confidential and more recent information on these plants during other projects, exhibiting the same data quality and system boundaries as required for the present Eco-profile.

## System Boundaries

This Eco-profile refers to the production of VCM (polymer precursor) and S-PVC and E-PVC (polymer) and is based on a cradle-to-gate system (see Figure 4).

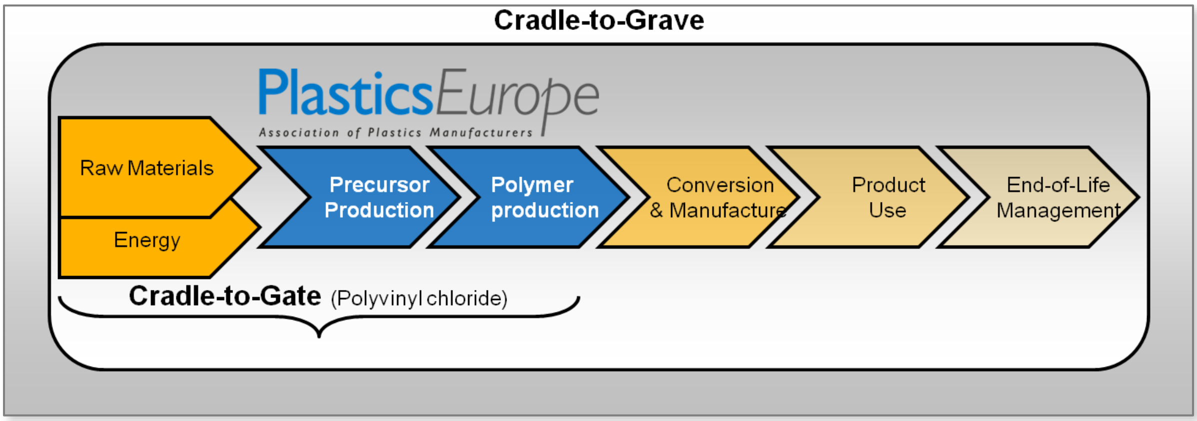


*Figure 4: Cradle-to-gate system boundaries for the production of polyvinyl chloride (PVC)*

**Cradle-to-Gate System Boundaries for Production**

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

- Extraction of non-renewable resources (e.g. of oil and natural gas)
- Growing and harvesting of renewable resources (e.g. biomass production)
- Beneficiation or refining, transfer and storage of extracted or harvested resources into feedstock for production;
- Recycling of production waste or secondary materials for use in production
- Converting of non-renewable or renewable resources or waste into energy
- Production processes
- All relevant transportation processes (transport of materials, fuels and intermediate products at all stages)
- Management of production waste streams and related emissions generated by processes within the system boundaries.

According to the methodology of Eco-profiles (PlasticsEurope 2021a) capital goods, i.e. the construction of plants and equipment as well as the maintenance of plants, vehicles, and machinery is outside the LCI system boundaries. The end-of-life treatment of PVC and its consecutive products is also outside the LCI system boundaries of this Eco-profile. Inputs and outputs of secondary materials and wastes for recovery (e.g. used catalysts for recycling) are noted as crossing the system boundaries without environmental burdens. An exception is low-radioactive waste from electricity generation for which a final storage has not been found yet; it is declared as output.

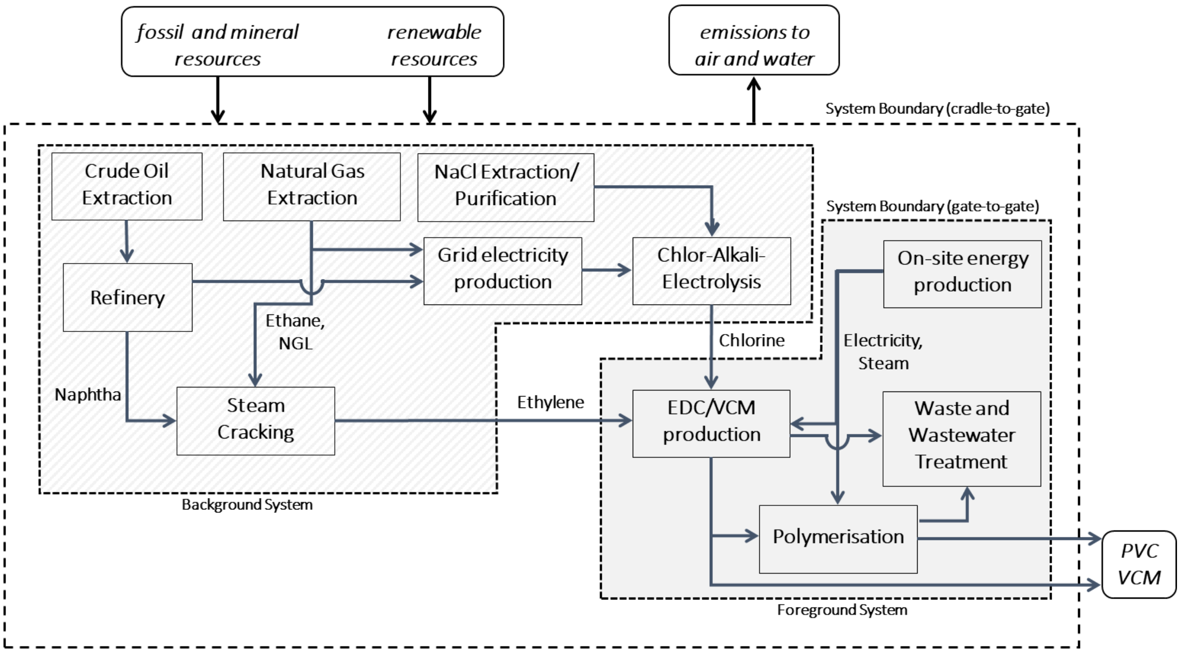


*Figure 5: Flowchart of PVC production with the most important background and foreground processes, indicating the cradle-to-gate system boundaries and gate-to-gate system boundaries (the latter referring to processes under direct control of ECVM).*

## Technological Reference

The production processes were modelled using specific values from primary data collection at site, representing the specific technology for the precursor and polymer production of the companies. The LCI data represent the production mix of technologies in use in the defined production region employed by participating producers. For the on-site energy supply, primary data were collected as well.

Primary data were used for all foreground processes (under operational control of ECVM members) as well as for the provision of on-site-energy.

The Eco-profile participants cover **73 %** of S-PVC producers and **81 %** of E-PVC producers in Europe in 2021 (with respect to the installed nameplate capacity of all European producers, Source: communications with PlasticsEurope, 2022), so the technological coverage is understood as fairly representative. The coverage with respect to VCM production comprises **68 %** of the sum of nameplate capacities of European plants. Additionally, the Eco-profile includes one pure EDC producing plant. The coverage with respect to EDC production is difficult to access, though, since EDC is also exported from combined EDC/VCM plants in varying amounts. Please refer to Table 2 for an overview of the nameplate capacity sum of all participating plants compared to reported production of EDC/VCM and S-/E-PVC in the reporting years 2013 to 2021.

*Table 2: Participating VCM and PVC production units: nameplate capacity vs. reported production.*

| | Nameplate capacity[1)] sum in kt | Reported production sum in kt | Production / Nameplate capacity % |
|---|---|---|---|
| **S-PVC** | 4,100 | 3,706 | 90% |
| **E-PVC** | 690 | 607 | 88% |
| **VCM** | 4,705 | 4,053 | 86% |

From the total number of 59 EDC, VCM and PVC producing plants in Europe 39 volunteered to take part in this study, constituting the ECVM member plants. 9 of these plants were requested to provide new complete primary data of 2021 production processes for this Eco-profile, while the other plants did not undergo major changes and were modelled considering data from previous Eco-profiles, i.e. (PlasticsEurope 2016), assuming the present production process data to be still valid. This Eco-profile relies on complete data sets for the ethylene dichloride (EDC) and vinyl chloride monomer (VCM) production from 13 plants, and for polyvinyl chloride (PVC) production from 26 plants. Of these PVC producing plants, 17 were producing suspension polyvinyl chloride (S-PVC) and 9 emulsion polyvinyl chloride (E-PVC).

Relating to the individual products (EDC, VCM and PVC), the data coverage in relation to the European nameplate capacity can be differentiated as shown in Table 3.

*Table 3: Selected and participating PVC production units and their share in European ethylene dichloride, vinyl chloride monomer and polyvinyl chloride production capacity (nameplate capacity):*

| | Participating units data from 2013 to 2021 | Participating units providing data for 2021 | Coverage of production by nameplate capacity[1)] |
|---|---|---|---|
| **S-PVC** | 17 | 5 | 73% |
| **E-PVC** | 9 | 1 | 81% |
| **VCM** | 12 | 3 | 68% |
| **EDC** | 1 | 0 | n.a. |

[1)] Based on total installed European nameplate capacity; Source: communications with PlasticsEurope, 2022

The data quality rating is considered as good (2), because the technology mix is subject to market equilibrium which is reasonably stable within the expected temporal validity.

According to the PlasticsEurope LCI methodology and product category rules inputs of secondary materials (recyclate) and outputs of waste for recovery or disposal shall be noted as crossing the system boundaries. While there is no input of recyclates at all, outputs of wastes for recovery or disposal only contribute very little to the total proceedings under consideration in this Eco-profile. The following list shows the waste streams of the VCM and PVC production processes and their treatment (total amount of waste: 1.0 % related to feedstock input).

*Table 4: Waste produced per kg product (foreground process) and treatment*

| | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| Hazardous waste to Landfill | kg | 1.89E-04 | 4.95E-05 | - |
| Hazardous waste to Recovery | kg | 2.21E-03 | 3.11E-05 | 5.54E-05 |
| Hazardous waste to Incineration | kg | 9.30E-03 | 9.45E-05 | 3.67E-04 |
| Hazardous waste to Others | kg | - | 1.56E-06 | 7.56E-06 |
| Non-hazardous waste to Landfill | kg | 1.36E-04 | 9.07E-04 | 2.12E-03 |
| Non-hazardous waste to Recovery | kg | 6.85E-05 | 4.50E-04 | 5.79E-04 |
| Non-hazardous waste to Incineration | kg | 1.91E-05 | 1.65E-04 | 5.80E-04 |
| Non-hazardous waste to Others | kg | - | 9.20E-06 | 3.49E-05 |

## Temporal Reference

The LCI data for this Eco-profile represents the most recent available data and therefore represents the average technology in Europe. Data for EDC, VCM and PVC production was collected during the last Eco-profile and refers to the production year 2013. For the present Eco-profile, primary data were collected from 9 plants identified by ECVM, which exhibit major changes in production or energy supply since 2013. A small group of plants is represented by data from 2017 – 2020, since the practitioner has gained confidential and more recent information on these plants during other projects – the data could be used, since quality and system boundaries were identical to those required for the present Eco-profile. In spite of its age, the data is considered to be still valid, since – due to the high investment costs for production facilities – only small changes are expected at those plants not identified for new data collection.

The overall reference year for this Eco-profile is 2021 with a maximum temporal validity until 2026. It seems adequate to refer to the 5-year interval that is proposed in the product category rules for polymers (PlasticsEurope 2021a).

The data quality rating is considered fair (3) because production data is up to 8 years older than the reference year but was considered still valid by ECVM and its member companies. Data from the year 2021 were collected where the data quality was considered as not sufficient.

## Geographical Reference

This Eco-profile refers to the average production of PVC in Europe (EU27+NO+CH+UK) with a total coverage of 68 % of installed production capacity for VCM, 73 % for S-PVC and 81 % for E-PVC. For 8 of the considered countries – Belgium, Germany, Netherlands, Norway, Portugal, Sweden, Spain, UK – the overall data coverage is 100 % or close to 100 % (related to production capacity of the participating companies). For 4 countries – Czech Republic, Hungary, Poland, Slovakia – the data coverage is 0 %, since the respective production sites were not participating in the Eco-profile. France exhibits a coverage rate of around 50 %. In total, the geographical coverage is biased towards the production from western European sites: 32 % of total European VCM production, 27 % of S-PVC production, and 19 % of E-PVC production are missing in the production quantities covered in the present ECVM Eco-profile, mainly from eastern European production sites in Czech Republic, Hungary, Poland, Slovakia as well as France.

The data quality rating is considered good (2) because the covered set of plants represents a major portion of the European VCM and PVC production, though biased towards western Europe, where ECVM membership is more established.

## Cut-off Rules

To achieve completeness, i.e. a closed mass and energy balance, any cut-off of material and energy flows have been avoided in this Eco-profile. For commodities with an input < 1 wt.-% of the total material input (additives, other compounds, etc.) generic datasets from the LCA database ecoinvent v3.8 (Wernet et al. 2016) were used. In ecoinvent datasets, waste for recycling is generally cut off. Furthermore, expenses for capital equipment were not considered in this Eco-profile.

Simplified generic processes are assumed for catalysts and a few commodities (input < 0.1 wt.-% of the precursor's output) with missing secondary production data. The process input/output relation has been determined by reaction equations from literature. The upstream production of the used metals (antimony, cobalt, manganese and palladium) and chemicals are implemented using ecoinvent v3.8 data (Wernet et al. 2016) . Thus, the potential environmental relevant metal extraction and refinement processes are included in the LCI data.

## Data Quality Requirements

**Data Sources**

The LCI data used in this Eco-profile and EPD is representative of the production processes of VCM and PVC in Europe, both in terms of technology and market share. Average data representative of the respective foreground production process, both in terms of technology and market share, are used. Foreground processes comprise the production units for EDC, VCM, S-PVC and E-PVC, including water treatment and on-site energy production as part of the respective site. The primary data for the production units and the on-site energy were collected from the participating member companies (see Producer Description).

Data concerning the production of chlorine are taken from the most recent Euro Chlor Eco-profile (Chlor-alkali process) (EuroChlor 2022) of which the full dataset is known to the LCA practitioner.

Concerning HCl input, the same data as for chlorine was used. This procedure is in line with the previous version of this Eco-profile (PlasticsEurope 2016) and is based on the conservative assumption that one molecule HCl carries half the load of a $Cl_2$ molecule. The conservative assumption is chosen over the assessment of specific HCl production information, which states that a majority (> 85 %) of the imported HCl originates from MDI production (corresponding to 20 % of total chlorine input to the EDC/VCM processes modelled). This approach is justified by the fact that in the published Eco-profile for MDI/TDI (PlasticsEurope 2021c) burdens are allocated by mass between the main product MDI and the by-product HCl, resulting in unreasonably high environmental loads for HCl.

There is a rising awareness in scientific literature about unwanted methane emissions during oil and gas extraction, processing and transport which are higher than assumed in previous Eco-profiles and in current LCA databases. These additional methane emissions are also reported by the International Energy Agency who built a methane tracker website. To reflect different approaches, two additional sensitivity cases are calculated for ethylene. In general, the latest (not yet published) PlasticsEurope Eco-profile of ethylene will be applied (PlasticsEurope 2021d). The following different datasets for oil and gas extraction will be used:

- Base Case: Oil and gas extraction dataset based on a reviewed report of ESU services which does not consider the mentioned increased methane losses until an international consensus can be established. This case reflects the amount of methane losses as assumed in the previous Eco-profile.
- Oil and gas extraction dataset based on the same report of ESU services but including the increased methane losses according to the IEA methane tracker.

- Ecoinvent datasets, version 3.8 (latest available version in the most used LCA softwares) as a neutral background data source, serving as a comparison until the acceptance of the ESU datasets is established.
    - market for natural gas, high pressure [m3], country specific
    - market for petroleum [RER], European mix. The mix refers to the latest information available on petroleum imports to Europe and applies ecoinvent datasets for producer specific data and transport distances.

The data set mentioned under the first bullet point will be used as the base case in this study for ethylene from ethane and fossil fuel inputs. While it reflects comparable fugitive methane losses as in the previous Eco-profile, there are some differences in the oil and gas upstream dataset by ESU (base case) compared to the dataset used in the previous Eco-profile. One of the differences is the geographical reference of the dataset: while the previous Eco-profile applied country-specific oil and gas upstream information, the ESU dataset provides information on an average European basis; this includes transportation modes and distances as well as venting and flaring. On the other hand, the ESU dataset includes most recent information on energy demands as well as venting/flaring. Updated knowledge on energy demands, venting/flaring and an assumption of longer transport distances result in generally higher Global Warming Potential (GWP) values compared to the old Eco-profile. Resource use from oil and gas upstream is considered in more depth in the ESU dataset as well, leading to higher results for the respective indicator Abiotic Depletion Potential (ADP, min). Also, updated figures for $SO_2$ lead to higher results for acidification (AP). For more details see section “Sensitivity analysis, general” on p.36f).

The oil and gas upstream data sets based on ESU with IEA based methane emissions and on ecoinvent will be presented as sensitivity cases with respect to GWP results.

Hard coal, hydrogen and fuel gas oil are less important fuels for on-site energy generation, with coal mostly used in combined heat and power plants, and hydrogen and fuel gas used in steam generators and/or for direct heating of cracking furnaces. The datasets for those fuels representing a European average are taken directly from the database ecoinvent v3.8 (Wernet et al. 2016).

For transport processes the main data sources are:

- Rail: (TREMOD 2019) and (EcoTransIT 2018)
- Road: (HBEFA 2022) and (TREMOD 2019)
- Ship: (EcoTransIT 2018) and ecoinvent v3.8 (Wernet et al. 2016)
- Pipeline: ecoinvent v3.8 (Wernet et al. 2016)

Electric power supply was modelled using country specific grid electricity mixes, since the environmental burdens of power production varies strongly depending on the electricity generation technology. The country-specific electricity mixes are obtained from a master network for grid power modelling maintained and annually updated at ifeu as described in (Fehrenbach et al. 2016). This network considers the basic power plant types and their respective raw material processes. Using network parameters, the fuel mix and essential technical characteristics of the energy systems are freely adjustable. Thus, the national grid electricity mix for each European country has been calculated. It is based on national electricity mix data by (Eurostat 2022) for the year 2019.

The system boundary of the electricity module includes:

- power plant processes for electricity generation using coal and lignite, fuel oil, natural gas, biomass and waste as well as nuclear, hydroelectric, geothermal, solar and wind power;
- upstream fuel chains in the case of coal, lignite, fuel oil, natural gas, biomass and nuclear power;

- distribution of electricity to the consumer with appropriate management and transformer losses.

The network also includes combined heat and power generation. The share of district heat produced in coupled form is adjustable according to the power plant type. An allocation of the burdens to electricity and district heating is performed through allocation based on exergetic values of products. Additional information concerning the applied electricity grid model can be found on the ifeu website.

Data sources of on-site energy and utilities:

- Steam and electricity: Data from several ifeu projects and ecoinvent v3.8 (Wernet et al. 2016),
- Compressed air (low and high pressure): Several data from ifeu projects, ecoinvent v3.8 (Wernet et al. 2016).
- Industrial gases: oxygen and nitrogen according to ecoinvent v3.8 (Wernet et al. 2016) and ifeu internal database
- Process water: ecoinvent v3.8 (Wernet et al. 2016)

Auxiliary materials and input materials such as non-water cooling agents, catalysts, and other additives were modelled using ecoinvent v3.8 (Wernet et al. 2016) modules. Wherever accurate data sets were not available, the closest fitting assumption was made (e.g. sodium bisulfite was modelled using the stochiometric mix of sodium bicarbonate and sulfur dioxide). Some generic additives such as “antifoam” had to be modelled using typical representatives (i.e. 90 % paraffin + 10 % silicone products) available in the ecoinvent database.

**Relevance and Representativeness**

With regard to the goal and scope of this Eco-profile, the process data, i.e. data for the foreground processes, are of high relevance as the collected primary data for the VCM and PVC processes represent the best available data to describe the European landscape of PVC production. The used data reflect the current technology in Europe and the current upstream chains of feedstock relevant for production in (EU27+NO+CH+UK) member countries.

The data used for this study covers 73 % and 81 % of the installed S-PVC and E-PVC nameplate capacities, respectively, and 68 % of the installed VCM nameplate capacities in Europe (EU27.NO+CH+UK) in 2021. The background data used can be regarded as representative for the intended purpose, as these are averaged data sets, which are not in the focus of the analysis.

**Consistency**

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 (e.g. allocation principles, background datasets, waste treatment) are used throughout the whole system. Those parts of the model defined as background systems according to the PlasticsEurope LCI methodology (PlasticsEurope 2021a) have been treated with the same thoroughness as if they were foreground systems.

The data quality rating is considered very good (1) because the model is fully consistent with the methodology herein.

**Reliability**

In the questionnaires, the site managers were encouraged to classify their data into one of the following reliability grades: measured, calculated or estimated. According to these statements, the data of foreground processes provided directly by producers were almost completely measured. Data of relevant background processes, e.g. grid electricity, is based on ifeu models that are regularly updated with statistical data, with available primary data, and with data derived from literature after it has been reviewed and checked for its quality. Thus, the overall data quality rating for reliability is considered good (2), since either verified data partly based on assumptions or non-verified data based on measurements was used.

**Completeness**

The data collection covers relevant inputs (e.g. amount of raw materials, energy or water) and main output products (e.g. S-PVC, E-PVC, recovered energy) as well as relevant output data, covering emissions to air and water, amounts of waste, and transport information.

In general, the collected and applied data can be stated as complete, because no flows are omitted or substituted. However, for a few production sites it was not possible to obtain detailed emission data due to site-specific measurement and recording practices. In order to compensate for missing information on certain important inputs and outputs, average values (calculated based on the data reported by other production sites of the same process type weighted by product output) are used. This procedure avoids missing information to be treated as "zero" in the calculation of average values. This procedure is applied to the following substances/process flows:

- emissions to air from VCM process: NMVOC, NOx, dioxins and furans, tetrachloromethane, trichloromethane, Ethylene, HCl
- emissions to air from PVC processes: ammonia, dust
- emissions to water from VCM process: total nitrogen, total phosphorus, VCM, dioxins and furans, TOC, chlorides
- emissions to water from PVC processes: total nitrogen, total phosphorus, VCM, TOC, suspended matter

In case of missing information about the fuel mix (natural gas, fuel oil, coal, etc.) used for on-site energy production, the average fuel mix of all participating sites is assumed. This method is also applied for thermal or electrical efficiencies of on-site energy installations as well as for means and distances of raw materials and wastes.

The data quality rating is considered good (2) because cut-offs are smaller than 1%.

**Precision and Accuracy**

The relevant foreground data consist of primary data or modelled data based on primary information sources of the owner of the technology, such that the best possible precision has been achieved within this goal and scope. The accuracy of results with respect to systematic errors can be considered very high due to the high level of detail within both, input data and model.

The overall qualitative assessment of data accuracy is as follows (overall data quality rating: 2):

- There is a high accuracy of relevant material flows, especially of feedstock input and product outputs within the production system
- There is good accuracy for energy flows and combustion related air emissions ($CO_2$, $SO_2$, NOx, $CH_4$)
- There is satisfactory accuracy for other air emissions and emissions to water bodies.

**Reproducibility**

All data and information used are either documented in this report or are available from the mathematical model of the processes and process plans designed within the Umberto 5.6 software. The reproducibility is given for internal use since the owners of the technology provided the data and the models are stored and available in a database. Sub-systems are modelled by ‘state-of-art’ technology using data from a publicly available and internationally used database. It is worth noting that – for external audiences – full reproducibility in any degree of detail may not be available for confidentiality reasons. However, experienced experts would be able to easily recalculate and reproduce parts of the system or key indicators.

**Data Validation**

Data on EDC, VCM and PVC production were collected from PlasticsEurope members in an iterative process with several feedback steps if necessary. The collected data were validated using existing data from published sources or expert knowledge.

The relevant background information from those sources mentioned under ‘data sources’ has been validated and is regularly updated by the LCA practitioner.

**Life Cycle Model**

The investigated product system is modelled in Umberto 5.6, a standard software tool for LCA. Figure 3 gives an overview of the model in a simplified manner. The associated database integrates ISO 14040/44 (ISO 14040 2006; ISO 14044 2006) requirements. Due to confidentiality reasons, details on software modelling and applied methods cannot be given within the framework of this report. Data for production processes have been transferred to the model after successful validation.

The model applied in this Eco-profile comprises extraction and refinery of crude oil for the ethylene production, salt recovery and chlorine electrolysis, as well as production of ethylene dichloride, the production of vinyl chloride monomer and the final polymerisation yielding PVC. The modelled polymer production process includes suspension process and emulsion process. Impacts related to abnormal process conditions (e.g. accidents) are not considered in this study.

Fuel and energy inputs in the system reflect site specific conditions wherever applicable. Only in cases site specific information was missing, average European values have been used. Therefore, the study results are intended to be applicable within EU27+NO+CH+UK boundaries. In order to be applied in other regions, adjustments might be required. PVC products imported into Europe are not considered in this Eco-profile.

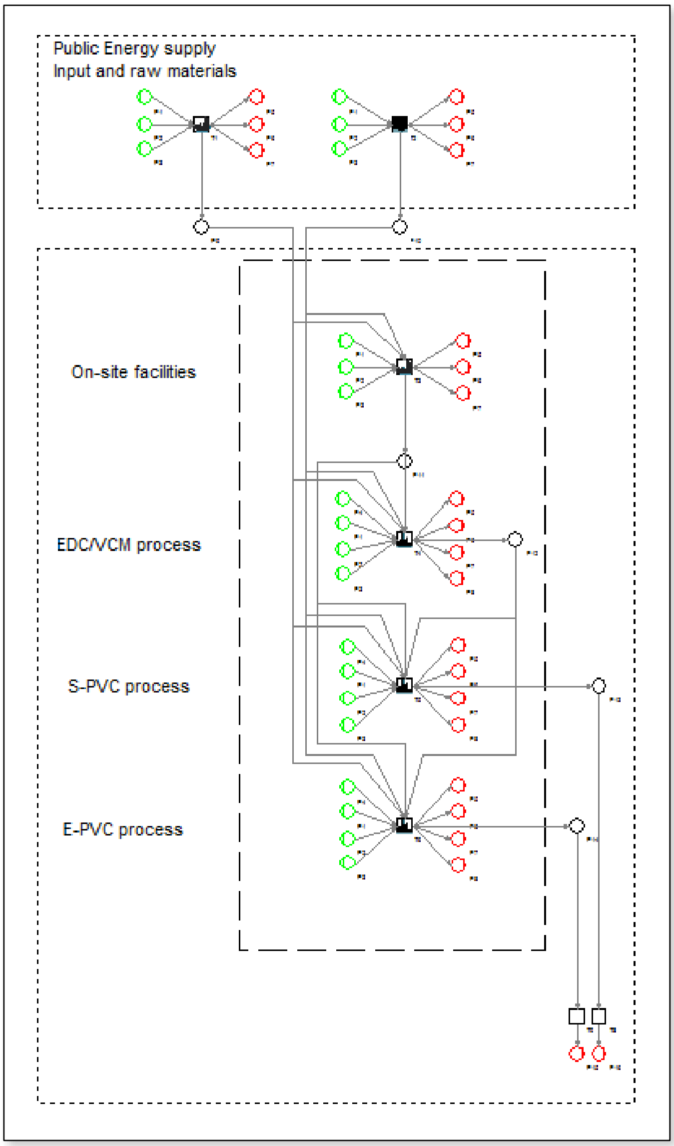


*Figure 6: A simplified flow chart of the Life cycle model for the production of polyvinyl chloride (PVC) in Europe in Umberto 5.6. Here, only one production site is shown (inside the dashed box), connected to the prechains of public energy, input materials and raw materials. For the complete model, additional production sites were inserted in adjacent columns*

## Calculation Rules

### Horizontal/Vertical Averaging

According to the Plastics Europe methodology (PlasticsEurope 2021a), vertical averaging should be applied wherever possible. This means that wherever information on the supply chain was at hand, the following operations were calculated together for each production site: EDC/VCM production, PVC production, on-site energy supply (electricity and steam if produced on-site), on-site production of supply materials like compressed air, nitrogen, or process water, transport of input materials and waste, waste treatment, and wastewater treatment. In cases where the EDC/VCM supplier was not specified, European average EDC/VCM was used (i.e. horizontal average). National electricity mixes were used to calculate the grid electricity supply, and (horizontally) averaged data sets were used for ethylene, chlorine and other raw materials.

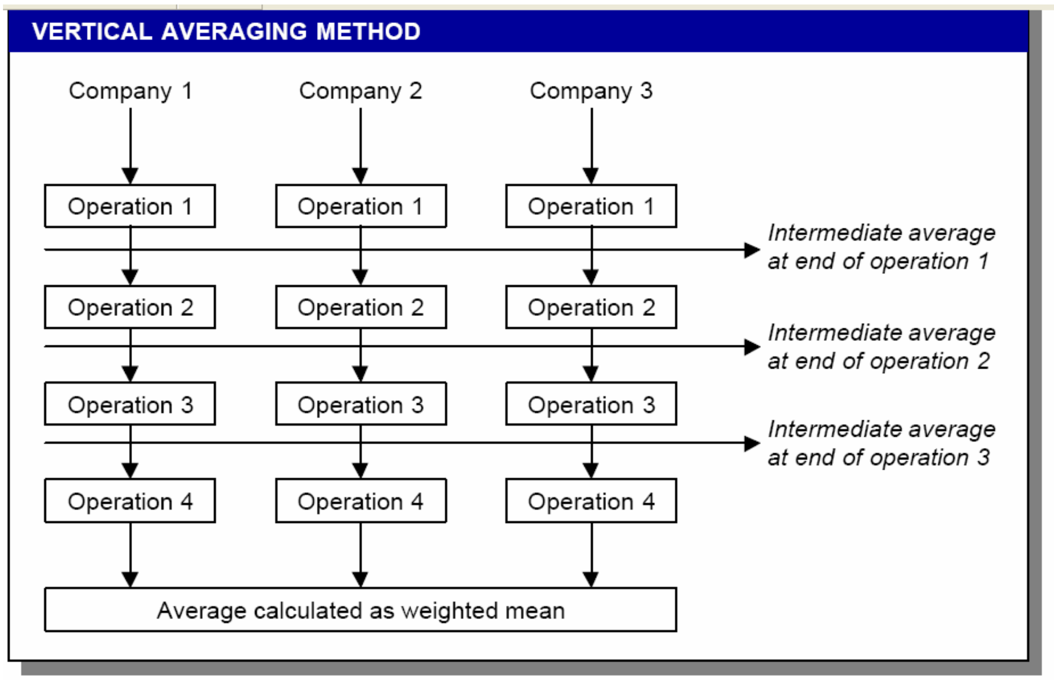


*Figure 7: Vertical Averaging (source: Eco-profile of high-volume commodity phthalate esters, ECPI European Council for Plasticisers and Intermediates, 2001)*

**Allocation Rules**

Production processes in the chemical and plastics industry are usually multi-functional systems, i.e. they exhibit not one but several valuable product and co-product outputs. Wherever possible, and according to PlasticsEurope's LCI methodology (PlasticsEurope 2021a), allocation should be avoided by expanding the system to include the additional functions related to the co-products. To achieve this, a generic process with the same function (product) can be introduced such that the examined system receives credits for the associated burdens avoided elsewhere (»avoidance allocation«). System expansion should only be used where there is a dominant, identifiable displaced product, and if there is a dominant, identifiable production path for the displaced product.

Often, however, avoiding allocation is not feasible in technical reality; stand-alone processes do not exist in reality to serve as alternatives, or alternative technologies exhibit completely different technical performances and product qualities. 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.

The vinyl chloride and the polyvinyl chloride production processes themselves are regarded as single-output processes with certain exceptions. Generally, each plant features one main product, which is either EDC, VCM, S-PVC, or E-PVC, according to the main purpose of the facility.

Additionally, an installation may yield minor amounts of certain by-products, e.g. excess of EDC from a combined EDC/VCM unit, or low-grade PVC products from either S- or E-PVC units. These other or lower grade products (together with recovered material) are in the order of 0.01 % of overall VCM production (ethyl chloride production), 0.08 % of S-PVC production, and 0.48 % of E-PVC production. In total PVC, about 19 % of this material is made up of "recovered PVC" (20 % for S-PVC and 17 % for E-PVC). In these cases of recovered material and/or additional products with an assigned value burdens were allocated by economic factors describing the relative price of the products related to the price of PVC. The economic allocation factors for each product are shown in Table 5. Each production unit declaring an output stream of recovered and low-grade PVC was asked to provide a relative price of this product compared to PVC. Low grade products were classified into three grades with similar relative prices (<15 %, 15 – 35 %, >35 % relative value). For each grade, the economic allocation factor was calculated as the weighted average (by mass) of the relative prices. Relative prices of EDC and VCM were provided by ECVM. In spite of the fact that market prices tend to be subject to changes, this method was chosen due to the inappropriateness of physical allocation between high value products and low-grade by-products.

*Table 5: Economic allocation factors for valuable products (based information supplied by ECVM and companies).*

| **Product** | **Average price in EUR/t** | **Economic allocation factor** |
|---|---|---|
| PVC | 1,229 | 1.000 |
| Low grade PVC (<15 % rel. value) | n/a | 0.082 |
| Low grade PVC (15 - 35 % rel. value) | n/a | 0.209 |
| Low grade PVC (>35 % rel. value) | n/a | 0.400 |
| VCM | 638 | 0.520 |
| EDC | 451 | 0.367 |
| Ethylchloride | 150% of VCM | 0.780 |

Some further products, e.g. monomers being recycled to the cracker or distillation, or hydrocarbons being used thermally, are treated as internal flows replacing the respective input materials (i.e. monomers or energy carriers). Hence, no allocation is needed in these cases. A similar approach was chosen for excess HCl from cracking of EDC: to avoid allocation excess HCl is sent to the input side of the model where it replaces the equivalent amount of HCl or chlorine input.

The allocation rule for waste management is the following: process waste with a recycling potential (e.g. catalysts) leaving the system (<0.5 wt.-% of the total output) does not receive any burdens or credits (Cut-Off). Other process waste is treated within the system.

# Life Cycle Inventory (LCI) Results

### Delivery and Formats of LCI Dataset

This Eco-profile comprises

- a report in PDF format and
- a dataset in ILCD format (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.

Please note that values may not exactly add up to the respective sum reported in the same table. Minor deviations may be caused by rounding of values.

### Energy Demand

The **primary energy demand** (system input) in MJ/kg indicates the cumulative energy requirements at the resource level, accrued along the entire process chain (system boundaries), quantified as gross calorific value (upper heating value, UHV). The net calorific values (lower heating value, LHV) are also presented in Table 6 for information purposes.

The **energy content of the product** 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), in MJ/kg.

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

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

| **Primary Energy Demand** | **VCM** | **S-PVC** | **E-PVC** |
|---|---|---|---|
| Energy content in product [MJ] (energy recovery potential, quantified as gross calorific value) | 17.5 | 20.0[a)] | 20.0[a)] |
| Process energy [MJ] (quantified as difference between primary energy demand and energy content of product) | 34.5 | 37.8 | 41.1 |
| **Total primary energy demand [MJ UHV]** | **52.0** | **57.8** | **61.1** |
| Total primary energy demand [MJ LHV] | 48.6 | 54.0 | 57.1 |

[a)] Communications with ECVM, value for PVC resin

**Water use (withdrawal) foreground (gate to gate)**

The following tables show the values for water use (=withdrawal) of the VCM and PVC production processes (gate-to-gate level).

*Table 7: Water use and source per 1 kg of product (gate-to-gate).*

| Source | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| from River or Lake: | | | | |
| Cooling water | kg | 26.8 | 4.9 | 14.4 |
| Process and Boiler Feed Water | kg | 0.3 | 1.6 | 0.5 |
| from Groundwater: | | | | |
| Cooling water | kg | 0.1 | 3.1 | 12.8 |
| Process Water | kg | 0.4 | 1.7 | 1.4 |
| from Sea/Ocean: | | | | |
| Cooling water | kg | 0.0 | 0.0 | 0.0 |
| Process Water | kg | 0.0 | 0.0 | 0.0 |
| unspecified: | | | | |
| Cooling water | kg | 2.6 | 2.6 | 3.6 |
| Process Water | kg | 0.5 | 0.3 | 1.7 |
| **Total** | **kg** | **30.6** | **14.2** | **34.3** |

The water demands as reported directly by the participating production sites yield the following picture: The production average water demand of the…

- EDC/VCM process is 26.7 kg/kg EDC+VCM for cooling and 1.9 kg/kg EDC+VCM for process, boiler feed and in heat products.
- S-PVC process is 8.0 kg/kg S-PVC for cooling and 3.9 kg/kg S-PVC for process, boiler feed and in heat products.
- E-PVC process is 27.2 kg/kg E-PVC for cooling and 5.1 kg/kg E-PVC for process, boiler feed and in heat products.

These values refer to the water demands of the plants without allocation in contrast to the values in Table 7, which represent water demands allocated to the products VCM and PVC, considering EDC and VCM as well as lower grade PVC products via economic allocation.

VCM plants use about 60 % direct cooling and 40 % cooling tower; direct cooling involves a significant share of river water sent to the ocean. S-PVC plants on average use about 90 % direct cooling and 10 % cooling tower, while E-PVC plants have reported almost 100 % direct cooling.

The following tables show the further handling/processing of the water output of the VCM and PVC production processes (gate-to-gate level and allocated to products).

*Table 8: Treatment of Water Output per 1 kg of product (gate-to-gate).*

| Treatment | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| to River or Lake: | | | | |
| Cooling Water* | kg | 0.4 | 4.5 | 20.6 |
| Process Water** | kg | 0.1 | 2.4 | 2.0 |
| to Sea/Ocean: | | | | |
| Cooling Water* | kg | 13.3 | 1.0 | 3.0 |
| Process Water** | kg | 0.1 | 0.9 | 0.4 |
| unspecified: | | | | |
| Cooling Water* | kg | 2.2 | 4.8 | 6.9 |
| Process Water** | kg | 0.5 | 0.3 | 1.1 |
| Water Vapour | kg | 14.0 | 0.3 | 0.2 |
| **Totals** | **kg** | **30.6** | **14.2** | **34.3** |

* untreated; ** after WWTP

### Water consumption foreground (gate to gate)

The following tables show the water consumption, i.e. water not fed back to the same water body (gate-to-gate level). Water from the ocean or sea is not considered consumed. Water consumption is given when an amount of water is not returned to the water body it was taken from (e.g. evaporation, use in products or flow of river water to sea/ocean). VCM water consumption for cooling is high due to the use of cooling towers (evaporation) and river water released to the ocean. For E-PVC there is a significant share of groundwater (wells) for cooling returned to river or unspecified destinations.

*Table 9: Water consumption per 1 kg of product (gate to gate). Sea water withdrawal and turbined water not included.*

| Consumption | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| Process | kg | 0.5 | 1.7 | 2.0 |
| Cooling | kg | 26.9 | 3.5 | 12.8 |
| **Total water consumption (kg)** | **kg** | **27.4** | **5.2** | **14.7** |

### Water use (withdrawal) cradle to gate

The following table shows the values for water use of the complete supply chain (cradle-to-gate level).

*Table 10: Water use (withdrawal) per source per 1 kg of product (cradle to gate).*

| Source/Use | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| Cooling | | | | |
| Lake | kg | 2.5 | 2.5 | 2.5 |
| River | kg | 106.4 | 109.0 | 164.0 |
| Well | kg | 13.8 | 14.9 | 15.7 |
| Ocean | kg | 15.6 | 16.9 | 17.8 |
| Unspecified | kg | 1.0 | 1.1 | 1.1 |
| **Total cooling** | **kg** | **139.3** | **144.4** | **201.1** |
| Process | | | | |
| Lake | kg | 0.0 | 0.0 | 0.0 |
| River | kg | 0.7 | 2.3 | 1.3 |
| Well | kg | 5.3 | 10.1 | 20.0 |
| Ocean | kg | 0.0 | 0.0 | 0.0 |
| Unspecified | kg | 16.0 | 18.8 | 22.3 |
| **Total process** | **kg** | **22.0** | **31.2** | **43.6** |
| Turbine use | kg | 1140.0 | 1266.0 | 1486.0 |
| **Total (excl. Turbine)** | **kg** | **161.3** | **175.6** | **244.7** |

### Water consumption cradle to gate

*Table 11: Water consumption per 1 kg of product (cradle to gate). Sea water withdrawal and turbined water not included.*

| Consumption | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| Process | kg | 19.3 | 24.8 | 36.8 |
| Cooling | kg | 27.8 | 17.4 | 49.5 |
| **Total water consumption (kg)** | **kg** | **47.1** | **42.1** | **86.3** |

## Life Cycle Impact Assessment (LCIA) Results

For Life Cycle Impact Assessment the set of impact categories and methodologies was used according to the rules for Product Environmental Footprint using the latest available characterization factors (EF-v3.0) from EC-JRC/ILCD (Fazio et al. 2018). However, to allow the Eco-profile to be comparable to older versions of Eco-profiles, the results for the impact categories using the same methodology as in the previous Eco-profile are shown as well. The following list gives an overview of the applied methodology for each impact category.

Please note that values may not exactly add up to the respective sum reported in the same table. Minor deviations may be caused by rounding of values.

**Disclaimer**:

- GWP results are based on an LCA calculation using the current dataset for oil and gas production (European averages), which – in the base case – does not include information on possible higher methane emission from oil and gas exploration, production and processing. This choice of base case reflects the need of an international consensus to be established. The base case reflects the sources of methane emissions regarded in the previous Eco-profile (PlasticsEurope 2016).
- The following LCIA methods are recommended by JRC but the results of these environmental impact indicators shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator (recommendation level III, (Fazio et al. 2018)):
  - Ecotoxicity freshwater
  - Human toxicity, cancer
  - Human toxicity, non-cancer
  - Land use
  - Resource use, fossils (or Abiotic Depletion Potential, fossil)
  - Resource use, elements (or Abiotic Depletion Potential, mineral)
  - Water use

The comparison of the LCIA methodologies does not show the following information which however causes significant differences:

- **Climate change**: the EF 3.0 methodology generally applies higher characterisation factors for methane (36.75 vs. 30) and $N_2O$ (298 vs. 265), leading to slightly higher climate change (GWP) results with EF 3.0 for all products except for hydrogen compared to the previous methodology. In contrast, hydrogen is not counted as a greenhouse gas in the ELCD/PEF methodology while this was the case in the previous Eco-profile with a factor of 5.8 based on the works by (Derwent et al. 1998).
- **Resource use, fossils**: uranium is counted as fossil resource in the EF 3.0 methodology, while this is not the case in the CML methodology. Therefore, the EF 3.0 results for fossil resource use are higher than in the old methodology.
- **Resource use, elements (minerals and metals)**: Uranium is considered a mineral resource in the CML methodology, while in EF 3.0 uranium is considered a fossil resource.
- **Ozone Depletion**: In the previous Eco-profile methodology, $N_2O$ was counted as an ozone depleting substance with a factor of 0.017 based on the publications of (WMO 2014) and (Ravishankara et al. 2009). The EF 3.0 methodology does not consider this factor and therefore the EF 3.0 results for ozone depletion are significantly lower than the previous methodology.

*Table 12: List of impact categories and methodologies used for LCIA in the present Eco-profile (PlasticsEurope 2021a) and in the previous report (PlasticsEurope 2011, 2016).*

| | This Eco-profile (ELCD/PEF) | | Previous Eco-profile | |
|---|---|---|---|---|
| **Impact Category** | **Methodology** | **Unit** | **Methodology** | **Unit** |
| Acidification | Accumulated Exceedance (AE); (Posch et al. 2008; Seppälä et al. 2006) | mol $H^+$ eq. | (Hauschild und Wenzel 1998); characterisation factors of CML 2012 | kg $SO_2$ eq. |
| Climate change | Baseline model of 100 years of the IPCC (IPCC 2014) | kg $CO_2$ eq. | Baseline model of 100 years of the IPCC (IPCC 2014) | kg $CO_2$ eq. |
| Ecotoxicity, freshwater | USEtox model (Rosenbaum et al. 2008) | CTUe | Not considered | |
| Particulate Matter | PM method recommended by UNEP (UNEP 2016) | disease incidence | (De Leeuw 2002; Heldstaab et al. 2003) | kg PM10 eq. |
| Eutrophication marine | EUTREND-model, (Goedkoop et al. 2008) | kg N eq. | (Heijungs et al. 1992); characterisation factors of CML 2012 | kg $PO_4$ eq. |
| Eutrophication, freshwater | EUTREND-model, (Goedkoop et al. 2008) | kg P eq. | | |
| Eutrophication, terrestrial | Accumulated Exceedance (AE); (Posch et al. 2008; Seppälä et al. 2006) | mol N eq. | | |
| Human toxicity, cancer | USEtox model (Rosenbaum et al. 2008) | CTUh | Not considered | |
| Human toxicity, non-cancer | USEtox model (Rosenbaum et al. 2008) | CTUh | Not considered | |
| Ionising radiation, human health | Human health model; (Dreicer et al. 1995; Frischknecht et al. 2000) | kg U235 eq. | Not considered | |
| Land use | Soil quality index based on LANCA (Bos et al. 2016) | - | Not considered | |
| Ozone depletion | EDIP model over an infinite time horizon (excl. $N_2O$); (WMO 2014) | kg CFC-11 eq. | EDIP model over an infinite time horizon (incl. $N_2O$); (WMO 2014) | kg CFC-11 eq. |
| Photochemical ozone formation - human health | LOTOS-EUROS, (van Zelm et al. 2008), as in ReCiPe | kg NMVOC eq. | (Derwent et al. 1998; Jenkin und Hayman 1999); characterisation factors of CML 2012 | kg Ethene eq. |
| Resource use, fossils | CML 2002 (CML 2002; van Oers et al. 2002) | MJ (LHV) | CML 2002 (CML 2002; van Oers et al. 2002) | MJ (LHV) |
| Resource use, minerals and metals | CML 2002 (CML 2002; van Oers et al. 2002) | kg Sb eq. | CML 2002 (CML 2002; van Oers et al. 2002) | kg Sb eq. |
| Water use | Available WAter REmaining (AWARE) as recommended by (UNEP 2016) | $m^3$ world eq. | Only on inventory level | kg |

In the following tables the LCIA results are shown for each of the considered products both using the ELCD methods (PlasticsEurope 2021a) and the methods applied in the previous Eco-profile studies (PlasticsEurope 2011).

*Table 13: LCIA results for the products of the VCM and PVC production using the ELCD/PEF methodology (PlasticsEurope 2021a).*

| Impact Category | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| Climate change **GWP** | kg $CO_2$ eq. | 1.72 | 2.03 | 2.18 |
| Acidification **AP** | mol $H^+$ eq. | 8.7E-03 | 9.7E-03 | 1.1E-02 |
| Eutrophication, freshwater **EP_FW** | kg P eq. | 4.3E-04 | 5.0E-04 | 6.4E-04 |
| Eutrophication, marine **EP_MW** | kg N eq. | 1.1E-03 | 1.3E-03 | 1.4E-03 |
| Eutrophication, terrestrial **EP_Terr** | mol N eq. | 1.2E-02 | 1.4E-02 | 1.9E-02 |
| Ozone depletion **ODP** | kg CFC-11 eq. | 1.4E-06 | 1.6E-06 | 1.1E-06 |
| Photochemical ozone formation **POCP** | kg NMVOC eq. | 4.9E-03 | 5.5E-03 | 5.6E-03 |
| Particulate Matter **PM10** | disease incidents | 3.6E-08 | 4.2E-08 | 5.6E-08 |
| Human toxicity, cancer **HT_Ca** | CTUh | 4.9E-09 | 5.0E-09 | 5.7E-09 |
| Human toxicity, non-cancer **HT_NC** | CTUh | 1.4E-08 | 1.5E-08 | 1.7E-08 |
| Ecotoxicity, freshwater **HT_FW** | CTUe | 43.0 | 46.8 | 48.0 |
| Ionising radiation **IoRad** | kg U235 eq. | 2.1E-01 | 2.5E-01 | 3.0E-01 |
| Resource use, fossils **ADP_fos** | MJ (LHV) | 48.0 | 53.3 | 56.4 |
| Resource use, minerals and metals **ADP_min** | kg Sb eq. | 3.9E-06 | 4.7E-06 | 5.4E-06 |
| Water use | $m^3$ world eq. | 2.02 | 1.81 | 3.71 |
| Land use | - | 4.72 | 5.18 | 5.79 |

*Table 14: LCIA results for the products of the VCM and PVC production using the previous Eco-profile methodology (PlasticsEurope 2011).*

| Impact Category | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| Climate change | kg $CO_2$ eq. | 1.72 | 2.03 | 2.17 |
| Acidification | g $SO_2$ eq. | 7.68 | 8.44 | 9.57 |
| Eutrophication, total | g $PO_4$ eq. | 1.83 | 2.12 | 2.70 |
| Eutrophication, terrestrial | g $PO_4$ eq. | 0.36 | 0.42 | 0.57 |
| Eutrophication, aquatic | g $PO_4$ eq. | 1.47 | 1.70 | 2.12 |
| Ozone depletion | g CFC-11 eq. | 2.1E-03 | 2.3E-03 | 2.0E-03 |
| Photochemical ozone formation | g $C_2H_4$ eq. | 0.51 | 0.55 | 0.53 |
| Dust and Particulate Matter | g PM10 eq. | 5.70 | 6.40 | 7.17 |
| Resource use, fossils | MJ (LHV) | 43.3 | 47.7 | 49.7 |
| Resource use, minerals and metals | kg Sb eq. | 2.0E-05 | 2.0E-05 | 2.2E-05 |
| Water consumption | kg | 47.1 | 42.1 | 86.3 |

### Dominance Analysis

The abbreviations for the ELCD impact categories in this section can be looked up in Table 13.

*Table 15: Dominance analysis of impacts per 1 kg VCM*

| | GWP | AP | EP_FW | EP_MW | EP_Terr | ODP | POCP | PM10 |
|---|---|---|---|---|---|---|---|---|
| | kg $CO_2$ eq. | mol $H^+$ eq. | kg P eq. | kg N eq. | mol N eq. | kg CFC-11 eq. | kg NMVOC eq. | disease incidents |
| EDC+VCM production | 11.68% | 1.09% | 0.54% | 4.19% | 4.55% | 84.44% | 8.03% | 0.64% |
| Electricity a) | 3.81% | 2.00% | 8.63% | 3.16% | 3.76% | 0.15% | 1.84% | 2.73% |
| Thermal energy and utilities a) | 6.94% | 7.22% | 2.07% | 6.71% | 6.94% | 3.41% | 7.02% | 7.78% |
| Disposal a) | 1.40% | 0.25% | 0.04% | 0.88% | 0.82% | 0.04% | 0.58% | 0.38% |
| Subtotal Foreground process | 23.83% | 10.55% | 11.27% | 14.94% | 16.07% | 88.04% | 17.47% | 11.53% |
| Ethylene Production | 48.38% | 68.69% | 10.36% | 52.45% | 49.15% | 7.35% | 63.45% | 56.94% |
| Chlorine Production | 26.30% | 18.07% | 74.35% | 29.21% | 31.31% | 3.26% | 16.97% | 28.06% |
| Other raw materials | 1.23% | 2.14% | 4.01% | 2.13% | 2.09% | 1.36% | 1.27% | 2.88% |
| Transport of precursors and other raw materials | 0.26% | 0.55% | 0.01% | 1.27% | 1.38% | 0.00% | 0.84% | 0.59% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| | HT_Ca | HT_NC | ET_FW | IoRad | ADP_fos | ADP_min | WaterUse | LandUse |
|---|---|---|---|---|---|---|---|---|
| | CTUh | CTUh | CTUh | kg U235 eq. | MJ (LHV) | kg Sb eq. | $m^3$ world eq. | - |
| EDC+VCM production | 3.20% | 3.07% | 3.02% | 0.01% | 0.01% | 0.00% | 58.26% | 0.00% |
| Electricity a) | 0.46% | 7.39% | 1.56% | 18.05% | 2.77% | 6.12% | 1.19% | 4.41% |
| Thermal energy and utilities a) | 0.95% | 4.32% | 4.17% | 1.23% | 10.08% | 8.26% | 1.38% | 5.09% |
| Disposal a) | 0.03% | 0.75% | 0.02% | 0.01% | 0.07% | 0.00% | 0.02% | 0.01% |
| Subtotal Foreground process | 4.65% | 15.54% | 8.77% | 19.29% | 12.94% | 14.38% | 60.86% | 9.52% |
| Ethylene Production | 4.40% | 43.02% | 57.34% | 14.09% | 69.51% | 36.98% | 5.52% | 57.49% |
| Chlorine Production | 90.57% | 38.75% | 32.31% | 62.63% | 16.55% | 33.14% | 31.85% | 30.80% |
| Other raw materials | 0.36% | 2.65% | 1.57% | 3.94% | 0.87% | 15.50% | 1.76% | 2.20% |
| Transport of precursors and other raw materials | 0.01% | 0.05% | 0.01% | 0.04% | 0.13% | 0.00% | 0.01% | 0.00% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

[a] only relating to direct input/output of the EDC/VCM production process

*Table 16: Dominance analysis of impacts per 1 kg S-PVC*

| | **GWP** | **AP** | **EP_FW** | **EP_MW** | **EP_Terr** | **ODP** | **POCP** | **PM10** |
|---|---|---|---|---|---|---|---|---|
| | kg $CO_2$ eq. | mol $H^+$ eq. | kg P eq. | kg N eq. | mol N eq. | kg CFC-11 eq. | kg NMVOC eq. | disease incidents |
| S-PVC production | 1.28% | 0.84% | 0.94% | 2.29% | 2.75% | 0.11% | 0.74% | 1.49% |
| Electricity a) | 3.88% | 2.14% | 8.88% | 3.33% | 3.85% | 0.17% | 2.00% | 3.03% |
| Thermal energy and utilities a) | 7.95% | 4.49% | 1.45% | 4.80% | 5.03% | 2.31% | 4.59% | 5.54% |
| Disposal a) | 0.03% | 0.01% | 0.00% | 0.04% | 0.02% | 0.00% | 0.02% | 0.01% |
| Subtotal Foreground process | 13.13% | 7.49% | 11.27% | 10.45% | 11.65% | 2.59% | 7.36% | 10.06% |
| EDC+VCM production | 22.09% | 12.38% | 12.90% | 16.38% | 17.20% | 87.45% | 18.48% | 13.39% |
| Ethylene Production | 40.97% | 61.99% | 9.07% | 45.32% | 41.81% | 6.75% | 56.68% | 49.29% |
| Chlorine Production | 22.30% | 16.33% | 65.18% | 25.28% | 26.67% | 3.00% | 15.18% | 24.33% |
| Other raw materials | 1.34% | 1.36% | 1.57% | 1.60% | 1.63% | 0.20% | 1.64% | 2.47% |
| Transport of precursors and other raw materials | 0.17% | 0.44% | 0.01% | 0.96% | 1.03% | 0.00% | 0.66% | 0.46% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| | **HT_Ca** | **HT_NC** | **ET_FW** | **IoRad** | **ADP_fos** | **ADP_min** | **WaterUse** | **LandUse** |
|---|---|---|---|---|---|---|---|---|
| | CTUh | CTUh | CTUh | kg U235 eq. | MJ (LHV) | kg Sb eq. | $m^3$ world eq. | - |
| S-PVC production | 1.06% | 0.83% | 3.00% | 0.02% | 0.04% | 0.00% | 2.83% | 0.00% |
| Electricity a) | 0.47% | 6.57% | 1.68% | 13.67% | 2.56% | 5.25% | 1.22% | 4.41% |
| Thermal energy and utilities a) | 0.72% | 2.33% | 2.37% | 0.43% | 5.76% | 4.41% | 0.79% | 2.73% |
| Disposal a) | 0.00% | 0.03% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Subtotal Foreground process | 2.25% | 9.75% | 7.05% | 14.11% | 8.36% | 9.66% | 4.84% | 7.15% |
| EDC+VCM production | 5.24% | 16.66% | 9.72% | 20.58% | 12.99% | 25.49% | 51.51% | 10.80% |
| Ethylene Production | 4.27% | 37.85% | 52.58% | 11.80% | 62.43% | 31.02% | 6.16% | 52.36% |
| Chlorine Production | 88.01% | 34.15% | 29.68% | 52.51% | 14.89% | 27.85% | 35.59% | 28.09% |
| Other raw materials | 0.23% | 1.56% | 0.96% | 0.99% | 1.24% | 5.99% | 1.89% | 1.61% |
| Transport of precursors and other raw materials | 0.01% | 0.03% | 0.01% | 0.02% | 0.09% | 0.00% | 0.01% | 0.00% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

[a] only relating to direct input/output of the S-PVC production process

*Table 17: Dominance analysis of impacts per 1 kg E-PVC*

| | GWP | AP | EP_FW | EP_MW | EP_Terr | ODP | POCP | PM10 |
|---|---|---|---|---|---|---|---|---|
| | kg $CO_2$ eq. | mol $H^+$ eq. | kg P eq. | kg N eq. | mol N eq. | kg CFC-11 eq. | kg NMVOC eq. | disease incidents |
| E-PVC production | 2.35% | 9.77% | 0.15% | 3.63% | 25.79% | 0.07% | 1.92% | 16.46% |
| Electricity a) | 6.35% | 3.62% | 21.36% | 6.13% | 5.68% | 0.33% | 3.21% | 4.27% |
| Thermal energy and utilities a) | 13.66% | 7.97% | 3.15% | 9.01% | 7.15% | 5.50% | 8.96% | 9.64% |
| Disposal a) | 0.10% | 0.02% | 0.01% | 0.10% | 0.05% | 0.00% | 0.07% | 0.03% |
| Subtotal Foreground process | 22.46% | 21.38% | 24.67% | 18.88% | 38.68% | 5.91% | 14.17% | 30.39% |
| EDC+VCM production | 16.11% | 9.27% | 15.04% | 12.81% | 10.29% | 79.51% | 12.46% | 9.46% |
| Ethylene Production | 37.99% | 52.58% | 6.99% | 41.33% | 29.27% | 9.72% | 54.93% | 37.05% |
| Chlorine Production | 21.18% | 14.19% | 51.47% | 23.61% | 19.12% | 4.42% | 15.07% | 18.73% |
| Other raw materials | 2.14% | 2.41% | 1.84% | 2.89% | 2.24% | 0.43% | 3.03% | 4.21% |
| Transport of precursors and other raw materials | 0.12% | 0.18% | 0.00% | 0.48% | 0.39% | 0.00% | 0.35% | 0.17% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| | HT_Ca | HT_NC | ET_FW | IoRad | ADP_fos | ADP_min | WaterUse | LandUse |
|---|---|---|---|---|---|---|---|---|
| | CTUh | CTUh | CTUh | kg U235 eq. | MJ (LHV) | kg Sb eq. | $m^3$ world eq. | - |
| E-PVC production | 11.33% | 2.02% | 1.11% | 0.02% | 0.03% | 0.00% | 2.48% | 0.00% |
| Electricity a) | 0.78% | 10.74% | 2.83% | 25.02% | 4.56% | 8.50% | 1.76% | 9.89% |
| Thermal energy and utilities a) | 1.12% | 4.43% | 5.43% | 0.86% | 10.09% | 6.70% | 0.87% | 5.04% |
| Disposal a) | 0.00% | 0.08% | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.00% |
| Subtotal Foreground process | 13.23% | 17.27% | 9.38% | 25.90% | 14.68% | 15.19% | 5.11% | 14.93% |
| EDC+VCM production | 3.22% | 13.28% | 8.62% | 18.82% | 10.01% | 23.03% | 73.18% | 10.49% |
| Ethylene Production | 3.73% | 33.14% | 50.87% | 9.79% | 58.59% | 26.65% | 2.99% | 46.47% |
| Chlorine Production | 78.81% | 30.62% | 29.41% | 44.62% | 14.31% | 24.50% | 17.67% | 25.54% |
| Other raw materials | 1.00% | 5.68% | 1.72% | 0.88% | 2.34% | 10.62% | 1.04% | 2.56% |
| Transport of precursors and other raw materials | 0.01% | 0.02% | 0.01% | 0.00% | 0.06% | 0.00% | 0.00% | 0.00% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

[a)] only relating to direct input/output of the E-PVC production process

- **GWP:** VCM has the highest contribution to the climate change indicator (almost 50 %) from ethylene (of these emissions ca. half from steam cracking and half from the extraction of natural gas for ethylene). Chlorine is the next biggest contributor to GWP with about half the impact of ethylene, since chlorine relies more on electricity and less on the extraction and processing of fossil fuels. The category EDC+VCM covers direct emissions from incineration of fuels (for heat) within the foreground system. Average direct emissions of $CO_2$ from the EDC/VCM plants are 0.17 kg $CO_2$/kg EDC+VCM, so that EDC+VCM contributes 12 % to the GWP category. In comparison, PVC exhibits 0.02 kg $CO_2$/kg S-PVC and 0.05 kg $CO_2$/kg E-PVC, causing lower contribution of these foreground processes to GWP.
- **AP:** E-PVC shows a higher contribution (10 %) from the foreground process (E-PVC) to acidification than the S-PVC and VCM products: direct emissions of ammonia to air from 6 of the 9 covered E-PVC plants are reported significantly higher than from any of the S-PVC plants. The strongest contribution to AP is based on ethylene production, i.e. the extraction and processing of natural gas.

- **EP_FW:** Freshwater eutrophication is dominated by emissions from the chlorine production category due to the high electricity demand. Especially coal power and the related emissions contribute to freshwater eutrophication.
- **EP_MW:** Marine water eutrophication is caused to about 50 % by the production process of ethylene, more specifically by the extraction of natural gas as feedstock.
- **EP_Terr:** The contribution of the E-PVC process (25 %) to terrestrial eutrophication is significantly higher than for the S-PVC and VCM products. This is mainly caused by direct emission of ammonia to air (similar to the AP indicator). Highest contributions for all products are visible from ethylene (natural gas extraction) and chlorine production.
- **ODP**: Direct emissions of halogenated hydrocarbons to the air (e.g. TCM) were reported in detail by the VCM producers, resulting in a 84 % contribution of EDC+VCM production to **ODP**. These emissions propagate to the PVC products in the VCM category.
- **POCP:** Similar to the indicators acidification and marine eutrophication, ethylene production (natural gas extraction) plays the most important role in the emission of tropospheric ozone producing chemicals.
- **PM10:** Dust and particulate matter emissions are strongly related to ethylene production, as they make up about 57 % of the overall result for VCM. The noticeable contribution (16 %) of the E-PVC foreground category to particulate matter emissions related to E-PVC is based on high direct emissions of ammonia and particulate matter to air from 6 of 9 E-PVC plants (significantly higher than any of the S-PVC plants).
- **HT_Ca:** The emissions of chemicals causing cancer (equally based on emissions of metals and organic compounds) in humans is dominated by the chlorine production category (directly related to emissions from the electrolysis process of the chlorine production).
- **HT_NC:** The emissions of toxic chemicals other than cancer-related (HT_Ca) is mainly related to the two feedstock materials chlorine and ethylene production: the electricity demand for chlorine production and the extraction of natural gas for ethylene. The electricity demand of processes in the life cycle of VCM and PVC also play a significant role in the emission of toxic substances with 7 – 11 % contribution. The indicator result for ethylene is based on emissions of metals (about 2/3) and inorganic compounds (1/3). Toxic emissions from chlorine production (and generally from electricity production) are mainly based on the emission of metals.
- **ET_FW:** Ethylene production (natural gas extraction) plays the most important role in the emission of substances toxic to the environment. Those are realted to both, emissions of metals and inorganics during natural gas extraction.
- **IoRad:** The health hazard of ionising radiation is caused by electricity demands of all process steps. The chlorine category with high electricity demands for the electrolysis process plays a major role here.
- **ADP_fos:** A large part of the abiotic depletion related to fossil resources rely on those processes and feedstocks that are based on the extraction of fossil resources. This is especially valid for ethylene as a feedstock, with a contribution of 70 % to the VCM result of the fossil ADP indicator.
- **ADP_min:** Abiotic depleation related to mineral resources is mainly influenced by ethylene and chlorine production, and here by feedstock and energy resource extraction.
- **WaterUse** within the ELCD methodology is a consumption indicator, covering water inputs and outputs to the environment. I.e. VCM cooling water consumption plays a strong role for WaterUse (see Table 8: high consumption caused by cooling tower evaporation and river CW released to sea/ocean). Accordingly, the EDC+VCM production contributes 58 % to the WaterUse indicator. This contribution propagates to PVC in the VCM category.

**Sensitivity analysis, general**

There is a rising awareness in scientific literature about unwanted methane emissions during oil and gas extraction, processing and transport which are higher than assumed in previous Eco-profiles and in current LCA databases. These additional methane emissions are also reported by the International Energy Agency who built a methane tracker website[3]. As a base case the present Eco-profile is using an oil and gas extraction dataset (separate Eco-profile report, not yet published by PlasticsEurope, (PlasticsEurope 2021e)) which does not consider these increased methane losses as an international consensus is not yet established. Accordingly, the amount of methane losses considered in the base case reflects the assumptions of the previous PVC Eco-profile. However, a separate case named “IEA methane venting” for oil and gas was also published to reflect a possible carbon footprint connected with oil and gas extraction in case the increased methane losses are considered. Therefore, these results were also used for a sensitivity analysis of the VCM and PVC products. The third set of results represents a simple assumption of oil and gas data from the latest available ecoinvent datasets for the most used LCA softwares (v3.8):

The following different datasets for oil and gas extraction will be used:

- Base Case: Oil and gas extraction dataset based on a reviewed report of ESU services which does not consider the mentioned increased methane losses in the meantime that an international consensus can be established. This case reflects the amount of methane losses as assumed in the previous Eco-profile.
- Oil and gas extraction dataset based on the same report of ESU services but including the increased methane losses according to the IEA methane tracker.
- ecoinvent datasets (latest available version in the most used LCA softwares: v3.8)
    - market for natural gas, high pressure [m3], European mix.
    - market for petroleum [RER], European mix. The mix refers to the latest information available on crude oil imports to Europe and applies ecoinvent datasets for producer specific data and transport distances for petroleum.

The dataset mentioned under the first bullet point is used in this study as the base case for ethylene from ethane and fossil fuel inputs. It reflects comparable fugitive methane losses as in the previous Eco-profile. However, there are some differences in the oil and gas upstream dataset by ESU (base case) compared to the dataset used in the previous Eco-profile (for more detail see section Data Sources on page 17ff.).

- Geographical reference: The ESU dataset for oil and gas extraction and processing provides average European datasets for oil and gas supply, while the previous Eco-profile used country-specific supply mixes, transportation modes and distances as well as venting and flaring. On the other hand, the ESU dataset includes most recent information on energy demands as well as venting/flaring.
- The updated knowledge on energy demands, venting/flaring and an assumption of longer transport distances leads to generally higher Global Warming Potential (GWP) results compared to the old Eco-profile, introduced by the use of oil and gas as well as via the ethylene feedstock.
- Abiotic depletion potential (ADP, mineral) or resource use was not considered in the previous oil and gas upstream but is now considered in the ESU dataset. Accordingly, the indicator Resource use, elements (or ADP, mineral) increases compared to the previous Eco-profile.

---

[3] https://www.iea.org/reports/methane-tracker-2020

- Figures for $SO_2$ emissions in oil and gas extraction were updated in the ESU dataset, leading to higher values in Acidification Potential (AP).

These differences contribute to the changes between the previous and the present Eco-profile, along with a number of other changes such as improvements of the refinery and steam cracker background, the latest electricity mixes, and the updated chlorine Eco-profile.

The oil and gas upstream data sets based on ESU with IEA based methane emissions and on ecoinvent will be presented as sensitivity cases with respect to GWP results.

The dataset mentioned under the second bullet point is of increased interest, considering possible future developments to accept and use the latest scientific insights on methane emissions from the oil and gas extraction sector. Accordingly, the sensitivity related to this dataset is reported in an extent equivalent to the base case in the following section.

Table 18 shows an overview comparison of the base case (used throughout this Eco-profile) and the IEA methane venting case on the basis of GWP.

The comparison makes clear that in case the increased methane emissions reported by IEA Methane Tracker are considered, the GWP results of VCM increases by about 0.18 kg $CO_2$ eq./kg, and the GWP of S-PVC and E-PVC increases by about 0.19 kg $CO_2$ eq./kg.

*Table 18: Sensitivity analysis of the carbon footprint of the investigated products with increased methane losses according to IEA Methane Tracker and the ecoinvent dataset (v3.8).*

| Scenario | Unit | VCM | S-PVC | E-PVC |
|---|---|---|---|---|
| Base case | kg $CO_2$ eq. | 1.72 | 2.03 | 2.18 |
| IEA methane venting | kg $CO_2$ eq. | 1.90 | 2.22 | 2.37 |
| ecoinvent datasets | kg $CO_2$ eq. | 1.68 | 1.96 | 2.11 |

**Sensitivity Analysis, increased Methane Emissions Case**

The dataset mentioned under 2. is described in this section in an equivalent degree of detail as the base case in the earlier sections of this Eco-profile.

The LCIA results of the base case as presented in Table 13 are given in Table 19 for the sensitivity case with increased methane losses according to IEA. To enable a comparison with the previous Eco-profile for VCM and PVC, Table 20 (analogue to Table 14 for the base case) shows the results according to the old PlasticsEurope methodology (V2.0) (PlasticsEurope 2011).

The tables following the LCIA results hold the dominance analysis for the sensitivity case, comparable to Table 15 to Table 17 (base case dominance analysis).

*Table 19: LCIA results for the products of the VCM and PVC production using the ELCD/PEF methodology (PlasticsEurope 2021a), sensitivity case: increased methane losses.*

| **Impact Category** | **Unit** | **VCM** | **S-PVC** | **E-PVC** |
|---|---|---|---|---|
| Climate change **GWP** | kg $CO_2$ eq. | 1.90 | 2.22 | 2.37 |
| Acidification **AP** | mol $H^+$ eq. | 8.7E-03 | 9.6E-03 | 1.1E-02 |
| Eutrophication, freshwater **EP_FW** | kg P eq. | 4.3E-04 | 5.0E-04 | 6.4E-04 |
| Eutrophication, marine **EP_MW** | kg N eq. | 1.1E-03 | 1.3E-03 | 1.4E-03 |
| Eutrophication, terrestrial **EP_Terr** | mol N eq. | 1.1E-02 | 1.3E-02 | 1.9E-02 |
| Ozone depletion **ODP** | kg CFC-11 eq. | 1.4E-06 | 1.6E-06 | 1.1E-06 |
| Photochemical ozone formation **POCP** | kg NMVOC eq. | 7.1E-03 | 7.8E-03 | 7.9E-03 |
| Particulate Matter **PM10** | disease incidents | 3.6E-08 | 4.2E-08 | 5.5E-08 |
| Human toxicity, cancer **HT_Ca** | CTUh | 4.9E-09 | 5.0E-09 | 5.7E-09 |
| Human toxicity, non-cancer **HT_NC** | CTUh | 1.4E-08 | 1.5E-08 | 1.7E-08 |
| Ecotoxicity, freshwater **HT_FW** | CTUe | 43.0 | 46.8 | 48.0 |
| Ionising radiation **HT_IoRad** | kg U235 eq. | 2.1E-01 | 2.5E-01 | 3.0E-01 |
| Resource use, fossils **ADP_fos** | MJ (LHV) | 48.2 | 53.5 | 56.6 |
| Resource use, minerals and metals **ADP_min** | kg Sb eq. | 3.9E-06 | 4.7E-06 | 5.4E-06 |
| Water use | $m^3$ world eq. | 2.02 | 1.81 | 3.71 |
| Land use | - | 4.72 | 5.17 | 5.78 |

*Table 20: LCIA results for the products of the VCM and PVC production using the previous Eco-profile methodology, sensitivity case: increased methane losses (PlasticsEurope 2011).*

| **Impact Category** | **Unit** | **VCM** | **S-PVC** | **E-PVC** |
|---|---|---|---|---|
| Climate change | kg $CO_2$ eq. | 1.86 | 2.18 | 2.32 |
| Acidification | g $SO_2$ eq. | 7.67 | 8.43 | 9.56 |
| Eutrophication, total | g $PO_4$ eq. | 1.82 | 2.12 | 2.69 |
| Eutrophication, terrestrial | g $PO_4$ eq. | 0.36 | 0.42 | 0.57 |
| Eutrophication, aquatic | g $PO_4$ eq. | 1.46 | 1.70 | 2.12 |
| Ozone depletion | g CFC-11 eq. | 2.1E-03 | 2.4E-03 | 2.0E-03 |
| Photochemical ozone formation | g $C_2H_4$ eq. | 0.86 | 0.93 | 0.92 |
| Dust and Particulate Matter | g PM10 eq. | 5.71 | 6.41 | 7.18 |
| Resource use, fossils | MJ (LHV) | 43.5 | 47.9 | 49.9 |
| Resource use, minerals and metals | kg Sb eq. | 2.0E-05 | 2.0E-05 | 2.2E-05 |

*Table 21: Dominance analysis of impacts per 1 kg VCM, sensitivity case: increased methane losses*

| | **GWP** | **AP** | **EP_FW** | **EP_MW** | **EP_Terr** | **ODP** | **POCP** | **PM10** |
|---|---|---|---|---|---|---|---|---|
| | kg $CO_2$-eq. | mol $H^+$ eq. | kg P eq. | kg N eq. | mol N eq. | kg CFC-11 eq. | kg NMVOC eq. | disease incidents |
| EDC+VCM production | 10.61% | 1.09% | 0.54% | 4.21% | 4.57% | 85.25% | 5.57% | 0.64% |
| Electricity a) | 3.46% | 2.00% | 8.63% | 3.18% | 3.78% | 0.16% | 1.27% | 2.73% |
| Thermal energy and utilities a) | 7.42% | 7.17% | 2.05% | 6.53% | 6.75% | 3.00% | 8.22% | 7.72% |
| Disposal a) | 1.27% | 0.25% | 0.04% | 0.89% | 0.83% | 0.04% | 0.40% | 0.38% |
| Subtotal Foreground process | 22.76% | 10.51% | 11.26% | 14.79% | 15.92% | 88.44% | 15.47% | 11.47% |
| Ethylene Production | 52.01% | 68.71% | 10.35% | 52.44% | 49.13% | 6.90% | 71.30% | 56.94% |
| Chlorine Production | 23.88% | 18.09% | 74.37% | 29.35% | 31.46% | 3.29% | 11.77% | 28.10% |
| Other raw materials | 1.11% | 2.15% | 4.01% | 2.14% | 2.10% | 1.37% | 0.88% | 2.89% |
| Transport of precursors and other raw materials | 0.24% | 0.55% | 0.01% | 1.28% | 1.39% | 0.00% | 0.58% | 0.60% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| | **HT_Ca** | **HT_NC** | **ET_FW** | **IoRad** | **ADP_fos** | **ADP_min** | **WaterUse** | **LandUse** |
|---|---|---|---|---|---|---|---|---|
| | CTUh | CTUh | CTUh | kg U235 eq. | MJ (LHV) | kg Sb eq. | $m^3$ world eq. | - |
| EDC+VCM production | 3.21% | 3.06% | 3.02% | 0.01% | 0.01% | 0.00% | 58.26% | 0.00% |
| Electricity a) | 0.46% | 7.37% | 1.56% | 18.05% | 2.76% | 6.13% | 1.19% | 4.42% |
| Thermal energy and utilities a) | 0.94% | 4.32% | 4.16% | 1.23% | 10.04% | 8.19% | 1.38% | 5.04% |
| Disposal a) | 0.03% | 0.75% | 0.02% | 0.01% | 0.07% | 0.00% | 0.02% | 0.01% |
| Subtotal Foreground process | 4.64% | 15.50% | 8.76% | 19.29% | 12.88% | 14.32% | 60.86% | 9.47% |
| Ethylene Production | 4.39% | 43.17% | 57.35% | 14.09% | 69.64% | 36.95% | 5.52% | 57.49% |
| Chlorine Production | 90.59% | 38.64% | 32.31% | 62.64% | 16.48% | 33.20% | 31.86% | 30.83% |
| Other raw materials | 0.36% | 2.64% | 1.57% | 3.94% | 0.86% | 15.53% | 1.76% | 2.20% |
| Transport of precursors and other raw materials | 0.01% | 0.05% | 0.01% | 0.04% | 0.13% | 0.00% | 0.01% | 0.00% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

[a] only relating to direct input/output of the EDC/VCM production process

*Table 22: Dominance analysis of impacts per 1 kg S-PVC, sensitivity case: increased methane losses*

| | **GWP** | **AP** | **EP_FW** | **EP_MW** | **EP_Terr** | **ODP** | **POCP** | **PM10** |
|---|---|---|---|---|---|---|---|---|
| | kg $CO_2$ eq. | mol $H^+$ eq. | kg P eq. | kg N eq. | mol N eq. | kg CFC-11 eq. | kg NMVOC eq. | disease incidents |
| S-PVC production | 1.17% | 0.84% | 0.94% | 2.30% | 2.77% | 0.11% | 0.52% | 1.49% |
| Electricity a) | 3.55% | 2.15% | 8.88% | 3.35% | 3.87% | 0.17% | 1.40% | 3.03% |
| Thermal energy and utilities a) | 7.91% | 4.46% | 1.44% | 4.68% | 4.90% | 2.02% | 5.20% | 5.50% |
| Disposal a) | 0.03% | 0.01% | 0.00% | 0.04% | 0.02% | 0.00% | 0.02% | 0.01% |
| Subtotal Foreground process | 12.66% | 7.46% | 11.26% | 10.37% | 11.56% | 2.30% | 7.14% | 10.03% |
| EDC+VCM production | 21.22% | 12.34% | 12.89% | 16.27% | 17.09% | 88.10% | 16.16% | 13.34% |
| Ethylene Production | 44.35% | 62.03% | 9.06% | 45.36% | 41.83% | 6.36% | 64.43% | 49.31% |
| Chlorine Production | 20.40% | 16.36% | 65.21% | 25.42% | 26.83% | 3.04% | 10.65% | 24.37% |
| Other raw materials | 1.22% | 1.36% | 1.58% | 1.61% | 1.64% | 0.21% | 1.15% | 2.48% |
| Transport of precursors and other raw materials | 0.16% | 0.44% | 0.01% | 0.97% | 1.04% | 0.00% | 0.46% | 0.46% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| | **HT_Ca** | **HT_NC** | **ET_FW** | **IoRad** | **ADP_fos** | **ADP_min** | **WaterUse** | **LandUse** |
|---|---|---|---|---|---|---|---|---|
| | CTUh | CTUh | CTUh | kg U235 eq. | MJ (LHV) | kg Sb eq. | $m^3$ world eq. | - |
| S-PVC production | 1.06% | 0.82% | 3.00% | 0.02% | 0.04% | 0.00% | 2.83% | 0.00% |
| Electricity a) | 0.47% | 6.55% | 1.68% | 13.67% | 2.55% | 5.26% | 1.22% | 4.42% |
| Thermal energy and utilities a) | 0.71% | 2.32% | 2.36% | 0.42% | 5.73% | 4.37% | 0.79% | 2.69% |
| Disposal a) | 0.00% | 0.03% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Subtotal Foreground process | 2.24% | 9.73% | 7.04% | 14.11% | 8.32% | 9.62% | 4.84% | 7.12% |
| EDC+VCM production | 5.23% | 16.63% | 9.71% | 20.58% | 12.93% | 25.47% | 51.51% | 10.76% |
| Ethylene Production | 4.26% | 37.99% | 52.59% | 11.79% | 62.59% | 31.00% | 6.16% | 52.38% |
| Chlorine Production | 88.03% | 34.06% | 29.67% | 52.51% | 14.84% | 27.90% | 35.59% | 28.14% |
| Other raw materials | 0.23% | 1.55% | 0.96% | 0.99% | 1.23% | 6.00% | 1.89% | 1.61% |
| Transport of precursors and other raw materials | 0.01% | 0.03% | 0.01% | 0.02% | 0.09% | 0.00% | 0.01% | 0.00% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

[a] only relating to direct input/output of the S-PVC production process

*Table 23: Dominance analysis of impacts per 1 kg E-PVC, sensitivity case: increased methane losses*

| | GWP | AP | EP_FW | EP_MW | EP_Terr | ODP | POCP | PM10 |
|---|---|---|---|---|---|---|---|---|
| | kg $CO_2$ eq. | mol $H^+$ eq. | kg P eq. | kg N eq. | mol N eq. | kg CFC-11 eq. | kg NMVOC eq. | disease incidents |
| E-PVC production | 2.16% | 9.78% | 0.15% | 3.65% | 25.90% | 0.08% | 1.36% | 16.48% |
| Electricity a) | 5.84% | 3.62% | 21.36% | 6.16% | 5.71% | 0.34% | 2.27% | 4.28% |
| Thermal energy and utilities a) | 13.61% | 7.92% | 3.14% | 8.85% | 7.01% | 4.85% | 9.73% | 9.59% |
| Disposal a) | 0.09% | 0.02% | 0.01% | 0.10% | 0.05% | 0.00% | 0.05% | 0.03% |
| Subtotal Foreground process | 21.69% | 21.35% | 24.66% | 18.76% | 38.67% | 5.27% | 13.40% | 30.37% |
| EDC+VCM production | 15.41% | 9.25% | 15.03% | 12.78% | 10.26% | 80.59% | 10.79% | 9.45% |
| Ethylene Production | 41.34% | 52.60% | 6.98% | 41.34% | 29.23% | 9.19% | 62.80% | 37.05% |
| Chlorine Production | 19.47% | 14.21% | 51.48% | 23.73% | 19.20% | 4.50% | 10.63% | 18.75% |
| Other raw materials | 1.97% | 2.42% | 1.84% | 2.91% | 2.25% | 0.44% | 2.14% | 4.21% |
| Transport of precursors and other raw materials | 0.11% | 0.18% | 0.00% | 0.48% | 0.39% | 0.00% | 0.24% | 0.17% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| | HT_Ca | HT_NC | ET_FW | IoRad | ADP_fos | ADP_min | WaterUse | LandUse |
|---|---|---|---|---|---|---|---|---|
| | CTUh | CTUh | CTUh | kg U235 eq. | MJ (LHV) | kg Sb eq. | $m^3$ world eq. | - |
| E-PVC production | 11.33% | 2.02% | 1.11% | 0.02% | 0.03% | 0.00% | 2.48% | 0.00% |
| Electricity a) | 0.78% | 10.71% | 2.83% | 25.02% | 4.54% | 8.51% | 1.76% | 9.91% |
| Thermal energy and utilities a) | 1.11% | 4.43% | 5.42% | 0.86% | 10.04% | 6.64% | 0.87% | 4.98% |
| Disposal a) | 0.00% | 0.08% | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.00% |
| Subtotal Foreground process | 13.23% | 17.24% | 9.37% | 25.90% | 14.62% | 15.15% | 5.11% | 14.90% |
| EDC+VCM production | 3.21% | 13.26% | 8.62% | 18.82% | 9.98% | 23.04% | 73.19% | 10.48% |
| Ethylene Production | 3.73% | 33.27% | 50.88% | 9.79% | 58.74% | 26.63% | 2.98% | 46.48% |
| Chlorine Production | 78.83% | 30.55% | 29.40% | 44.63% | 14.26% | 24.54% | 17.67% | 25.57% |
| Other raw materials | 1.00% | 5.67% | 1.72% | 0.88% | 2.34% | 10.64% | 1.04% | 2.56% |
| Transport of precursors and other raw materials | 0.01% | 0.02% | 0.01% | 0.00% | 0.06% | 0.00% | 0.00% | 0.00% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

[a)] only relating to direct input/output of the E-PVC production process

The following short overview highlights some of the changes of this sensitivity case compared to the base case:

Wherever **natural gas** extraction plays a role, results are affected. Higher emissions of methane as assumed in the sensitivity case are accompanied by an increased extraction amount and processing burdens for natural gas.

Natural gas burdens are present especially in the categories of thermal energy and ethylene extraction and processing. This becomes visible in the indicators **GWP**, **POCP** and **ADP_fos**, which are related to the extraction of resources and emissions from combustion.

Within the EDC-VCM foreground production, the use (combustion) of direct fuels is affected, causing an increase in the VCM category in the PVC dominance analysis tables.

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

The following tables compare the present results with the previous version of the Eco-profile of 2016 (PlasticsEurope 2016). This comparison is done based on the impact assessment methods used in the previous Eco-profile (PlasticsEurope 2011). The following major changes have been applied in the VCM and PVC model during the update of the Eco-profile:

For the current study, datasets on electricity production, oil and gas extraction, refinery and steam cracking of hydrocarbons were updated to the most recent datasets. In all of them, significant changes occurred which have an influence on the results:

- Abiotic depletion potential (ADP), elements increased strongly compared to the previous Eco-profile mostly since mineral depletion was not considered in the previous oil and gas upstream and additionally due to the higher input values for NaOH for the steam cracker water treatment (impacts via ethylene and direct use of fossil fuels, e.g. for heat).
- Global warming potential (GWP): Oil and gas extraction shifted to assumptions with higher energy requirements, longer transport distances, higher emissions from flaring and in general higher GWP impacts, leading to higher impacts for ethylene and fossil fuels compared to the previous Eco-profile. An exception is E-PVC: according to the latest process data the electricity per kg E-PVC decreased slightly, while plants shifted from the use of on-site electricity (from fossil CHP) to grid supply; VCM demand also decreased slightly.
- Acidification Potential increased strongly due to updated figures for $SO_2$ emissions in oil and gas extraction and in refinery operations.
- Eutrophication Potential (AP), aquatic increased strongly since the model for coal for power plants was improved (considering a wider range of emissions) compared to the previous Eco-profile, now including increased eutrophication results for lignite mining.
- Ozone Depletion Potential (ODP) increased since a higher number of ODP substances were considered (NMVOC, halogenated, fluorinated hydrocarbons) according to the methodology. However, ODP has decreased for E-PVC compared to the earlier Eco-profile.
- Photochemical Ozone Creation Potential (POCP) increased slightly due to the implementation of characterisation factors for NMVOC.
- The results for water consumption have decreased for all products. This change can be attributed mainly to an increased accuracy in the assessment of water within the last 15 years, with respect to an increased effort to understand the water balance of every single plant, concerning the modelling of the PVC production system itself, and also significantly within the ecoinvent database used for background data since version 2.

In addition to the update of electricity supply and fossil fuel pre-chains, affecting indicators such as GWP and ADP, the Eco-profiles of ethylene and chlorine were updated recently with the following changes propagating to the PVC production system:

**Chlorine** (EuroChlor 2020), changes between the Eco-profiles of 2013 and 2021:

- Mercury technology was phased out, leading to lower toxicity burdens from mercury emissions (not represented in Table 24).
- ODP decreased by about 50 % for chlorine production, since emissions of halogenated hydrocarbons from chlor-alkali units were strongly reduced. However, considering overall PVC, this is masked by the general increase due to reasons mentioned above.
- EP increased strongly due to the assessment of power plants as mentioned above, while electricity is a main driver for environmental burdens associated with chlorine.

- Abiotic Depletion Potential (ADP) elements increased due to a higher reported salt input compared to the 2013 Eco-profile.
- Photochemical Ozone Creation Potential decreased for chlorine due to the decreased use of fossil fuels for electricity production leading to lower NOx emissions.

**Ethylene** (currently unpublished PlasticsEurope Eco-profile,(PlasticsEurope 2021d)):

- A feedstock dependent cracker model was developed, i.e. resulting in different feedstock/main product ratios, energy consumption, product distribution, leading to result changes for all steam cracker products.
- Overall, the GWP of steam cracking itself decreased by about 10 % compared to the last Eco-profile.
- ADP, elements, AP and ODP strongly increased for Ethylene due to the reasons mentioned above (by over 10,000 %, 184 % and 158 %, respectively).

*Table 24: Comparison of the present Eco-profile of the VCM and PVC with its previous version (2015, updated 2016). Impacts were calculated with the methodology used in the previous Eco-profile report.*

| **Environmental Impact Categories** | **VCM** | | | **S-PVC** | | | **E-PVC** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2016** | **2022** | **Diff.** | **2016** | **2022** | **Diff.** | **2016** | **2022** | **Diff.** |
| Gross primary energy from resources [MJ] | 54.7 | 52.0 | -5.0% | 60.7 | 57.8 | -4.6% | 70.8 | 61.1 | -13.7% |
| Renewable energy resources [MJ] | 3.6 | 1.5 | -59.7% | 3.7 | 1.7 | -73.9% | 4.7 | 2.1 | -55.3% |
| Global Warming Potential (GWP) [kg $CO_2$ eq.] | 1.71 | 1.72 | 0.6% | 1.99 | 2.03 | 2.0% | 2.56 | 2.17 | -15.3% |
| Acidification Potential (AP) [g $SO_2$ eq.] | 4.50 | 7.68 | 70.6% | 5.05 | 8.44 | 67.1% | 6.93 | 9.57 | 38.2% |
| Eutrophication Potential (EP) [g $PO_4$ eq.] | 0.81 | 1.83 | 125.4% | 0.94 | 2.12 | 125.6% | 1.25 | 2.70 | 115.8% |
| Eutrophication Potential, terrestrial [g $PO_4$ eq.] | 0.33 | 0.36 | 9.1% | 0.39 | 0.42 | 8.2% | 0.61 | 0.57 | -5.8% |
| Eutrophication Potential, aquatic [g $PO_4$ eq.] | 0.48 | 1.47 | 205.3% | 0.55 | 1.70 | 208.9% | 0.64 | 2.12 | 231.6% |
| Ozone Depletion Potential (ODP) [g CFC-11 eq.] | 1.9E-03 | 2.1E-03 | 8.8% | 2.2E-03 | 2.3E-03 | 6.0% | 2.4E-03 | 2.0E-03 | -16.6% |
| Photochemical Ozone Creation Potential (POCP) [g $C_2H_4$ eq.] | 0.50 | 0.51 | 2.5% | 0.56 | 0.55 | -1.6% | 0.54 | 0.53 | -1.0% |
| Abiotic Depletion Potential (ADP), elements [kg Sb eq.] | 1.3E-05 | 2.0E-05 | 51.3% | 1.3E-05 | 2.0E-05 | 57.3% | 1.4E-05 | 2.2E-05 | 55.1% |
| Abiotic Depletion Potential (ADP), fossil fuels [MJ] | 42.8 | 43.3 | 1.3% | 47.2 | 47.7 | 1.1% | 54.2 | 49.7 | -8.3% |
| Water Consumption [kg] | 88.0 | 47.1 | -46.5% | 77.4 | 42.1 | -45.6% | 102.2 | 86.3 | -15.5% |

# Review Statement

## Review Details

| | |
|---|---|
| Commissioned by: | PlasticsEurope AISBL, ECVM |
| Prepared by: | Sabrina Ludmann, Dr.-Ing. Thomas Fröhlich<br>ifeu Institut für Energie- und Umweltforschung Heidelberg gGmbH |
| Reviewed by: | Matthias Schulz<br>Schulz Sustainability Consulting |
| References: | • PlasticsEurope 2021: Eco-profiles program and methodology. PlasticsEurope. Version 3.1, September 2021<br>• ISO 14040 (2006): Environmental Management – Life Cycle Assessment – Principles and Framework<br>• ISO 14044 (2006): Environmental Management – Life Cycle Assessment – Requirements and Guidelines |

## Review Summary

As recommended in accordance with the PlasticsEurope methodology version 3.1 (2021), an external independent critical review was conducted for this Eco-profile before publication of the respective dataset. The outcome of the critical review is reproduced below.

The subject of the critical review was this Eco-profile report for the following vinyl products:

- vinyl chloride (VCM),
- polyvinyl chloride from suspension polymerisation (S-PVC) and
- polyvinyl chloride from emulsion polymerisation (E-PVC).

The critical review included two iterations of the final Eco-profile report review (October and November 2022), in which the reviewer raised questions and comments and the LCA practitioners responded with clarifications and revisions in the Eco-profile report. On 15.11.2022, a web-based review meeting was held, during which open issues were discussed and a model review as well as spot checks of data and calculations were carried out.

The final version of the report was provided to the reviewer on 18.11.2022. The reviewer checked the implementation of the comments and agreed to conclude the critical review process.

A minor update of the study was carried out in March 2023. As part of the update, the gate-to-gate water data were adjusted. The corresponding changes refer to Tables 7 – 9 in the report. Further related explanations were added to the text. The changes have no impact on other results presented in the Eco-profile.

A minor revision was carried out in June 2023. As part of the revision, ethylene values were corrected due to a minor error in the steam cracker model. This had consequences for many result values presented in the Eco-profile report, however, the values only changed marginally.

The reviewer acknowledges the unrestricted access to all requested information, the dedicated efforts of the LCA practitioners to address the comments provided, as well as the open and constructive dialogue during the entire critical review process. All versions of the documentation (reports and data), including the individual reviewer’s comments, questions and associated answers, are archived and can be made available upon request.

A three-pronged approach to primary data collection was used: 1) Plants exhibiting significant changes when compared to the last data collection in 2013 provided updated annual input-output data for 2021. 2) For vinyl plants with no significant changes in energy consumption or other process modifications influencing their environmental performance, the same data was used as for the last Eco-profile (reference year 2013). 3) A small group of plants is represented by data from 2017 – 2020, to which the LCA practitioner had access during other LCA projects. Primary data take into account site-specific technologies for ethylene di-chloride (EDC), VCM and PVC production. In total, data from 39 vinyl plants (EDC: 1, VCM: 12, S-PVC: 17, E-PVC: 9) were included in this study, leading to a representativeness of 68 % (VCM), 73 % (S-PVC) and 81 % (E-PVC) with regards to total European production. It should be noted that plants not considered for this Eco-profile are mainly located in Eastern Europe. Overall, primary data quality can be considered to be good, however, data gaps exist for certain emissions to air and water, see details under ‘Completeness’ in the main report.

Background data for the main precursors chlorine and ethylene were taken from the most current PlasticsEurope Eco-profiles (Eco-profile chlorine: EuroChlor 2022; Eco-profile ethylene: PlasticsEurope 2021d (unpublished)). Despite the data for crude oil and natural gas production and processing not yet having been published as an Eco-profile (either), the most recently available data were used, based on a life cycle inventory analysis carried out by ESU-services Ltd. (PlasticsEurope 2021e). Although the environmental profile and associated data, in particular the increased emissions from methane venting and flaring, is still being discussed amongst various stakeholders in the relevant fields, both the LCA practitioners and the reviewer consider this data to be most representative and best available at this point in time. It should be noted that the base case for this Eco-profile does not consider the scenario with the increased methane losses. Instead, this scenario has been included as part of a sensitivity analysis.

Other background process data, e.g. for transport data, additives, surfactants, or auxiliary materials and electricity were sourced from Ecoinvent as well as specific data sources from the LCA practitioners (e.g. updated country-specific electricity grid mixes). All background datasets used for this Eco-profile are described in detail in the report and are considered appropriate for the goal and scope of this study.

Economic allocation was applied to small amounts of lower grade VCM and PVC output according to prices provided by the manufacturers. Concerning HCl input, the same data as for chlorine was used. This procedure is in line with the previous version of this Eco-profile and is based on the conservative assumption that one molecule HCl carries half the load of a $Cl_2$ molecule.

In general, the potential environmental impacts for VCM and PVC are dominated by the precursor products ethylene and chlorine. For VCM production, emissions of tetrachloromethane contribute significantly to the indicator Ozone Depletion Potential. Another contributor in particular to the GWP impact category are greenhouse gas emissions from the EDC/VCM plants, due to the combustion of fossil fuels for thermal energy production. A detailed results analysis can be obtained from the dominance analysis presented in Tables 15 – 17 in the report.

The Eco-profile report also contains a sensitivity analysis in which the results are based on oil and gas extraction processes considering higher methane losses, i.e. scenario “IEA methane venting”. Results for all indicators as well as an updated dominance analysis for this scenario are presented in Tables 18 – 23 in the report.

Furthermore, the Eco-profile report also includes a detailed comparison of the results with the previous version of the VCM and PVC Eco-profile from 2016. For details, please refer to the chapter 'Comparison of the present Eco-profile with its previous version'.

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 and Environmental Declarations – LCI Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors (PCR version 3.1, September 2021). As a result, this dataset is assessed to be a reliable and high-quality representation of VCM, S-PVC and E-PVC produced in Europe.

Stuttgart, 28.06.2023

Matthias Schulz

Schulz Sustainability Consulting, Stuttgart, Germany

# References


Bos, U.; Horn, R.; Beck, T.; Lindner, J. P.; Fischer, M. (2016): LANCA® - Characterization Factors for Life Cycle Impact Assessment. Version 2.0. Fraunhofer Verlag.

CML (2002): Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards. Kluwer Academic Publ., Dordrecht.

De Leeuw, F. A. A. M. (2002): A set of emission indicators for long-range transboundary air pollution. In: *Environmental Science & Policy*. Vol. 5, S. 135–145.

Derwent, R. G.; Jenkin, M. E.; Saunders, S. M.; Pilling, M. J. (1998): Photochemical ozone creation potentials for organic compounds in northwest Europe calculated with a master chemical mechanism. In: *Atmospheric Environment*. Vol. 32, S. 2429–2441.

Dreicer, M.; Tort, V.; Manen, P. (1995): ExternE: Externalities of energy Vol. 5. Nuclear.

EcoTransIT (2018): EcoTransIT World - Ecological Transport Information Tool for Worldwide Transports. ifeu, INFRAS, IVE, Heidelberg, Berne, Hannover. *https://www.ecotransit.org/download/EcoTransIT_World_Methodology_ShortVersion_2018.pdf* (26.09.2022).

EuroChlor (2020): Chlor-alkali industry review 2019 - 2020. Euro Chlor. S. 24. *https://www.eurochlor.org/wp-content/uploads/2020/09/Industry-Review-2019_2020.pdf* (12.05.2021).

EuroChlor (2022): An Eco-profile and Environmental Product Declaration of the European Chlor-Alkali Industry. Chlorine (The Chlor-Alkali Process). EuroChlor. *https://www.eurochlor.org/wp-content/uploads/2022/02/2022-Euro-Chlor-Eco-profile.pdf* (26.09.2022).

Eurostat (2022): Energy – Yearly statistics 2019. Eurostat, Luxembourg. *https://ec.europa.eu/eurostat/de/data/database* (26.09.2022).

Fazio, S.; Biganzioli, F.; De Laurentiis, V.; Zamperoni, L.; Sala, S.; Diaconu, E. (2018): Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods. European Commission, Joint Research Center. S. 49. *https://eplca.jrc.ec.europa.eu/permalink/TR_SupportingCF_FINAL.pdf* (29.09.2022).

Fehrenbach, H.; Lauwigi, C.; Liebich, A.; Ludmann, S. (2016): Documentation for the UMBERTO based ifeu electricity model. S. 31. *https://www.ifeu.de/en/project/power_generation_model/*.

Fischer, I.; Schmitt, W. F.; Porth, H.-C.; Allsopp, M. W.; Vianello, G. (2014): Poly(Vinyl Chloride). In: *Ullmann's Encyclopedia of Industrial Chemistry*. American Cancer Society. S. 1–30.

Frischknecht, R.; Braunschweig, A.; Hofstetter, P.; Suter, P. (2000): Human health damages due to ionising radiation in life cycle impact assessment. In: *Environmental Impact Assessment Review*. Vol. 20, No. 2, S. 159–189.

Goedkoop, M.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; Van Zelm, R. (2008): ReCiPe 2008. In: *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. Vol. 1, S. 1–126.

Hauschild, M. Z.; Wenzel, H. (1998): Scientific background. Environmental Assessment of products Chapman & Hall, London.

HBEFA (2022): HBEFA - Handbook Emission Factors for Road Transport v4.2. https://hbefa.net/e/index.html. (26.09.2022).

Heijungs, R.; Guinée, J. B.; Huppes, G.; Lankreijer, R. M.; Udo de Haes, H. A.; Wegener Sleeswijk, A.; Ansems, A. M. M.; Eggels, P. G.; Duin, R. van; De Goede, H. P. (1992): Environmental life cycle assessment of products: guide and backgrounds (part 1).

Heldstaab, J.; de Haan van der Weg, P.; Künzle, T.; Keller, M.; Zbinden, R. (2003): Modelling of PM10 and PM2.5 ambient concentrations in Switzerland 2000 and 2010. Environmental Documentation Swiss Agency for the Environment, Forests and Landscape (SAEFL), Bern. *http://www.dehaan.ch/pubs/EnvDoc169.pdf* (26.09.2022).

IPCC (2014): Climate Change 2013: The physical science basis. contribution of working group I to the fifth assessment report of IPCC the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change. *https://www.cambridge.org/core/books/climate-change-2013-the-physical-science-basis/BE9453E500DEF3640B383BADDC332C3E* (26.09.2022).

ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework. International Standardisation Organisation, Geneva.

ISO 14044 (2006): Environmental management - Life cycle assessment - Requirements and guidelines. International Standardisation Organisation, Geneva.

Jenkin, M. E.; Hayman, G. D. (1999): Photochemical ozone creation potentials for oxygenated volatile organic compounds: sensitivity to variations in kinetic and mechanistic parameters. In: *Atmospheric Environment*. Vol. 33, S. 1275–1293.

LVOC BREF (2017): Best Available Techniques (BAT) Reference Document for the Production of Large Volume Organic Chemicals. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). European Commission. *https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC109279_LVOC_Bref.pdf* (28.10.2020).

NIST (2022): webbook.nist.gov.

van Oers, L.; de Koning, A.; Guinée, J. B.; Huppes, G. (2002): Abiotic resource depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam. *https://web.universiteitleiden.nl/cml/ssp/projects/lca2/report_abiotic_depletion_web.pdf* (26.09.2022).

PlasticsEurope (2011): Eco-profiles and Environmental Declarations, Version 2.0. PlasticsEurope. *https://web.archive.org/web/20140912210604/http://www.plasticseurope.org:80/documents/document/20110421141821-plasticseurope_eco-profile_methodology_version2-0_2011-04.pdf* (04.10.2022).

PlasticsEurope (2016): Vinyl chloride (VCM) and Polyvinyl chloride (PVC) PlasticsEurope / The European Council of Vinyl Manufacturers (ECVM). PlasticsEurope.

PlasticsEurope (2021a): PlasticsEurope Ecoprofiles program and methodology, Version 3.1. *https://plasticseurope.org/wp-content/uploads/2022/11/Ecoprofiles-Methodology-V3.1.zip*.

PlasticsEurope (2021b): Plastics - the Facts 2021. An analysis of European plastics production, demand and waste data. PlasticsEurope. *https://plasticseurope.org/wp-content/uploads/2021/12/AF-Plastics-the-facts-2021_250122.pdf* (26.09.2022).

PlasticsEurope (2021c): Eco-profile of toluene diisocyanate (TDI) and methylene diphenyl diisocyanate (MDI). PlasticsEurope. *http://www.isopa.org/media/1101/ISOPA_Eco-profile_TDI_MDI_2021.pdf* (26.09.2022).

PlasticsEurope (2021d): Eco-profile of Steam Cracker Products: Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), Ethylene Glycols (MEG, DEG, TEG), unpublished. PlasticsEurope.

PlasticsEurope (2021e): Eco-profile Building Block: Crude oil and Natural Gas, unpublished. PlasticsEurope.

Posch, M.; Seppälä, J.; Hettelingh, J. P.; Johansson, M.; Margni, M.; Jolliet, O. (2008): The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. In: *International Journal of Life Cycle Assessment*. Vol. 13, No. 6, S. 477–486.

Ravishankara, A. R.; Daniel, J. S.; Portmann, R. W. (2009): Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. In: *Science*. American Association for the Advancement of Science. Vol. 326, No. 5949, S. 123–125.

Rosenbaum, R. K.; Bachmann, T. M.; Gold, L. S.; Huijbregts, M. A. J.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H. F.; MacLeod, M.; Margni, M.; McKone, T. E.; Payet, J.; Schuhmacher, M.; van de Meent, D.; Hauschild, M. Z. (2008): USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. In: *The International Journal of Life Cycle Assessment*. Vol. 13, No. 7, S. 532.

Seppälä, J.; Posch, M.; Johansson, M.; Hettelingh, J. P. (2006): Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. In: *International Journal of Life Cycle Assessment*. S. 403–416.

TREMOD (2019): TREMOD - Transport Emission Model: „Daten- und Rechenmodell Schadstoffemissionen aus dem motorisierten Verkehr in Deutschland 1960-2030“. Institut für Energie- und Umweltforschung (ifeu). *http://www.ifeu.de/english/index.php?bereich=ver&seite=projekt_tremod*.

UNEP (2016): Global Guidance for Life Cycle Impact Assessment Indicators Volume 1. United Nations Environment Programme. *https://www.lifecycleinitiative.org/wp-content/uploads/2016/10/LCIA-publication-preview.pdf* (26.09.2022).

VinylPlus (2017): PVC recycling technologies. VinylPlus. *https://vinylplus.eu/wp-content/uploads/2017/02/VinylPlus_PVC_recycling_tech_20092017.pdf* (26.09.2022).

Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. (2016): The ecoinvent database version 3 (part I): overview and methodology. In: *The International Journal of Life Cycle Assessment*. Vol. 21, No. 9, S. 1218–1230.

WMO (2014): Scientific Assessment of Ozone Depletion: 2014. World Meteorological Organization (WMO), Geneva.

van Zelm, R.; Huijbregts, M. A. J.; den Hollander, H. A.; van Jaarsveld, H. A.; Sauter, F. J.; Struijs, J.; van Wijnen, H. J.; van de Meent, D. (2008): European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. In: *Atmospheric Environment*. Vol. 42, No. 3, S. 441–453.