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)

May 2015

Environmental Product Declaration

Introduction

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

This EPD describes the production of the 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
Programme Manager, Reviewer	DEKRA Assurance Services GmbH
Number of plants included in data collection	38
Representativeness	VCM 71% S-PVC 60% - E-PVC 83%
Reference year	2013
Year of data collection and calculation	2014
Expected temporal validity	2018
Cut-offs	none
Data Quality	good
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), most ethylene used in the manufacture of EDC is produced by steam cracking of naphtha. Chlorine is produced by electrolysis of sodium chloride (NaCl).

The model of this Eco-profile comprises extraction and refinery of crude oil for the ethylene production, salt recovery and chlorine electrolysis 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 Eco-profile and EPD for ethylene [PLASTICSEUROPE 2012A] and chlorine production is based on the Eco-profile and EPD for chlorine [EUROCHLOR 2013].

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 of each considered PVC type.

Input Parameters

Indicator	**Unit**	**Vinyl chloride (VCM)**	**Suspension PVC (S-PVC)**	**Emulsion PVC (E-PVC)**
Non-renewable energy resources 1)	MJ	51.1	56.9	66.1
• Fuel energy	MJ	30.4	36.2	45.4
• Feedstock energy	MJ	20.7	20.7	20.7
Renewable energy resources (biomass) 1)	MJ	3.6	3.7	4.7
• Fuel energy	MJ	3.6	3.7	4.7
• Feedstock energy	MJ	0.0	0.0	0.0
Abiotic Depletion Potential				
• Elements	kg Sb eq	1.3×10^{-5}	1.3×10^{-5}	1.4×10^{-5}
• Fossil fuels	MJ	42.8	47.2	54.2
Water use	kg	162.0	197.7	280.9
• for process	kg	41.4	44.2	48.2
• for cooling	kg	120.6	153.5	232.7

1) Calculated as upper heating value (UHV)

Output Parameters

Indicator	**Unit**	**Vinyl chloride (VCM)**	**Suspension PVC (S-PVC)**	**Emulsion PVC (E-PVC)**
Global Warming Potential (GWP)	kg CO2 eq	1.71	1.99	2.56
Ozone Depletion Potential (ODP)	g CFC-11 eq	1.9 x 10-^{3}	2.2 x 10-^{3}	2.4 x 10-^{3}
Acidification Potential (AP)	g SO2 eq	4.50	5.05	6.93
Photochemical Ozone Creation Potential (POCP) 2)	g Ethene eq	0.50	0.56	0.54
Eutrophication Potential (EP)	g PO4 eq	0.81	0.94	1.25
Dust/particulate matter ≤ 10 µm 3) (PM10)	g PM10	3.36	3.84	5.05
Total particulate matter 2)	g	3.63	4.18	5.60
Waste	g	17.86	21.41	27.33
• Non-hazardous	g	14.64	12.47	16.20
• Hazardous	g	1.28	1.83	1.08
• Unspecified	g	1.94	7.11	10.04

2) Including NMVOC (0.15 / 0.16 / 0.19 g Ethene eq./kg VCM/S-PVC/E-PVC)

3) Including secondary PM10 (particulate matter formed from precursors, see Chapter "Life Cycle Assessment" for details)

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 Vinyl 2010 commitments, the European PVC industry launched VinylPlus in 2011, the new ten-year voluntary commitment of the European PVC industry. It addresses five key sustainable development challenges, including controlled loop management of PVC and sustainable use of additives. (More information can be found under: [VINYLPLUSA]). Recycling and more generally end-of-life treatment of PVC is described in the "PVC recycling technologies brochure available for download from [VINYLPLUSB]. 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 on [PVC].

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.

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 1930s 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; from a global point of view, however, demand and production of PVC are still growing.

Information

Data Owners

The European Council of Vinyl Manufacturers (ECVM); PVC sector group of PlasticsEurope
Avenue E van Nieuwenhuyse 4, Box 4
B-1160 Brussels, Belgium
Tel.: +32 (2) 676 74 45, Fax: +32 (2) 676 74 47
E-mail: info@plasticseurope.org.

Programme Manager & Reviewer

DEKRA Assurance Services GmbH

This Environmental Product Declaration has been reviewed by DEKRA Assurance Services GmbH. It was approved according to the Product Category Rules PCR version 2.0 (2011-04) and ISO 14025:2006.

Registration number: PlasticsEurope 2015-005, validation expires on 30 June 2018 (date of next revalidation review).

Programme Owners

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

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

References

- PlasticsEurope 2011: Eco-profiles and environmental declarations – LCI methodology and PCR for uncompounded polymer resins and reactive polymer precursor (version 2.0, April 2011).

- PlasticsEurope 2012: Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers - Ethylene, Propylene, Butadiene, Pyrolysis Gasoline, Ethylene Oxide (EO), Ethylene Glycols (MEG, DEG, TEG), November 2012.

- EuroChlor 2013: Eco-profiles and Environmental Product Declarations of the European Chlor Manufacturers - Chlorine (The chlor-alkali process). November 2013.

Goal & Scope

Intended Use & Target Audience

➢ *Eco-profiles (LCIs) and EPDs from this programme are intended to be used as »cradle-to-gate« building blocks of life cycle assessment (LCA) studies of defined applications or products. LCA studies considering the full life cycle (»cradle-to-grave«) of an application or product allow for comparative assertions to be derived. It is essential to note that comparisons cannot be made at the level of the polymer or its precursors. In order to compare the performance of different materials, the whole life cycle and the effects of relevant life cycle parameters must be considered.*

PlasticsEurope Eco-profiles and EPDs represent polymer production systems with a defined output. They can be used as modular building blocks in LCA studies. However, these integrated industrial systems cannot be disaggregated further into single unit processes, such as polymerisation, because this would neglect the interdependence of the elements, e.g. the internal recycling of feedstock and precursors between different parts of the integrated production sites.

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

As a consequence, a direct comparison of Eco-profiles or EPDs makes no sense because 1 kg of a certain polymer is not functionally equivalent with 1 kg of any other polymer.

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

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

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

Product Category and Declared Unit

Product Category

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

Functional Unit and Declared Unit

The Functional Unit and Declared Unit of this 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 and Producer Description

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 industrial production of each product. Main characteristics of the products under investigation are presented in Table 1.

Table 1: Characteristics of the products 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 2011]

b) communications with ECVM, value for PVC resin

Vinyl chloride (VCM) is a colourless, toxic, flammable, and carcinogenic gas with a sweet odor. 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) demand has a share of 10.4% on the polymer market [PLASTICSEUROPE 2014]. In the years 2011-2013 the European demand of polyvinyl chloride is indicated with about 5 Mt/year [PLASTICSEUROPE 2014].

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 2014].

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.

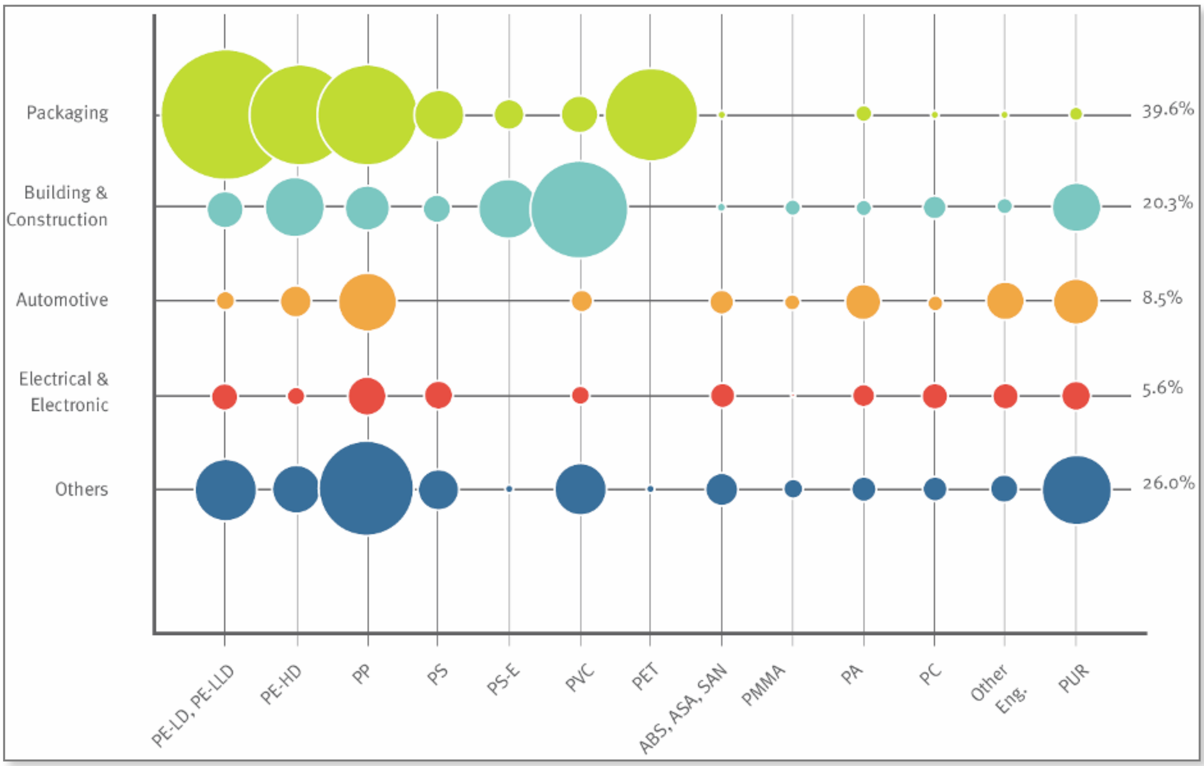

Figure 1: European (EU27+NO+CH) plastics demand by segment and resin type 2013. Source: [PlasticsEurope 2014].

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.

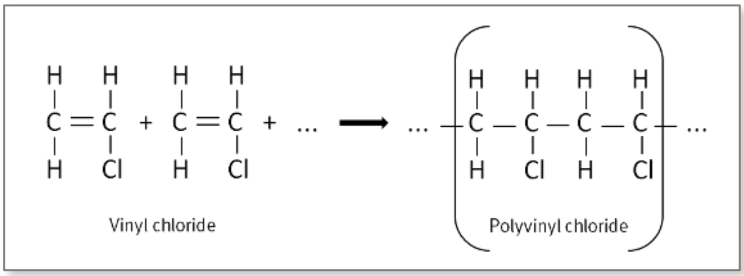

Figure 2: Polymerisation of vinyl chloride yield polyvinyl chloride

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.

Production Process Description

[**Allsopp 2010**, **BREF 2003**, **BREF 2007**, **BREF 2014**, **Kaiser 2011**]

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) 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 EPD and Eco-profiles, in particular the EPD of steam cracker products (ethylene) [PlasticsEurope 2012A], and the EPD for chlorine (Chlor-alkali process) [EuroChlor 2013]. 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.

The reactions are represented by the formulae:

Direct chlorination: $\mathrm{C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2\ (EDC)}$; $\Delta \mathrm{H_{R,0}} = -220\ \mathrm{kJ/mol}$
Cracking: $\mathrm{C_2H_4Cl_2 \rightarrow C_2H_3Cl\ (VCM) + HCl}$; $\Delta \mathrm{H_{R,0}} = +\ 97\ \mathrm{kJ/mol}$
Oxychlorination: $\mathrm{C_2H_4 + ½\ O_2 + 2\ HCl \rightarrow C_2H_4Cl_2\ (EDC) + H_2O}$; $\Delta \mathrm{H_{R,0}} = -320\ \mathrm{kJ/mol}$

For the production of EDC in a balanced unit the raw material requirements comprise 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.

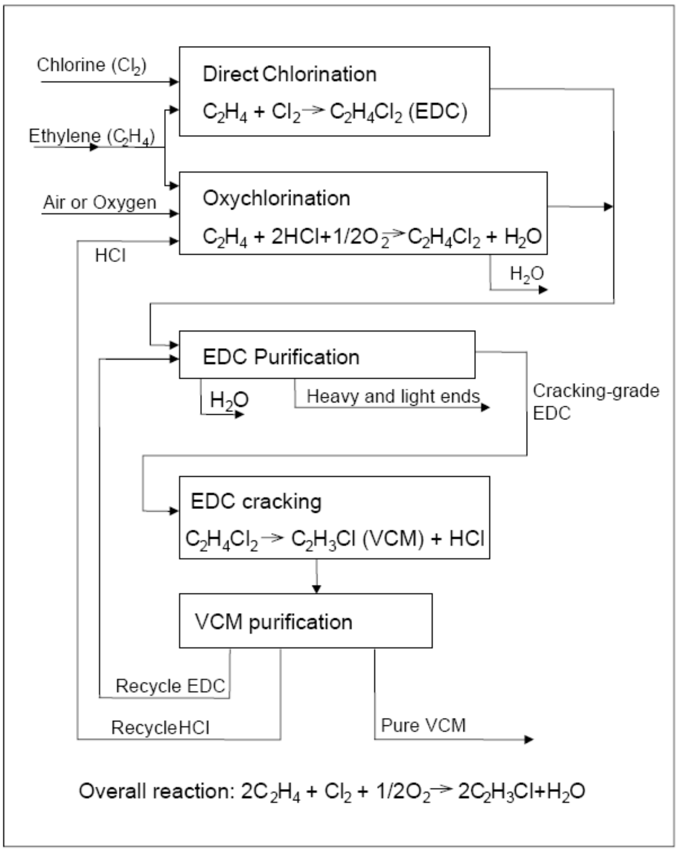

Figure 3: Flow diagram of EDC and VCM manufacturing process. Source: [BREF 2003]

Direct chlorination of Ethylene

The direct chlorination process of ethylene and chlorine is an exothermic reaction, using the EDC product as the reaction medium. The operating temperatures are normally 50 - 120°C and the applied pressure ranges from atmospheric to 5 bar.

The reaction takes place in the liquid phase in the presence of a catalyst (usually Fe(III) chloride). A slight excess of chlorine or ethylene is preferred to ensure high ethylene conversion. The reaction product consists of >99% pure EDC. Less than 1% is made up of other chlorinated hydrocarbons, predominantly 1,1,2-trichloroethane and ethyl chloride. To reduce the formation of chlorinated by-products an inhibitor can be added, typically oxygen (especially to reduce the formation of 1,1,2-trichloroethane).

Currently, two variants of the direct chlorination reaction are used: low temperature chlorination and high temperature chlorination. According to BREF, approximately half of the plants in the EU operate with a low temperature DC design and the rest operate with a high temperature approach.

For low temperature chlorination the reaction is operated below the EDC boiling point at about 20 – 70°C. The heat of the reaction can be dissipated by external cooling, either by means of heat exchangers inside the reactor or by circulation through exterior heat exchangers. The catalysts have to be removed from the liquid EDC when it leaves the reactor. For this purpose, EDC is generally washed and thus requires drying and distillation before cracking to a liquid effluent, which again requires further treatment.

For high temperature chlorination the reaction is operated above the EDC boiling point. The temperature range is about 85 – 200°C, with a most commonly applied operation temperature at about 100°C. The EDC leaves the reaction section as a vapour and can be directly sent to the EDC cracking unit. In this process, energy may be recovered from the hot vapour.

The application of low temperature chlorination produces fewer by-products than high temperature chlorination. However, this process requires considerably higher energy inputs – compared to high temperature chlorination – due to the need for EDC distillation.

Oxychlorination of Ethylene

Compared to direct chlorination the oxychlorination process yields less EDC but provides the HCl sink that realises the balanced process. EDC and water are formed by the gas phase reaction of HCl, ethylene and oxygen over a copper-salt catalyst at 220 – 250°C at a pressure of 2 - 6 bar. Typically, fluidised bed reactors are used as reaction-technology; fixed beds are also used in some plants. Regarding this highly exothermic reaction, temperature control is important to minimise the production of undesirable by-products. The recovered heat of the exothermic reaction is usually used to generate steam.

The used HCl has to be of suitable purity. HCl from external sources can be used if the required purity is given. Sources may be the production processes of MDI/TDI, K_2SO_4, allyl chloride, MCA, DCM or chloroform[1], where HCl is formed as a by-product (or waste). Additionally, HCl is recycled from the EDC cracking unit and from VCM purification. The oxygen source can be ambient air, or oxygen, or a mixture of both. The use of air systems results in an increased formation of chlorinated by-products and larger waste streams, whereas oxygen systems require a larger excess of ethylene in the feed and an additional energy input for the production of oxygen. The resulting EDC and the by-products are separated from the inert gases by cooling and condensing at successively decreasing temperatures. After quenching and condensation water and EDC (including other organic chlorinated hydrocarbons) separate naturally into two phases due to the low solubility of EDC and most of the other chlorinated hydrocarbons in water.

The oxychlorination stage generates a number of waste streams which do not occur in the case of direct chlorination, comprising impurities removed from the EDC as by-products from the EDC distillation section, process vents requiring treatment, aqueous effluents containing dissolved chlorinated organic compounds, traces of catalyst material in aqueous effluents or spent catalyst, and dioxin related compounds. However, these wastes are not directly emitted into the environment. Instead, further control measures allow for a significant reduction of problematic substances before discharge.

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[1] MDI/TDI - methylene diphenyl diisocyanate and toluene diisocyanate, production uses Cl_2
K_2SO_4 – potassium sulphate production, production uses potassium chloride KCl
Allyl chloride – 3-chloropropene, production uses Cl_2
MCA – monochloroacetic acid, using acetic acid and Cl_2, or trichloroethylene
DCM or chloroform – dichloromethane or trichloromethane, production uses Cl_2

EDC purification

EDC products, whether they originate from direct chlorination or oxychlorination, from VCM purification recycling or external sources, have to be purified, since EDC cracking may be susceptible to inhibition and fouling by trace quantities of impurities. Purification may entail washing with water or caustic, azeotropic drying, heavy ends distillation, etc.

EDC cracking

The production of VCM from EDC is achieved by a cracking reaction followed by quenching of the process gas stream. When subjected to thermal cracking in heated furnaces at temperatures of approximately 500°C, purified EDC splits into VCM and HCl with conversion rates of 50 – 65%. The pyrolysis gases have to be cooled rapidly to reduce the formation of tars and heavy by-products. As mentioned above, the purity of the EDC feed has to be very high and greater than 99.5 wt. to reduce coke formation and fouling of the pyrolysis reactor.

VCM purification

After the cracking reaction, HCl and unconverted EDC are separated from VCM by two-stage distillation. Unconverted EDC is transferred back to EDC purification and recycled to the cracking furnaces. After an optional hydrogenation stage to remove any remaining traces of acetylene, distilled HCl is recycled as feedstock to oxychlorination. Most of the volatile by-products are removed via the HCl flow to oxychlorination. The liquid VCM product is transferred to storage after an optional step to remove the last traces of HCl.

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. The suspension polymerisation, yielding about 85% of the global production [PlasticsEurope 2008a], emulsion polymerisation, with a share of about 12% [PlasticsEurope 2008b] and mass resp. bulk polymerisation with about 3% [PlasticsEurope 2005]. . The bulk polymerisation process lost importance over the past years and has, therefore, not been discussed within BREF 2007. This Eco-profile is omitting bulk polymerisation PVC for similar reasons. 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 microsuspension 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.

Suspension polymerisation

PVC resin resulting from the suspension process (S-PVC) has a mean particle size of 50 – 200 µm. The essential differences between S-PVC grades result from the average length of polymer chains and from the porosity of the particles. Suspension PVC is always produced batch wise in a stirred vessel. The monomer is dispersed in demineralised water by the combination of mechanical stirring and surfactants. The polymerisation takes place inside the VCM droplets under the influence of VCM soluble initiators. The suspension polymerisation of polyvinyl chloride is illustrated in Figure 4.

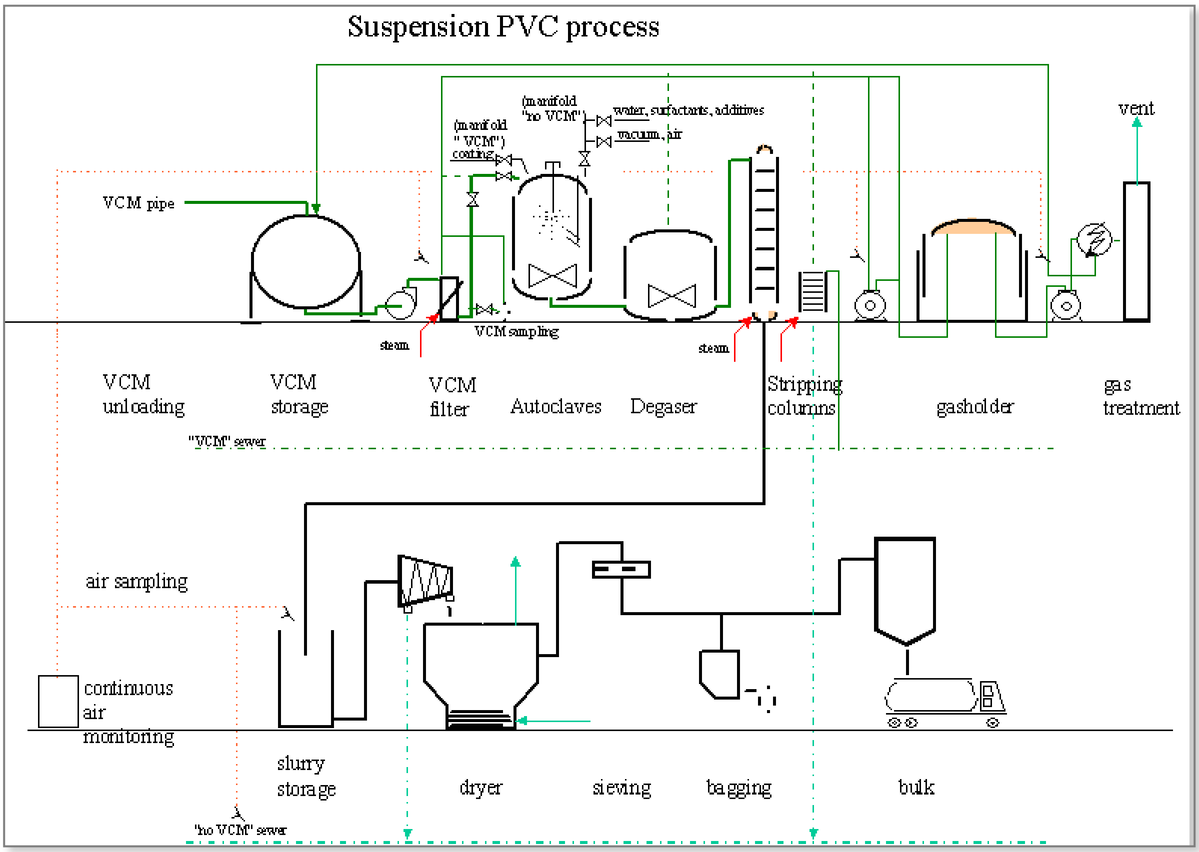

Figure 4: *Flow diagram of an S-PVC polymerisation process. Source: [BREF 2007]*

Emulsion polymerisation

The mean particle size of E-PVC, polyvinyl chloride polymerised in emulsion process, is about 0.1 – 3 µm. E-PVC is mainly manufactured via one of three polymerisation processes: batch emulsion, continuous emulsion and microsuspension. Depending on the process used, the mean particle size of the E-PVC can be adjusted, affecting the product properties and application possibilities. Regarding paste or plastisol polymer properties, e.g., the PVC particle size distribution achieved during the polymerisation process will largely determine the rheology of the plastisol, when the polymer is redispersed in plasticiser.

In the batch emulsion process, the emulsifier used is usually a sodium alkyl, aryl sulphonate, or alkyl sulphate. The polymerisation takes place in the VCM-water boundary layer, supported by a water-soluble initiator such as alkali metal persulphate. A redox system involving traces of copper and a reduction agent is often used. This reaction system produces small and narrow width unimodal PVC particles (approximately 0.2 µm). Using seed particles allows them to grow while new particles are forming simultaneously, resulting in a bimodal particle size distribution.

During the continuous emulsion polymerisation process fresh VCM, emulsifier and an initiator are constantly fed to the reactor and the dispersed PVC particles are withdrawn continuously.

A wide particle size distribution can also be achieved via the microsuspension polymerisation process. In this process an initiator such as lauroyl peroxide is used, being highly soluble in VCM but insoluble in water. The water insolubility helps to stabilise the VCM droplet, which reduces the amount of emulsifier needed for the microsuspension process. Reducing the input of emulsifier can be advantageous for the environmental impact of the production process, influence material properties such as water absorption or transparency, or reduce health issues of food packaging products. The emulsion polymerisation process of PVC is illustrated in Figure 5.

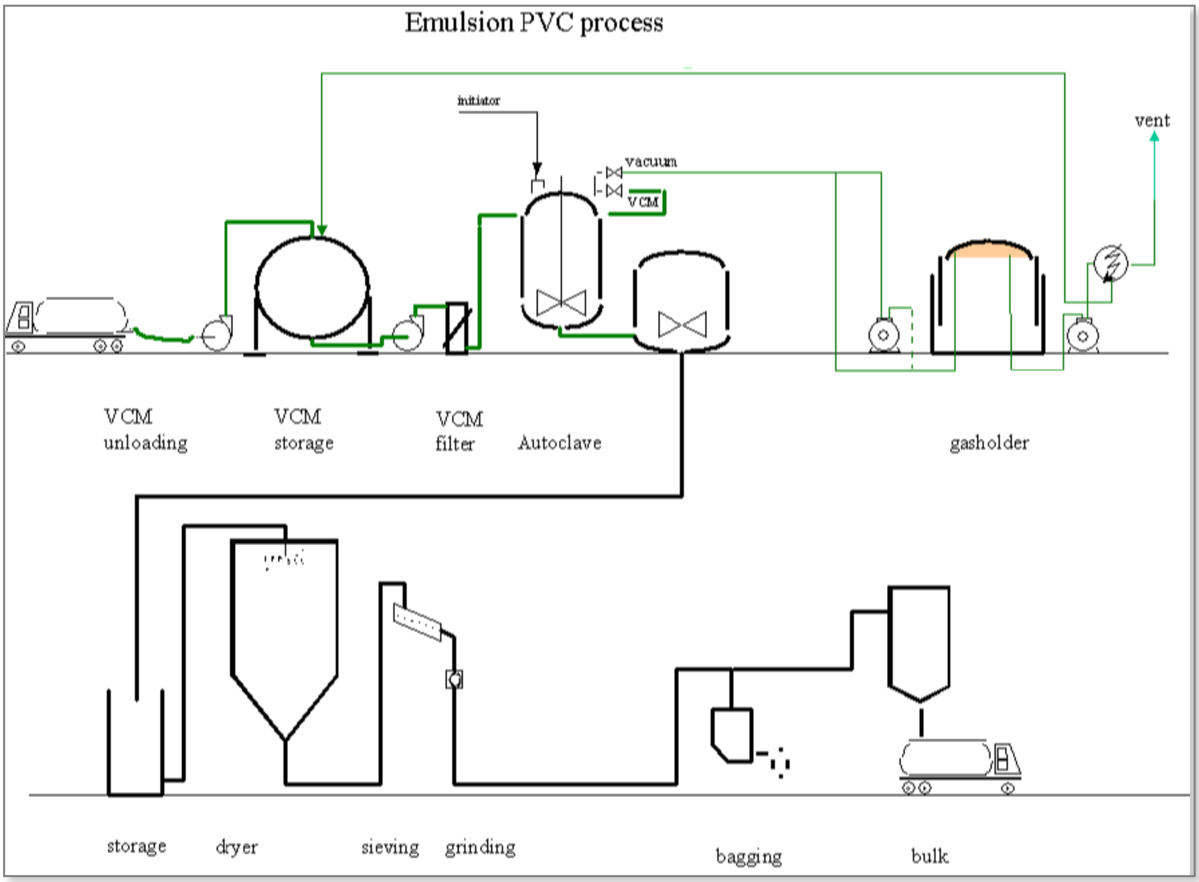

Figure 5: Flow diagram of an E-PVC polymerisation process. Source: [BREF 2007]

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)*
- *INEOS ChlorVinyls*
- *Shin-Etsu Chemical Co., Ltd.*
- *SolVin SA*
- *VESTOLIT GmbH*
- *Vinnolit GmbH & Co. KG*

Data was collected from the European 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 2013) were requested.

Eco-profile – Life Cycle Inventory

System Boundaries

PlasticsEurope Eco-profiles and EPDs refer to the production of polymers as a cradle-to-gate system (Figure 6).

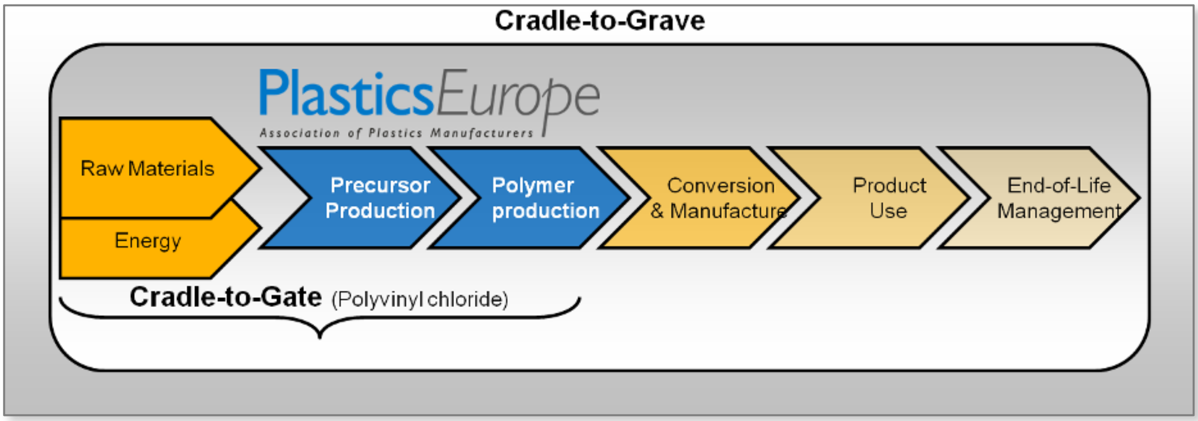

Figure 6: *Cradle-to-gate system boundaries for the production of polyvinyl chloride (PVC)*

Cradle-to-Gate System Boundaries for Production

The following processes are included in the cradle-to-gate LCI system boundaries:

- 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 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 for Eco-profiles (PlasticsEurope v 2.0, April 2011) capital goods, i.e. the construction of plants and equipment as well as the maintenance of plants, vehicles, and machinery, are 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.

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 **60%** of S-PVC producers and **83%** of E-PVC producers in Europe in 2013 (with respect to the installed nameplate capacity of all European producers, Source: communications with PlasticsEurope, 2014), so the technological coverage is understood as fairly representative. The coverage with respect to VCM production comprises **71%** 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 2013.

Table 2: Participating EDC/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	3,403	2,986	88%
E-PVC	791	663	84%
EDC/VCM	5,275	4,472	85%

[1)] Based on total installed European nameplate capacity; Source: communications with PlasticsEurope, 2014

From the total number of 73 EDC, VCM and PVC producing plants in Europe 43 have been requested to take part in this study, constituting the PlasticsEurope member plants. 38 of these plants have succeeded in providing complete data sets for this Eco-profile and can thus be considered as participants of this study. 13 plants provided complete data sets for the ethylene dichloride (EDC) and vinyl chloride monomer (VCM) production, 25 for polyvinyl chloride (PVC) production. Of these PVC producing plants, 14 were able to provide data for suspension polyvinyl chloride processing (S-PVC) and 11 for emulsion polyvinyl chloride processing. The remaining 5 of the total number of 43 monomer and polymer plants did fail to participate in the data collection due to several reasons:

- converting from EDC/VCM to only EDC in 2013 (1 EDC/VCM)
- being in a shut-down phase in 2013 (1 S-PVC)
- failure to deliver complete data sets, due to internal reasons (3 S-PVC)

In the year 2013, the 28 running PVC plants (17 S-PVC and 11 E-PVC, excluding one S-PVC plant in shut-down phase, assumed to have no production in 2013) owned by ECVM members represented 73% and 83% of the European nameplate capacities of S-PVC and E-PVC production, respectively. However, within the S-PVC fraction only 14 plants provided sufficient data sets, representing a share of 60% of the European nameplate capacity.

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):

	Selected units for Eco-profile	**Participating units providing data**	**Coverage of production by nameplate capacity[1)]**
S-PVC	18	14	60%
E-PVC	11	11	83%
VCM	13	12	71%
EDC	1	1	n.a.

[1)] Based on total installed European nameplate capacity; Source: communications with PlasticsEurope, 2014

According to the PlasticsEurope LCI methodology and product category rules for uncompounded polymer resins and reactive polymer precursors v.2.0, Eco-profiles shall differentiate:

- primary data from foreground processes, i.e. those that are under operational control (polymer production process, on-site utilities), and
- secondary data from background processes, i.e. those operated by third parties where only indirect management control or no control exists.

Temporal Reference

The LCI data for production was collected as 12 month averages representing the year 2013, to compensate seasonal influence of data. The overall reference year for this Eco-profile is 2013 with a maximal temporal validity until 2018. It seems adequate to refer to the 5-year interval that is proposed in the Product Category Rules for Polymers [PLASTICSEUROPE 2011]. Thus, the dataset can be adjusted to current process improvements or changes in the European electricity production mix.

Geographical Reference

Primary production data for the PVC production is from 25 different suppliers in the EU27 member states, Norway, and Switzerland (EU27+NO+CH). For 6 of the considered countries – Belgium, Germany, Netherlands, Norway, Portugal, Sweden – 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. The remaining 3 countries – France, Spain, UK – exhibit coverage rates of around 50%. In total, the geographical coverage is biased towards the production from western European sites, excluding 12% of VCM production, 13% of S-PVC production, and 6% of E-PVC production from Czech Republic, Hungary, Poland and Slovakia combined.

Cut-off Rules

To achieve completeness, i.e. a closed mass and energy balance, any cut-off of material and energy flows has been avoided in this Eco-profile. For commodities with a total input of less than 1 wt.-% of the total material input (additives, other compounds, etc.) generic datasets from the LCA database Ecoinvent v3.1 [ECOINVENT 2014] have been used. Waste for recycling is generally cut off within Ecoinvent datasets. Furthermore, expenses for capital equipment were not considered in this Eco-profile.

Data Quality Requirements

Data Sources

This Eco-profile and EPD uses average data representative of the respective foreground production process, both in terms of technology and market share. 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 precursor production, i.e. ethylene and chlorine, are taken from published Eco-profiles, in particular the Eco-profile of steam cracker products (ethylene) [PlasticsEurope 2012A], and the Eco-profile for chlorine (Chlor-alkali process) [EUROCHLOR 2013] 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 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 18% of total chlorine input). This approach is justified by the fact that in the published Eco-profile for MDI/TDI [PLASTICSEUROPE 2012B] burdens are allocated by mass between the main product MDI and the by-product HCl, resulting in unreasonably high environmental loads for HCl. For example, the GWP of HCl from MDI production is higher than the GWP of Cl_2 by a factor of 2.6. A sensitivity analysis was performed to estimate the effects of using one of the three possible approaches: a) calculate HCl as if it was primary Cl_2, b) use the published HCl from MDI (mass allocated) c) use an unpublished dataset for HCl from MDI (price allocated). The results of this sensitivity analysis are presented in section "Sensitivity Analysis for HCl data sources" (p. 38).

As fuel oil and natural gas are commonly used as fuels for the production of heat, i.e. in the form of process steam or on-site power generation, it is necessary to represent their upstream chains adequately to achieve appropriate LCI results in this study, especially regarding air emissions. For the compilation of this Eco-profile up-to-date data of the upstream chains of fuel oil and natural gas, which had been collected and implemented recently, are used. They are based on the database Ecoinvent v2.2 [ECOINVENT 2010]. A country-specific mix according to the respective polymer production site is considered, applying statistical data from Eurostat for the year 2011. The upstream chains for crude oil and natural gas have been updated with primary data for the main production countries/regions, particularly concerning the inputs and outputs. Primary data derive from environmental/annual reports, either of associations of the oil and gas producing industry, or directly from major producers representing specific regions (e.g. the North Sea region, Russia, OPEC countries). Furthermore, data from scientific studies is used for the update of the upstream chain of natural gas.

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 v2.2 [ECOINVENT 2010].

For transport processes the main data sources are

- Rail: ECOTRANSITWORLD 2011
- Road: Handbook Emission Factors for Road Transport [HBEFA 2014]
- Ship: ECOTRANSITWORLD 2011
- Pipeline: Ecoinvent v3.1 [ECOINVENT 2014]

Datasets for other relevant inputs, e.g. additives, surfactants, or auxiliary materials used in waste management or water preparation are also taken from the database Ecoinvent v2.2 [ECOINVENT 2010].

Electric power supply is modelled using country-specific grid electricity mixes, since the environmental burdens of power production vary significantly 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 IFEU 2011. This network considers all 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 is calculated. It is based on national electricity mix data by EUROSTAT [2014] for the reference year, which is 2012 for all countries.

The system boundary of the electricity module contains:

- 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 from cogeneration of heat and power 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 website of IFEU [IFEU 2011].

Relevance

With respect to the goal and scope of this Eco-profile, the collected primary data of foreground processes are of high relevance, comprising data from the most important producers in Europe in order to generate results for a European industry average production. The environmental contributions of each process to the overall LCI results can be found in Chapter ‘Life Cycle Impact Assessment’.

Representativeness

The data used for this study covers 60% and 83% of the installed S-PVC and E-PVC nameplate capacities, respectively, and 71% of the installed VCM nameplate capacities in Europe (EU27 + Norway + Switzerland) in 2013. 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

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

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, are based on IFEU models that are regularly updated with statistical data, available primary data, and data derived from literature after quality reviews and checks. Thus, the overall reliability of data for this Eco-profile is considered very high.

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

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 PVC plants 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 waste transport.

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.

Reproducibility

All data and information used are either documented in this report or 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 provided data and 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 applied database. It is worth noting that for external audiences full reproducibility with a certain degree of detail will not be available for confidentiality reasons. However, experienced experts should be able to easily recalculate and reproduce suitable parts of the system as well as 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 life cycle system is modelled in Umberto 5.6, a standard software tool for LCA (see Figure 7 for a simplified model). 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 calculation follows the vertical calculation methodology, i.e. the averaging is done after modelling the specific processes.

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 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.

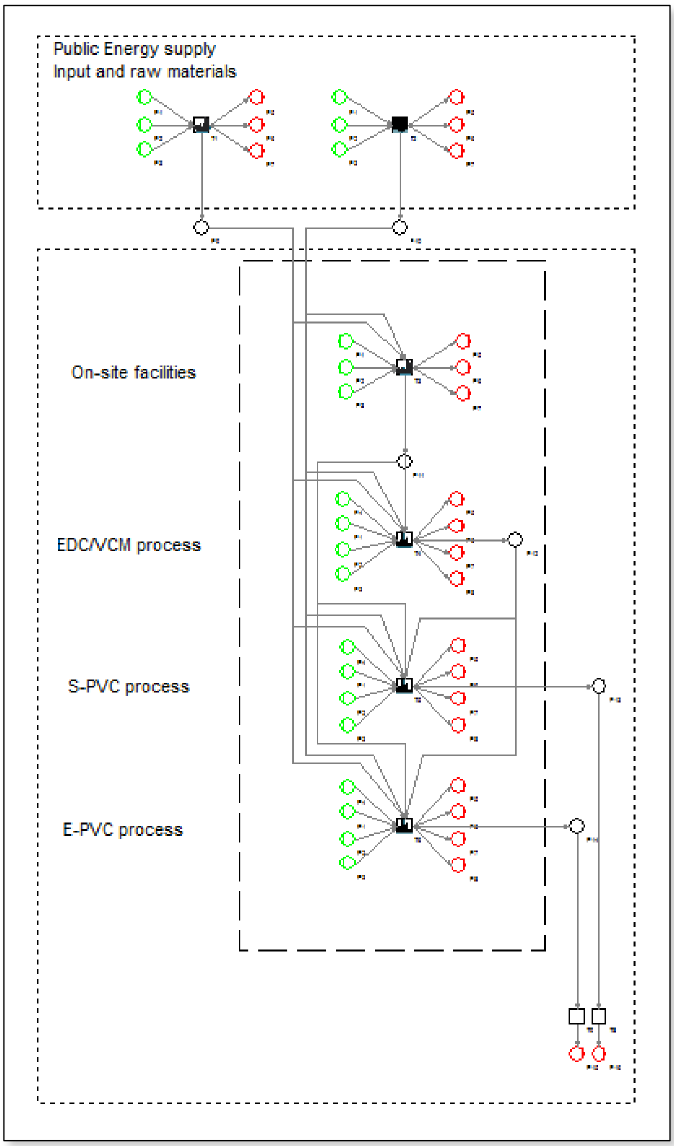

Figure 7: *A simplified flow chart of the Life cycle model for the production of polyvinyl chloride (PVC) in Europe in Umberto 5.6. Here, only one production site is shown (inside the dashed box), connected to the prechains of public energy, input materials and raw materials. For the complete model, additional production sites were inserted in adjacent columns.*

Calculation Rules

Vertical Averaging

When modelling and calculating average Eco-profiles from the collected individual LCI datasets, vertical averages are calculated as far as possible (Figure 8). 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.

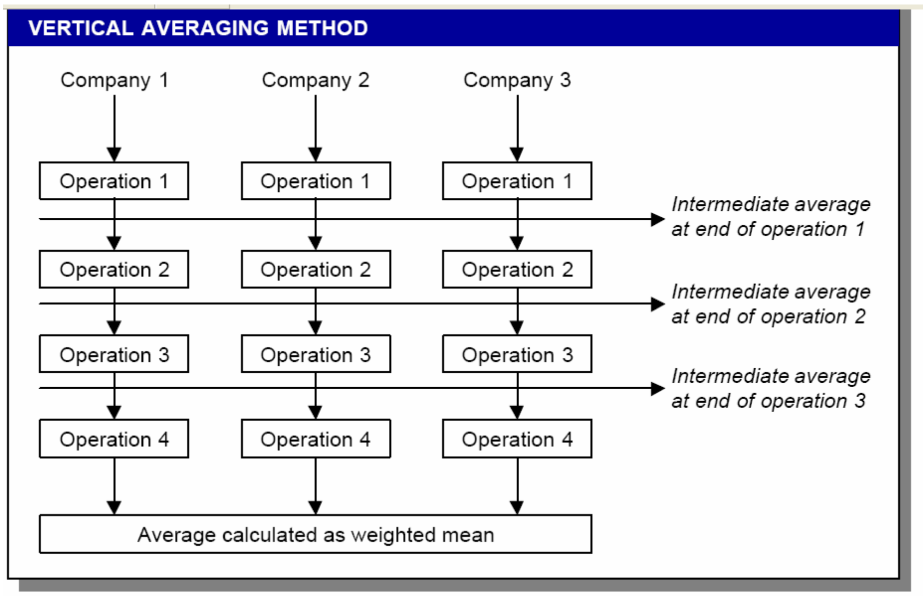

Figure 8: *Vertical Averaging (source: Eco-profile of high volume commodity phthalate esters, ECPI* Europe*an Council for Plasticisers and Intermediates, 2001)*

Allocation Rules

Production processes in the chemical and plastics industry are usually multi-functional systems, i.e. they have not one but several valuable products and co-products. Wherever possible, allocation should be avoided by expanding the system to include the additional functions related to the co-products. Often, however, avoiding allocation is not feasible in technical reality; 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: 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 (ethylchloride production), 0.20% of S-PVC production, and 0.63% of E-PVC production. In total PVC, about 48% of this material is made up of “recovered PVC” (41% for S-PVC and 61% 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 4. 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 (0 - <20%, 20 - <30%, 30 - 50% 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 calculated using a long term market analysis based on the European market. 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 4: Economic allocation factors for valuable products

Product	Average price US $/t	Economic allocation factor
PVC	980	1.000
Low grade PVC (0 - <20% rel. value)	n/a	0.075
Low grade PVC (20 - <30% rel. value)	n/a	0.204
Low grade PVC (30 - 50% rel. value)	n/a	0.365
VCM	885	0.903
EDC	363	0.371
Ethylchloride	n/a	0.371

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

Formats of LCI Dataset

The Eco-profile is provided in three electronic formats:

- As input/output table in Excel®
- As XML document in EcoSpold format (www.ecoinvent.org)
- As XML document in ILCD format [ILCD 2010] (http://lct.jrc.ec.europa.eu)

Key results are summarised below.

Energy Demand

As a key indicator on the inventory level, the **primary energy demand** (system input) shown in Table 5 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 value (lower heating value, LHV) is also presented in Table 5 for information purposes.

As a measure of the share of primary energy incorporated in the product, and hence indicating a recovery potential, the **energy content in the polymer** (system output), quantified as the gross calorific value (UHV) is shown in Table 5able 5 as well. Please note that in the case of PVC products the gross calorific value is highly dependent on the plasticiser content of the polymer. For Table 5, a value was provided by ECVM corresponding to the pure resin.

Table 5: Primary energy demand (system boundary level) per 1 kg of product

Primary Energy Demand	VCM	S-PVC	E-PVC
Energy content in polymer [MJ] (energy recovery potential, quantified as gross calorific value of polymer)	17.5	20.0[a)]	20.0[a)]
Process energy [MJ] (quantified as difference between primary energy demand and energy content of polymer)	37.2	40.7	50.8
Total primary energy demand [MJ] (upper heating value)	**54.7**	**60.7**	**70.8**
Total primary energy demand [MJ] (lower heating value)	51.2	56.7	66.1

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

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

Table 6 to Table 8 show how the total energy input (primary energy demand) is used as fuel or feedstock, while Table 9 shows the primary energy demand by renewability. Fuel use means generating process energy, whereas feedstock use means incorporating hydrocarbon resources into the polymer. Note that some feedstock input may still be valorised as energy; furthermore, process energy requirements may also be affected by exothermal or endothermal reactions of intermediate products. Hence, there is a difference between the feedstock energy input and the energy content of the polymer (measurable as its gross calorific value).

Table 6 to Table 9 illustrate that the main contribution to primary energy demand is made by non-renewable resources. Since the plants within the scope of this study are exclusively using feedstock produced from fossil resources (crude oil and natural gas), the share of non-renewable energy resources is higher than 90%. The share of renewables is mainly caused by the national electricity mixes.

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	2.42	0.118		2.42
Oil	28.99	0.633	17.40	11.59
Natural gas	13.66	0.297	3.30	10.36
Lignite	2.44	0.224		2.44
Nuclear	3.60	7.00E-10		3.60
Biomass	0.00			0.00
Hydro	0.71			0.71
Solar	0.76			0.76
Geothermics	1.86			1.86
Wood	0.00			0.00
Wind	0.24			0.24
Other renewable fuels	0.00			0.00
Sub-total renewable	**3.6**	**0.0**	**0.0**	**3.6**
Sub-total Non-renewable	**51.1**	**1.3**	**20.7**	**30.4**
Total	**54.7**	**1.3**	**20.7**	**34.0**

Table 7: *Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg S-PVC*

Primary energy resource input	**Total Energy Input [MJ]**	**Total Mass Input [kg]**	**Feedstock Energy Input [MJ]**	**Fuel Energy Input [MJ]**
Coal	3.10	0.153		3.10
Oil	29.59	0.646	17.40	12.19
Natural gas	17.28	0.375	3.30	13.98
Lignite	2.66	0.245		2.66
Nuclear	4.31	8.64E-10		4.31
Biomass	0.00			0.00
Hydro	0.80			0.80
Solar	0.77			0.77
Geothermics	1.87			1.87
Wood	0.00			0.00
Wind	0.29			0.29
Other renewable fuels	0.00			0.00
Sub-total renewable	**3.7**	**0.0**	**0.0**	**3.7**
Sub-total Non-renewable	**56.9**	**1.4**	**20.7**	**36.2**
Total	**60.7**	**1.4**	**20.7**	**40.0**

Table 8: *Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg E-PVC*

Primary energy resource input	**Total Energy Input [MJ]**	**Total Mass Input [kg]**	**Feedstock Energy Input [MJ]**	**Fuel Energy Input [MJ]**
Coal	4.64	0.231		4.64
Oil	31.69	0.692	17.40	14.29
Natural gas	20.31	0.441	3.30	17.01
Lignite	4.06	0.373		4.06
Nuclear	5.41	1.02E-09		5.41
Biomass	0.00			0.00
Hydro	1.10			1.10
Solar	1.06			1.06
Geothermics	2.10			2.10
Wood	0.42			0.42
Wind	0.00			0.00
Other renewable fuels	0.00			0.00
Sub-total renewable	**4.7**	**0.0**	**0.0**	**4.7**
Sub-total Non-renewable	**66.1**	**1.7**	**20.7**	**45.4**
Total	**70.8**	**1.7**	**20.7**	**50.1**

Table 9: Primary energy demand by renewability

Fuel/energy input type	**VCM**	**S-PVC**	**E-PVC**
Renewable energy resources	6.5%	6.2%	6.6%
Non-renewable energy resources	93.5%	93.8%	93.4%
Total	**100.0%**	**100.0%**	**100.0%**

In Table 10 the types of useful energy inputs into the VCM and PVC production processes are analysed. Thermal energy input plays a major role for all processes, whereas cooling energy is also important for VCM production.

Table 10: Analysis by type of useful energy for each separate production process (excluding upstream processes, e.g. VCM production is not included in PVC figures) per 1 kg of product

Type of useful energy in process input	**VCM**	**S-PVC**	**E-PVC**
Electricity [MJ]	0.53	0.70	0.27
Heat, thermal energy [MJ]	2.91	2.27	5.01
Thermal energy, cooling [MJ]	2.12	0.49	1.46
Total (for selected key process) [MJ]	**5.56**	**3.45**	**6.74**

In order to analyse the upstream operations more closely, please refer to the Eco-profiles of the respective precursors (e.g. ethylene and chlorine). It should be noted, however, that the LCI tables in the annex account for the entire production chain from cradle to gate. Please refer to the dominance analysis in Table 29 to Table 31 on page 34ff. of this report.

Water Use

Table 11, Table 13, and Table 15 show the water use for the VCM and PVC production process (foreground process only!) whereas Table 12, Table 14, and Table 16 show the water use along the total process chain from cradle to gate for each product.

Table 11: Gross water resources used in foreground processes for VCM production (EDC+VCM production including on-site utilities) per 1 kg VCM

Source	**Process water [kg]**	**Cooling water [kg]**	**Total [kg]**
Lake	0.2	13.4	13.6
River/canal	0.1	41.9	42.0
Sea	0.0	0.0	0.0
Unspecified	0.7	7.3	7.9
Well	0.7	8.3	9.0
Totals	**1.7**	**70.9**	**72.6**

Table 12: Gross water resources used in the total process chain (cradle-to-gate) per 1 kg VCM

Source	**Process water [kg]**	**Cooling water [kg]**	**Total [kg]**
Lake	0.2	13.4	13.6
River/canal	0.1	42.1	42.2
Sea	0.0	2.0	2.0
Unspecified	40.3	54.0	94.3
Well	0.8	9.1	9.9
Totals	**41.4**	**120.6**	**162.0**

Table 13: Gross water resources used in foreground processes for S-PVC production (PVC production including on-site utilities but excluding EDC/VCM production) per 1 kg S-PVC

Source	**Process water [kg]**	**Cooling water [kg]**	**Total [kg]**
Lake	0.1	1.8	1.8
River/canal	0.7	4.4	5.1
Sea	0.0	0.0	0.0
Unspecified	0.1	20.7	20.8
Well	1.9	3.0	4.9
Totals	**2.7**	**29.8**	**32.5**

Table 14: Gross water resources used in the total process chain (cradle-to-gate) per 1 kg S-PVC

Source	**Process water [kg]**	**Cooling water [kg]**	**Total [kg]**
Lake	0.2	8.7	9.0
River/canal	0.8	45.7	46.4
Sea	0.0	3.1	3.1
Unspecified	40.3	82.5	122.8
Well	2.9	13.5	16.4
Totals	**44.2**	**153.5**	**197.7**

Table 15: Gross water resources used in foreground processes for E-PVC production (PVC production including on-site utilities but excluding EDC/VCM production) per 1 kg E-PVC

Source	**Process water [kg]**	**Cooling water [kg]**	**Total [kg]**
Lake	0.5	3.8	4.3
River/canal	0.2	10.5	10.7
Sea	0.0	0.0	0.0
Unspecified	0.3	44.4	44.6
Well	2.1	11.7	13.8
Totals	**3.0**	**70.4**	**73.4**

Table 16: Gross water resources used in the total process chain (cradle-to-gate) per 1 kg E-PVC

Source	Process water [kg]	Cooling water [kg]	Total [kg]
Lake	0.8	12.6	13.4
River/canal	0.3	79.4	79.7
Sea	0.0	2.2	2.2
Unspecified	43.8	118.6	162.4
Well	3.3	19.9	23.1
Totals	**48.2**	**232.7**	**280.9**

Air Emission Data

Table 17 shows a few selected air emissions which are commonly reported and used as key performance indicators for the VCM and PVC production process (foreground process only!), including the on-site energy production. For a full inventory of air emissions, please refer to the complete LCI table in the annex of this report.

Table 17: Selected air emissions for the foreground process (EDC+VCM / PVC production including on-site utilities) per 1 kg of product. Note that emissions from EDC/VCM production are not included in PVC figures.

Air emissions	VCM	S-PVC	E-PVC
Carbon dioxide, fossil [kg]	0.25	0.15	0.42
Carbon monoxide (CO) [kg]	1.08E-04	2.92E-05	1.98E-04
Ethylene [kg]	8.81E-05	2.53E-07	6.86E-07
Chlorinated Hydrocarbons [kg]	9.36E-05	2.37E-05	2.93E-04
Non-methane volatile organic compounds (NMVOC) [kg]	5.24E-05	1.29E-05	1.15E-04
Sulphur dioxide (SO_2) [kg]	2.27E-05	3.93E-05	8.54E-05
Nitrogen oxides (NO_x) [kg]	1.62E-04	1.53E-04	4.48E-04
PM10, Particulate matter ≤ 10 µm [kg]	2.42E-06	1.31E-05	3.29E-05

Wastewater Emissions

Table 18 shows a few selected wastewater emissions which are commonly reported and used as key performance indicators; for a full inventory of wastewater emissions, please refer to the complete LCI table in the annex of this report.

Table 18: Selected water emissions of the foreground process (EDC+VCM / PVC production including on-site utilities) per 1 kg of product. Note that emissions from EDC/VCM production are not included in PVC figures.

Water emissions	VCM	S-PVC	E-PVC
Biological oxygen demand after 5 days (BOD 5) [kg]	2.49E-05	4.04E-05	1.76E-05
Chemical oxygen demand (COD) [kg]	8.70E-05	2.09E-04	1.84E-04
Total organic carbon (TOC) [kg]	2.97E-11	7.34E-05	5.81E-05
Chloride, ion [kg]	8.94E-03	9.08E-04	8.23E-04
Sodium, ion [kg]	1.29E-10	1.77E-04	1.93E-04
Sulfate [kg]	1.10E-04	7.88E-06	3.25E-05

Solid Waste

In Table 19 the amounts of solid waste generated in the VCM and PVC production processes are presented. These values relate to the foreground processes only and represent the amounts of waste sent to waste treatment.

Table 20 shows the amounts of waste generated along the whole production chain including all upstream processes. According to the methodology of PlasticsEurope [PlasticsEurope 2011] only waste for recovery is assumed to leave the system boundary. For additional information, Table 20 contains the amount of radioactive waste for final disposal.

Table 19: Solid waste generation of the foreground process (before treatment) (EDC+VCM / PVC production including on-site utilities) by type and destination per 1 kg of product. Note that wastes from EDC/VCM production are not included in PVC figures.

	Waste for –	Incineration	Landfill	Recovery	Unspecified	Total
Product		**kg**	**kg**	**kg**	**kg**	**kg**
VCM	Hazardous	7.8E-03	5.8E-05	4.3E-04	0	8.3E-03
	Non-hazardous	2.2E-04	5.3E-05	7.8E-04	4.7E-07	1.1E-03
	Unspecified	0	0	3.8E-08	0	3.8E-08
S-PVC	Hazardous	5.3E-05	1.5E-05	3.9E-04	3.3E-06	4.7E-04
	Non-hazardous	1.8E-04	4.2E-04	1.7E-03	2.2E-05	2.4E-03
	Unspecified	0	0	3.0E-08	0	3.0E-08
E-PVC	Hazardous	2.0E-04	1.1E-05	6.0E-05	1.3E-05	2.9E-04
	Non-hazardous	6.2E-04	1.0E-03	3.4E-03	4.2E-05	5.1E-03
	Unspecified	0	0	3.2E-08	0	3.2E-08

Table 20: Solid waste generation of the total process chain (cradle-to-gate, after treatment) by type and destination per 1 kg of product

	Waste for –	Incineration	Landfill	Recovery	Unspecified	Total
Product		**kg**	**kg**	**kg**	**kg**	**kg**
VCM	Hazardous	0		1.3E-03	0	1.3E-03
	Non-hazardous	0	0	1.5E-02	0	1.5E-02
	Unspecified	0	0	1.9E-03	0	1.9E-03
	Radioactive waste a)	0	4.4E-05	0	0	4.4E-05
S-PVC	Hazardous	0	0	1.8E-03	0	1.8E-03
	Non-hazardous	0	0	1.2E-02	0	1.2E-02
	Unspecified	0	0	7.1E-03	0	7.1E-03
	Radioactive waste a)	0	5.2E-05	0	0	5.2E-05
E-PVC	Hazardous	0	0	1.1E-03	0	1.1E-03
	Non-hazardous	0	0	1.6E-02	0	1.6E-02
	Unspecified	0	0	1.0E-02	0	1.0E-02
	Radioactive waste a)	0	7.2E-05	0	0	7.2E-05

a) This is for information purposes only. Radioactive waste sent to final storage is not considered crossing the system boundaries. Radioactive waste in final storage is covered in the LCI tables with the volume of the underground deposit and the emissions from this deposit to air and water.

Life Cycle Impact Assessment

Input

Natural Resources

The Abiotic Depletion Potential (ADP) measures the extraction of natural resources such as iron ore, scarce minerals, and fossil fuels such as crude oil. This indicator is based on ultimate reserves and extraction rates. It is distinguished into the two subcategories ‘ADP, elements’ and ‘ADP, fossil fuels’. For ‘ADP, elements’ Antimony (Sb) is used as a reference for the depletion of minerals and metal ores and for ‘ADP, fossil fuels’ the lower heating value (LHV) of extracted fossil fuels is considered. It is calculated according to updated characterisation factors of CML [CML 2013]. 'ADP, fossil fuels' is not identical with the 'Primary Energy Resource Input' since the latter is based on upper heating values and ADP is based on lower heating values, while nuclear energy is not included in ADP.

Table 21: Abiotic Depletion Potential per 1 kg of product

Natural resources	**VCM**	**S-PVC**	**E-PVC**
ADP, elements [Sb eq]	1.3×10^{-5}	1.3×10^{-5}	1.4×10^{-5}
ADP, fossil fuels [MJ]	42.8	47.2	54.2

Output

Climate Change

The impact category climate change is represented by the Global Warming Potential (GWP) with a time horizon of 100 years. The applied characterisation factors are based on the last report of the Intergovernmental Panel on Climate Change [IPCC 2013].

Table 22: Global Warming Potential (100 years) per 1 kg of product

Climate change	**VCM**	**S-PVC**	**E-PVC**
GWP [kg CO_2 eq.]	1.71	1.99	2.56

Acidification

The Acidification Potential (AP) is quantified according to HAUSCHILD 1998 with updated characterisation factors of CML [CML 2013].

Table 23: Acidification Potential per 1 kg of product

Acidification of soils and water bodies	**VCM**	**S-PVC**	**E-PVC**
AP [g SO_2 eq.]	4.50	5.05	6.93

Eutrophication

The Eutrophication Potential (EP) is calculated according to HEIJUNGS 1992 with updated characterisation factors of CML [CML 2013].

Table 24: Eutrophication Potential per 1 kg of product

Eutrophication of soils and water bodies	VCM	S-PVC	E-PVC
EP, terrestrial [g PO_4^{3-} eq.]	0.33	0.39	0.61
EP, aquatic [g PO_4^{3-} eq.]	0.48	0.55	0.64
EP, total [g PO_4^{3-} eq.]	0.81	0.94	1.25

Ozone Depletion

The calculation of Ozone Depletion Potential (ODP) is based on characterisation factors of the World Meteorological Organisation [WMO 2011]. This implies also the consideration of dinitrogen monoxide (N_2O) as ozone depleting substance with an ODP of 0.017 kg CFC-11 eq. per kg of N_2O. This emission plays a relevant role for the overall ODP result of the considered products in this study with 32% to 54%. The second highly relevant substance for ODP with a share of 30% to 50% is tetrachloromethane emitted during EDC/VCM production.

Table 25: Ozone Depletion Potential per 1 kg of product

Ozon depletion potential	VCM	S-PVC	E-PVC
ODP [g CFC-11 eq.]	1.9×10^{-3}	2.2×10^{-3}	2.4×10^{-3}

Summer Smog

The Photochemical Ozone Creation Potential (POCP) is quantified according to JENKIN 1999 and DERWENT 1998 with updated characterisation factors of CML [CML 2013]. For the calculation of POCP the group species "non-methane volatile organic compounds" (NMVOC) was also taken into account under the assumption of an impact factor of 0.15 kg Ethene eq./kg NMVOC [CML 2013]. Thus, the contribution of NMVOC to POCP is about 30%.

Table 26: Photochemical Ozone Creation Potential per 1 kg of product

Photochemical ozone creation potential	VCM	S-PVC	E-PVC
POCP from NMVOC [g Ethene eq.]	0.15	0.16	0.19
POCP from other substances [g Ethene eq.]	0.35	0.40	0.35
POCP, total [g Ethene eq.]	0.50	0.56	0.54

Dust & Particulate Matter

Particulate matter with an aerodynamic diameter of less than 10 µm (PM10) is suspected to cause heart and circulatory diseases. Studies from internationally recognised organisations (e.g. WHO 2006) confirm a high mortality risk from fine dust.

Large scale air pollution of PM10 is caused by direct emissions of particulate matter and secondary particles that are formed by precursors such as nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ammonia (NH_3) and Non-Methane Volatile Organic Compounds (NMVOC). The characterisation factors shown in Table 27 are based on works of DE LEEUW 2002 and HELDSTAB 2003 for NMVOC.

Table 27: PM10 characterisation factors of air emissions according to DE LEEUW *2002and* HELDSTAB *2003*

PM10 and precursors	kg PM10 eq. / kg air emission
Particulate matter PM10	1
Secondary aerosol formers (precursors)	
NO_x (as NO_2)	0.88
SO_2	0.54
NH_3	0.64
NMVOC	0.012

Table 28: Emissions of particulate matter / dust per 1 kg of product

Particulate matter	VCM	S-PVC	E-PVC
PM10, direct emissions [g PM10 eq.]	0.22	0.25	0.32
PM10, secondary [g PM10 eq.]	3.15	3.59	4.73
PM10, total [g PM10 eq.]	3.36	3.84	5.05
Particles larger than 10 µm [g]	0.26	0.31	0.45
Total particulate matter [g]	3.63	4.18	5.60

Dominance Analysis

Table 29 to Table 31 show the main contributions to the results presented above. In this context, the term "foreground process" refers to the EDC/VCM or PVC production itself, including heat exchangers, compressors, flares, as well as on-site utilities like water preparation and wastewater treatment. Expenses and emissions concerning electric and thermal (including on-site generation of compressed air and nitrogen) energy production for the foreground process are treated separately. The sections "Ethylene Production", "Chlorine Production", and "VCM Production" (for the PVC related tables only) refer to the production of the respective precursors including their pre-chains from the extraction of fossil resources to gate. Other raw materials include catalysts, solvents or additives and their pre-chains. Transport includes the transport of all the materials directly fed to the foreground process. Disposal refers to the waste treatment and the transport of wastes to the respective treatment facility.

The production of the precursors ethylene and chlorine is highly dominant in most of the analysed environmental impact categories. The energy intensive processes required for ethylene production lead to a domination of Total Primary Energy Demand, Abiotic Depletion Potential of fossil resources (ADP fossil), and Eutrophication Potential (EP), whereas chlorine production is dominating in the Abiotic Depletion Potential of elemental resources (ADP elements) due to the high input of sodium chloride.

For Global Warming Potential (GWP), the upstream processes also contribute the largest shares but the foreground processes of EDC/VCM and PVC production contribute significantly due to input of thermal and electrical energy produced by burning of fossil fuels. The same applies for the Acidification Potential (AP) which is mostly caused by SO_2 emissions from using fossil energy resources.

Concerning the Ozone Depletion Potential (ODP), the VCM production shows a major contribution due to emissions of tetrachloromethane from EDC/VCM production units. The second major contributor to ODP is chlorine production caused by dinitrogen monoxide (N_2O) emitted during electricity generation for the chlor-alkali electrolysis.

Photochemical Ozone Creation Potential (POCP) is dominated by ethylene production caused by emissions of ethylene and NMVOC from the steam cracking process. However, during the production of EDC/VCM significant amounts of ethylene and NMVOC are emitted which is reflected by the considerable share of EDC/VCM production on the total POCP.

Water use is dominated by EDC/VCM production and by chlorine production (incl. chlorine pre-chain). For the exothermal processes in EDC/VCM high amounts of cooling water are used, whereas chlorine production requires both process and cooling water.

Table 29: Dominance analysis of impacts per 1 kg of VCM

	Total Primary Energy	**ADP Elements**	**ADP Fossil**	**GWP**	**AP**	**EP**	**ODP**	**POCP**	**PM10**	**Water**
	MJ	kg Sb eq.	MJ	kg CO_2 eq.	g SO_2 eq.	g PO_4^{3-} eq.	g CFC-11 eq.	g C_2H_4 eq.	g PM10 eq.	kg
EDC+VCM production	0.0%	0.0%	0.0%	11.7%	1.6%	2.3%	49.6%	22.4%	2.5%	40.6%
Electricity [a)]	4.0%	0.0%	2.2%	7.1%	5.1%	3.3%	4.6%	1.8%	5.9%	3.6%
Thermal energy and utilities [a)]	8.0%	0.0%	8.6%	3.4%	2.6%	3.3%	1.6%	3.0%	3.1%	4.6%
Disposal [a)]	0.1%	0.0%	0.1%	1.6%	0.5%	0.4%	0.1%	0.6%	0.5%	0.0%
Subtotal Foreground process	12.0%	0.1%	10.9%	23.8%	9.8%	9.4%	55.9%	27.8%	11.9%	48.8%
Ethylene Production	63.8%	0.1%	73.7%	40.7%	37.6%	64.2%	7.6%	57.4%	47.5%	5.4%
Chlorine Production	23.2%	97.5%	14.7%	33.9%	49.8%	24.5%	34.8%	13.8%	37.8%	44.1%
Other raw materials	0.9%	2.3%	0.6%	1.4%	2.3%	1.3%	1.5%	0.8%	1.9%	1.7%
Transport of precursors and other raw materials	0.1%	0.0%	0.1%	0.2%	0.6%	0.5%	0.2%	0.2%	0.9%	0.0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

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

Table 30: Dominance analysis of impacts per 1 kg of S-PVC

	Total Primary Energy	**ADP Elements**	**ADP Fossil**	**GWP**	**AP**	**EP**	**ODP**	**POCP**	**PM10**	**Water**
	MJ	kg Sb eq.	MJ	kg CO_2 eq.	g SO_2 eq.	g PO_4^{3-} eq.	g CFC-11 eq.	g C_2H_4 eq.	g PM10 eq.	kg
S-PVC production	0.0%	0.0%	0.0%	0.5%	0.8%	2.2%	1.6%	0.4%	0.5%	6.0%
Electricity a)	3.0%	0.0%	1.6%	5.5%	4.2%	2.6%	3.5%	1.4%	4.8%	2.9%
Thermal energy and utilities a)	5.3%	0.0%	5.7%	6.4%	2.9%	5.0%	2.0%	2.0%	3.7%	10.7%
Disposal a)	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Subtotal Foreground process	8.3%	0.0%	7.3%	12.6%	7.9%	9.8%	7.2%	3.8%	9.1%	19.6%
VCM production	11.8%	2.4%	10.8%	21.7%	11.3%	9.7%	49.6%	28.8%	12.9%	39.0%
Ethylene Production	57.5%	0.1%	66.9%	34.8%	33.5%	55.4%	6.7%	51.3%	41.6%	4.4%
Chlorine Production	20.8%	97.2%	13.3%	28.9%	44.2%	21.1%	30.4%	12.3%	33.0%	36.0%
Other raw materials	1.4%	0.2%	1.5%	1.6%	2.1%	3.2%	5.9%	3.5%	2.1%	0.9%
Transport of precursors and other raw materials	0.2%	0.0%	0.2%	0.4%	1.0%	0.8%	0.2%	0.3%	1.4%	0.0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

a) only relating to direct input/output of the PVC production process

Table 31: Dominance analysis of impacts per 1 kg of E-PVC

	Total Primary Energy	**ADP Elements**	**ADP Fossil**	**GWP**	**AP**	**EP**	**ODP**	**POCP**	**PM10**	**Water**
	MJ	kg Sb eq.	MJ	kg CO_2 eq.	g SO_2 eq.	g PO_4^{3-} eq.	g CFC-11 eq.	g C_2H_4 eq.	g PM10 eq.	kg
E-PVC production	0.0%	0.0%	0.0%	3.8%	11.5%	12.3%	1.7%	4.0%	7.6%	10.3%
Electricity [a)]	5.0%	0.0%	3.2%	11.0%	7.0%	4.4%	8.4%	3.3%	8.2%	4.1%
Thermal energy and utilities [a)]	10.4%	0.0%	11.5%	11.0%	5.5%	9.9%	4.7%	6.0%	7.0%	15.7%
Disposal [a)]	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
Subtotal Foreground process	15.5%	0.1%	14.7%	26.0%	24.1%	26.6%	14.8%	13.4%	22.9%	30.1%
VCM production	11.9%	3.5%	9.9%	19.4%	11.5%	9.5%	37.0%	13.8%	13.2%	38.5%
Ethylene Production	51.0%	0.1%	60.3%	28.1%	25.3%	42.8%	6.4%	54.2%	32.8%	3.2%
Chlorine Production	19.3%	95.9%	12.5%	24.3%	34.8%	17.0%	30.5%	13.6%	27.1%	27.3%
Other raw materials	2.4%	0.5%	2.6%	2.1%	4.2%	3.9%	11.2%	5.0%	3.8%	0.9%
Transport of precursors and other raw materials	0.1%	0.0%	0.1%	0.1%	0.2%	0.2%	0.1%	0.1%	0.2%	0.0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

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

Sensitivity estimation for chlorine input

The application of data from the existing Eco-profile for chlorine [EUROCHLOR 2013] introduces a systematic error due to the underlying selection of sites, which is supposed to represent European chlorine production but could not include all active European production sites. The same is true for the selection of EDC/VCM and PVC producing sites within the current Eco-profile with respect to the true total European production. Accordingly, the average chlorine from the respective Eco-profile does not necessarily reflect the average chlorine used for the EDC/VCM production within the current study.

As stated in the interpretation section of the chlorine Eco-profile [EUROCHLOR 2013], the LCIA results for chlorine from energy intensive chlor-alkali electrolysis are highly sensitive to the way the electricity is produced. The public electricity production is country-specific and depends on a mix of different parameters, e.g. energy carriers, plant efficiencies and technologies. This mix is determined by the sample of data-supplying production sites and their associated national electricity grid. In particular, according to the chlorine Eco-profile report the GWP results are over-estimated due to the selection of contributing sites.

To create a more representative chlorine dataset for the European production of PVC it would be ideal to use primary data supplied by those chlorine manufacturers supplying chlorine to EDC/VCM plants. Due to time, cost and confidentiality restrictions this approach could not be realized.

A simplified sensitivity calculation shows the potential impact of more representative chlorine data on GWP results. This estimation is based on the assumption that chlorine for PVC is produced in the same country as the respective PVC production site. This is a reasonable assumption due to the fact that transport distances of chlorine are minimized, and only a small portion of VCM, is reported to pass country borders. In this sensitivity analysis the documented electricity mix of the chlorine Eco-profile was replaced by a more PVC specific mix: electricity mixes, which represent the PVC production capacity country mix (a) in Europe and (b) of the PVC Eco-profile sample. These calculations lead to a GWP reduction of 0.04 – 0.05 kg CO_2 eq. per kg S-PVC, and 0.03 – 0.06 kg CO_2 eq. per kg E-PVC. These values correspond to a relative reduction of 2.0 – 2.5% for S-PVC and 1.2 – 2.3% for E-PVC (compare Table 22). Accordingly it is very likely that the collection and application of primary data for chlorine would also result in a reduction of GWP and other LCIA indicators. Nevertheless, the current PVC Eco-profile uses original chlorine data as a conservative approach.

Sensitivity Analysis for HCl data sources

For EDC production two main production options exist: a) direct chlorination of ethylene with chlorine, and b) oxychlorination of ethylene with HCl and oxygen. For the oxychlorination route, HCl can either be supplied internally from the EDC cracking process or imported from outside. In the current investigation, provided data show that about 22 % of total chlorine input from outside sources comes in the form of HCl, and that about 85 % (i.e. 18 % of total chlorine) of this HCl originates from Methylenediphenyl diisocyanate (MDI) production.

In the current study (as in the previous Eco-profiles of VCM and PVC), HCl from external sources was treated as if it was primary chlorine (**basic scenario (HCl as Cl_2)**). This is a conservative approach as it can be assumed that HCl – being a by-product of another process that uses Cl_2 – should bear lower burdens than primary chlorine (not to be confused with HCl being specifically produced from chlorine and hydrogen).

The second option for treating HCl from external sources is using the published Eco-profiles of processes producing HCl as by-products. In the data provided from participants, MDI was clearly stated as originating process representing 85 % of total HCl input to EDC/VCM production. Thus, in the first sensitivity scenario (**HCl from MDI**) the published LCI table from the Eco-profile of MDI [PLASTICSEUROPE 2012B] was used for assigning loads to HCl with defined origin from MDI production. The conservative approach described above was used for other HCl sources. Under the assumption that the method of mass allocation on all products equally distributes the environmental burdens among MDI and HCl, the LCI table of MDI can be used for HCl without changes other than replacing the output product.

One problem of the method of mass allocation between MDI and HCl is that HCl receives relatively high burdens compared to MDI. Table 32 shows that the Global Warming Potential (GWP) of HCl from MDI production is by a factor of 2.6 higher than the GWP of primary chlorine. Keeping in mind the low market price of HCl compared to MDI, the authors of the MDI Eco-profile provided confidential datasets (LCI tables) of both MDI and HCl based on economic allocation of the environmental burdens, which was used in the second sensitivity scenario (**HCl from MDI, price allocation**). As shown in Table 32 this method leads to a dramatically decreased GWP for HCl.

Table 32: *Global Warming Potential (cradle-to-gate) of HCl fed to EDC/VCM plants based on different data sources/assumptions*

Assumption / Data Source	GWP kg CO_2 eq. / kg HCl	Reference
HCl treated as if Chlorine	0.88	EUROCHLOR 2013[a)]
HCl as MDI by-product	2.39	PLASTICSEUROPE 2012B
HCl as MDI by-product, price allocation	0.11	not published

[a)] GWP for chlorine corrected with a factor of 35/36 representing the mass ratio between Cl and HCl

Exemplarily for the results of this sensitivity analysis, the impact on Global Warming Potential is presented in Table 33. The choice of the dataset describing the HCl input from external sources into the EDC/VCM production process has a high importance on the results (+/- 10 %). Using the price allocated dataset for HCl from MDI production would be preferential for the overall results. This dataset is, however, a) not publicly available and b) using price allocation for one product (HCl) and mass allocation for another product of the same process (MDI) creates inconsistencies since the environmental impacts of the two products do not sum up to the total impacts of the combined production process.

Table 33: *Sensitivity analysis results: Global Warming Potential of VCM, S- and E-PVC depending on chosen data source for HCl from external sources, in kg CO_2 eq / kg product (values in brackets: relative difference to Base Case)*

Scenarios	VCM	S-PVC	E-PVC
Base Case	1.71	1.99	2.56
HCl from MDI	1.89 (+11%)	2.17 (+9%)	2.76 (+8%)
HCl from MDI, price allocation	1.62 (-5%)	1.90 (-5%)	2.46 (-4%)

Comparison of the present Eco-profile with its previous version of EPD (2008)

Table 34 to Table 36 compare the present results with the previous version of the Eco-profiles of VCM, S-PVC, and E-PVC from 2006 [PLASTICSEUROPE 2006A, PLASTICSEUROPE 2006B, PLASTICSEUROPE 2006C]. For S-PVC and E-PVC, an EPD was published in 2008 which was based on the 2006 LCI results but contained more LCIA impact factors [PLASTICSEUROPE 2008A, PLASTICSEUROPE 2008B]. No information on ADP elements was contained in the previous reports. For the comparison, these values were calculated from the published LCI tables. Furthermore, for VCM, no information on Acidification and Eutrophication Potential was published in the previous report. These values were also calculated from the published LCI tables. Please note that, at the time when the previous report was produced, only limited information on the substances causing eutrophication was collected. Therefore, it is not recommended to compare the results of this impact category with the current Eco-Profile.

Primary Energy Demand slightly increased compared to the previous study. This is caused mostly by ethylene production where a 10 % increase in primary energy demand was observed. Usage of renewable energy sources increased by more than 200 % (the shares of renewable energy resources increased from about 2% to more than 6%) which reflects the changes in electricity production in Europe during the last decade.

An increase in Global Warming Potential was observed for all products, especially for VCM, and to a lesser extent for S- and E-PVC. The largest part of this increase is caused in the pre-chain processes: the most recent Eco-profiles of both ethylene and chlorine revealed an increase in GWP of 5 % and 14 %, respectively, compared to their predecessors. Concerning chlorine production, this increase is mostly caused by the over-representation of countries with comparably high specific GWP per kWh electricity in the chlorine Eco-profile. As was shown in the previous section (Sensitivity estimation for chlorine input), aligning the electricity mix for chlorine production with the PVC production capacity distribution would lead to a decrease in the order of 2 % for the overall GWP result.

Acidification Potential slightly increased for all products. This is in line with the increased usage of energy from non-renewable resources since AP is mostly caused by sulphur and nitrous oxides from burning of fossil fuels.

Concerning the Photochemical Ozone Creation Potential (POCP), it should be noted that in this study, the group species "non-methane volatile organic compounds" (NMVOC) was also taken into account under the assumption of a conservative impact factor of 0.15 kg Ethene eq./kg NMVOC. When comparing the POCP values of the previous report and the current study without taking the NMVOC into account, a reduction in POCP is observed.

Table 34: Comparison of the present Eco-profile data of VCM with its previous version (2006)

Environmental Impact Categories	Eco-profile VCM (2006)	Eco-profile VCM (2015)	Difference
Gross primary energy from non-renewable resources [MJ]	49.93	51.10	2.4%
Gross primary energy from renewable resources [MJ]	1.15	3.57	209.8%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	1.04E-05 [a]	1.29E-05	24.1%
Global Warming Potential (GWP) [kg CO_2 eq.]	1.59	1.71	7.8%
Acidification Potential (AP) [g SO_2 eq.]	4.38 [a]	4.50	2.9%
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	0.44 [a]	0.81	85.8%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	n/a [b]	0.0019	n/a [b]
Photochemical Ozone Creation Potential [g Ethene eq.]	n/a [b]	0.50 (0.35) [c]	n/a [b]

[a] Results are not included in previous Eco-profile; values have been calculated based on published LCI table

[b] not applicable: relevant substances for impact category are not listed in previous Eco-profile

[c] values without taking the NMVOC into account

Table 35: Comparison of the present Eco-profile data of S-PVC with its previous version (2006)

Environmental Impact Categories	Eco-profile S-PVC (2006)	Eco-profile S-PVC (2015)	Difference
Gross primary energy from non-renewable resources [MJ]	55.46	56.93	2.7%
Gross primary energy from renewable resources [MJ]	1.27	3.73	193.1%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	1.00E-05 [a]	1.29E-05	28.0%
Global Warming Potential (GWP) [kg CO_2 eq.]	1.90	1.99	4.7%
Acidification Potential (AP) [g SO_2 eq.]	5.30	5.05	-4.7%
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	0.62	0.94	51.1%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	n/a [b]	0.0022	n/a [b]
Photochemical Ozone Creation Potential [g Ethene eq.]	0.42	0.56 (0.40) [c]	33.8% (-4.7%) [c]

[a] Results are not included in previous Eco-profile; values have been calculated based on published LCI table

[b] not applicable: relevant substances for impact category are not listed in previous Eco-profile

[c] values without taking the NMVOC into account

Table 36: Comparison of the present Eco-profile data of E-PVC with its previous version (2006)

Environmental Impact Categories	Eco-profile E-PVC (2006)	Eco-profile E-PVC (2015)	Difference
Gross primary energy from non-renewable resources [MJ]	64.38	66.12	2.7%
Gross primary energy from renewable resources [MJ]	1.52	4.68	207.0%
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	1.24E-05 [a]	1.40E-05	13.2%
Global Warming Potential (GWP) [kg CO_2 eq.]	2.50	2.56	2.6%
Acidification Potential (AP) [g SO_2 eq.]	7.00	6.93	-1.1%
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	0.80	1.25	56.9%
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	n/a [b]	0.0024	n/a [b]
Photochemical Ozone Creation Potential [g Ethene eq.]	0.45	0.54 (0.35) [c]	20.8% (-22.2%) [c]

[a] Results are not included in previous Eco-profile; values have been calculated based on published LCI table

[b] not applicable: relevant substances for impact category are not listed in previous Eco-profile

[c] values without taking the NMVOC into account

This section mainly aims at the comparison of Eco-profile results, which naturally include a multitude of processes prior to those monomer and polymer production processes under direct influence of the PVC producing companies. Yet, the separation of processes under direct control of the industry's companies from these precursor processes is not part of the scope of an Eco-profile. Their importance for the overall Eco-profile results is clearly stated in the dominance analysis section and within Table 29 to Table 31. In particular noticeable are the roles of ethylene and chlorine production with respect to many environmental impact categories.

Comparison Scenario: Keeping the upstream processes constant between the 2006 & 2015 studies

As was shown before, both chlorine and ethylene production (including their upstream processes) are highly dominant for the Eco-profiles of VCM and PVC. Since large changes were observed in the Eco-profiles of these two VCM/PVC precursors, a comparison scenario was created to eliminate these changes from the VCM/PVC Eco-profiles. Therefore, the LCI results for both ethylene and chlorine from the 2006 Eco-profile were used and implemented into the current model. The impact category results of the current Eco-profile with 2005 ethylene and chlorine may then be compared with the previous Eco-profile results to deduce progress within the VCM/PVC production unmasked by effects from upstream chains.

Table 37: Comparison of the present Eco-profile data calculated with 2005 ethylene and chlorine pre-chains with the previous Eco-profile version (2006)

Environmental Impact Categories and Products	Eco-profile (2006)	Altered Eco-profile (2015) [a]	Difference	Original Eco-profile (2015)
Global Warming Potential (GWP) [kg CO_2 eq.]				
• VCM	1.59	1.56	-1.9%	1.71
• S-PVC	1.90	1.84	-3.1%	1.99
• E-PVC	2.50	2.41	-3.6%	2.56

[a] ethylene and chlorine production data from 2005

A comparison of the previous Eco-profile with the altered current Eco-profile (featuring ethylene and chlorine from 2005) leads to different conclusions than the comparison with the original Eco-profile. In Table 37 the results concerning GWP are presented. It is shown that when comparing these scenarios the GWP for VCM and PVC has decreased between 2006 and 2015 by about 2-3 %. This decrease can be attributed to an increased energy efficiency of the VCM/PVC production processes and to a reduction in GWP of electricity production throughout Europe. In contrast to this, an increase in GWP of about 3-8 % was observed taking the original data into account. The main reasons for this difference lie within the over-representation of countries with comparably high specific GWP per kWh electricity in the recent chlorine Eco-profile and in an underestimation of energy consumption in the ethylene Eco-profile from 2006.

Review

External Independent Review Summary

The subject of this critical review is the development of the Eco-profile for Vinyl Chloride Monomer (VCM) and Polyvinyl Chloride Polymer (PVC), whereby two production processes for PVC were treated separately, i.e. S-PVC from suspension polymerisation and E-PVC from emulsion polymerisation.

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

Primary industry data were collected for the foreground processes comprising the production of the precursor ethylene dichloride (EDC), VCM and PVC taking into account the specific production processes of 38 production facilities of six participating companies. Background data for the main precursors ethylene and chlorine were taken from existing Eco-profiles [PlasticsEurope 2012A], [EuroChlor 2013]. Other background process data (e.g. transport and energy data) were sourced from Ecoinvent as well as specific data sources from the LCA practitioner.

A sensitive issue in this study is the treatment of hydrogen chloride (HCl) as input for EDC production. Since most HCl used for PVC production originates from the production of MDI (as a by-product), the allocation approach suggested in the MDI Eco-profile [PlasticsEurope 2012B] should have been adopted in order to achieve greatest possible consistency among interconnected Eco-profiles. However, in the MDI/TDI project mass allocation between the main product MDI and the by-product HCl was performed resulting in unreasonably high environmental loads for HCl. Hence – and after detailed discussions among the LCA practitioner, the reviewer and selected industry representatives – it was decided to use the environmental profile for chlorine as a proxy for HCl. This procedure is in line with the previous version of this Eco-profile and is based on the conservative assumption that one molecule of HCl carries half the load of a chlorine molecule. The effects of alternative approaches are analysed in detail via a sensitivity analysis (see Chapter ‘Sensitivity Analysis for HCl data sources’).

In general, the potential environmental impacts for VCM and PVC are dominated by the precursor products ethylene and chlorine. However, for VCM production, emissions of tetrachloromethane contribute significantly to the indicator Ozone Depletion Potential and emissions of ethylene and NMVOC contribute to the indicator Photochemical Ozone Creation Potential. Due to the exothermal processes in EDC/VCM production, also large amounts of cooling water are needed. In case of PVC production, thermal energy requirements influence impacts for Global Warming Potential and Acidification Potential.

The Eco-profile report also includes a detailed comparison of the results with the previous version of the VCM and PVC Eco-profiles. For details, please refer to Chapter ‘Comparison of the present Eco-profile with its previous version of EPD (2008)’.

The LCA practitioners have demonstrated very good competence and experience, with a track record of LCA projects in the chemical and plastics industry. The critical review confirms that this Eco-profile adheres to the rules set forth in the PlasticsEurope’s Eco-profiles and Environmental Declarations – LCI

Methodology and PCR for Uncompounded Polymer Resins and Reactive Polymer Precursors (PCR version 2.0, April 2011). As a result, this dataset is assessed to be a reliable and high quality representation of VCM, S-PVC and E-PVC produced in Europe.

Name and affiliation of reviewer:

Reviewer: Matthias Schulz – Product Line Manager, Product Sustainability, *DEKRA Assurance Services GmbH*, Stuttgart, Germany

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PlasticsEurope AISBL

Avenue E. van Nieuwenhuyse 4/3
B-1160 Brussels ł Belgium

Phone +32 (0)2 675 3297
Fax +32 (0)2 675 3935

info@plasticseurope.org
www.plasticseurope.org