An Eco-profile and Environmental Product Declaration of the European Chlor-Alkali Industry

Chlorine (The Chlor-Alkali Process)

Euro Chlor

September 2022

Final report – updated

Summary

This Environmental Product Declaration (EPD) is based upon life cycle inventory (LCI) data from Euro Chlor member companies. It has been prepared according to **Eco-profiles program and methodology –PlasticsEurope – V3.0 (2019)** [PlasticsEurope 2019]. It provides environmental performance data representative of the average European production of chlorine by chlor-alkali electrolysis from cradle to gate (from production of salt/brine to liquid chlorine, sodium hydroxide, hydrogen and hypochlorite at plant).

Please keep in mind that comparisons cannot be made at the level of the chemicals alone: it is necessary to consider the full life cycle of an application in order to compare the performance of different materials and the effects of relevant life cycle parameters. It is intended to be used by member companies to support product-orientated environmental management; by users of chemicals from the chlor-alkali industry 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	Euro Chlor
LCA Practitioner	ifeu Heidelberg gGmbH
Programme Owner	Euro Chlor
Reviewers	Matthias Schulz, Accredited Reviewer on behalf of DEKRA Assurance Services GmbH
Number of plants included in data collection	35
Representativeness	covering 75 % of European (EU + GB, NO, CH) chlorine production capacity (based on installed nameplate capacity; Source: Euro Chlor)
Reference year	2020
Year of data collection and calculation	2021
Expected temporal validity	2025 The relevance of an update will be considered every 3 years.
Cut-offs	None
Data Quality	Overall good quality (DQ rating 2, Confirmed by assessment of each single DQ indicator)
Allocation method	Stoichiometric allocation for salt, mass allocation for all other input and emissions. Sensitivity analysis for other allocation methods was performed.

Description of the Product and the Production Process

This Eco-profile and EPD represents the average industrial production of chlorine, sodium hydroxide, hydrogen and sodium hypochlorite by chlor-alkali electrolysis from cradle to gate.

Production Process

Salt (NaCl) recovered from various sources (rock salt, solar salt, solution-mined brine, vacuum salt) is dissolved in water and the resulting brine is purified and fed to the electrolysis unit where the brine is electrochemically decomposed into chlorine, hydrogen, and sodium hydroxide. Two different electrolysis techniques are applied: diaphragm and membrane cell technology (monopolar, mono/bipolar, bipolar, oxygen depolarised cathodes). Sodium hypochlorite is produced by feeding chlorine to a dilute sodium hydroxide solution. Upstream processes like salt production, electricity, and steam production are included in the model, as well as transportation of feedstock and waste treatment.

Data Sources and Allocation

The model of the electrolysis unit – including brine preparation and processing of the products – is based on confidential process and emission data obtained directly from chlorine producers. On-site production of electricity and steam was partially modelled using primary data from chlorine producers; data gaps in on-site energy production were closed using European average data of power plants and steam boilers. Country specific electricity mixes were used for grid electricity supply.

Allocation by mass was generally applied, except for salt input, which was allocated by stoichiometry to products containing sodium and/or chlorine. As different partitioning approaches are possible, sensitivities were calculated for several allocation approaches.

Use Phase and End-of-Life Management

The use phase and end-of-life processes of the products investigated are outside the system boundaries of this cradle-to-gate system: since the objects of this study are widely applied, even a qualitative discussion of these aspects is considered out of scope of this study. 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 each chlor-alkali electrolysis product.

Input Parameters

Indicator	**Unit**	**Chlorine (Cl_2)**	**Sodium Hydroxide (NaOH)**	**Hydrogen (H_2)**	**Sodium Hypochlorite (NaOCl)**
Non-renewable energy resources (UHV) 1)	MJ	12.02	11.10	10.21	16.26
Renewable energy resources (UHV) 1)	MJ	1.56	1.51	1.48	1.63
Abiotic Depletion Potential					
Elements	kg Sb eq.	2.05E-06	1.82E-06	1.77E-06	2.16E-06
Fossil fuels	MJ	12.45	11.54	10.59	16.18
Water use (w/o sea water)	kg	85.8	75.5	62.6	105.1
for process	kg	0.9	0.9	0.9	1.4
for cooling	kg	84.9	74.6	61.7	103.7
Water consumption	kg	22.5	14.9	5.1	23.0
for process	kg	0.4	0.4	0.4	0.7
for cooling	kg	22.1	14.5	4.7	22.3

1) upper heating value (UHV); a differentiation between feedstock and fuel energy was not made as no feedstock energy is incorporated

LCIA Results

Impact Category	Unit	Chlorine (Cl_2)	Sodium Hydroxide (NaOH)	Hydrogen (H_2)	Sodium Hypochlorite (NaOCl)
Climate change	kg CO_2 eq.	0.71	0.66	0.55	0.64
Acidification	mol H^+ eq.	2.5E-03	2.2E-03	1.8E-03	2.3E-03
Eutrophication, freshwater	kg P eq.	5.1E-04	5.0E-04	4.5E-04	2.1E-04
Eutrophication marine	kg N eq.	5.2E-04	4.7E-04	3.7E-04	4.9E-04
Eutrophication, terrestrial	mol N eq.	5.7E-03	5.1E-03	4.3E-03	5.1E-03
Ozone depletion	kg CFC-11 eq.	7.4E-08	6.0E-08	6.8E-08	2.1E-07
Photochemical ozone formation	kg NMVOC eq.	1.3E-03	1.2E-03	9.4E-04	1.4E-03
Particulate Matter	disease incidents	1.6E-08	1.4E-08	1.1E-08	1.4E-08
Human toxicity, cancer	CTUh	6.9E-09	7.1E-09	7.2E-09	5.0E-10
Human toxicity, non-cancer	CTUh	8.2E-09	7.8E-09	7.5E-09	9.1E-09
Ecotoxicity, freshwater	CTUe	21.8	11.9	8.3	15.4
Ionising radiation	kg U235 eq.	2.1E-01	1.9E-01	2.0E-01	4.1E-01
Water use	m^3 world eq.	0.95	0.64	0.22	0.99
Land Use	-	2.05	1.91	1.79	1.48

Additional Environmental and Health Information

Most direct releases of chlorine to the environment are to air and to surface water.

Effects of chlorine on human health depend on the amount of chlorine that is present, and the length and frequency of exposure. Chlorine enters the body by e.g. inhalation of contaminated air or e.g. consumption of contaminated food or water. It does not remain in the body due to its reactivity.

Additional Technical Information

Electrolysis of an aqueous sodium chloride solution co-produces chlorine, sodium hydroxide or potassium hydroxide solution, and hydrogen in a fixed ratio. Chlorine is used largely for the production of chlorinated hydrocarbons, especially for polyvinyl chloride (PVC) and polymer precursors (isocyanates, oxygenates). A small share of the chlorine gas produced is directed into diluted sodium hydroxide solution to produce sodium hypochlorite solution. Sodium hypochlorite solutions are used instead of chlorine for bleaching, disinfection, biofouling control, and odour control.

Sodium/potassium hydroxide solution is a strong chemical base mostly used in the manufacture of pulp and paper, food industry, soaps and detergents, and for water disinfection.

Hydrogen from electrolysis is mostly used on site as a chemical (e.g. production of hydrochloric acid, hydrogen peroxide etc.), to fuel steam boilers or generators or it is sold to a distributor.

Additional Economic Information

According to Cefic figures, 9,221 kt of chlorine was produced in 2020. This is 2 % lower compared to 2019 production and is most likely explained by the Covid pandemic. Production levels have been stable between ca. 9,000 and 10,000 kt of chlorine during the past decade, showing a slight downward trend. However, while capacities were expanded by 1.4 % during 2019, production dropped, leading to a decrease in utilisation rate from 81.0 % to 79.5 % in 2020 [Euro Chlor 2021].

Over the past 20 years, mercury cell technology was phased out, reaching zero production by the end of 2017, with membrane cell production increasing to compensate.

Germany, Belgium/the Netherlands and France remained the top three regions accounting together for nearly 73 % of the total European chlorine production capacities by the beginning of 2020 (Germany: 45 %; Belgium/the Netherlands: 16 %; France: 12 %).

Information

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

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References

PlasticsEurope 2019: Life Cycle Inventory (LCI). Methodology and Product Category Rules (PCR) for Uncompounded Polymer Resins and Reactive Polymer Precursors. Version 3.0, October 2019.

Euro Chlor 2021: Chlorine Industry Review 2020-2021

Eco-profile Report

Update Statement

This report is the updated version of the final report dated January 2022. The earlier version of this report included an error in the Climate Change indicator results of all products. The corrected values cover only the fossil part of the Global Warming Potential, while the earlier version included biogenic emissions, leading to inappropriately high results. The biogenic emissions have been removed, leading to lower Climate Change results in this updated report.

Functional Unit and Declared Unit

The Functional Unit and Declared Unit of the present Eco-profile and EPD are (unless otherwise specified):

1 kg of chlorine

1 kg of sodium hydroxide (in solution but excluding water)

1 kg of hydrogen

1 kg of sodium hypochlorite (in solution but excluding water)

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

Product Description

The substances considered in this process comprise the primary products of the chlor-alkali electrolysis, namely chlorine, sodium hydroxide (in aqueous solution up to 50 %), and hydrogen. Furthermore, sodium hypochlorite is accounted for as a secondary product. Table 1 gives an overview of selected characteristics and physical data of these substances.

Table 1: Characteristics of the products under consideration in this Eco-profile.

IUPAC name	CAS number	Chemical formula	Molar mass g/mol
Chlorine	7782-50-5	Cl_2	70.9
Sodium hydroxide	1310-73-2	NaOH	40.0
Hydrogen	1333-74-0	H_2	2.0
Sodium hypochlorite	7681-52-9	NaOCl	74.4

Chlorine is largely used in the synthesis of chlorinated organic compounds. PVC and isocyanates are the main drivers of chlorine production in EU and EFTA countries. As it is difficult to store and transport economically, chlorine is generally produced near its consumers. In 2020, only 4.8 % of the chlorine produced was transported via rail and road, the remainder was used on the same or adjacent sites, including chlorine transported by pipelines [Euro Chlor 2021].

The production of sodium hydroxide (also called caustic soda) is proportional to that of chlorine. Due to market requirements, sodium hydroxide is commercially produced in two forms: the 50 wt.-% solution is most common, whereas the solid state in form of pills, flakes, or cast shapes is less frequent. For some applications, sodium hydroxide is supplied in lower concentrations or used directly. The applications of sodium hydroxide in Europe cover a wide range. Synthesis of organic and inorganic compounds, as well as pulp and paper production, are among the most important applications in terms of share.

The co-production of chlorine and sodium hydroxide in fixed proportions has always been delicate for the chlor-alkali industry; the products are used for very different end uses with differing market dynamics; thus, it is rare that the demands are comparable, and prices vary accordingly.

Chlorine itself is difficult to transport over long distances, but it is traded over long distances as chlorinated derivates such as vinyl chloride monomer (VCM) and PVC, as well as chlorinated solvents. Sodium hydroxide, in contrast, is a globally traded commodity.

Another by-product of chlor-alkali electrolysis of brine is hydrogen. This highly pure hydrogen product (purity > 99.5 %) is usually used on site, on an adjacent site or sold to a distributor. In 2019, 89.2 % of the hydrogen produced by chlor-alkali installations in the EU and EFTA countries was utilised, while the remainder was emitted to air [Euro Chlor 2021].

Sodium hypochlorite (NaOCl) is produced by directing gaseous chlorine into a dilute solution of sodium hydroxide. A hypochlorite unit is attached to each chlor-alkali plant to render harmless the dilute chlorine that cannot be recovered economically. Sodium hypochlorite solutions can be used in various concentrations instead of chlorine for bleaching, disinfection, biofouling control, and odour control.

Manufacturing Description

The commercial production of chlorine

The most important technology for the production of chlorine is the electrolysis of aqueous solutions of sodium chloride (chlor-alkali electrolysis), co-producing both an aqueous solution of sodium hydroxide and gaseous hydrogen in a fixed stochiometric ratio of 1.1 kg sodium hydroxide and 0.03 kg hydrogen per kg of chlorine. To a lesser extent, potassium chloride solutions are used for electrolysis, resulting in the co-production of potassium hydroxide instead of sodium hydroxide. Other electrochemical processes for the production of chlorine include the electrolysis of hydrochloric acid and the electrolysis of molten alkali metal and alkaline earth metal chlorides. In 2019, the latter processes together accounted for less than 5 % of the European (EU and EFTA) production capacity [Euro Chlor 2021].

Since the scope of the current report is to investigate the commercially most relevant production of chlorine via the chlor-alkali electrolysis and the focus has been given to the routes co-producing sodium hydroxide, the following description of the production technology will concentrate exclusively on the electrolysis of sodium chloride solutions.

The chlor-alkali process [O'BRIEN 2005, SCHMITTINGER 2000, SCHMITTINGER 2006]

In the chlor-alkali electrolysis process, a sodium chloride solution is decomposed electrochemically by direct current. Three basic techniques exist for the electrolytic process: diaphragm and membrane cell technique, as well as the mercury cell technique. The mercury cell technique, however, has been phased out in recent years and is not further discussed in this document. The two remaining techniques applied differ in terms of electrode reaction and electrode materials, and in the way the chlorine produced is kept separate from sodium hydroxide and hydrogen.

The chemical processes at the anode are the same for the two techniques: chloride ions are oxidised and gaseous chlorine (Cl_2) is formed:

Anode: $2\ Cl^- \rightarrow Cl_2 + 2\ e^-$

In membrane and diaphragm cells, water is decomposed at the cathode into hydrogen and hydroxide ions:

$2\ Na^+ + 2\ e^- + 2\ H_2O \rightarrow 2\ NaOH + H_2$

As a result, the overall reaction in the chlor-alkali unit for all techniques is:

$2\ NaCl + 2\ H_2O \rightarrow Cl_2 + 2\ NaOH + H_2$

More detailed information on the techniques applied for chlor-alkali electrolysis and the closely linked unit operations for brine treatment and chlorine product processing can be found, for example, in SCHMITTINGER 2006, O'BRIEN 2005, and SCHMITTINGER 2000.

Treatment of sodium hydroxide is slightly different for the two cell types due to the difference in product output quality (composition and concentration of the sodium hydroxide produced). Hydrogen leaving the cells is highly concentrated (> 99.9 vol.-%) and usually only a little processing is needed.

Sodium hypochlorite is produced by feeding gaseous chlorine into a dilute solution of sodium hydroxide. The chlorine reacts with the sodium hydroxide under the formation of sodium hypochlorite, sodium chloride, and water:

$Cl_2 + 2\ NaOH \rightarrow NaOCl + NaCl + H_2O$

When the desired concentration of sodium hypochlorite is reached, the solution is withdrawn from circulation and directed to a cooled storage tank.

Producer Description

This Eco-profile and EPD represents a European industry average within the scope of Euro Chlor as the issuing trade federation. Hence, it is not attributed to any single producer, but rather to the European chlor-alkali industry as represented by the Euro Chlor membership and production sites participating in the Eco-profile data collection. The following companies contributed with primary data to the dataset of the chlor-alkali electrolysis:

- ANWIL S.A., Poland
- BASF SE, Germany
- Bondalti CHEMICALS S.A, Portugal
- BorsodChem Zrt., Hungary
- CABB GmbH, Germany
- Società Chimica Bussi S.p.A., Italy
- Covestro Deutschland AG, Germany
- Dow Deutschland Anlagengesellschaft mbH, Germany
- Electroquimica de Hernani S.A., Spain
- Ercros S.A., Spain
- INOVYN ChlorVinyls Limited, United Kingdom
- Kemira Oyj, Finland
- Nobian, Nouryon Industrial Chemicals B.V., the Netherlands
- PCC Rokita S.A., Poland
- Quimica del Cinca S.L.U, Spain
- SPOLCHEMIE - Spolek pro chemickou a hutní výrobu a.s., Czech Republic
- Vestolit GmbH, Germany
- Vinnolit GmbH & Co. KG, Germany
- VYNOVA Group N.V., Belgium

System Boundaries

This Eco-profile and EPD refers to the production of chlorine, sodium hydroxide (50 wt.-% solution), hydrogen, and sodium hypochlorite as products of the chlor-alkali process. It is based on a cradle-to-gate system (see Figure 1).

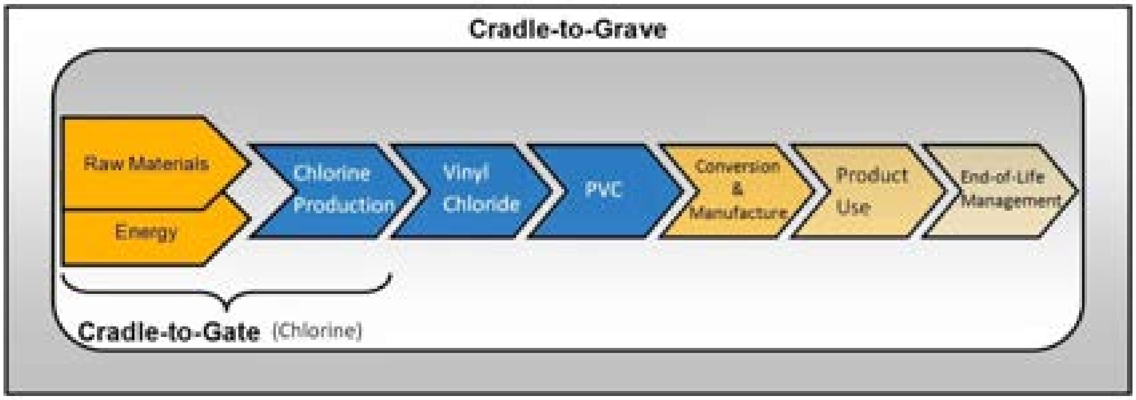

Figure 1: Cradle-to-gate system boundaries (Source: PlasticsEurope, modified)

Cradle-to-Gate System Boundaries for Production

The following processes are included in the cradle-to-gate LCI system boundaries (see Figure 2):

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

According to the methodology of Eco-profiles (PlasticsEurope v 3.0, October 2019, [PlasticsEurope 2019]), 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 the products from chlor-alkali production and their resulting products are also outside the LCI system boundaries of this Eco-profile. Inputs and outputs of secondary materials and wastes for recovery or disposal are noted as crossing the system boundaries. An exception is low-radioactive waste from electricity generation, for which a final storage has not been found yet; it is declared as output.

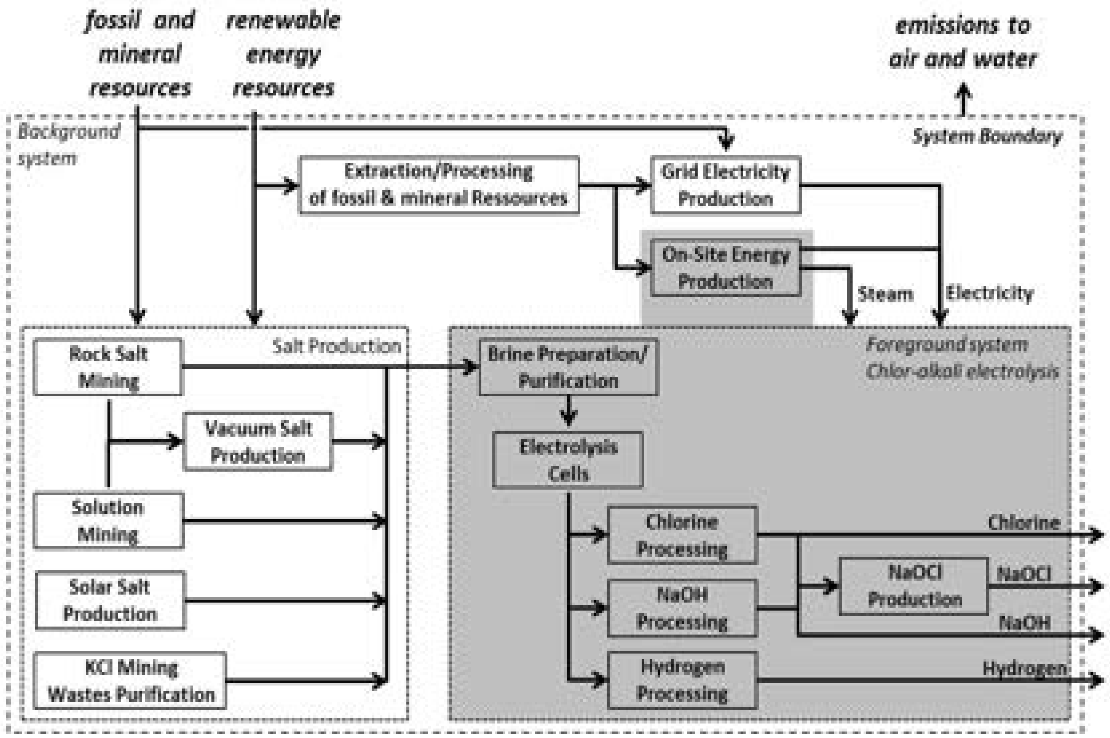

Figure 2: Schematic flow chart of the processes under consideration in this study.

Technological Reference

The LCI data in this Eco-profile represents the average applied technologies for the production of chlorine from chlor-alkali electrolysis in Europe. The production processes were modelled using specific values from primary data collection at site, representing the specific technologies of chlor-alkali electrolysis, i.e. diaphragm and membrane process. The LCI data represents the technology mix in use in the defined production region employed by participating producers.

From the total number of 67 chlor-alkali sites in Europe, 36 agreed on participation in this study; excluded were non-members of Euro Chlor (7), pure potassium chloride units (3), 7 units having full or partly HCl electrolysis, HCl oxidation, production of alcoholates or solid sodium production and a part of the units with chlorine production capacities < 20 kt/year (10). Thus, the maximum coverage reachable by this study is 79 % of the total installed production capacity of chlorine produced by chlor-alkali electrolysis in Europe (which was 11,953 kt by the beginning of 2020 [EURO CHLOR 2020]). Data was provided by 34 production sites covering 8,796 kt or 75 % of the European chlorine production capacity. Of the 36 sites that agreed to participate, one unit was later excluded since it was operating in a start-up phase in 2020. Another two sites failed to supply data due to internal workflow issues. Since fewer than three diaphragm plants provided data, it is not possible to show information separately for the diaphragm and membrane cell processes. The technological coverage can be understood as representative for membrane technology, whereas the representativeness of diaphragm technology is rather low.

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

For on-site energy, primary data was collected where possible. In most cases, it was provided by site-operators via the Euro Chlor member company.

Thus, primary data was used for all foreground processes (under operational control), as well as for the provision of on-site energy if applicable. This input data is complemented by secondary data from background processes, e.g. grid electricity supply. However, due to their relevance to the results of this Eco-profile (and subsequent Eco-profiles for polymers), all processes taking place within the system boundaries have been treated as foreground processes as far as research on and validation of the under-lying data are concerned.

According to the PlasticsEurope LCI methodology [PlasticsEurope 2019] Eco-profiles shall differentiate

- primary data from foreground processes, i.e. those that are under operational control, and
- secondary data from background processes, i.e. those operated by third parties where only indirect management control or no control exists.

As indicated in Figure 2, the foreground system comprises the chlor-alkali electrolysis step and the related on-site energy supply, while the background system contains all upstream processes for salt production, grid electricity supply, additives and auxiliary materials production.

According to the PlasticsEurope LCI methodology and product category rules, inputs of secondary materials (recyclate) and outputs of waste for recovery or disposal shall be noted as crossing the system boundaries. While there is no input of recyclates at all, outputs of wastes for recovery or disposal only contribute very little to the total proceedings under consideration in this Eco-profile. The following list shows the waste streams of the chlor-alkali unit and their treatment (total amount of waste: < 0.1 % related to feedstock input):

Table 2: Waste produced per kg chlorine (foreground process) and treatment

	Unit	
Hazardous waste to Landfill	kg	1.36E-03
Hazardous waste to Recovery	kg	2.20E-04
Hazardous waste to Incineration	kg	2.32E-04
Hazardous waste to Others	kg	9.27E-04
Non-hazardous waste to Landfill	kg	1.62E-03
Non-hazardous waste to Recovery	kg	7.80E-04
Non-hazardous waste to Incineration	kg	1.12E-04
Non-hazardous waste to Others	kg	3.96E-04

Temporal Reference

The LCI data for production was collected as 12-month averages representing the year 2020 (6 plants reported for 2019 stating that fluctuation can be considered low), to compensate seasonal influence of data.

Electricity data refers to the year 2019, while the dataset for salt production refers to the year 2011.

The overall reference year for this Eco-profile is 2020, with a maximal temporal validity until 2025. This five-year interval was chosen since major changes in the European electricity production mix are to be expected over the coming years. According to the PlasticsEurope LCI methodology [PlasticsEurope 2019] updates of Eco-profiles must at least be considered every three years.

The data quality rating is considered good (2) since almost all relevant data is less than three years older than the reference year, with the exception of salt production.

Geographical Reference

This Eco-profile refers to the average production of chlor-alkali-electrolysis in the EU28 (incl. UK) Member States plus Norway and Switzerland. The LCI data describing direct inputs and outputs of the production processes is representative of the defined production region. In order to be applied in other regions, adjustments might be required. Products of the chlor-alkali process imported into Europe were not considered in this Eco-profile.

The data quality rating is considered very good (1) because all relevant datasets refer to the area under study.

Cut-off Rules

To achieve completeness, i.e. a closed mass and energy balance, any cut-off of material and energy flows have been avoided in this Eco-profile. For commodities with an input < 1 % of the chlorine output, e.g. sulphuric acid, soda, generic datasets from the LCA database Ecoinvent v3.7.1 [Ecoinvent 2021] were used. In Ecoinvent datasets, waste for recycling is generally cut off. Furthermore, expenses for capital equipment were not considered in this Eco-profile.

Data Quality Requirements

Data Sources

Foreground data was collected from the chlor-alkali electrolysis units of the participating companies (see Producer Description). The data collection aimed at information on all energy and material inputs and outputs of a specific chlor-alkali unit, distances and means of transportation of each material input, emissions to air and water, and the amount, destination, and transport distances of wastes produced inside the battery limits. Furthermore, a similar set of data was collected on the on-site production of electricity and steam by either power plants or steam boilers delivering energy directly (i.e. not via the national electricity grid) to the chlor-alkali unit. Total amounts for one year (the reference year 2020) have been asked for.

Concerning the salt feedstock, the same model was used as in the previous Euro Chlor Eco-profile of Chlorine [Euro Chlor 2013]. It provides LCI results for the different types of salt and represents average European production technologies.

Table 3: Sources of salt used for chlor-alkali-electrolysis

Salt type	Share
Vacuum	35.4 %
Rock	11.6 %
Brine	53.0 %
Solar	0.0 %
Diaphragm	0.0 %

Electric power supply was modelled using country-specific grid electricity mixes, since the environmental burdens of power production varies strongly depending on the electricity generation technology. The country-specific electricity mixes are obtained from a master network for grid power modelling maintained and annually updated at ifeu as described in [IFEU 2016]. This network considers the basic power plant types and their respective raw material processes. Using network parameters, the fuel mix and essential technical characteristics of the energy systems are freely adjustable. Thus, the national grid electricity mix has been calculated for each European country. It is based on national electricity mix data from Eurostat [2021] for the year 2019.

The system boundary of the electricity module includes:

- power plant processes for electricity generation using coal and lignite, fuel oil, natural gas, biomass and waste, as well as nuclear, hydroelectric, geothermal, solar and wind power;
- upstream fuel chains in the case of coal, lignite, fuel oil, natural gas, biomass and nuclear power;
- distribution of electricity to the consumer with appropriate management and transformer losses.

The network also includes combined heat and power generation. The share of district heat produced in coupled form is adjustable according to the power plant type. An allocation of the burdens to electricity and district heating is performed through allocation based on exergetic values of products. Additional information concerning the electricity grid model applied can be found on the ifeu website and in Table 4.

Table 4: Global Warming Potential (GWP 100 - ELCD/PEF) of country-specific electricity supply mixes (2019)

Country	2019 GWP 100 kg CO_2 eq./kWh
Belgium	0.195
Czech Republic	0.675
Finland	0.187
France	0.086
Germany	0.464
Hungary	0.363
Italy	0.419
Norway	0.020
Poland	0.987
Portugal	0.337
Spain	0.285
Sweden	0.033
The Netherlands	0.457
United Kingdom	0.275
Supply mix, weighed by chlorine production capacity covered in this study	0.392

Data sources of on-site energy and utilities:

- Steam and electricity: Data from several ifeu projects and Ecoinvent v3.7.1 [Ecoinvent 2021]
- Compressed air (low and high pressure): Several data from ifeu projects, Ecoinvent v3.7.1 [Ecoinvent 2021]
- Industrial gases: oxygen and nitrogen according to Ecoinvent v3.7.1 [Ecoinvent 2021] and ifeu internal database
- Process water: Ecoinvent v3.7.1 [Ecoinvent 2021]

Relevance and Representativeness

With regards to the goal and scope of this Eco-profile, the process data are of high relevance as the combination of primary data collected from the most important producers in Europe represent the best available data to describe the European landscape of chlor-alkali-electrolysis. The data used reflect the current technology in Europe, current upstream chains for salt production, and current electricity production in in EU28 (incl. UK) member countries + Norway + Switzerland. Primary data was collected from plant operators covering 75 % of the chlorine capacity within Europe. Due to the large coverage of primary data, the process data can be considered representative for > 90 % of the European chlorine production.

Consistency

Relevant process and upstream chain data have been validated to comply with the goal and scope of this Eco-profile. The datasets along the process chains of salt production, electricity generation and chlor-alkali electrolysis were built together and checked for consistency.

While building up the model, cross-checks concerning the plausibility of mass and energy flows were continuously conducted. The methodological framework is consistent throughout the whole model as the same methodological principles (e.g. allocation principles, background datasets, waste treatment) are used throughout the whole system. Those parts of the model defined as background systems according to the PlasticsEurope LCI methodology [PlasticsEurope 2019] have been treated with the same thoroughness as if they were foreground systems.

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

Reliability

In this Eco-profile, process data originates from confidential data from chlor-alkali electrolysis plant operators. Data of the upstream chains of salt production were taken from the previous Eco-profile, which was externally reviewed.

The site managers were encouraged to classify their data in the questionnaires, 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 from relevant background processes, e.g. grid electricity, is based on ifeu models that are regularly updated with statistical data, available primary data, and data derived from literature after it has been reviewed and checked for its quality.

Thus, the overall data quality rating for reliability is considered good (2), since either verified data partly based on assumptions or non-verified data based on measurements was used.

Completeness

In general, the data collected and applied can be stated as complete, because no flows are omitted or substituted, except for area occupation information of the chlor-alkali electrolysis plants which was not available. However, for some 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 electrolysis units and weighted by chlorine output) were used in cases of data gaps. This procedure prevents missing information to be treated as "zero" in the calculation of average values. This procedure was applied to the following substances/process flows:

- emissions of hydrogen and chlorine to air
- emissions of Cr, Cu, Hg, Ni, Zn, chlorine and chlorides to water
- the total amount of flue gas from process
- the total amount of wastewater

In case of missing information on the fuel mix (natural gas, fuel oil, coal, etc.) used for on-site energy production, the average fuel mix of all participating plants was assumed. The same method was applied for thermal or electrical efficiencies of on-site energy installations, as well as for means and distances of raw materials and waste transport. Therefore, the data is considered as complete as possible for all relevant flows (data quality rating: 2; cut-offs ≤ 1 %).

Precision and Accuracy

For the assessment of data, it is desirable to calculate a confidence range for the LCI (and Life Cycle Impact Assessment - LCIA) results. Technically this confidence interval of the results could be calculated with the help of the Monte-Carlo simulation (in Umberto). For this, standard deviations (or distribution functions) of every flow and unit process would have to be known that are not available in reality. due to insufficient independent data points. An alternative option to determine the uncertainty could be an estimation of the standard deviations based on a pedigree matrix, as practised e.g. in Ecoinvent v3.7.1 [Ecoinvent 2021]. The disadvantage of this method would be that incorrect estimates of relevant flows would lead to wrong confidence intervals and basic misinterpretations of results. Hence, a quantitative uncertainty assessment cannot be provided. The overall qualitative assessment of data accuracy is as follows:

- There is a high accuracy of relevant material flows, especially of salt input and product output, for energy flows (electricity and steam) and combustion-related air emissions (CO_2, SO_2, NO_x, CH_4) within the production system
- There is good accuracy for other air emissions and emissions to water bodies.

The data quality rating is considered good (2) since mostly measured data is used in the foreground system, extrapolated data in background.

Reproducibility

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

Data Validation

The data of the core process chlor-alkali electrolysis was provided by plant operators, which was thoroughly checked and validated by the LCA practitioner.

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

Life Cycle Model

The product system investigated is modelled in Umberto 5.6, a standard software tool for LCA. Figure 3 gives an overview of the model, including upstream processes and chlor-alkali-electrolysis. The associated database integrates ISO 14040/44 requirements. Due to confidentiality reasons, details on software modelling and methods used cannot be shown here. Data for production processes have been transferred to the model after a successful data validation.

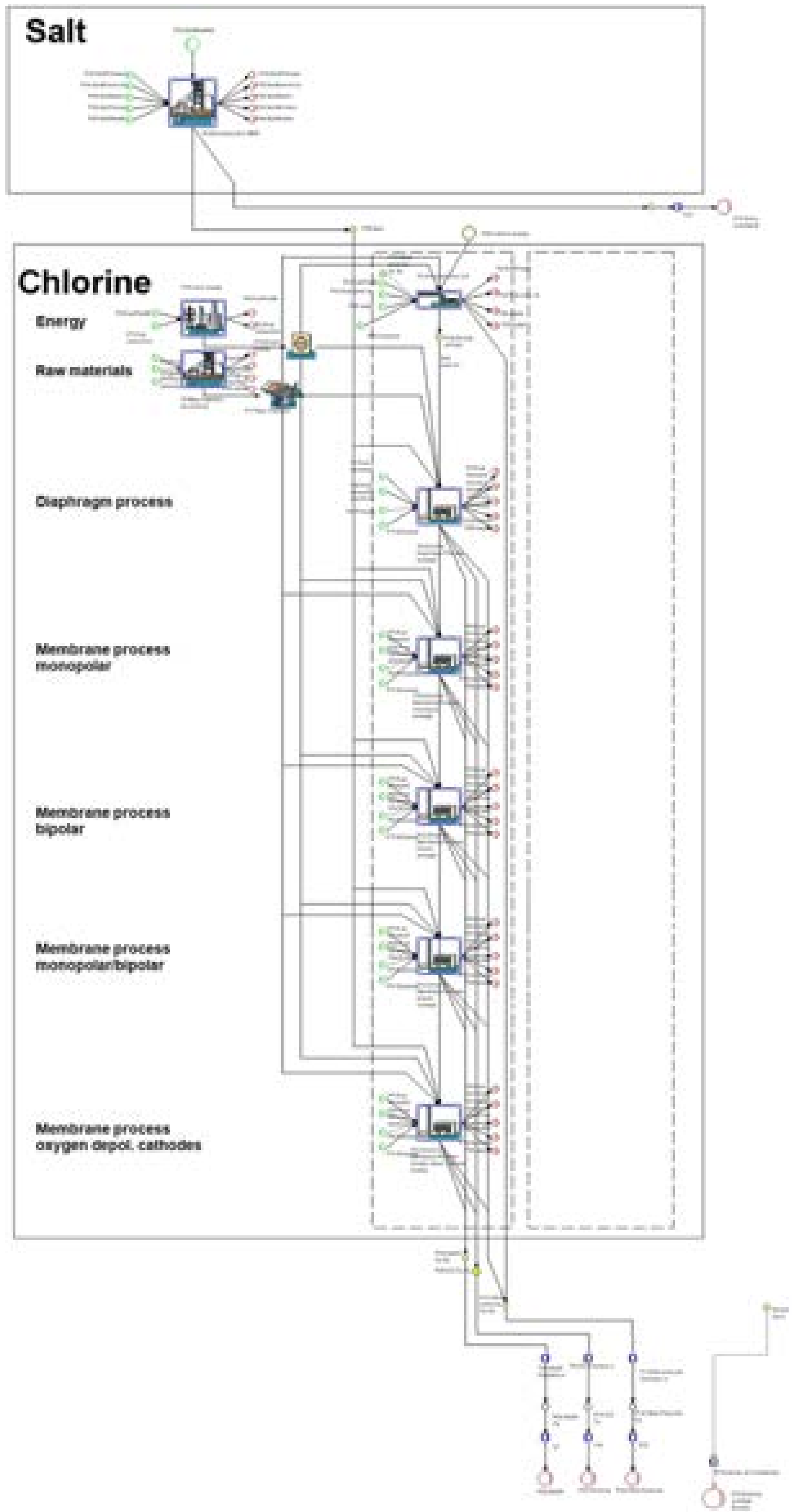

Figure 3: A simplified flow chart of the life cycle model for the production of chlorine in Europe in Umberto 5.6. Here, only one production site is shown (inside the dashed box), connected to the pre-chains of public energy, salt and other raw materials. For the complete model, additional production sites were inserted in parallel as indicated by the empty dashed box to the right.

Table 5: Chlor-alkali electrolysis gate-to-gate process data: chlorine production weighted average of selected material and energy inputs and outputs per kg chlorine. The values in this table do not represent allocated but total in- and outputs of the average electrolysis process divided by the chlorine amount produced.

	Unit	Value				
Input						
Grid electricity	kWh	2.36				
On-Site electricity	kWh	0.26				
Thermal energy	kJ	2064				
Salt	kg	2.15				
Sulphuric acid	kg	0.010				
Compressed Air	Nm³	0.033				
Nitrogen	Nm³	0.011				
Water Input		**Water source**				
		total	unspecific	river/lake	groundwater	sea/ocean
Process Water	kg	1.7	0.1	1.0	0.6	0.0
Cooling Water	kg	37.0	5.8	24.0	7.2	0.0
Steam	kg	0.7				
Water in Feedstocks	kg	3.3				
Output						
Chlorine	kg	0.96				
NaOH (excl. water)	kg	1.03				
Hydrogen	kg	0.026				
HCl - excl. water)	kg	0.016				
NaOCl - excl. water)	kg	0.026				
Water Output		**Water destination**				
		total	unspecific	river/lake	groundwater	sea/ocean
Process Water to WWT	kg	0.7	0.0	0.4	-	0.3
Cooling Water	kg	35.8	7.0	26.0	-	2.8
Condensate	kg	0.4				
Water Vapour	kg	2.0				
Water in products [1)]	kg	3.8				
Emissions to air						
CO_2	g	5.52				
Hydrogen (H_2)	g	3.31				
Chlorine (Cl_2)	g	3.22E-04				
Emissions to water						
Chromium (total as Cr)	kg	2.31E-08				
Copper (total, as Cu)	kg	8.57E-08				
Mercury (total, as Hg)	kg	8.51E-09				
Nickel (total, as Ni)	kg	4.15E-08				
Zinc (total, as Zn)	kg	9.21E-07				
Chlorides	kg	3.90E-02				
Chlorine	kg	1.83E-07				

[1)] encompassing HCl, NaOH, NaOCl as solvent, depleted brine output, water incorporated as OH within NaOH

Calculation Rules

Horizontal/Vertical Averaging

When modelling and calculating average Eco-profiles from the collected individual LCI datasets, vertical averages were calculated (Figure 4). These vertical averages comprise the chlor-alkali production unit itself, the specific salt supply, country-specific electricity generation, the on-site energy supply (electricity and steam if produced on-site), on-site production of supply materials like pressurised air, nitrogen, or process water, transport of input materials and waste, waste treatment, and wastewater treatment.

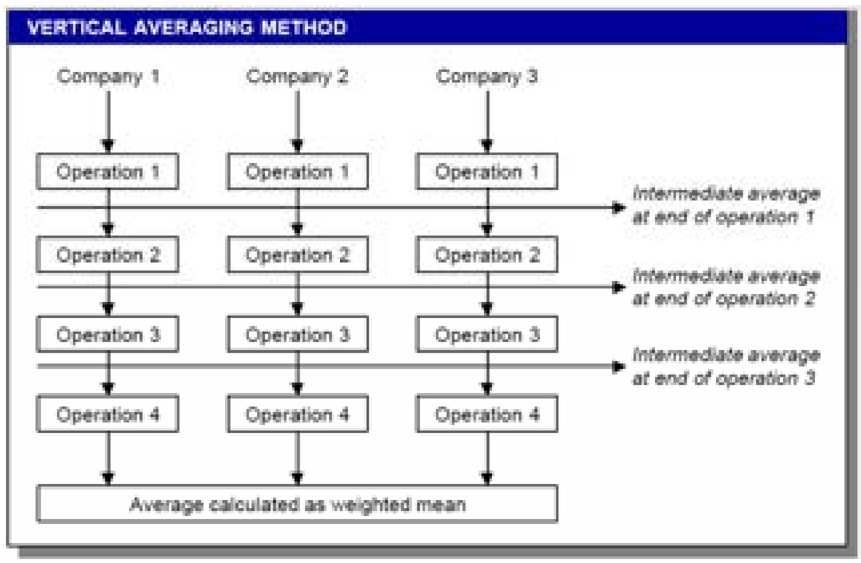

Figure 4: Vertical Averaging (source: Eco-profile of high-volume commodity phthalate esters, ECPI European Council for Plasticisers and Intermediates, 2001)

Allocation Rules

Production processes in the chemical and plastics industry are usually multi-functional systems, i.e. they exhibit not one but several valuable product and co-product outputs. Wherever possible, and according to the PlasticsEurope LCI methodology [PlasticsEurope 2019], allocation should be avoided by expanding the system to include the additional functions related to the co-products. To achieve this, a generic process with the same function (product) can be introduced, such that the system examined receives credits for the associated burdens avoided elsewhere (»avoidance allocation«). System expansion should only be used where there is a dominant, identifiable displaced product, and if there is a dominant, identifiable production path for the displaced product.

In this Eco-profile, where the main production technologies for the chlor-alkali electrolysis are considered, avoiding allocation is not feasible because of the co-production of chlorine, sodium hydroxide, and hydrogen. 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. In principle, allocation rules should reflect the goal of the production process.

The following allocation rules were applied for the chlor-alkali unit (base case):

Sodium chloride input was allocated by means of stoichiometry to all products containing either sodium or chlorine atoms (or both): chlorine, sodium hydroxide, sodium hypochlorite and sodium sulphate.

Sulphuric acid input was allocated to chlorine production only, since it is used for chlorine drying.

Hydrogen emissions were allocated to hydrogen production only, since they refer to losses of hydrogen to the atmosphere.

Chlorine gas emissions were allocated to chlorine production only, since they refer to losses of chlorine to the atmosphere.

Electricity input was allocated by mass to all valuable products (chlorine, sodium hydroxide, hydrogen, sodium hypochlorite, potassium hydroxide), for solutions to mass content of active molecule. The allocation of electricity to the products of the chlor-alkali unit was well discussed in the past. None of the methods gained universal approval, so the traditional method of allocation by mass was chosen in the present work as the default allocation method. Furthermore, since allocation by mass was used in the previous Eco-profile, the methodology of both reports is comparable. Other allocation methods were investigated in a sensitivity analysis.

Steam input was allocated by mass to all valuable products (see above). In previous publications, steam was attributed to the concentration of sodium hydroxide. From the data collected, however, it is not possible to attribute the steam input only to sodium hydroxide concentration since other plants without concentration stages also reported significant steam use. A correlation between sodium hydroxide concentration and steam input could not be derived from the data collected.

All other expenses (inputs and emissions) were allocated by mass to the valuable products. The following outputs of the chlor-alkali unit were not considered as valuable products of the chlor-alkali electrolysis and are thus not receiving burdens from this process: sulphuric acid, sodium sulphate (except salt input).

Furthermore, a sensitivity analysis for partitioning method was performed, where two other allocation scenarios were tested:

- Pure mass allocation:
  Same method as the base case with the difference that sodium chloride input is also allocated by mass (for solutions to mass content of active molecule) not by stoichiometry. The most significant change is that hydrogen now receives burdens from salt production.
- Economic allocation:
  This partitioning method is based on average long-term market prices of the products. The main problem of this methodology is to obtain the long-term prices for all products. For the main products of chlorine, sodium hydroxide and hydrogen, as well as for hydrogen chloride and (general) hypochlorites, the Eurostat production statistics (Eurostat 2021) provide data for 2010 until 2020. The average market prices applied in the sensitivity calculation are shown in Table 6. The expenses (inputs and emissions) in general were allocated to the products based on these prices. For sulphuric acid input, as well as for emissions of hydrogen and chlorine, the allocations rules of the base case were used.

Table 6: Prices used for economic allocation (per ton of active molecule). Source: Eurostat Prodcom [2021]

Product	Average price on European market in 2010-2020 €/t
Hydrogen	1,642
Chlorine	165
Sodium hydroxide in aqueous solution	224
Potassium hydroxide	505
Hypochlorites	263

Life Cycle Inventory (LCI) Results

Delivery and Formats of LCI Dataset

This Eco-profile comprises

- a dataset in International Reference Life Cycle Data System (ILCD) format (http://lct.jrc.ec.europa.eu) according to the last version at the date of publication of the Eco-profile and including the reviewer (internal and external) input and
- a report in pdf format.

Energy Demand

As a key indicator on the inventory level, the **primary energy demand** (system input), shown in Table 7, indicates the cumulative energy requirements at the resource level, accrued along the entire process chain (system boundaries), quantified as gross calorific value (upper heating value, UHV). The net calorific values (lower heating value, LHV) are also presented in Table 7 for information purposes.

Table 7: Primary energy demand (system boundary level) per 1 kg of product

Primary Energy Demand	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Total primary energy demand (Upper heating value) [MJ]	13.58	12.60	11.69	17.89
Total primary energy demand (Lower heating value) [MJ]	12.81	11.89	11.07	17.15

Water use (withdrawal) cradle to gate

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

Table 8: Water use (withdrawal) per source per 1 kg of product (cradle to gate).

Source/Use	Unit	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Cooling					
Lake	kg	3.9	4.1	4.1	3.6
River	kg	53.4	47.6	38.4	60.4
Well	kg	18.3	15.3	13.8	28.8
Ocean	kg	0.0	0.0	0.0	0.0
Unspecified	kg	9.2	7.6	5.4	10.8
Total cooling	kg	84.9	74.6	61.7	103.7
Process					
Lake	kg	0.0	0.0	0.0	0.0
River	kg	0.0	0.0	0.0	0.0
Well	kg	0.3	0.3	0.3	0.4
Ocean	kg	0.0	0.0	0.0	0.0
Unspecified	kg	0.6	0.6	0.6	1.0
Total process	kg	0.9	0.9	0.9	1.4
Turbine use	kg	601	437	232	657
Total (excl. Turbine)	kg	85.8	75.5	62.6	105.1

Water consumption cradle to gate

Table 9: Water consumption per 1 kg of chlor-alkali electrolysis product (cradle to gate). Sea water withdrawal and turbined water not included.

Use	Unit	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Process	kg	0.4	0.4	0.4	0.7
Cooling (w/o sea water)	kg	22.1	14.5	4.7	22.3
Total water consumption	kg	22.5	14.9	5.1	23.0

Life Cycle Impact Assessment (LCIA) Results

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

Disclaimer:

- The following LCIA methods are recommended by JRC, but the results of these environmental impact indicators shall be used with care as the uncertainties on these results are high or as there is limited experience with the indicator (recommendation level III, EC-JRC 2018):
  - Ecotoxicity freshwater
  - Human toxicity, cancer
  - Human toxicity, non-cancer
  - Land use
  - Resource use, fossils
  - Resource use, minerals and metals
  - Water use

Table 10: List of impact categories and methodologies used for LCIA in the present Eco-profile and in the previous version.

	This Eco-profile (ELCD/PEF)		Previous Eco-profile	
Impact Category	**Methodology**	**Unit**	**Methodology**	**Unit**
Acidification	Accumulated Exceedance; Seppälä et al. 2006, Posch et al., 2008	mol H^+ eq.	Hauschild 1998; characterisation factors of CML [CML 2012]	kg SO_2 eq.
Climate change	Baseline model of 100 years of the IPCC (based on IPCC 2013)	kg CO_2 eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013)	kg CO_2 eq.
Ecotoxicity, freshwater	USEtox model (Rosenbaum et al, 2008)	CTUe	Not considered	
Particulate Matter	PM method recommended by UNEP (UNEP 2016)	disease incidence	DE LEEUW 2002 and HELDSTAB 2003	kg PM10 eq.
Eutrophication marine	EUTREND-model, Struijs et al., 2009b, as in ReCiPe 2008	kg P eq.	HEIJUNGS 1992; characterisation factors of CML [CML 2012]	kg PO_4 eq.
Eutrophication, freshwater	EUTREND-model, Struijs et al., 2009b, as in ReCiPe 2008	kg N eq.		
Eutrophication, terrestrial	Accumulated Exceedance (AE); Seppälä et al. 2006, Posch et al., 2008	mol N eq.		
Human toxicity, cancer	USEtox model (Rosenbaum et al, 2008)	CTUh	Not considered	
Human toxicity, non-cancer	USEtox model (Rosenbaum et al, 2008)	CTUh	Not considered	
Ionising radiation, human health	Human health model; Dreicer et al., 1995, Frischknecht et al, 2000	kg U235 eq.	Not considered	
Land use	Soil quality index based on LANCA (Beck et al. 2010and Bos et al. 2016)	-	Not considered	
Ozone depletion	EDIP model over an infinite time horizon. WMO 2014 (excl. N_2O)	kg CFC-11 eq.	EDIP model over an infinite time horizon. WMO 2014, incl. N_2O	kg CFC-11 eq.
Photochemical ozone formation - human health	LOTOS-EUROS, van Zelm et al., 2008, as in ReCiPe	kg NMVOC eq.	JENKIN 1999 and DERWENT 1998; characterisation factors of CML [CML 2012]	kg Ethene eq.
Resource use, fossils	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.	MJ (LHV)	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.	MJ (LHV)
Resource use, minerals and metals	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.	kg Sb eq.	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.	kg Sb eq.
Water use	Available WAter REmaining (AWARE) as recommended by UNEP, 2016	m^3 world eq.	Only on inventory level	kg

In the following tables, the LCIA results are shown for each of the considered product both using the ELCD methods and the methods applied in the previous Eco-profile studies.

Table 11: LCIA results for the products of the chlor-alkali electrolysis system using the ELCD/PEF methodology.

Impact Category	Unit	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Climate change	kg CO_2 eq.	0.71	0.66	0.55	0.64
Acidification	mol H^+ eq.	2.5E-03	2.2E-03	1.8E-03	2.3E-03
Eutrophication, freshwater	kg P eq.	5.1E-04	5.0E-04	4.5E-04	2.1E-04
Eutrophication marine	kg N eq.	5.2E-04	4.7E-04	3.7E-04	4.9E-04
Eutrophication, terrestrial	mol N eq.	5.7E-03	5.1E-03	4.3E-03	5.1E-03
Ozone depletion	kg CFC-11 eq.	7.4E-08	6.0E-08	6.8E-08	2.1E-07
Photochemical ozone formation	kg NMVOC eq.	1.3E-03	1.2E-03	9.4E-04	1.4E-03
Particulate Matter	disease incidents	1.6E-08	1.4E-08	1.1E-08	1.4E-08
Human toxicity, cancer	CTUh	6.9E-09	7.1E-09	7.2E-09	5.0E-10
Human toxicity, non-cancer	CTUh	8.2E-09	7.8E-09	7.5E-09	9.1E-09
Ecotoxicity, freshwater	CTUe	21.8	11.9	8.3	15.4
Ionising radiation	kg U235 eq.	2.1E-01	1.9E-01	2.0E-01	4.1E-01
Resource use, fossils	MJ (LHV)	12.45	11.54	10.59	16.18
Resource use, minerals and metals	kg Sb eq.	2.05E-06	1.82E-06	1.77E-06	2.16E-06
Water use	m^3 world eq.	0.95	0.64	0.22	0.99
Land use	-	2.05	1.91	1.79	1.48

Table 12: LCIA results for the products of the chlor-alkali electrolysis system using the previous Eco-profile methodology.

Impact Category	Unit	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Climate change	kg CO_2 eq.	0.71	0.65	1.19	0.63
Acidification	g SO_2 eq.	3.03	2.36	1.44	2.90
Eutrophication, total	g PO_4 eq.	1.79	1.74	1.54	0.86
Eutrophication, terrestrial	g PO_4 eq.	0.17	0.16	0.13	0.16
Eutrophication, aquatic	g PO_4 eq.	1.62	1.58	1.41	0.70
Ozone depletion	g CFC-11 eq.	5.4E-04	5.0E-04	4.7E-04	5.9E-04
Photochemical ozone formation	g C_2H_4 eq.	3.9E-02	3.4E-02	3.2E-02	4.6E-02
Particulate Matter	g PM10 eq.	1.48	1.31	1.05	1.49
Resource use, fossils	MJ (LHV)	7.4	6.9	5.9	7.4
Resource use, minerals and metals	kg Sb eq.	2.6E-05	1.6E-05	1.8E-06	1.9E-05

The comparison of both LCIA result tables reveals some differences between the methodologies used:

- **Climate change**: the ELCD methodology generally applies higher characterisation factors for methane (36.75 vs. 30) and N_2O (298 vs. 265), leading to slightly higher Global Warming Potential (GWP) results for NaOH (0.66 vs. 0.65 kg CO_2 eq.) and NaOCl (0.64 vs. 0.63 kg CO_2 eq.) in the ELCD/PEF compared to the previous methodology. In contrast, hydrogen is not counted as a greenhouse gas in the ELCD/PEF methodology while this was the case in the previous Eco-profile with a factor of 5.8 based on the works by Derwent (2006). This leads to very much higher GWP results for hydrogen according to the previous methodology (1.19 vs. 0.55 kg CO_2 eq.).

- **Resource use, fossils**: uranium is counted as fossil resource in the ELCD/PEF methodology, while this is not the case in the CML methodology. Therefore, the ELCD/PEF results for fossil resource use are higher than in the old methodology (11-17 MJ vs. 6-8 MJ).
- **Resource use, minerals and metals**: In the previous Eco-profile methodology, NaCl was counted as mineral resource with a factor of 1.65E-05 kg Sb eq., which is not counted in the ELCD/PEF methodology. Therefore, the results for mineral resource use are higher with the old methodology for chlorine, NaOH and NaOCl (1.8E-06– 2.6E-5 vs. 1.8 – 2.3E-6 kg Sb eq.)
- **Ozone Depletion**: In the previous Eco-profile methodology, N_2O was counted as an ozone depleting substance with a factor of 0.017 based on the publications of WMO (2014) and Ravishankara (2009). The ELCD/PEF methodology does not consider this factor and therefore the ELCD/PEF results for ozone depletion are much lower than the previous methodology (6 – 20E-5 vs. 5 – 6E-4 g CFC-11 eq.).

Dominance Analysis

Table 13: Dominance analysis of impacts per 1 kg chlorine.

Impact Category	Thermal energy	Electricity	Aux. Materials	Others (Transp.+ Disposal)	Salt	Electrolysis Process	Utilities
Climate change	10.98%	69.71%	0.89%	1.14%	17.15%	0.14%	0.00%
Acidification	9.01 %	65.91 %	6.89 %	2.76 %	15.31 %	0.12 %	0.00 %
Eutrophication, freshwater	2.46 %	90.05 %	0.45 %	0.11 %	6.86 %	0.07 %	0.00 %
Eutrophication marine	7.30 %	64.03 %	2.32 %	4.13 %	21.79 %	0.42 %	0.00 %
Eutrophication, terrestrial	6.91 %	70.52 %	1.19 %	4.21 %	16.96 %	0.20 %	0.00 %
Ozone depletion	24.48 %	22.96 %	37.06 %	0.10 %	15.13 %	0.27 %	0.00 %
Photochemical ozone formation	17.85 %	56.83 %	2.05 %	4.70 %	18.33 %	0.25 %	0.00 %
Particulate Matter	5.64 %	72.57 %	6.89 %	2.07 %	12.71 %	0.13 %	0.00 %
Human toxicity, cancer	0.28 %	2.25 %	0.10 %	0.02 %	0.32 %	97.03 %	0.00 %
Human toxicity, non-cancer	3.77 %	80.43 %	0.94 %	0.21 %	8.25 %	6.41 %	0.00 %
Ecotoxicity, freshwater	2.29 %	21.91 %	0.95 %	0.08 %	61.49 %	13.28 %	0.00 %
Ionising radiation	0.33 %	89.35 %	0.33 %	0.15 %	9.84 %	0.01 %	0.00 %
Resource use, fossils	14.36 %	71.32 %	1.07 %	0.92 %	12.28 %	0.04 %	0.00 %
Resource use, minerals and metals	6.02 %	75.31 %	8.21 %	0.10 %	10.36 %	0.00 %	0.00 %
Water use	1.15 %	16.38 %	1.41 %	0.05 %	76.36 %	4.68 %	-0.03 %
Land use	3.61 %	82.10 %	1.82 %	0.09 %	12.38 %	0.00 %	0.00 %

Table 14: Dominance analysis of impacts per 1 kg sodium hydroxide.

Impact Category	Thermal energy	Electricity	Aux. Materials	Others (Transp.+ Disposal)	Salt	Electrolysis Process	Utilities
Climate change	11.72%	76.13%	0.71%	0.70%	10.55%	0.19%	0.00%
Acidification	10.24 %	75.43 %	2.57 %	1.93 %	9.67 %	0.16 %	0.00 %
Eutrophication, freshwater	2.48 %	93.04 %	0.34 %	0.06 %	4.01 %	0.07 %	0.00 %
Eutrophication marine	8.14 %	72.67 %	2.20 %	2.80 %	13.69 %	0.51 %	0.00 %
Eutrophication, terrestrial	7.54 %	78.21 %	0.93 %	2.80 %	10.26 %	0.26 %	0.00 %
Ozone depletion	30.32 %	28.57 %	30.34 %	0.07 %	10.36 %	0.33 %	0.00 %
Photochemical ozone formation	19.96 %	64.16 %	1.17 %	3.18 %	11.22 %	0.31 %	0.00 %
Particulate Matter	6.31 %	82.00 %	2.70 %	1.41 %	7.42 %	0.15 %	0.00 %
Human toxicity, cancer	0.28 %	2.18 %	0.06 %	0.01 %	0.16 %	97.31 %	0.00 %
Human toxicity, non-cancer	3.94 %	85.72 %	0.63 %	0.12 %	3.26 %	6.32 %	0.00 %
Ecotoxicity, freshwater	4.20 %	39.92 %	1.22 %	0.08 %	29.89 %	24.68 %	0.00 %
Ionising radiation	0.36 %	93.14 %	0.24 %	0.09 %	6.16 %	0.01 %	0.00 %
Resource use, fossils	15.52 %	75.78 %	0.62 %	0.56 %	7.47 %	0.05 %	0.00 %
Resource use, minerals and metals	6.76 %	84.13 %	4.95 %	0.06 %	4.09 %	0.00 %	0.00 %
Water use	1.68 %	24.28 %	0.58 %	0.04 %	66.20 %	7.25 %	-0.04 %
Land use	3.87 %	88.56 %	1.38 %	0.06 %	6.12 %	0.00 %	0.00 %

Table 15: Dominance analysis of impacts per 1 kg hydrogen.

Impact Category	Thermal energy	Electricity	Aux. Materials	Others (Transp.+ Disposal)	Salt	Electrolysis Process	Utilities
Climate change	13.47%	85.35%	0.94%	0.00%	0.00%	0.23%	0.00%
Acidification	11.94 %	84.68 %	3.19 %	0.00 %	0.00 %	0.19 %	0.00 %
Eutrophication, freshwater	2.74 %	96.79 %	0.39 %	0.00 %	0.00 %	0.08 %	0.00 %
Eutrophication marine	10.08 %	86.21 %	3.04 %	0.01 %	0.00 %	0.66 %	0.00 %
Eutrophication, terrestrial	8.78 %	89.68 %	1.22 %	0.00 %	0.00 %	0.31 %	0.00 %
Ozone depletion	25.58 %	25.23 %	48.90 %	0.00 %	0.00 %	0.29 %	0.00 %
Photochemical ozone formation	23.82 %	74.21 %	1.58 %	0.01 %	0.00 %	0.39 %	0.00 %
Particulate Matter	7.64 %	88.67 %	3.50 %	0.00 %	0.00 %	0.19 %	0.00 %
Human toxicity, cancer	0.26 %	2.18 %	0.09 %	0.00 %	0.00 %	97.47 %	0.00 %
Human toxicity, non-cancer	3.97 %	88.78 %	0.68 %	0.00 %	0.00 %	6.57 %	0.00 %
Ecotoxicity, freshwater	5.75 %	57.10 %	1.73 %	0.00 %	0.00 %	35.43 %	0.00 %
Ionising radiation	0.36 %	99.38 %	0.26 %	0.00 %	0.00 %	0.01 %	0.00 %
Resource use, fossils	16.27 %	82.92 %	0.76 %	0.00 %	0.00 %	0.05 %	0.00 %
Resource use, minerals and metals	6.74 %	87.82 %	5.44 %	0.00 %	0.00 %	0.00 %	0.00 %
Water use	4.99 %	71.93 %	1.89 %	0.00 %	0.00 %	21.30 %	-0.11 %
Land use	3.96 %	94.58 %	1.46 %	0.00 %	0.00 %	0.00 %	0.00 %

Table 16: Dominance analysis of impacts per 1 kg sodium hypochlorite.

Impact Category	Thermal energy	Electricity	Aux. Materials	Others (Transp.+ Disposal)	Salt	Electrolysis Process	Utilities
Climate change	19.15%	56.84%	1.44%	1.55%	19.66%	1.37%	0.00%
Acidification	14.14 %	61.25 %	2.64 %	5.28 %	16.08 %	0.61 %	0.00 %
Eutrophication, freshwater	6.96 %	74.85 %	1.10 %	0.23 %	16.67 %	0.19 %	0.00 %
Eutrophication marine	11.87 %	53.29 %	3.10 %	7.35 %	22.89 %	1.51 %	0.00 %
Eutrophication, terrestrial	11.69 %	60.00 %	1.52 %	7.66 %	17.77 %	1.36 %	0.00 %
Ozone depletion	12.46 %	7.26 %	74.51 %	0.04 %	5.58 %	0.15 %	0.00 %
Photochemical ozone formation	23.88 %	50.50 %	1.58 %	7.01 %	15.88 %	1.16 %	0.00 %
Particulate Matter	9.08 %	70.65 %	3.14 %	3.91 %	12.83 %	0.39 %	0.00 %
Human toxicity, cancer	5.82 %	35.83 %	3.70 %	0.21 %	4.06 %	50.37 %	0.00 %
Human toxicity, non-cancer	5.23 %	82.48 %	0.82 %	0.19 %	4.94 %	6.34 %	0.00 %
Ecotoxicity, freshwater	4.64 %	33.62 %	1.33 %	0.12 %	38.16 %	22.12 %	0.00 %
Ionising radiation	0.25 %	94.42 %	0.19 %	0.06 %	5.09 %	0.01 %	0.00 %
Resource use, fossils	15.89 %	72.53 %	0.91 %	0.85 %	9.77 %	0.05 %	0.00 %
Resource use, minerals and metals	8.29 %	79.21 %	6.22 %	0.08 %	6.21 %	0.00 %	0.00 %
Water use	1.69 %	12.04 %	0.69 %	0.05 %	75.33 %	10.23 %	-0.03 %
Land use	7.20 %	76.05 %	2.26 %	0.10 %	14.38 %	0.01 %	0.00 %

Sensitivity Analysis Regarding the Influence of the Allocation Method

As described in the Allocation Rules section on page 18f, a sensitivity analysis was performed to examine the influence of the chosen allocation method on the results of the present study. In Table 17, the sensitivity of two selected impact categories (GWP and Primary Energy Demand - PED) is shown.

The difference between the base case and pure mass allocation is relatively small. Using pure mass allocation, both chlorine and sodium hydroxide receive almost the same burdens.

Economic allocation using the prices shown in Table 6 leads to highly increased burdens of sodium hydroxide and a simultaneous decrease of the burdens of chlorine by about 25 %. This is due to the low price of chlorine on the open market compared to the prices of sodium hydroxide and especially hydrogen.

It has to be noted, however, that the pricing of chlorine is quite difficult to access and associated with a high uncertainty, because a high share of chlorine is not sold on the open market but used internally by the company. Furthermore, it can be questioned whether hydrogen from chlor-alkali electrolysis would be associated with the same price as hydrogen from steam reforming. The overall significance of the economic allocation is limited in this case as the quality of price data for sodium hypochlorite and potassium hydroxide is not satisfactory and the market prices for chlorine and sodium hydroxide are volatile.

According to the sensitivity results, the ‘base case’ allocation method is a conservative determination for the Eco-profile of chlorine and sodium hydroxide. This choice ensures the comparability with former Eco-profiles.

Table 17: Influence of the allocation method on two selected impact factors: Global Warming Potential (GWP) and Primary Energy Demand (PED).

Impact Factor	Allocation Method	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Global Warming Potential (GWP) in kg CO_2 eq. per kg product	Base case	0.71	0.66	0.55	0.64
	Pure mass allocation	0.68	0.68	0.55	0.67
	Economic allocation	0.53	0.73	4.24	0.84
Total Primary Energy Demand (PED) in MJ per kg product	Base Case	13.58	12.60	11.69	17.90
	Pure mass allocation	13.20	12.96	11.69	17.91
	Economic allocation	10.21	13.76	89.49	22.86

Comparison of the present Eco-profile with its previous version

The following tables compare the present results with the previous version of the Eco-profile of 2013. This comparison is done based on the impact assessment methods used in the previous Eco-profile. The following major changes have been applied to the chlor-alkali electrolysis model during the update of the Eco-profile:

- Mercury technology was phased out
- Electricity generation was updated to the situation in 2019. This led to a significant decrease in GWP for electricity production in most countries

The main differences for the products are:

- GWP for chlorine, sodium hydroxide and NaOCl decreased by around 22 – 33 % due to changes in grid electricity GWP and less electricity use for electrolysis
- GWP for hydrogen increased slightly (5 %) due to more hydrogen venting, while at the same time impacts from electricity were decreased.
- Ozone Depletion Potential (ODP) decreased by about 50 % for all products since emissions of halogenated hydrocarbons from chlor-alkali units were strongly reduced.
- Eutrophication Potential increased strongly, since datasets for electricity production were updated now incorporating eutrophication from lignite mining.
- Abiotic Depletion Potential (ADP) elements increased due to a higher salt input compared to the 2013 Eco-profile. The increase in ADP elements for hydrogen is caused by the updated electricity dataset now covering much more detailed emissions from infrastructure and construction.
- Photochemical Ozone Creation Potential decreased due to the decreased use of fossil fuels for electricity production leading to lower NO_x emissions.

Table 18: Comparison of the present Eco-profile of the chlor-alkali electrolysis chlorine product with its previous version (2013). Impacts were calculated with the methodology used in the previous Eco-profile report.

Environmental Impact Categories	Chlorine		
	2013	**2021**	**Diff.**
Gross primary energy from resources [MJ]	19.9	13.6	-31.8 %
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	1.90E-05	2.60E-05	+36.6 %
Global Warming Potential (GWP) [kg CO_2 eq.]	0.90	0.70	-22.3 %
Acidification Potential (AP) [g SO_2 eq.]	3.46	3.03	-12.3 %
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	0.34	1.79	+427 %
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	1.10E-03	5.31E-04	-51.8 %
Photochemical Ozone Creation Potential [g Ethene eq.]	0.092	0.039	-57.9 %

Table 19: Comparison of the present Eco-profile of the chlor-alkali electrolysis sodium hydroxide product with its previous version (2013). Impacts were calculated with the methodology used in the previous Eco-profile report.

Environmental Impact Categories	NaOH		
	2013	**2021**	**Diff.**
Gross primary energy from resources [MJ]	18.1	12.6	-30.4 %
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	1.10E-05	1.56E-05	+41.8 %
Global Warming Potential (GWP) [kg CO_2 eq.]	0.86	0.65	-24.4 %
Acidification Potential (AP) [g SO_2 eq.]	2.7	2.36	-12.5 %
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	0.32	1.73	+441 %
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	1.10E-03	5.03E-04	-54.3 %
Photochemical Ozone Creation Potential [g Ethene eq.]	0.077	0.034	-56.0 %

Table 20: Comparison of the present Eco-profile of the chlor-alkali electrolysis hydrogen product with its previous version (2013). Impacts were calculated with the methodology used in the previous Eco-profile report.

Environmental Impact Categories	Hydrogen		
	2013	2021	Diff.
Gross primary energy from resources [MJ]	15.7	11.7	-25.5 %
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	2.10E-07	1.84E-06	+774 %
Global Warming Potential (GWP) [kg CO_2 eq.]	1.14	1.19	+4.5 %
Acidification Potential (AP) [g SO_2 eq.]	1.96	1.44	-26.5 %
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	0.3	1.54	+412 %
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	1.10E-03	4.68E-04	-57.5 %
Photochemical Ozone Creation Potential [g Ethene eq.]	0.071	0.032	-54.5 %

Table 21: Comparison of the present Eco-profile of the chlor-alkali electrolysis NaOCl product with its previous version (2013). Impacts were calculated with the methodology used in the previous Eco-profile report.

Environmental Impact Categories	NaOCl		
	2013	2021	Diff.
Gross primary energy from resources [MJ]	39.6	17.9	-54.8 %
Abiotic Depletion Potential (ADP), elements [kg Sb eq.]	1.30E-05	1.91E-05	+46.6 %
Global Warming Potential (GWP) [kg CO_2 eq.]	0.93	0.63	-32.5 %
Acidification Potential (AP) [g SO_2 eq.]	3.16	2.90	-8.3 %
Eutrophication Potential (EP) [g PO_4^{3-} eq.]	0.29	0.86	+196 %
Ozone Depletion Potential (ODP) [g CFC-11 eq.]	1.20E-03	5.92E-04	-50.7 %
Photochemical Ozone Creation Potential [g Ethene eq.]	0.100	0.046	-53.5 %

Review Details

Commissioned by:	Euro Chlor
Prepared by:	Dr.-Ing. Thomas Fröhlich, Sabrina Ludmann ifeu Institut für Energie- und Umweltforschung Heidelberg
Reviewed by:	Matthias Schulz, Accredited Reviewer on behalf of DEKRA Assurance Services GmbH Stuttgart, Germany
References:	• PlasticsEurope 2019: Eco-profiles program and methodology – PlasticsEurope – V3.0 (2019). • ISO 14040 (2018): Environmental Management – Life Cycle Assessment – Principles and Framework • ISO 14044 (2018): Environmental Management – Life Cycle Assessment – Requirements and Guidelines

Review Statement

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

The subject of this critical review was the development of the Eco-profile for liquid chlorine (Cl_2), sodium hydroxide ($NaOH$), Hydrogen (H_2) and sodium hypochlorite ($NaOCl$).

The critical review included two iterations of final Eco-profile report review (both in January 2022) in which the reviewer provided comments for clarification by the LCA practitioner. On 18 January 2022, a web-based review meeting was held in which open issues were discussed and spot checks of data and calculations were carried out. The final version of the report was provided to the reviewer on 24 January 2022 (update 22 July 2022). The reviewer checked the implementation of the comments and agreed to conclude the critical review process. The reviewer acknowledges the unrestricted access to all requested information, the dedicated efforts of the practitioners to address comments, as well as the open and constructive dialogue during the entire critical review process. All versions of the documentation (reports and data), including the reviewer's comments, questions and associated answers, are archived and can be made available upon request.

Primary data were collected for all foreground processes from 34 chlor-alkali production sites in Europe covering 8,796 kt of the European chlorine production capacity which is representative of 75 % of total European production in 2020. Site-specific technologies for all chlor-alkali electrolysis plants were taken into account; the large majority of sites apply membrane cell technology. For salt production, primary data for the mix of salt types/sources was collected, the respective background processes are the same as in the last Eco-profile (2013). Overall, primary data quality can be considered to be good (according to individual data quality rating for each indicator). The reviewer carried out various plausibility checks of the data and results. In the end, all raised questions were clarified, and the reviewer found the data to be credible and without perceivable errors or shortcomings.

All background datasets used for this Eco-profile are described in detail in the report and are considered appropriate for the goal and scope of this study. For example, country-specific grid electricity mixes from

2019 were applied: these were weighted according to the relevant chlorine production capacity covered in this study.

Allocation approaches applied in this Eco-profile are transparently explained and justified in the report. The issue of whether it is appropriate to allocate H_2 emissions to hydrogen production only or to allocate those emissions to all valuable products was discussed during the review meeting. Due to the fact that hydrogen is not a characterised flow for the EF v3.0 impact categories, neither allocation approach impacts on the results in any case. Independently of the allocation approach for H_2 emissions, it is highly recommended to improve hydrogen use (e.g. for clean energy production) and avoid venting large amounts into the atmosphere.

In addition, two sensitivity analyses were performed to investigate the potential environmental impacts on the chlor-alkali products if mass or economic allocation were applied. The relevant results are discussed and evaluated in the report.

The potential environmental impacts for chlor-alkali products are quantified using the EF v3.0 methodology, as recommended in the current PlasticsEurope methodology. The contribution analysis shows the predominant influence of electricity use for the indicator GWP (between 657 % for NaOCl and 85 % for hydrogen). Results for other impact categories and the contributions of other processes are transparently presented in the report.

This Eco-profile also contains a comparison of results with the previous Eco-profile (2013) as well as an interpretation of the most important changes. Most noticeably, the overall reductions in terms of GWP for chlorine, sodium hydroxide and sodium hypochlorite are due to reductions in the greenhouse gas emissions associated with the grid electricity mix used, as well as a reduction in electricity use for the electrolysis process.

The LCA practitioners have demonstrated high levels of competence and experience, with a track record of LCA projects in the chemical and plastics industry. The critical review confirms that this Eco-profile adheres to the rules set forth in the PlasticsEurope's Eco-profiles methodology version 3.0 (2019) and represents best available data for chlor-alkali production in Europe.

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