



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

Chlorine (The chlor-alkali process)

Euro Chlor

September 2013

Introduction

This Environmental Product Declaration (EPD) is based upon life cycle inventory (LCI) data from Euro Chlor's member companies. It has been prepared according to the rules of PlasticsEurope's LCI Methodology "Eco-profiles and Environmental Declarations" (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 chlorine by chlor-alkali electrolysis from cradle to gate (from production of salt/brine to liquid chlorine, sodium hydroxide, and hypochlorite at plant). **Please keep in mind that comparisons cannot be made on 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. This EPD 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 GmbH
Programme Owner	PlasticsEurope aisbl
Programme Manager, Reviewer	DEKRA Consulting GmbH
Number of plants included in data collection	50
Representativeness	68 % of European (EU27 + EFTA) chlorine production capacity (based on installed nameplate capacity; Source: Euro Chlor)
Reference year	2011
Year of data collection and calculation	Collection: 2012 Calculation: 2013
Expected temporal validity	31.12.2016
Cut-offs	None
Data Quality	Overall good quality

Allocation method	Stoichiometric allocation for Salt, mass allocation for all other input and emissions. Sensitivity analysis for other allocation methods was performed.
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Description of the Product and the Production Process

This Eco-profile and EPD represents the European 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. Three different electrolysis techniques are applied: mercury, diaphragm, and membrane cell technology. 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. Data from several European salt producers (primary data) as well as literature data was used for modelling sodium chloride production. 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 investigated products are outside the system boundaries of this cradle-to-gate system: since the objects of this study are substances, which are widely applied in various production processes, 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 each chlor-alkali electrolysis product and of 1 kg of sodium chloride (average mix of salt types; based on information from the participating chlorine production sites).

Input Parameters

Indicator	Unit	Chlorine (Cl ₂)	Sodium Hydroxide (NaOH)	Hydrogen (H ₂)	Sodium Hypochlorite (NaOCl)	Sodium chloride ²⁾ (NaCl)
Non-renewable energy resources ¹⁾						
• Fuel energy	MJ	15.4	14.8	14.1	16.7	1.1
• Feedstock energy	MJ	0.0	0.0	0.0	0.0	0.0
Renewable energy resources ¹⁾						
• Fuel energy	MJ	4.5	3.3	1.7	22.9	2.6
• Feedstock energy	MJ	0.0	0.0	0.0	0.0	0.0
Abiotic Depletion Potential						
• Elements	kg Sb eq	1.9E-05	1.1E-05	2.1E-07	1.3E-05	1.6E-05
• Fossil fuels	MJ	10.5	10.0	9.6	12.0	0.8
Water use (only of chlor-alkali electrolysis)						
• for process	kg	1.7	1.6	1.6	1.4	- ³⁾
• for cooling	kg	28.7	28.9	27.5	15.4	- ³⁾

¹⁾ Calculated as upper heating value (UHV)

²⁾ Average salt mix used as input to the participating chlorine production sites

³⁾ not calculated as sodium chloride is no product of chlor-alkali electrolysis

Output Parameters

Indicator	Unit	Chlorine (Cl ₂)	Sodium Hydroxide (NaOH)	Hydrogen (H ₂)	Sodium Hypochlorite (NaOCl)	Sodium chloride ²⁾ (NaCl)
Global Warming Potential (GWP)	kg CO ₂ eq	0.90	0.86	1.14	0.93	0.06
Ozone Depletion Potential (ODP)	g CFC-11 eq	1.1E-03	1.1E-03	1.1E-03	1.2E-03	4.0E-05
Acidification Potential (AP)	g SO ₂ eq	3.46	2.70	1.96	3.16	0.96
Photochemical Ozone Creation Potential (POCP)	g Ethene eq	0.09	0.08	0.07	0.10	0.01
Eutrophication Potential (EP)	g PO ₄ eq	0.34	0.32	0.30	0.29	0.02
Dust/particulate matter ¹⁾	g PM10 eq	2.00	1.77	1.62	2.23	0.12
Total particulate matter ¹⁾	g	2.14	1.91	1.76	2.33	0.12
Waste (only from chlor-alkali electrolysis)						
• Hazardous	kg	2.3E-03	2.4E-03	2.3E-03	3.8E-03	- ³⁾
• Non-hazardous	kg	7.0E-03	7.2E-03	1.3E-02	1.0E-03	- ³⁾

¹⁾ Including secondary PM10

²⁾ Average salt mix used as input to the participating chlorine production sites

³⁾ not calculated as sodium chloride is no product of chlor-alkali electrolysis

Additional Environmental and Health Information

Chlorine dissolves when mixed with water. It can also escape from water and enter air under certain conditions. Most direct releases of chlorine to the environment are to air and to surface water.

Effects of chlorine on human health depend on how the amount of chlorine that is present, and the length and frequency of exposure.

Chlorine enters the body breathed in with contaminated air or when consumed with 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 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).

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

Hydrogen from electrolysis is mostly used on site as a chemical, to fuel steam boilers or generators or it is sold to a distributor.

A small share of the produced chlorine gas is directed into diluted sodium hydroxide solution to produce sodium hypochlorite solution. Sodium hypochlorite solutions are used instead of chlorine for bleaching, disinfection, bio-fouling control, and odour control.

Additional Economic Information

The growth in European chlor-alkali industry output in 2011 was eventually weaker than expected because of increased business uncertainty and reduction in inventories. Caustic soda stocks position was low and relatively static. Chlorinated solvents market went down in 2011, after a recovery in 2010.

With 9,939k tonnes, the 2011 European chlorine production was just 0.6% below the 2010 level, and the 2011 average capacity utilisation rate stood at 78.7% compared to 79.0% in the previous year.

Germany, Belgium/The Netherlands and France remained the top three regions accounting together for nearly 70% of the total European chlorine production in 2011 (Germany: 43.8%; Belgium/The Netherlands: 15.0%; France: 11,0%).

Information

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

Data Owner

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Programme Manager & Reviewer

DEKRA Consulting GmbH

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

Registration number: PlasticsEurope 2013-001
validation expires on 31 December 2016 (date of next revalidation review).

Programme Owner

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References

- PlasticsEurope: Eco-profiles and environmental declarations - LCI methodology and PCR for uncompounded polymer resins and reactive polymer precursor (version 2.0, April 2011).
- Euro Chlor: Chlorine Industry Review 2011-2012

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 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.*

This Eco-profile and EPD represents the production system for chlorine (Cl₂), sodium hydroxide (NaOH), hydrogen (H₂) and sodium hypochlorite (NaOCl) as well as for average sodium chloride (NaCl) used in European chlor-alkali units. It can be used as modular building block in LCA studies. The different salt types (i.e. rock salt, solar salt, vacuum salt, brine from solution mining, and waste salt from KCl mining) were aggregated to an average salt data set based on the salt input to the participating production sites.

Euro Chlor 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 chemical substances. 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, Euro Chlor EPDs are derived from Eco-profiles, i.e. with the same »cradle-to-gate« system boundaries.

Therefore, a direct comparison of Eco-profiles or EPDs makes no sense because the same mass of different chemicals is not functionally equivalent.

Once a full life cycle model for a defined product application among several functionally equivalent systems is established then, and only then, comparative assertions can be derived. The same goes for EPDs, for instance, of products where Euro Chlor 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 chemicals, as a building block of life cycle assessment (LCA) studies of applications and products; and
- other interested parties, as a source of life cycle information.

Product Category and Declared Unit

Product Category

The core product category is defined as **products of the chlor-alkali electrolysis**, notably chlorine, sodium hydroxide, hydrogen, and sodium hypochlorite. This product category is defined »at gate« of the chlor-alkali electrolysis unit and is thus fully within the scope of Euro Chlor as a federation. Furthermore, sodium chloride (NaCl), as the main input material is considered in this study. This product is defined »at gate« of the respective production site.

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 50 % solution)

1 kg of hydrogen

1 kg of sodium hypochlorite

1kg of sodium chloride (average salt mix used as input to the participating chlorine production sites) »at gate« (production site output) representing a European industry production average.

Product and Producer Description

Product Description

The substances considered in this process comprise the primary products of the chlor-alkali electrolysis, namely chlorine (liquefied if the case), sodium hydroxide (in aqueous solution up to 50 %), and hydrogen. Furthermore, sodium hypochlorite as a secondary product is taken into account. Sodium chloride (NaCl) as the main input material is also within the scope of this study. 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	Chemical formula	CAS number	Molar Mass g/mol
Chlorine	Cl ₂	7782-50-5	70.9
Sodium hydroxide	NaOH	1310-73-2	40.0
Hydrogen	H ₂	1333-74-0	2.0
Sodium hypochlorite	NaOCl	7681-52-9	74.4
Sodium chloride	NaCl	7647-14-5	58.4

Chlorine is largely used in the synthesis of chlorinated organic compounds. Poly-vinyl-chloride (PVC) and isocyanates are the main drivers of chlorine production in EU27 and EFTA countries (see Figure 1). As it is difficult to store and transport economically, chlorine is generally produced near its consumers. Only when no other solutions can be found, chlorine is transported by pipeline (mostly distances ≤ 10 km), road, and rail. Imports and exports of chlorine to/from EU27 and EFTA countries are both negligible (< 0.5 % of overall production) [BREF 2013]. In 2011, with almost 600 kt just a little less than 6 % of the chlorine produced was transported via rail and road, the remainder of 94 % was used on the same or adjacent sites including the chlorine transported by pipelines [EURO CHLOR 2012].

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 prills, 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 are among the most important applications in terms of share. The whole spectrum of caustic soda applications is shown in Figure 2. A look on the balance of trade reveals that EU 27 and EFTA

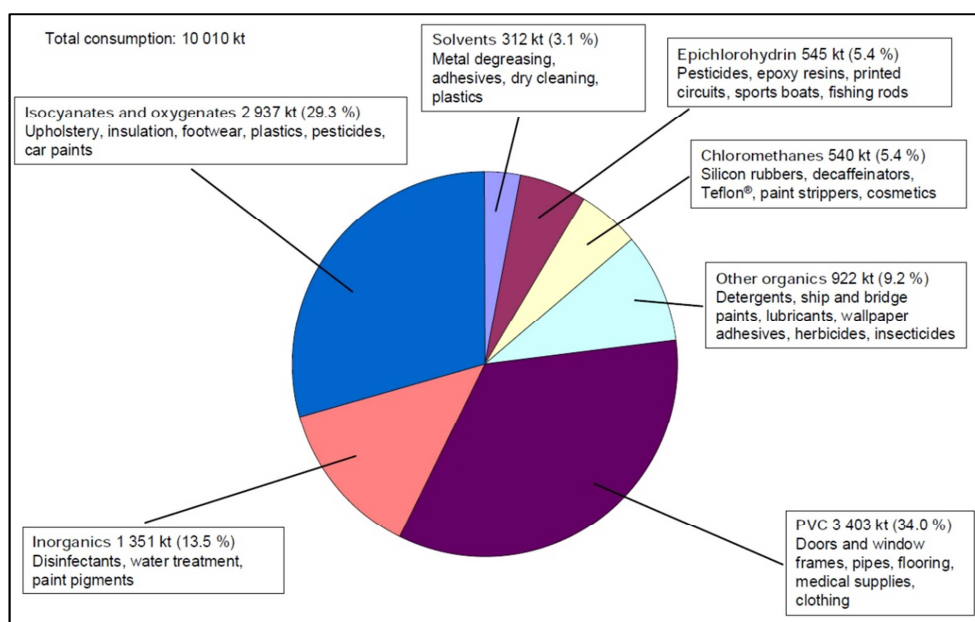


Figure 1: Applications of chlorine in EU 27 and EFTA countries in 2010 (Source: BREF 2013, based on EURO CHLOR 2011)

countries are net exporters of sodium hydroxide. In 2010 imports of liquid and solid hydroxide accounted for 601 kt and 46 kt, respectively, while exports accounted for 785 kt and 90 kt, respectively [BREF 2013].

The co-production of chlorine and sodium hydroxide in fixed proportions has always been delicate for the chlor-alkali industry; each product is used for very different end use with differing market dynamics and thus it is rare that the demand for the two coincides. Depending on which demand is dominant, either chlorine or sodium hydroxide can be regarded as the main product and the prices vary accordingly.

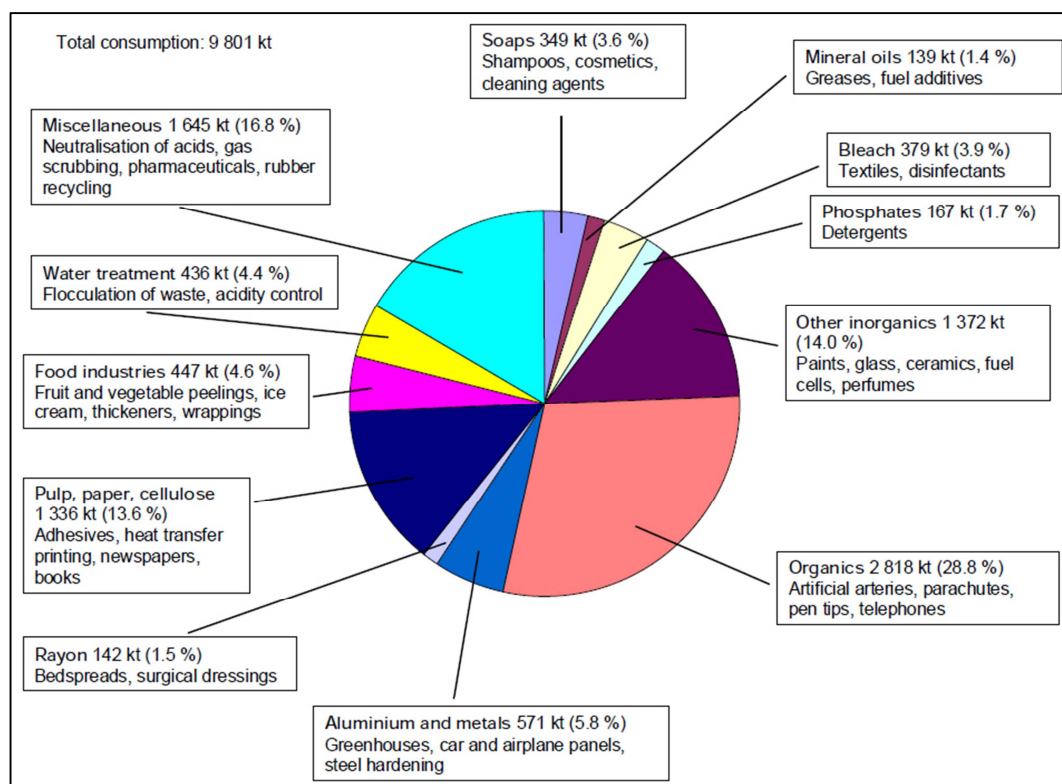


Figure 2: Applications of sodium hydroxide in EU 27 and EFTA countries in 2010 (Source: BREF 2013, based on EURO CHLOR 2011)

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

Another co-product of the electrolysis of brine is hydrogen. This highly pure hydrogen (purity >99.5 %) is usually used on site, on an adjacent site or sold to a distributor. In 2010, 90.4 % of the hydrogen produced by chlorine-alkali installations in the EU27 and EFTA countries was used as a chemical reagent or fuel while the remaining 9.6 % was emitted to air.

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 in various concentrations can be used instead of chlorine for bleaching, disinfection, bio-fouling control, and odour control [VOGT 2005].

Sodium chloride (NaCl) is predominantly used in the chemical industry as a feedstock to chlor-alkali electrolysis and sodium carbonate production. Other uses comprise the de-icing of road surfaces, water-softening by ion exchange, and, to a minor extent, human consumption.

The commercial production of chlorine

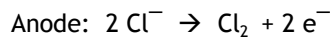
The most important technology for the production of chlorine is the electrolysis of aqueous solutions of sodium chloride (chlor-alkali electrolysis) co-producing both an aqueous solution of sodium hydroxide and gaseous hydrogen in a fixed ratio of 1.1 kg sodium hydroxide and 0.03 kg hydrogen per kg of 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 2011, the latter processes together accounted for less than 3 % of the European (EU-27 and EFTA) production capacity [EURO CHLOR 2012].

Since the scope of the current report is to investigate the commercially most relevant production of chlorine via the chlor-alkali electrolysis and since the focus has been laid on the routes co-producing sodium hydroxide, the following description of the production technology will concentrate exclusively on the electrolysis of sodium chloride solutions. Sections covering product treatment, brine preparation, and the production of sodium hypochlorite (NaOCl) are included since these processes are regarded as inside the battery limits of the chlor-alkali plant.

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 for the electrolytic process exist: diaphragm, mercury, and membrane cell technique. The techniques differ from each other in terms of electrode reaction and electrode materials, and in the way, the produced chlorine is kept separate from sodium hydroxide and hydrogen. A simplified scheme of the three electrolysis cells is shown in Figure 3. Table 2 gives an overview of the main characteristics of the three techniques.

The chemical processes at the anode are the same for all three techniques: chloride ions are oxidised and gaseous chlorine (Cl₂) is formed:



Concerning the cathode processes, a differentiation between the mercury cell on one hand and the diaphragm and membrane cells on the other hand has to be made. In the mercury cell, sodium amalgam

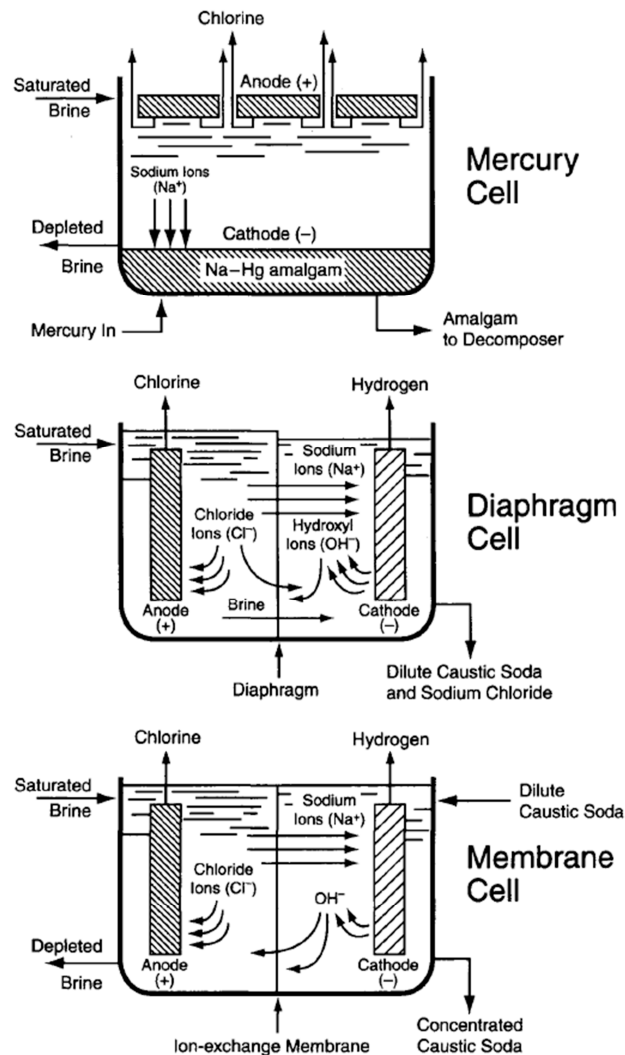
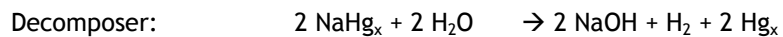
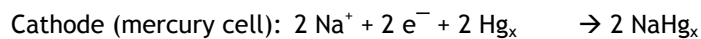
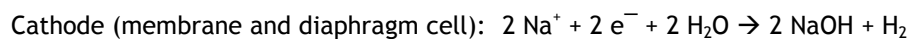


Figure 3: Schematics of mercury, diaphragm, and membrane cells [O'BRIEN 2005].

(NaHg_x) is formed at the cathode, which is subsequently decomposed by addition of water producing hydrogen and sodium hydroxide:



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



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

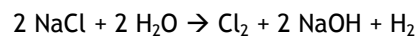


Table 2: *Main characteristics of the different electrolysis techniques [SCHMITTINGER 2006]*

Criterion	Mercury	Diaphragm	Membrane
Anode	Titanium coated with Ru/Ti oxides	Titanium coated with Ru/Ti/Sn oxides	Titanium coated with Ru/Ti/Ir oxides
Cathode	Mercury	Steel	Nickel coated with high-surface area nickel-based or noble metal-based coatings
Separator	None	Polymer-based (outdated: asbestos) diaphragm	Ion-exchange membrane
Cell voltage	3.15 - 4.80 V	2.90 - 3.60 V	2.35 - 4.00 V
Current density	2.2 - 14.5 kA m ⁻²	0.8 - 2.7 kA m ⁻²	1.0 - 6.5 kA m ⁻²
Concentration of Sodium Hydroxide	50 wt.-%	10 - 12 wt.-%	30 - 33 wt.-%
Quality of Sodium Hydroxide solution (50 wt.-%)	NaCl: ~ 50 mg/kg NaClO ₃ : ~ 5 mg/kg Hg: ~ 0.1 mg/kg	NaCl: ~ 10 000 mg/kg NaClO ₃ : ~ 1 000 mg/kg	NaCl: ~ 50 mg/kg NaClO ₃ : ~ 10 - 50 mg/kg
Chlorine quality	O ₂ : 0.1 - 0.3 vol.-% H ₂ : 0.1 - 0.5 vol.-% N ₂ : 0.2 - 0.5 vol.-%	O ₂ : 0.5 - 2.0 vol.-% H ₂ : 0.1 - 0.5 vol.-% N ₂ : 1.0 - 3.0 vol.-%	O ₂ : 0.5 - 2.0 vol.-% H ₂ : 0.03 - 0.3 vol.-%
Advantages	50 wt.-% high-purity NaOH directly from cell, high-purity Cl ₂ and H ₂ , simple brine purification	Low quality requirements of brine, low electrical energy consumption	Low total energy consumption, low investment and operating costs, high-purity NaOH, further improvements expected
Disadvantages	Use of mercury, expensive cell operation, costly environmental protection, large floor space	High steam consumption for NaOH concentration in expensive evaporators, low-purity of NaOH and Cl ₂ , some cells still operated with asbestos diaphragms	High-purity brine required, low Cl ₂ quality, high cost of membranes
Share of European Production Capacity (2011) [EURO CHLOR 2012]	32 %	14 %	54 %

According to stoichiometry, the products of electrolysis are formed in a fixed ratio which is about 1100 kg of NaOH (100 wt.-%) and approximately 28 kg of H₂ per ton of Cl₂ produced. This product combination is often referred to as the electrochemical unit (ECU).

In the following paragraphs, a brief description of the three different techniques for chlor-alkali electrolysis will be given. Additionally, the closely linked unit operations for brine treatment and product processing are described. Information that is more detailed can be found for example in SCHMITTINGER 2006, O'BRIEN 2005, and SCHMITTINGER 2000.

Mercury cell process

The mercury cell process comprises an electrolysis cell and a decomposer. Purified and saturated brine (25-28 wt.-% NaCl in water) is fed to the electrolysis cell on top of a film of mercury (Hg) flowing down the inclined base of the cell. The base of the cell is connected to the negative pole of a direct current supply forming the cathode of the cell. Anodes consisting of titanium coated with oxides of ruthenium and titanium are placed in the brine without touching the mercury film. At the anodes, chlorine gas is formed which is collected and directed to further processing. Due to a high overpotential of hydrogen at the mercury electrode, no gaseous hydrogen is formed; instead, sodium is produced and dissolved in the mercury as an amalgam (mercury alloy). The liquid amalgam is removed from the electrolytic cell and fed to a decomposer, where it reacts with demineralised water in the presence of a graphite-based

catalyst to form sodium hydroxide solution and hydrogen. The sodium-free mercury is recirculated back into the cell. Cooling of hydrogen is essential to remove any water and mercury. The sodium hydroxide solution is very pure, almost free from chloride contamination and has usually a concentration of 50 %. Further treatment comprises cooling and removal of catalyst and mercury traces by centrifuges or filters. Advantages of the mercury cell process are the high quality of chlorine and the high concentration and purity of sodium hydroxide solution produced. The consumption of electric energy for electrolysis is, however, higher than for the other techniques and a high purity of the feed brine is required. Inherently, the use of mercury gives rise to environmental releases of mercury.

Diaphragm cell process

In the diaphragm process, all reactions take place in only one cell. A diaphragm is used to separate the feed brine (anolyte) and the chlorine formed at the anode from the sodium hydroxide containing solution (catholyte) and the hydrogen formed at the cathode. Without the diaphragm being present during electrolysis, chlorine and hydrogen would form an explosive mixture and sodium hydroxide and chlorine would react to form sodium hypochlorite (NaOCl). Diaphragms used to be made from asbestos but up-to-date technology allows for asbestos-free polymer-based diaphragms. Purified brine is fed to the anode compartment and percolates through the diaphragm into the cathode compartment. The percolation rate is controlled by a difference in liquid level between both compartments. At the anodes (metal oxide coated titanium), chlorine gas is formed which is collected and directed to further processing. Cathodes, where water decomposition takes place, are made of activated carbon steel. Catholyte leaving the cell, also called cell liquor, is a mixture of 10-12 wt.-% sodium hydroxide and 15-17 wt.-% sodium chloride in water. This solution is usually evaporated to 50 wt.-% NaOH. In this process, simultaneously most of the salt is removed by precipitation to a final residual of 1 wt.-%. The resulting salt is typically recirculated to brine preparation.

The advantage of diaphragm cells is that the quality requirements for the brine and the electrical energy consumption are low. Disadvantageous are the high amount of thermal energy necessary for sodium hydroxide concentration and the comparably low quality of the produced sodium hydroxide and chlorine.

Membrane cell process

In the membrane cell process, the anode and cathode compartments are separated by a perfluoropolymer cation-exchange membrane that selectively transmits sodium ions but suppresses the migration of hydroxyl ions (OH^-) from the catholyte into the anolyte. Saturated brine flows through the anode compartment, where chlorine gas is produced at the anode. The electric field in the electrolysis cell causes hydrated sodium ions to migrate through the membrane into the cathode compartment. The cathode compartment is fed with diluted sodium hydroxide solution. Water is electrolysed at the cathode releasing gaseous hydrogen and hydroxyl ions, which combine with the sodium ions and thus increase the concentration of sodium hydroxide in the catholyte. Typically, the outlet concentration of sodium hydroxide is around 32 wt.-%. A part of the product stream is diluted with demineralised water to about 30 wt.-% and used as catholyte inlet. In some units, a more diluted 23 wt.-% NaOH solution is produced. In these cases, the inlet concentration is adjusted to 20-21 wt.-%. Usually the NaOH solution is evaporated to the marketable concentration of 50 wt.-% using steam. Depleted brine leaving the anode compartment is saturated with chlorine and is therefore sent to a dechlorination unit to recover the dissolved chlorine before it is resaturated with salt for recirculation.

The advantages of the membrane cell technique are the very high purity of the sodium hydroxide solution produced and the comparably low energy demand. Disadvantages comprise the high requirements on

brine purity, the need for sodium hydroxide evaporation to increase concentration, and the comparably high oxygen content in the produced chlorine.

In general, multiple cell elements are combined into a single unit, called electrolyser, of whom the design can be either monopolar or bipolar. In a monopolar electrolyser, the anodes and cathodes of the cells are connected electrically in parallel, whereas in the bipolar design, they are connected in series. Therefore, monopolar electrolyzers require high current and low voltage, whereas bipolar electrolyzers require low current and high voltage. Since bipolar systems allow higher current densities inside the cells, investment and operating costs are usually lower than for monopolar systems.

Brine Preparation and Purification

The sodium chloride used as an input to the electrolysis cell may be of various origins: rock salt from underground mines, solar salt obtained by solar evaporation of seawater, brine obtained by solution-mining of underground depots, or vacuum salt from purifying and evaporating solution-mined brine or dissolved rock salt. To be used as feedstock, the solid salts have to be dissolved in water and both the resulting brine and the solution-mined brine have to be purified according to the requirements of the applied electrolysis technique.

Dissolving of solid salts is usually carried out by either spraying water and/or depleted brine onto the salt or by feeding the solvent to the base of the saturator for progressive saturation. Modern units comprise closed vessels to reduce the emission of salt spray, mist, and mercury (in case of the mercury cell technique). Saturated brine contains about 315-320 g/l NaCl and has a density of about 1.200 kg/m³.

The most important impurities that have to be removed from the brine are (a more elaborate list can be found in O'BRIEN 2005):

- Sulphate anions (SO_4^{2-}), which can precipitate inside the membrane or diaphragm;
- Calcium and magnesium cations (Ca^{2+} , Mg^{2+}), which can precipitate inside the membrane or diaphragm and can promote hydrogen formation on mercury cathode;
- Metal cations (e.g. iron, titanium, molybdenum, nickel, chromium, vanadium, tungsten), which can promote hydrogen formation on mercury cathode, can precipitate inside the membrane or can deposit on cathode.

In the primary purification step, sodium carbonate (Na_2CO_3) and sodium hydroxide (NaOH) are used to precipitate calcium and magnesium as calcium carbonate (CaCO_3) and magnesium hydroxide ($\text{Mg}(\text{OH})_2$). During this operation, metals may also precipitate as hydroxides. Sulphate anions can be precipitated by adding calcium chloride (CaCl_2) or barium salts (BaCO_3 or BaCl_2). If barium salts are used, the sulphate precipitation can be done simultaneously to magnesium and calcium precipitation, whereas the usage of calcium chloride requires a separate vessel. For membrane cells, no barium salts are used to avoid their precipitation inside the membrane.

Precipitated solids are removed by filtration alone or by sedimentation followed by filtration. The filter cake is separated and concentrated in filter presses, vacuum filters, or centrifuges before disposal.

In general, the requirements on purity of the brine are lowest for diaphragm cells and highest for membrane cells. Thus, for diaphragm cells the removal of sulphate is not always necessary, because it can be removed from the cell liquor as pure sodium sulphate (Na_2SO_4) during the concentration process. For mercury and diaphragm cells, the brine should ideally meet the following specifications:

- $c(\text{Ca}^{2+}) < 2 \text{ mg/l}$;
- $c(\text{Mg}^{2+}) < 1 \text{ mg/l}$;
- $c(\text{SO}_4^{2-}) < 5 \text{ g/l}$.

Membrane cells have higher requirements on brine purity so that a secondary purification step is necessary. In most cases, a so-called polishing filtration (using candle-type, plate frame or pressure leaf filters, in some cases with a cellulose-based coating) is applied in order to further reduce the content of suspended particles. This is followed by an ion-exchange unit where the calcium and magnesium concentrations are reduced to < 20 ppb (0.02 mg/l).

Before entering the electrolysis cell, the purified brine is usually acidified with hydrochloric acid to pH < 6, which increases the lifetime of the anode coating and reduces the formation of oxygen, hypochlorite, and chlorate. For membrane cells, adjusting the pH is crucial for cell performance since over-acidification increases the risk that precipitations of impurities such as iron or aluminium occur inside the membrane instead of near the surface. Furthermore, too low pH (< 2) can lead to a protonation of the carboxylate groups responsible for the high ion selectivity resulting in membrane damage.

Mercury and membrane cell units usually operate with brine recirculation and resaturation. Since the depleted brine contains significant amounts (0.4-1 g/l) of dissolved chlorine, dechlorination is necessary. This is especially important for the membrane cell technique where active chlorine can destroy the ion exchange membrane of the secondary purification unit. Partial dechlorination (to 10-30 mg/l) is done by acidification to pH = 2-2.5 followed by extraction either in an air-blown packed column or in a vacuum system. Total dechlorination (to < 0.5 mg/l) is achieved by either adsorption on activated carbon, catalytic reduction, or chemical reduction (e.g. with sulphite).

Chlorine processing

Chlorine gas coming from the electrolyzers usually has a temperature of 80 - 90 °C, is saturated with water and contains impurities like H₂, N₂, O₂, CO₂, and chlorinated hydrocarbons. Furthermore, it is obtained at atmospheric pressure. In most cases, chlorine processing comprises cooling, cleaning, drying, compression, and liquefaction. The chlorine can be used also as dry compressed gas without the need for liquefaction.

In the primary cooling process, the total volume of gas to be handled is reduced and a large amount of moisture is condensed. Cooling is accomplished in either one stage with chilled water or in two stages, with chilled water only used in the second stage. Care is taken to avoid excessive cooling because, at around 10 °C, chlorine can combine with water to form solid chlorine hydrate (Cl₂ · n H₂O; n = 7 - 8). Both direct (in a spray tower) and indirect (in a heat-exchanger) cooling is common. Indirect cooling generates less chlorine-saturated water, which has to be treated, whereas direct cooling has a higher thermal efficiency. The combination of both advantages is obtained in closed-circuit direct cooling of chlorine where the chlorine-laden water is cooled in a heat exchanger and fed back to the cooling tower. After primary cooling, water droplets and impurities such as brine mist are removed either mechanically by filters or by means of an electrostatic precipitator.

Moisture is reduced from 1-3 vol.-% to less than 20 mg/m³ by drying the chlorine gas with concentrated sulphuric acid (96-98 wt.-%) in countercurrent contact towers. The contact towers contain structured packing made of plastics resistant to chlorine and sulphuric acid. Liberated heat from the dilution of sulphuric acid is removed in titanium heat exchangers and the spent acid is dechlorinated chemically or by stripping. The concentration of the spent acid depends on the number of drying stages. In some cases, the acid is reconcentrated to 96 wt.-% by heating under vacuum for recirculation. If the acid cannot be sold or used in wastewater treatment, it has to be treated as a waste. Droplets of sulphuric acid are removed from the dry chlorine gas in demisters or packed beds.

Further potential cleaning steps after chlorine drying include:

- Adsorption on carbon beds to remove organic impurities;
- Absorption-desorption using a suitable solvent such as carbon tetrachloride to remove nitrogen trichloride and organic impurities;
- Scrubbing with liquid chlorine to remove nitrogen trichloride, organic impurities, carbon dioxide and bromine;
- Irradiation with UV to destroy nitrogen trichloride and hydrogen.

After drying and cleaning, chlorine gas may be compressed using a variety of compressors, depending on mass flow and desired pressure. Dry chlorine can ignite iron upon contact at elevated temperature. Therefore, heat from compression is usually removed by coolers between compressor stages in order to keep temperatures below 120 °C.

If all the gaseous chlorine is not fed directly into the next process, it is liquefied for storage and/or transportation purposes. Liquefaction can be accomplished either at high (< 40 °C, 7-16 bar), medium (-20-10 °C, 2-6 bar) or low (<-40 °C, 1 bar) temperature and pressure. Higher pressures and temperatures lead to low energy costs because the efforts for cooling are low, and water can be used for cooling. If lower temperatures/pressures are needed for subsequent processes, other refrigerants such as HCFCs, HFCs, or ammonia are used today. Liquefaction yields are typically limited to 90-95 % in a single-stage installation because otherwise hydrogen concentrations can increase in the residual gas up to the explosion limit. Achieving higher yields requires small volume explosion-protected multi-stage liquefiers and/or the addition of inert gas to keep the mixture below the explosion limit. The residual chlorine in the tail gas can either be valorised as an educt for the production of hypochlorite, iron(III) chloride or hydrochloric acid, or it has to be removed from the off-gas in an absorption unit.

Sodium Hydroxide processing

Treatment of sodium hydroxide is slightly different for the three cell types due to the difference in composition and concentration.

In case of the mercury cell technique, a 50 wt.-% sodium hydroxide solution is obtained from the decomposer. This is usually cooled before residues of mercury are removed by filtration in a plate filter with carbon pre-coat.

Sodium hydroxide solutions from diaphragm cells typically have concentrations of 10-12 wt.-% and carry an additional 15-17 wt.-% of NaCl. In multiple effect evaporators the concentration of NaOH is usually increased to 50 wt.-%. During this process, NaCl precipitates to a residual concentration of approximately 1 wt.-%. Precipitated salt is continuously removed from the evaporator by scraper blades and can be used for brine preparation or has to be disposed of.

Membrane cells produce high quality sodium hydroxide solutions with typical concentrations of 30-33 wt.-% which are usually concentrated to 50 wt.-% in multiple effect evaporators.

In some plants, sodium hydroxide is further concentrated or even dried to solid prills or flakes with a water content of 0.5-1.5 wt.-%. In general, steam is used as energy carrier for the concentration of sodium hydroxide.

Hydrogen processing

Hydrogen leaving the cells is highly concentrated (>99.9 vol.-%) and usually only little processing is needed. Cooling is necessary to remove water vapour, sodium hydroxide, and salt, which are either redirected to the electrolysis cells or to brine preparation, or they are sent to waste water treatment. In the case of the mercury cell technique, hydrogen is saturated with mercury (0.8-2.4 g/m³) and a primary cooling unit directly at the electrolyser allows the condensation of mercury vapour, which is redirected

into the main mercury circuit. Further cooling and mercury removal in a multi-stage process is necessary to reduce mercury concentrations to $< 0.03 \text{ g/m}^3$.

After cooling (and mercury removal) hydrogen is either distributed by booster fans or fed to a compression plant for further use or it is vent to the atmosphere.

Sodium hypochlorite (NaOCl) production [VOGT 2005]

Sodium hypochlorite is produced by feeding gaseous chlorine into a dilute solution of sodium hydroxide. Care has to be taken to keep the temperature below 40°C (usually temperatures between 30 and 35°C are applied) and the pH in the alkaline range to avoid the formation of chlorate.

A mixture of diluted sodium hydroxide and sodium hypochlorite in water is circulated through the chlorination column, a buffer tank, a heat exchanger back into the chlorination column. Chlorine gas, diluted with air, is introduced into the bottom of the chlorination column. The chlorine reacts with the sodium hydroxide under formation of sodium hypochlorite, sodium chloride, and water:



When the desired concentration of sodium hypochlorite is reached, the solution is withdrawn from the circulation and directed to a cooled storage tank. In this case fresh sodium hydroxide solution is fed to the tank for continuous production. If necessary, the inert gas leaving the chlorination column can be scrubbed before entering the atmosphere.

Upstream Processes

Salt production [KIRK-OTHMER 2004 O'BRIEN 2005, WESTPHAL 2005]

Sodium chloride (NaCl), commonly referred to as "salt", is the main input material for the chlor-alkali electrolysis since it is the most important and almost abundantly available natural resource of chlorine. For industrial purposes, the following sources of salt are commonly used:

- Rock salt, recovered by classical mechanical mining from underground deposits.
Mine shafts are drilled into the rock down to salt bearing underground deposits. In salt deposits with horizontal or gently inclined seams, the standard method is room and pillar mining. In this method, the extraction process produces large chambers with rectangular cross sections of ca. $50 - 400 \text{ m}^2$ and lengths of up to 500 m . The parallel extraction chambers are separated from each other by rock salt pillars left behind during mining. These pillars must be of such dimensions that they can carry the weight of the overlying rock. The mining of the salt during the construction of the tunnels and in the extraction chambers is either by undercutting, drilling and blasting using explosives or by cutting the salt by part-face heading or full-section cutting machines. The most commonly used explosive is ANFO (ammonium nitrate fuel oil mixture) in the form of loose prills. It is charged pneumatically into the boreholes. To load the mined material and to transport it to the first crusher diesel-powered front loaders or dumper trucks with capacities of up to 50 t are used. After crushing the salt to $< 300 \text{ mm}$ using equipment near to the working face, it is transported by either electricity or diesel driven band conveyors to the hoisting shaft. In mines where the salt has a purity of $> 99 \text{ wt.-% NaCl}$, the salt can be marketed directly after grain-size classification. Where the natural purity is lower (e.g., 94 wt.-% NaCl in South German mines), impact mills are used in the first processing stage. As rock salt is more brittle than the clay and anhydrite inclusions, it is more readily size reduced. A screening operation follows, separating the two size fractions, which increases the NaCl content by $2 - 3 \text{ wt.-%}$ compared to the crude salt. Further purification of the salt to $> 99 \text{ wt.-% NaCl}$ for industrial use is carried out in heavy media hydro-cyclones.

- Brine, produced by forcing an aqueous stream into underground deposits of rock salt.
An underground salt deposit may be solution-mined by drilling wells into it, injecting fresh or recycled water through the well casings to dissolve the salt, and leaving a residence time long enough for the brine solution to reach saturation with sodium chloride (at 26-28 wt.-% or 317-323 g/L). Solution mines can vary in depth from 150 to 1500m and they can operate with a single well or with a linkage of several wells in a brine field. Insoluble impurities, such as anhydrite (calcium sulphate) settle out in the underground gallery, while the saturated sodium chloride brine is pumped to holding tanks on the surface.
- Solar salt, obtained by solar evaporation of seawater in large ponds.
Sodium chloride is the largest component of dissolved solids found in seawater with an average concentration of 2.6 wt.-%. For commercial production, seawater is directed to a series of large earthen ponds either by gravity or by pumps where 90 % of the water is evaporated by solar radiation and wind action. From the concentrated brine, several mineral salts can be separated by fractional crystallisation. After the precipitation of iron, calcium, and magnesium carbonates and calcium sulphate in pre-crystallisers, sodium chloride is precipitated, forming salt layers 10-25 cm thick. The remaining solution is highly concentrated magnesium brine, also called bitterns. The bitterns are either discharged or collected for additional product crystallisation. The salt layers are typically harvested using diesel driven heavy tractors, loaded into conveyor belts or trucks and transported to a central washing plant, where all solid impurities as well as remains of the bitterns by washing with saturated brine. After final drying, purities of > 99.7 wt.-% NaCl and a yield of up to 80 % related to the salt content in the seawater can be reached by proper process control.
- Purified NaCl-containing wastes incurred from KCl mining.
The mineral processing of potash minerals leads to over 78 % solid or liquid tailings, which are usually either discarded onto heaps, backfilled into abandoned parts of the potash mine, or discharged into rivers or the sea. Since KCl and NaCl have the same marine origin, they often occur together in a single deposit and therefore the solid tailings of KCl mining consist to the largest part (89-94 wt.-%) of NaCl (Halite) [BREF 2009]. Especially in Spain, instead of piling the KCl tailings, some parts are purified from potassium and magnesium and NaCl is obtained.
- Vacuum salt, produced by purification and evaporation of either brine or dissolved rock salt.
In general, every type of the above-mentioned crude salts can be used for the production of high purity vacuum salt. However, typically rock salt and solution-mined brine are used in commercial evaporation plants. In case of rock salt, the first step is dissolving the crude salt in fresh water. The crude brine is then purified to remove impurities like calcium, magnesium, and sulphate ions. Purification is done by adding calcium hydroxide ($\text{Ca}(\text{OH})_2$) or sodium hydroxide (NaOH) to precipitate magnesium and sulphate ions, followed by the precipitation of calcium using sodium carbonate (Na_2CO_3) or carbon dioxide gas (CO_2). The resulting sludge consisting of calcium sulphate, calcium carbonate, and magnesium hydroxide is usually suspended with water and either pumped back into abandoned caverns of the salt mine or washed into nearby surface water systems. Water is evaporated from purified brine using multiple-effect or vapour recompression evaporators. Multiple-effect systems typically contain three or four forced-circulation evaporating vessels connected together in a series. Heat is supplied by steam from boilers and this steam is fed from one evaporator to the next to increase energy efficiency. Simultaneously, the pressure decreases from unit to unit. Vapour-recompression forced-circulation evaporators consist of only one crystallizer, a compressor, and a vapour scrubber. Feed brine enters the crystallizer vessel, where salt is precipitated. Vapour is withdrawn,

scrubbed, and compressed for reuse in the heater. Ultimately, weak brine from the process is recycled to the solution-mined cavern. Crystallized salt is removed from the elutriation leg as slurry. Recompression evaporators are widely used where cheap electrical energy is available. The salt slurry from either type of evaporator is dewatered first by centrifuging or vacuum drying, followed by rotary kiln or fluidized-bed drying to less than 0.05 % moisture resulting in a product of more than 99.9 wt.-% NaCl.

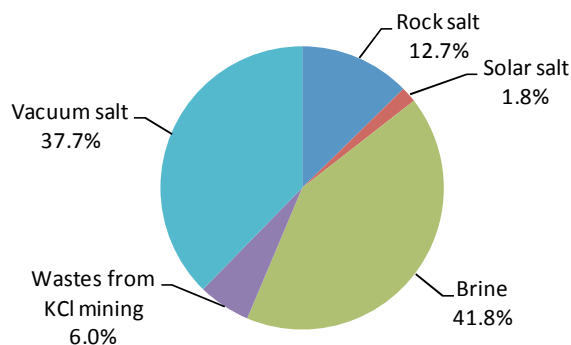


Figure 4: *Share of different sodium chloride types used as an input to the European chlor-alkali industry (as reported from the participating companies).*

In general, all five types of salt are used as a feedstock for chlor-alkali electrolysis. However, as shown in Figure 4, the most important types in the European chlor-alkali industry are brine from solution mining and vacuum salt. Both rock salt and waste salts from KCl mining have still significant contributions, whereas solar salt is only used in minor quantities.

Grid electricity supply

The operation of a chlor-alkali plant depends on the availability of huge quantities of electric power, which is usually obtained from the national electricity grid in the form of alternating current (AC) power. For electrolysis, the alternating-current electricity is converted to direct current (DC) power by rectifiers.

A national grid electricity mix represents a typical mix of electric power from different types of power plants. Those include hard coal, lignite, oil and gas power plants among the fossil-fuel-fired plants, biomass, geothermal, photovoltaic and hydropower plants as well as wind farms among renewable energies power generators, nuclear power plants, and waste incineration plants. Power supply implies the generation of electricity from the respective energy carrier by using the according electricity-generating technology, the extraction or production of the fuel in the case of fuel-based energy carriers, e.g. coal, natural gas or biomass, as well as the distribution of electricity within the grid, which comes along with losses due to transformation and transportation.

Table 3 shows the Global Warming Potential (GWP 100) of the country specific electricity supply mixes for the European countries (EU27+NO+CH) as well as averages weighed by electricity production, by chlorine production capacity, and by the chlorine production capacity covered in this study.

Table 3: Global Warming Potential (GWP 100) of country specific electricity supply mixes (2011).

Country	GWP kg CO ₂ eq./kWh
Austria	0.210
Belgium	0.142
Czech Republic	0.731
Finland	0.292
France	0.060
Germany	0.605
Greece	0.958
Hungary	0.436
Italy	0.419
Norway	0.016
Poland	1.077
Portugal	0.394
Romania	0.625
Slovak Republic	0.252
Spain	0.383
Sweden	0.033
Switzerland	0.011
The Netherlands	0.467
UK	0.454
Mix EU27+NO+CH, weighted by electricity production	0.414
Mix EU27+NO+CH, weighted by chlorine production capacity	0.447
Mix EU27+NO+CH, weighed by chlorine production capacity covered in this study	0.479

On-site energy production / Process steam generation

Besides the power supply from the electricity grid, thermal (i.e. heat) and electric energy are often generated on-site. As sodium hydroxide from the membrane cell and diaphragm processes has concentrations of far below 50 wt.-% when it leaves the electrolysis cell, its needs to be concentrated to commercial 50 wt.-% by the use of process steam. The latter is produced with heat from on-site energy plants.

On-site energy generating plants produce either heat only or both heat and electricity, the latter in the case of combined heat and power (CHP) plants. Fuel oil, natural gas, hard coal, and lignite are the most commonly used fuels for on-site energy generating plants.

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 Euro Chlor's membership and the production sites participating in the Eco-profile data collection.

The companies contributing data to this Eco-profile and EPD are:

- Akzo Nobel Industrial Chemicals BV, The Netherlands
- Anwil SA, Poland
- BASF SE, Germany
- Bayer MaterialScience AG, Germany
- BorsodChem Zrt., Hungary
- CABB AG, Switzerland
- CABB GmbH, Germany
- CUF-Químicos Industriais, S.A., Portugal
- Dow Deutschland Anlagengesellschaft mbH, Germany
- EHERSA - Electroquímica de Hernani S.A., Spain
- ELNOSA - Electroquímica del Noroeste S.A., Spain
- Ercros SA, Spain
- Hellenic Petroleum SA, Greece
- INEOS ChlorVinyls, United Kingdom
- Oltchim S.A., Romania
- Química del Cinca S.A., Spain
- Solvay SA, Belgium
- SolVin SA, Belgium
- Spolana, Poland
- Spolchemie a.s., Poland
- Syndial SpA, Italy
- Vencorex France, France
- VESTOLIT GmbH & Co. KG, Germany
- Vinnolit GmbH & Co. KG, Germany
- Zachem, Poland

Data was collected from the chlor-alkali electrolysis units of the above-mentioned companies. The data collection aimed at information on all energy and material inputs and outputs of a certain chlor-alkali unit, on distances and means of transportation of each material input, on emissions to air and water, and on the amount, destination, and transport distances of wastes produced inside the battery limits. Furthermore, the same set of data was collected concerning 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 2011) have been asked for.

Eco-profile - Life Cycle Inventory

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 chlorine-alkali process. It is based on a cradle-to-gate system (Figure 5).

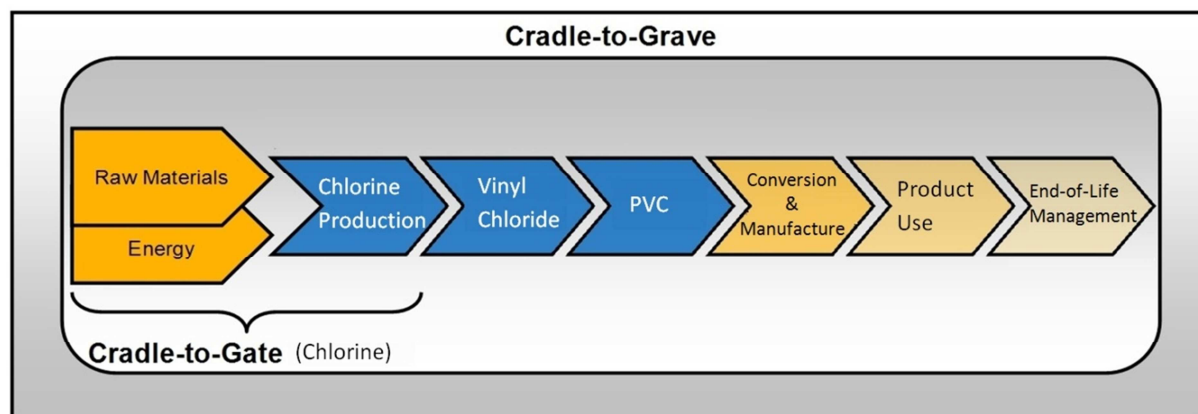


Figure 5: Cradle-to-gate system boundaries of chlorine using the example of products from PVC

(Source: PLASTICSEUROPE 2011, modified)

Cradle-to-Gate System Boundaries for Production

The following processes are included in the cradle-to-gate LCI system boundaries (see also Figure 6):

- 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 of Eco-profiles (PlasticsEurope v 2.0, April 2011) capital goods, i.e. the construction of plant and equipment as well as the maintenance of plants, vehicles, and machinery is outside the LCI system boundaries. The end-of-life treatment of the products of the chlor-alkali electrolysis and their resulting products is 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.

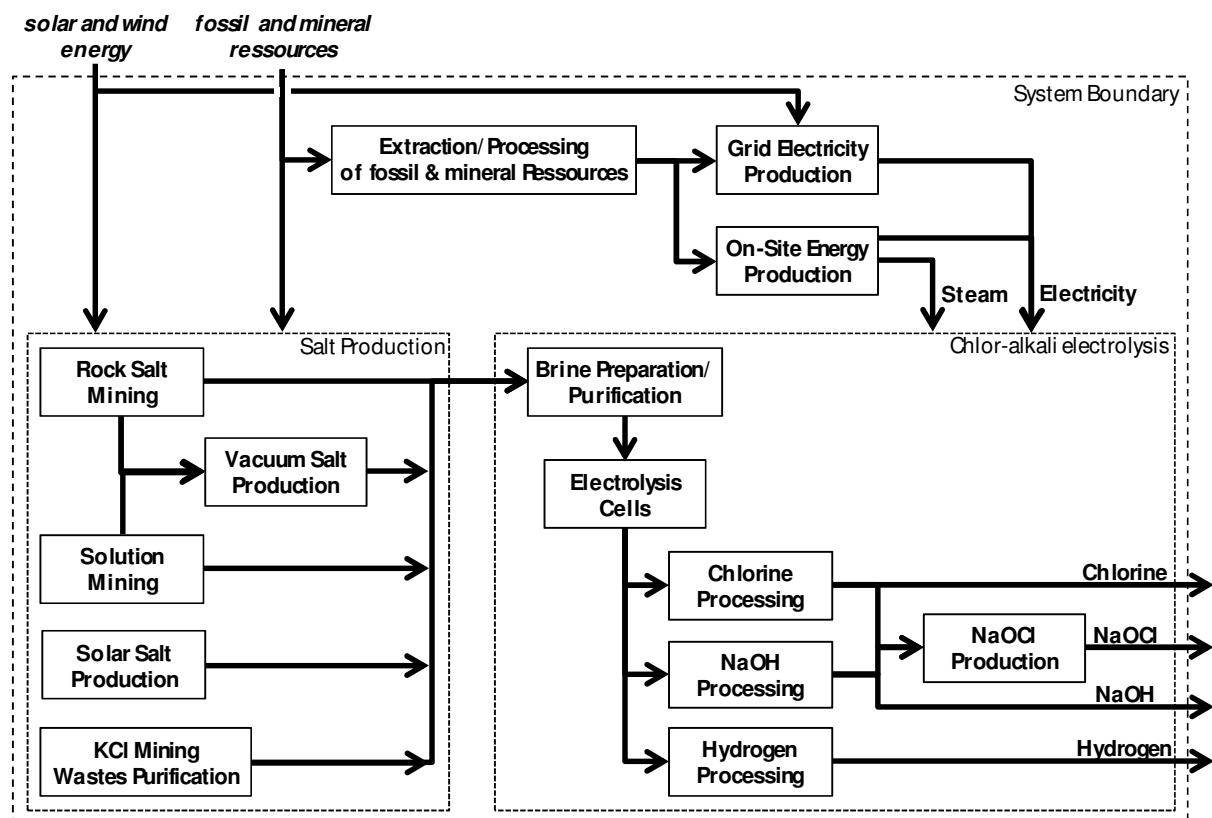


Figure 6: Schematic flow chart of the processes under consideration in this study.

Technological Reference

The production processes were modelled using specific values from primary data collection at site, representing the specific technologies of the chlorine-alkali electrolysis, i.e. mercury, diaphragm, and membrane process as well as the water treatment that is applied on-site. The LCI data represents technology in use in the defined production region employed by participating producers. From the total number of 88 chlor-alkali plants in Europe, 67 were selected for participation in this study; excluded were non-members of Euro Chlor (5), pure potassium chloride units (6), a part of the units with chlorine production capacities < 20 kt/year (5), and mercury plants that started their conversion to another process (5). Furthermore, one diaphragm unit was excluded since its products are neither fed to the open market nor used for polymer production. Thus, the maximum coverage reachable by this study is 82 % of the total installed production capacity of chlorine produced by chlor-alkali electrolysis in Europe (which was 12,208 kt in 2011 [EURO CHLOR 2012]). Data was provided by 50 production sites covering 8,320 kt, or 68 % of the European chlorine production capacity. All of the three techniques in use for electrolysis are covered, however with different coverage as shown in Table 4. The technological coverage can be understood as representative for membrane and mercury technologies, whereas representativeness of diaphragm technology is rather low.

Table 4: *Participating chlorine production units and their share of European chlorine production capacity by electrolysis technique.*

	Selected units	Participating units	Coverage by chlorine capacity of this technique ¹⁾
Mercury	26	21	65 %
Diaphragm	5	2	14 %
Membrane	37	27	84 %
Total	67	50	68 %

¹⁾ based on installed nameplate capacity; Source: EURO CHLOR 2012

Furthermore, for salt production primary data for all relevant kinds of salt used in chlor-alkali electrolysis have been collected. Parts of the salt producers that provided data are also chlorine producers and Euro Chlor members. This primary data was complemented with literature data (see Section 'Data Sources').

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 were 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 with secondary data from background processes, e.g. grid electricity supply. However, due to their relevance for 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 underlying data are concerned.

Temporal Reference

The LCI data for production was collected as 12 month averages representing the year, to compensate seasonal influence of data. The overall reference year for this Eco-profile is 2011 with a maximal temporal validity until 2016. This 5-year interval was chosen as major changes in the European electricity production mix are to be expected within the next years. Furthermore, the commitment of Euro Chlor members to phase out mercury cell technology by 2020 leads to upcoming major changes in technology distribution.

Geographical Reference

Primary production data for the chlorine-alkali electrolysis production is from 50 different production units in the EU27 member states, Norway, and Switzerland (EU27+NO+CH). It has to be noted, that for France and Belgium, the largest chlorine-producing countries in Europe after Germany, only 36 % and 42 % respectively, of the chlor-alkali electrolysis capacity is covered by the participating production sites. Fuel and energy inputs in the system reflect average country-specific conditions and whenever applicable, site-specific conditions were applied to reflect representative situations. Therefore, the study results are intended to be applicable within EU27+NO+CH boundaries and in order to be applied in other regions adjustments might be required. Products of the chlorine-alkali process imported into Europe were not considered in this Eco-profile.

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 an input of approx. 3 wt.-% and less of the chlorine output (e.g. H_2SO_4 , agents for brine preparation, cooling agents, etc.) generic datasets from the LCA database Ecoinvent v 2.2 [ECOINVENT 2010] have been 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

This Eco-profile and EPD uses average data representative of the respective foreground production process, both in terms of technology and market share. These processes consist of the chlor-alkali unit including water treatment, on-site energy production, and salt production. The primary data for the chlor-alkali unit and the on-site energy production are derived from site-specific information for processes under operational control supplied by the participating member companies of Euro Chlor (see Producer Description).

For the salt production primary data for all types of salt, i.e. rock salt, brine, solar salt and vacuum salt production have been collected from relevant producers within Europe - regardless if they are also a chlorine producer or a supplier to the chlorine-alkali industry. Since mostly only one or two companies contributed (confidential) data per type of salt, this information was verified and averaged with literature data and with publicly available environmental reports:

- K+S Umweltbericht 2002
- Südsalz Umweltbericht 2003 + 2006
- SEDIVY 2009
- WESTPHAL 2005
- O'BRIEN 2005
- KIRK-OTHMER 2004
- ECOINVENT 2010

As the operation of a chlor-alkali plant needs huge quantities of electric power and as the environmental burdens of power production varies strongly depending on the electricity generation technology, the country-specific grid electricity mixes have been used. These 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 the basic power plant types and their respective raw material processes. Using network parameters, the fuel mix and essential technical characteristics of the energy systems are freely adjustable. Thus, the national grid electricity mix for each country with chlorine production sites belonging to Euro Chlor member companies has been calculated. It is based on national electricity mix data by EUROSTAT [2013] for the reference year, which is 2011 for all countries.

The system boundary of the electricity module includes

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

The network also includes combined heat and power generation. The share of district heat produced in coupled form is adjustable according to the power plant type. An allocation of the burdens to electricity and district heating is performed through allocation based on exergetic values of products. Additional information concerning the applied electricity grid model can be found the website of IFEU (2011).

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 power on-site, it was necessary to represent their upstream chains adequately to achieve appropriate LCI results in this study, especially concerning the 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, could be used. They are based on the database Ecoinvent v2.2 [ECOINVENT 2010]. A regional provenance mix according to the respective chlorine production site was considered using statistical data from Eurostat for the year 2011. The upstream chains for crude oil and natural gas were updated for the main production countries/regions with primary data, notably in view of its inputs and outputs. The primary data derives from the environmental/annual reports either of associations of the oil and gas producing industry or directly from important producers representing specific regions (e.g. the North Sea region, Russia, OPEC countries). Furthermore, data from scientific studies was used for the update of the upstream chain of natural gas.

Hard coal and lignite are less important fuels for on-site energy generation, which are used mostly in combined heat and power plants. The datasets for those fuels representing a European average were taken directly from the database Ecoinvent v2.2 [ECOINVENT 2010].

For transport processes the main data sources are

- Rail: TREMOD 2009 and EcoTRANSIT 2011
- Road: HBEFA 2010 (v2.1) and TREMOD 2009
- Ship: BORKEN 1999 and Ecoinvent v2.2 [ECOINVENT 2010]
- Pipeline: Ecoinvent v2.2 [ECOINVENT 2010]

Other relevant background inputs, i.e. auxiliary materials such as sulphuric acid or sodium carbonate are also taken from the database Ecoinvent v2.2 [ECOINVENT 2010].

Relevance

With regard to the goal and scope of this Eco-profile, the collected primary data of foreground processes are of high relevance. Production and on-site energy data as well as salt production data from the most important (chlorine and salt) producers in Europe was used in order to model the European industry average production. The environmental contributions of each process to the overall LCI results are presented in Chapter 'Life Cycle Impact Assessment'.

Representativeness

The data used for this study covers 57 % of all production sites and 68 % of the installed chlorine production capacity related to chlor-alkali electrolysis in Europe (EU27 + Norway + Switzerland) in 2011. The background data used can be regarded as representative for the intended purpose, as it is average data and 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' were used. While building up the model, cross-checks

concerning the plausibility of mass and energy flows were continuously conducted. The methodological framework is consistent throughout the whole model as the same methodological principles are used throughout the whole system.

Reliability

In the questionnaires, the site managers were encouraged to classify their data into one of the following reliability grades: measured, calculated or estimated. According to these statements, the data of foreground processes provided directly by producers were almost completely measured. Data of relevant background processes, e.g. grid electricity, is based on IFEU models that are regularly updated with statistical data, with available primary data, and with data derived from literature after it has been reviewed and checked for its quality. Thus, the overall reliability of data for this Eco-profile is considered very high.

Completeness

In general, the collected and applied data could be stated as complete, because no flows are omitted or substituted. For several production sites, it was not possible to obtain detailed emission data due to site-specific measurement and recording practices. For these cases, instead of neglecting these emissions, a list of "inevitable emissions"¹ was defined and the amount of the undeclared emissions was assumed to equal the average emission for the respective technology. This average emission was calculated based on the data reported by other production sites and weighted by the chlorine output. The same approach was chosen for missing transport distances.

Precision and Accuracy

As the relevant foreground data is either primary data or modelled based on primary information sources of the owner of the technology, higher precision is not reachable within this goal and scope.

Reproducibility

All data and information used either are 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, it may be the case that full reproducibility in any degree of detail will not be available for confidentiality reasons. However, experienced experts would easily be able to recalculate and reproduce suitable parts of the system as well as key indicators.

Data Validation

Data on chlorine and salt production was collected from Euro Chlor members and European salt producers in an iterative process with several feedback steps if necessary. The collected data was validated using existing data from published sources or expert knowledge.

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

¹ The list of "inevitable emissions" contains:

Emissions to air: Mercury (only for mercury cell technology), hydrogen, chlorine

Emissions to water: Arsenic, cadmium, chromium, copper, mercury, nickel, lead, zinc, adsorbable organohalogens (AOX), total organic carbon (TOC), chemical oxygen demand (COD), biochemical oxygen demand (BOD), chlorides, chlorine, sulphates, chlorate, bromate, suspended matter.

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 methods used cannot be shown here. Data for production processes have been transferred to the model after a successful data validation. The calculation follows the vertical calculation methodology, i.e. that the averaging is done after modelling the specific processes.

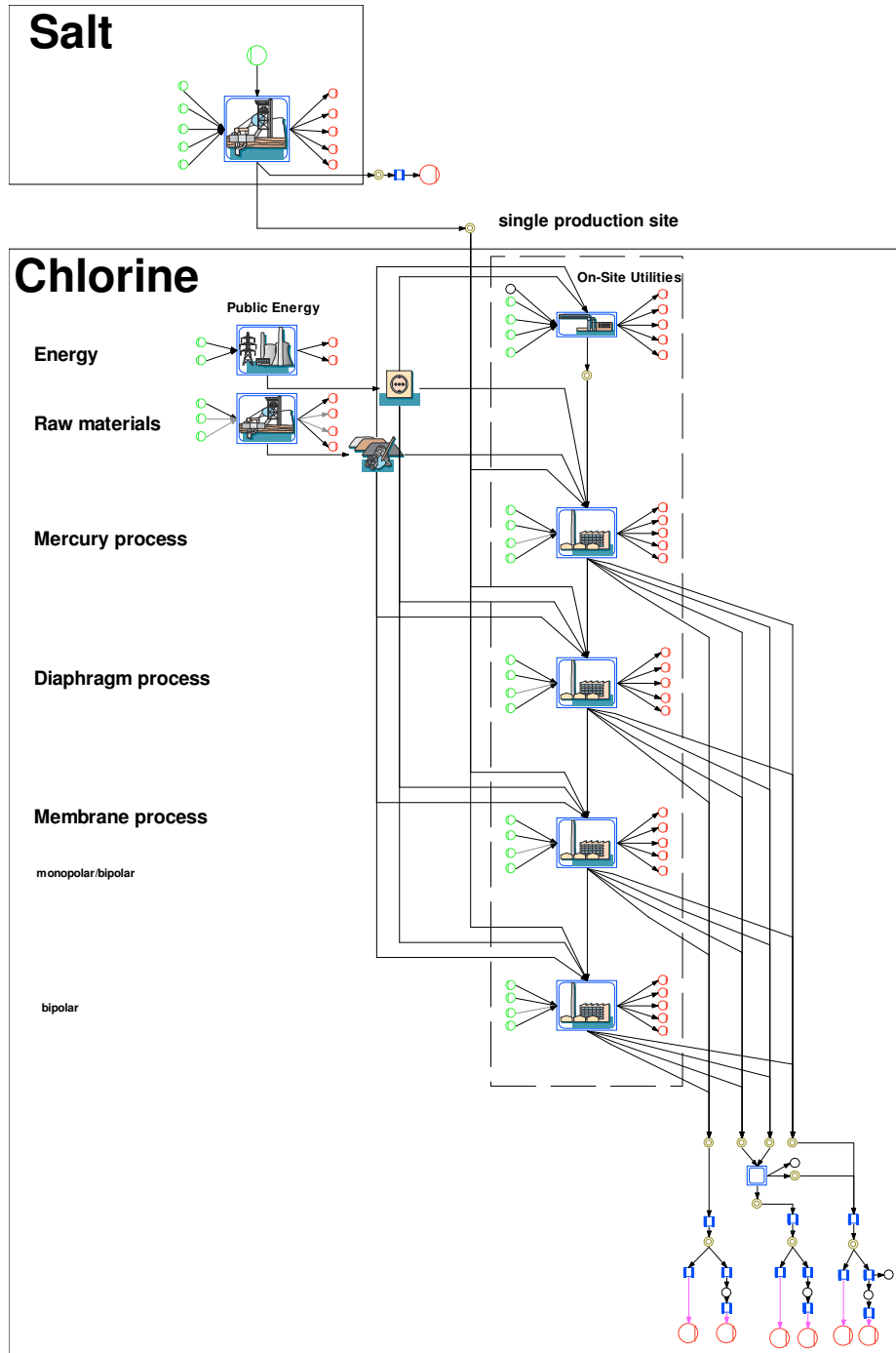


Figure 7:

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 prechains of public energy, salt and other raw materials. For the complete model, additional production sites were inserted in parallel.

Calculation Rules

Vertical Averaging

When modelling and calculating average Eco-profiles from the collected individual LCI datasets, vertical averages were calculated (Figure 8). These vertical averages comprise the chlor-alkali production unit itself, 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. National electricity mixes were used to calculate the grid electricity supply, and horizontal averages were used for sodium chloride (distinguished by type of origin), and other raw materials.

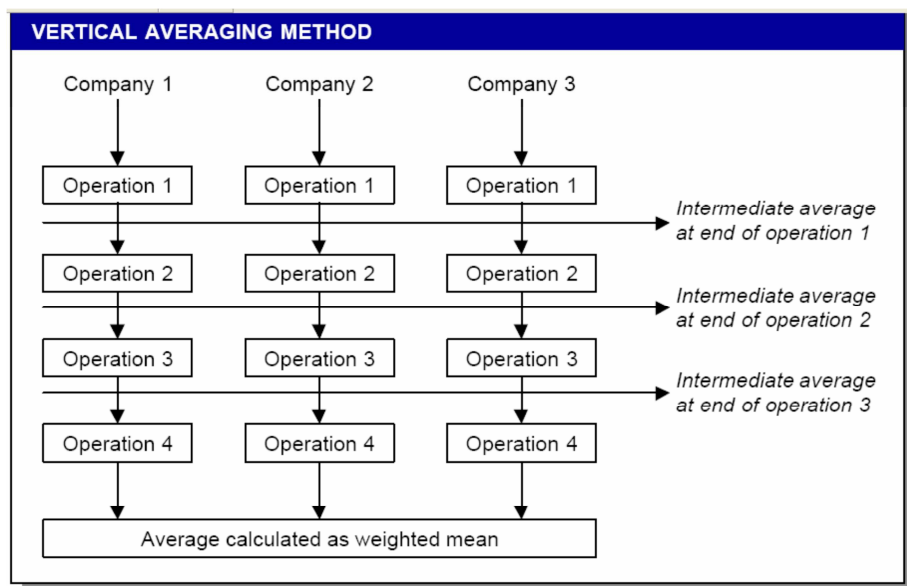


Figure 8: Vertical Averaging (source: Eco-profile of high volume commodity phthalate esters, ECPI European Council for Plasticisers and Intermediates, 2001)

Allocation Rules

Production processes in chemical industry are often multi-functional systems, i.e. they have not one, but several valuable product and co-product outputs. According to PlasticsEurope's LCI methodology [PLASTICEUROPE 2011], allocation should be avoided by expanding the system to include the additional functions related to the co-products, wherever possible. To this aim, a generic process with the same function (product) can be introduced, and the examined system receives credits for the associated burdens avoided elsewhere («avoidance allocation»). System expansion should only be used where there is a dominant, identifiable displaced product, and if there is a dominant, identifiable production path for the displaced.

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 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 collected data, 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 collected data.

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: hydrochloric acid, sulphuric acid, sodium sulphate (except salt input).

Furthermore, a sensitivity analysis for partitioning method was performed, where three 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 chlorine, sodium hydroxide and hydrogen the Eurostat production statistics (Eurostat 2013) provides data for 2003 until 2011. For potassium hydroxide and for sodium hypochlorite the data availability is reduced with data for the years 2006 until 2008 respectively 2006 and 2007 for hypochlorites (in general). The average market prices applied in the sensitivity calculation are shown in Table 5. 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.
- 'Calorific value of hydrogen' (avoided burden):
Same as the base case but with a different allocation of electricity accounting for the use of hydrogen in a fuel cell to produce electricity for the electrolysis on-site. Assuming a fuel cell efficiency of 50 %, from 1 kg of hydrogen about 20 kWh of electricity can be produced. This

amount is subtracted from the electricity input and the remaining electricity input is allocated to the other products by mass.

Table 5: Prices used for economic allocation (per ton of active molecule). Source: Eurostat [2013]

Product	Average price on European market 2006-2011 €/t
Hydrogen	1697
Chlorine	165
Sodium hydroxide in aqueous solution	224
Potassium hydroxide in aqueous solution	496
Hypochlorites	263

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

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

Primary Energy Demand	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
Total primary energy demand (Upper heating value) [MJ]	19.9	18.1	15.7	39.6	3.7
Total primary energy demand (Lower heating value) [MJ]	18.6	16.9	14.5	38.2	3.6

Table 11 show how the total energy input (primary energy demand) is used as fuel or feedstock for the different substances under consideration. Fuel use means generating process energy, whereas feedstock use means incorporating hydrocarbon resources into the product. Note that some feedstock input may still be valorised as energy; furthermore, process energy requirements may also be affected by exothermal or endothermic reactions of intermediate products. Hence, there is a difference between the feedstock energy input and the energy content of the respective substance (measurable as its gross calorific value).

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	2.66	0.129		2.66
Oil	0.96	0.021		0.96
Natural gas	5.26	0.115		5.26
Lignite	2.82	0.258		2.82
Nuclear	3.73	0.000		3.73
Other non-renewable fuels	0.00			0.00
Biomass	0.81			0.81
Hydro	0.56			0.56
Solar	2.80			2.80
Geothermics	0.00			0.00
Wind	0.32			0.32
Other renewable fuels	0.00			0.00
Sub-total renewable	4.5	0.0	0.0	4.5
Sub-total Non-renewable	15.4	0.5	0.0	15.4
Total	19.9	0.5	0.0	19.9

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

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	2.56	0.124		2.56
Oil	0.77	0.017		0.77
Natural gas	5.08	0.111		5.08
Lignite	2.78	0.254		2.78
Nuclear	3.62	0.000		3.62
Other non-renewable fuels	0.00			0.00
Biomass	0.79			0.79
Hydro	0.56			0.56
Solar	1.65			1.65
Geothermics	0.00			0.00
Wind	0.31			0.31
Other renewable fuels	0.00			0.00
Sub-total renewable	3.3	0.0	0.0	3.3
Sub-total Non-renewable	14.8	0.5	0.0	14.8
Total	18.1	0.5	0.0	18.1

Table 9: *Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg Hydrogen*

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	2.40	0.116		2.40
Oil	0.55	0.012		0.55
Natural gas	5.12	0.112		5.12
Lignite	2.61	0.239		2.61
Nuclear	3.40	0.000		3.40
Other non-renewable fuels	0.00			0.00
Biomass	0.74			0.74
Hydro	0.53			0.53
Solar	0.08			0.08
Geothermics	0.00			0.00
Wind	0.30			0.30
Other renewable fuels	0.00			0.00
Sub-total renewable	1.7	0.0	0.0	1.7
Sub-total Non-renewable	14.1	0.5	0.0	14.1
Total	15.7	0.5	0.0	15.7

Table 10: *Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg Sodium Hypochlorite*

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	2.43	0.118		2.43
Oil	1.30	0.029		1.30
Natural gas	7.84	0.169		7.84
Lignite	1.61	0.147		1.61
Nuclear	3.50	0.000		3.50
Other non-renewable fuels	0.00			0.00
Biomass	0.71			0.71
Hydro	0.65			0.65
Solar	20.89			20.89
Geothermics	0.00			0.00
Wind	0.62			0.62
Other renewable fuels	0.00			0.00
Sub-total renewable	22.9	0.0	0.0	22.9
Sub-total Non-renewable	16.7	0.5	0.0	16.7
Total	39.6	0.5	0.0	39.6

Table 11: *Analysis by primary energy resources (system boundary level), expressed as energy and/or mass (as applicable) per 1 kg sodium chloride*

Primary energy resource input	Total Energy Input [MJ]	Total Mass Input [kg]	Feedstock Energy Input [MJ]	Fuel Energy Input [MJ]
Coal	0.09	0.005		0.09
Oil	0.29	0.006		0.29
Natural gas	0.37	0.009		0.37
Lignite	0.09	0.008		0.09
Nuclear	0.21	0.000		0.21
Other non-renewable fuels	0.00			0.00
Biomass	0.03			0.03
Hydro	0.03			0.03
Solar	2.53			2.53
Geothermics	0.00			0.00
Wind	0.02			0.02
Other renewable fuels	0.00			0.00
Sub-total renewable	2.6	0.0	0.0	2.6
Sub-total Non-renewable	1.1	0.0	0.0	1.1
Total	3.7	0.0	0.0	3.7

Table 12 shows the distribution of the primary energy demand between renewable and non-renewable resources. Please note that most of the share of renewable energy resources for all substances results from the solar energy used for the production of solar salt. As shown in Table 11, the contribution of solar energy to the total primary energy input of sodium chloride is considerably high, even when solar salt has a share of only 1.8 % on the total sodium chloride input to chlor-alkali plants (see Figure 4). This is due to the comparably large amounts of water (about 60 l/kg NaCl) that have to be evaporated for the crystallisation of salt from sea water.

The comparably high share of renewable energy resources input to the production of sodium hypochlorite is a result of the applied vertical averaging method. Units producing large amounts of sodium hypochlorite have a higher share of solar salt input than units with no or low sodium hypochlorite production.

Table 12: *Primary energy demand by renewability.*

Fuel/energy input type	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
Renewable energy resources	22.6%	18.3%	10.5%	57.8%	71.3%
Non-renewable energy resources	77.4%	81.7%	89.5%	42.2%	28.7%
Total	100.0%	100.0%	100.0%	100.0%	100.0%

The following tables give information on the foreground processes. This means that in contrast to the other tables in this section, only direct inputs and outputs of the chlor-alkali process (for the products chlorine, sodium hydroxide, hydrogen, and sodium hypochlorite) and the salt production (for sodium chloride) were analysed.

Table 13 analyses the types of useful energy inputs in the foreground process: thermal energy has a minor contribution, whereas the majority is electric energy. It should be noted, that the LCI tables in the annex account for the entire cradle-to-gate primary energy demand of the considered production system.

Table 13: *Analysis by type of useful energy for foreground processes (chlor-alkali electrolysis) per 1 kg of product*

Type of useful energy in process input	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Electricity [MJ]	5.29	5.27	5.27	5.99
Heat, thermal energy [MJ]	1.1	1.0	1.0	0.9
Total (for selected key processes) [MJ]	6.3	6.3	6.3	6.9

Water Consumption

Table 14: *Gross water resources used in foreground processes (chlor-alkali electrolysis) per 1 kg of product*

Water use	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Process water [kg]	1.7	1.6	1.6	1.4
Cooling water [kg]	28.7	28.9	27.5	15.4
Boiler feed water [kg]	7.8E-04	7.8E-04	3.4E-04	7.2E-04
Unspecified [kg]	8.0E-04	4.7E-04	1.6E-08	5.7E-04
Total [kg]	30.4	30.5	29.1	16.8

Air Emission Data

Table 15 shows a few selected air emissions which are commonly reported and used as key performance indicators; for a full inventory of air emissions, please refer to the complete LCI table in the annex of this report.

Table 15: *Selected air emissions of foreground processes (chlor-alkali electrolysis) per 1 kg of product*

Air emissions	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Carbon dioxide, fossil [kg]	4.8E-03	3.1E-03	1.1E-03	4.6E-03
Carbon monoxide (CO) [kg]	5.6E-06	3.2E-06	1.2E-07	6.3E-06
Sulphur dioxide (SO ₂) [kg]	3.8E-05	2.2E-05	5.8E-07	3.9E-05
Nitrogen oxides (NO _x) [kg]	1.4E-03	1.3E-03	1.2E-03	1.7E-03

Particulate matter $\leq 10 \mu\text{m}$ [kg]	2.7E-06	1.5E-06	1.9E-08	3.0E-06
Hydrogen [kg]	0.0E+00	0.0E+00	5.6E-02	0.0E+00
Chlorine [kg]	9.7E-07	0.0E+00	0.0E+00	9.5E-07

Wastewater Emissions

Table 16 shows a few selected wastewater emissions, which are commonly reported and used as key performance indicators (KPI); for a full inventory of wastewater emissions, please refer to the complete LCI table in the annex of this report.

Table 16: *Selected water emissions of foreground processes (chlor-alkali electrolysis) per 1 kg of product.*

Water emissions	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite
Biological oxygen demand after 5 days (BOD 5) [kg]	1.76E-05	1.78E-05	1.76E-05	2.53E-05
Chemical oxygen demand (COD) [kg]	5.60E-05	4.84E-05	5.78E-05	4.15E-05
Total organic carbon (TOC) [kg]	9.94E-06	8.57E-06	1.00E-05	1.07E-05
Mercury [kg]	1.73E-08	1.67E-08	1.77E-08	1.28E-08
Other metals [kg]	7.66E-07	5.86E-07	4.65E-07	7.38E-07
AOX [kg]	9.92E-07	7.04E-07	1.01E-06	4.73E-07
Chlorides [kg]	1.55E-02	1.58E-02	1.78E-02	5.20E-02
Chlorine [kg]	1.11E-05	1.09E-05	1.09E-05	1.93E-05

Solid Waste

Table 17: *Solid waste generation of foreground processes (chlor-alkali electrolysis) per 1 kg of product.*

Product	Waste for -	Incineration kg	Landfill kg	Recovery kg	Unspecified kg	Total kg
Chlorine	Hazardous	7.7E-05	1.4E-03	7.5E-04	1.4E-04	2.3E-03
	Non-hazardous	3.1E-05	2.9E-03	4.0E-03	1.1E-04	7.0E-03
Sodium Hydroxide	Hazardous	7.7E-05	1.5E-03	7.4E-04	1.4E-04	2.4E-03
	Non-hazardous	3.0E-05	3.2E-03	3.9E-03	1.1E-04	7.2E-03
Hydrogen	Hazardous	7.5E-05	1.3E-03	7.6E-04	1.4E-04	2.3E-03
	Non-hazardous	2.9E-05	8.6E-03	4.0E-03	1.2E-04	1.3E-02
Sodium Hypochlorite	Hazardous	3.8E-05	3.2E-03	1.1E-04	4.3E-04	3.8E-03
	Non-hazardous	1.4E-05	1.7E-05	9.5E-04	4.5E-05	1.0E-03

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 2012].

Table 18: Abiotic Depletion Potential per 1 kg of product

Natural resources	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
ADP, elements [kg Sb eq]	1.9E-05	1.1E-05	2.1E-07	1.3E-05	1.6E-05
ADP, fossil fuels (LHV) [MJ]	10.5	10.0	9.6	12.0	0.8

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 basing on the last report of the Intergovernmental Panel on Climate Change [IPCC 2007]. Additionally, the Global Warming Potential of hydrogen was considered with a value of 5.8 kg CO₂ eq./kg H₂ [DERWENT 2006]. The comparably high GWP of the product hydrogen is a result of unused hydrogen being vented to the atmosphere.

Table 19: Global Warming Potential (100 years) per 1 kg of product

Climate change	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
GWP [kg CO ₂ eq.]	0.90	0.86	1.14	0.93	0.06

Acidification

The Acidification Potential (AP) is quantified according to HAUSCHILD 1998 with updated characterisation factors of CML 2012.

Table 20: Acidification Potential per 1 kg of product

Acidification of soils and water bodies	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
AP [g SO ₂ eq.]	3.46	2.70	1.96	3.16	0.96

Eutrophication

The Eutrophication Potential (EP) is calculated according to Heijungs (1992) with updated characterisation factors of CML 2012.

Table 21: Eutrophication Potential per 1 kg of product

Eutrophication of soils and water bodies	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
EP, terrestrial [g PO ₄ ³⁻ eq.]	0.19	0.18	0.16	0.23	0.01
EP, aquatic [g PO ₄ ³⁻ eq.]	0.15	0.14	0.13	0.06	0.01
EP, total [g PO ₄ ³⁻ eq.]	0.34	0.32	0.30	0.29	0.02

Ozone Depletion

The calculation of Ozone Depletion Potential (ODP) is basing on characterisation factors of the World Meteorological Organisation (WMO 2011). This implies also the consideration of dinitrogen monoxide (N₂O) as ozone depleting substance with an ODP of 0.017 kg CFC-11 eq. per kg of N₂O.

Table 22: Ozone Depletion Potential per 1 kg of product

Ozone Depletion Potential	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
ODP [g CFC-11 eq.]	1.1E-03	1.1E-03	1.1E-03	1.2E-03	4.0E-05

Summer Smog

The Photochemical Ozone Creation Potential (POCP) is quantified according to JENKIN 1999 and DERWENT 1998 with updated characterisation factors of CML 2012.

Table 23: Photochemical Ozone Creation Potential per 1 kg of product

Photochemical Ozone Creation Potential	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
POCP [g Ethene eq.]	9.2E-02	7.7E-02	7.1E-02	9.6E-02	5.6E-03

Dust & Particulate Matter

Particulate matter with an aerodynamic diameter of less than 10 µm (PM10) is suspected to cause heart and circulatory diseases. New 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 (NO₂), sulphur dioxide (SO₂), ammonia (NH₃) and Non-Methane Volatile Organic Compounds (NMVOC). The characterisation factors shown in Table 24 are based on works of DE LEEUW 2002 and HELDSTAB 2003 for NMVOC.

Table 24: *PM10 characterisation factors of air emissions according to De Leeuw (2002) and 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 25: *PM10 emissions per 1kg of product*

Particulate matter ≤ 10 µm	Chlorine	Sodium Hydroxide	Hydrogen	Sodium Hypochlorite	Sodium Chloride
PM10, direct emissions [PM10 eq.]	0.14	0.13	0.12	0.16	0.01
PM10, secondary [PM10 eq.]	1.86	1.63	1.50	2.07	0.11
PM10, total [PM10 eq.]	2.00	1.77	1.62	2.23	0.12

Dominance Analysis

Table 26 to

Table 29 show the main contributions to the results presented above. An average based on the weighted mean from the different technologies of the participating producers is used.

Table 26: *Dominance analysis of impacts per 1 kg chlorine*

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g C ₂ H ₄ eq.]	[g PM10 eq.]
Foreground process (chlor-alkali electrolysis)	0.0%	0.0%	0.0%	0.2%	0.1%	4.3%	0.0%	0.1%
Electricity for foreground processes	62.2%	0.0%	61.8%	82.8%	53.3%	46.0%	68.0%	76.6%
Thermal energy and utilities for foreground processes	16.5%	0.0%	28.2%	7.1%	3.3%	29.8%	6.7%	4.9%
Salt production	20.5%	99.1%	8.9%	8.2%	32.9%	8.3%	7.4%	7.1%
Other raw materials	0.5%	0.9%	0.7%	0.8%	8.4%	3.3%	14.7%	8.4%
Transport of salt and other raw materials	0.3%	0.0%	0.4%	0.4%	2.0%	1.7%	2.2%	2.9%
Disposal	0.0%	0.0%	0.0%	0.5%	0.0%	6.6%	1.1%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 27: Dominance analysis of impacts per 1 kg sodium hydroxide

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq]	[g C ₂ H ₄ eq.]	[g PM10 eq.]
Foreground process (chlor-alkali electrolysis)	0.0%	0.0%	0.0%	0.2%	0.1%	2.9%	0.0%	0.1%
Electricity for foreground processes	68.4%	0.1%	64.6%	86.1%	68.1%	48.6%	80.9%	86.1%
Thermal energy and utilities for foreground processes	18.1%	0.0%	29.5%	7.4%	4.2%	32.8%	8.0%	5.5%
Salt production	12.9%	98.3%	5.2%	4.7%	24.0%	4.9%	4.8%	4.4%
Other raw materials	0.4%	1.6%	0.5%	0.7%	2.1%	2.9%	3.4%	2.0%
Transport of salt and other raw materials	0.2%	0.0%	0.3%	0.3%	1.4%	1.0%	1.5%	1.9%
Disposal	0.0%	0.0%	0.0%	0.5%	0.0%	6.9%	1.3%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 28: Dominance analysis of impacts per 1 kg hydrogen

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq]	[g C ₂ H ₄ eq.]	[g PM10 eq.]
Foreground process (chlor-alkali electrolysis)	0.0%	0.0%	0.0%	28.8%	0.1%	5.0%	0.0%	0.1%
Electricity for foreground processes	76.6%	4.3%	65.6%	64.3%	90.3%	50.7%	84.4%	90.9%
Thermal energy and utilities for foreground processes	22.7%	0.1%	33.7%	5.7%	6.0%	33.0%	9.4%	6.3%
Salt production	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other raw materials	0.7%	94.7%	0.8%	0.8%	3.4%	4.0%	4.7%	2.7%
Transport of salt and other raw materials	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Disposal	0.0%	0.0%	0.0%	0.4%	0.1%	7.2%	1.5%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 29: Dominance analysis of impacts per 1 kg sodium hypochlorite

	Total Primary Energy	ADP Elements	ADP Fossil	GWP	AP	EP	POCP	PM10
	[MJ]	[kg Sb eq.]	[MJ]	[kg CO ₂ eq.]	[g SO ₂ eq.]	[g PO ₄ ³⁻ eq.]	[g C ₂ H ₄ eq.]	[g PM10 eq.]
Foreground process (chlor-alkali electrolysis)	0.0%	0.0%	0.0%	0.5%	0.1%	1.2%	0.0%	0.1%
Electricity for foreground processes	35.4%	0.1%	65.7%	85.3%	73.2%	66.7%	79.2%	86.3%
Thermal energy and utilities for foreground processes	9.7%	0.0%	28.8%	6.7%	3.5%	9.7%	7.3%	4.6%
Salt production	54.3%	95.0%	3.9%	4.0%	17.9%	5.6%	3.5%	3.4%
Other raw materials	0.4%	4.9%	1.1%	2.0%	2.9%	6.6%	4.8%	2.7%
Transport of salt and other raw materials	0.1%	0.0%	0.4%	0.5%	2.3%	2.1%	2.2%	2.8%
Disposal	0.0%	0.0%	0.0%	1.2%	0.1%	8.1%	2.9%	0.1%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Sensitivity Analysis Regarding the Influence of the Allocation Method

As described in the section Allocation Rules on page 29f., a sensitivity analysis was performed to examine the influence of the chosen allocation method on the results of the present study. In Table 30, the sensitivity of two selected impact categories (GWP and 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 5 leads to highly increased burdens of hydrogen and a simultaneous decrease of the burdens of chlorine by about 25 %. This is due to the comparably low price of chlorine on the open market compared to the prices of hydrogen and sodium hydroxide.

Table 30: 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	0.90	0.86	1.14	0.93
	Pure mass allocation	0.88	0.87	1.14	0.93
	Economic allocation	0.68	0.91	7.19	1.09
	Hydrogen avoided burden	0.82	0.78	7.46	0.85
Total Primary Energy Demand (PED) in MJ per kg product	Base Case	19.92	18.11	15.73	39.56
	Pure mass allocation	18.99	18.94	15.73	39.51
	Economic allocation	14.73	19.89	141.84	46.51
	Hydrogen avoided burden	18.21	16.39	162.37	37.81

It has to be noted, however, that the pricing of chlorine is quite difficult and associated with a high uncertainty because a high share of chlorine is not sold on the open market but used company-internal. Furthermore, it can be questioned if hydrogen from chlor-alkali electrolysis would get 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.

In the scenario "Hydrogen avoided burden", it was assumed that hydrogen from the electrolysis cell is fed to a fuel cell producing electricity with an efficiency of 50 %. This electricity was subtracted from the electricity input of the chlor-alkali electrolysis. As a result, the electricity input was reduced by 14 % (weighted average) compared to the base case. Therefore, the calculated burdens for all other products are about 10 % lower than in the base case. Hydrogen, as it is used to produce electricity, takes the burdens of the replaced electricity. This scenario shows a possibility for chlor-alkali units, how to improve their environmental performance.

According to the sensitivity results, the allocation method 'Base Case' is a conservative determination for the Eco-profiles of chlorine and sodium hydroxide. This choice ensures the comparability with former Eco-profiles.

Comparison of the present Eco-profile with its previous version (2006)

Table 31 compares the present results with the previous version of the Eco-profile of 2006. This comparison shows two major differences: The Global Warming Potential (GWP) is significantly higher in the current calculation whereas the Primary Energy Demand (PED) from non-renewable resources is significantly lower. These effects are mainly caused by the very different electricity mixes used in the two studies. The electricity mix is dependent on the participating production sites, since for each site the country specific electricity mix was applied in the model in both studies. The resulting electricity mixes of both studies do not equal the chlorine production capacity distribution across European countries. For example, in the present study, countries with comparably low specific GWP per kWh electricity, like France and Belgium, are significantly underrepresented with only about 40 % coverage of national chlorine production capacity. In contrast, these countries were over-represented in the previous study.

Nuclear energy is calculated by definition with an electrical efficiency of 33 %, whereas other fuels are calculated with the real plant efficiencies. Therefore, the lower share of nuclear power in the present study leads to an overall lower PED of non-renewable resources.

Furthermore, the Primary Energy Demand from renewable resources significantly increased compared to the previous study. This is mainly caused by the fact that in the present study the solar energy used for the production of solar salt was taken into account.

Table 31: Comparison of the present Eco-profile with its previous version (2006)

Environmental Impact Categories	Chlorine Eco-profile Process data 2004 Calculated 2006	Chlorine Eco-profile 2013	Difference
Gross primary energy from non-renewable resources [MJ]	18.9	15.4	-18 %
Gross primary energy from renewable resources [MJ]	1.3	4.5	+257 %
Global Warming Potential (GWP) [kg CO ₂ eq.]	0.79	0.90	+14 %

Interpretation of results and improvement options

The chlor-alkali electrolysis is an energy intensive process, with electricity being the main energy carrier. This leads to a high sensitivity of all LCIA indicators on the electricity mix used for the calculation. Especially the Global Warming Potential (GWP) is highly sensitive to the electricity mix of a country as was shown in

Table 3.

As discussed before, some countries are overrepresented whereas some are underrepresented in the current study, regarding their chlorine production capacity. The country-mix is determined by the chlor-alkali plants supplying data, namely by their location and their production volume. The sample of data received is leading to an over-estimation of the GWP of chlor-alkali products (q.v.).

Table 3).

The best way to increase the representativeness of a comparable study would be to increase the coverage of the production sites, i.e., to convince all companies and site managers of the high value of their contribution in the sense of data collection. However, the aim of 100 % coverage is most likely not reachable for studies with a high number of production sites.

Therefore, the authors propose another approach to increase the representativeness of this study. According to the methodology of Eco-profiles and EPDs of PlasticsEurope (2011), national electricity mixes were used to calculate the grid electricity supply of each site. This procedure could be modified, replacing the country-specific electricity mix of all sites with an average European electricity mix of chlor-alkali units in EU27, Norway and Switzerland. This weighted average European electricity mix should consider the chlorine nameplate capacity of each country as well as the applied technologies of the chlor-alkali units. The results obtained with this new methodology will still be inaccurate, since the nameplate capacity distribution does not equal the actual production distribution, and since the demand of electricity from the public grid not always correlates with the capacity, especially, when a high share of electricity is produced on-site. Nevertheless the expected error will be comparably smaller.

This proposed approach is a hybrid to calculate the electricity mix closer to reality, using collected, primary data which are complemented with publicly available data for those facilities that have not reported any data for this Eco-profile. Following this approach, the results presented in this report would be extrapolated to obtain a more complete and possibly more accurate picture and a “quasi-representativeness” of (close to) 100 % for the electricity production mix. This approach would have to be tested in order to understand its feasibility, implications and appropriateness.

Review

Review Summary

As part of the CEFIC / Euro Chlor programme management and quality assurance, DEKRA Consulting GmbH conducted an external independent critical review of this work. The outcome of the critical review is reproduced below.

The subject of this critical review was the development of the Eco-profile for the European chlor-alkali process which includes the products chlorine, sodium hydroxide, hydrogen, and sodium hypochlorite. In addition, the potential environmental impacts associated with sodium chloride production were also quantified.

The project included milestone meetings with representatives of participating producers, the LCA practitioner and the reviewer. In addition, interim results were discussed at the General Assembly of Euro Chlor in 2012. Furthermore, various review meetings between the LCA practitioner and the reviewer were held, which included a model and database review and spot checks of data and calculations. The final Eco-profile report was also reviewed by Jean-Pol Debelle of Euro Chlor and the reviewer. All questions and recommendations were discussed with the LCA practitioner, and the report was adapted and revised accordingly.

Original industry data were collected for all foreground processes taking into account the specific technologies of the chlorine-alkali electrolysis, i.e. mercury, diaphragm, and membrane process, while background process data were sourced from Ecoinvent as well as specific data sources from the LCA practitioners (e.g. updated country-specific electricity grid mixes). Primary industry data was collected from 50 production sites of 25 companies which lead to an overall representativeness of 68% of the European chlorine production capacity. For salt production, primary data have been collected from relevant producers within Europe; this data was verified and averaged with literature data.

The potential environmental impacts for chlorine, sodium hydroxide, hydrogen, and sodium hypochlorite by chlor-alkali electrolysis are dominated by electricity use (e.g. for chlorine: 62% Total Primary Energy, 83% Global Warming Potential (GWP)) and - to a lesser extent - by sodium chloride production (e.g. for chlorine 21% Total Primary Energy, 8% GWP, 33% Acidification Potential). Consequently, the country-specific production of electricity has a great influence on the results, especially with respect to the GWP indicator. It should be noted, that in this study countries with low specific GWP per kWh of electricity produced, such as France and Belgium, are significantly underrepresented, whereas countries with a comparatively higher GWP per kWh of electricity produced are over-represented. This leads to higher GWP results in comparison with the last Eco-profile published in 2006. In contrast, the Primary Energy Demand from renewable resources significantly increased compared to the previous study due to the fact that in the present study the solar energy used for the production of solar salt was taken into account. Against the background outlined above, it would be desirable to increase the representativeness of the data by collecting primary data from a greater number of chlor-alkali production sites. An alternative approach to potentially increase the European representativeness of the data is described in the Eco-profile report. At the moment, the resulting datasets are considered best available data and good quality with respect to the goal and scope.

The LCA practitioner has 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 chlor-alkali products produced in Europe.

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References

- BORKEN 1999 Borken, J., Patyk, A., Reinhardt, G.A. 1999. Basisdaten für ökologische Bilanzierungen. Einsatz von Nutzfahrzeugen in Transport, Landwirtschaft und Bergbau (Basic data for life cycle assessments: Use of commercial vehicles in transport, agriculture, and mining; in German). Vieweg Verlag, Braunschweig/Wiesbaden, Germany.
- BREF 2009 European Integrated Pollution Prevention and Control Bureau (EIPPCB) of the European Commission's Joint Research Centre (JRC): Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities (MMR BREF). January 2009.
- BREF 2013 European Integrated Pollution Prevention and Control Bureau (EIPPCB) of the European Commission's Joint Research Centre (JRC): Best Available Techniques (BAT) Reference Document for the Production of Chlor-alkali (CAK BREF). Final Draft, April 2013.
- CML 2012 CML - Institute of Environmental Sciences: Impact assessment characterisation factors, version 4.1. CML, Leiden, October, 2012
→ <http://www.leidenuniv.nl/interfac/cml/ssp/index.html>
- DE LEEUW 2002 De Leeuw, F.A.A.M., 2002. A set of emission indicators for long-range transboundary air pollution. Environmental Science & Policy 5, 135-145.
- DERWENT 1998 Derwent, R.G., Jenkin, M.E., Saunders, S.M., Pilling, M.J. 1998. Photochemical ozone creation potentials for organic compounds in Northwest Europe calculated with a master chemical mechanism. Atmospheric Environment 32, 2429-2441.
- DERWENT 2006 Derwent, R., Simmonds, P., O'Doherty, S., Manning, A., Collins, W., Stevenson, D. 2006. Global environmental impacts of the hydrogen economy. International Journal of Nuclear Hydrogen Production and Application 1, 57-67.
- ECOINVENT 2010 Life cycle inventory database ecoinvent v2.2. Ecoinvent Centre, St. Gallen, 2010. → <http://www.ecoinvent.org>
- ECOTRANSIT 2011 IFEU Heidelberg, Öko-Institut, IVE/RMCON, 2011. EcoTransIT World - Ecological Transport Information Tool for Worldwide Transports.
- EURO CHLOR 2011 Chlorine Industry Review 2010-2011, Euro Chlor, 2011.
- EURO CHLOR 2012 Chlorine Industry Review 2011-2012, Euro Chlor, 2012.
- EUROSTAT 2011 Energy - Yearly statistics 2009. Eurostat, Luxembourg, 2011
→ <http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home>
- EUROSTAT 2013 PRODCOM ANNUAL SOLD [DS-043408]. Eurostat, Luxembourg, 2013
→ <http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home>
- EYERER 1996 Ganzheitliche Bilanzierung - Werkzeug zum Planen und Wirtschaften in Kreisläufen, 1996

GUINÉE ET AL. 2002	Guinée, J.B., Gorée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L.F.C.M., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment: An operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht, The Netherlands.
HAUSCHILD 1998	Hauschild, M, Wenzel, H.: Environmental Assessment of products. Volume 2: Scientific background. Chapman & Hall, London, 1998
HBEFA 2010	INFRAS AG, Handbook of Emission Factors for Road Transport (HBEFA) version 2.1, January 2010. → http://hbefa.net
HEIJUNGS 1992	Heijungs, R., Guinée, J.B., Huppes, G., Lankreijer, H.M, Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., van Duin, R., de Goede, H.P., 1992. Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Science (CML), Leiden University, Leiden.
HELDSTAB 2003	Heldstab, J., de Haan van der Weg, P., Künzle, T., Keller, M. Zbinden, R., 2003. Modelling of PM10 and PM2.5 ambient concentrations in Switzerland 2000 and 2010. Environmental Documentation No.169.Swiss Agency for the Environment, Forests and Landscape (SAEFL), Bern, Switzerland.
IFEU 2011	Lauwigi, Ch., Fehrenbach, H., October 2011: Documentation for the UMBERTO based electricity grid model created by IFEU. Institute for Energy and Environmental Research, Heidelberg, Germany. → http://ifeu.de/english/index.php?bereich=ind&seite=energieerzeugung
ILCD 2010	European Commission (2010): ILCD Handbook - General guide for Life Cycle Assessment (LCA) - Detailed guidance
IPCC 2007	IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change. [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
ISO 14040: 2006	ISO 14040 Environmental Management - Life Cycle Assessment - Principles and Framework. Geneva, 2006
ISO 14044: 2006	ISO 14044 Environmental management -- Life cycle assessment -- Requirements and guidelines. Geneva, 2006
JENKIN 1999	Jenkin, M.E. and Hayman, G.D., 1999. Photochemical ozone creation potentials for oxygenated volatile organic compounds: sensitivity to variations in kinetic and mechanistic parameters. Atmospheric Environment 33, 1775-1293.
KIRK-OTHMER 2004	Kirk-Othmer Encyclopedia of Chemical Technology, John Wiley & Sons, New York, USA, 2004.

O'BRIEN 2005	O'Brien, T.F., Bommaraju, T.V., Hine, F., 2005. Handbook of Chlor-Alkali Technology. Springer Science + Business Media, Inc, New York, USA.
PLASTICSEUROPE 2011	Eco-profiles and Environmental Declarations, Plastics Europe. Version 2.0, April 2011.
SCHMITTINGER 2000	Schmittinger, P. (Ed.), 2000. Chlorine - Principles and Industrial Practice. Wiley-VCH Verlag, Weinheim, Germany.
SCHMITTINGER 2006	Schmittinger, P. et al., 2006. "Chlorine" in: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag, Weinheim, Germany (Online electronic edition).
SEDIVY 2009	Sedivy, V.M., 2009. Environmental Balance of Salt Production Speaks in Favor of Solar Saltworks. Global NEST Journal 11 (1), 41-48.
TREMOT 2009	IFEU 2009. TREMOD - Transport Emission Model: "Daten- und Rechenmodell Schadstoffemissionen aus dem motorisierten Verkehr in Deutschland 1960-2030".
UMBERTO 5.6	Umberto for Eco-Efficiency, Version 5.6. Ifu Hamburg GmbH, Hamburg, Germany
VOGT 2005	Vogt, H. et al., 2005. "Chlorine Oxides and Chlorine Oxygen Acids" in: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag, Weinheim, Germany (Online electronic edition).
WESTPHAL 2005	Westphal, G. et al., 2005. "Sodium Chloride" in: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag, Weinheim, Germany (Online electronic edition).
WHO 2006	World Health Organization (WHO), Joint WHO / Convention Task Force on the Health Aspects of Air Pollution, 2006. Health risk of particulate matter from long-range transboundary air pollution.
WMO 2011	World Meteorological Organization (WMO), 2011. Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project - Report No. 52, Geneva, Switzerland.

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