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Life Cycle Assessment according to ISO 14040:2006 and ISO 14044:2006

Life Cycle Assessment for End of Life Treatment of Expandable Polystyrene (EPS) from External Thermal Insulation Composite Systems (ETICS)

22nd January 2018, Version 6

by:

TÜV Rheinland LGA Products GmbH, Germany

in cooperation with:

BASF SE, Germany

Impressum

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Further versions of the report are:

- Version 1, 28th March 2017
- Version 2, 11th April 2017
- Version 3, 25th April 2017
- Version 4, 26th April 2017
- Version 5, 13th December 2017

Executive Summary

Goal and Scope

A consortium of the companies Sunpor, Synbra and ICL has formed a project team to build a pilot plant for the recycling of Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS) with flame retardant hexabromcyclododecane (HBCDD), called the PolyStyreneLoop (PS Loop) Cooperative. The PS Loop Cooperative is a non-profit organization under Dutch law. Members of the foundation are industry representatives from the whole polystyrene (PS) foam value chain: PS foam manufacturers, raw material and additives suppliers, foam converters and recyclers.

The objective of the PS Loop Cooperative is to enable the recycling of construction waste EPS and XPS. The process consists of the CreaSolv®[1] Technology and a Bromine Recovery Unit (BRU). Due to these process steps HBCDD is destructed while PS and bromine can be recycled and used for further applications in the construction industry. The planned demo plant will be located in Terneuzen, Netherlands. It is planned to start operation in the 1st quarter 2019.

The demo plant shall have an annual recycling capacity of up to 3,300 tons HBCDD containing EPS and XPS. It will combine the CreaSolv® Process and BRU technology for the recycling of PS and bromine.

BASF, experienced in conducting Life Cycle Assessments (LCA) and supporter of the PS Loop Cooperative, was asked by the consortium to perform a LCA to quantify and compare the environmental performance of two different end of life options for 1 ton of EPS (equal to 10 wt% EPS) coming from External Thermal Insulation Composite Systems (ETICS) from dismantling of houses in Europe:

- the Current Status Quo Process (incineration with energy recovery) and
- the PS Loop Process.

A fraction of 10 wt% EPS in ETICS were assumed according to information of IWARU of FH Münster, but higher respectively lower fractions are also possible. Conclusions from this study can only be drawn for the assessed environmental impacts. Therefore, no conclusion on economic aspects can be drawn.

[1] CreaSolv® is a registered trademark of CreaCycle GmbH.

The Current Status Quo Process comprises an incineration with energy recovery of untreated ETICS waste. Energy recovery refers to operations that aim to use the released energy obtained during the combustion of plastics waste. This energy can be used to produce heat and/or electricity for domestic or industrial use.

The PS Loop Process considers the following steps:

- ETICS waste from construction and demolition sites with 10 wt% EPS is pretreated such that only compacted and mechanically separated EPS with < 10 % impurities is fed forward into a selective extraction recycling process (CreaSolv® Process).
- In this process EPS is reduced to PS granulate and is further purified. PS is gathered as recycling product (comparable quality to virgin material) which is ready for reuse in PS insulation foams again. Due to the fact that no CreaSolv® Process plant for PS Loop Process exists, only laboratory based data (Input amount 30 kg) were available at the time of preparation of study.
- The released flame retardant HBCDD is then recovered in an existing Bromine Recovery Unit (BRU), located at the ICL plant in Terneuzen, Netherlands and bromine can be recovered (equal quality to virgin material). All considered in- and output data for the BRU process is based on a pilot plant run with an output of 400 kg bromine recovery per hour.

The results of the study will be used for communication with interested parties and stakeholders. Therefore, potential environmental impacts for different end of life technologies of ETICS with EPS (Current Status Quo Process (incineration with energy recovery) and PS Loop Process) were assessed. The results can create a basis for decision making concerning new processes for recycling of EPS insulation foam waste and for the recovery of bromine.

Key Results

The PS Loop Process shows a lower environmental impact in the impact categories (climate change, eutrophication (freshwater), summer smog, resource depletion (fossil, elements), human toxicity (non-cancer, cancer) and freshwater ecotoxicity in comparison to Current Status Quo Process (incineration with energy recovery). Effects for acidification and eutrophication (marine) are comparable for both alternatives (differences < 15%).[2]

The environmental impacts of Current Status Quo Process (incineration with energy recovery) are mainly influenced by incineration of untreated ETICS waste. Furthermore, the used system expansion, especially for the production of PS, influences the overall results for this end of life technology.

[2] The results are valid as far as recycled material (PS derived from CreaSolv® and bromine derived from BRU) is substituted with virgin material on a one to one ratio.

Main driver for environmental effects of PS Loop Process are the respective system expansion (production of electricity and steam) to fulfill the same performance for both alternatives and incineration of the remaining inert material from ETICS. The inert matter and plastic (dowels) are incinerated and only the remaining metals (dowels) are recycled or landfilled. The pre-treatment (separation, shredding and compaction) considers more process steps than the Current Status Quo Process (incineration with energy recovery) alternative, therefore higher environmental impacts result for these pre-treatment steps.

The CreaSolv® Process is not a main driver for the overall results of the PS Loop Process alternative. However, it leads to visible influences in all considered impact categories. Main contributor of the CreaSolv® Process is the required energy demand. Environmental impacts of the BRU lead to very limited contributions in all considered impact categories. Main driver are used utilities, especially hydrazine.

The following table shows the overall results of all considered impact categories and the primary energy demand for both alternatives (base case).

Table 1: Overall Life Cycle Impact Assessment results- Base case

Impact Category	Unit	Base Case Current Status Quo	Base Case PS Loop Process	Difference Base Case
Climate change	kg CO_2 eq	6,448	3,433	-47%
Acidification	mol H+ eq	7.4	7.5	+2%
Summer smog	kg NMVOC eq	6.9	5.9	-15%
Eutrophication, marine	kg N eq	2.3	2.2	-3%
Eutrophication, freshwater	kg P eq	6.6E-03	4.9E-03	-26%
Resource depletion, fossil	MJ	7.5E+04	3.7E+04	-51%
Resource depletion, elements	kg Sb eq	7.7E-04	6.4E-04	-17%
Human toxicity - cancer	CTU_h	2.1E-05	3.1E-06	-85%
Human toxicity – non-cancer	CTU_h	1.1E-04	4.6E-05	-57%
Ecotoxicity - freshwater	CTU_e	473	95.6	-80%
Primary energy demand	MJ	8.2E+04	5.6E+04	-32%

Sensitivity Analysis

A sensitivity analysis has been conducted and is described and discussed in this report. The conducted scenarios tackle the most relevant parameters for overall results of the assessed product system, such as

- treatment of inert material,
- used system expansion and fraction of EPS in ETICS,
- transport distances (deconstruction site to separation plant (treatment) and considered grid mixes,
- recovery rates of PS and losses of solvent (CreaSolv® Process) as well as recovery rates of Bromine (BRU process) and
- different allocation methodology (50:50 instead of system expansion).

All scenarios show significantly higher environmental impacts for the Current Status Quo Process (incineration with energy recovery) alternative. Thus none of the conducted scenarios does change the overall conclusions. By using the allocation methodology of 50:50 approach instead of system expansion the differences between Current Status Quo Process (incineration with energy recovery) and PS Loop Process are significantly higher.

Content

Glossary

Allocation	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. [3]
Allocation method	There are different kinds of allocation options. This study uses a 50:50 allocation approach in a scenario. Other methods are cut-off and end-of-life allocation approach.
Bromine Recovery Unit (BRU)	The BRU is in operationat at the ICL IP plant in Terneuzen, Netherlands since 2002. It was designed to meet future bromine recycling demands.
Expanded Polystyrene (EPS)	Expanded Polystyrene (EPS) is a rigid cellular plastic, which is found in a multitude of shapes and applications. It is used for fish boxes, packaging for electrical consumer goods and for insulation panels for building.
Dismantling	Process of removing of ETICS, which is mainly done manually. Products of dismantling are unsorted ETICS material.
EPC	The EPC Group is an international engineering and construction company. The focus of EPC Group business is the design and realization of industrial plants and infrastructural projects. EPC Group is the provider of CreaSolv® Technology. It produces a high-purity PS recyclate as a final product from PS and EPS waste. [4]
End of life	It indicates a life cycle step of a product or product system. Other life cycle steps are production and use phase. This study considers only end of life phase of the two different alternatives. This includes an incineration, recycling and/ or landfilling option.
Incinceration with energy recovery	Energy recovery refers to operations that aim to use the released energy obtained during the combustion of plastics waste. This energy can be used to produce heat and/or electricity for domestic or industrial use. This process should be applied to the plastic waste of bad quality which is not beneficial from an environmental and economic aspect.[5]
Environmental impact	The effects and changes on the environment through physical or chemical influence by human beings.[6] By applying the LCA methodology it is a quantity which reflects potential environmental effects.

[3] ISO14040, 2006 (further details of source can be found in Chapter References, valid for all footnotes)
[4] EPC, 2017
[5] Plastics Recyclers Europe, s.a.
[6] Hardmann et al., 1996

External Thermal Insulation Composite Systems (ETICS)	Component that increases the thermal efficiency of buildings. It is used for the reduction of thermal bridges and improving the greater thermal comfort due to the preservation of interior thermal inertia. [7]
EUMEPS	EUMEPS is the European association of the EPS industry. It represents converters of expandable polystyrene (EPS) to lobby and promote their interests in Europe.[8]
Functional unit	Quantified performance of a product system for use as a reference unit. [9]
ICL-IP	ICL IP manufactures flame retardant products to enhance fire safety and to protect life and property. It is the industrial chemicals segment of Israel Chemicals Limited (ICL) and is the world's largest producer of elemental bromine. [10] It is the provider of the bromine recovery unit.
GaBi ts software	Life Cycle Assessment modelling software and database. (German acronym for: Ganzheitliche Bilanzierung). It is a commercial database with public available documentation.[11]
Generic data as a synonym for secondary data	Data that are based on specific material- and energy flows in defined systems. They are prepared by the calculation of averages, so that they are useful for a Life Cycle Assessment.[12]
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impact of a product system throughout its life cycle.[13]
Life Cycle Impact Assessment (LCIA)	The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. The LCIA phase also provides information for the life cycle interpretation phase.[14]
Life Cycle Impact Assessment Category (LCIA Category)	Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned. [15]
Life Cycle Inventory (LCI)Analysis	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. [16]

[7] Barreira & de Freitas, 2016
[8] Synbra technology, s. a.
[9] ISO14040, 2006
[10] Synbra technology, s. a.
[11] GaBi ts 7.2, 1, 2016
[12] Klöpffer & Grahl, 2009
[13] ISO14040, 2006
[14] ibid.
[15] ibid.
[16] ibid.

Normalization	Calculating the magnitude of Life Cycle Impact Assessment category relative to reference information. The reference information may relate to a given community, person or other system, over a given period of time. Normalization is considered as an optional element of a Life Cycle Impact Assessment. [17]
Polystyrene (PS)	PS is a synthetic aromatic polymer made from the monomer styrene, a liquid petrochemical. PS can be rigid or foamed.
PolyStyrene Loop Process (PS Loop Process)	A sustainable, process for the recycling of polystyrene insulation foam waste and recovery of bromine.[18]
Primary data	Data that is immediate collected from a source and contain all collected data including outliers, instrument reading or data entry errors. [19]
Product system	Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product. [20]
Recycling	The process of converting waste into new materials and objects e.g. for using them as production material. [21]
Synbra Technology bv.	Is the in-house polymerization and R&D facility 'Technology & Innovation' and the center of excellence in materials and product development in the Synbra Group in Etten-Leur, The Netherlands.[22]
System expansion	The considered system will be expanded so that (unlike the allocation method) side products will be included into the system. [23]
Transport capacity	The weight or volume of the load which can be carried by means of transport under given conditions.[24]
Technology Readyness Level (TRL)	Technology readiness levels are a method of estimating technology maturity of Critical Technology Elements (CTE) of a program during the acquisition process. They are determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRL are based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology. A comprehensive approach and discussion about TRLs has been published by the European Association of Research and Technology Organizations.[25]

[17] ISO14040, 2006
[18] PolyStyreneLoop, s.a
[19] Klöpffer & Grahl, 2009
[20] ISO14040, 2006
[21] German Recycling Law §3 (23), 2017
[22] Synbra technology, s. a.
[23] Klöpffer & Grahl, 2009
[24] Free Dictionary, 2017
[25] EARTO, 2014

UN Basel Convention	The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal was adopted on 22 March 1989 by the Conference of Plenipotentiaries in Basel, Switzerland. The overarching objective is to protect human health and the environment against the adverse effects of hazardous wastes. Its scope of application covers a wide range of wastes defined as “hazardous wastes” based on their origin and/or composition and their characteristics, as well as two types of wastes defined as “other wastes” - household waste and incinerator ash.[26]
Utilization rate [%]	It describes the efficiency of used payload capacity of a vehicle. It is calculated as (actual payload capacity of vehicle)/ (potential payload capacity of vehicle) multiplied by 100%.[27]

[26] Basel Convention, 2011
[27] Dictonary.com, 2017

1. General Information

BASF SE and TÜV Rheinland LGA Products GmbH carried out a Life Cycle Assessment (LCA) for two different end of life treatment options for ETICS with expanded polystyrene (EPS) containing a flame retardant (HBCDD). The two different end of life options are:

- incineration with energy recovery of ETICS (Current Status Quo Process)) and
- PS Loop Process with recovery of EPS (CreaSolv® Process) and BRU.

Different parties were involved in the project and provided expertise to conduct this LCA study. Fachhochschule Münster (FH Münster), Fachbereich Bauingenieurwesen, Institut für Infrastruktur Wasser·Ressourcen·Umwelt, (IWARU) Arbeitsgruppe Ressourcen, Prof. Dr.-Ing. Sabine Flamme provided estimated data on the pre-treatment process of ETICS before the CreaSolv® Process. EPC and ICL-IP provided data for the CreaSolv® Process and the BRU. Together with other partners (e.g. Synbra Technology and EUMEPS) they take part in the PS Loop Cooperative. The PS Loop Cooperative is a non-profit organization under Dutch law, focusing on the operational implementation of a circular economy. The Cooperative's key project is to build and to operate a large-scale demo plant that provides a sustainable, closed-loop route for the recycling of PS insulation foam waste and for the recovery of bromine. The demo plant will be built next to the BRU of the ICL-IP site in Terneuzen, and will work with a polymer dissolution process, e.g. CreaSolv® Technology. It will start its operation in 2019.
BASF, as producer of EPS grades and supporter of the PS Loop Cooperative is interested to gain more information about the environmental performance of this initiative in comparison to other recovery options. As inventor of the eco efficiency analysis BASF was asked by the consortium to perform a LCA.

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- Dr. Bodo Müller (bodo.mueller@basf.com) of BASF SE, Corporate Sustainability Strategy

1.1. Background

Plastic producers in Europe regularly report on increasing recycling rates, but still half of the plastic consumed is collected as waste and thereof only one third is recycled. Without new plastic recycling technologies, recycling will be limited to "pure" plastic waste collection streams (e.g. PET bottles, EPS packaging) and the rest will end up as heating fuel in incinerators or will be landfilled[28]. PS foam boards have been widely used for building insulation in Europe since the 1960s. As the service life of these boards ranges from 30 to 100 years, the construction industry expects a significant increase of PS foam waste from demolition. These large quantities represent quite a challenge for the recycling industry. According to information of the PS Loop Cooperative it can be expected that more than 20 million tons in Europe will need to be disposed in the next 50 years. [29] So far, reliable data on PS waste from demolition exists only for Germany: at present, some 7.2 million tons of PS waste containing HBCDD is still present in existing buildings. It can be expected that the amount of PS waste will increase from 37 to 100 kilo tons in 2050 in Germany[30].

Another issue is the presence of HBCDD in many existing PS foam boards. HBCDD is a brominated flame-retardant which was commonly used to assure high fire safety of buildings and their inhabitants [31].Because of its persistence in the environment, HBCDD has been listed as a substance of very high concern (SVHC) under the EU REACH Regulation, and as a persistent organic pollutant (POP) under the UNEP Stockholm Convention. Today, all PS foam producers in Europe substituted HBCDD by the new polymeric flame retardant. However, because of the long life time of PS insulation foam the waste management of PS waste containing HBCDD will remain a challenge for the upcoming 50 - 100 years. Art. 7 (2) of the POP Regulation ((EC) No 850/2004) provides that waste containing persistent organic pollutants (POPs) in all European member states must be disposed of or recovered in such a way as to ensure "that the persistent organic pollutant content is destroyed or irreversibly transformed". Waste is considered "POP-containing" if the POP-concentration in the waste is equal to or above a specific limit value, which is listed in Annex IV to the POPs Regulation. The limit value set for HBCDD of 1,000 mg/kg became effective on 30 September 2016. In the management of wastes containing HBCDD, the required destruction is achieved through thermal treatment in advanced solid waste incineration, hazardous waste incineration or in cement kiln co-incineration.[32] In the future, mechanical recycling of HBCDD-containing insulation foam waste will be allowable only if its HBCDD content is below the limit value of 100 mg/kg listed in Annex I to the POPs Regulation, which has been applicable since 22 March 2016 for materials and articles newly placed on the market.

[28] CreaCycle GmbH, s.a.
[29] PolyStyreneLoop project, 2017
[30] BKV, 2017
[31] PolyStyreneLoop [1], s.a.
[32] UNEP/ CHW. 13/28, 2017:

In Germany, a new regulation for PS foam containing HBCDD entered into force on 7th August 2017 (POP-Abfall-Überwachungs-Verordnung). The regulation states that PS foam containing HBCDD is no longer classified as hazardous waste but has to be registered by an electronic waste registration system. Collectors and waste management operators of HBCDD waste have to assure that such waste is separately collected from non-POP/ HBCD- waste for recovery.

To find other alternative recovery routes for HBCDD waste, the PS value chain is currently partnering with flame retardant producers to develop an innovative solution to recycle PS foams: the PS Loop Process. The PS Loop Process demonstration plant allows industry to separate out the restricted flame retardant HBCDD from PS foams through a special dissolution technique. This technique delivers a high-quality PS recyclate from construction waste and additionally allows recovery of the bromine which can be used again for the production of new flame retardants. In fact the technology, on which PS Loop Process is based, was accepted by the UN Basel convention as a best available technology for the pretreatment of waste containing POPs.[33]

The study only considers EPS waste containing HBCDD. Therefore, no statements for Extruded Polystyrene (XPS) or PS with other flame retardants such as perfluorooctanesulfonic acid (PFOS) components can be made.

[33] PolyStyreneLoop [2], s.a.

2. Goal

2.1. Goal of the Study

A Life Cycle Assessment (LCA) was conducted to provide an assessment on the influence of different end of life options for ETICS containing EPS with flame retardant (HBCDD) on potential environmental aspects. Within this study incineration with energy recovery of ETICS (Current Status Quo Process) and the PS Loop Process are compared to each other using the LCA methodology according to the ISO 14040 and 14044 standards.

2.2. Reasons for Carrying Out this Study

In line with the objectives of this LCA study there is a need to investigate the estimated potential impact of different end of life options for EPS coming from ETICS from dismantling of houses in Europe. One option considers incineration with energy recovery of ETICS ((Current Status Quo Process) and the other option is the PS Loop Process with recovery of PS making use of the CreaSolv® Process and a bromine recovery unit (BRU).

TÜV Rheinland LGA Products GmbH was assigned by BASF to carry out a comparative LCA study for this topic. The study quantifies and compares the environmental performance of different end of life treatment options for ETICS. The other project partners provide their expertise on the new PS Loop Process. EPC and ICL-IP provide primary data for CreaSolv® Process and the BRU. Together with Synbra Technology and EUMEPS they take part in the PS Loop Cooperative. BASF, as producer of EPS raw material and supporter of the PS Loop Cooperative is interested to gain more information about the environmental performance of the PS Loop Process in comparison to other recovery options. As inventor of the eco efficiency analysis BASF was asked by the consortium to perform a LCA.

2.3. Intended Application and Audience

There is no intention to publish the study as such but to publish main results of it. It will be used to communicate the environmental performance of the PS Loop Process in comparison to Current Status Quo Process (incineration with energy recovery, for the internal PS value chain. It is also one requirement among others to receive funds from the European LIFE programme. LIFE is the EU's financial instrument supporting environmental, nature conservation and climate action projects throughout the EU. An additionally intention is to use results of the study for external communication with national authorities, regulators, NGOs and different actors of the construction industry.

3. Scope of Study

The following sections describe the scope of the study, which has been defined to achieve the stated goals.

3.1. Functional Unit

The functional unit provides a basis for comparing all life cycle components on a common basis: namely, the amount of that component required to fulfill the described function. It also allows direct comparisons among the product systems in question.

The functional unit for this study is:

End of life treatment of 1 t of EPS coming from ETICS from dismantling of houses in Europe

Alternative 1 (Current Status Quo Process (incineration with energy recovery) and alternative 2 (PS Loop Process) consider in relation to the defined functional unit the treatment of 10.00 t ETICS incl. 1.00 t EPS. Other parts of ETICS are 3.22 t plaster, 3.16 t adhesives, 2.42 t finishing coat, 0.15 t fabrics and 0.05 t dowels (plastic (polyethylene (PE)) and metallic parts).

Thus EPS accounts for 10.00 wt% of the total mass of ETICS.

3.2. System Boundaries

This study considers only the end of life treatment of the different compounds of ETICS. Thus production and use phase are not taken into account. Conclusions from this study can only be drawn for the assessed environmental impacts. Therefore, no conclusion on economic aspects can be drawn.

The system boundaries cover the end of life phase of all different materials of ETICS. Due to that following principle life cycle stages are included:

- Deconstruction of ETICS,
- Pre-treatment
- Various transportation steps and
- End of life treatment with different disposal options: incineration with energy recovery, recycling (incl. CreaSolv® Process[34] and the BRU) and landfilling.

[34] A detailed block flow diagram can be found in annex V.

The assumed composition of ETICS is (relation between different components[35], fractions of EPS[36]):

- 10.0 wt% EPS,
- 32.2 wt% plaster,
- 31.6 wt% adhesives (80% mineral, 18% dispersal, 2% mechanical),
- 24.2 wt% finishing coat,
- 1.5 wt% fabrics.
- 0.5 wt% dowel (87.5% metal, 12.5% plastic)

10 wt% EPS were assumed according to information of IWARU of FH Münster, but higher respectively lower fractions are also possible.[37]

The following graphs describe an overview of the product systems for alternative 1. The different colors are identical to the colors used in chapter 5.

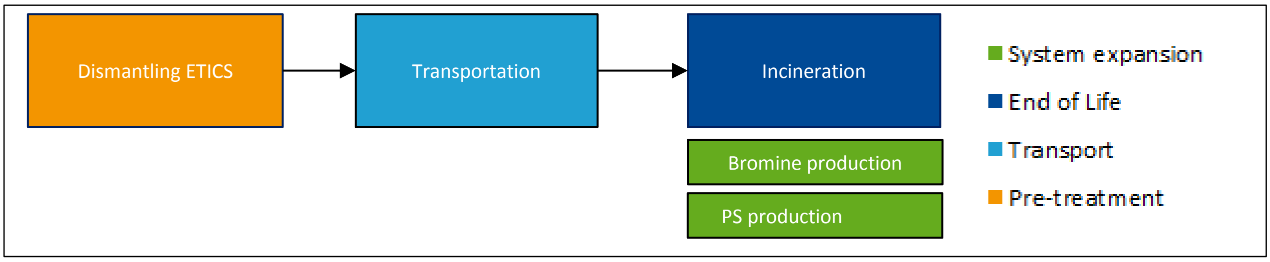

Figure 1: Overview of Current Status Quo (incineration with energy recovery)

The Current Status Quo Process (incineration with energy recovery) alternative evaluates the environmental impacts for dismantling ETICS, transportation of ETICS components to incineration plant and incineration of the components. After the incineration process of inert material and EPS the 0.4 wt% metal parts (dowels) are recycled or landfilled. In addition, production of virgin bromine and PS granulate is considered to fulfill the requirements for system expansion (see chapter 3.4). The dismantling is reflected by a demolition process with concrete breakers. No separation of compounds and compaction takes place before incineration. The incineration process is divided into incineration of the material mix (89.6 wt%), which is mainly inert material and incineration of plastic material (10.0 wt% EPS as well as PE plastic parts of dowels (0.1 wt%)). The utilization rate of the trucks for transportation is determined by the density of EPS. Therefore only 33% of the available load capacity can be used (see chapter 4.4).

[35] Albrecht et al., page 36, 2014
[36] IWARU of FH Münster, 2017
[37] Albrecht et al., page 34, 2014

Figure 2 shows the system boundaries of alternative 2 (PS Loop demo plant). The different colors are identical to the colors used in chapter 5.

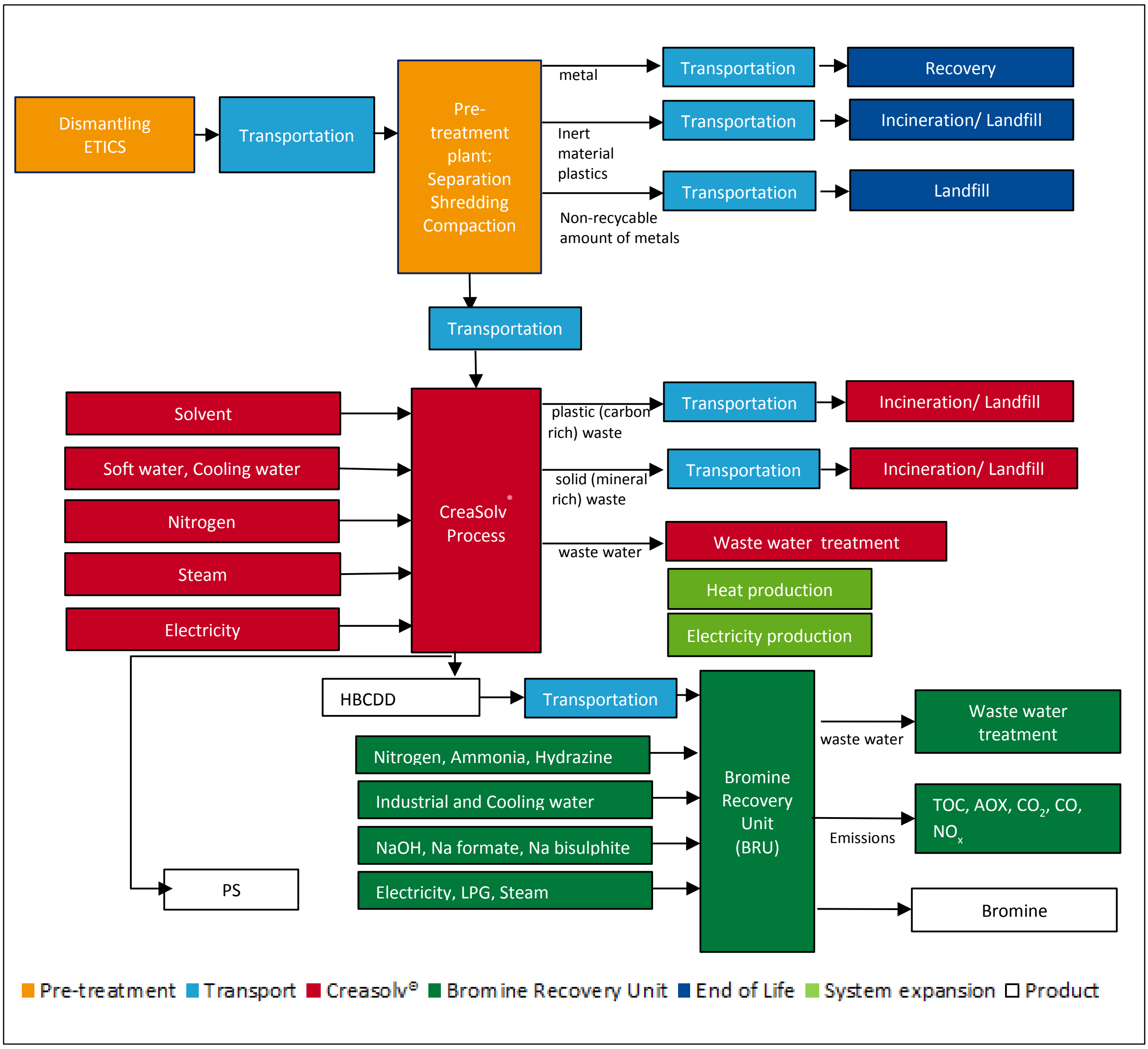

Figure 2: Overview of PS Loop Process

The PS Loop Process alternative shows also a dismantling of ETICS. After transportation (utilization rate 33%) of demolished ETICS components a separation takes place. In preparation of CreaSolv® Process shredding and compaction of EPS is necessary. Due to information of IWARU Technical Center of FH Münster demolished ETICS components are crushed and sieved and metals as well as inert material are separated (caused by different physical properties of materials). Finally, a compaction of EPS takes place. Subsequently an EPS with around 10wt% impurities results as an input for CreaSolv® Process.

For the three separated streams different end of life treatment options are assumed. 89.5 wt% of total mass is incinerated as inert material mix and 0.1 wt% PE (dowels) can be burned separately. In addition, a recycling (90%) or landfilling (10%) process of metal compounds from dowels (0.4 wt%) take place. Landfilling is assumed only for the amount of metal, which cannot be recycled. The utilization rate of trucks transporting inert material to further treatment is 85%, because no EPS is transported at this point. Before compaction step the utilization rate for transported EPS is 33%, due to low density. After compaction, a utilization rate of 85% is assumed (see chapter 4.4).

After the compaction and shredding process the material is fed to the CreaSolv® Process and the BRU. The CreaSolv® Process is a selective extraction recycling process. First step is the dissolution of EPS using a selective solvent (other components in the waste fraction remain undissolved). After dissolution a separation of contaminants from the recovered polymer solution takes places. Finally a precipitation of PS from the purified polymer solution follows. One component of polymer solution is the flame retardant HBCDD.[38] The HBCDD is then transported to the BRU plant (Terneuzen, Netherlands) where bromine is recovered.

For this alternative, a production of heat and electricity is considered due to system expansion (see chapter 3.4).

A detailed process material balance for PS Loop Process alternative is provided in Annex IV – Process material balance for PS Loop alternative (Base Case)

3.3. Temporal, Geographical, and Technological Scope

The geographical scope is the dismantling of houses in Europe. The study refers to lab-scale data for the CreaSolv® Process and to data of the pilot plant in Terneuzen, Netherlands for the BRU process (see chapter 3.6). All primary data were collected in 2016 and secondary data are close to this year (2014 - 2016).[39] Technological state-of-the-art is Europe for the dismantling and end of life treatment. Europe is chosen as the respective area, because the CreaSolv® Plant will be initially built in Terneuzen, Netherlands. If the demo plant in Terneuzen runs successfully, the intention is to have several decentralized CreaSolv® Plants located over Europe, starting with Germany. These developments have been taken into consideration for the calculation of the LCA (see chapter 3.6.). The BRU plant will always be located in Terneuzen. There is no further expansion expected. The study only focuses on end of life treatment, therefore production and use of ETICS were not considered. All incineration processes result in energy recovery of electricity and steam. This assumption is mainly valid for Germany (due to the reason that most of the EPS originates from Germany (see chapter 1.1)) and will be analyzed in detail in a scenario (see chapter 7.2).

[38] Fraunhofer IVV, 2017
[39] Definitions of primary and secondary data can be found in chapter Glossary.

The data provided for the pre-treatment phase are based on first trials in the IWARU Technical Center of FH Münster by given information of plant operators. For a validated calculation, further trials would be needed. Input specifications are referring to conventional dismantled ETICS. The same is valid for the data provided for CreaSolv® demonstration plant. Data given by EPC are based on laboratory trials. The CreaSolv® demonstration plant aims to begin operations in 2019 and will have the capacity to treat up to 3,300 tons of PS waste per year.

Still it remains unclear what kind of waste streams and specifications would be realistic for a large-scale application. This will have to be tested during the operation phase of the pilot plant. Due to these limitations and due to the fact that the PS Loop demo plant will be fully operational in 2019 the Technology Readyness Level (TRL) vary between TRL 3 (experimental proof of concept) and TRL 4, which mean technology is validated in lab.[40]

3.4. Allocation

An allocation of the environmental impacts on the different products or life cycles is necessary when a process produces more than one product or by-products (multifunctional systems). An allocation is also necessary if the product is reused (recycling of products), or substances and energies were used in other product systems.

With regard to ISO 14044 and ISO 14040 following allocation procedures shall be applied:

Step 1: Wherever possible, allocation should be avoided by

- dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
- expanding the product system to include the additional functions related to the coproducts.

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

[40] Assumption for TRL is done by process manager of styrene and polystyrene plant of BASF on 23.08.2017 (see annex VI). For further information of TRL concept see glossary.

This study follows the allocation procedures of the ISO standards and uses a system expansion. As a result of this no credits e.g. for electricity from waste incineration were considered in the calculation. Both systems were modelled with the same overall performance to fulfill the functional unit (production of additional electricity, heat, PS and bromine).

For the Current Status Quo Process (incineration with energy recovery the production of virgin bromine and PS has to be taken into account additionally. These are the products from CreaSolv® Process and the BRU. It is assumed that the PS recyclate and bromine – derived from the CreaSolv® Process and BRU – provides the same properties as virgin PS and bromine provides. On the one hand, the PS Loop Process is modelled with further production of heat and electricity. These energy products occur from the incineration of the different ETICS components during Current Status Quo Process (incineration with energy recovery). All incineration processes result in energy recovery of electricity and steam (Assumption: TÜV Rheinland). Also, scenarios with a lower recovery rate of electricity and steam, as well as for PS and bromine are considered (see chapter 7.2).

In order to show the robustness of the system expansion approach a scenario (see chapter 7.2) considers a 50:50 allocation approach. The 50:50 approach is often used in chemical sector and reflects the Product Environmental Footprint (PEF) guide recommendation of the European Commission[41]. PEF recommends allocating the impacts and benefits due to recycling equally between the producer using recycled material and the producer producing a recycled product (50/50 allocation split). This approach credits the user of recycled material, but does not give full credit because of the assumption that there is only a limited supply of recycled material to be used. The resulting waste is partitioned equally to both product systems. Furthermore, the raw material savings are also credited to both product systems. In order to execute this allocation rule, both product systems have to be identified, though. Since both product systems are rewarded to some extent, this rule seems to be fair. For the Current Status Quo Process (incineration with energy recovery) 50% credits for avoided electricity and steam production as well as 50% burden of incineration process are taken into account. These energy products occur from the incineration of the respective inert material and EPS. PS Loop Process alternative is modelled with 50% burden for recycling efforts and 50% credits for avoided production efforts of PS granulate and bromine. These are the products from CreaSolv® Process and the BRU.

Furthermore, no allocation was needed in the documented input data (foreground data). However, some of the used LCI inventory data (background data) are allocated inventories using common allocation approaches such as physical allocation or economic allocation. These assumptions concerning allocation are documented in the corresponding databases.[42]

[41] PEFCR, 2015, page 88
[42] GaBi ts 7.2, 1, 2017

3.5. Cut-off Criteria

All inputs and outputs have been included in cases where the necessary information are readily available or a reasonable estimate can be made. In cases where information is not available, inputs and outputs may have been omitted only if their environmental impacts (see Glossary) are anticipated to fall well below 1% contribution of the total system impacts. It is likely that cut-offs have been applied for inventories taken from generic databases, this is described in the respective documentation.

3.6. Assumptions

The following assumptions (valid for base case), if not already described in the respective sections of this report, apply for this study:

- Production of ETICS and usage of ETICS are excluded because the impacts of the process step are beyond the scope of the present study. Scope of the study is to provide an assessment of the influence of potential impacts of different end of life options for ETICS containing EPS with flame retardant (HBCDD). The production of ETICS and the use phase are not relevant for decision making within the PS Loop Cooperative.
- The study only considers EPS waste containing HBCDD. Therefore, no statements for XPS and other flame retardants like Polymeric Flame Retardants (Polymer FR) can be made. ETICS contains a maximum water content of 3 wt% (worst case assumption IWARU Technical Center of FH Münster). Therefore, no drying process is needed before CreaSolv® Process.[43]

Current Status Quo Process incineration with energy recovery- base case:

- For the demolition of houses an energy demand of 0.2 MJ/kg ETICS is assumed (assumption TÜV Rheinland based on Graubner & Hulin[44]).
- The transportation utilization rate for the transport step from demolition to incineration plant is 33%, caused by the relative low density of EPS.
- All incineration processes result in recovery of electricity and steam for the given regional scope. This assumption is mainly valid for Germany (due to the reason that many EPS originates from Germany (see chapter 1.1).
- A distance of 100 km (assumption TÜV Rheinland) from deconstruction to incineration plant is defined.

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[43] Water content for fascade application is probably higher, but this usage is not considered in the study
[44] Graubner & Hulin, 2013, S.55

PS Loop Process- base case:

- For the demolition of houses an energy demand of 0.2 MJ/kg ETICS is assumed (assumption TÜV Rheinland based on Graubner & Hulin[45]).
- Energy demand for separation, shredding and compaction of EPS is 0.13 MJ/kg EPS (information from IWARU Technical Center of FH Münster[46]).
- The transportation utilization rate for the transport step from demolition to pre-treatment plant is 33%, caused by the relative low density of EPS. All other materials are calculated with an utilization rate of 85% (assumption TÜV Rheinland). A distance of 100 km from dismantling to pre-treatment and to further treatment, as well as for production wastes of the CreaSolv® Process is considered.
- The initial CreaSolv® Plant will be built in Terneuzen, Netherlands. If the demo plant in Terneuzen runs successfull, the intention is to have several decentralized CreaSolv® plants located over Europe, starting with Germany. To reflect this development a distance of 500 km to CreaSolv® Plant (assumption one plant Germany) and 500 km to the BRU in Terneuzen (transport from Germany to the Netherlands) are assumed.

For a better understanding all transportation steps for the base case are displayed in Figure 3.

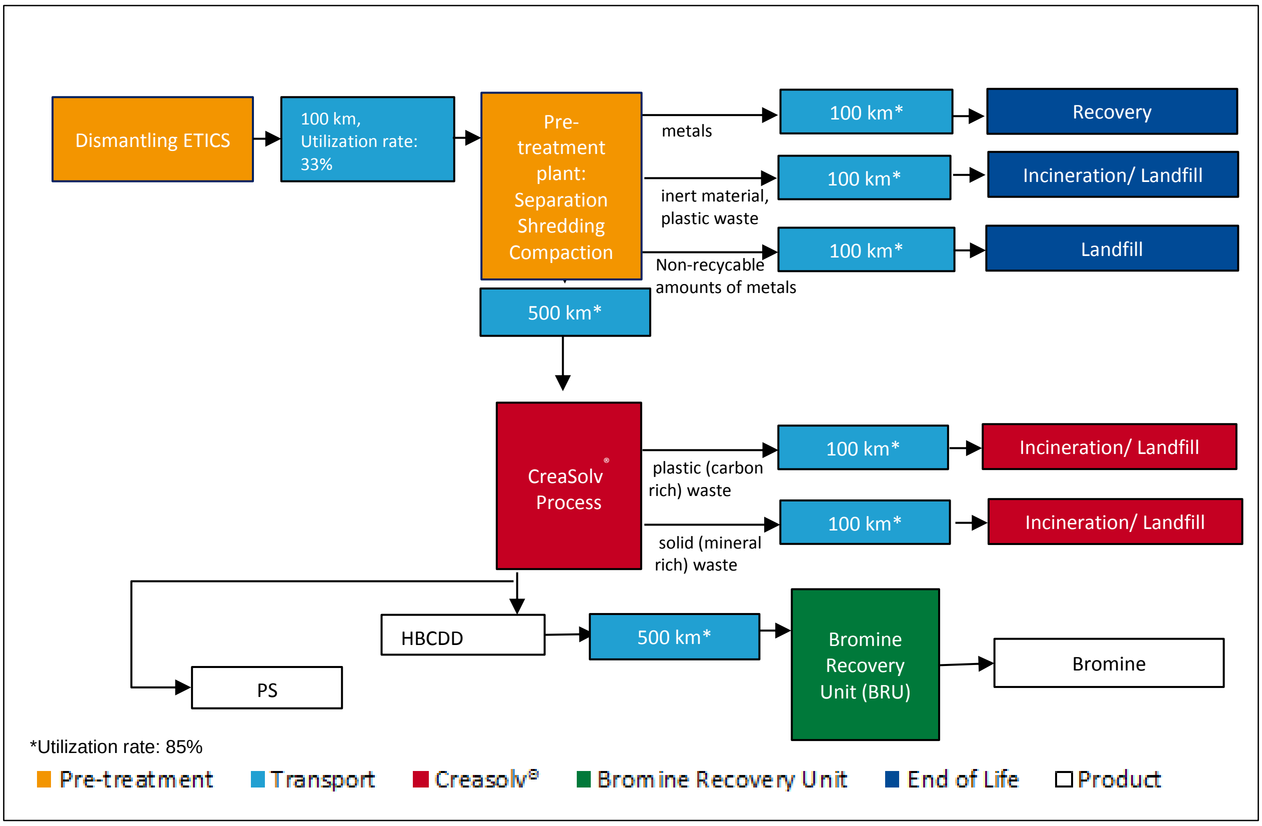

Figure 3: Transportation steps PS Loop Process

[45] Graubner & Hulin, 2013, S.55
[46] IWARU of FH Münster, 2017

- All in- and outputs for CreaSolv® Process are laboratory based data (trials with input material of 30 kg compacted EPS briquettes with 1.5wt% HBCDD). The considered CreaSolv® Process is assumed to need no anti-solvent as an input for separation of PS and HBCDD out of compacted EPS material.[47] The predicted plant size can range from 2 to 4,000 t compacted EPS input material per year[48]. For the base case the recycling rate of EPS to PS is assumed to be is approximately 99.9 wt%.[49]
- Data for the BRU originate from running ICL pilot plant in Terneuzen based on an output of 400 kg bromine recovery per hour.[50] For the base case, the recovery rate for HBCDD to elemental bromine is defined with 99.9 wt%.[51]
- The quality of recycled PS (CreaSolv® Process) is comparable and for bromine (BRU) equal to virgin material. Due to simplification of calculation an equal quality of virgin material and recyclate is assumed for PS.
- Composition and used amount of solvent for CreaSolv® Process reflects a worst case assumption (information from EPC).

For a clearer differentiation between Current Status Quo (incineration with energy recovery) and PS Loop Process, two different Material Mixes (A& B) were defined. The difference between Material Mix A and B is the consideration of the 10.00 wt% EPS which is either incinerated or recycled. Therefore, Material Mix A considers inert material and EPS. In comparison Material Mix B takes only inert material into an account.

The following assumptions concerning end of life treatment are considered in the study (see Table 2).

[47] EPC LCA Support, 2017, EPC E-Mail communication 08. September 2017
[48] CreaCycle GmbH 2, s. a
[49] EPC LCA Support, 2017. Sensitivity analyses for this assumption can be found under Chapter 7.2.
[50] Information is given on data collection sheet by Mr. Lein Tange. Sensitivity analyses for this assumption can be found under Chapter 7.2.
[51] ICL-IP Terneuzen, 2016

Table 2: End of life treatments

Alternative	Material	Treatment	Source
Current Status Quo Process (incineration with energy recovery	Material mix A	89.5 wt% incineration of inert matter (plaster, adhesive, finishing coat, fabrics) 10.1 wt% incineration of plastic (10.0 wt% EPS and 0.1 wt% PE dowels (plastic parts)) and 0.4 wt% dowels (metallic parts): 90% wt recycling/ 10 wt% landfill	IWARU Technical Center of FH Münster
PS Loop Process	Material mix B	89.5 wt% incineration of inert matter (plaster, adhesive, finishing coat, fabrics) 0.1 wt% incineration of PE dowels (plastic parts)), 0.4 wt% dowels (metallic parts): 90% wt recycling/ 10 wt% landfill	IWARU Technical Center of FH Münster
	EPS (10 wt%)	Recycling (CreaSolv® Process)	-

For the Current Status Quo Process (incineration with energy recovery) two different incineration processes are considered (incineration of plastic and incineration of inert material). The 89.5 wt% of inert material consists of 32.2 wt% plaster, 31.6 wt% adhesive.[52] 24.2 wt% finishing coat, 1.5 wt% fabrics and 10.1 w% plastics of 10 wt% EPS and 0.1% dowels (PE plastic parts). Also 0.36 wt% dowels (metallic parts) were recycled and 0.04 wt% going to landfill (environmental impacts added to material mix A). The PS Loop Process considers an amount of 89.5 wt% incineration of inert material, incineration of 0.1wt% PE (dowels),as well as recycling and landfilling of 0.4 wt% dowels (metallic components). The 89.5 wt% incineration mix consists of 32.2 wt% plaster, 31.6 wt% adhesive, 24.2 wt% finishing coat and 1.5 wt% fabrics.

The location of all end of life processes is Europe, due to defined geographical area of LCA study (see chapter 3.1).

3.7. Limitations

The present study considers only different end of life options of ETICS. Conclusions from this study can only be drawn for the assessed environmental impacts. Therefore, no conclusion on economic aspects can be drawn. Data for the CreaSolv® Process originate from laboratory trials and for the BRU from a pilot plant (established in 2002) in the Netherlands (Terneuzen). Thus use of more realistic process data can lead to different results. Furthermore, the used solvent for the CreaSolv® Process is confidential. To consider it properly, worst-case assumptions regarding its environmental impact were made. Another solvent can lead to different influences in the considered impact categories. The environmental impacts for used solvent (production and emissions) varies from 0.3% (resource depletion- elements) to 7.7% (human toxicity- non-cancer effects) of overall results for PS Loop Process alternative within considered impact categories.

[52] 31.6 wt% adhesives consist of 80 wt% mineral, 18 wt% dispersal and 2 wt% mechanical components. Related to simplification all adhesive amount is assumed as inert material, due to high amount of mineral component.

Environmental impacts of resulting solvent emissions slightly influence (impact < 1%) only the impact categories “freshwater eco toxicity” and “human toxicity (cancer and non-cancer)”. All impacts of the solvent production and emissions were evaluated in chapter 5. For the future it is suggest that an environmental profile should be calculated for the solvent and thereafter verified by a third party. This profile should then be used in future studies.

For the incineration processes of inert materials as well as for plastic material (PS and PE) generic datasets (see Glossary) from GaBi ts 7.2 software of thinkstep AG are used. The used bromine dataset (based on BASF SE assumption) considers Israel as place of production. This country reflects the main production areaand ICL-IP produces bromine in its premises in Israel. Therefore, the use of this dataset is appropriate for the study. The use of primary data (see Glossary) can lead to different overall results.

Furthermore, all limitations, like consideration of ETICS with 10 wt% EPS containing 0.4 wt% HBCCD flame retardants, defined water content of maximum 3 wt% of ETICS and incineration with energy recovery (see chapter 3.6) should be taken into account by interpretation of the results.

3.8. Life Cycle Impact Assessment (LCIA) Methods

The environmental effects of the studied product systems will be discussed in chapter 5 with the following impact categories (see Table 3). The impact categories for the present study are explained in more detail in Annex I. The following table shows all evaluated impact categories, related units, LCIA methods, indicators and sources of used impact categories.

Table 3: Life Cycle Impact Assessment methods (for further explanations see Annex I)

Impact Category	Unit	LCIA method	Indicator	Source
Climate change	kg CO_2-eq	EU PEF V1.09	Radiative forcing as Global Warming Potential (GWP100)	Baseline model of 100years of the IPCC, 2007
Acidification	mol H^+-eq	EU PEF V1.09	Accumulated Exceedance (AE)	Seppälä et al., 2006, Posch et al., 2008
Summer smog	kg NMVOC-eq	EU PEF V1.09	Tropospheric ozone concentration increase	LOTOS-EUROS (van Zelm et al., 2008) as applied in ReCiPe
Eutrophication - marine	kg N-eq	EU PEF V1.09	EUTREND model	Struijs et al., 2009
Eutrophication - freshwater	kg P-eq	EU PEF V1.09	EUTREND model	Struijs et al., 2009
Resource depletion - fossil	MJ	CML 2001	Scarcity	CML 2002 (Guinée et al., 2002)
Resource depletion - elements	kg Sb-eq	CML 2001	Scarcity	CML 2002 (Guinée et al., 2002)
Human toxicity - cancer	CTU_h	EU PEF V1.09	USEtox model	Rosenbaum et al., 2008
Human toxicity – non-cancer	CTU_h	EU PEF V1.09	USEtox model	Rosenbaum et al., 2008
Ecotoxicity - freshwater	CTU_e	EU PEF V1.09	USEtox model	Rosenbaum et al., 2008

Water scarcity is not considered as an environmental impact in this study, because the data for background-process is not of a quality that allows a sound assessment. Also the topic of water scarcity is not a major issue of the region under investigation.

3.9. Critical Review

The panel review is performed to ensure a good overall quality of the assessment and its conclusions. The review statement, comments of the practitioner and any response to recommendations made by the reviewer are included in the appendices to the present report.

The following panel reviewed the study:

- Dr. Michael Spielmann, Quantis, chairmen of review panel
- Prof. Dr.-Ing. Matthias Kind, Technical Consulting, Karlsruhe, critical reviewer
- Ulrich Schlotter, BKV, expert platform end-of-life and plastics, critical reviewer

4. Life Cycle Inventory Analysis

4.1. Modelling and Database

Data for CreaSolv® Process originate from lab-scale trials and for the BRU from a pilot plant in the Netherlands provided by EPC and ICL-IP. The trials consider an input material of 30 kg compacted EPS briquettes with 1.5 wt% HBCDD. Data for the BRU originate from a pilot plant in Terneuzen (production run with an output of 400 kg bromine recovery per hour).

IWARU Technical Center of FH Münster provided estimated data on the pre-treatment process (basis: 30,000 t ETICS per year) of ETICS producing shredded and compacted EPS-rich feed for further processing by the CreaSolv® Process. All data reflect the production in the year 2016.

The inventories for all other processes are expert judgments or are based on literature sources (see Chapter 4.3). The modelling was carried out using the GaBi ts 7.2 software (see Glossary) of thinkstep AG[53].

4.2. Background Data

The used LCIs in this study are mainly based on thinkstep AG GaBi database[54]. Furthermore, some datasets of BASF, ELCD and PlasticsEurope are used. A list of the respective LCIs in this study is displayed in Table 4:

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[53] GaBi ts 7.2, 2, 2017
[54] GaBi ts 7.2, 3, 2017

Table 4: Background Data

Input	used dataset	Source	Year	Geography
Electricity	Electricity grid mix AC, technology mix	thinkstep	2013	Europe
Waste incineration EPS	PS in waste incineration plant	thinkstep	2015	Europe
Waste incineration PE/PP (dowel)	PE in waste incineration plant	thinkstep	2015	Europe
Landfill plastics (EPS; PE/PP)	Plastic waste on landfill	thinkstep	2015	Europe
Recycling of metals	Value of scrap	thinkstep	2007	Global
Landfill of metals	Landfill for inert matter	thinkstep	2013	Europe
Waste incineration of adhesive, plaster, fabrics, finishing coat	Waste incineration of glass/inert material	ELCD	2006	Europe
Landfilling of mixture	Landfill for inert matter	thinkstep	2013	Europe
Solvent	Solvent for CreaSolv® Process	EPC	2017	Global
Nitrogen	Nitrogen via cryogenic air separation	thinkstep	2013	Europe
Soft water	Water (desalinated, deionised)	thinkstep	2013	Europe
Cooling water/ industrial water	Tap water, water purification treatment	thinkstep	2013	Europe
Waste water treatment	Municipal waste water treatment (mix)	thinkstep	2013	Europa
Ammonia 25%	Ammonia solution 25%	BASF	2003	Germany
Hydrazine 55%	Hydrazine	BASF	2004	Germany
NaOH 25%	Sodium hydroxide 25%	BASF	2010	Germany
Na formate 25%	Sodium formate 25%	BASF	2016	Global
Na bisulphite 25%	Sodium hydrogensulphite (7810)	BASF	2016	Global
Steam	Process steam from natural gas 95%	thinkstep	2013	Europe
Transport	Truck transport 17.3 t payload	thinkstep	2015	Global
Bromine [55]	Bromine	BASF/ ICL	2013	Israel
Polystyrene	Polystyrene expandable granulate (EPS)	Plastic Europe	2015	Europe

The used datasets in this study are mainly derived from a commercial database (GaBi ts 7.2) with public available documentation. Completeness with respect to completeness of inventory data and used data for the LCIA are checked by practitioner of the study.

All energy demand is modelled with the same European electricity grid mix related to regional and technological scope of the study (see chapter 3.3). Thus there are no differences in the results due to different electricity mixes applied in the foreground system. The used dataset considers 27.1% nuclear,16.1% hard coal, 15.7% natural gas, 12.4% hydro, 10.2% lignite, 7.3% wind, 2.5% photovoltaic, 1.7% biogas and 7% others (source: International Energy Agency, GaBi ts Software).[56]Dataset of waste incineration of inert material is used due to the high amounts (> 80 wt%) of inert material of Material Mix A and B[57] (31.6 wt% adhesives (80 wt% mineral), 32.2 wt%

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[55] The used bromine dataset considers Israel as place of production. Due to the reasons that this country reflects the main production area and ICL-IP source bromine from there the use of this dataset is appropriate for the study.

[56] Electricity grid mix, 2016

[57] For further Information see Table 2. For a clearer differentiation between Current Status Quo (incineration with energy recovery) and PS Loop Process, two different Material Mixes (A& B) were defined. The difference between Material Mix A and B is the consideration of the 10.00 wt% EPS which is either incinerated or recycled. Therefore, Material Mix A considers inert material and EPS. In comparison Material Mix B takes only inert material into an account.

plaster, 24.2 wt% finishing coat, and 1.5 wt% fabrics). The dataset represents an average European waste-to-energy plant (WtE) with typical technology used in Europe. The data set covers all relevant process steps/ technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. Environmental impacts for waste collection, transport or any pre-treatment of the waste are not included in the dataset. The average efficiency of the steam production is about 81.9%. Produced steam is used internally as process-steam and the balance is used to generate electricity or exported as heat to industry or households. An energy balance for the plant was made using data from the "CEWEP Energy Report" (2006) representing 97 waste-to energy plants in Europe. All utilities used in the waste incineration plant, the operation of the underground deposit and the landfill for bottom ash and air pollution control (APC) residues as well as the meltdown processes for the recovered metals are included in the system. [58] According to low heating value the dataset is modelled as energy sink.

Used dataset Process steam from natural gas 95% reflects a process steam efficiency of 95%. It is chosen related to usually high efficiency rates in industry. [59]

The dataset for consideration of PS granulate production: Polystyrene expandable granulate (EPS) is provided by PlasticsEurope. It covers 80% of the European EPS production (EU-27) in 2013 from cradle to gate. Primary data are used for all foreground processes (under operational control) complemented with secondary data (2010- 2012) for background processes (under indirect management control). The maximum temporal validity is until end of 2023. The datasets has been reviewed by an independent reviewer. As a result, this dataset is assessed to be a reliable and high quality representation of EPS produced in Europe. The dataset is intended to be used as cradle to gate building block of LCA studies of defined applications or products. LCA studies considering the full life cycle (cradle to grave) of an application or product allow for comparative assertions to be derived. It is essential to note that comparisons cannot be made at the level of the polymer or its precursors. In order to compare the performance of different materials, the whole life cycle and the effects of relevant life cycle parameters must be considered. [60]

[58] Waste incineration of glass/inert material, 2013
[59] Process steam from natural gas 95%, 2017
[60] PlasticsEurope, 2015

4.3. Process Data

The input data for Current Status Quo Process (incineration with energy recovery) is displayed in Table 5

Table 5: Input data Current Status Quo Process (incineration with energy recovery)

Input	Amount	Unit	Source
Electricity (demolition)	0.20	MJ/kg ETICS	Assumption
Disposal of Material Mix A (incineration plant)	10	t	Albrecht et al., 2014
Transport dismantling to incineration plant	100	km	Assumption

All assumptions for the Current Status Quo (incineration with energy recovery) can be found in chapter 3.6. The different parts of ETICS as well as a description of the different process steps are described in chapter 3.2. For demolition of 1 kg ETICS 0.2 MJ energy is required, due to use of tools e.g. hammer drill. Main effort of demolition is done by manual work which results in no environmental impacts. The transport distance from deconstruction to incineration plant is defined as 100 km.

Material Mix A (see Table 2) consists of 89.5 wt% inert material with 32.2 wt% plaster, 31.6 wt% adhesive, 24.2 wt% finishing coat, 1.5 wt% fabrics as well as 10.1 wt% plastics with 10 wt% EPS and 0.1 wt% dowels (PE plastic parts). Furthermore, 0.36 wt% dowels (metallic parts) were recycled and 0.04 wt% are going to landfill (environmental impacts added to Material Mix A).

All inputs for the PS Loop Process alternative are shown in Table 6.

Table 6: Input data for the PS Loop Process

	Input	Amount	Unit	Source
Pre-treatment	Electricity (selective deconstruction)	0.20	MJ/kg ETICS	Assumption
	Transport dismantling to separation	100	km	Assumption
	Electricity (separation)	0.04	MJ/kg ETICS	IWARU Technical Center of FH Münster
	Transport separation to further treatment (recovery, incineration, landfill)	100	km	Assumption
	Recovery/landfill steel (dowels)	0.9/ 0.1	kg/kg steel	Assumption
	Incineration/ landfill PE (dowels)	0.5/ 0.5	kg/ kg plastic	Assumption
	Disposal of material mix B (incineration plant)	8.94	t/ t EPS	
	Electricity (shredding, compaction)	0.09	MJ/t EPS	IWARU Technical Center of FH Münster
	Incineration of losses (plastics)	0.05	t/ t EPS	Assumption
	Transport to CreaSolv® Plant (Assumption location of plant: Germany)	500	km	Assumption
CreaSolv® Process	Solvent	0.01	t/t EPS	EPC, 2016
	Nitrogen	1.60	kg/t EPS	EPC, 2016
	Soft water	0.02	t/t EPS	EPC, 2016
	Cooling water	174	t/t EPS	EPC, 2016
	Electricity (average European grid mix)	816	kWh/t EPS	EPC, 2016
	Steam	1.47	t/t EPS	EPC, 2016
	Wastewater	0.06	m^3/t EPS	EPC, 2016
	Solid waste	0.08	t/t EPS	EPC, 2016
	HBCDD slurry	0.02	t/t EPS	EPC, 2016
	PS	0.99	t/t EPS	EPC, 2016
	Transport CreaSolv® Plant to incineration	100	km	Assumption
	Transport to BRU plant ((1 pilot plant in the Netherlands)	500	km	Assumption
Bromine Recovery Unit	HBCDD slurry	1,510	kg/t Bromine	ICL-IP, 2016
	Nitrogen	100	kg/t Bromine	ICL-IP, 2016
	Ammonia 25% bulk	12.0	kg/t Bromine	ICL-IP, 2016
	Hydrazine 55%	102	kg/t Bromine	ICL-IP, 2016
	Industrial water	680	kg/t Bromine	ICL-IP, 20 16
	NaOH 25%	765	kg/t Bromine	ICL-IP, 2016
	Na formate 25%	100	kg/t Bromine	ICL-IP, 2016
	Na bisulphite 25%	140	kg/t Bromine	ICL-IP, 2016
	Electricity	500	kWh/t Bromine	ICL-IP, 2016
	LPG	174	m^3/t Bromine	ICL-IP, 2016
	Steam	0.54	t/t Bromine	ICL-IP, 2016
	Cooling water	9.00	m^3/t Bromine	ICL-IP, 2016
	CO_2	1,250	kg/t Bromine	ICL-IP, 2016
	CO	21.1	mg/ t Bromine	ICL-IP, 2016
	NO_x	50.0	µg/t Bromine	ICL-IP, 2016
	Waste water	3.00	m^3/t Bromine	ICL-IP, 2016
	Total Organic Carbon (TOC)	10.0	mg/l waste water	ICL-IP, 2016
	Adsorbable Organic Halides (AOX)	10.0	µg/l waste water	ICL-IP, 2016

Material Mix B (see Table 2) considers incineration with 32.2 wt% plaster, 31.6 wt% adhesive, 24.2 wt% finishing coat and 1.5 wt% fabrics. Also incineration of 0.1wt% PE (dowels), as well as recycling and landfilling of 0.4 wt% dowels (metallic components) are considered.

All assumptions for the PS Loop Process can be found in chapter 3.6. The different parts of ETICS as well as a description of the different process steps were given in chapter 3.2. Data for the CreaSolv® Process originate from lab-scale trials provided by EPC and data on the BRU from an operating plant in the Netherlands provided by ICL-IP. For the CreaSolv® Process also the emissions of used solvent were considered. The effected impact categories are: summer smog, human toxcitiy non-cancer and freshwater ecotoxicity. The BRU data as well as data for related emissions are real measured values of pilot plant in Terneuzen, the Netherlands[61]. All information for the different transport steps can be found in chapter 4.4.

A detailed process material balance for the PS Loop Process alternative is provided in Annex IV – Process material balance for PS Loop alternative (Base Case).

[61] Measurement and reporting of the emission data partly based on Directive 2000/76/EC (Waste Incineration Directive).

4.4. Transport

Following assumptions (not based on existing routes) were made for transportation steps (see Table 7). Different components of Material Mix A and B can be found in Table 2.

Table 7: Transportation steps

Material	(A → B)	Distance [km]	Utilization Rate [%]
Current Status Quo Process(incineration with energy recovery)			
Material Mix A	deconstruction site to incineration plant	100	33
PS Loop Process			
Material Mix B	deconstruction site to pre-treatment	100	33
Material Mix B	Pre-treatment to recovery/ incineration/ landfill	100	85
EPS	Pre-treatment plant to CreaSolv® Plant	500	85
PS (waste during CreaSolv® Process)	CreaSolv® plant to incineration/ landfill	100	85
HBCDD slurry	CreaSolv® plant to BRU	500	85

The distances for different alternatives are mainly based on assumptions by experts. It is assumed that the BRU plant is located at Terneuzen, Netherlands and CreaSolv® plant in Germany. Due to the fact there could be more than one CreaSolv® plant an average distance from pre-treatment to CreaSolv® plant and from CreaSolv® plant to the BRU plant of 500 km is assumed. A distance of 100 km is defined for all others cases.

Utilization rate differs between 33% and 85%, caused by the relative low density of PS. The following formula was used for calculation of utilization rate[62]:

$$Load\ factor = \frac{\text{utilization [t]}/}{\text{payload capacity of vehicle [t]}}$$

$$\text{Utilization (volume capacity)[t]} = \text{good density } [\text{t}/m^3] \times \text{ volume capacity } [m^3]$$

$$\text{Utilization rate [\%]} = \text{load factor} \times\ 100\%$$

All assumptions concerning transportation steps can also be found in chapter 3.6.

[62] Fraunhofer IBP& Universität Stuttgart (LBP), 2012, S.9

4.5. Primary Energy Demand

The primary energy demand (PED, see Annex I) is a key indicator in LCA and a useful screening indicator for the environmental performance of products or processes. However, it is not considered to be an environmental impact category and hence is not aggregated to the total environmental score. All impact categories (see Table 3) are discussed under chapter 5.

The following Table 8 shows the results for the PED of both alternatives. Furthermore, all limitations, like consideration of ETICS with 10 wt% EPS containing 0.4 wt% HBCCD flame retardants, defined water content of maximum 3 wt% of ETICS and incineration with energy recovery (see chapter 3.6 and 3.7) should be taken into account by interpretation of the results.

Table 8: Results primary energy demand (PED)

	Current Status Quo Process (incineration with energy recovery)	PS Loop Process
PED renewable and non-renewable [MJ]	8.2E+04	5.5E+04
PED non-renewable [MJ]	8.0E+04	4.8E+04
PED renewable [MJ]	2,545	7,157

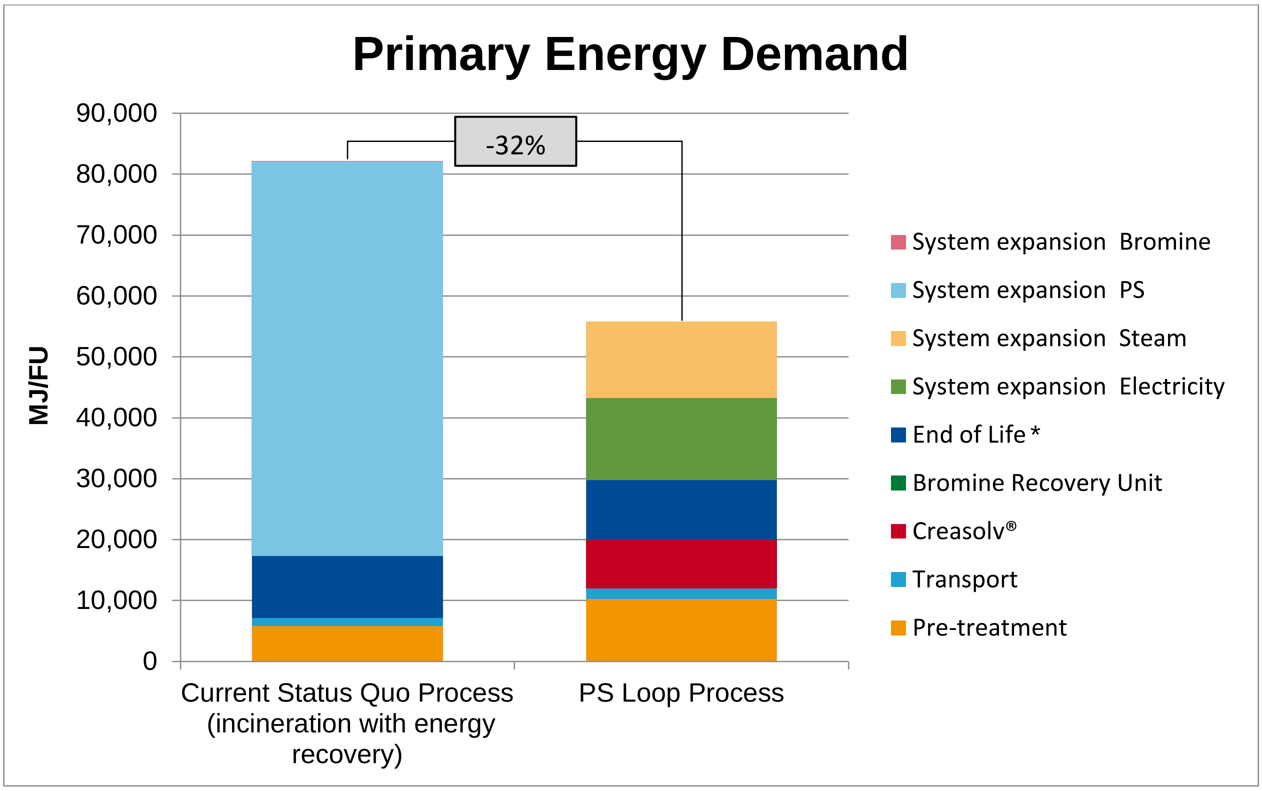

Figure 4: Primary energy demand in MJ/FU

* Current Stauts Quo Process (incineration with energy recovery): Material Mix A 89.5 wt% incineration of inert matter, 10.0 wt% incineration of EPS, 0.1 wt% incineration of PE (dowels), 0.36 wt% recycling of metals and 0.04 wt% landfilling of metals (dowels)

PS Loop Process: Material Mix B 89.5 wt% incineration of inert matter, 0.1 wt% incineration of PE (dowels), 0.36 wt% recycling of metals and 0.04 wt% landfilling of metals (dowels)

The PED is higher for the Current Status Quo Process (incineration with energy recovery) in relation to the PS Loop Process (difference: 32%).

Most important life cycle steps are incineration[63] of the material mixes[64], as well as production of PS granulate to fulfill the requirements of the system expansion. System expansion is more relevant for the Current Status Quo Process (incineration with energy recovery) than for the PS Loop Process, due to production of PS (see chapter 3.4). The PED of end of life treatment for both alternatives is almost the same. The PED for the pre-treatment for the PS Loop Process is higher in relation to the Current Status Quo Process (incineration with energy recovery), caused by a higher effort for separation of ETICS. The main driver for the CreaSolv® Process is the required electricity for the dissolution process. The BRU and transportation steps (both alternatives) are not significantly influencing the overall results.

For a better understanding of the different processes further assessments for primary energy demand were made. The following graph illustrates the end of life of the Current Status Quo Process (incineration with energy recovery).

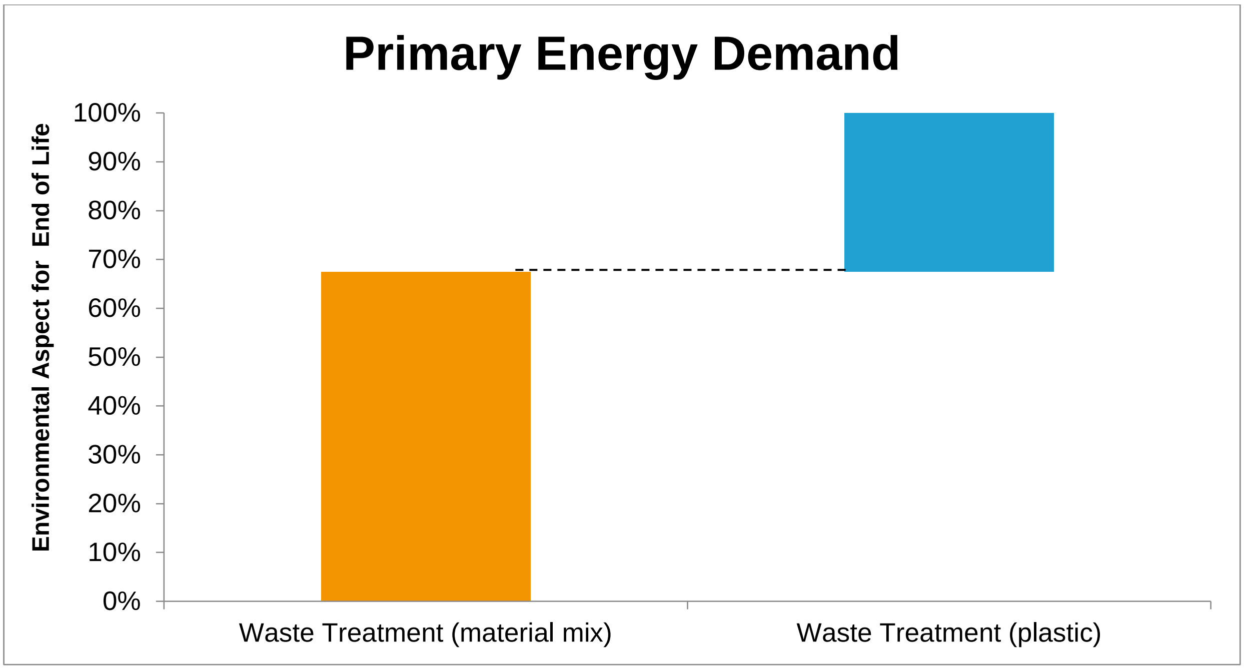

Figure 5: Primary energy demand (environmental aspect) of end of life for the Current Status Quo Process (incineration with energy recovery) [%]

[63] The used dataset represents an average European waste-to-energy plant (WtE) with typical technology used in Europe. All utilities used in the waste incineration plant, the operation of the underground deposit and the landfill for bottom ash and air pollution control (APC) residues as well as the meltdown processes for the recovered metals are included in the system.

[64] Further information for Material Mixes can be found in Table 2. For a clearer differentiation between Current Status Quo (incineration with energy recovery) and PS Loop Process, two different Material Mixes (A& B) were defined. The difference between Material Mix A and B is the consideration of the 10.00 wt% EPS which is either incinerated or recycled. Therefore, Material Mix A considers inert material and EPS. In comparison Material Mix B takes only inert material into an account.

The main contributor for the PED of Current Status Quo Process (incineration with energy recovery) is the waste treatment of material mix (68%)[65], incineration of plastic (EPS and PE (dowels)) is related to 32%.

Figure 6 shows the primary energy demand of different process steps within the CreaSolv® Process.

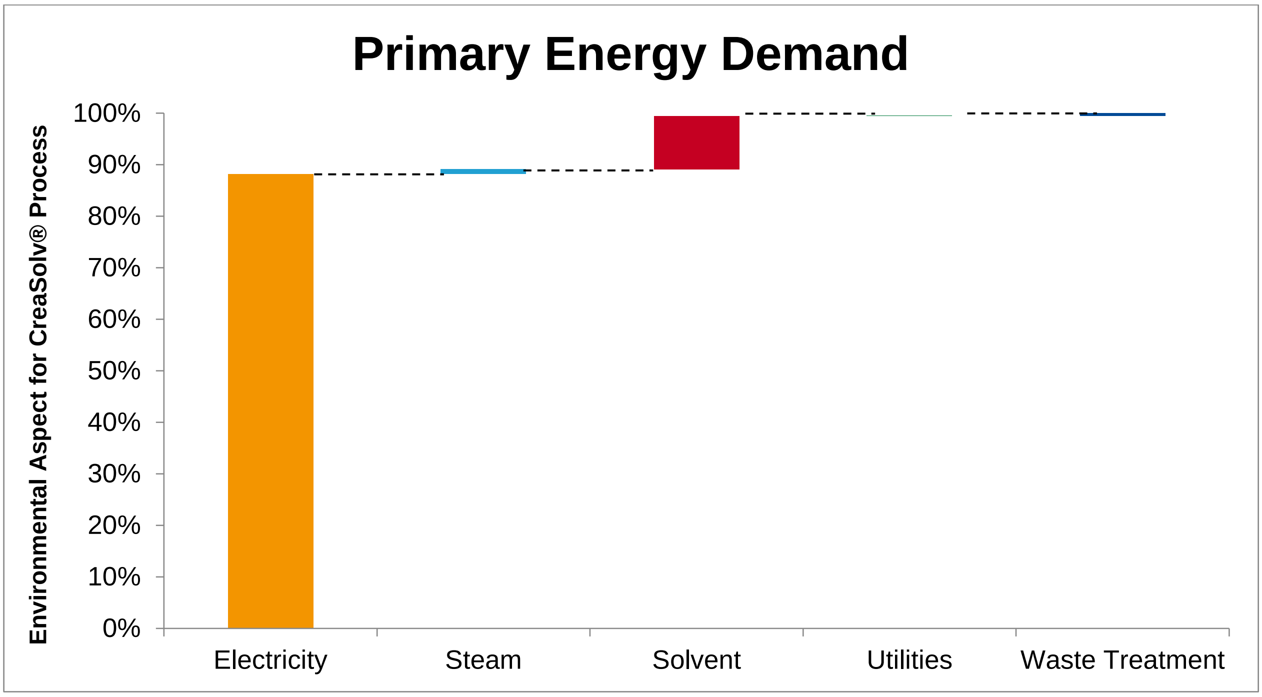

Figure 6: Different steps of the CreaSolv® Process contributing to primary energy demand [%]

Main contributor for the PED of the CreaSolv® Process is the electricity demand (88%). Waste treatment is related to incineration of EPS, which cannot be further processed. The used solvent influences this process step by 10%, due to use of crude oil and natural gas during production process.

Figure 7 shows the primary energy demand of different process steps within the BRU

[65] Environmental impacts of material mix include impacts of incineration of 89.5wt% inert material, 0.36wt% recycling and 0.04wt% landfill of metallic parts (dowels).

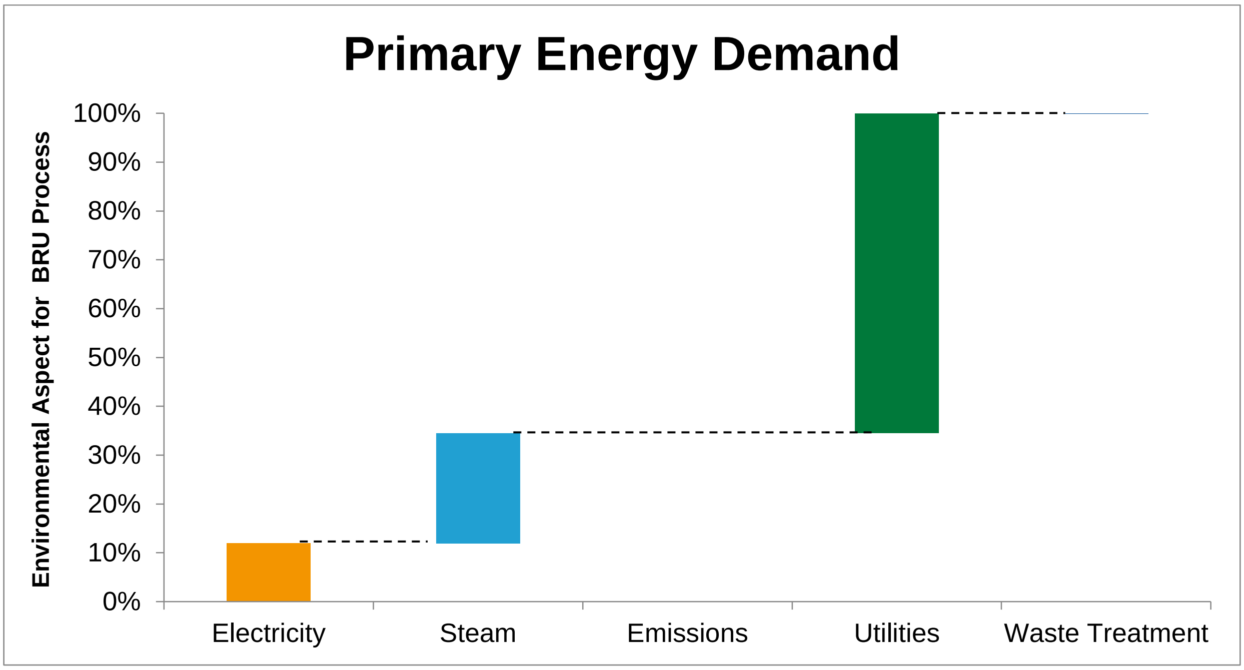

Figure 7: Different steps of the BRU contributing to primary energy demand [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 65%. The production of steam and electricity results in an impact of 35%. Direct process emissions have no influence for primary energy demand.

5. Life Cycle Impact Assessment

5.1. Life Cycle Impact Assessment Results

All following results are calculated per functional unit. Furthermore, all limitations, like consideration of ETICS with 10 wt% EPS containing 0.4 wt% HBCCD flame retardants, defined water content of maximum 3 wt% of ETICS and incineration with energy recovery (see chapter 3.6 and 3.7) should be taken into account by interpretation of the results.

5.1.1 Climate Change

For the evaluation of the global warming potential (GWP) the baseline model of 100 years of the IPCC 2007 is used.

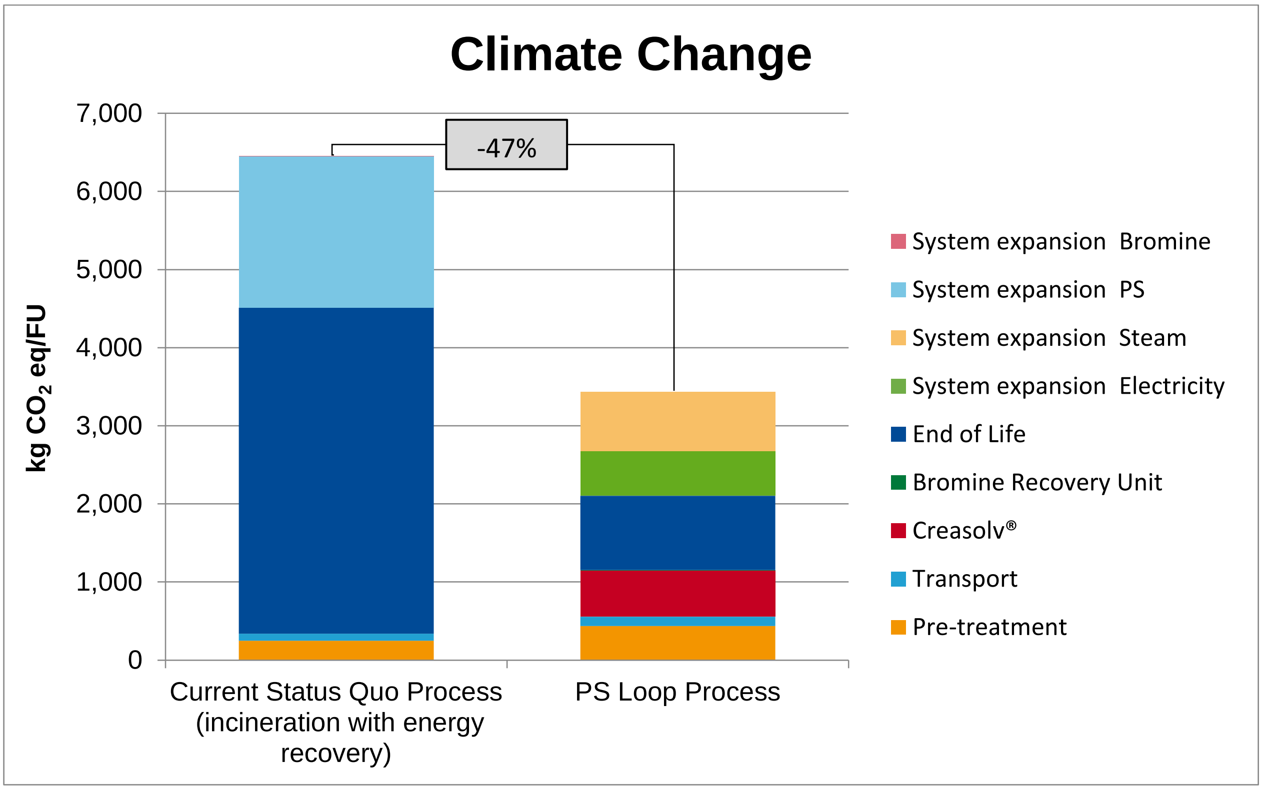

Figure 8: Climate Change in kg CO_2 eq/FU

The effects on climate change are higher for the Current Status Quo Process (incineration with energy recovery) (difference: 47%) than for PS Loop Process. Most important life cycle steps are incineration of the PS during current status quo (energy recovery) process as well as production of PS granulate to fulfill the requirements of the system expansion. These processes are related to high CO_2 emissions. No credits were given for the avoided production of electricity and steam (from incineration) in another product system due to the fact that a system expansion was applied (see chapter 3.4). End of life for the Current Status Quo Process (incineration with energy recovery) is higher than for the PS Loop Process, due to additional incineration of 10.0 wt% PS. System expansion for Current Status Quo Process (incineration with energy recovery) is also higher in comparison to the PS Loop Process, caused by production of PS to fulfill the requirements of the system expansion. The PS Loop Process has a higher impact for pre-treatment, due to higher energy demand for separation, shredding and compaction in relation to current status quo. The CreaSolv® Process is mainly influenced by the required electricity and the waste treatment (incineration of plastic waste). Transportation steps and the BRU have only a minor influence in this impact category. Impacts for transportation are slightly higher for PS Loop Process alternative than for current status quo due to a lower utilization rate and higher transport distances (see chapter 4.4).

For a better understanding of the different processes further assessments for climate change were made. The following graph (Figure 9) illustrates the end of life phase of Current Status Quo Process (incineration with energy recovery).

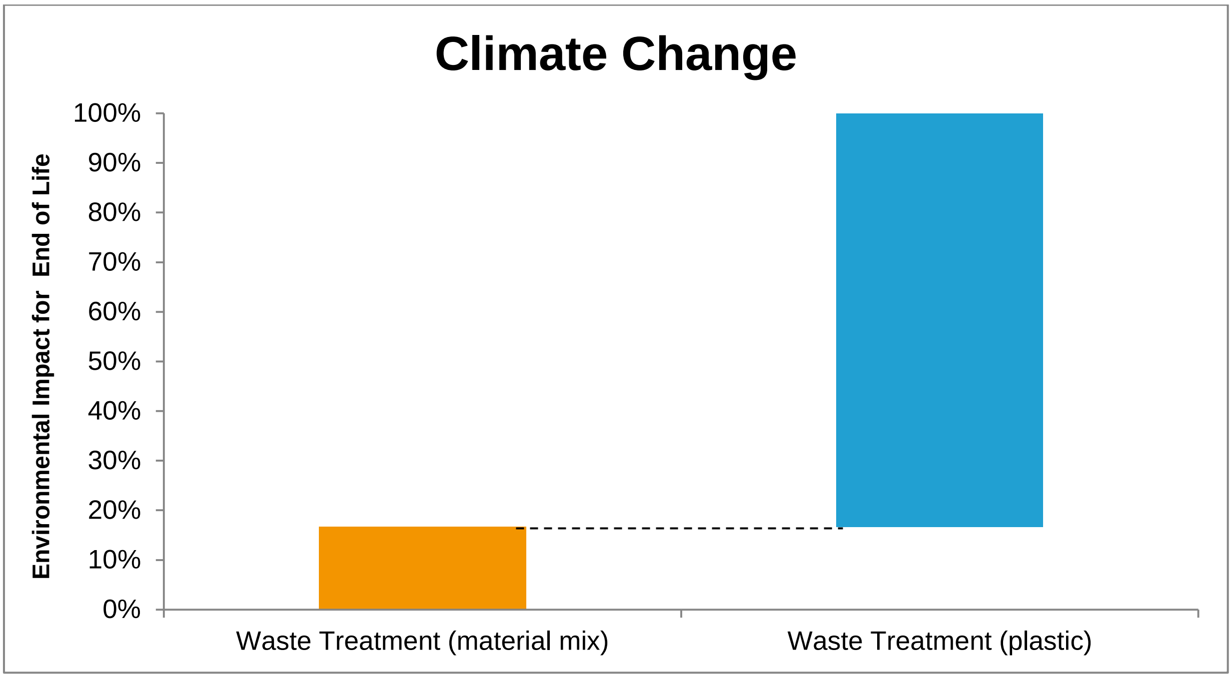

Figure 9: Climate change of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 83% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of plastic, mainly EPS. Waste treatment of material mix is related to 17%. This process step includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 10 shows the GWP of different process steps within the CreaSolv® process.

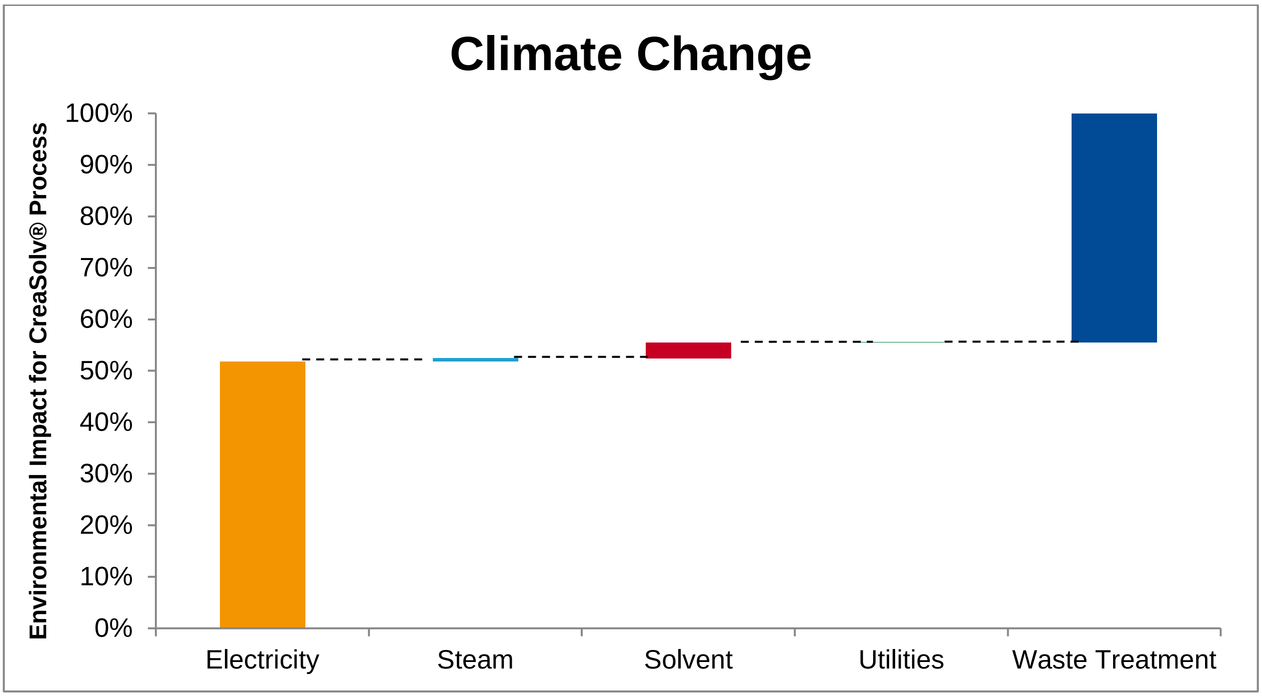

Figure 10: Different steps of the CreaSolv® Process contributing to climate change [%]

Main contributors of the CreaSolv® Process are electricity (52%) and waste treatment (44%). Waste treatment is related to incineration of EPS, which cannot be further processed. The production of used solvent influences this process step by 3%.

Figure 11 shows the GWP of different process steps within the BRU.

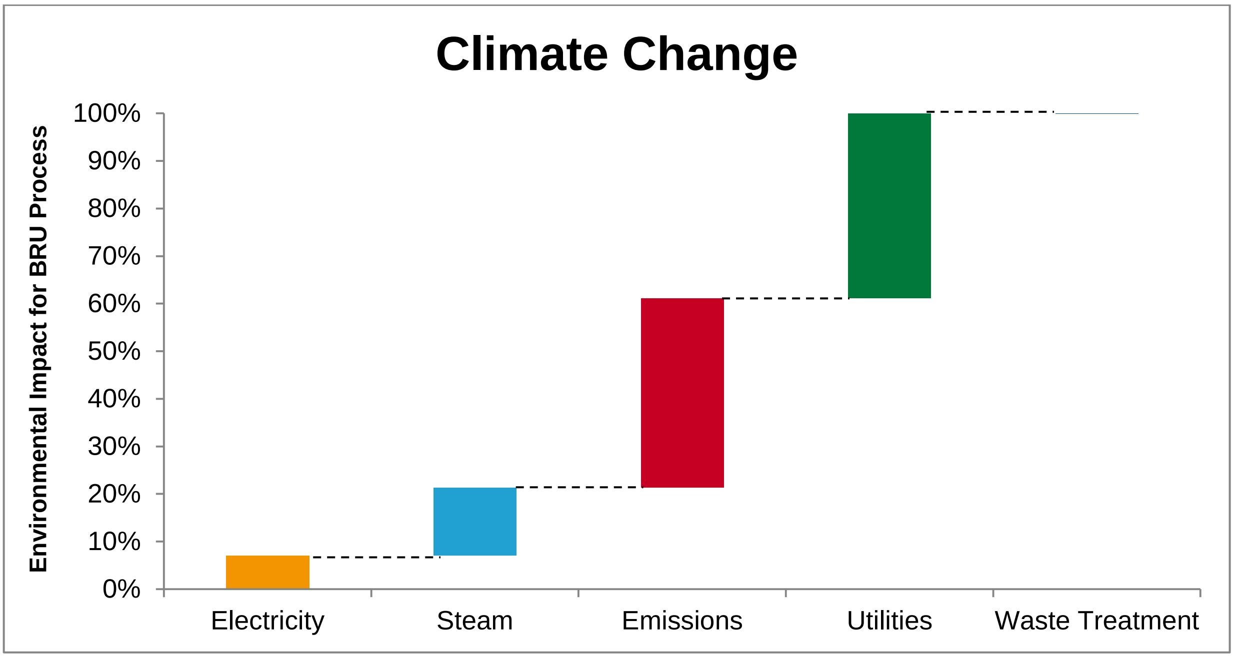

Figure 11: Different steps of the BRU contributing to climate change [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 39%. Direct CO_2 process emissions have an influence of 40%.

5.1.2 Acidification

For the evaluation of the acidification potential (AP) the accumulated exceedance method according to Seppälä et al. 2006 and Posch et al. 2008 is used.

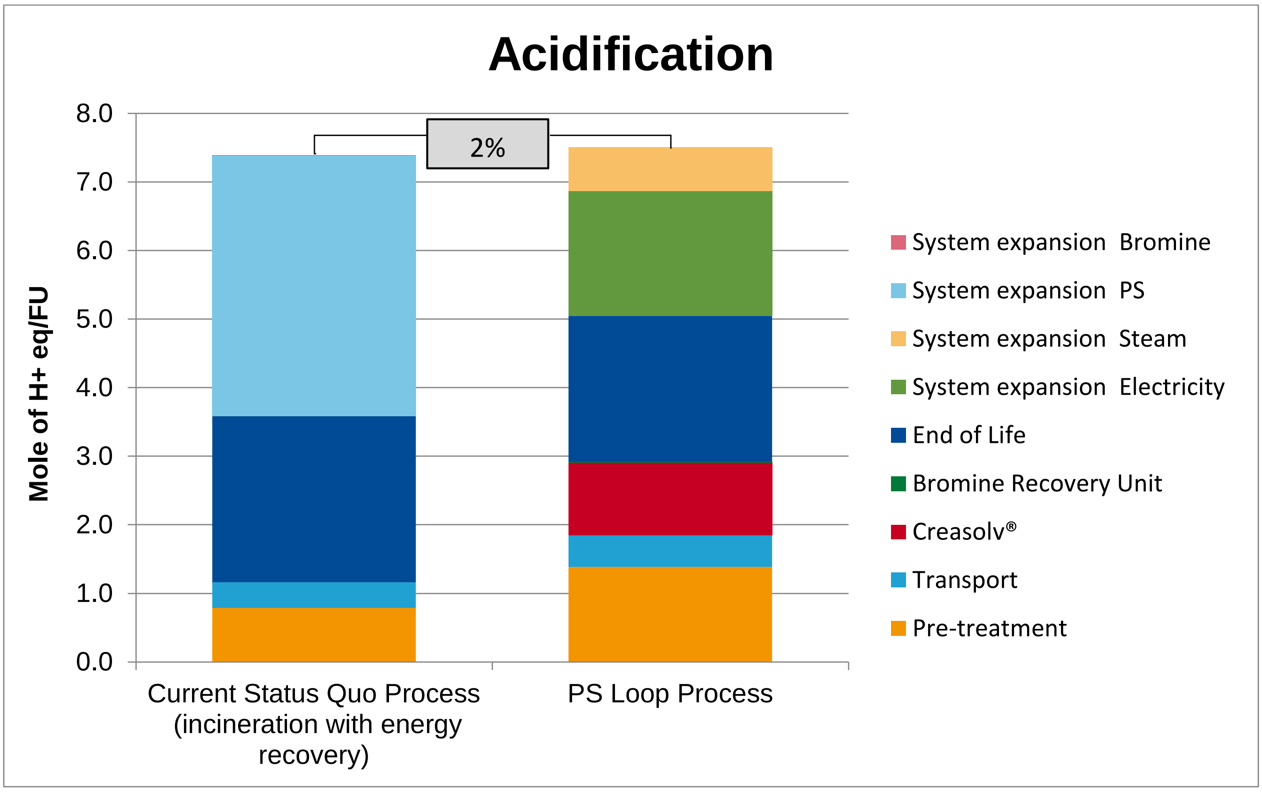

Figure 12: Acidification in mol H^+ eq/FU

The acidification potentials are similar for both process alternatives (difference: 2%). The main contributors are incineration of the material mixes[66] and the production of PS granulate to fulfill the requirements of the system expansion as well as the CreaSolv® Process. Impacts for transportation are slightly higher for the PS Loop Process in comparison to Current Status Quo (incineration with energy recovery) due to a lower utilization rate (see chapter 4.4). Main driver for acidification potential are sulphur dioxide and nitrogen dioxide emissions during PS granulate production and incineration of material mixes (see Table 2).

For a better understanding of the different processes further assessments for acidification were made. The following graph (Figure 13) illustrates the end of life phase of Current Status Quo Process (incineration with energy recovery).

[66] For a clearer differentiation between Current Status Quo (incineration with energy recovery) and PS Loop Process, two different Material Mixes (A& B) were defined. The difference between Material Mix A and B is the consideration of the 10.00 wt% EPS which is either incinerated or recycled. Therefore, Material Mix A considers inert material and EPS. In comparison Material Mix B takes only inert material into an account. For further Information see Table 2.

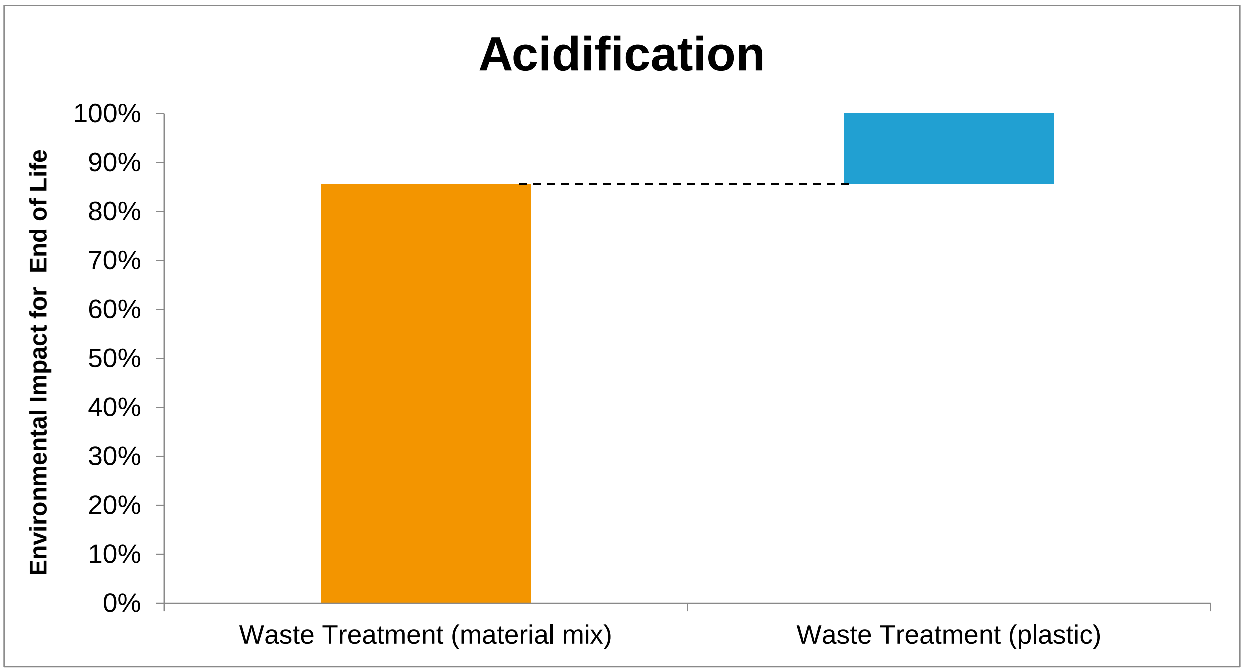

Figure 13: Acidification of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 86% of Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix. Incineration of plastic (EPS and PE (dowels)) is related to 14%. Waste treatment of material mix includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 14 shows the acidification potential of different process steps within the CreaSolv® Process.

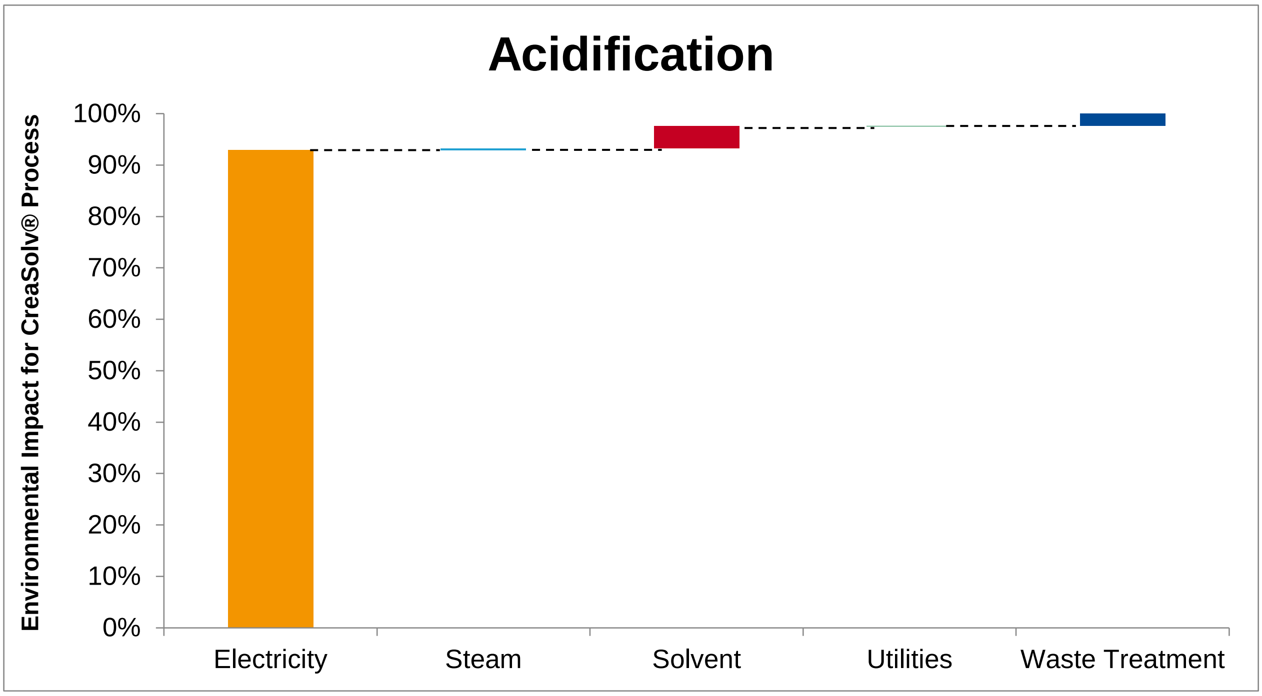

Figure 14: Different steps of the CreaSolv® Process contributing to acidification [%]

Main contributors of the CreaSolv® Process are electricity (93%), due high amounts of sulphur dioxide and nitrogen dioxide emissions during incineration of fossil energy resources like lignite and hard coal. The production of used solvent influences this process step by 4%.

Figure 15 shows the acidification potential of different process steps within the BRU.

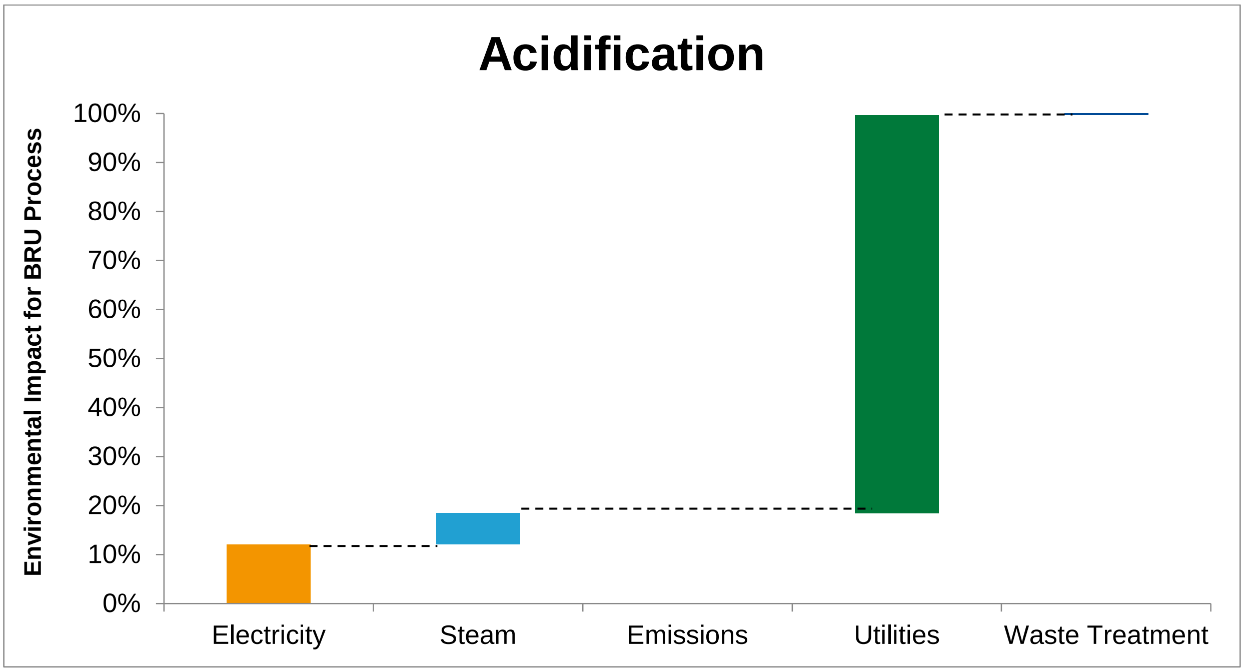

Figure 15: Different steps of the BRU contributing to acidification [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 82%.

5.1.3 Summer Smog

For the evaluation of summer smog (POCP) the tropospheric ozone concentration increase method according to Zelm et al. 2008 is used.

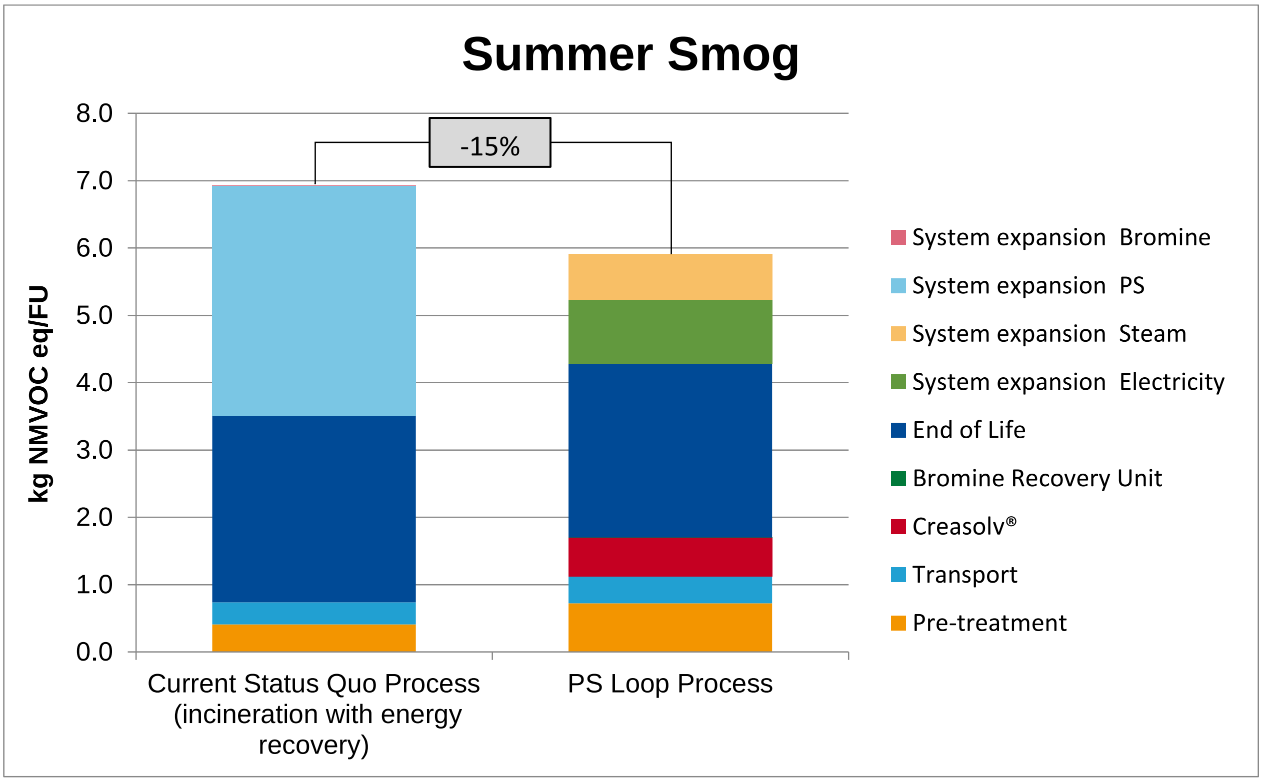

Figure 16: Summer smog in kg NMVOC eq/FU

Ozone creation potential is slightly higher for the Current Status Quo Process (incineration with energy recovery) than for the PS Loop Process (difference: 15%).

Most important life cycle steps are incineration of the material mixes (see Table 2), as well as production of PS granulate to fulfill the requirements of the system expansion. The incineration process results in high nitrogen oxide emissions. The end of life for the Current Status Quo Process (incineration with energy recovery) is slightly higher in comparison to the PS Loop Process due to incineration of PS instead of recycling (CreaSolv® Process). Likewise, system expansion is also higher for the Current Status Quo Process (incineration with energy recovery) than for the PS Loop Process caused by production of PS. The PS Loop Process has a higher influence for pre-treatment due to the higher energy demand for separation, shredding and compaction in contrast to Current Status Quo Process (incineration with energy recovery). Main driver for the CreaSolv® Process is the required electricity. Transportation steps for both alternatives as well as the BRU have no significant influence on the overall results.

For a better understanding of the different processes further assessments for summer smog were made. The following graph (Figure 17) illustrates the end of life phase of the Current Status Quo Process (incineration with energy recovery).

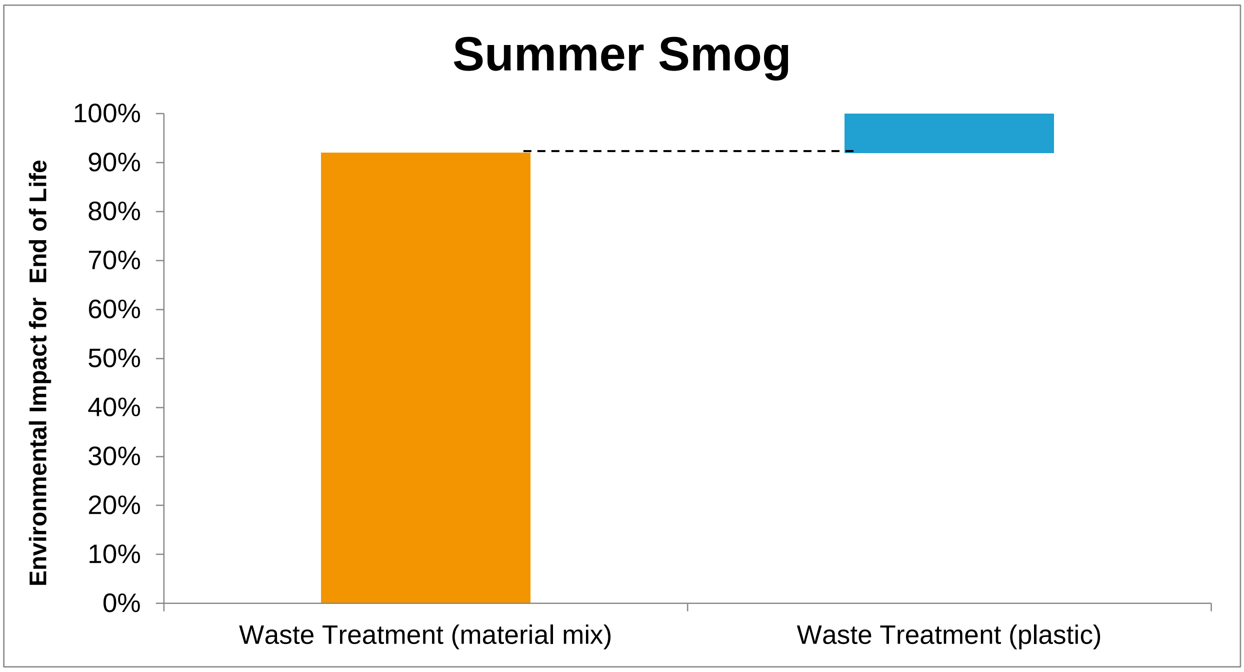

Figure 17: Summer smog of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 92% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix (incineration of plastic (EPS and PE (dowels)) is related to 8%). Waste treatment of material mix includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 14 shows the summer smog of different process steps within the CreaSolv® Process.

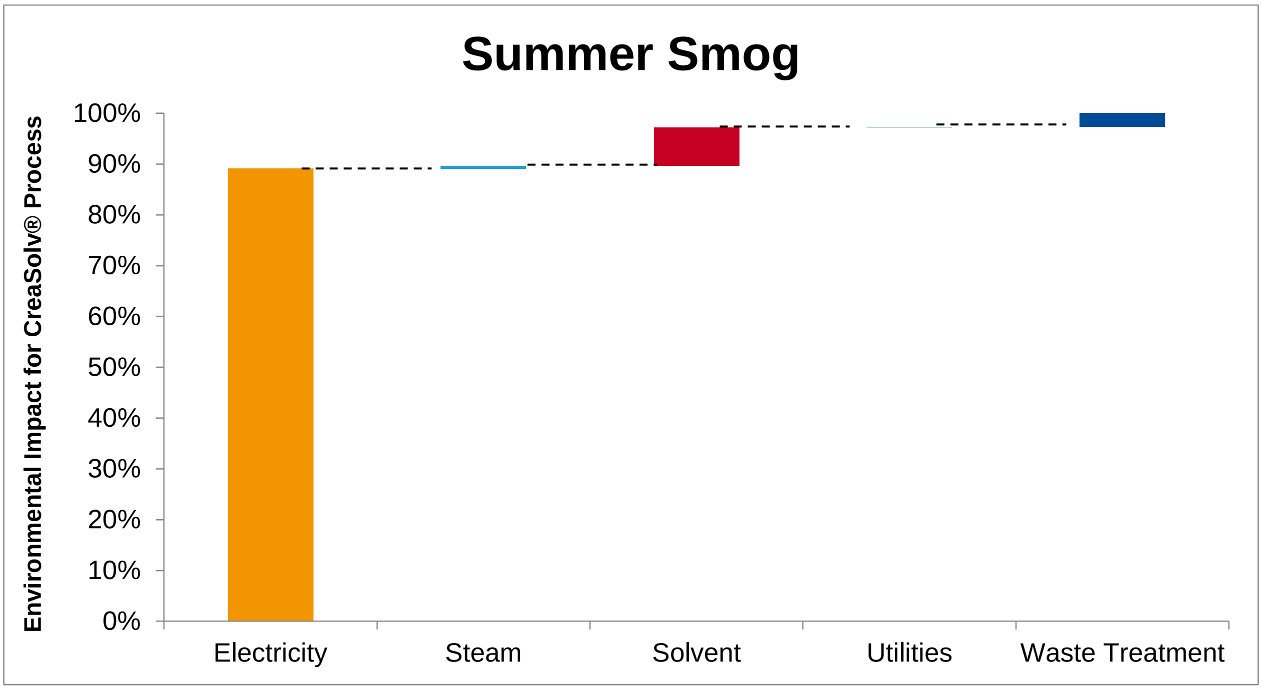

Figure 18: Different steps of the CreaSolv® Process contributing to summer smog [%]

Main contributors of the CreaSolv® Process are electricity (89%), due to high nitrogen oxide emissions. Waste treatment is related to incineration of EPS, which cannot be further processed. The production of used solvent influences this process step by 8%.

Figure 19 shows the summer smog of different process steps within the BRU.

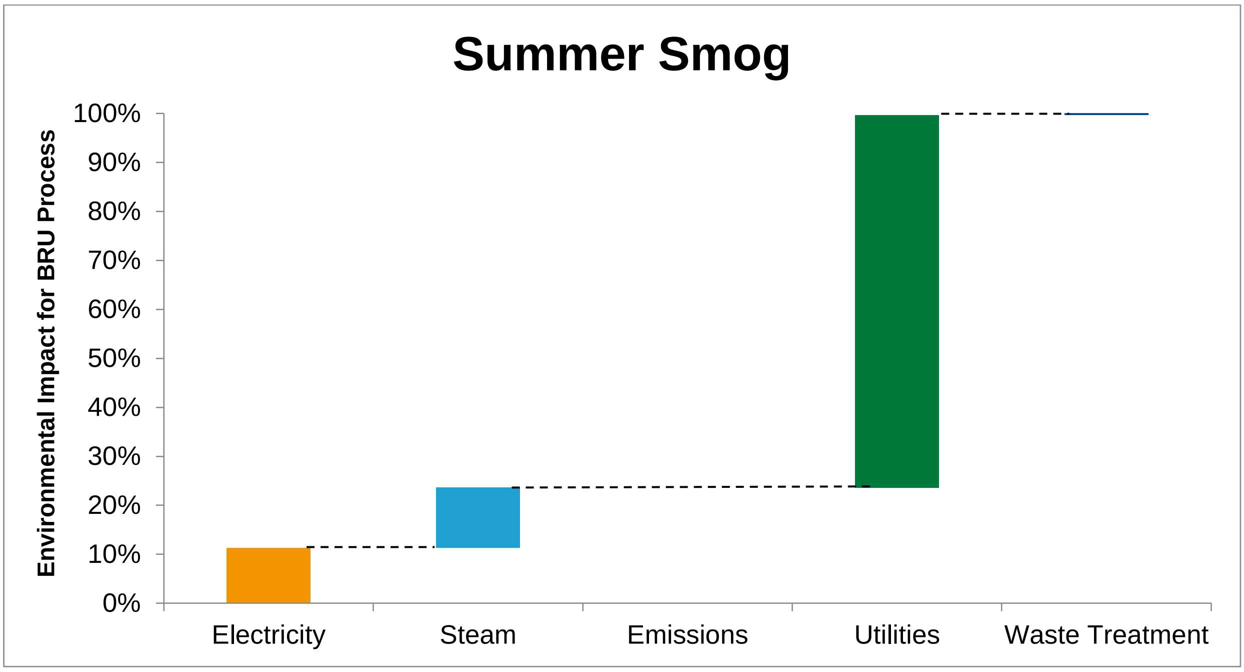

Figure 19: Different steps of BRU contributing to summer smog [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 76%. Direct process emissions have no influence in this impact category.

5.1.4 Eutrophication - Marine

For the evaluation of the eutrophication potential - marine the EUTREND model according to Struijs et al. 2009 is used.

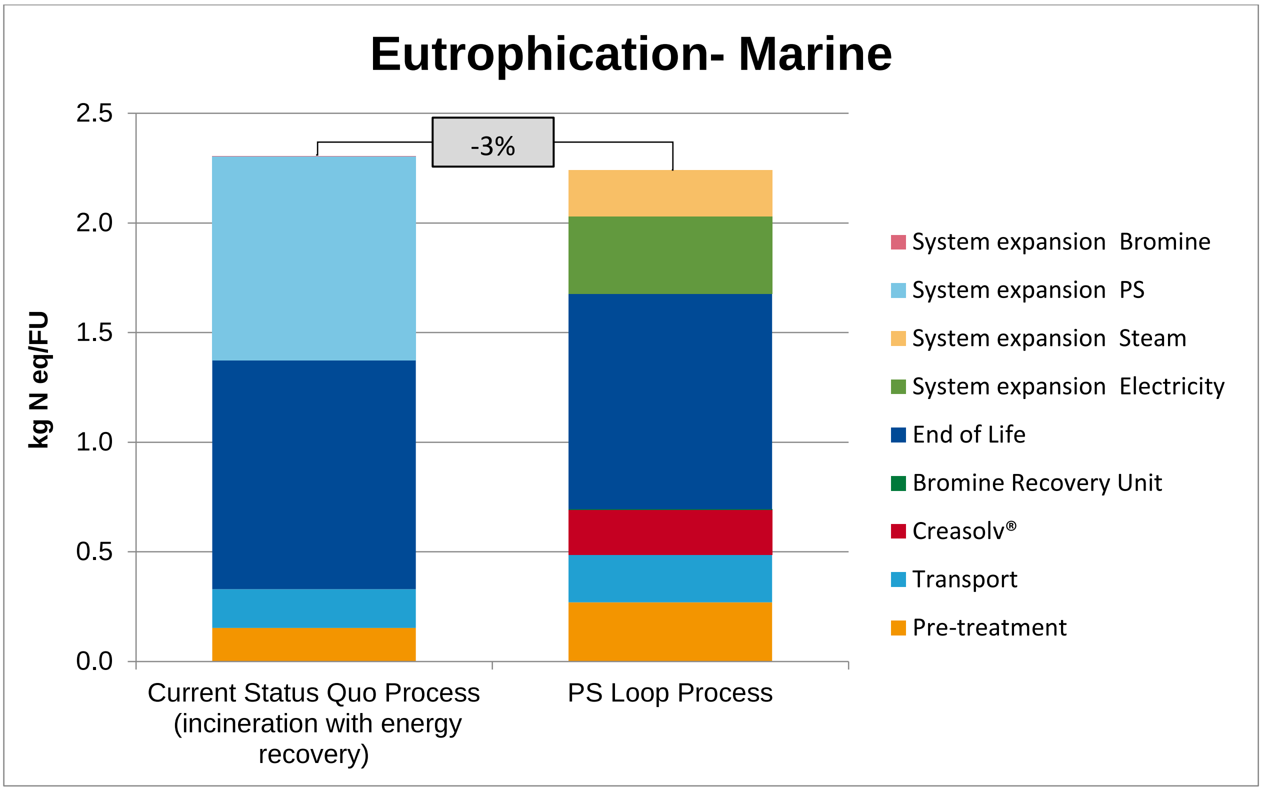

Figure 20: Eutrophication - marine in kg N eq/FU

Marine eutrophication potentials are similar for both alternatives (difference: 3%).

The overall results are influenced by incineration of the material mixes (see Table 2) as well as the production of PS granulate to fulfill the requirements of the system expansion. The incineration processes lead to nitrate and ammonia emissions. End of life is higher for the Current Status Quo Process (incineration with energy recovery) caused by the incineration of PS instead of recycling (PS Loop Process). System expansion is also higher for the Current Status Quo Process (incineration with energy recovery) in contrast to the PS Loop Process due to the production of PS to fulfill the modelling principles of system expansion. The PS Loop Process shows a higher impact than the Current Status Quo (incineration with energy recovery) for pre-treatment related to the required energy. Main driver for the CreaSolv® Process in this impact category is the respective energy demand.

For a better understanding of the different processes further assessments for marine eutrophication were made. The following graph (Figure 21) illustrates the end of life phase of Current Status Quo Process (incineration with energy recovery).

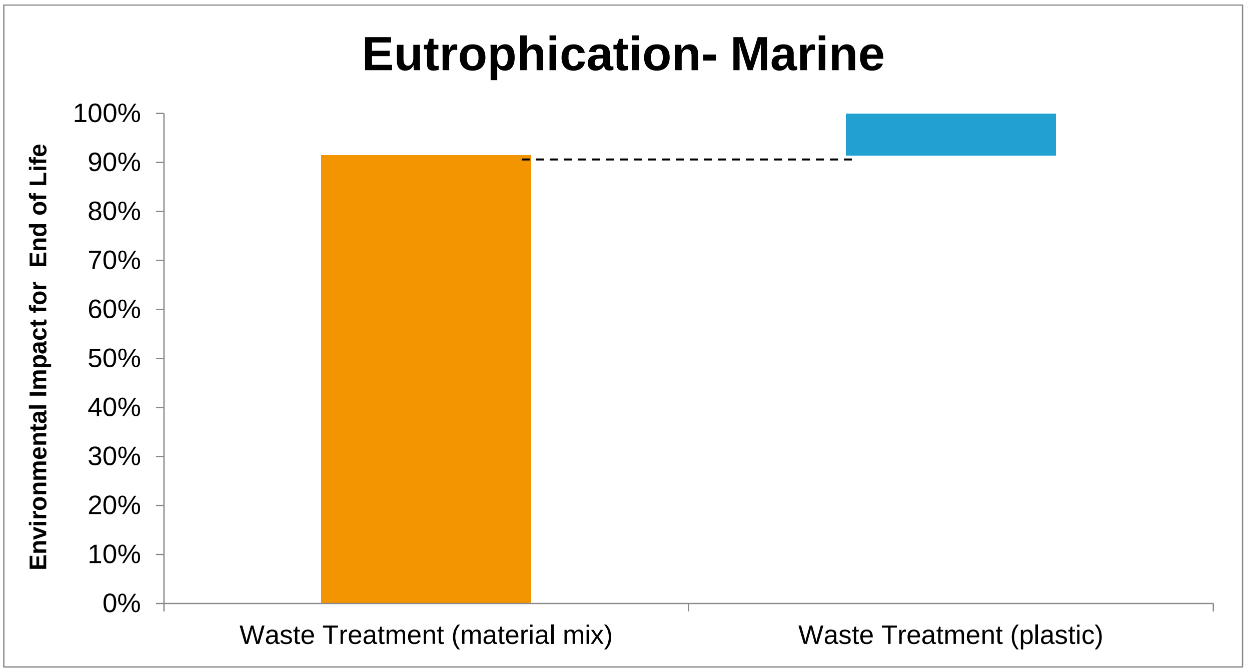

Figure 21: Eutrophication - marine of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 91% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix. Incineration of plastic (EPS and PE (dowels)) is related to 9%. Waste treatment of material mix includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 22 shows the eutrophication potential - marine of different process steps within the CreaSolv® Process.

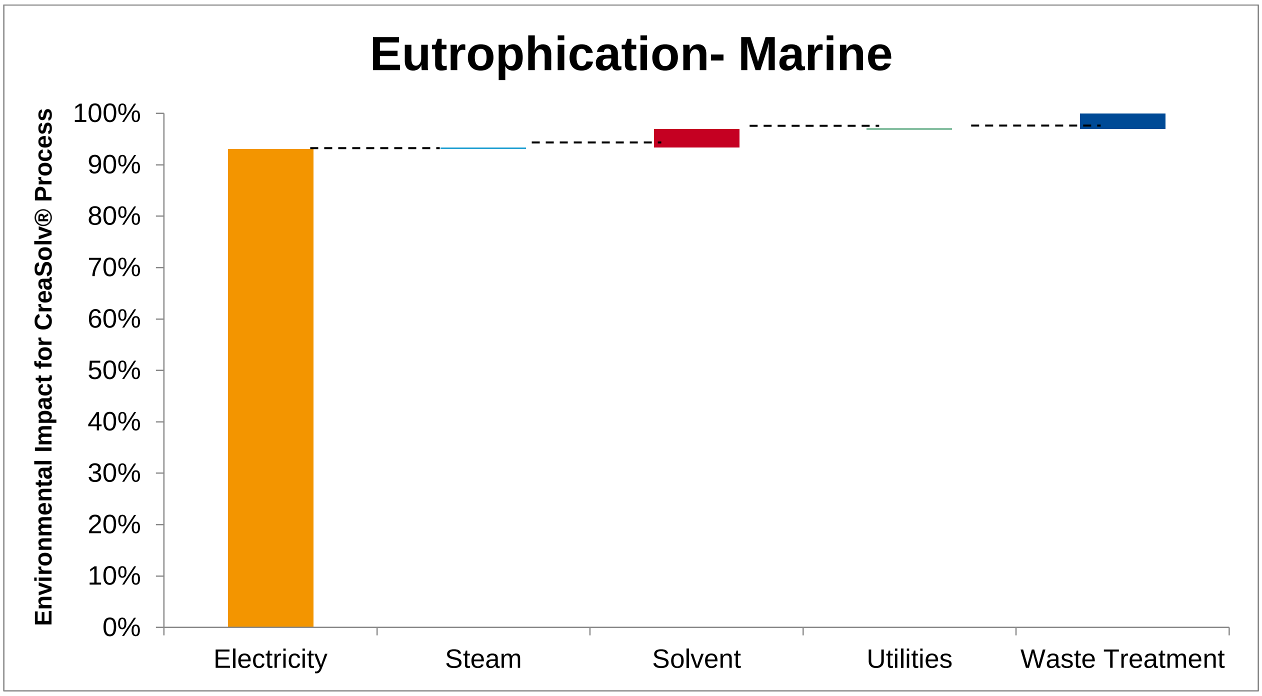

Figure 22: Different steps of the CreaSolv® Process contributing to eutrophication- marine [%]

Main contributor of the CreaSolv® Process is the electricity demand (93%) related to resulting nitrogen oxide emissions. Waste treatment is related to incineration of EPS, which cannot be further processed. The production of used solvent influences this process step by 3%.

Figure 23 shows the eutrophication potential - marine of different process steps within the BRU.

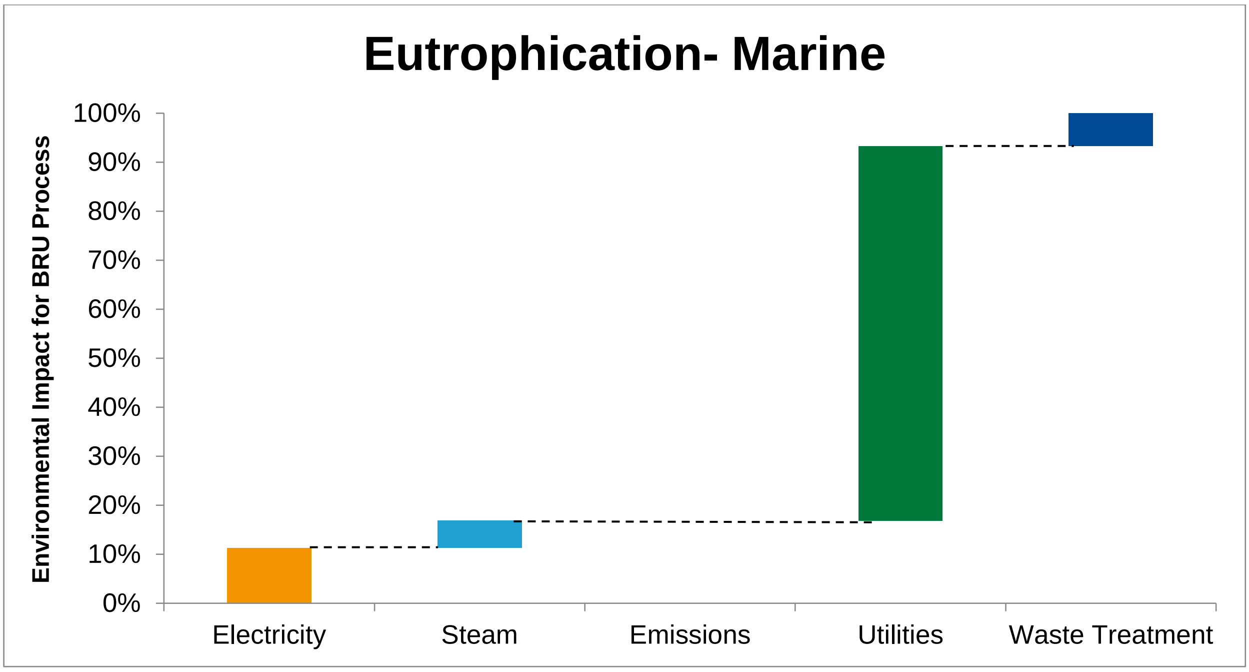

Figure 23: Different steps of the BRU contributing to eutrophication- marine [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 76%. Direct process emissions have no influence in this impact category. Waste treatment of process water (wastewater treatment) leads to an influence of 7%, caused by nitrate and ammonia emissions.

5.1.5 Eutrophication - Freshwater

For the evaluation of the eutrophication potential - freshwater the EUTREND model according to Struijs et al. 2009 is used.

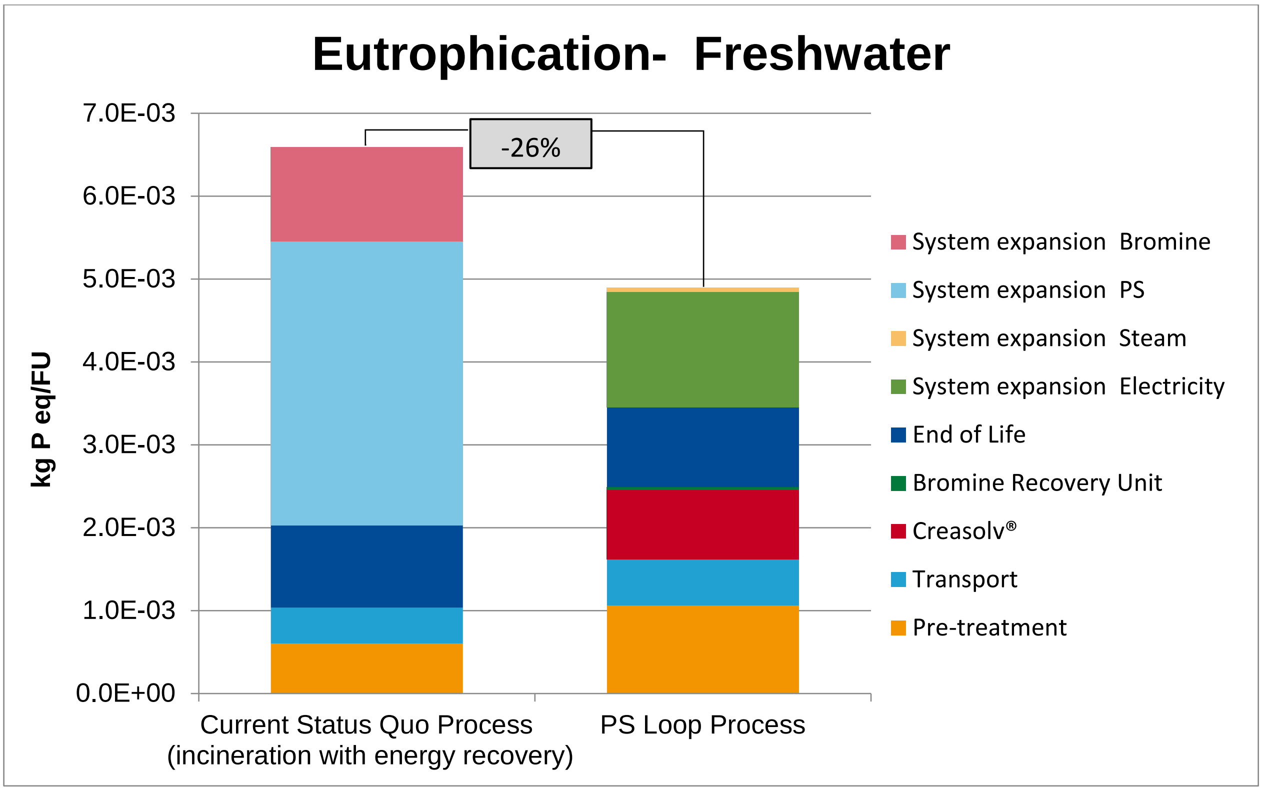

Figure 24: Eutrophication - freshwater in kg P eq/FU

The freshwater eutrophication potential is higher for the Current Status Quo Process (incineration with energy recovery) in relation to the PS Loop Process (difference: 26%).

Most important life cycle steps are production of PS granulate to fulfill the requirements of the system expansion as well as end of life treatment. The incineration processes of Material Mixes (see Table 2) as well as the production of PS lead to phosphate and phosphorus emissions. The eutrophication potential from system expansion is higher for the Current Status Quo Process (incineration with energy recovery) than for the PS Loop Process caused by the production of PS. The Current Status Quo Process (incineration with energy recovery) shows a lower influence in contrast to the PS Loop Process for pre-treatment due to a lower energy demand. Main driver for the CreaSolv® Process is the needed electricity for dissolution process.

For a better understanding of the different processes further assessments for freshwater eutrophication were made. The following graph (Figure 25) illustrates the end of life phase of the Current Status Quo Process (incineration with energy recovery).

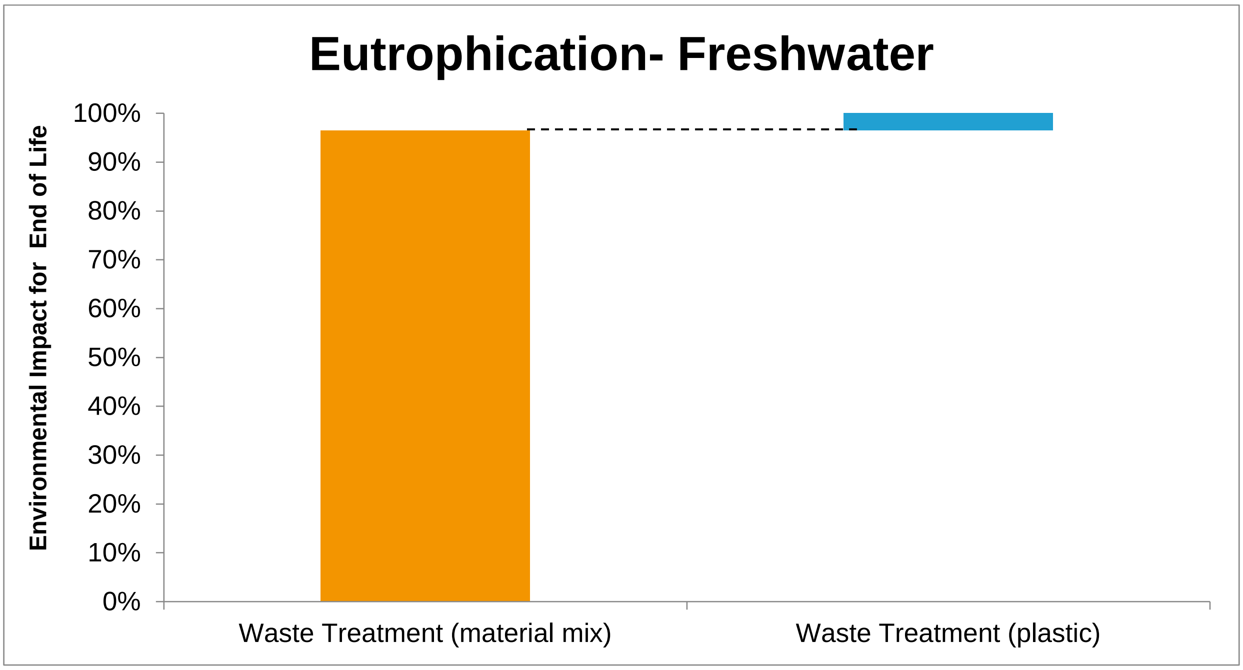

Figure 25: Eutrophication – freshwater of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 96% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix (incineration[67] of plastic (EPS and PE (dowels)) is related to 4%). Waste treatment of material mix includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 26 shows the eutrophication potential - freshwater of different process steps within the CreaSolv® Process.

[67] The used dataset represents an average European waste-to-energy plant (WtE) with typical technology used in Europe. All utilities used in the waste incineration plant, the operation of the underground deposit and the landfill for bottom ash and air pollution control (APC) residues as well as the meltdown processes for the recovered metals are included in the system.

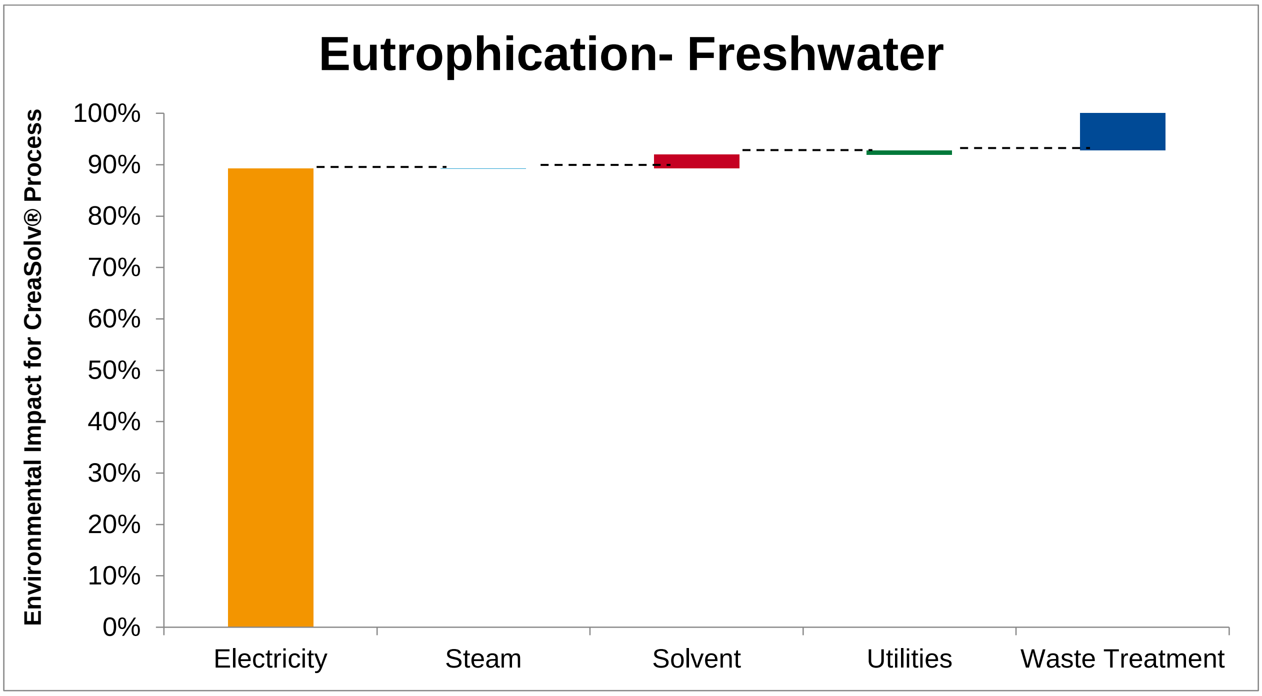

Figure 26: Different steps of the CreaSolv® Process contributing to eutrophication - freshwater [%]

Main contributors of the CreaSolv® Process are electricity (89%) related to resulting phosphate and phosphorus emissions. Waste treatment is related to incineration of EPS, which cannot be further processed. The production of used solvent influences this process step by 3%.

Figure 27 shows the eutrophication potential - freshwater of different process steps within the BRU.

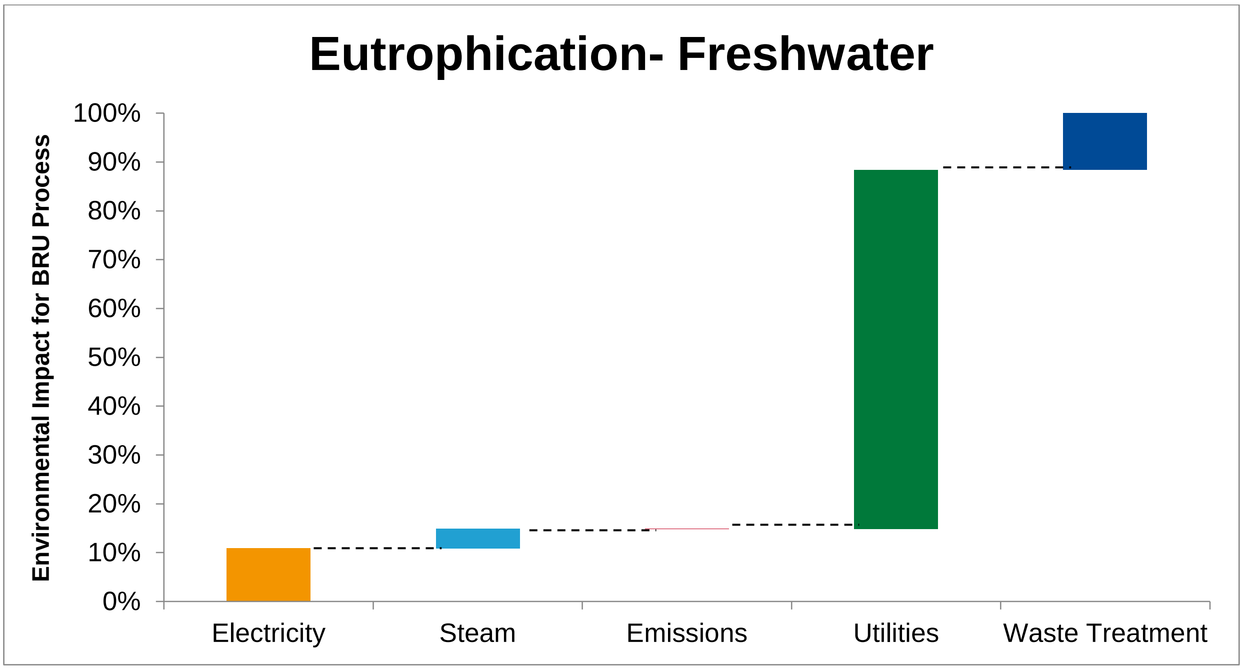

Figure 27: Different steps of the BRU contributing to eutrophication- freshwater [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 76%. Direct process emissions have nearly no influence (< 0.001%) in this impact category. Waste treatment of process water (wastewater treatment) leads to an influence of 12%, caused by phosphate and phosphorus emissions.

5.1.6 Resource Depletion - Fossil

For the evaluation of the resource depletion - fossil (ADPF) the CML method of Guinée et al. 2002 is used.

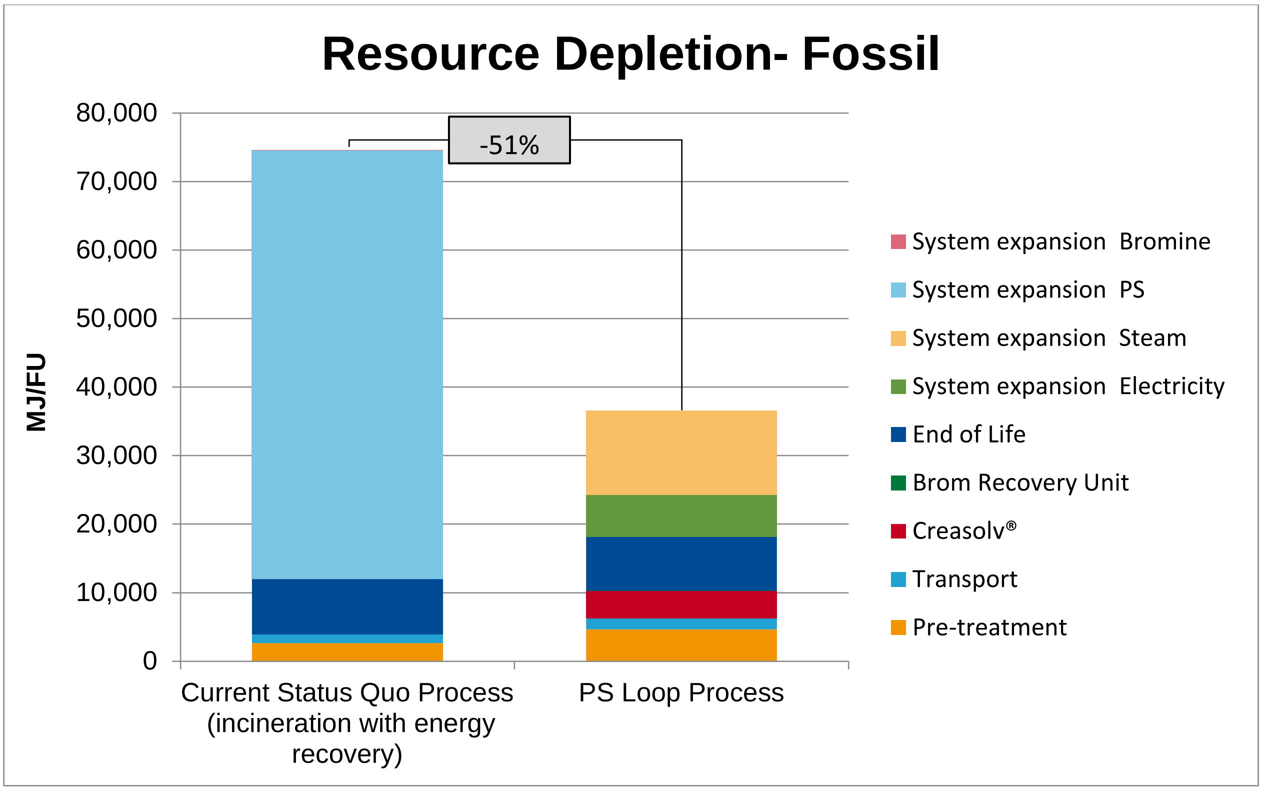

Figure 28: Resource depletion - fossil in MJ/FU

Resource depletion - fossil is higher for the Current Status Quo Process (incineration with energy recovery) in relation to the PS Loop Process (difference: 51%).

Most important life cycle steps are system expansion (production of electricity, steam, PS and bromine) and end of life treatment. The Current Status Quo Process (incineration with energy recovery) has a higher ADPF, due to a high energy demand for PS production to fulfill the requirements of the system expansion. The end of life for the Current Status Quo Process (incineration with energy recovery) is also higher compared to the PS Loop Process caused by the additional incineration of 10 wt% PS. The environmental impact of pre-treatment for the PS Loop Process is higher in comparison to the Current Status Quo (incineration with energy recovery) related to the required electricity for separation, shredding and compaction. Main driver for the CreaSolv® Process is the respective electricity demand. The BRU has nearly no impact on the overall results in this impact category.

For a better understanding of the different processes further assessments for fossil resource depletion were made. The following graph (Figure 29) illustrates the end of life phase of the

Current Status Quo Process (incineration with energy recovery).

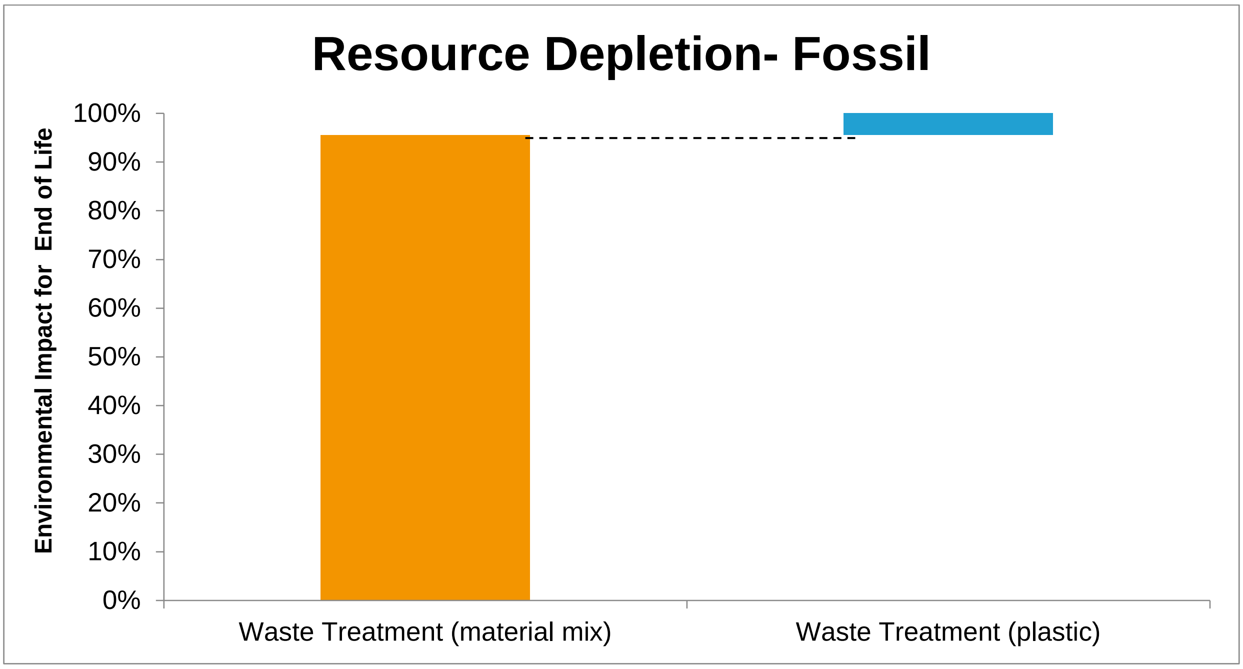

Figure 29: Resource depletion – fossil of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 96% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix (incineration of plastic (EPS and PE (dowels)) is related to 4%). Waste treatment of material mix includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 30 shows the resource depletion potential - fossil of different process steps within the CreaSolv® Process.

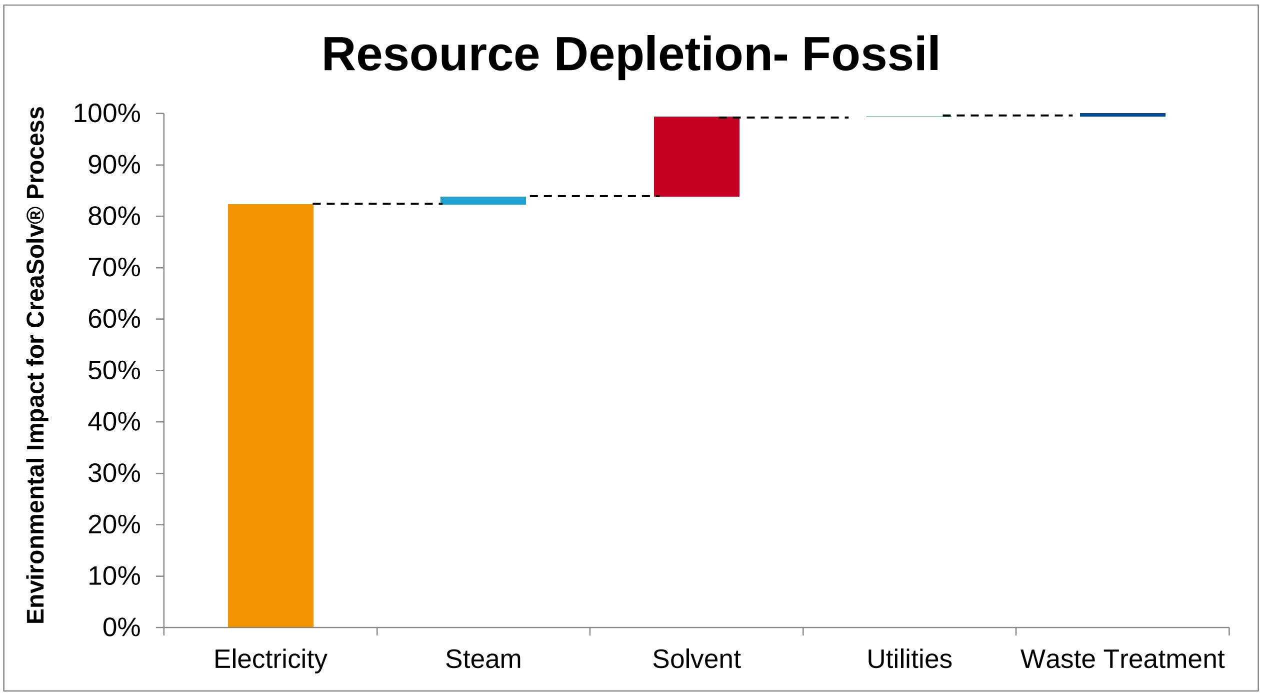

Figure 30: Different steps of the CreaSolv® Process contributing to resource depletion- fossil [%]

Main contributor of the CreaSolv® Process is the electricity demand (82%), due to use of lignite and hard coal as energy resources. Waste treatment is related to incineration of EPS, which cannot be further processed. The production of used solvent influences this process step by 16%, due to use of crude oil and natural gas.

Figure 31 shows the resource depletion potential - fossil of different process steps within the BRU.

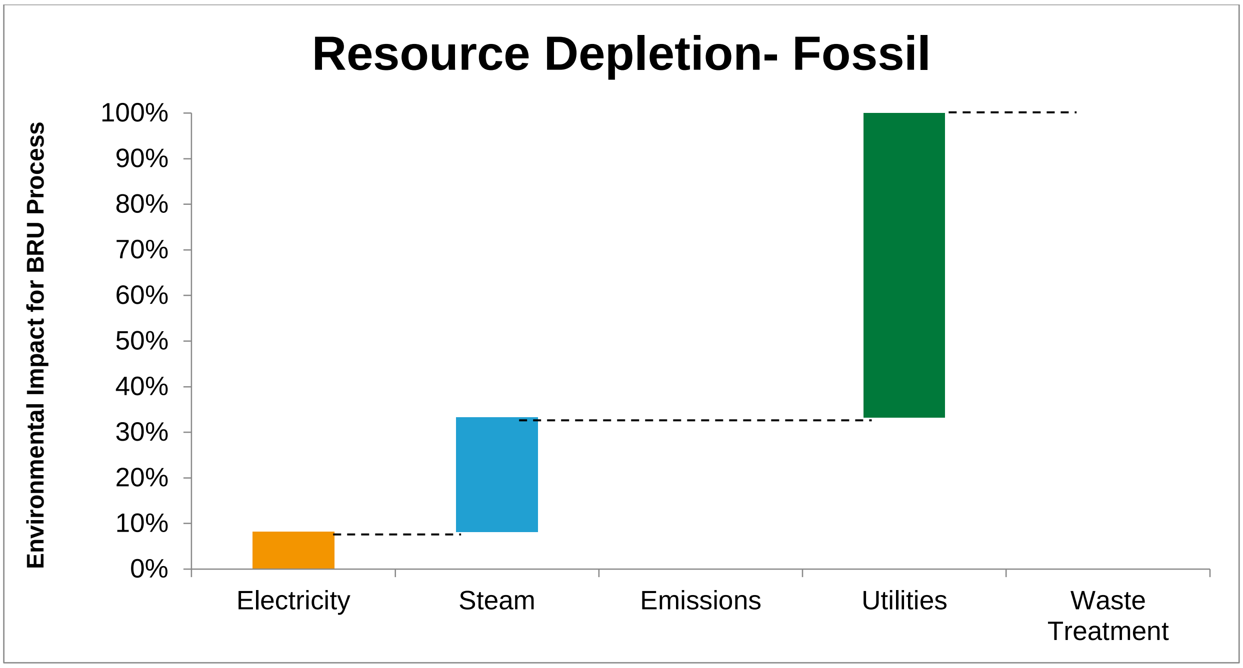

Figure 31: Different steps of the BRU contributing to resource depletion- fossil [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 67%. The production of steam and electricity results in an impact of 33%. Direct process emissions have no influence in this impact category.

5.1.7 Resource Depletion- Elements

For the evaluation of the resource depletion - elements (ADPE) the CML method of Guinée et al. 2002 is used.

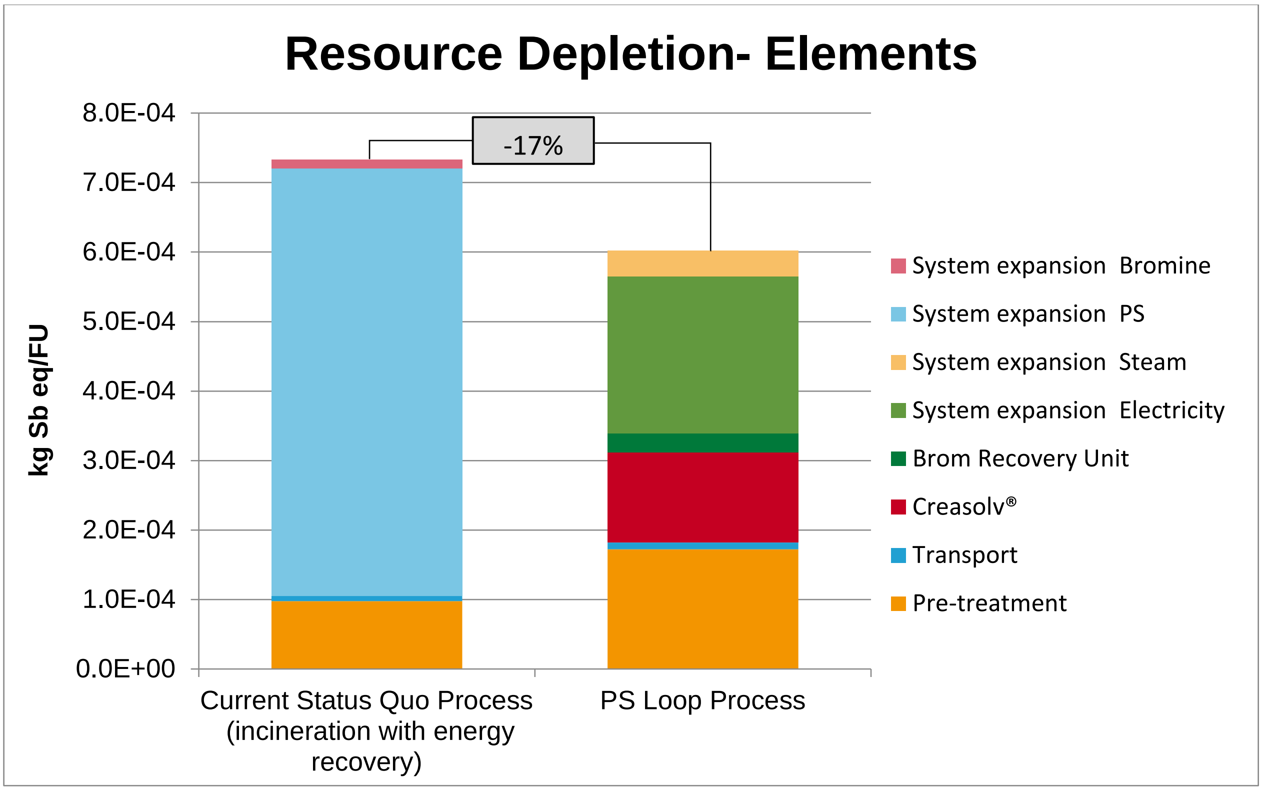

Figure 32: Resource depletion - elements in Sb eq/FU

Resource depletion - elements is higher for the Current Status Quo Process (incineration with energy recovery) in relation to the PS Loop Process (difference: 17%).

The life cycle stage end of life was not considered, due to missing appropriate data for the incineration processes. The available datasets show credits for precious metals (e.g. gold and silver), which would lead to negative results within this impact category.

Most important life cycle steps are system expansion (production of electricity, steam, PS and bromine) and pre-treatment due to the required resources. The Current Status Quo Process (incineration with energy recovery) has a higher ADPE in comparison to the PS Loop Process due to a higher mineral resource demand for PS production to fulfill the requirements of system expansion. The pre-treatment for the PS Loop Process is higher related to the electricity for separation. Main driver for the CreaSolv® Process is the respective electricity demand. The BRU is significantly influenced by the mineral resources demand for electricity production and the required utilities like hydrazine.

For a better understanding of the different processes further assessments for element resource depletion were made. Figure 33 shows the resource depletion potential - elements of different process steps within the CreaSolv® Process.

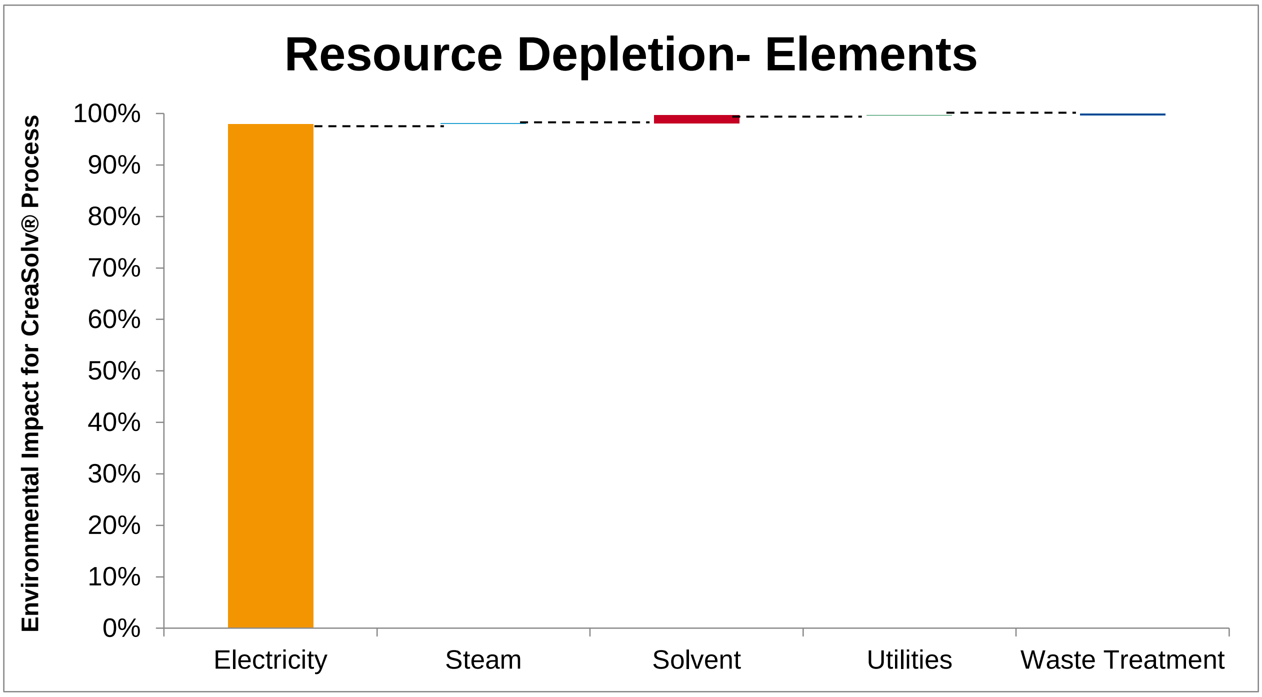

Figure 33: Different steps of the CreaSolv® Process contributing to resource depletion- elements [%]

Main contributor of the CreaSolv® Process is the electricity demand (98%), due to depletion of silver, copper, and lead in upstream processes. The production of used solvent influences this process step by 2%, due to use of sodium chloride (rock salt).

Figure 27 shows the resource depletion potential - elements of different process steps within the BRU.

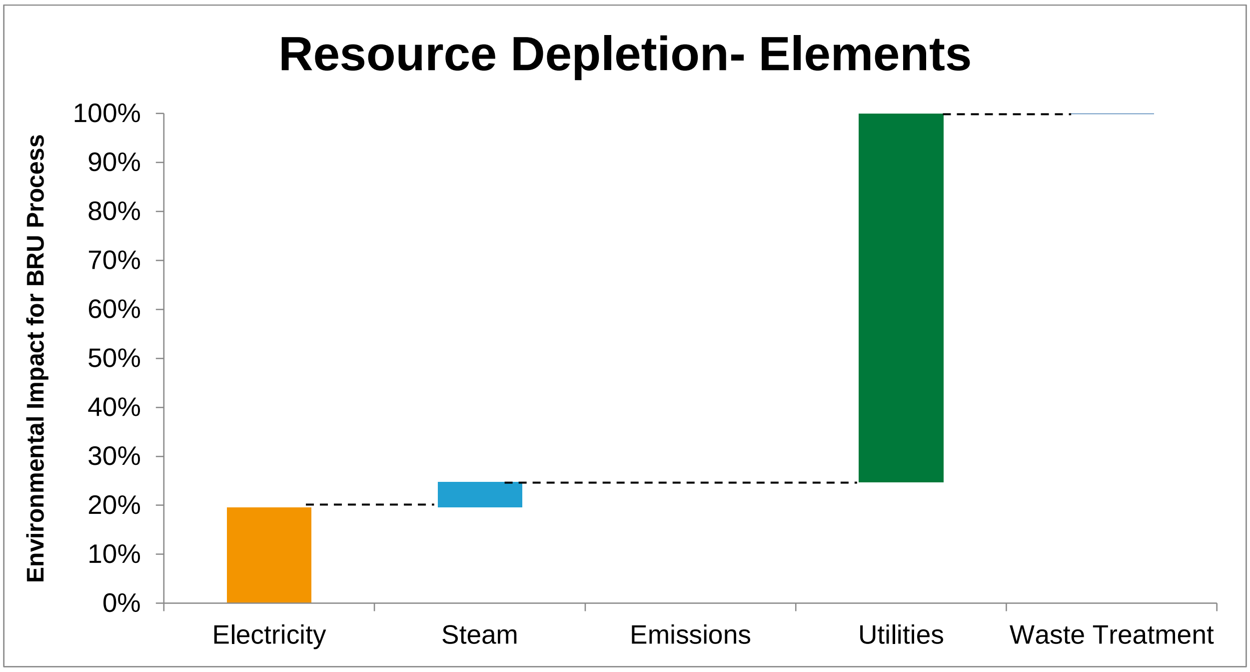

Figure 34: Different steps of the BRU contributing to resource depletion - elements [%]

The production processes of utilities mainly hydrazine and additionally sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 75%. The production of steam and electricity results in an impact of 25%. Direct process emissions have no influence in this impact category.

5.1.8 Human Toxicity - Cancer

For the evaluation of the human toxicity potential - cancer the USEtox model according to Rosenbaum et al. 2008 is used. The USEtox model has been developed specifically to assess potential impacts of toxic emissions in a comparative context such as LCA, providing characterization factors as substance-specific measures of relative impact potential. There are many sources of uncertainty in the process of human-health and environmental impact assessment. Many of these uncertainties, which are associated with knowledge or data gaps, are not reducible. [68]

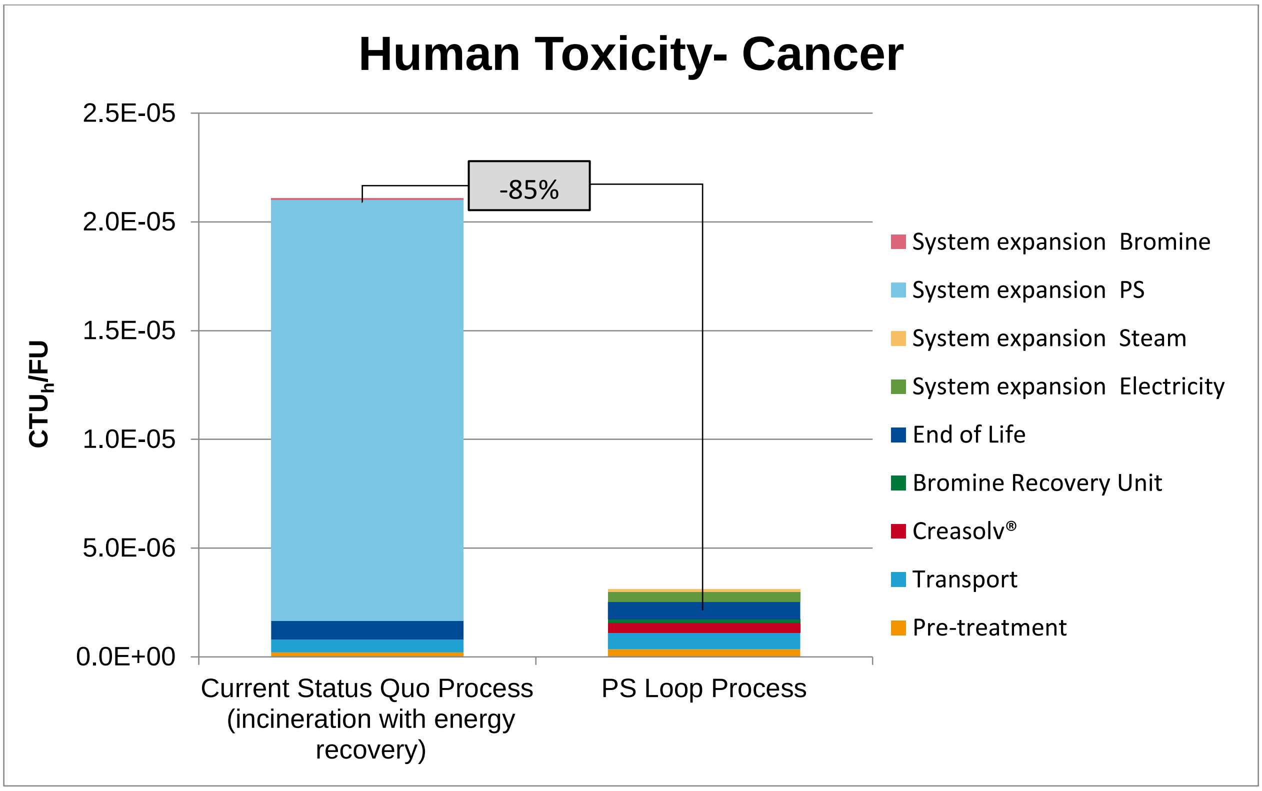

Figure 35: Human toxicity - cancer in CTU_h/FU

Human toxicity potential - cancer is higher for the Current Status Quo Process (incineration with energy recovery) in relation to the PS Loop Process (difference: 85%). Toxicity categories show significant differences, if one alternative results in a three times higher impact compared to the other one. This high difference is related to unreliable background data and low data availability for products and processes.

[68] USEtox®, 2017

Most important life cycle step is production of PS granulate to fulfill the requirements of the system expansion, related to resulting chromium emissions during the production of capital goods e.g. boiler. Solvent emissions during the CreaSolv® Process have no influence in this category (<1%). Main driver for the BRU is the needed utility hydrazine.

For a better understanding of the different processes further assessments for human toxicity - cancer effects were made. The following graph (Figure 36) illustrates the end of life phase of the Current Status Quo Process (incineration with energy recovery).

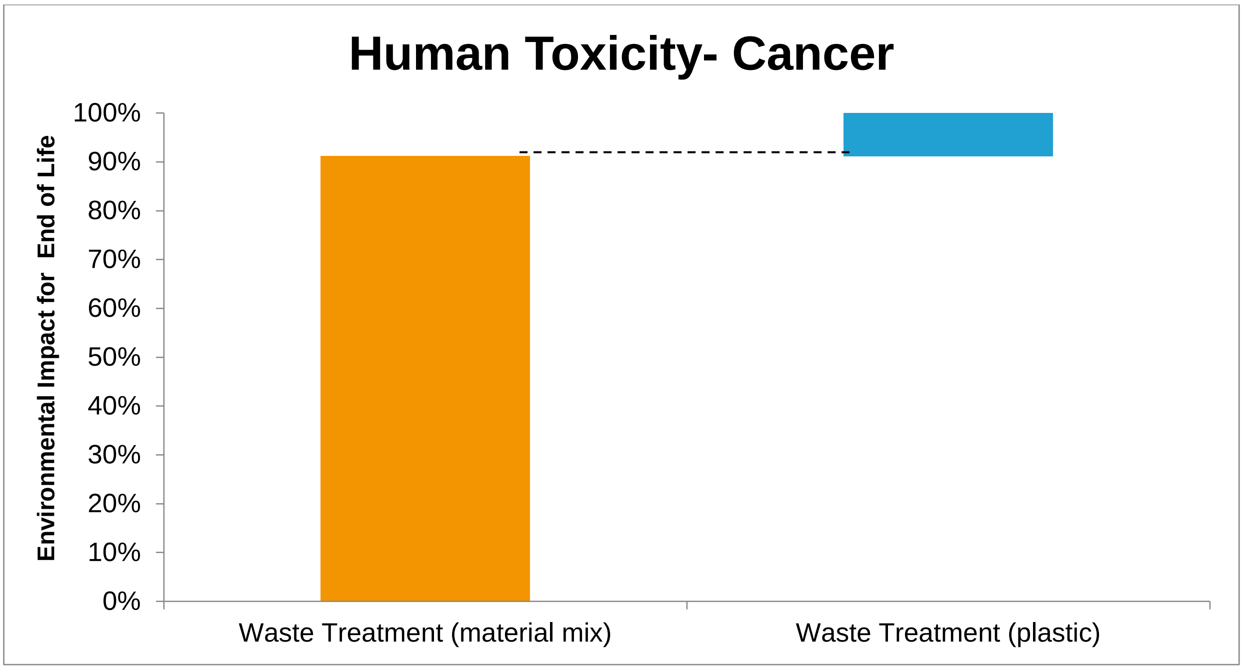

Figure 36: Human toxicity – cancer of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 91% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix (incineration of plastic (EPS and PE (dowels)) is related to 9%). Waste treatment of material mix includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 33 shows the human toxicity potential - cancer of different process steps within the CreaSolv® Process.

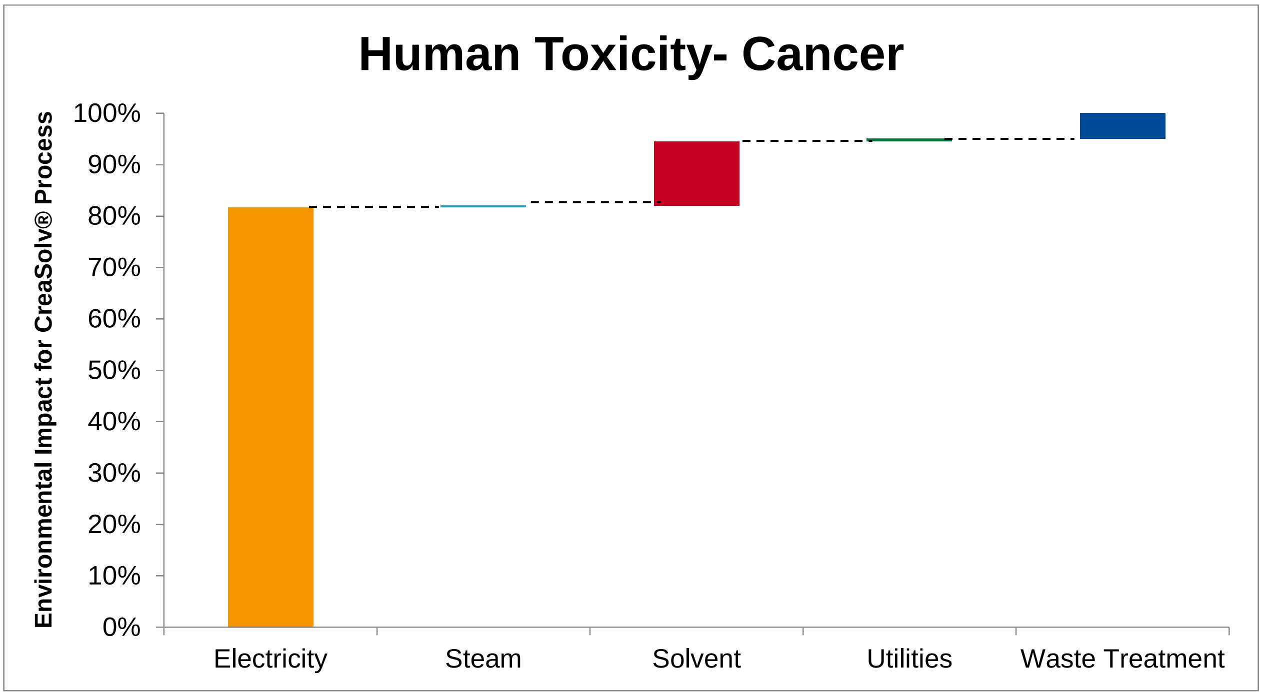

Figure 37: Different steps of the CreaSolv® Process contributing to human toxicity - cancer [%]

Main contributors of the CreaSolv® Process are electricity (82%) and production of used solvent (13%) due to resulting chromium emissions. Waste treatment is related to incineration of EPS, which cannot be further processed.

Figure 38 shows the human toxicity potential - cancer of different process steps within the BRU.

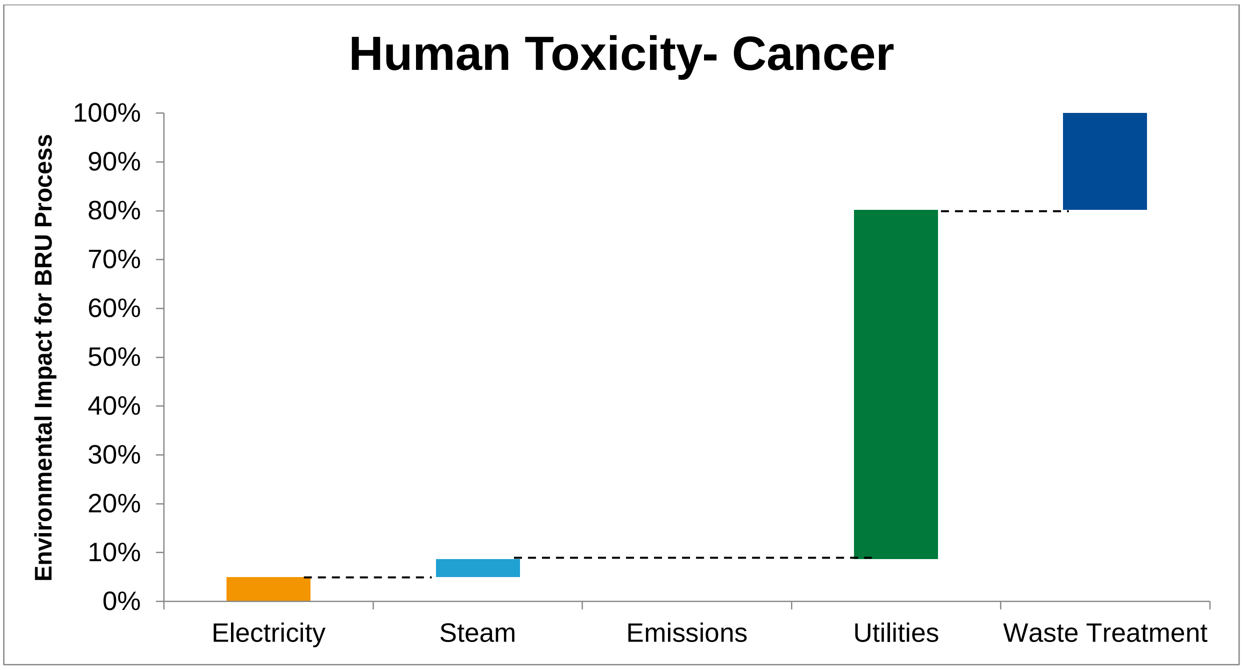

Figure 38: Different steps of the BRU contributing to human toxicity - cancer [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 72%. Direct process emissions have no influence in this impact category. Waste treatment of process water (wastewater treatment) leads to an influence of 20%, caused by chromium emissions.

5.1.9 Human Toxicity - Non-cancer

For the evaluation of the human toxicity potential - non-cancer the USEtox model according to Rosenbaum et al. 2008 is used. The USEtox model has been developed specifically to assess potential impacts of toxic emissions in a comparative context such as LCA, providing characterization factors as substance-specific measures of relative impact potential. There are many sources of uncertainty in the process of human-health and environmental impact assessment. Many of these uncertainties, which are associated with knowledge or data gaps, are not reducible. [69]

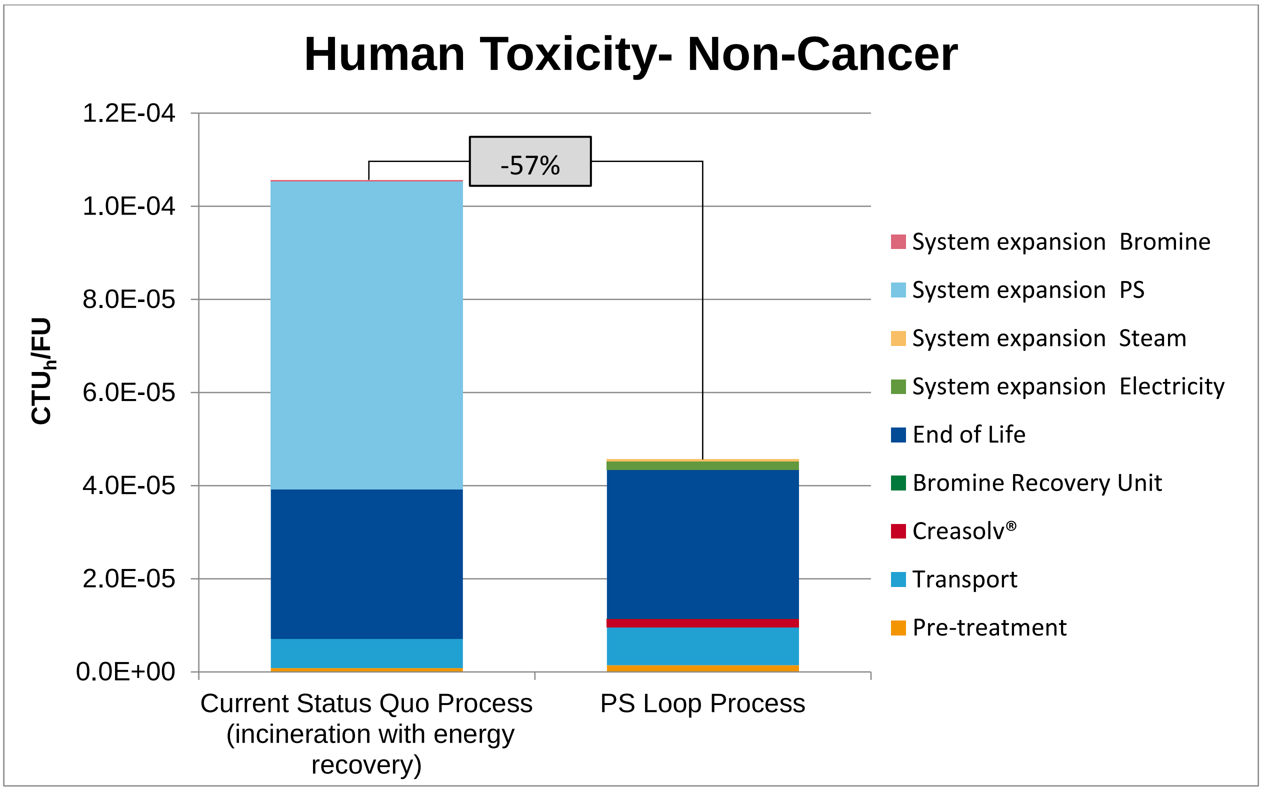

Figure 39: Human toxicity - non-cancer in CTU_h/FU

Human toxicity potential - non-cancer is higher for the Current Status Quo Process (incineration with energy recovery) in relation to the PS Loop Process (difference: 57%). No significant difference can be detected between these alternatives. Toxicity categories show significant differences, if one alternative results in a three times higher impact compared to the other one. This high difference is related to unreliable background data and low data availability for products and processes. Most important life cycle steps are incineration of the Material Mix A (see Table 2) during Current Status Quo Process (incineration with energy recovery) as well as production of PS granulate to fulfill the requirements of the system expansion. Main driver for these processes are lead and mercury emissions. End of life treatment of both alternatives are similar (low

[69] USEtox®, 2017

influence of incineration of PS and high influence of incineration of material mixes). System expansion is higher for the Current Status Quo Process (incineration with energy recovery) than for the PS Loop Process due to production of PS. Main impact of the CreaSolv® Process is the required electricity demand. Solvent emissions during the CreaSolv® Process have nearly no influence on the overall results (<1%). Impacts for transportation are slightly higher for the PS Loop Process due to a lower utilization rate (see chapter 4.4).

For a better understanding of the different processes further assessments for human toxicity - non-cancer effects were made. The following graph (Figure 40) illustrates the end of life phase of the Current Status Quo Process (incineration with energy recovery).

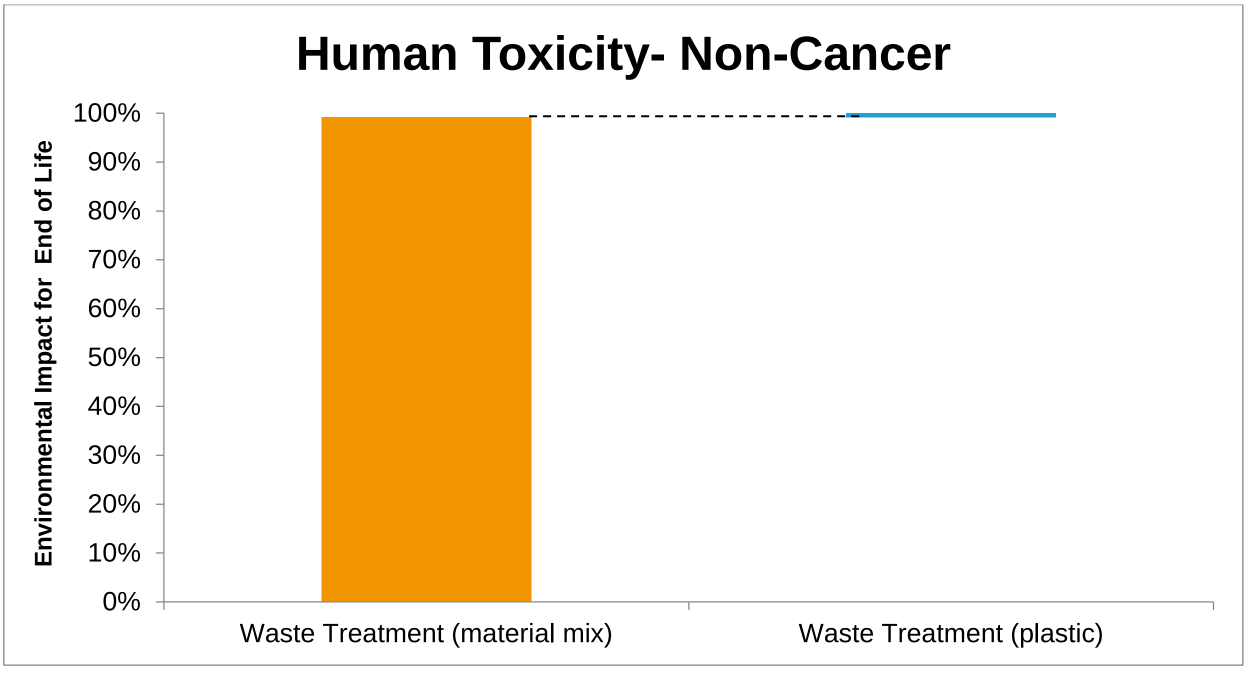

Figure 40: Human toxicity - non-cancer of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 99% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix (incineration of plastic (EPS and PE (dowels)) is related to 1%). Waste treatment of material mix includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 41 shows the human toxicity potential - non-cancer of different process steps within the CreaSolv® Process.

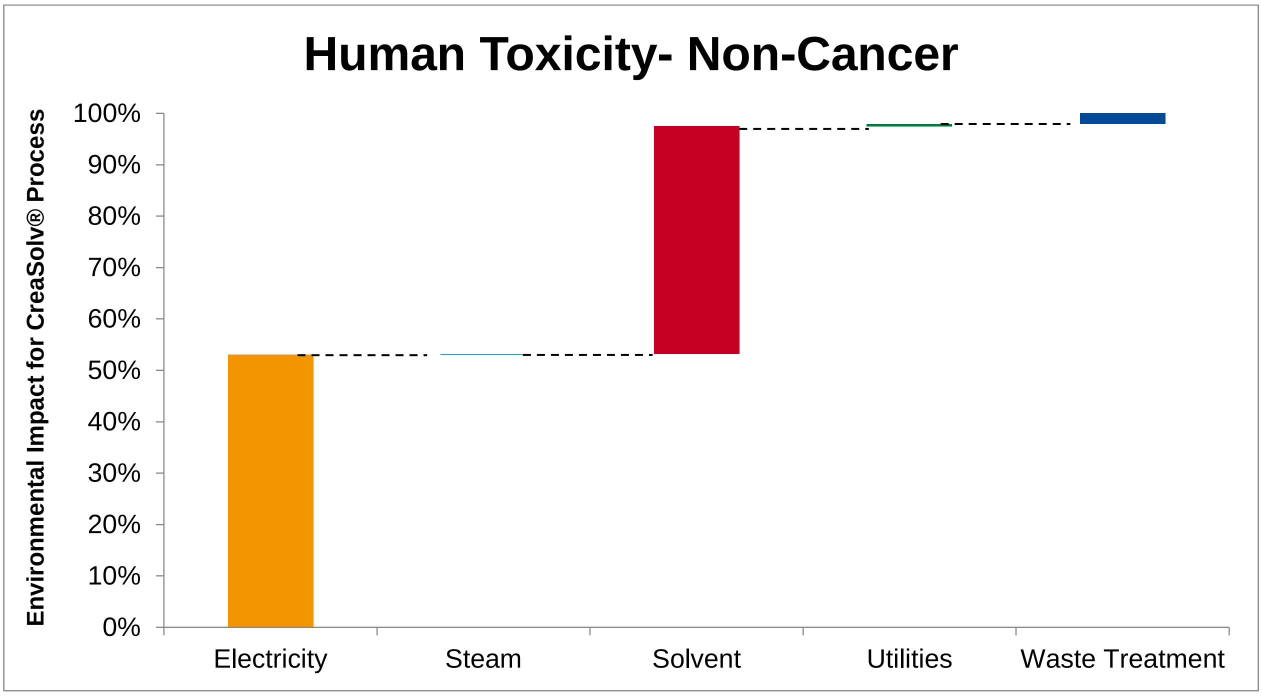

Figure 41: Different steps of the CreaSolv® Process contributing to human toxicity - non-cancer [%]

Main contributor of the CreaSolv® Process is the electricity demand (82%), due to use of zinc in upstream processes. Waste treatment is related to incineration of EPS, which cannot be further processed. The production of used solvent influences this process step by 44%, due to arsenic emissions.

Figure 42 shows the human toxicity potential - non-cancer of different process steps within the BRU.

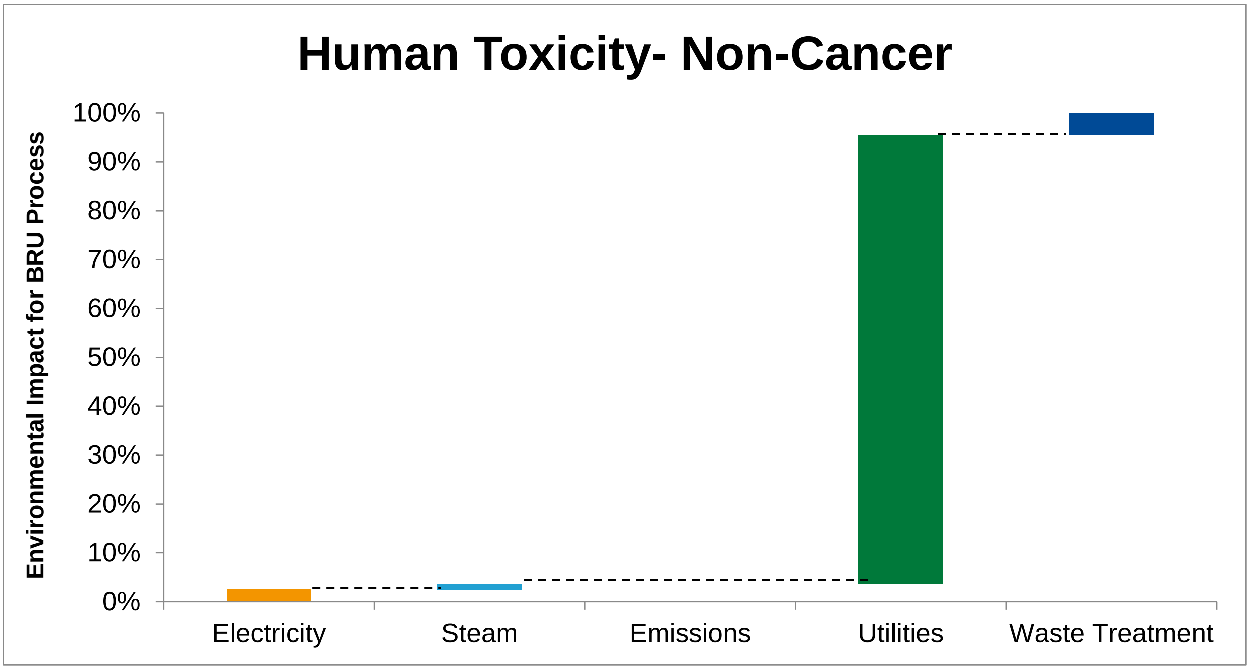

Figure 42: Different steps of the BRU contributing to human toxicity - non-cancer [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 92%. Direct process emissions have no influence in this impact category. Waste treatment of process water (wastewater treatment) leads to an influence of 5%, caused by mercury emissions.

5.1.10 Ecotoxicity - Freshwater

For the evaluation of the ecotoxicity - freshwater the USEtox model according to Rosenbaum et al. 2008 is used. The USEtox model has been developed specifically to assess potential impacts of toxic emissions in a comparative context such as LCA, providing characterization factors as substance-specific measures of relative impact potential. There are many sources of uncertainty in the process of human-health and environmental impact assessment. Many of these uncertainties, which are associated with knowledge or data gaps, are not reducible. [70]

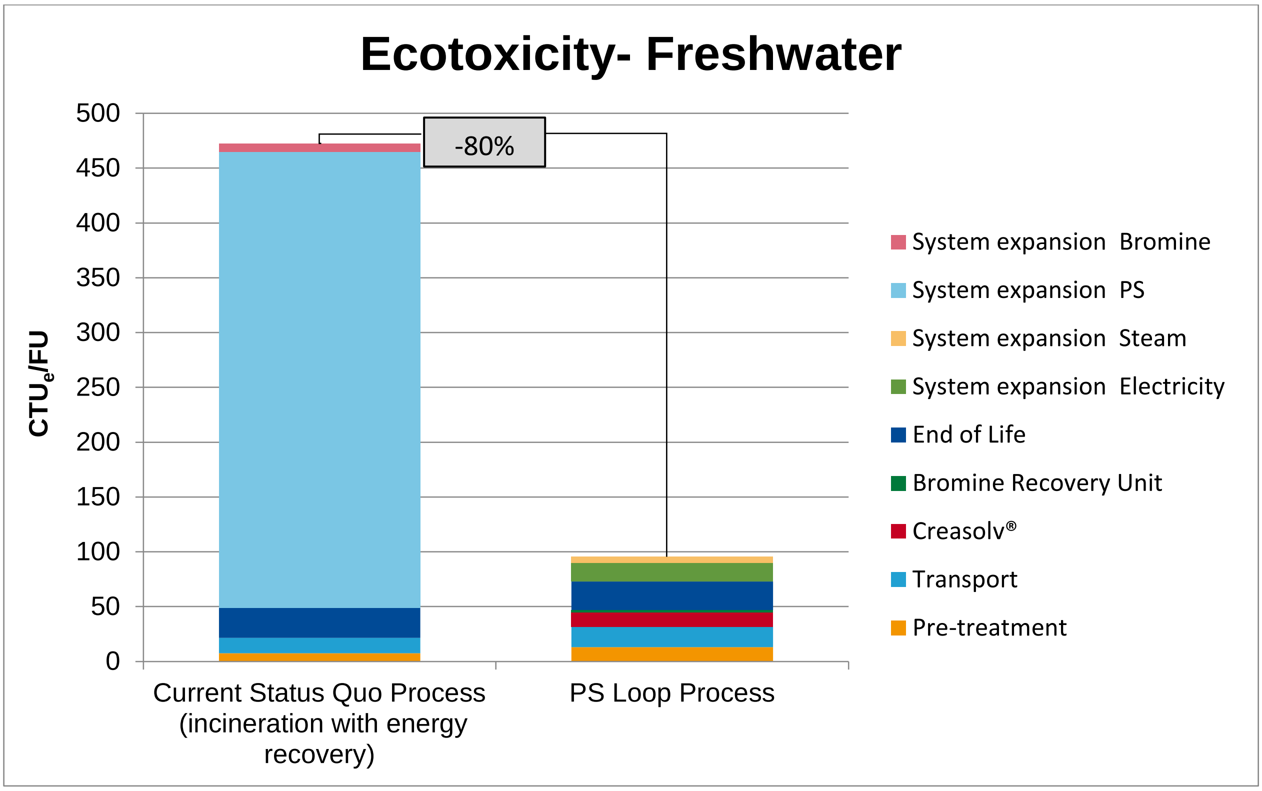

Figure 43: Ecotoxicity - freshwater in CTU_e/FU

Ecotoxicity potential is higher for the Current Status Quo Process (incineration with energy recovery) process in relation to the PS Loop Process (difference: 80%). Toxicity categories show significant differences, if one alternative results in a three times higher impact compared to the other one. This high difference is related to unreliable background data and low data availability for products and processes.

Most important life cycle step is production of PS granulate to fulfill the requirements of the system expansion. Main driver in this impact category are nickel emissions, which result from production of needed capital goods. Main driver for the BRU is the production of the utility hydrazine. Solvent emissions during the CreaSolv® Process have nearly no influence on the overall results (<1%).

[70] USEtox®, 2017

For a better understanding of the different processes further assessments for freshwater ecotoxicity were made. The following graph (Figure 44) illustrates the end of life phase of the Current Status Quo Process (incineration with energy recovery).

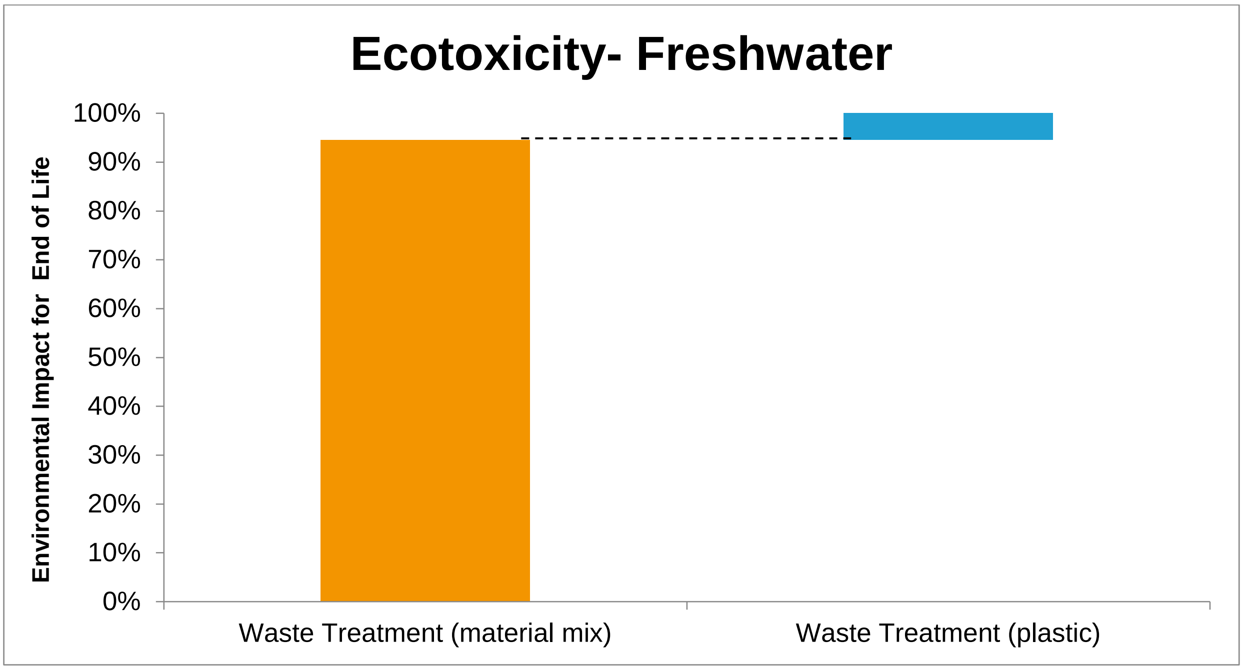

Figure 44: Ecotoxicity – freshwater of end of life for Current Status Quo Process (incineration with energy recovery) [%]

The main contributor with 95% of the Current Status Quo Process (incineration with energy recovery) is waste treatment of material mix (incineration of plastic (EPS and PE (dowels)) is related to 5%). Waste treatment of material mix A includes incineration of inert material (adhesives, plaster, fabrics and finishing coat), as well as landfilling and recycling of metals (dowels).

Figure 45 shows the freshwater ecotoxicity potential of different process steps within the CreaSolv® Process.

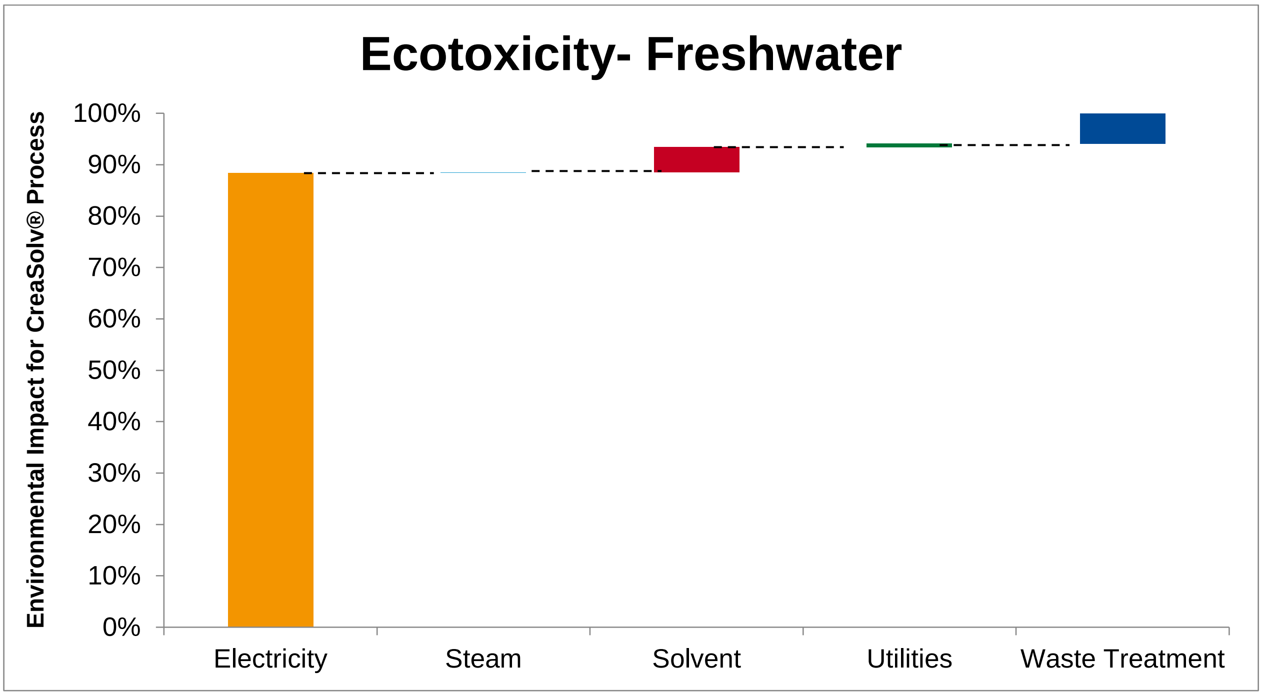

Figure 45: Different steps of the CreaSolv® Process contributing to ecotoxicity - freshwater [%]

Main contributor of the CreaSolv® Process is the electricity demand (82%), due to use of zinc, chromium and copper in upstream processes. Waste treatment is related to incineration of EPS, which cannot be further processed. The production of used solvent influences this process step by 5%.

Figure 46 shows the freshwater ecotoxicity potential of different process steps within the BRU.

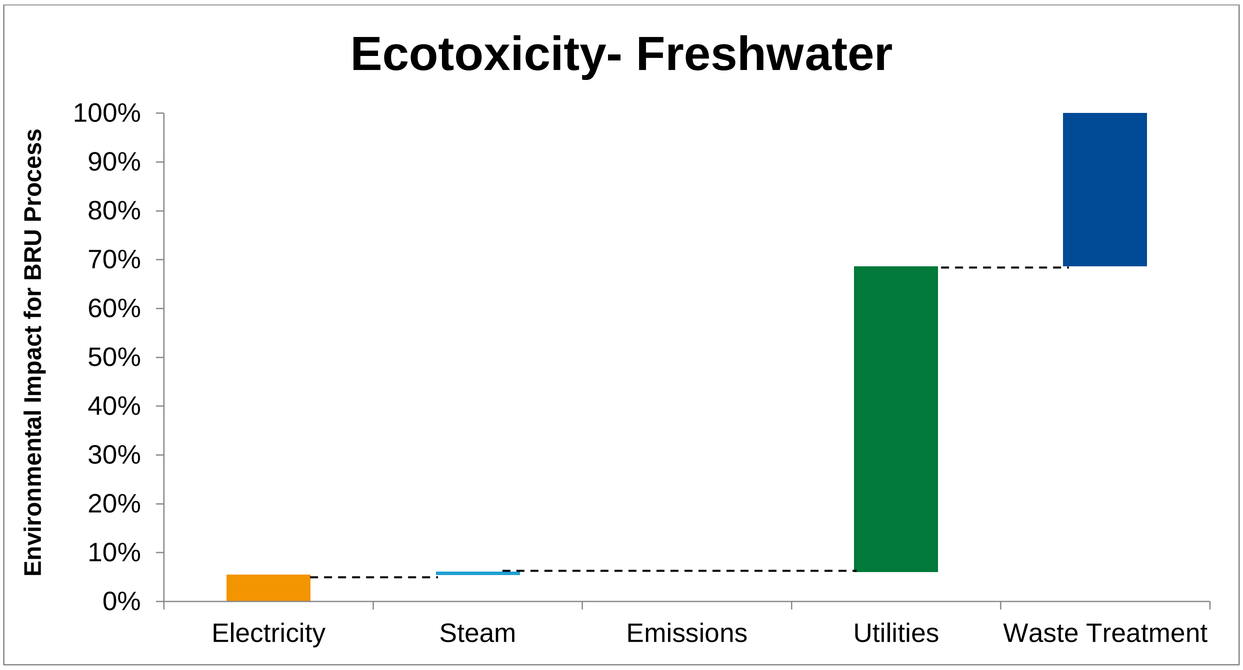

Figure 46: Different steps of the BRU contributing to ecotoxicity - freshwater [%]

The production processes of utilities like nitrogen, ammonia, hydrazine, sodium hydroxide, sodium formate and sodium bisulphite lead to an impact of 62%. Direct process emissions have no influence in this impact category. Waste treatment of process water (wastewater treatment) leads to an influence of 32%, caused by zinc and chromium emissions.

6. Interpretation of Results

6.1. Normalization

Normalization is considered as an optional element of an LCA. The LCIA results are normalized. Normalization means that the LCIA results are scaled with corresponding references and hence yield dimensionless results. Normalization values are regional statistical values (e.g. for this study: CO_2 eq. emissions emitted in Europe in one year) provided with standard market tools. These are EU statistics for the impact categories used in the European methods such as EU PEF[71]. The normalized value is calculated from the alternative impact divided by the respective statistical value. Normalized result shows the magnitude of a LCIA category result relative to environmental impacts caused by all citizens of the EU in one year.

Following calculation is carried out (e.g. LCIA category climate change for the PS Loop Process):

$$\begin{aligned}&\mathit{Normalized\ environmental\ impact\ for\ climate\ change}_{abs}\\&=\frac{\mathit{LCIA\ for\ climate\ change}(\mathit{see\ chapter}\ 5)}{\mathit{Normalization\ value\ for\ climate\ change}\ (\mathit{see\ table}\ 9)}\\&=\frac{3.4\cdot 10^{3}\ kg\ CO_2\ eq}{4.6\cdot 10^{12}\ kg\ CO_2\ eq}=\underline{\underline{7.5\cdot 10^{-10}}}\end{aligned}$$

$$\begin{aligned}&\mathit{Normalized\ environmental\ impact\ for\ climate\ change}_{\%}\\&=\frac{\mathit{Normalized\ environmental\ impact\ for\ climate\ change}_{abs}}{\sum \mathit{Normalized\ environmental\ impact\ for\ all\ LCIA\ categories}_{abs}}\times 100\%\\&=\frac{7.5\cdot 10^{-10}\ kg\ CO_2\ eq}{3.1\cdot 10^{-9}\ kg\ CO_2\ eq}\times 100\%=\underline{\underline{24.0\%}}\end{aligned}$$

[71] PEF Pilot Guidance, 2016

6.2. Normalized Environmental Results

The following Table 9 shows the used normalization values. These values are related to the environmental impact of one EU citizen in one year.

Table 9: Normalization values (sources: EU PEF, 2010[72], EU 27& CML, 2008, EU 28[73])

Impact Category	Unit	Normalization Value	Source
Climate change	kg CO_2 eq	4.6E+12	EU PEF, 2010, EU 27
Acidification	mol H^+ eq	2.4E+10	EU PEF, 2010, EU 27
Summer smog	kg NMVOC eq	1.6E+10	EU PEF, 2010, EU 27
Eutrophication- marine	kg N eq	8.4E+09	EU PEF, 2010, EU 27
Eutrophication- freshwater	kg P eq	7.4E+08	EU PEF, 2010, EU 27
Resource depletion - fossil	MJ	3.5E+13	CML, 2008, EU 28
Resource depletion - elements	kg Sb eq	1.6E+08	CML, 2008, EU 28
Human toxicity - cancer	CTU_h	1.8E+04	EU PEF, 2010, EU 27
Human toxicity – non-cancer	CTU_h	2.7E+05	EU PEF, 2010, EU 27
Ecotoxicity - freshwater	CTU_e	4.4E+12	EU PEF, 2010, EU 27

The normalization values of Institute of Environmental Sciences, Universities Leiden (CML) are additionally used, due to lack of appropriate data for resource depletion elements and fossil impacts in PEF Pilot Guidance, 2016.

Figure 47 illustrates the environmental impacts of the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process. All impact categories are weighted equal.

[72] PEF Pilot Guidance, 2016
[73] CML, 2015

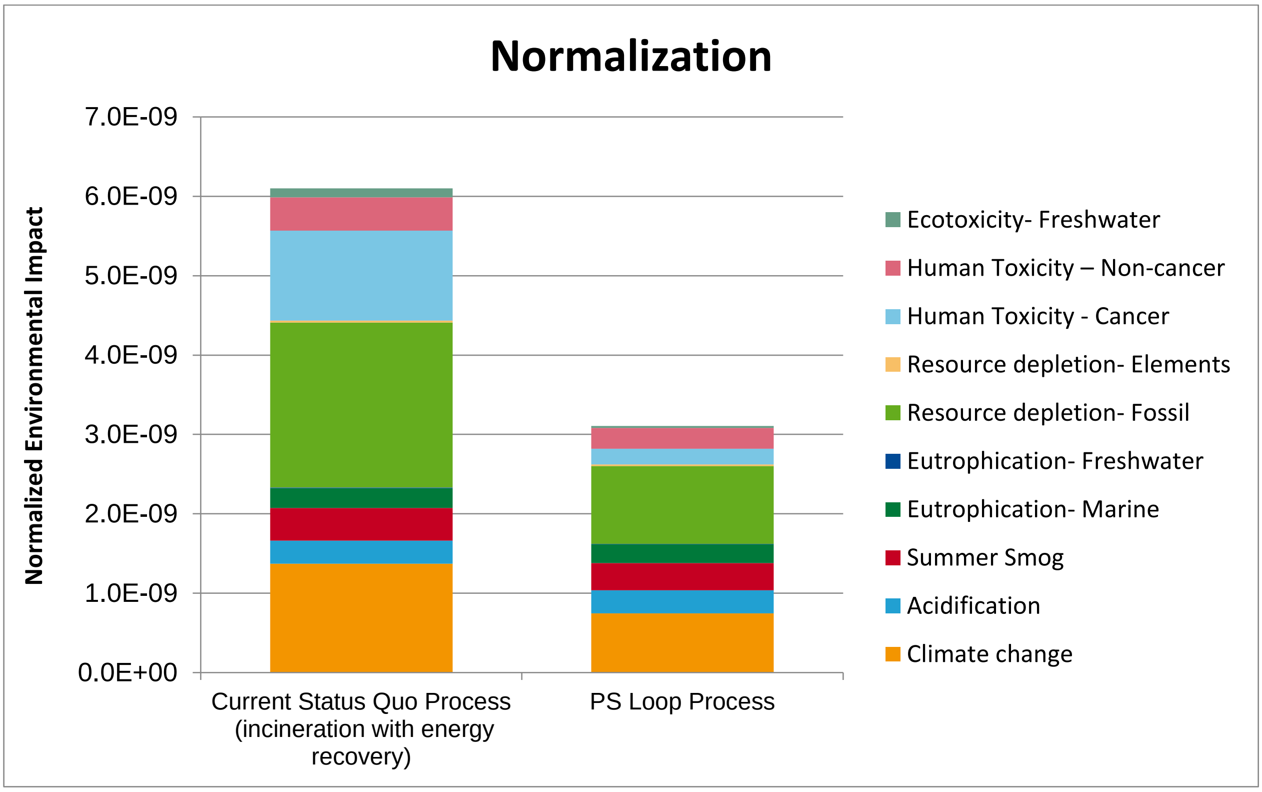

Figure 47: Normalized results for environmental impacts

The main contributors for the Current Status Quo Process (incineration with energy recovery) are resource depletion - fossil (34%), climate change (23%) and human toxicity – cancer (19%), due to production and incineration of PS to fulfill the requirements of system expansion. For the PS Loop Process also resource depletion - fossil (32%) and climate change (24%) have the highest influence. These occur mainly from production of heat and electricity for system expansion as well as from incineration of Material Mix B (see Table 2).

7. Discussion

7.1. Identification of Significant Parameters

System expansion (production of PS to fulfill the requirements) and end of life treatment (incineration of Material Mixes A and B, see Table 2) are the main driver on the overall environmental impacts.

The BRU has only a relevant impact on resource depletion - elements (ADPE) caused by the required utility hydrazine.

The CreaSolv® Process is no main driver for the overall results, but leads to visible influences in all considered impact categories. Main contributor of the CreaSolv® Process is the required energy demand.

Impacts for pre-treatment and transportation steps are always slightly higher for the PS Loop Process. The reason for higher impacts of pre-treatment is the higher energy demand for separation and compaction. Environmental impacts of transportation are slightly higher for the PS Loop Process than for the Current Status Quo Process (incineration with energy recovery) due to a lower utilization rate and longer transport distances (see chapter 4.4).

7.2. Sensitivity Analysis

The results show that the main influencing factors in this study are system expansion (main driver: production of virgin PS granulate) and end of life treatment of Material Mixes A and B as well as incineration of PS. Furthermore, the process step pre-treatment influences the overall results in some impact categories.

In order to investigate the robustness of the study results, and to avoid false interpretation of the results based on assumptions, sensitivity analyses were carried out by investigating the effect of the following parameter choices on impact results.

Following parameter variations (see Table 10) were considered:

Table 10: Sensitivity analyses

Scenario	Base Case Assumption	Scenario Assumption
1- Dismantling method	Demolition	Selective Deconstruction
2- Treatment of material mix A& B	Incineration	Landfill
3- Allocation approach	System expansion	50:50 allocation approach
4,5- Fractions of EPS in ETICS	10 wt%	12 wt%, 15 wt%, 100 wt%
6,7*-Settings for CreaSolv® Process	Table 6	Table 22, Table 24
8*- Settings for BRU process	Recovery rate 95 %	Recovery rate 90%
9- Electricity Grid Mixes	European grid mix	German and Dutch grid mix
10- Transport Distance	100 km	2,000 km
11- Treatment of Material Mix A& B	incineration	50% incineration/ 50% landfill

* Scenarios 6 to 8 were carried out to show different recovery rates of PS and use of various amounts of solvent (CreaSolv® Process) as well as different recovery rate of bromine (BRU process).

The following results are only shown for the impact category climate change.

Scenario 1- Different Dismantling Method of ETICS (Selective Deconstruction)

In the base case demolition (deconstruction with use of tools e.g. hammer drill) of the house was considered. To show the influence of a different deconstruction method (selective deconstruction, mainly manual) a scenario was considered. Thus a lower energy demand for separation is needed.

For the Current Status Quo Process (incineration with energy recovery) in scenario 1 the following distances were considered (for PS Loop Process no changes occur).

Table 11: Input data scenario 1 - transport

Material	(A→ B)	Distance [km]	Utilization Rate [%]
Current Status Quo Process (incineration with energy recovery), selective deconstruction			
EPS	Separation site to incineration plant	100	11
Metals	Separation site to recycling plant	100	85
Plastics	Separation site to incineration plant	100	85
Inert material	Separation site to incineration plant	100	85

It was assumed, that all materials were transported separately. Therefore, only the utilization rate of EPS is lower than 85%, due to the relative low density of EPS.

Table 8 illustrates all input data of the Current Status Quo Process (incineration with energy recovery) for scenario 1. For the PS Loop Process only the energy demand for separation is lower (0.01 MJ/kg ETICS), due to a higher EPS-purity in the waste stream.

Table 12: Input data scenario 1 - process data

Input	Amount	Unit	Source
Current Status Quo Process (incineration with energy recovery), selective deconstruction			
Electricity (selective)	0.20	MJ/kg ETICS	Assumption
Transport dismantling to incineration plant	100	km	Assumption
Electricity (separation)	0.01	MJ/kg ETICS	Assumption
Disposal (incineration)	0.05	kg/kg ETICS	Assumption
EPS	1.00	kg/kg ETICS	Albrecht et al., 2014
PP/ PE (dowel)	0.01	kg/kg ETICS	Albrecht et al., 2014
Metals	0.05	kg/kg ETICS	Albrecht et al., 2014
Adhesive, plaster, fabrics, finishing coat	7.79	kg/kg ETICS	Albrecht et al., 2014

The results for scenario 1 are shown in Figure 48.

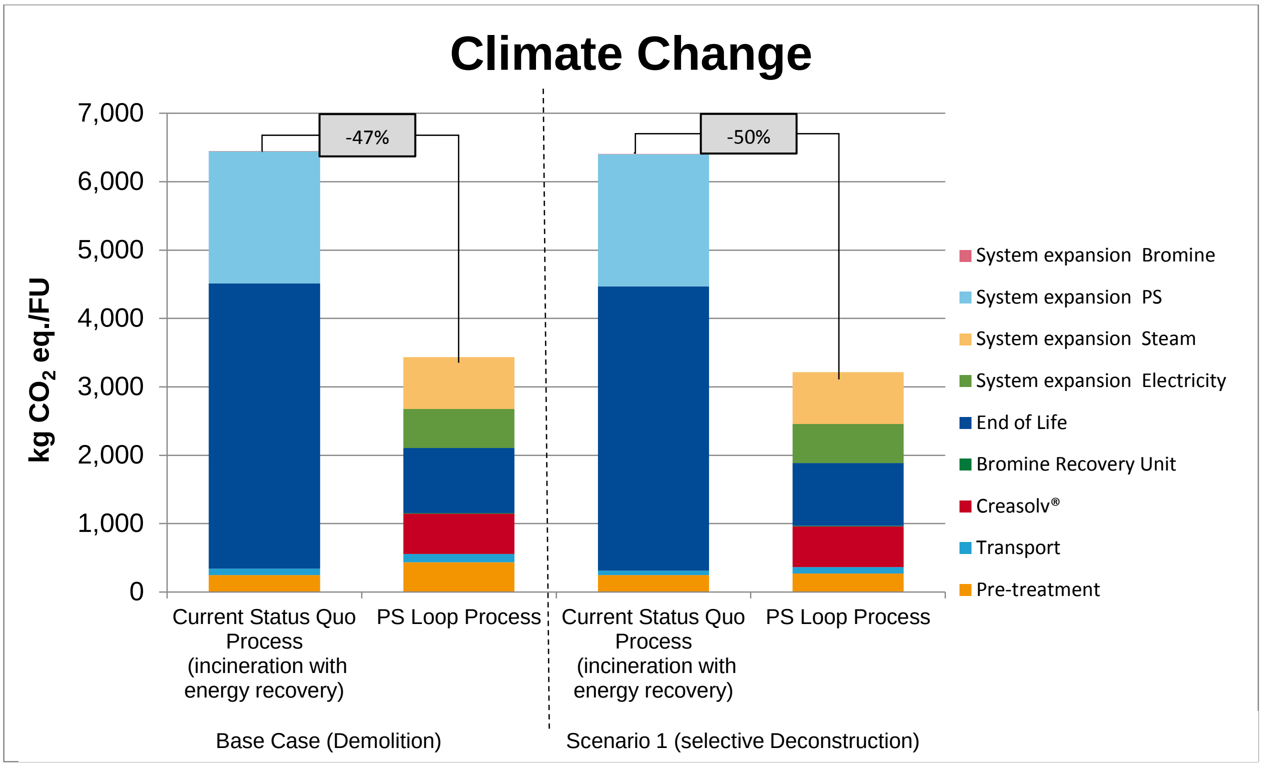

Figure 48: Climate change in kg CO_2 eq/FU - scenario 1

No significant differences occur between the Current Status Quo Process (incineration with energy recovery) and PS Loop Process for climate change if another deconstruction method is used (3% difference).

The overall results for other impact categories are displayed in Table 13.

Table 13: Additional Life Cycle Impact Assessment results- scenario 1

Impact Category	Unit	Scenario 1 Current Status Quo	Scenario 1 PS Loop Process	Difference Scenario 1	Difference Base Case
Acidification	mol H+ eq	7.3	6.8	-7%	+2%
Summer smog	kg NMVOC	6.8	5.5	-20%	-15%
Eutrophication, marine	kg N eq	2.3	2.1	-8%	-3%
Eutrophication, freshwater	kg P eq	6.5E-03	4.9E-03	-32%	-26%
Resource depletion, fossil	MJ	7.4E+04	3.4E+04	-54%	-51%
Resource depletion, elements	kg Sb eq	7.7E-04	5.8E-04	-25%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	2.8E-06	-86%	-85%
Human toxicity – non-cancer	CTU_h	1.0E-04	4.5E-05	-57%	-57%
Ecotoxicity - freshwater	CTU_e	469	89.2	-81%	-80%
Primary energy demand	MJ	8.2E+04	5.1E+04	-37%	-32%

The numbers of column “difference scenario 1”are calculated as follows (e.g. Acidification):

$$1-\frac{(6.8\ \mathrm{mol\ H^+\ eq})}{(7.3\ \mathrm{mol\ H^+\ eq})}\times 100\% = \underline{\underline{7\%}}$$

Calculation for other LCIA categories are the same as well as for other additional LCIA results tables in chapter 7.2.

For detailed information of difference between the two base case processes see chapter executive summary (Table 1) and chapter 5. No significant differences result for other considered impact categories by assuming a different deconstruction method.

Scenario 2- Demolition with Landfill of Material Mix A and B

In the base case both Material Mixes were incinerated (without credits due to system expansion). This scenario considers only landfilling of inert material to show the influence of a different end of life method. Still, some European countries do not recover waste in incineration plants but use landfills to dispose of the waste. This is why this scenario has also been taken into account.

The following table shows the different end of life treatments for scenario 2. Therefore, the Material Mixes end up on landfill instead of incineration.

Table 14: Input data scenario 2

Process	Material	Treatment	Source
Current process, demolition	Material Mix A	89.5 wt% landfill of inert material 10.1% incineration of plastics (10.0 wt% EPS and 0.1 wt% PE (dowels) metals (0.4 wt%): 90 wt% recycling/ 10 wt% landfill	IWARU Technical Center of FH Münster
PS Loop Process	Material Mix B	89.5 wt% landfill of inert material and incineration of 0.1 wt% PE (dowels), metals (0.4 wt%): 90 wt% recycling/ 10 wt% landfill	IWARU Technical Center of FH Münster
	EPS (10%)	Recycling (CreaSolv® Process)	-

The results for climate change for scenario 2 are shown in Figure 49.

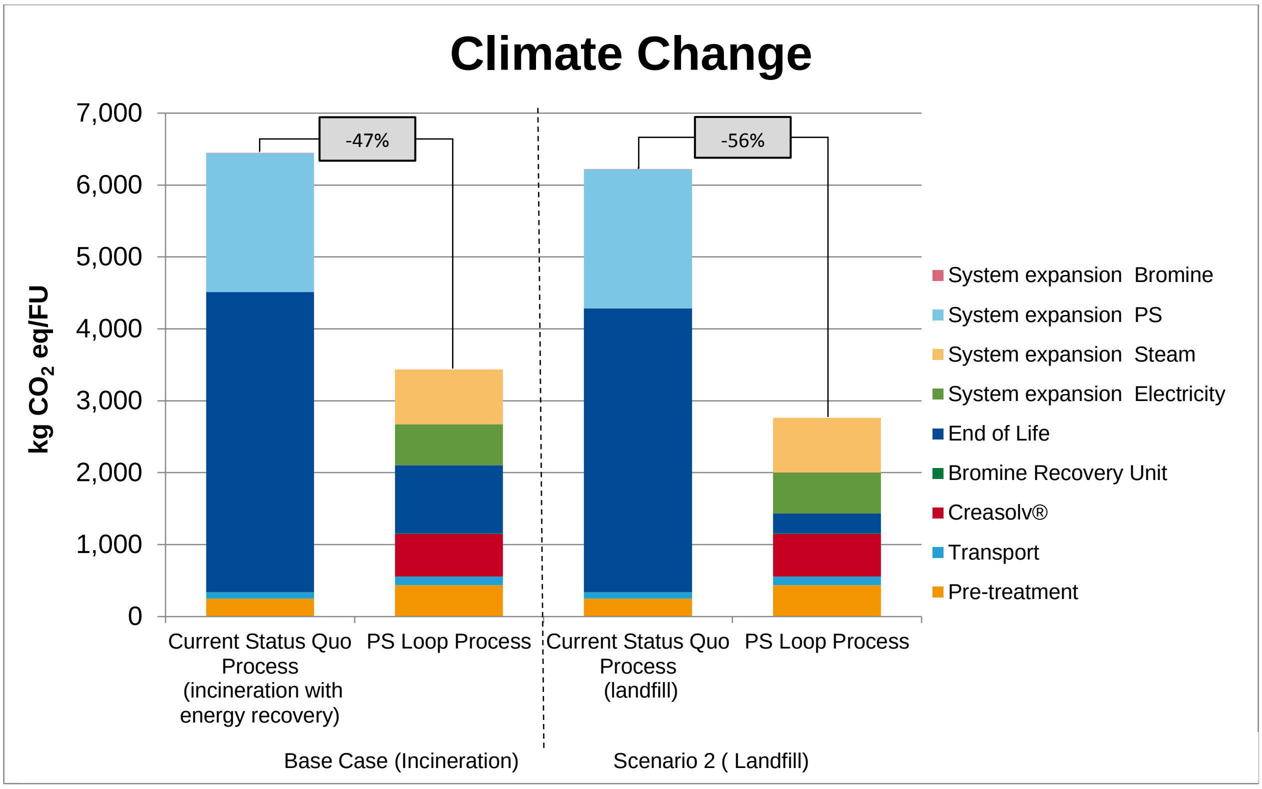

Figure 49: Climate change in kg CO_2 eq/FU - scenario 2

Consideration of landfilling instead of incineration of inert material (base case assumption) leads to an increase (base case - 47 %, scenario 2 - 56%) of the difference between the Current Status Quo Process and the PS Loop Process for climate change. Consequentially a different treatment method for the inert material leads to no significant changes (difference: 9%) in this impact category.

The overall results for other impact categories are displayed in Table 15.

Table 15: Additional Life Cycle Impact Assessment results- scenario 2

Impact Category	Unit	Scenario 2 Current Status Quo	Scenario 2 PS Loop Process	Difference Scenario 2	Difference Base Case
Acidification	mol H+ eq	6.3	6.4	+1%	+2%
Summer smog	kg NMVOC	5.2	4.1	-20%	-15%
Eutrophication, marine	kg N eq	1.6	1.6	-4%	-3%
Eutrophication, freshwater	kg P eq	8.6E-3	7.0E-03	-19%	-26%
Resource depletion, fossil	MJ	6.8E+04	3.0E+04	-56%	-51%
Resource depletion, elements	kg Sb eq	8.0E-04	6.5E-04	-19%	-17%
Human toxicity - cancer	CTU_h	2.2E-05	3.9E-06	-82%	-85%
Human toxicity – non-cancer	CTU_h	1.8E-04	1.2E-04	-49%	-57%
Ecotoxicity - freshwater	CTU_e	470	93.6	-80%	-80%
Primary energy demand	MJ	7.4E+04	4.8E+04	-36%	-32%

No significant differences result for other considered impact categories by assuming landfilling of inert material instead of incineration.

Scenario 3 - 50:50 Allocation Approach

In the base case a system expansion is considered. Therefore, no credits were given for avoided production process of bromine, PS, electricity and heat. To evaluate the impacts occurring from the allocation method choice a 50:50 allocation approach (see chapter 3.5). was used instead of system expansion. Therefore 50% of the resulting credits caused by the avoided production of PS, bromine, electricity and steam were considered in these product systems.

To gain a complete picture both deconstruction methods: demolition (base case) and selective deconstruction (scenario 1) were considered.

The results for climate change for scenario 3 are shown in Figure 50 and Figure 51.

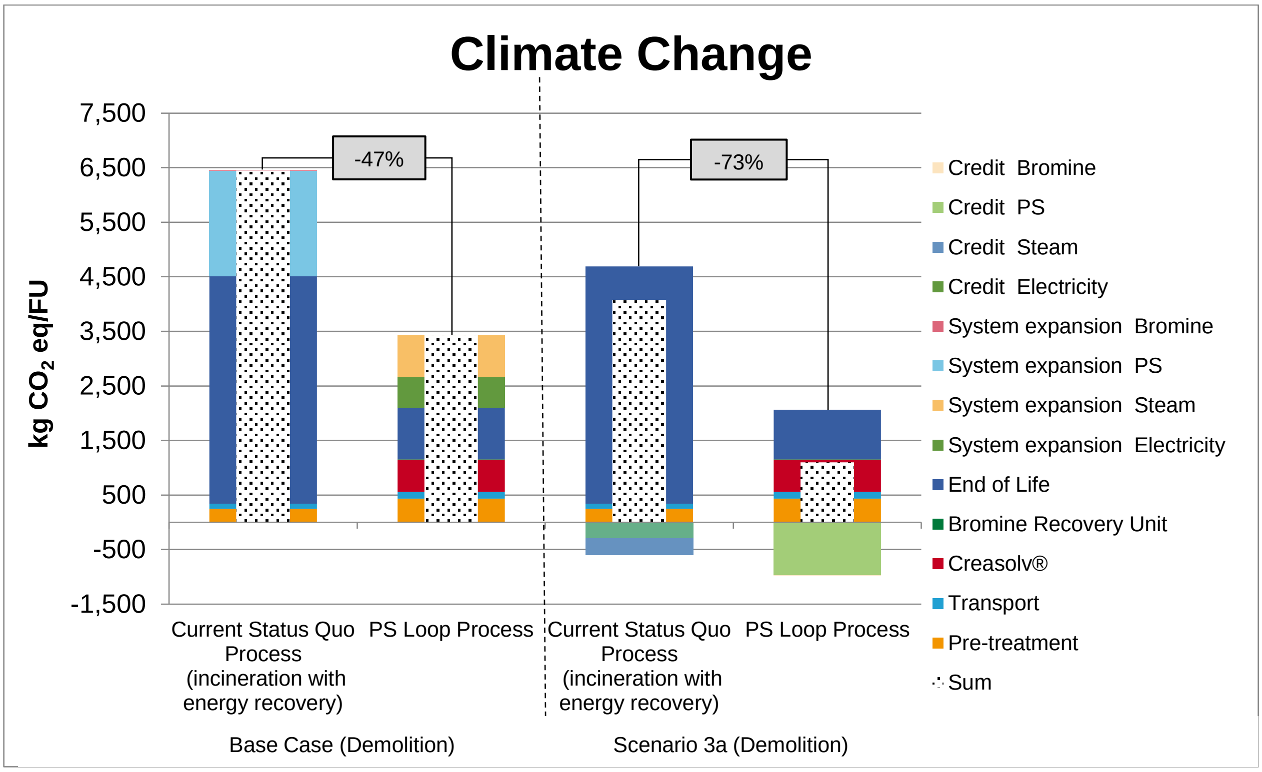

Figure 50: Climate change in kg CO_2 eq/FU - scenario 3a (demolition)

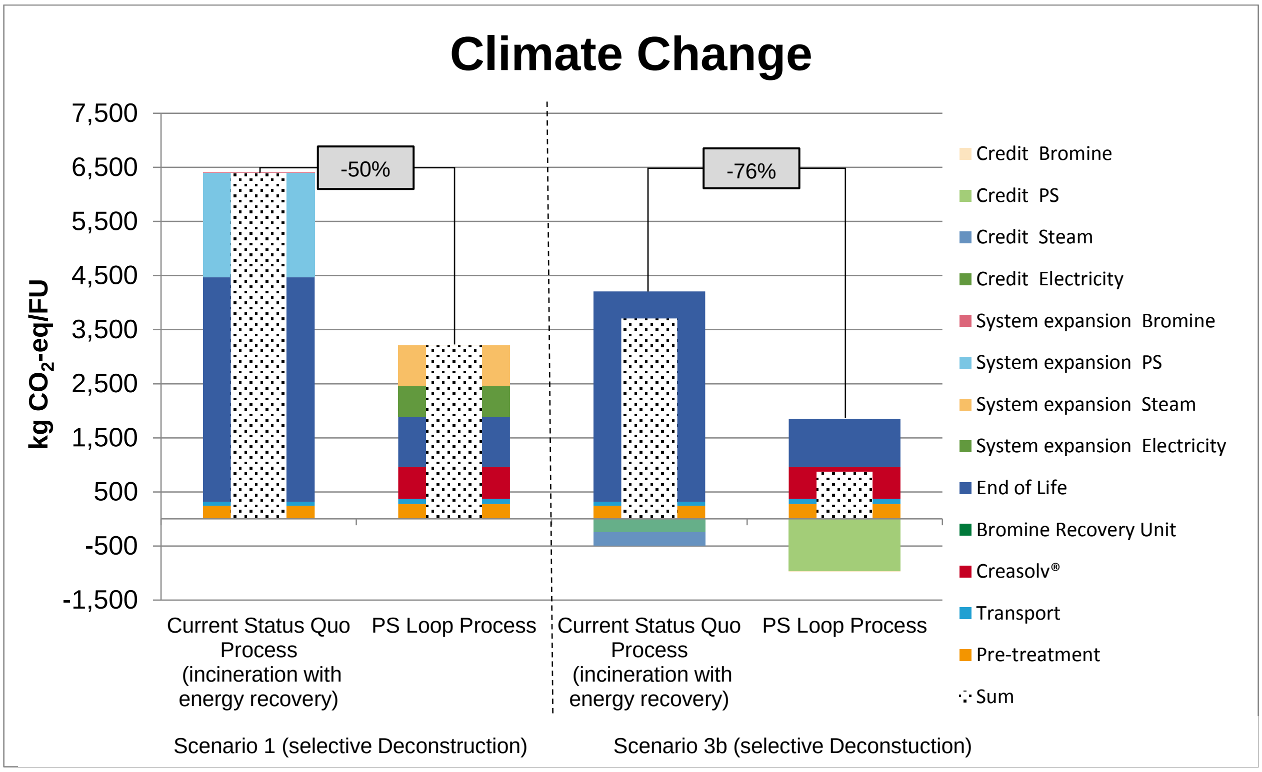

Figure 51: Climate change in kg CO_2 eq/FU - scenario 3b (selective deconstruction)

The overall results for other impact categories are displayed in Table 16 and Table 17.

Table 16: Additional Life Cycle Impact Assessment results- scenario 3a

Impact Category	Unit	Scenario 3a Current Status Quo	Scenario 3a PS Loop Process	Difference Scenario 3a	Difference Base Case
Acidification	mol H+ eq	2.0	2.5	+27%	+2%
Summer smog	kg NMVOC	2.4	2.2	-7%	-15%
Eutrophication, marine	kg N eq	1.0	1.1	+11%	-3%
Eutrophication, freshwater	kg P eq	1.0E-03	7.1E-04	-99%	-26%
Resource depletion, fossil	MJ	-5.7E+01	-1.6E+04	279.26	-51%
Resource depletion, elements	kg Sb eq	-2.6E-05	-8.1E-06	-69%	-17%
Human toxicity - cancer	CTU_h	1.3E-06	-7.4E-06	-6.92	-85%
Human toxicity – non-cancer	CTU_h	3.7E-05	9.2E-06	-75%	-57%
Ecotoxicity - freshwater	CTU_e	33.2	-142	5.40	-80%
Primary energy demand	MJ	-331	-7.6E+03	21.99	-32%

Table 17: Additional Life Cycle Impact Assessment results- scenario 3b

Impact Category	Unit	Scenario 3b Current Status Quo	Scenario 3b PS Loop Process	Difference Scenario 3b	Difference Scenario 1
Acidification	mol H+ eq	2.1	1.8	-12%	-7%
Summer smog	kg NMVOC	2.5	1.8	-27%	-20%
Eutrophication, marine	kg N eq	1.0	0.9	-7%	-8%
Eutrophication, freshwater	kg P eq	1.1E-03	2.1E-04	-81%	-32%
Resource depletion, fossil	MJ	1.2E+03	-1.8E+04	-16.67	-54%
Resource depletion, elements	kg Sb eq	-6.7E-06	-7.5E-05	10.15	-25%
Human toxicity - cancer	CTU_h	1.2E-06	-7.7E-06	-7.63	-86%
Human toxicity – non-cancer	CTU_h	3.6E-05	8.4E-06	-77%	-57%
Ecotoxicity - freshwater	CTU_e	31.9	-153	-5.78	-81%
Primary energy demand	MJ	2.2E+03	-1.2E+04	-6.59	-37%

By using the 50:50 approach instead of system expansion the differences between the Current Status Quo Process (incineration with energy recovery) and PS Loop Process are significantly higher. Thus a different allocation method leads to significant changes in this impact category. However, the PS Loop Process result in a lower GWP independent of what allocation method is used for evaluation. Main driver for resulting differences occurs from given credits for avoided PS and bromine production (PS Loop Process alternative), as well as for avoided steam and electricity production (see chapter 3.4).

For the Current Status Quo Process (incineration with energy recovery) 50% credits for avoided electricity and steam production as well as 50% burden of incineration process are taken into account. These energy products occur from the incineration of the respective Material Mix A incl. EPS[74] (all ETICS components). The PS Loop Process is modelled with 50% burden for recycling efforts and 50% credits for avoided production efforts of PS granulate and bromine. These are the products from the CreaSolv® Process and the BRU. As shown in Table 16 and Table 17 significant differences result for most of other considered impact categories, due to applied 50:50 allocation approach.

[74] Further Information can be found in Table 2.

Scenario 4a & b - Different Masses of EPS in Installed ETICS Components

In the base case a fraction of 10% EPS in ETICS was considered. To show the influence of a higher percentage of EPS in ETICS two scenarios are calculated.

The following table shows the different masses of ETICS compounds for scenario 4a and b. Scenario 4a considers a fraction of 12% EPS and scenario 4b a fraction of 15% EPS.

Table 18: Input data scenario 4a & b

Material	Base case	Scenario 4a	Scenario 4b
Adhesive	31.6%	30.9%	29.8%
EPS	10.0%	11.8%	15.0%
Mortar	32.2%	31.6%	30.4%
Reinforcing fabric	1.5%	1.4%	1.4%
Top coat	24.2%	23.7%	22.8%
Dowel	0.5%	0.6%	0.6%

The results for climate change for scenario 4a & b are shown in Figure 52.

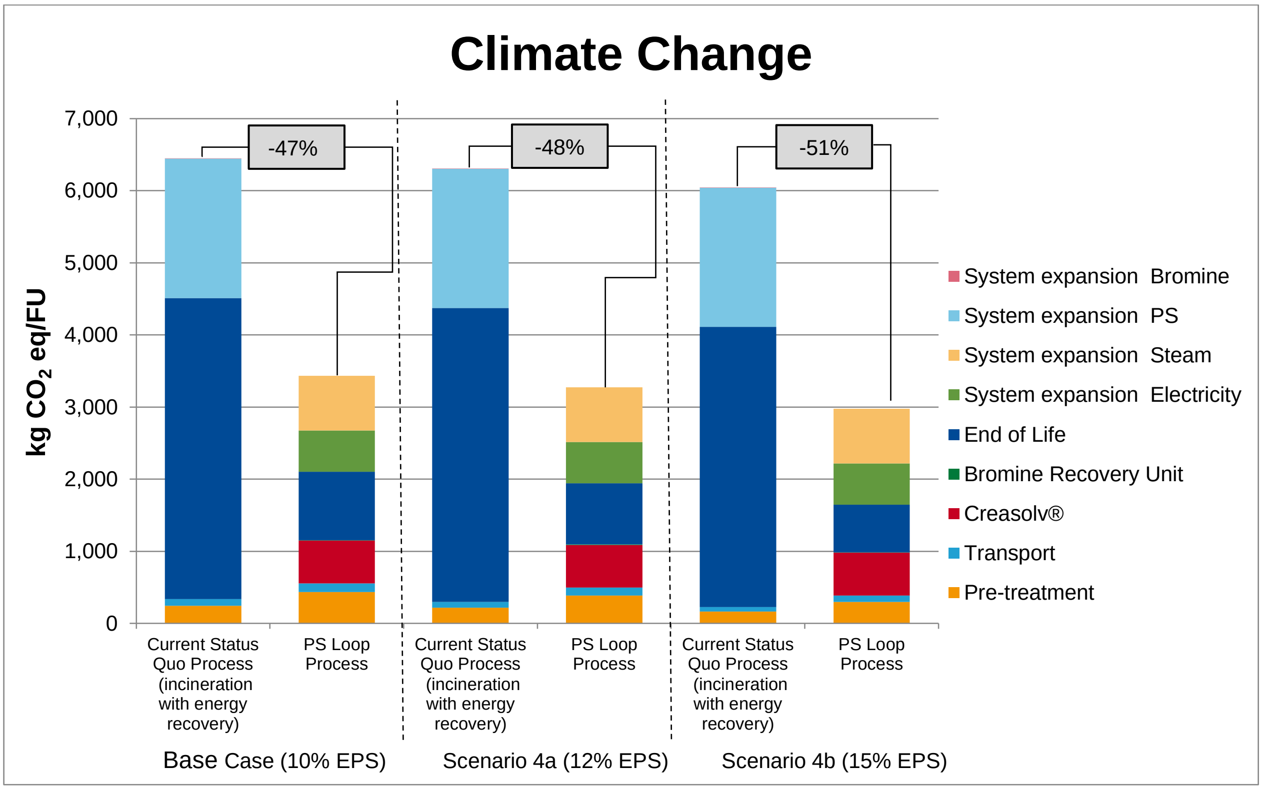

Figure 52: Climate change in kg CO_2 eq/FU - scenario 4a & b

No significant difference (difference between 1 % and 4 %) between the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process occur for climate change if another EPS fraction in ETICS is considered. Consequentially a higher fraction of EPS leads to no significant changes in this impact category.

The overall results for other impact categories are displayed in Table 19 and Table 20.

Table 19: Additional Life Cycle Impact Assessment results- scenario 4a

Impact Category	Unit	Scenario 4a Current Status Quo	Scenario 4a PS Loop Process	Difference Scenario 4a	Difference Base Case
Acidification	mol H+ eq	7.0	7.0	+1%	+2%
Summer smog	kg NMVOC	6.5	5.5	-16%	-15%
Eutrophication, marine	kg N eq	2.1	2.1	-4%	-3%
Eutrophication, freshwater	kg P eq	6.4E-03	4.6E-03	-27%	-26%
Resource depletion, fossil	MJ	7.3E+04	3.5E+04	-52%	-51%
Resource depletion, elements	kg Sb eq	7.6E-04	6.2E-04	-18%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	2.9E-06	-86%	-85%
Human toxicity – non-cancer	CTU_h	1.0E-04	4.1E-05	-60%	-57%
Ecotoxicity - freshwater	CTU_e	467	89.2	-81%	-80%
Primary energy demand	MJ	8.0E+04	5.3E+04	-33%	-32%

Table 20: Additional Life Cycle Impact Assessment results- scenario 4b

Impact Category	Unit	Scenario 4b Current Status Quo	Scenario 4b PS Loop Process	Difference Scenario 4b	Difference Base Case
Acidification	mol H+ eq	6.2	6.2	-1%	+2%
Summer smog	kg NMVOC	5.7	4.6	-19%	-15%
Eutrophication, marine	kg N eq	1.8	1.7	-5%	-3%
Eutrophication, freshwater	kg P eq	5.9E-03	4.1E-03	-31%	-26%
Resource depletion, fossil	MJ	7.1E+04	3.2E+04	-55%	-51%
Resource depletion, elements	kg Sb eq	7.2E-04	5.7E-04	-21%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	2.5-06	-88%	-85%
Human toxicity – non-cancer	CTU_h	9.1E-05	3.1E-05	-66%	-57%
Ecotoxicity - freshwater	CTU_e	456	77.1	-83%	-80%
Primary energy demand	MJ	7.6E+04	4.9E+04	-36%	-32%

No significant differences result for other considered impact categories by assuming different masses of EPS for installed ETICS components.

Scenario 5 - Consideration of 100% EPS

In the base case ETICS with a fraction of 10 wt% EPS was considered. To show the influence of EPS without other materials (100 wt%) this scenario was calculated. The results for climate change are illustrated in Figure 53.

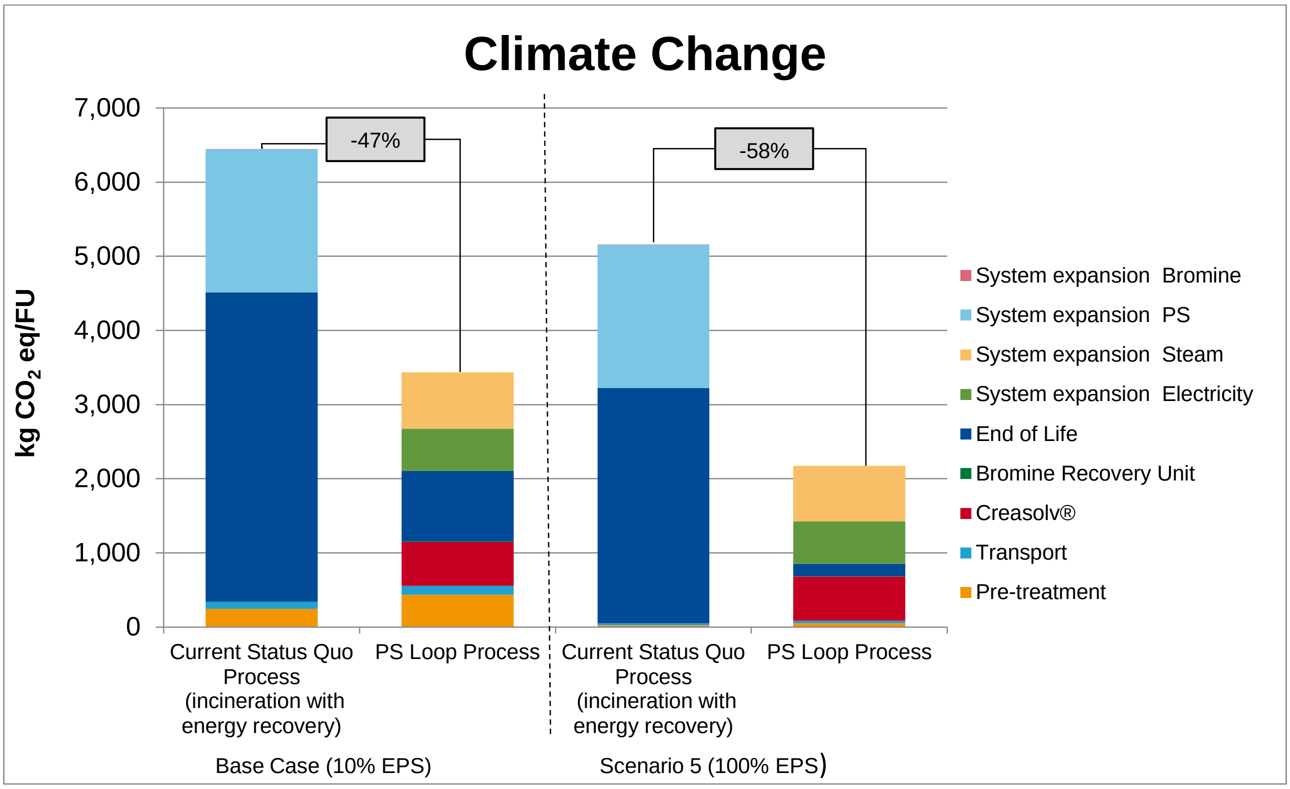

Figure 53: Climate change in kg CO_2 eq/FU - scenario 5

If only EPS is considered instead of ETICS the difference between the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process increases by 11% for climate change.

The overall results for other impact categories are displayed in Table 21.

Table 21: Additional Life Cycle Impact Assessment results- scenario 5

Impact Category	Unit	Scenario 5 Current Status Quo	Scenario 5 PS Loop Process	Difference Scenario 5	Difference Base Case
Acidification	mol H+ eq	4.2	3.8	-10%	+2%
Summer smog	kg NMVOC	3.7	2.4	-35%	-15%
Eutrophication, marine	kg N eq	1.1	0.9	-19%	-3%
Eutrophication, freshwater	kg P eq	4.7E-03	2.6E-03	-46%	-26%
Resource depletion, fossil	MJ	6.3E+04	2.3E+04	-63%	-51%
Resource depletion, elements	kg Sb eq	6.6E-04	4.4E-04	-33%	-17%
Human toxicity - cancer	CTU_h	2.0E-05	1.5E-06	-93%	-85%
Human toxicity – non-cancer	CTU_h	7.0E-05	6.9E-06	-90%	-57%
Ecotoxicity - freshwater	CTU_e	432	45.0	-90%	-80%
Primary energy demand	MJ	6.6E+04	3.6E+04	-46%	-32%

For some considered impact categories significant changes (> 15% differences) result, due to changes of life cycle steps pre-treatment and end of life.

Scenario 6 – Consideration of Different Settings for the CreaSolv® Process I (4 plant shutdowns per year / increased solvent losses/ 0.4wt% HBCDD)

This scenario considers four plant shut-downs per year (these are resulting in an off spec waste stream of PS). Furthermore, the adhesive solvent on the solid waste (separated at the filtration) was increased drastically. This might be the case if these residuals are highly absorptive. The effects of the plant shut-downs have a minor influence on the process material balance. If the filter residuals will be absorptive higher solvent losses occur and also remaining dissolved PS gets lost. Nevertheless, the calculation has shown that 98% of PS can be recycled.

The following table shows the different in- and outputs for scenario 6. Detailed information can be found in annex V.

Table 22: Setting for CreaSolv® Process I

Material	Base case	Scenario 6	Unit
Solvent	0.01	0.07	t/t EPS
Nitrogen	1.60	1.60	kg/t EPS
Soft water	0.02	0.02	t/t EPS
Cooling water	174	174	t/t EPS
Electricity	816	816	kWh/t EPS
Steam	1.47	1.47	t/t EPS
Wastewater	0.06	0.06	m^3/t EPS
Solid Waste	0.08	0.14	t/t EPS
HBCDD Slurry	0.02	0.02	t/t EPS
PS	0.99	0.98	t/t EPS

The results for climate change are illustrated in Figure 54.

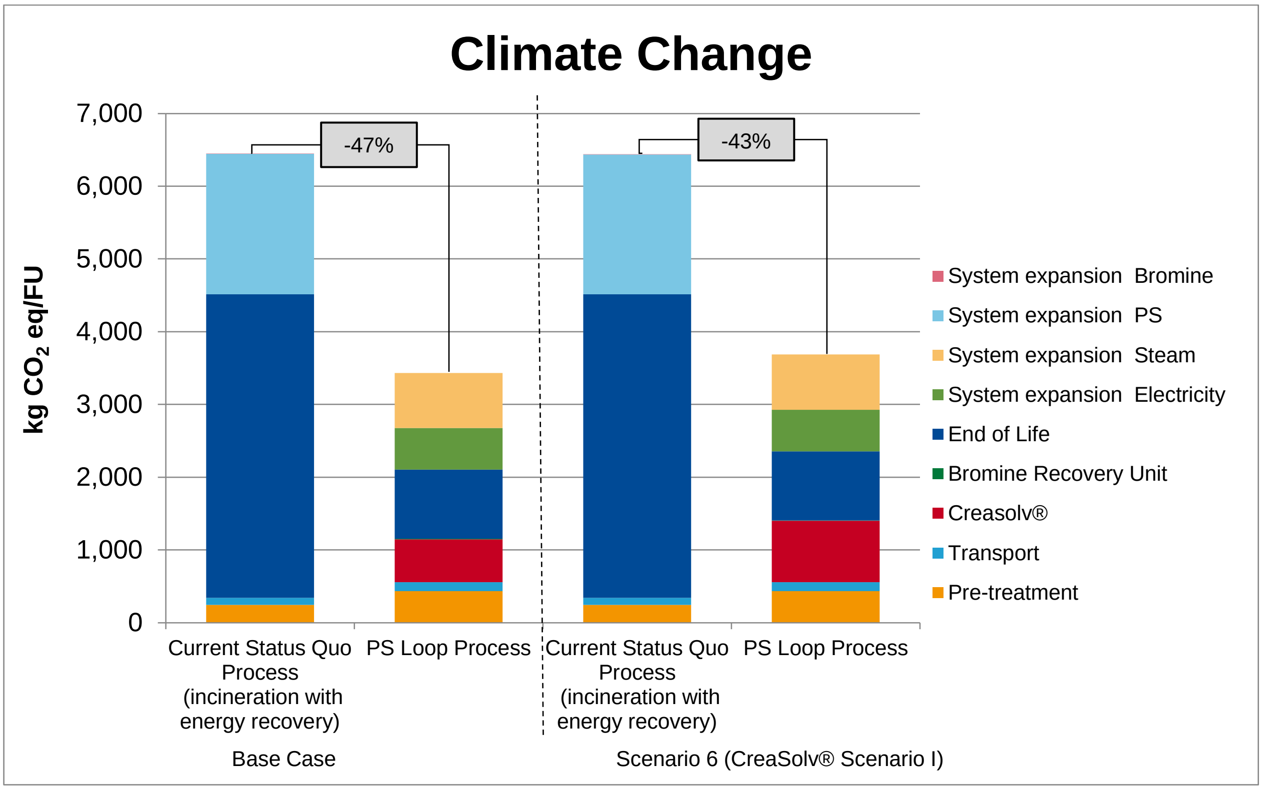

Figure 54: Climate change in kg CO_2 eq/FU - scenario 6

Consideration of different settings for the CreaSolv® Process leads to decrease of the difference between the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process (difference: 4%) for climate change. Consequentially different settings for the CreaSolv® Process lead to no significant changes in this impact category.

The overall results for other impact categories are displayed in Table 23.

Table 23: Additional Life Cycle Impact Assessment results- scenario 6

Impact Category	Unit	Scenario 6 Current Status Quo	Scenario 6 PS Loop Process	Difference Scenario 6	Difference Base Case
Acidification	mol H+ eq	7.4	7.70	+5%	+2%
Summer smog	kg NMVOC	6.9	6.10	-12%	-15%
Eutrophication, marine	kg N eq	2.3	2.28	-1%	-3%
Eutrophication, freshwater	kg P eq	6.6E-03	5.0E-03	-24%	-26%
Resource depletion, fossil	MJ	7.4E+04	3.9E+04	-47%	-51%
Resource depletion, elements	kg Sb eq	7.3E-04	6.3E-04	-14%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	3.8E-06	-82%	-85%
Human toxicity – non-cancer	CTU_h	1.1E-04	4.9E-05	-53%	-57%
Ecotoxicity - freshwater	CTU_e	470	112	-76%	-80%
Primary energy demand	MJ	8.2E+04	5.8E+04	-29%	-32%

No significant differences result for other considered impact categories by assuming different settings for the CreaSolv® Process.

Scenario 7 – Consideration of Different Settings for the CreaSolv® Process II (12 Plant Shutdowns per year / increased solvent losses/ 1.5 wt% HBCDD)

A monthly plant shut down is considered as well as a permanent HBCDD concentration of 1.5 wt% which is equal to the maximum occurring HBCDD concentration in ETICS. These assumptions executed together with increased solvent losses due to high absorbent filter residuals. This calculation contains all worst case assumptions at the same time.

The following table shows the different in- and outputs for scenario 7. Detailed information can be found in annex V.

Table 24: Setting for CreaSolv® Process II

Material	Base case	Scenario 7	Unit
Solvent	0.01	0.10	t/t EPS
Nitrogen	1.60	1.50	kg/t EPS
Soft water	0.02	0.03	t/t EPS
Cooling water	174	258	t/t EPS
Electricity	816	816	kWh/t EPS
Steam	1.47	2.49	t/t EPS
Wastewater	0.06	0.06	m³/t EPS
Solid waste	0.08	0.14	t/t EPS
HBCDD Slurry	0.02	0.08	t/t EPS
PS	0.99	0.97	t/t EPS

The results for climate change are illustrated in Figure 55.

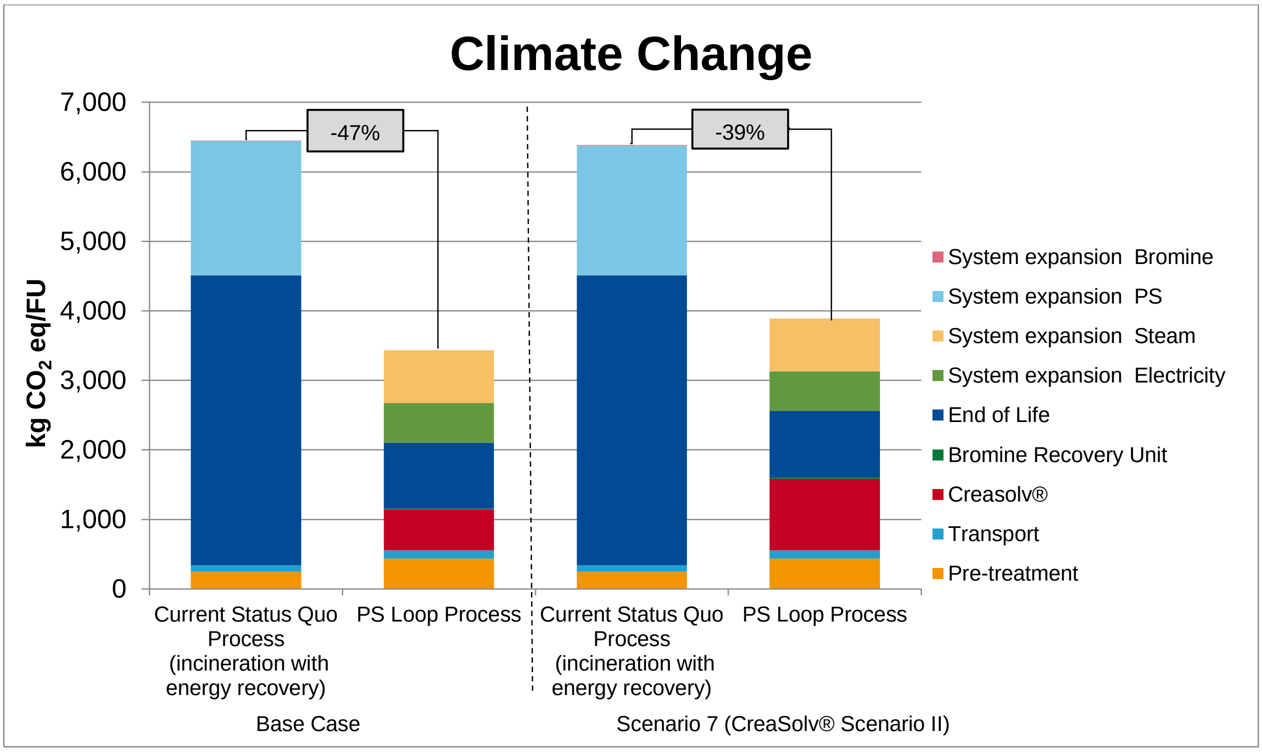

Figure 55: Climate change in kg CO_2 eq/FU - scenario 7

Consideration of different settings for the CreaSolv® Process lead to a decrease of the difference between the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process (difference: 8%) for climate change. Consequentially different settings for the CreaSolv® Process lead to no significant changes in this impact category.

The overall results for other impact categories are displayed in Table 25.

Table 25: Additional Life Cycle Impact Assessment results- scenario 7

Impact Category	Unit	Scenario 7 Current Status Quo	Scenario 7 PS Loop Process	Difference Scenario 7	Difference Base Case
Acidification	mol H+ eq	7.3	7.9	+8%	+2%
Summer smog	kg NMVOC	6.8	6.2	-9%	-15%
Eutrophication, marine	kg N eq	2.3	2.3	+2%	-3%
Eutrophication, freshwater	kg P eq	9.7E-03	5.1E-03	-47%	-26%
Resource depletion, fossil	MJ	7.3E+04	4.1E+04	-44%	-51%
Resource depletion, elements	kg Sb eq	7.5E-04	7.2E-04	-4%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	4.7E-06	-77%	-85%
Human toxicity – non-cancer	CTU_h	1.0E-04	5.1E-05	-51%	-57%
Ecotoxicity - freshwater	CTU_e	479	127	-74%	-80%
Primary energy demand	MJ	8.0E+04	6.0E+04	-25%	-32%

Some other considered impact categories resulting in significant changes (> 15% differences), due to changes of in- and outputs of the CreaSolv® Process.

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Scenario 8 – Consideration of Different Settings for the BRU Process

The base case calculation considers for the PS Loop Process a HBCDD stream from the CreaSolv® Process to the BRU, which contains about 60 wt% bromine and a yield of elementary bromine of 95 wt%. This scenario assesses a HBCDD stream containing 60 wt% bromine and a yield at the BRU plant of 90 wt% elementary bromine. All needed utilizes as well as resulting emissions and wastes of the BRU process were scaled according to lower recovery rate. This scenario is calculated to show a lower recovery rate of bromine.

The results for climate change are illustrated in Figure 56.

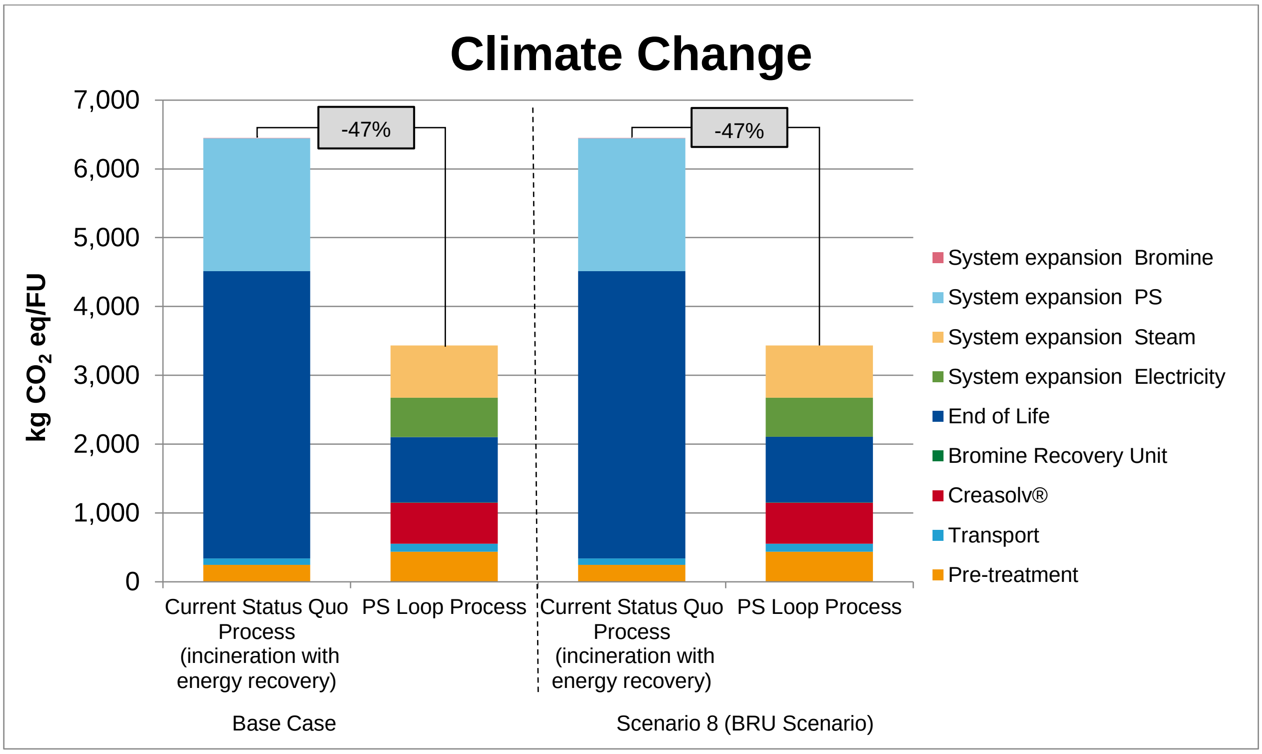

Figure 56: Climate change in kg CO_2 eq/FU - scenario 8

Consideration of different settings for the BRU Process leads to nearly no changes (difference: 0.01%) in relation to base case calculations.

The overall results for other impact categories are displayed in Table 26.

Table 26: Additional Life Cycle Impact Assessment results- scenario 8

Impact Category	Unit	Scenario 8 Current Status Quo	Scenario 8 PS Loop Process	Difference Scenario 8	Difference Base Case
Acidification	mol H+ eq	7.4	7.5	+2%	+2%
Summer smog	kg NMVOC	6.9	5.9	-15%	-15%
Eutrophication, marine	kg N eq	2.3	2.2	-3%	-3%
Eutrophication, freshwater	kg P eq	6.5E-03	4.9E-03	-25%	-26%
Resource depletion, fossil	MJ	7.5E+04	3.7E+04	-51%	-51%
Resource depletion, elements	kg Sb eq	7.3E-04	6.0E-04	-18%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	3.1E-06	-86%	-85%
Human toxicity – non-cancer	CTU_h	1.1E-04	4.6E-05	-57%	-57%
Ecotoxicity - freshwater	CTU_e	472	95.7	-80%	-80%
Primary energy demand	MJ	8.2E+04	5.6E+04	-32%	-32%

No significant differences occur for other considered impact categories, related to consideration of different settings for the BRU Process.

Scenario 9 – Consideration of Different Electricity Grid Mixes

The base case calculation considers for all electricity demands the average European grid mix. The following scenario evaluates the impacts for the use of an average German grid mix and an average Dutch grid mix. These countries were chosen according to the location of the considered plants in this study. The share of different energy sources can be found in Table 27.

Table 27: Energy sources of different grid mixes (Source International Energy Agency, GaBi ts Software)

Energy source	EU grid mix	German grid mix	Dutch grid mix
Lignite [%]	10.2	25.5	-
Hard coal [%]	16.1	19.3	24.4
Nuclear [%]	27.1	15.4	2.9
Natural gas [%]	15.7	10.9	54.8
Wind [%]	7.3	8.9	5.6
Biogas [%]	1.7	4.7	1.0
Hydro [%]	12.4	4.6	0.1
Photovoltaic [%]	2.5	4.9	0.5
Others [%]	7.0	6.0	10.7

The results for climate change are illustrated in Figure 57.

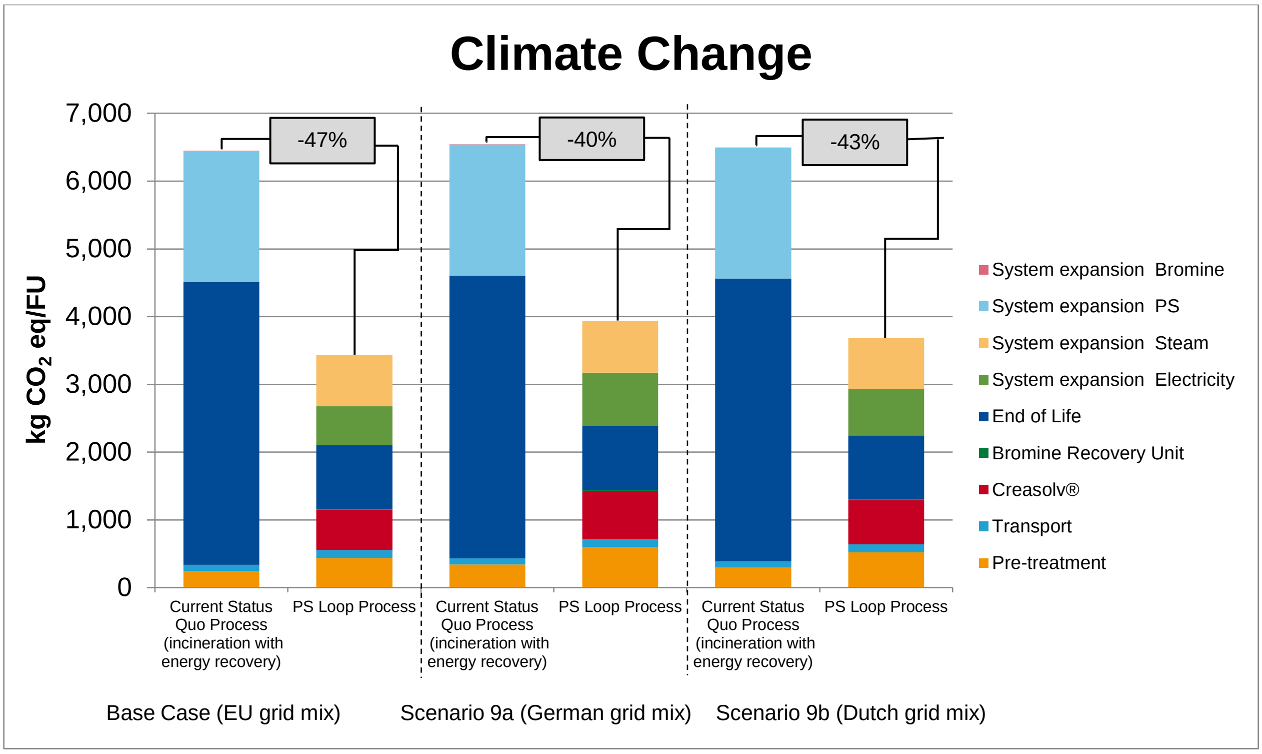

Figure 57: Climate change in kg CO_2 eq/FU - scenario 9

No significant difference (difference between 4 % and 7%) between the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process occur for climate change if another grid mix is considered. Consequentially different grid mixes (consideration of German grid mix and Dutch grid mix) for all foreground systems lead to no significant changes in this impact category.

The overall results for other impact categories are displayed in Table 28 and Table 29.

Table 28: Additional Life Cycle Impact Assessment results- scenario 9a

Impact Category	Unit	Scenario 9a Current Status Quo	Scenario 9a PS Loop Process	Difference Scenario 9a	Difference Base Case
Acidification	mol H+ eq	7.2	6.4	-11%	+2%
Summer smog	kg NMVOC	6.9	5.9	-15%	-15%
Eutrophication, marine	kg N eq	2.3	2.3	-1%	-3%
Eutrophication, freshwater	kg P eq	7.3E-03	8.7E-03	-19%	-26%
Resource depletion, fossil	MJ	7.5E+04	4.0E+04	-47%	-51%
Resource depletion, elements	kg Sb eq	8.1E-04	9.9E-04	-23%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	3.2E-06	-85%	-85%
Human toxicity – non-cancer	CTU_h	9.7E-05	2.8E-06	-97%	-57%
Ecotoxicity - freshwater	CTU_e	466	62.4	-87%	-80%
Primary energy demand	MJ	8.3E+04	5.8E+04	-30%	-32%

Table 29: Additional Life Cycle Impact Assessment results- scenario 9b

Impact Category	Unit	Scenario 9b Current Status Quo	Scenario 9b PS Loop Process	Difference Scenario 9b	Difference Base Case
Acidification	mol H+ eq	7.0	5.4	-23%	+2%
Summer smog	kg NMVOC	6.8	5.5	-20%	-15%
Eutrophication, marine	kg N eq	2.3	2.2	-6%	-3%
Eutrophication, freshwater	kg P eq	6.9E-03	7.2E-03	+3%	-26%
Resource depletion, fossil	MJ	7.6E+04	4.1E+04	-45%	-51%
Resource depletion, elements	kg Sb eq	7.0E-04	4.3E-04	-38%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	2.9E-06	-86%	-85%
Human toxicity – non-cancer	CTU_h	1.1E-04	4.6E-05	-56%	-57%
Ecotoxicity - freshwater	CTU_e	470	81.3	-83%	-80%
Primary energy demand	MJ	8.1E+04	5.1E+04	-37%	-32%

For some other considered impact categories significant changes (> 15% differences) occur, due to different energy sources for the country-specific grid mixes.

Scenario 10 – Consideration of Different Transport Distance

The base case calculation considers a distance from construction site to pre-treatment plant of 100 km with a utilization rate of 33% (see chapter 3.6, relevant for the PS Loop Process). This scenario considers a distance of 2,000 km to pre-treatment plant, due to the fact that there are only a limited amount of pre-treatment plants available in Europe. Therefore this distance reflects a worst case assumption.

The results for climate change are illustrated in Figure 58.

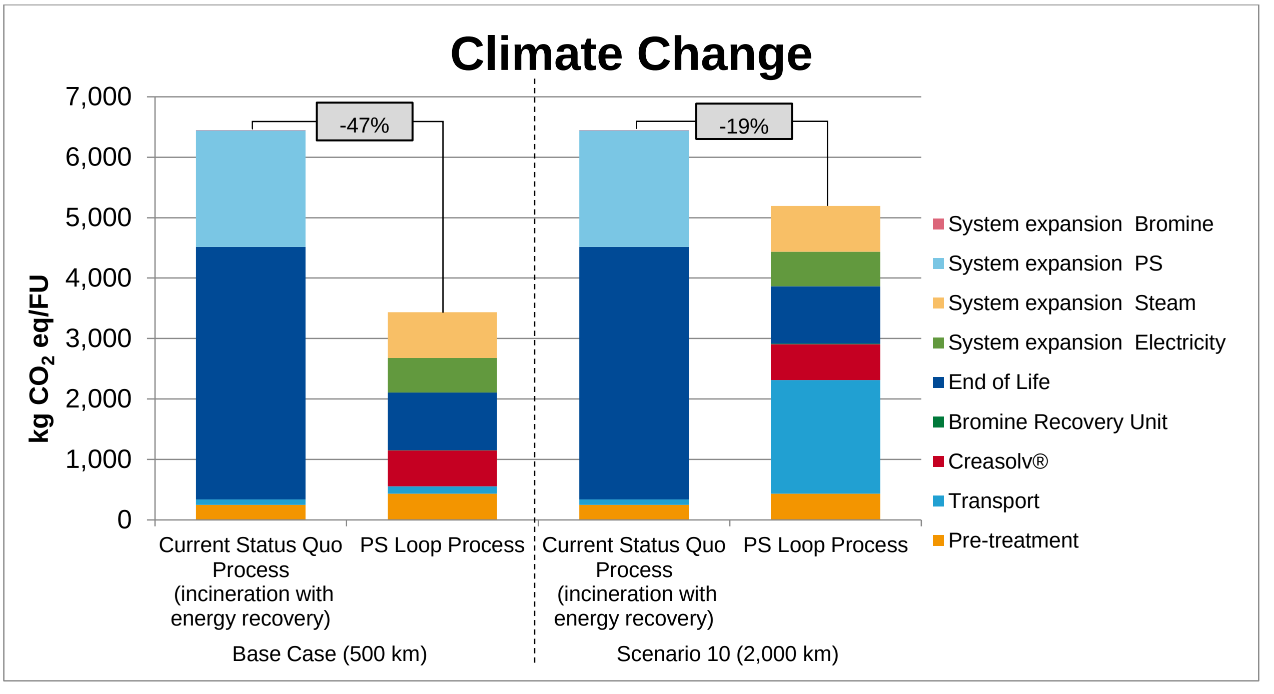

Figure 58: Climate change in kg CO_2 eq/FU - scenario 10

Consideration of a different transport distance for the PS Loop Process leads to a significantly decrease of the difference between the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process (difference: 28%) for climate change. Consequentially the assumed transport distances lead to significant changes in this impact category. Other transport steps like transport of material to the CreaSolv® Process and to the BRU do not influence the overall results significantly, due to higher utilization rate of 85 % (see chapter 4.4). Nevertheless, the Current Status Quo Process (incineration with energy recovery) have a higher impact within the considered impact category in relation to the PS Loop Process.

The overall results for other impact categories are displayed in Table 30.

Table 30: Additional Life Cycle Impact Assessment results- scenario 10

Impact Category	Unit	Scenario 10 Current Status Quo	Scenario 10 PS Loop Process	Difference Scenario 10	Difference Base Case
Acidification	mol H+ eq	7.4	14.6	+49%	+2%
Summer smog	kg NMVOC	6.9	12.1	+43%	-15%
Eutrophication, marine	kg N eq	2.3	5.6	+58%	-3%
Eutrophication, freshwater	kg P eq	6.6E-03	1.3E-02	+50%	-26%
Resource depletion, fossil	MJ	7.5E+04	6.1E+04	-24%	-51%
Resource depletion, elements	kg Sb eq	8.1E-04	7.8E-04	-3%	-17%
Human toxicity - cancer	CTU_h	2.1E-05	1.4E-05	-47%	-85%
Human toxicity – non-cancer	CTU_h	1.1E-04	1.7E-05	-542%	-57%
Ecotoxicity - freshwater	CTU_e	473	366	-29%	-80%
Primary energy demand	MJ	8.2E+04	8.1E+04	-1%	-32%

For other considered impact categories significant changes (> 15% differences) occur. Therefore the considered transport distance is a significant assumption for overall results.

Scenario 11 – Consideration of Different Treatment of Material Mix A& B

The base case calculations consider an incineration with energy recovery of Material Mix A, as well as for Material Mix B (see Table 2). To evaluate the impacts of different treatment options this scenario assumes 50% landfilling and 50% incineration with energy recovery for relevant materials. These assumptions were chosen in accordance with Environmental Footprint Category Rules (PEFCRs) for thermal insulation.[75]

The results for climate change are illustrated in Figure 59.

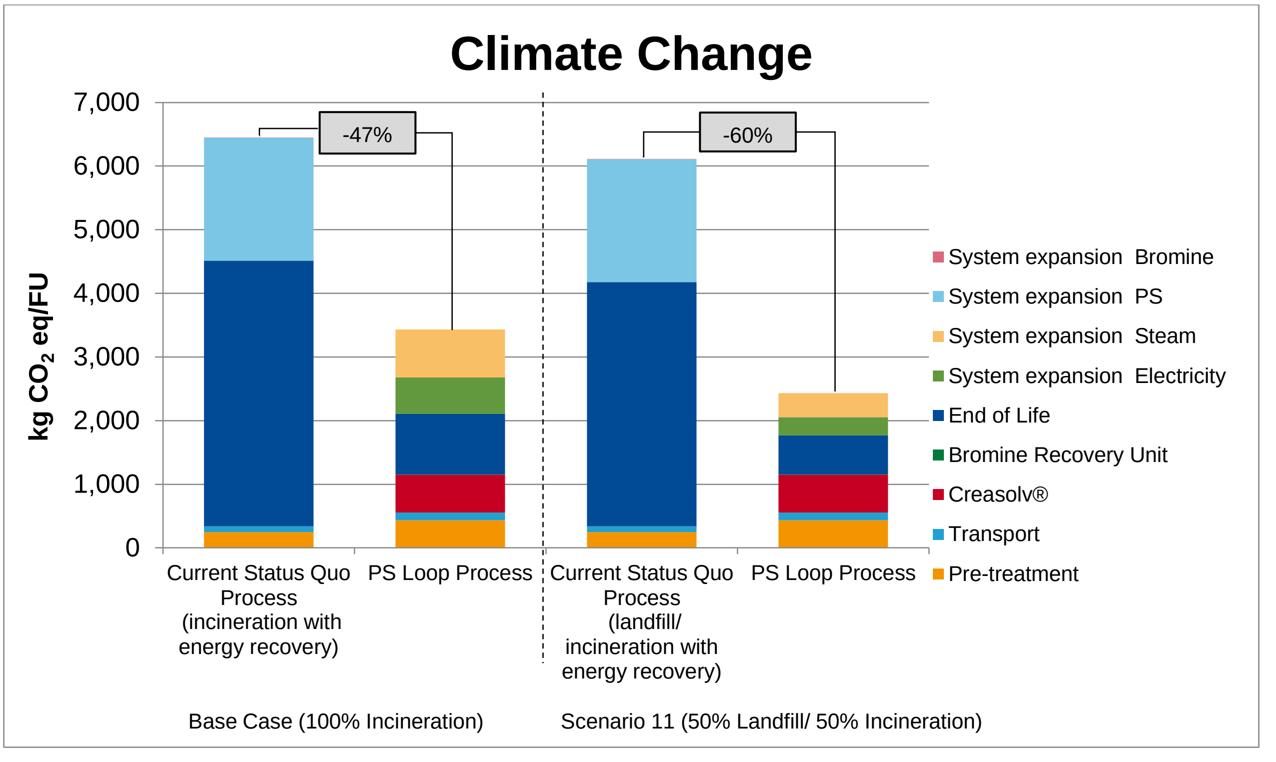

Figure 59: Climate change in kg CO_2 eq/FU - scenario 11

Consideration of a different disposal option for Material Mix A and Material Mix B leads to an increase of the difference between the Current Status Quo Process (incineration with energy recovery) and the PS Loop Process (difference: 13%) for climate change. Therefore, results no significant changes (difference: <15%) in this impact category.

The overall results for other impact categories are displayed in Table 31.

[75] Draft Product Environmental Footprint Category Rules (PEFCRs) for thermal insulation, Version V 1.1, Sep. 2015, table 6

Table 31: Additional Life Cycle Impact Assessment results- scenario 11

Impact Category	Unit	Scenario 11 Current Status Quo	Scenario 11 PS Loop Process	Difference Scenario 11	Difference Base Case
Acidification	mol H+ eq	6.8	5.7	-16%	+2%
Summer smog	kg NMVOC	6.0	4.1	-32%	-15%
Eutrophication, marine	kg N eq	2.0	1.6	-18%	-3%
Eutrophication, freshwater	kg P eq	7.7E-03	5.2E-03	-32%	-26%
Resource depletion, fossil	MJ	7.2E+04	2.4E+04	-66%	-51%
Resource depletion, elements	kg Sb eq	7.3E-04	4.7E-04	-36%	-17%
Human toxicity - cancer	CTU_h	2.2E-05	3.2E-06	-85%	-85%
Human toxicity – non-cancer	CTU_h	1.4E-04	8.1E-05	-43%	-57%
Ecotoxicity - freshwater	CTU_e	472	83.3	-82%	-80%
Primary energy demand	MJ	7.8E+04	3.9E+04	-50%	-32%

For some other considered impact categories significant changes (> 15% differences) occur, due to different treatment of Material Mix A& B.

7.3. Data Quality

The geographical scope of the study is the dismantling of ETICS of houses in Europe. Therefore, mainly European datasets were used for calculation. If European datasets were not available German or global datasets have been used. For instance, a global dataset was used for recycling of metals. An exception is the dataset of bromine (location: Israel). The use of this dataset is appropriate for the study, due to the reasons that this country reflects the main production area, the ICL-IP headquarter is located in Israel and they source bromine from there. The dataset for PS granulate production covers 80% of the European EPS production (EU-27) in 2013 from cradle to gate. The dataset is intended to be used as cradle to gate building block of LCA studies of defined applications or products. LCA studies considering the full life cycle (cradle to grave of an application or product allow for comparative assertions to be derived. All considered electricity demand is modelled with an average European grid mix (see chapter 4.2). Only for some considered impact categories significant changes for the overall results (> 15% differences) occur, due to different energy sources for country-specific grid mixes.
The study refers to lab-scale data for the CreaSolv® Process and data of one pilot plant in Terneuzen, the Netherlands for the BRU process. Data were provided by EPC and ICL-IP. The lab-scale trials consider an input material of 30 kg compacted EPS briquettes with 1.5wt% HBCDD. Data for the BRU considers a production run with an output of 400 kg bromine recovery per hour. IWARU Technical Center of FH Münster provided estimated data on the pre-treatment process (basis: 30,000 t ETICS per year) of ETICS before relayed to the CreaSolv® Process. However, some literature data and expert judgments were used for calculations especially for the Current Status Quo Process (incineration with energy recovery) (see chapter 4.3). All transportation steps and energy demand for pre- treatment are mainly based on expert judgments. The composition of ETICS, as well as the energy demand for dismantling originates from published literature sources. All incineration, landfill and recycling processes were calculated with generic datasets. Furthermore, it remains unclear what kind of waste streams and specifications would be realistic for a large-scale application. This has to be tested during the operation phase of the demo plant. Due to these and the fact that the PS Loop demo plant will be fully operational in 2019 the TRL vary between TRL 3 (experimental proof of concept) and TRL 4, which mean technology is validated in lab.[76]

All data provided by EPC, ICL-IP and IWARU Technical Center of FH Münster reflect the year 2016. Secondary data were intended to be close to this year. The oldest datasets originate from 2003-2004 (Ammonia and Hydrazine production datasets for the BRU process). These datasets also reflect the current status quo of production and are suitable for calculation.

[76] Assumption for TRL is done by process manager of styrene and polystyrene plant of BASF on 23.08.2017 (see annex VI). For further information of TRL concept see glossary.

7.4. Completeness and Consistency

The CreaSolv® Process and BRU are based on data from EPC and ICL-IP. These data reflect lab-scale trials respectively data of production runs at a pilot plant.

Furthermore, pre-treatment, transportation steps and incineration processes, as well as recycling and landfilling are based on literature or expert judgments. Thus all relevant information and data for all alternatives are available and complete. Secondary data from well-known databases (GaBi, PlasticsEurope, ELCD) were used for all alternatives consistently. These data are considered to be appropriate for the study. The used data are consistent and applicable to the purpose of the study. For the most important information European datasets were available.

The used system expansion and the system boundaries were applied consistently for the whole study.

7.5. Conclusions and Recommendations

A base case has been developed for both systems, for which various assumptions have been made and documented (see chapter 3.6). The results of the base case lead to the following robust conclusions:

- The PS Loop Process shows a lower or comparable overall environmental impact compared to the Current Status Quo Process (incineration with energy recovery) (see Table 1).
- Mainly all considered impact categories (climate change, eutrophication (freshwater), summer smog, resource depletion (fossil, elements), human toxicity (non-cancer, cancer) and freshwater ecotoxicity) show a significantly higher environmental influence for the Current Status Quo Process (incineration with energy recovery) than for the PS Loop Process. Effects for acidification and eutrophication (marine) are comparable for both alternatives (differences < 15%).
- The main driver of the Current Status Quo Process (incineration with energy recovery) is incineration of Material Mix A with 10.1% plastics (see Table 2), mainly EPS. Furthermore, the system expansion (especially production of PS) influences the results. The pre-treatment has only a small impact on the overall results.

- The environmental effects of the PS Loop Process are mainly influenced by system expansion (production of electricity and steam) and end of life. During end of life treatment Material Mix B (see Table 2) with plastics (dowels) are incinerated and metals (dowels) are recycled respectively landfilled. The pre-treatment considers compaction and shredding of EPS, therefore higher impacts result for this process step compared to Current Status Quo Process (incineration with energy recovery). The CreaSolv® Process is no main driver for the overall results of the PS Loop Process. However, it leads to visible influences in all considered impact categories. Main contributor of the CreaSolv® Process is the required energy demand. Environmental impacts of the BRU lead to very limited contributions in all considered impact categories. Only a relevant impact on ADPE is caused by the used utilities, especially hydrazine.
- The overall effects of transportation steps show only minor impacts for both alternatives. A slightly higher impact for the PS Loop Process occurs caused by a lower utilization rate and higher transport distances (see chapter 4.4).

In order to check the robustness of the outcomes of these base case various sensitivity analyses have been performed (see chapter 7.2). The results of the sensitivity analysis lead to the following conclusions:

- For different deconstruction method (selective deconstruction in comparison to demolition), other treatment of Material Mixes A and B (landfilling instead of incineration with energy recovery), various masses of EPS in installed ETICS (12% and 15% instead of 10%), slightly higher solvent losses of the CreaSolv® Process (around 1% higher compared to base case) as well as different settings for the BRU Process (yield of elementary bromine of 90% instead of 95%) leads to no significant change (< 15% differences) for all considered impact categories.
- By using 50:50 allocation approach instead of system expansion, variation of transport distance from deconstruction to separation plant to 2,000 km (relevant for the PS Loop Process, base case: 500 km) and assuming of different treatment of Material Mix A& B (50% landfilling and 50% incineration with energy recovery instead of incineration with energy recovery) leads to significant change (> 15% differences) for all impact categories. However, the PS Loop Process is less environmental harmful in relation to Current Status Quo Process (incineration with energy recovery).
- Consideration of 100% EPS in ETICS, higher solvent losses of the CreaSolv® Process (around 10% higher compared to base case) as well as taking account of other grid mixes for foreground systems (German and Dutch grid mix instead of European grid mix) leads to significant changes (> 15% differences) for some considered impact categories.

It should be taken into consideration that evaluation of environmental impacts for Current Status Quo Process (incineration with energy recovery) is based on background data from GaBi ts 7.2 software of thinkstep AG (commercial database) whilst the PS Loop Process system is mainly based on simulation data (assumed data for pre-treatment, lab-scale trials for CreaSolv® Process and data of a pilot plant for BRU).

In order to remove some of the remaining uncertainties linked to the data and assumptions used in this study it is recommended to acquire up-to-date primary data for the CreaSolv® Process and the BRU process, pre-treatment and incineration. New update of LCA data will be needed if pilot plant phase has been finished and more reliable data are available.

Furthermore, all limitations, like consideration of ETICS with 10 wt% EPS containing 0.4 wt% HBCCD flame retardants, defined water content of maximum 3 wt% of ETICS and incineration with energy recovery (see chapter 3.6 and 3.7) should be taken into account by interpretation of the results.

8. Critical Review Statement

Critical Review statement for the study

"Life Cycle Assessment for End of Life Treatment of Expandable Polystyrene (EPS) from External Thermal Insulation Composite Systems (ETICS)"

February 08, 2018

1. Background

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Documents related:

LCA study report reviewed (final version after modifications): "**Life Cycle Assessment for End of Life Treatment of Expandable Polystyrene (EPS) from External Thermal Insulation Composite Systems (ETICS), Version 6**",

Provided by Susanne Jorre, TÜV Rheinland LGA Products GmbH.

Comments (all comments, compiled, with answers): "180208 Consolidated Comments for 2nd report V6.1 Final"

2. References and Scope of the Critical Review

References

ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework

ISO 14044 (2006): Environmental Management - Life Cycle Assessment - Requirements and Guidelines

ISO/TS 14071 (2014): Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

Scope of the critical review

The reviewers had the task to assess whether

1) the methods used to carry out the life cycle assessment (LCA) are consistent with the international standards ISO 14040 (2006) and ISO 14044 (2006),
2) the methods used to carry out the LCA are scientifically and technically valid,
3) the data used are appropriate and reasonable in relation to the goal of the study,
4) the interpretations reflect the limitations identified and the goal of the study, and
5) the study report is transparent and consistent.

The members of the critical review panel were chosen to ensure the required competence and expertise in LCA as well as in the scientific and technical aspects of the products system studied.

The analysis of individual datasets and the review of the LCA models used to calculate the results were outside the scope of this review.

This review statement is valid for Version 6 of the LCA report “**Life Cycle Assessment for End of Life Treatment of Expandable Polystyrene (EPS) from External Thermal Insulation Composite Systems (ETICS)**” of 2018.02.22. The critical review experts are not responsible for any communication, extract or summary of the study. The conclusions of the experts are linked to the state of the art and the level of information received during the review work. Conclusions could be different in different context.

3. Review Process

The review was performed based on ISO 14044 (2006) and ISO/TS 14071 (2014). The review process started in June 2017 and lasted until December 2017. The review involved several rounds of rigorous review and commenting on the respective reports as well as one physical meeting in Ludwigshafen (August 10, 2017) and several teleconferences and phone discussions. In an iterative way, the panel provided comments, on the report received, of general, technical, and editorial nature which were processed (and integrated) by the practitioners in a new version of the LCA report which was reviewed against the comments previously provided. The final version (version 6) of the LCA report ("**Life Cycle Assessment for End of Life Treatment of Expandable Polystyrene (EPS) from External Thermal Insulation Composite Systems (ETICS)**" of January 22, 2018) was approved by the reviewers. The full list of comments and their answers are provided in the file "180208 Consolidated Comments for 2nd report V6.1 Final".

The practitioners were very forthcoming in the dialogue with the reviewers and improvements in the report were introduced through the review process.

4. Results of the Critical Review

4.1 General remarks

The study uses LCA to quantify and compare the environmental performance of two different end of life (EoL) options for 1 ton of EPS coming from 10 tons External Thermal Insulation Composite Systems (ETICS) from dismantling of houses in Europe:

- the Current Status Quo EoL Process (incineration with energy recovery) and
- the PS Loop Process

The results of this study reveal – under the given conditions and chosen assumptions – a better environmental performance of the PS Loop Process compared to the Current Status Quo EoL Process (incineration with energy recovery) for most of the considered impact categories, including climate change. The exceptions are effects on acidification and eutrophication (marine) which show similar results for both alternatives and thus considered as comparable for both alternatives.

The main driver of environmental differences among the two process alternatives results from the preservation of the PS (polystyrene) as material and so avoiding the production of virgin material. It is assumed that the recycled PS material has the same performance than the substituted virgin material.

4.2 Applied methods

The selected environmental impact assessment methods and calculation models for each selected method do take into account the requirements of international standards ISO 14040: 2006 and ISO 14044: 2006.

The ISO standards, referred to in section 2, do not provide concrete requirements about which environmental impacts and which specific method for each impact category has to be selected.

Impact categories and methods applied in this study reflect current practice in Life Cycle Assessment and are in line with the objective and the scope of the study. The selection of impact categories and indicators reflect a comprehensive set of environmental issues related to the alternatives under study.

The comparison focuses on the end-of-life phase of a specific waste stream. Thus, no general statements with respect to the environmental performance of External Thermal Insulation Composite Systems (ETICS) can be derived.

4.3 Data and Modelling

For the PS Loop Process the study describes a future recycling scheme with large-scale application in place. However, today some of the technologies of this future recycling scheme are still in the development stage. Thus, no primary data representing large scale can be applied, in particular for the CreaSolv® Process. Data for the CreaSolv® Process originate from lab-scale trials provided by CreaCycle GmbH and EPC. Data for the Bromine Recovery Unit (BRU) from a full-scale plant (4000 mtons Brom/a), operated by ICL plant in Terneuzen in the Netherlands has been provided by ICL-IP. IWARU Technical Center of FH Münster provided calculated data on the pre-treatment process (basis: 30,000 t ETICS per year) of ETICS before going into the CreaSolv® Process. Expert judgement was applied frequently: All transportation steps and energy demand for pre- treatment are mainly based on expert judgments. The composition of ETICS, as well as the energy demand for dismantling originates from published literature sources.

A comprehensive sensitivity analysis has been performed to test the robustness of the assumptions made. In the course of the review process the data has been challenged by plausibility checks using stream tables as the one give in Appendix IV of the study. Some mistakes have been revealed and corrected. No apparent major mistakes have been found in the latest version of the report that was approved. Evaluations of the properties of the recycled PS material are based on recycled PS material derived from the lab-scale installation. The expected sameness for the demo plant has to be shown in particular to the behaviour of the solvent.

All incineration (with energy recovery), landfill and recycling processes were calculated with generic datasets. Thus, the current status quo is based on generic data.
Furthermore, it remains unclear what kind of waste streams and specifications would be realistic for a large-scale application. This has to be tested once the demo-plant starts its operation.

Background data
The used background data in this study are mainly based on GaBi database, thinkstep AG. Furthermore, some datasets of BASF, ELCD and PlasticsEurope are used. A comprehensive list of the respective background data has been provided by the authors of the study. For the production of PS granulate production: Polystyrene expandable granulate (EPS) is provided by producers that are members of PlasticsEurope. It covers 80% of the European EPS production (EU-27) in 2013 from cradle to gate. The maximum temporal validity is until end of 2023. The datasets have been reviewed by an independent reviewer in the frame work of the PlasticsEurope eco-profiles programme. As a result, this dataset is assessed to be a reliable and high-quality representation of EPS produced in Europe. The oldest datasets originate from 2003-2004 (Ammonia and Hydrazine production datasets for the BRU process). These datasets also reflect the current status quo of production and are suitable for calculation.
The background datasets have not been reviewed by the panel. Lack of calculation mistakes in the background datasets (as well as the choice of the appropriate datasets) cannot be guaranteed.

Modelling:
The modelling was carried out using the GaBi ts 7.2 software of thinkstep AG. The software is one of the most commonly used LCA software. No checks other than plausibility checks for revealing possible errors in data transfer from on to the other data sources have been performed.

4.4 Interpretations with respect to limitations identified and the goal of the study

The limitations are clearly stated in the study.
The reviewers want to point out some of the key aspects that need to be considered when interpreting the results:
The comparison is performed for the European market. The conclusions should therefore not be used outside the context of ETICS waste treatment in Europe. Also, it should be noted:

a) The Current Status Quo EoL Process (incineration with energy recovery) comprises an incineration with energy recovery of untreated ETICS waste. For Germany incineration plants are all equipped with energy recovery technologies, however for other European countries this may not be always the case.
b) The study only considers EPS waste containing HBCDD. Thus, the results can only create a basis for decision making concerning new processes for recycling of EPS insulation foam waste containing HBCDD with a recovery of bromine. Statements for XPS and other flame retardants like Polymeric Flame Retardants (Polymer FR) cannot be derived.
c) The study assumes certain efforts to achieve the wanted efficiencies concerning the various phase separations in the pre-treatment as well as in the CreaSolv® Process. The recovery of solvent and the quality of the produced PS product are highly dependent on these efficiencies. In case that these assumptions do not hold, the required effort may change considerably, in particular for the energy demand and the judgement on legal aspects (REACH, CLP), due to the different composition of the mixture (PS + solvent).

4.5 Transparency and Consistency

The reviewers have determined that the report follows the requirements of ISO 14040: 2006 and ISO 14044: 2006 and includes all the essential elements of these standards. Both the tabular and graphical representations of input data and results are clear and described by explanation. The explanations of assumptions and results are appropriate. The final report is coherent, easy to read and clear.
When publishing the report or parts of the report, it is strongly recommended that no individual impact categories or data, such as the climate change are communicated.

5. Conclusion

Overall, the critical review team found the quality of the chosen methodology and its application in the analysis to be adequate for the purpose of the study and in conformance with the ISO 14040 and ISO 14044 standards. The reporting of the study and its results are transparent. The discussion of the results covers the relevant aspects in accordance with the goal of the study, and the conclusions are well founded on the outcome of the study and in line with the defined goal.

For the PS Loop Process the study describes a future recycling scheme with large-scale application in place, which is currently still in the development phase. This results in some uncertainties with respect of waste streams and specifications as well as process data, in particular for the CreaSolv® Process. As stated in the study, the Technology Readyness Level (TRL) varies between TRL 3 (experimental proof of concept) and TRL 4, which mean technology and used data is validated in lab scale.
In order to subsequently remove some of these inherent uncertainties it is recommended to perform a comprehensive update of the study on the basis of results and experiences gathered from operating the pilot plant.

Dr. Michael Spielmann

Prof. Dr.-Ing. Matthias Kind

Ulrich Schlotter

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10. Annex

Annex I - Description of Life Cycle Impact Assessment Categories

1. Acidification

- Also referred to as acid rain and acidification potential (AP).

- This category summarizes the effect of total emissions of acidic gases to air. Deposition of these emissions can acidify water bodies and soils, and can cause building corrosion.

- AP-relevant gases include e.g. sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrochloric acid (HCl) and hydrofloric acid (HF). Typical sources of acidifying emissions are fossil fuel combustion for electricity production, heating and transport, and agriculture.

- The total impact is expressed in mol+ equivalents.

2. Climate Change

- Also referred to as global warming potential (GWP) and carbon footprint (CF).

- This category reflects the climate change impact of air emissions of greenhouse gases (GHGs). Increased GHGs in the troposphere result in warming of the earth's surface.

- The impact of greenhouse gas emissions – such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) – is assessed over a fixed time period of 100 years.

- The climate change category takes into account that different gases have different climate change impacts on global warming. The total impact is described in CO_2 equivalents.

3. Eutrophication - Marine and Freshwater

Emissions

- Also known as overfertilization and nutrification potential (NP).

- This category shows the impact of emissions (compounds containing phosphorus or nitrogen) on marine and freshwater bodies (lakes, slow moving rivers, estuaries, coastal areas etc.) that act as nutrients for vegetation.

- Nutrient emissions can lead to excessive plant and algal growth that depletes oxygen levels, killing, for example, fish, crustaceans, and plants to create dead zones.

- Water emissions differ in their effects on eutrophication. The impact is expressed in equivalent quantities of phosphorus (P) for freshwater and nitrogen (N) for marine eutrophication.

4. Freshwater Ecotoxicity

Biodiversity

- Also referred to as freshwater ecotoxicity potential.

- The ecotoxicity potential describes the environmental fate of chemical emissions and their impact on ecosystems.

- The methodology used to assess freshwater ecotoxicity is USEtox. USEtox is a consensus model developed within the framework of the UNEP-SETAC Life Cycle Initiative.

- The model evaluates the toxicological effects of a chemical emitted into the environment as a cause-effect chain that links emissions to impacts through three steps: environmental fate (behavior in the environment, i.e. movement within different environmental compartments), exposure and the effect on freshwater organisms.

- Freshwater ecotoxicity assessed using the USEtox model is reported in comparative toxic units (CTU_e).

Health & Safety

5. Human Toxicity – Cancer and Non-cancer

- The human toxicity potential expresses the estimated increase in morbidity in the total human population due to different types of emissions entering into the environment.

- The calculation is based on USEtox, which is a model that describes chemical fate, exposure, effect and optionally severity of emissions.

- The result is expressed in terms of Comparative Toxic Unit for Humans (CTU_h)

- The method is described in detail in Rosenbaum et al. (2008).

Resource Efficiency

6. Resource Depletion - Elements

- Also called abiotic depletion potential - elements (ADPE).

- This category reflects the consumption of raw materials. It assesses minerals impacts by taking into account the reserve base as well as current global rates of consumption of each substance. Therefore, use of raw materials with low reserves and/or high consumption rates is more critical.

- In the case of renewable raw materials, sustainable farming is assumed. This implies an endless reserve and thus a weighting factor of zero (in other words no consideration of biotic material depletion).

- The result is expressed in terms of Antimony (Sb)-equivalents.

Resource Efficiency

7. Resource Depletion - Fossil

- Also called abiotic depletion potential - fossil (ADPF).

- This category reflects the consumption of raw materials. It assesses fossil fuel impacts by taking into account the reserve base as well as current global rates of consumption of each substance. Therefore, use of raw materials with low reserves and/or high consumption rates is more critical.

- The result is expressed in Megajoule (MJ).

Emissions

8. Summer Smog

- Also referred to as photochemical ozone formation and photochemical ozone creation potential (POCP).

- This category reflects the impact of certain air emissions on summer smog formation. Emissions of VOCs (volatile organic compounds) in the presence of nitrogen oxides (NO_x) and sunlight can lead to chemical reactions that form ozone close to ground level (also called photochemical or tropospheric smog).

- Ground level ozone can result in negative health effects, including eye irritation, respiratory tract and lung irritation, as well as damage to vegetation.

- Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NO_x and VOC.

- Results are reported in kg NMVOC-equivalents (or in ethylene equivalents or O_3 equivalent dependent on the impact assessment methodology).

9. Primary Energy Demand

Energy

- Also referred to as cumulative energy demand (CED).

- The primary energy demand is a key indicator in LCA and an useful screening indicator for the environmental performance of products or processes. However, it is not considered to be an environmental impact category and hence is not aggregated to the total environmental score.

- The primary energy demand includes direct and indirect use of energy throughout the life cycle, encompassing extraction, manufacture, use and disposal of a product. It takes into account energy conversion losses along the process chain. It considered all kinds of different energy carriers, i.e. fossil-based as well as renewables (biomass and non-biomass).

- The result is reported in MJ.

Annex II – List of Figures and Tables

List of Figures

TÜVRheinland®
Precisely Right.

List of Tables

Annex III – Nomenclature

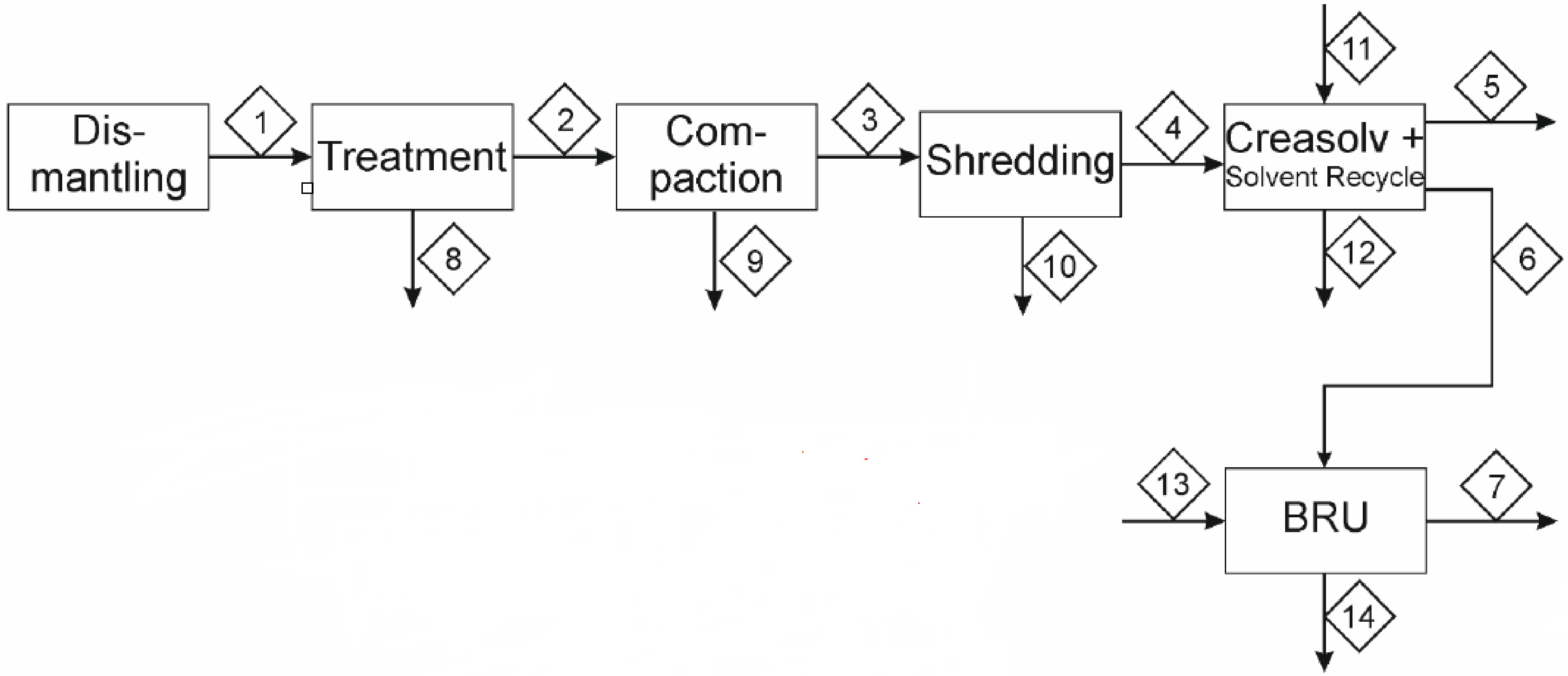
Nomenclature

ADPE	Abiotic Depletion Potential - elements
ADPF	Abiotic Depletion Potential - fossil
AE	Accumulated Exceedance
AP	Acidification Potential (acidification)
CED	Cumulative Energy Demand
CF	Carbon Footprint
CML	Institute of Environmental Sciences, Universities Leiden
CTU_e	Comparative Toxic Units for ecotoxicity- freshwater
CTU_h	Toxic Units for human toxicity (cancer and non-cancer)
EDP	Ecosystem Damage Points
EoL	End of life
EP	Eutrophication Potential
EPC	EPC Engineering Consulting GmbH
EPS	Expanded polystyrene
ETICS	External thermal insulation composite systems
EU PEF	EU Product Environmental Footprint
eq	equivalent
FU	Functional unit
GaBi	Ganzheitliche Bilanzierung
GWP	Global Warming Potential (climate change)
HBCDD	Hexabromocyclododecane (brominated flame retardant)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IWARU	Insitut für Infrastruktur, Wasser, Ressourcen, Umwelt
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-methane Volatile Organic Compounds
ODP	Ozone Depletion Potential (ozone depletion)
PFO	Perfluorooctanesulfonic acid
PED	Primary Energy Demand

POCP	Photochemical Ozone Creation Potential (photochemical ozone formation)
PS	Polystyrene
TRL	Technology Readyness Level
VOC	Volatile Organic Compounds
wt%	percentage by weight
XPS	Extruded rigid polystyrene

Annex IV – Process material balance for PS Loop alternative (Base Case)

Process flow diagram



Stream No.	1		2		3		4		5		6		7	
Stream Name	ETICS		EPS with impurities_1		EPS with impurities_2		EPS with impurities_3		PS		HBCDD		Bromine	
units	t	wt-%	t	wt-%	t	wt-%	t	wt-%	t	wt-%	t	wt-%	t	wt-%
EPS	**1.0**	**10.0%**	**1.0**	**100.0%**	**1.0**	**100.0%**	**0.95**	**100.0%**						
EPS pure	0.900	90.0%	0.900	90.0%	0.900	90.0%	0.855	90.0%						
HBCDD	0.004	0.4%	0.004	0.4%	0.004	0.4%	0.003	0.4%			0.003	19%		
Insolvable Impurities	0.066	6.6%	0.066	6.6%	0.066	6.6%	0.063	6.6%						
Water content	0.030	3.0%	0.030	3.0%			0.029	3.0%						
PS									0.850	99.9%	0.005	29%		
Bromine													0.002	100%
Other ETICS comp.	**9.0**	**90%**												
Adhesives	3.157	31.6%												
Plaster	3.221	32.2%												
Finsishing Coat	2.416	24.2%												
Dowel	0.050	0.5%												
Fabrics	0.146	1.5%												
Creasolv														
Solvent									0.001	0.1%	0.009	52%		
Soft Water														
Waste Water														
Insolvable Impurities														
Nitrogen														
Electricity [MJ]														
Steam [MJ]														
BRU supply														
Nitrogen														
Ammonia 25% bulk														
Hydrazine 55%														
Industrial Water														
NaOH 25%														
Na Formate 25%														
Na bisulphite 25%														
Electricity [kwh]														
LPG [m3]														
Steam [t]														
Cooling Water [m3]														
CO2 [kg]														
Nox [microg/m3 NCR]														
Wastewater [m3]														
anic Carbon (TOC) [mg/l]														
Halides (AOX) [microg/l]														
Sum	9.99	100%												
Gesamtmenge	10	t												

Stream No.	8 + 9 + 10		11		12		13		14	
Stream Name	Recect_3		Creasolve supplies		Reject_4		BRU supplies		Reject_5	
units	t	wt-%	t	wt-%	t	wt-%	t	wt-%	t	wt-%
EPS	0.05	0.6%								
EPS pure										
HBCDD										
Insolvable Impurities										
Water content										
PS										
Bromine										
Other ETICS comp.	8.99	99.4%								
Adhesives										
Plaster										
Finsishing Coat										
Dowel										
Fabrics										
Creasolv										
Solvent			0.011	34.4%	0.001	0.8%				
Soft Water			0.020	61.3%						
Waste Water					0.047	41.9%				
Insolvable Impurities					0.063	56.1%				
Nitrogen			0.001	4.2%	0.001	1.2%				
Electricity [MJ]			2790.7							
Steam [MJ]			50.274							
BRU supply										
Nitrogen							4.345E-07	5.3%		
Ammonia 25% bulk							5.214E-08	0.6%		
Hydrazine 55%							4.432E-07	5.4%		
Industrial Water							2.955E-06	35.8%		
NaOH 25%							3.324E-06	40.3%		
Na Formate 25%							4.345E-07	5.3%		
Na bisulphite 25%							6.084E-07	7.4%		
Electricity [kwh]							2.173E-06			
LPG [m3]							7.561E-07			
Steam [t]							2.347E-09			
Cooling Water [m3]							3.911E-08			
CO2 [kg]									2.809	
Nox [microg/m3 NCR]									0.112	
Wastewater [m3]									0.007	
anic Carbon (TOC) [mg/l]									0.022	
Halides (AOX) [microg/l]									0.022	
Sum										

Annex V – Further Information on CreaSolv® Process and scenario calculation (Process I and Process II)

Base Case Information

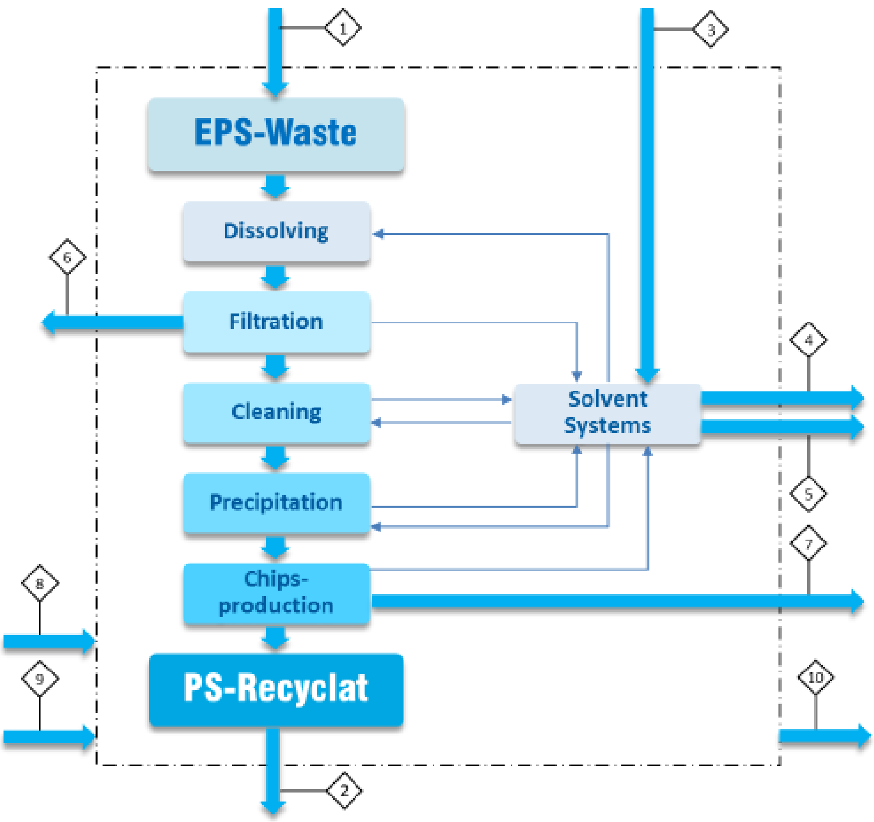
1 PROCESS MATERIAL BALANCE OF CREASOLV® PROCESS

1.1 BLOCK FLOW DIAGRAM WITH PROCESS STREAM NUMBERS

For a better understanding and more transparent handling of available data the following rough block flow diagram was created. As the information of this diagram might be used in the public LCA Report there might be not all internal process streams shown.

Additionally, the incoming and outgoing streams (position, number and composition) are dependent of the input stream (1) and its composition.

Energy demand is not shown in this diagram



1.2 PROCESS STEAM TABLES WITH HANDED OVER BASIC VALUES WITH FIRST LCA (BEFORE 09.08.17) (R1)

Stream No	1		2		3		4		5	
Stream Name	EPS raw material		PS Recyclat		Fresh solvent supply		Off-Gas ***)		HBCD Slurry ****)	
units	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%
PS	1,01E+01	90%	1,00E+01	100%		0%		0%	6,73E-02	30%
HBCD	4,48E-02	0,4%	*)	0%		0%		0%	4,37E-02	20%
Solvent		0%	1,00E-02	0%	1,32E-01	100%		0%	1,11E-01	50%
Insolvable impurities	7,39E-01	7%		0%		0%		0%		0%
Water	3,36E-01	3%	**)	0%		0%	1,60E-02	50%		0%
Nitrogen		0%		0%		0%	1,60E-02	50%		0%
Sum	11,20	100%	10,03	100%	0,13	100%	0,03	100%	0,22	100%

*) … HBCD content < 100ppm,

**) … Water content approx. <20ppm

***) … negligible traces of solvent and impurities coming with the EPS raw material (Flow 1) are possible.

****) … other high boiling substance potentially coming with the EPS raw material (Flow 1) are possible.

Stream No	6		7		8		9		10	
Stream Name	Solid waste		Off Spec		Soft Water		Nitrogen		Waste Water	
units	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%
PS	2,26E-03	0%				0%		0%		0%
HBCD		0%				0%		0%		0%
Solvent	1,13E-02	1%				0%		0%	1,60E-02	3%
Insolvable impurities	7,39E-01	98%				0%		0%		0%
Water		0%			2,17E-01	100%		0%	5,37E-01	97%
Nitrogen		0%				0%	1,60E-02	100%		0%
Sum	0,75	100%	0,00	0%	0,22	100%	0,02	100%	0,55	100%

Based on the above given figures the following efficiencies have been provided:

[1] Recycling rate of EPS to PS approx. 99 wt%

[2] Solvent losses approx. 0,13 t/d

Utility consumption figures:

Steam	ton / ton PS	1,47
Cooling Water	ton / ton PS	174
Power	kWh / ton PS	816

2.3 WORST CASE SCENARIOS (R1)

Two worst-case scenarios were calculated to see the influence on the complete LCA.

2.3.1 SCENARIO 1 (4 PLANT SHUT DOWNS PER YEAR / 0,4%HBCD / INCREASED SOLVENT LOSSES)

For this scenario 4 plant shut-downs per year were calculated (these are resulting in stream number 7 “off-spec”). Furthermore, the adhesive solvent on the solid waste (separated at the filtration) was increased drastically. This might be the case if these residuals are highly absorptive (e.g. wood or aerated concrete) → probably FH Münster can provide further details?!

The results show that the effect of the plant shut-downs have a minor influence on the process material balance. If the filter residuals will be absorptive higher solvent losses occur and also remaining dissolved PS gets lost. Nevertheless, the calculation has shown that 98% of PS can be recycled.

Stream No	1		2		3		4		5	
Stream Name	EPS raw material		PS Recyclat		Fresh solvent supply		Off-Gas ***)		HBCD Slurry ****)	
units	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%
PS	1,01E+01	90%	9,93E+00	100%		0%		0%	6,73E-02	30%
HBCD	4,48E-02	0,4%	*)	0%		0%		0%	4,37E-02	20%
Solvent		0%	9,93E-03	0%	6,53E-01	100%		0%	1,11E-01	50%
Insolvable impurities	7,39E-01	7%		0%		0%		0%		0%
Water	3,36E-01	3%	**)	0%		0%	1,60E-02	50%		0%
Nitrogen		0%		0%		0%	1,60E-02	50%		0%
Sum	11,20	100%	9,94	100%	0,65	100%	0,03	100%	0,22	100%

*) … HBCD content < 100ppm,

**) … Water content approx. <20ppm

***) … negligible traces of solvent and impurities coming with the EPS raw material (Flow 1) are possible.

****) … other high boiling substance potentially coming with the EPS raw material (Flow 1) are possible.

Stream No	6		7		8		9		10	
Stream Name	Solid waste		Off Spec		Soft Water		Nitrogen		Waste Water	
units	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%
PS	9,00E-02	7%	5,60E-03	100%		0%		0%		0%
HBCD		0%		0%		0%		0%		0%
Solvent	5,33E-01	39%		0%		0%		0%	1,60E-02	3%
Insolvable impurities	7,39E-01	54%		0%		0%		0%		0%
Water		0%		0%	2,17E-01	100%		0%	5,37E-01	97%
Nitrogen		0%		0%		0%	1,60E-02	100%		0%
Sum	1,36	100%	0,01	100%	0,22	100%	0,02	100%	0,55	100%

Utility consumption figures:

Steam	ton / ton PS	1,47
Cooling Water	ton / ton PS	174
Power	kWh / ton PS	816

2.3.2 SCENARIO 2 (12 PLANT SHUT DOWNS PER YEAR / 1,5%HBCD / INCREASED SOLVENT LOSSES)

In an additional calculation a monthly plant shut down is considered as well as a permanent HBCD concentration of 1,5% which is equal to the maximum occurring HBCD concentration in ETICS. This calculation was executed together with increased solvent losses due to high absorbent filter residuals. This calculation contains all worst case assumptions at the same time.

Stream No	1		2		3		4		5	
Stream Name	EPS raw material		PS Recyclat		Fresh solvent supply		Off-Gas ***)		HBCD Slurry ****)	
units	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%
PS	9,96E+00	89%	9,63E+00	100%		0%		0%	2,52E-01	30%
HBCD	1,68E-01	1,5%	*)	0%		0%		0%	1,66E-01	20%
Solvent		0%	9,65E-03	0%	9,60E-01	100%		0%	4,18E-01	50%
Insolvable impurities	7,39E-01	7%		0%		0%		0%		0%
Water	3,36E-01	3%	**)	0%		0%	2,10E-02	58%		0%
Nitrogen		0%		0%		0%	1,50E-02	42%		0%
Sum	11,20	100%	9,64	100%	0,96	100%	0,04	100%	0,84	100%

*) … HBCD content < 100ppm,

**) … Water content approx. <20ppm

***) … negligible traces of solvent and impurities coming with the EPS raw material (Flow 1) are possible.

****) … other high boiling substance potentially coming with the EPS raw material (Flow 1) are possible.

Stream No	6		7		8		9		10	
Stream Name	Solid waste		Off Spec		Soft Water		Nitrogen		Waste Water	
units	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%	t/day	wt.%
PS	6,98E-02	5%	1,68E-02	100%		0%		0%		0%
HBCD		0%		0%		0%		0%		0%
Solvent	5,33E-01	40%		0%		0%		0%	1,79E-02	3%
Insolvable impurities	7,39E-01	55%		0%		0%		0%		0%
Water		0%		0%	2,84E-01	100%		0%	5,99E-01	97%
Nitrogen		0%		0%		0%	1,50E-02	100%		0%
Sum	1,34	100%	0,02	100%	0,28	100%	0,02	100%	0,62	100%

Utility consumption figures:

Steam	ton / ton PS	2,49
Cooling Water	ton / ton PS	258
Power	kWh / ton PS	816

EPC E-Mail communication 08. September 2017

Von: Hamann Jörg [mailto:Joerg.Hamann@epc.com]
Gesendet: Montag, 4. September 2017 16:53
An: Nicole Kambeck <nicole.kambeck@basf.com>; Klaus Christian <Christian.Klaus@epc.com>
Cc: Susanne.jorre.de.tuv.com <Susanne.jorre@de.tuv.com>; Dominik Mueller <Dominik.mueller@de.tuv.com>
Betreff: AW: LCA - PSLoop

[…]

Bezgl. „Anti-Lösungsmittel" haben wir alle INPUT Ströme in der aktuellen Bilanz angegeben. Wie wir intern mit der Zusammensetzung und Mischung der einzelnen Ströme zum Fällen verfahren, möchten wir nur ungerne im LCA nach außen offen legen. Es werden nicht mehr als die angegebenen Ströme in die Anlage eintreten. Für die „Sensitivität" und das LCA sind aus unserer Sicht die Kreislaufströme intern doch nicht von Interesse. Evtl. Änderungen hier spiegeln sich im Energieverbrauch und den ein- und austretenden Strömen wieder.

Das ist nachvollziehbar und auch nicht nötig aber was ist denn nun das anti-solvent? Wo genau ist es in der Tabelle aufgeführt?

[Joerg Hamann] Wie oben ausgeführt, wir verwenden ausschließlich die dargestellten Ströme. Für den bei PSLoop beschriebenen Prozess werden keine weiteren Lösungsmittel in die Einlage eintreten.

Annex VI – Evaluation of TRL

Send by Ms Nicole Kambeck on 08/23/2017, 10:52

Hallo Herr Prof. Kind,

besten Dank, Ihre Einschätzung deckt sich weitestgehend mit der ersten Einschätzung unseres Prozessmanagers der Styrol und Polystyrol-Anlage, getroffen auf Basis der Infos aus dem review Artikel:

„Die Versuche der Extraktion sind im Labormaßstab durchgeführt worden, die Trocknungsversuche im Extruder fanden im Technikumsmaßstab statt.

Es wurden immer nur Teilschritte erprobt, nicht der vollständige Prozess in ihrer Gesamtheit. Einige Verfahrensschritte wurden offensichtlich gar nicht untersucht. Eine (thermodynamische) Simulation gibt es anscheinend nicht und somit auch kein vollständiges Prozessmodell.

Nach meiner Einschätzung befindet man sich bei TRL4 in einigen Verfahrensschritten vielleicht auch nur TRL3.

Es wird möglich sein, recyceltes EPS mit Restlösemittelgehalte unter 1000ppm herzustellen. Aber der Aufwand wird wahrscheinlich sehr hoch sein um dies zu erreichen. Die Technikumsversuche haben da noch keine Aussagekraft. In diesem Maßstab können sie mit relativ kleinen Aufwand praktisch alles erreichen.“

Mit freundlichen Grüßen/ Best regards

Nicole Kambeck
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