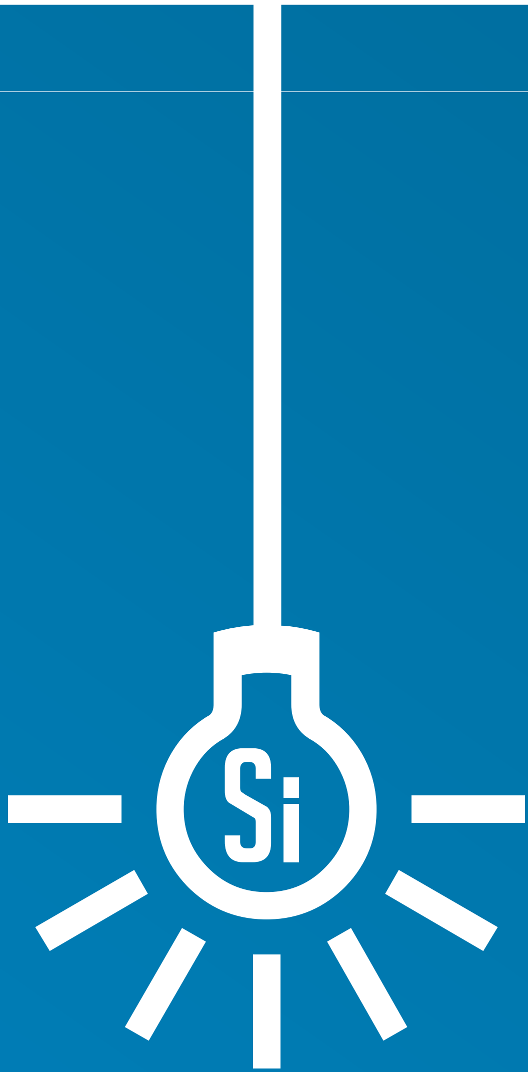
EXECUTIVE SUMMARY

SILICON-CHEMISTRY CARBON BALANCE

AN ASSESSMENT OF GREENHOUSE GAS EMISSIONS AND REDUCTIONS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EXECUTIVE SUMMARY

SILICON-CHEMISTRY CARBON BALANCE

AN ASSESSMENT OF GREENHOUSE GAS EMISSIONS AND REDUCTIONS

Covering the Production, Use and End-of-Life
of Silicones, Siloxanes and Silane Products
in Europe, North America and Japan

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Centre Européen des Silicones
Silicones Environmental, Health and Safety Council of North America
Silicone Industry Association of Japan

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01

INTRODUCTION

1|1 STATEMENT OF INTENT FOR INITIATING THIS STUDY

In order to better understand the sustainability of the products derived from the chemistry of silicon, the Global Silicones Council (GSC) has – as a first step – undertaken a study looking at the greenhouse gas (GHG) emissions of silicone and silane products from "cradle to grave", in other words from the production phase to the use phase and then to final waste treatment. The production of silicon metal, silicones and silanes is related to significant amounts of energy; therefore GHG emissions are assumed to be one of the most important sustainability parameters.

This study follows and updates a life cycle inventory of the production phase of silicones done in 2002 [CES, 2002]. It is expected that the data will help SEHSC, CES and SIAJ members to assess their own individual performance relative to the industry benchmark, to identify areas for further improvements, and to support communication about GHG impacts and benefits of silicone and silane products.

There is increasing attention by the general public, customers, regulators, governmental agencies and non-governmental organizations (NGOs) on the contribution of the manufacturing of materials including industrial chemicals to the formation of GHG and consequently their impact on climate change. This attention has increased since there is growing interest in reliable facts on the impact of available options allowing consumers, manufacturers, retailers and policymakers alike to help decide which of them to base their respective strategies on.

With this background, organisations such as the International Council of Chemical Associations [ICCA, 2009], PlasticsEurope [Pilz et al., 2010] or companies [BASF, 2008] conducted studies where they calculated life cycle impacts against use benefits of chemical and plastic products.

The Global Silicone Council, which is an umbrella organization coordinating activities of regional silicone industry associations (CES, SEHSC and SIAJ), considers the study as an important part of the sustainability strategy for silicone products.

Consumers, manufacturers, retailers and policymakers increasingly require reliable data that will allow them to implement effective sustainability measures and decisions.

1ST STUDY OF ITS KIND FOR SILICONES

1|2 PEER REVIEW

A critical scientific review of this study was performed by Professor Adisa Azapagic, based at the University of Manchester. The review is attached to this summary.

The aim of the critical review was to examine

- that the methods used are scientifically and technically valid given the goal of the study;
- that the data used are appropriate and reasonable in relation to the goal of the study;
- that the interpretation reflects the goal of the study and the limitations identified; and
- that the study report is transparent and consistent.

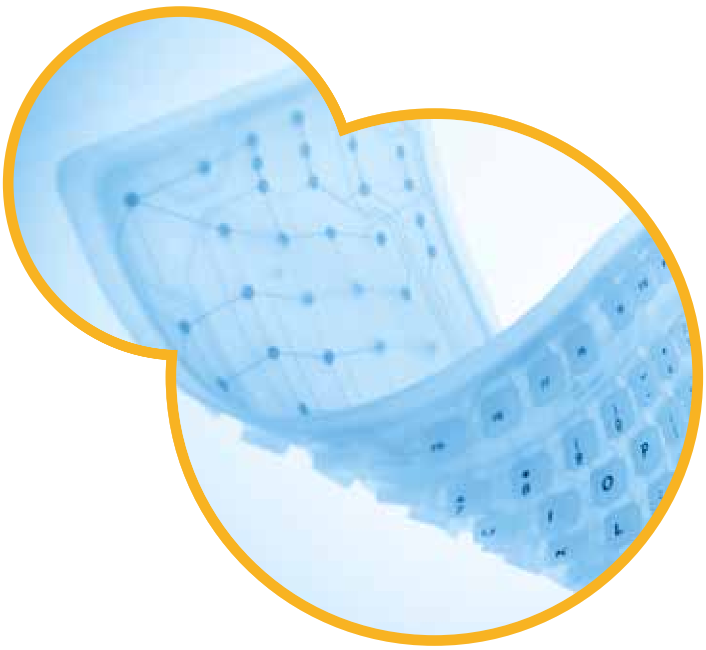
The goal of the study is to estimate the product carbon footprint or life cycle greenhouse gas emissions related to the total market of silicones, siloxanes and silane products in Europe, North America, and Japan. The GHG emissions related to production, usephase and end-of-life phase of these products are furthermore compared with GHG abatement effects resulting from the use of silicones, siloxanes and silane products. These abatement effects or "**GHG benefits**" are a consequence, among other things, of:

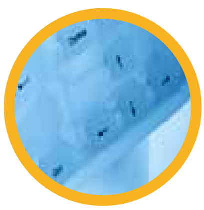
1|3 GOAL OF THE STUDY

A | reduced consumption of fossil fuels, because silicone and silane products enable more efficient transport, contribute to lighter vehicles and related fuel savings, to savings in heating energy and electricity consumption, and help to increase the efficiency of processes.

B | saved production of other materials, because silicone and silane products contribute to extending the lifetime of materials and to more efficient use of materials; in addition and when compared to alternatives, they can allow for a given function to be provided but with less material and/or a smaller carbon footprint in material production and recovery (details are described in Chapter 5.)

In this study, the term "Si-chemistry carbon balance" is used for the ratio of "GHG abatement benefits resulting from the use of silicone and silane products" divided by "GHG emissions related to production, use and end-of-life of silicone and silane products." In addition to this ratio of benefits and impacts, a second key figure is calculated: This is the GHG net benefit or net abatement realised by using silicone and silane products, and it is calculated by subtracting the impacts from the benefits.

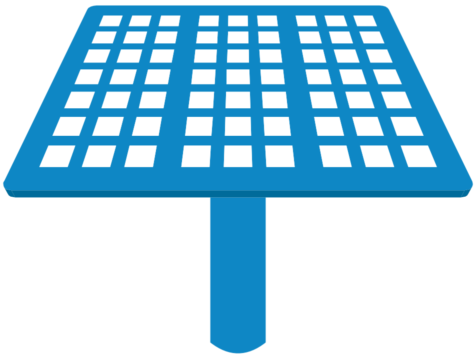




1|4 SCOPE OF WORK

The project is intended to enable silicone manufacturers to provide relevant carbon balance data to customers, regulators and other stakeholders on request, as well as identify opportunities for carbon balance improvements.

The project is intended to enable members of the silicon chemistry sector to provide relevant carbonbalance data to customers, regulators and other stake-holders on request.



1|4-1 ECO-PROFILE UPDATE

Based on an eco-profile of silicones [Boustead, 2003], which provides data on raw material usage and emissions from the production of a basic silicone material, polydimethyl-siloxane (PDMS), silicone fluids and silicone sealants in 2001, an update of the cradle-to-gate GHG emissions with data related to 2010 is performed within this study.

The scope of products covered by the ecoprofile update includes PDMS fluids (silicone oil) and PDMS used for sealants (the GWP data for sealants is calculated in the respective case studies for different formulations). GWP data for silicone rubbers and resins (higher number of crosslinks), for intermediates such as methylchlorosilanes and chlorosilanes as well as for fumed silica were generated as well.

1|4-2 SYSTEM DEFINITION

The temporal system boundary of the silicon carbon balance is defined as one year (mostly 2010); the spatial system boundary is represented by Europe, North America and Japan. The study follows a total market approach, which means that the total market volume of silicone products consumed in the defined regions is considered when calculating the overall carbon balance. The total market is broken down into detailed application sectors and product groups.

Although one single carbon balance is established for the sum of Europe, North America and Japan, regional differences in the total life cycle are considered. This is done by using regional electricity supply mixes, by accounting for regional transport effects and heating energy consumption, and by considering different regional waste management options.

1|4-3 SITUATION ANALYSIS

Silicone manufacturers should be provided with relevant carbon balance data to be able to inform downstream users, regulators and other stakeholders on request or proactively. Hence, the expectations of the supply chain as well as other stakeholders on such carbon balance data have to be determined.

For that purpose an analysis of supply chain expectations is conducted. This includes an inventory and analysis of the expectations of regulators, retailers and other downstream users regarding the availability of carbon balance information from silicone manufacturers in Europe, North America and Japan. This question is covered by DEKRA Industrial GmbH (see Chapter 2).

1|4-4 CASE STUDIES, CALCULATION MODEL, CONSERVATIVE EXTRAPOLATION

The carbon balance model is developed on the level of case studies and covers calculations concerning the entire life cycle of production, effects in use and waste management. For every case study, the “GHG benefits” resulting from using a silicone or silane product are defined and calculated.

The total market volume of silicone and silane products is split into differentiated product groups, as detailed as possible. **Twenty-six representative case studies** are identified – these are product groups where the use of silicone and silane products is linked to GHG abatement effects, or where silicone and silane products can be compared to alternative materials (see Chapter 3).

The results of the case studies are analysed and aggregated to a weighted average with regard to the market volumes of silicone products. Based on uncertainties of input data and respective sensitivity analyses, a range is calculated for the weighted average results of the case studies. Finally, a **conservative extrapolation** to the total market of silicone products is performed. This is done in order not to overestimate the benefits. The extrapolation is only applied to 10 % of the total market volume, and is based on the minimum value of the range for the weighted average results of the case studies (details are described in Chapter 6).

The underlying methodology was originally developed by GUA, one of the forerunner companies of denkstatt, for several studies commissioned by PlasticsEurope, e.g. [Pilz et al., 2010]. The methodology has been peer-reviewed several times and is widely accepted. Although this is not a full LCA study and therefore the ISO LCA standards cannot be applied, all calculations are carried out following recommendations in the [ISO 14040, 2006]/[ISO 14044, 2006] series. Special methodological aspects are described in Chapter 4.

Any data gaps or uncertainties were bridged with conservative assumptions. The study’s authors have chosen to be particularly conservative to avoid overestimating any carbon abatement results.

Conclusions are based on conservative assumptions and on a conservative extrapolation of results in order not to overestimate the benefits.

1|5 THE 80/20 APPROACH

CES and denkstatt have taken an "80/20 approach" (also known as the Pareto principle), which means covering 80 % of the results with 20 % of the data required for a more comprehensive study. Under the 80/20 approach, research efforts focus on the most relevant effects and influences whereas minor effects and influences are ignored. Decisions on which data to include and which to exclude was discussed with silicone industry representatives and with the peer reviewer at several occasions.

Thus, the results provide an indication of the status and trends of entire application sectors rather than the specific status of specific products. The study provides a realistic estimate of the overall GHG impact of the total market of silicone products, but it is not a "product-by-product" life cycle assessment. It also puts matters into perspective by distinguishing between the important and the negligible influences in the GHG balances across the total life cycle.

The study is based on a set of plausible assumptions to support the calculations and elaboration of the case studies, and on data that are in line with current knowledge, to the extent available and as needed within the 80/20 approach.

02

MARKET DATA AND CASE STUDIES

A bottom-up approach was combined with a top-down approach in order to estimate total market volumes as well as the split in different application sectors.

Under the bottom-up approach, the total market of silicone products in Europe, North America and Japan was modelled in a list of applications, structured by sector and by region. Market volumes were based on statistics provided by the regional silicone industry associations. The data were further refined together with member company experts.

The top-down approach involved obtaining total market volumes from an existing report [Simuch 2011] and verifying the data with an industry expert. As the sum of all estimates in the bottom-up approach was higher than the figures from the Simuch report, all market volumes of single applications except explicitly very well proven ones were reduced by the same factor to reach the desired totals.

Chlorosilanes for the production of solar and electronic grade silicon were excluded from the adjustment of market data and added afterwards. Other silanes with a combined market share of only 2 % are included in this adjustment.

The market volume of chlorosilanes for solar grade silicon is derived from [Sage 2011] and [EPIA 2011], those for microelectronic manufacturing was estimated on the basis of [Sage 2011] and company data.

The consumption market volume for the three regions considered, on which further calculations were based, totals 1,142,000 tons per year:

- **Europe** (384,000 t of silicones and 306,000 t of chlorosilanes)
- **North America** (296,000 t of silicones and 35,000 t of chlorosilanes)
- **Japan** (93,000 t of silicones and 28,000 t of chlorosilanes)

All market data refer only to silicones and silanes as pure substances (not formulated silicones or silanes). “Silicone” covers only silicone (PDMS) and its functional derivatives, including organosilicones, cyclic and linear siloxanes, but no fillers, solvents and additives. Chlorosilanes for the production of solar and electronic grade silicon are also included in the total market volumes mentioned above, but no other intermediates that are used to make silicones or alkoxysilanes. Furthermore all market data refer to consumption; they do not refer to production as there is considerable worldwide trade of products.

One original aim of the project was to cover a high market share (60 % – 70 %) by case study. However, some of the applications with considerable market shares turned out to have neither alternatives to which they could be compared to, nor any (quantifiable) GHG effects in their use phase, but other benefits that cannot be expressed in terms of CO_2. Therefore these applications – some of which have considerable market share – are not represented by the case studies.

The total market was split into groups with different suitability for defining case studies:

- applications covered by case studies (59%); these are product groups where the use of silicone and silane products is linked to GHG abatement effects, or where silicone and silane products can be compared to alternative materials;
- applications that were considered unsuitable for case studies, because the use of silicone and silane products is not linked to any (quantifiable) GHG effects (21%);
- applications not specified (20%).

Table 1 lists the selected case studies.
For these silicone or silane products both the GHG emissions from production and end-of-life phase as well as the GHG benefits resulting from using the product are quantified. It should be noted that the GHG emissions related to production and end-of-life of products and market sectors not included in the case studies are also covered by the final results of this study. For the latter no GHG benefits related to their use are taken into account.

The study combines bottom-up and top-down estimates to realistically gauge market volumes and the split between different application categories.

Case Study	Market volume (t/a)
Construction	**207.000**
• Sealants Kitchen/Bathroom	79.400
• Sealants Windows IG unit	56.700
• Sealants Expansion Joints for Outside Use	38.900
• High Quality Sealants & Adhesives	10.100
• Masonry Water Repellent - concrete	2.500
• Masonry Water Repellent - bricks	10.100
• PU Additives for Thermal Insulation in Construction	9.300
Electronics	**383.100**
• PU Additives for Thermal Insulation in Appliances	4.700
• Cooling Liquid in Transformers	8.700
• Electrical Isolators	9.600
• Chlorosilane for Solar Grade Silicon	360.100
Industrial	**19.100**
• Anti-foaming in Paper Production	10.200
• Paint Additives	1.900
• Silanes for Glass Fiber Coating	1.900
• Heat-Resistant Industrial Coatings	3.200
• Adhesion Promoter for Coatings	1.900
Personal & lifestyle	**13.200**
• Antifoaming in Detergents	7.800
• Baby Teats	1.900
• Heat Resistant Coating of Personal Appliances	1.600
• Bakeware	1.900
Transportation	**48.500**
• Rubber in Motor Construction	33.800
• Green Tyres	6.400
• Coating for Polycarbonate	1.800
• Coating for Car Exhausts	500
• Marine Coatings	100
• Automotive Bonding	5.900
Total	**670.900**

Table 1
List of selected case studies, subdivided by application sector, market volume in ton per annum (t/a); for each application these data are total market value assumptions and not company specific ones.

03

LIFE CYCLE GHG EMISSION DATA

3|1 METHODOLOGY

This study on the life cycle GHG emissions of products made of siloxanes and silanes broadly follows the methodological guidelines for LCAs given in ISO 14040/44. Nevertheless, due to the goal and scope of this study, there are some limitations, simplifications and additional elements in the methodology used:

- Limitation to **GHG emissions**; no other environmental impacts are considered.
- **80/20 approach** (see Chapter 1.5): Due to the large number of investigated products, and due to the intended character of the results (approximate ratio of impacts and benefits for the total market of silicone products, not accurate LCA results of single products), many estimations are used and simplifications are applied where the influence on the result is small, or where research to obtain more accurate data is not feasible within the agreed project scope and timing.
- **Comparative results**: Each case study is based on a comparison with alternative materials or alternative (sometimes historical) ways to provide the same service. The comparison always refers to the same functional unit.
- Data for **production** of siloxanes and silanes show differences in quality due to the availability of data sources: GHG emissions to produce silicon metal are not based on primary data from single plants, but on information from Euroalliages (the association of European ferroalloy producers), experts, literature, and on the regional electricity mix and the regional mix of reduction agents. GHG emissions to produce PDMS, chlorosilanes and fumed silica are based on detailed information from five companies. GHG data for special substances based on siloxanes or silanes, but containing certain functional groups with relevant mass shares, were estimated based on the GWP data of the raw materials used.
- **Use phase** effects are described and defined individually in each of the 26 case studies. Generally the methodological standards mentioned above do not (and cannot) regulate the calculation of use phase effects, as these effects and options to quantify them differ from product to product.
- **Waste management**: End-of-life effects mostly do not significantly influence the results of this study. Little information is available, such as the distribution of silicone products toward different waste flows in different regions, the rate of natural degradation of silicone on surfaces or the behaviour of silicones in residual waste landfills. End-of-life calculations are therefore based on reasonable assumptions derived from available regional waste management data.

- **Implementation of market data**: Results per kg of silicone material are combined with estimated market volumes to calculate absolute annual effects of the product, and to enable the calculation of aggregated results for the total market of silicones. Market data for alternative materials are used where case studies compare silicone to the market mix of alternative materials.

- **Allocation of benefits**: In some case studies, other materials or effects than the use of silicone contribute to the benefits realised. To produce results per kg of silicone it is necessary to allocate a certain share of the total use benefit to the silicone product. The allocation approaches used are defined individually in the different case studies.

The study broadly follows the methodological guidelines for lifecycle assessment under ISO 14040/44.

3|2 SYSTEM DEFINITION FOR SILICONE PRODUCTS

Figure 1, on the next page, describes the investigated products and processes in the life cycle of silicone products.

Products

Silicone products in the focus of this study – Sealants, silicone rubber and silicone resin account for the highest market share of the products in the system.

Other products, inputs and intermediates

Processes

Production processes in Si-industry; the four processes highlighted in yellow account for the main energy input in the production system.

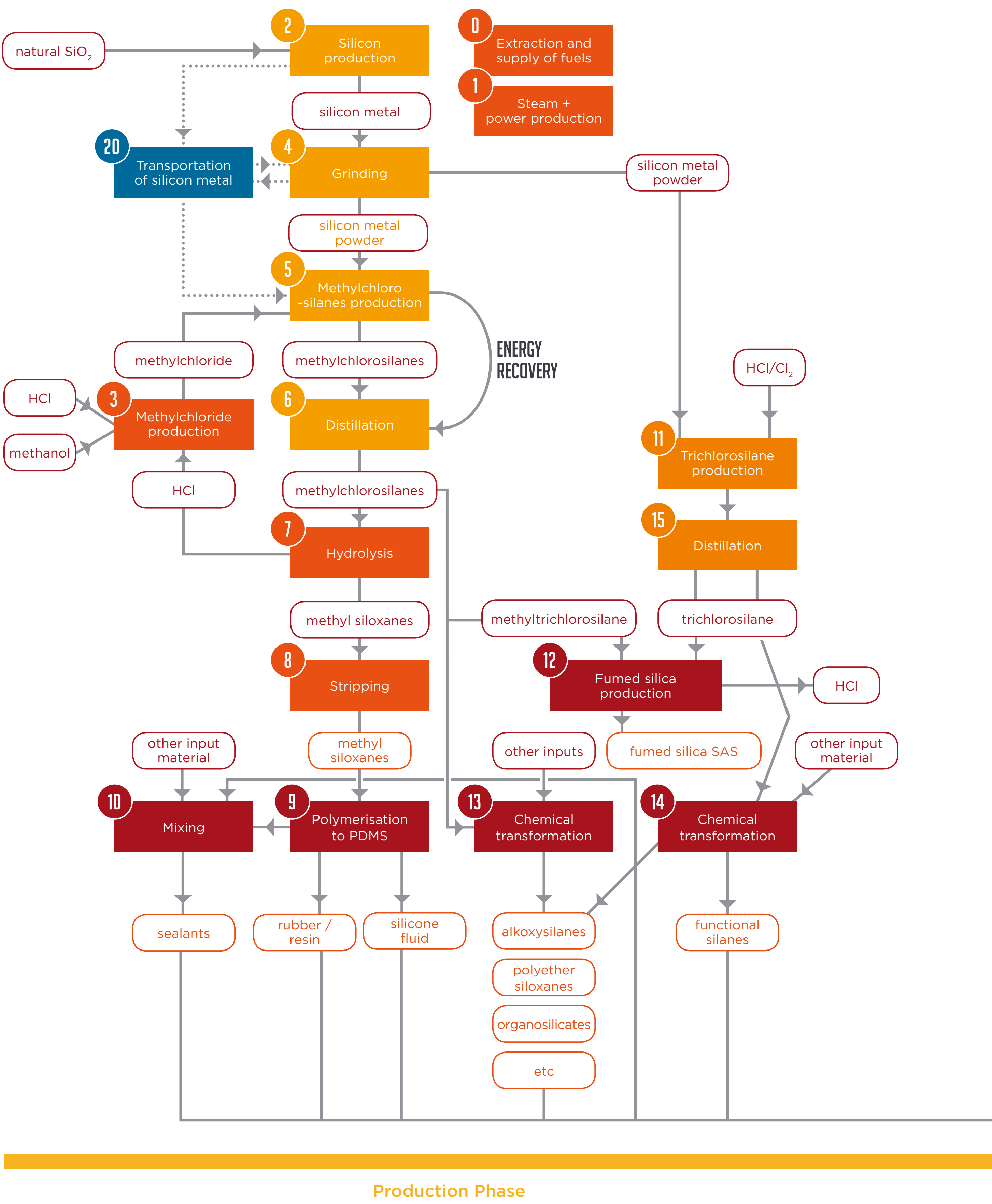
Production processes in Si-industry not considered in [Boustead 2003], but considered in this study because GWP data for additional products are needed.

Processes in the use phase.

End of life process - there is only little recycling of production waste (which is not considered in the study), but no end-of-life recycling.

Substituted process in end of life phase, e.g. generation of heat from fossil fuels that is substituted by generation of heat from waste incineration.

Transport processes - for clarity, not all transport processes considered are displayed (for example also transport of alternative materials is taken into account).


natural SiO_2
2 Silicon production
0 Extraction and supply of fuels
1 Steam + power production
silicon metal
20 Transportation of silicon metal
4 Grinding
silicon metal powder
silicon metal powder
5 Methylchloro -silanes production
ENERGY RECOVERY
methylchloride
methylchlorosilanes
HCl
3 Methylchloride production
methanol
6 Distillation
HCl/Cl_2
11 Trichlorosilane production
HCl
methylchlorosilanes
7 Hydrolysis
15 Distillation
methyl siloxanes
methyltrichlorosilane
trichlorosilane
8 Stripping
12 Fumed silica production
HCl
other input material
methyl siloxanes
other inputs
fumed silica SAS
other input material
10 Mixing
9 Polymerisation to PDMS
13 Chemical transformation
14 Chemical transformation
sealants
rubber / resin
silicone fluid
alkoxysilanes
polyether siloxanes
organosilicates
etc
functional silanes
Production Phase

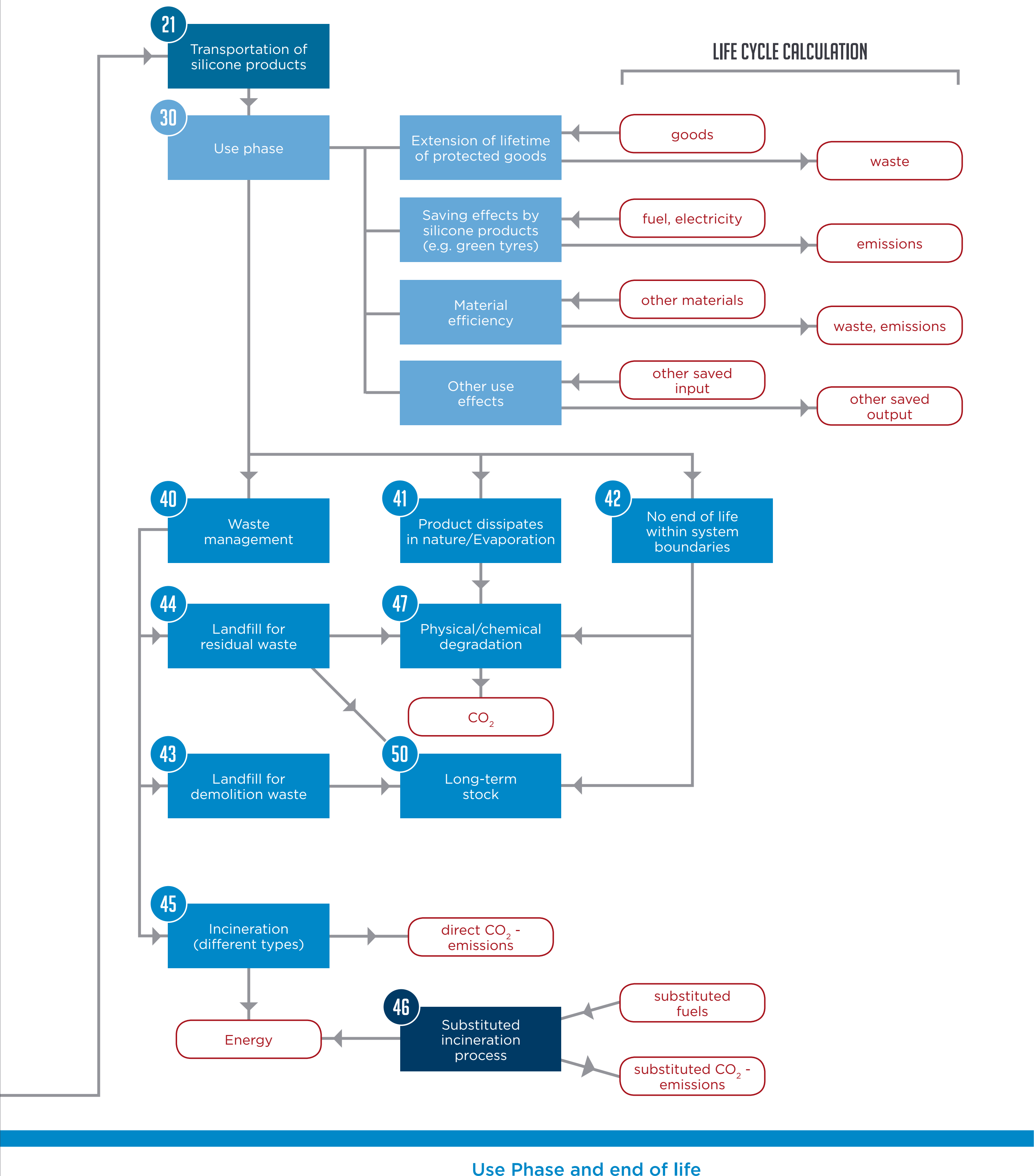


Figure 1

System definition and investigated processes for production of siloxanes, silanes and fumed silica as well as for use phase and end of life phase of siloxanes and silanes. The products shown in the figure above describe typical product families.

3|3 GHG EMISSIONS FROM PRODUCING SILICON METAL

The main raw materials used to produce the most common siloxanes and silanes are silicon metal, methanol and HCl. The GHG emissions to produce silicon metal are the most relevant contribution to the cradle-to-gate GHG emissions of silicones (66 %, see Chapter 4.4).

Silicon metal (or elemental silicon) is produced from mined quartz and various reduction agents in submerged electric arc furnaces. Reducing gas (CO, H2) is produced from fossil materials such as coal, pet coke and coke, and/or from biobased materials such as charcoal and woodchips.

In 2010 the total global production of silicon metal was slightly above 1.9 Mt. China's silicon metal output was 1.15 Mt, accounting for 60 % of worldwide production. According to the global demand for metallic silicon, about 40-50 % of the metallic silicon is used in aluminium alloy, 20 % in polysilicon, **30 % in the organic silicon market** (which is the relevant market share for silicone, siloxane and silane products), and a very small proportion in refractory materials (ResearchInChina 2011).

Investigations into the production GWP of silicon metal *used for silicone, siloxane and silane products in Europe, North America and Japan* led to a value of approximately 10.0 kg CO_2e/kg silicon metal with an uncertainty of +- 2.5 kg CO_2e:

GHG emissions related to electricity:
↳ 6.0 kg CO_2e/kg silicon metal [2]
GHG emissions related to reduction agents:
↳ 3.9 kg CO_2e/kg silicon metal [1]
Total GWP:
↳ 9.9 kg CO_2e/kg silicon metal
Uncertainty:
↳ +- 2.5 kg CO_2e (+- 25 %)

The main reason for the uncertainty is the significant influence of variable sources of electricity production in different regions of the world, and consequently the variations in the regional source mix from which silicon metal is purchased by manufacturers of silicones, siloxanes and silanes. In other words:
The regional origin of silicon metal is one of the most significant factors in the GHG balance of silicone, siloxane and silane products.

The regional origin of silicon metal is one of the most significant factors in the overall GHG balance of silicones, silanes and siloxanes.

[1] A detailed description of the general process and best available techniques is given in the respective reference document [European IPPC Bureau, 2001], pages 505 et sqq.
[2] After allocation of 3% of total GWP to the by-product silica fume (see text above).

3|4 GHG EMISSIONS FROM PRODUCING PDMS AND RELATED SUBSTANCES

Silicone fluids, sealants, rubbers, and resins based on PDMS or with a chemical composition which is very similar to PDMS cover more than 90 % of the total market amounts of siloxane and silane products. Therefore the GHG emissions related to the production of PDMS fluids, sealants, rubbers, and resins were investigated in detail.

PDMS is basically produced from silicon metal and methylchloride (for which HCl and methanol are the main inputs), which form methylchlorosilanes in the Müller-Rochow process. The methylchlorosilanes (mostly dichlorodimethylsilane) are transformed to polymeric methyl siloxanes (short linear or low molecular weight cyclic polymers) by hydrolysis. These products are separated into various fractions and further polymerised into PDMS. An increasing number of crosslinks between the polymers leads to rubbers and resins. A detailed description of the processes and best available techniques can be found in [IPPC, 2007].

Methylchlorosilanes and/or chlorosilanes are used to produce other siloxanes or silanes (e.g. alkoxysilanes, polyether siloxanes) or resins or pyrogenic silica. Trichlorosilane (HSiCl3) is used to produce functional silanes by replacing hydrogen with functional groups. Cradle-to-gate GHG emissions of input raw materials to produce functional silanes (e.g. heavy alcohols) can be important.

All downstream processes after distillation are small in terms of energy consumption (hydrolysis, alcoholysis, etc.), compared to the life cycle until distillation. Most of these processes are exothermic, but controlling the processes might need some energy.

In order to produce synthetic amorphous silica (“fumed” or “pyrogenic” silica), chlorosilanes or methylchlorosilanes are burned. HCl is recovered and used within the methyl chloride process. Pyrogenic silica provides strength as reinforcing filler. Some silica grades are chemically modified on their surface; many other types of filler are not. Silica is mostly bought from external sources, but also produced by some CES members.

Table 2 shows the resulting GWP data for intermediates, PDMS, and related substances, as well as for polymerisation, mixing, and transport of products as separate processes.

The GHG emissions related to the production of PDMS fluids, sealants, rubbers, and resins were investigated in detail.

GWP data in kg CO_2e / kg product	
Transport of raw materials	0,10
Methyl siloxanes production	6,12
Methyl siloxanes (MS)	**6,22**
Polymerisation MS to PDMS	0,10
PDMS - silicon fluid / oil	**6,31**
Polymerisation MS to rubber/resin	0,19
Mixing process	0,17
PDMS rubber/resin incl. mixing	**6,58**
Transport of products	0,19
Chlorosilane production	3,40
Methylchlorosilane production	3,38
Pyrogenic silica production	9,50

Table 2
Cradle-to-gate GWP estimated in this study for PDMS, intermediates, and related substances, as well as gate to gate GWP data for polymerisation, mixing, and transport of products as separate processes. Sums might not be matching due to rounding effects.

Figure 2 shows the relative contributions of important raw materials, of energy consumption and of other inputs and wastes to the total GHG emissions of methyl siloxanes.

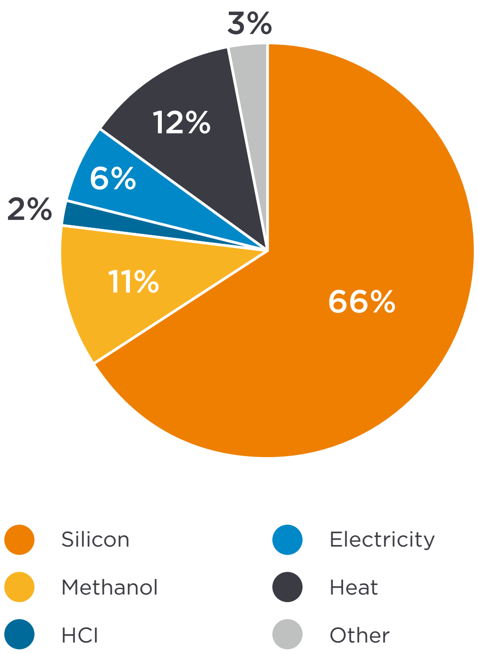


Figure 2
Relative contributions of important raw materials, energy consumption and other inputs and wastes to the total GHG emissions of methyl siloxanes.

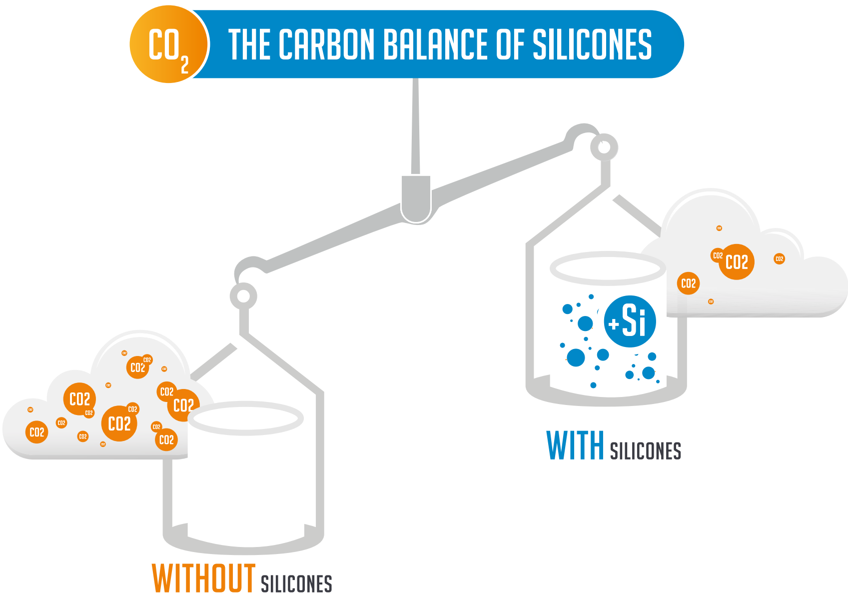
Including the estimated uncertainty, the **production GWP** of PDMS led to a value of approximately **6.3 ± 1.3 kg CO_2e/kg PDMS**. The GWP of the respective silicon metal input is related to 66 % of this value, heat and electricity needed for PDMS production are related to 18 % of this value, and methanol to 11 %. The accuracy of all other input or output data (such as HCl, Nitrogen, waste streams, and GHG emissions related to processes, not to fuels) as well as the respective GWP factors are of minor importance, because they collectively account for a modest 5 % of the GWP of PDMS.

3|5 GHG EMISSIONS FROM USE PHASE

There is a great variety of effects caused by the use of silicone products, with an equally widely varying extent. In some case studies, a small amount of silicone product leads to a huge GHG saving, in others only materials are compared and there is no GHG effect (or no effect at all) during the use phase. Table 3 gives an overview of all case studies and their use phase effects that can be expressed in CO_2e.

Some usephase effects are not solely enabled by products from the silicon industry; they are possible thanks a combination of silicone and other products or technologies. In this case, only an appropriate share of the use benefit is allocated to silicones (see detailed description of case studies).

In some case studies, a small amount of silicone being used will lead to huge reductions in greenhouse gas emissions.



Name of Case Study	Use effect that can be expressed in CO_2e
• Sealants Kitchen/Bathroom	No GHG effects in the use phase compared to other materials
• Sealants Windows IG unit	Difference in air tightness lead to different U-values, which lead to different heating demand
• Sealants Expansion Joints for Outside Use	No GHG effects in the use phase compared to other materials
• High Quality Sealants & Adhesives	System with silicone demands less material and saves energy for heating and cooling
• Masonry Water Repellent - concrete	Silane product protects concrete infrastructure, less concrete and steel must be produced
• Masonry Water Repellent - bricks	Silane product protects bricks against moisture, U-value is improved and heating energy is saved
• PU Additives for Thermal Insulation in Construction	Different GWP of foaming agents
• PU Additives for Thermal Insulation in Appliances	Different insulation properties lead to different electricity demand, plus different GWP of foaming agents
• Cooling Liquid in Transformers	Silicone enables compact design and improves fire safety; both aspects help to save infrastructure
• Electrical Isolators	No GHG effects in the use phase compared to other materials; differences in leakage current could not be quantified
• Chlorosilane for Solar Grade Silicon	Solar grade silicon is needed for photovoltaic plants, solar electricity production saves fossil energy resources
• Anti-foaming in Paper Production	Higher washer throughput makes pulp plant more efficient, less water must be vaporised, less process chemicals are lost
• Paint Additives	Without paint additives for better surface levelling there is an increase in paint used and in drying energy.
• Silanes for Glass Fibre Coating	Glass fibre reinforcement leads to higher material efficiency – less polymers need to be produced
• Heat-Resistant Industrial Coatings	Saved enamelling or saved production of iron and zinc coating
• Adhesion Promoter for Coatings	Saved production of paint, less evaporation of solvent
• Antifoaming in Detergents	Less electricity for washing, less detergents needed
• Baby Teats	No use effect, but different lifetimes compared to alternative material considered
• Heat Resistant Coating of Personal Appliances	Saved enamelling or saved production of iron and zinc coating
• Bakeware	No GHG effects in the use phase compared to other materials
• Rubber in Motor Construction	Contributes to more efficient motor technology which leads to fuel saving
• Green Tyres	Less rolling resistance leads to fuel saving
• Coating for Polycarbonate	Contributes to lighter automotive parts, which lead to fuel saving
• Coating for Car Exhausts	Saved enamelling or saved production of iron and zinc coating
• Marine Coatings	Prevent fouling of ship body which leads to fuel saving
• Automotive Bonding	No GHG effects in the use phase compared to other materials

Table 3

Use effects of case studies; details and sources are described in respective case studies.

3|6 GHG EMISSIONS FROM END-OF-LIFE PHASE

Much information is missing for detailed calculations in the end-of-life phase - such as the distribution of silicone products to different waste flows in different regions of the world, the rate of natural degradation of silicone on surfaces, or the physico-chemical degradation in residual waste landfills. This will be the subject of a follow- up project.

The end-of-life calculations in this study are therefore based on assumptions derived from available regional waste management data. This is acceptable because of the small relevance of the end-of-life phase in the results of this study (see Chapter 6): on average the end-of-life phase is related to 3% of the total GHG impact of silicone and silane products. The influence of the end-of-life phase on the total GHG net abatement is only in the order of 0.4%.

When silicone products (or alternative materials) are incinerated in municipal solid waste incineration plants (MSWI) or other industrial plants, the fossil carbon content is transformed to CO_2, which is included in the GHG balances of this study. In addition, a certain share of the calorific value of the waste input is often utilised for the production of electricity and/or heat (mostly district heat, supplied by MSWI plants), or the incinerated waste directly replaces fossil fuels (industrial plants). The respective GHG credits are also included in the calculations of this study.

Energy recovery outside MSWI is called “industrial energy recovery” and includes the use of RDF (“refuse derived fuel”) in power plants, cement kilns, and fluidised bed combustion processes. All of these processes typically substitute mainly the use of coal, partly heavy fuel oil and in a few cases natural gas.

In residual waste landfills silicones are mainly degraded by chemical processes due to chemical conditions in these kinds of landfills. In this process, carbon in the silicone products can be converted to CO_2. No quantitative information about this effect was available. Instead experts from the member companies of CES estimated possible degradation rates of silicones in landfills.

Silicone substances that are assumed to dissipate into nature, either by natural degradation (e.g. masonry water repellents on concrete or brick surfaces) or by mechanical abrasion (e.g. sulfosilanes in tyres), are assumed to be converted to CO_2 within 100 years.

End of life only accounts for 3% of the total average greenhouse-gas impact of silicone, silane and siloxane products.

04

RESULTS OF CASE STUDIES

4|1 OVERVIEW

In Table 4, the results of all case studies are summarized. Explanations regarding the data columns are given below the table.

No.	Name of Case Study	Share of silicone in silicone product	Net benefit of silicone product (kg CO_2e/kg)	Benefit/ impact ratio	Market volumes (t/a)
1	• Sealants Kitchen/Bathroom	90%	-0,6	1,1	79.400
2	• Sealants Windows IG unit	90%	-193,0	27,7	56.700
3	• Sealants Expansion Joints	45%	0,2	0,9	38.900
4	• High Quality Sealants & Adhesives	45%	-41,2	11,7	10.100
5	• Masonry Water Repellent - concrete	100%	-149,5	25,3	2.500
6	• Masonry Water Repellent - bricks	100%	-64,4	13,2	10.100
7	• PU Additives for Thermal Insulation in Construction	100%	-8,7	2,7	9.300
8	• PU Additives for Thermal Insulation in Appliances	100%	-79,8	17,0	4.700
9	• Cooling Liquid in Transformers	100%	-3,2	1,6	8.700
10	• Electrical Isolators	50%	-6,7	2,4	9.600
11	• Chlorosilane for Solar Grade Silicon	100%	-25,6	7,5	360.100
12	• Anti-foaming in Paper Production	20%	-48,6	27,1	10.200
13	• Paint Additives	100%	-2,5	6,8	1.900
14	• Silanes for Glass Fiber Coating	100%	-89,7	27,1	1.900
15	• Heat-Resistant Industrial Coatings	100%	-35,7	7,3	3.200
16	• Adhesion Promoter for Coatings	100%	-393,4	170,1	1.900
17	• Antifoaming in Detergents	100%	-99,8	12,7	7.800
18	• Baby Teats	100%	4,4	0,3	1.900
19	• Heat Resistant Coating of Personal Appliances	100%	-90,4	13,8	1.600
20	• Bakeware	100%	-1,7	1,2	1.900
21	• Rubber in Motor Construction	100%	-566,5	86,3	33.800
22	• Green Tyres	100%	-362,1	66,5	6.400
23	• Coating for Polycarbonate	100%	-14,0	2,9	1.800
24	• Coating for Car Exhausts	100%	-46,8	9,2	500
25	• Marine Coatings	100%	-1.257,8	182,2	100
26	• Automotive Bonding	100%	-183,1	28,4	5.900

Table 4

Results of case studies. "Silicone product" stands for "silicone and silane products". The market volumes relate to year 2010.

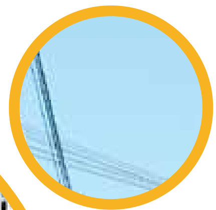
The "Share of silicone in silicone product" is not 100 % in every case study, e.g. when silicone is mixed with fillers or with other materials in the formulation of the final product. In case studies where the net benefit of silicone is related to the whole product containing components other than silicone, the percentage of silicone is taken into account in this table.

The "Net benefit of silicone product" is one of the crucial results of every case study. The figure represents the GHG abatement realised by the silicone product decreased by the GHG emissions from the production and end-of-life phases of the silicone product. A negative number means that there is a benefit; a positive number indicates that there is no benefit (or a net GHG impact.)

The "Benefit/impact ratio" is another essential result of every case study. It is calculated by dividing the benefit (realised by the silicone product) by the GHG emissions from the production and end-of-life phases of the silicone product. Figures smaller than 1 mean that the impacts of production and waste management are higher than the benefits, which means that the silicone product is less advantageous than the alternative in this case study in terms of GHG emissions; figures greater than 1 indicate an advantage of the use of silicone.

The "Market volume" is the sum of pure silicone / silane market volumes of the products produced in Europe, North America and Japan for each case study in tons per year.

Table 5 shows absolute GHG net benefits of investigated case studies, which are calculated in the following way: the net benefits listed above (kg CO_2e per kg silicone product) are divided by the "share of silicone in silicone product" and multiplied by the respective market volumes. Table 5 also shows that **the total GHG abatement realised by the investigated case studies is about 51 Mt of CO_2e per year, and the average benefit/impactratio is 13.7.**



No.	Name of Case Study	Market EU+ NA+JP	Benefit/ impact ratio	Absolute GHG net-benefits
		tons/a		1,000 t CO_2e
1	• Sealants Kitchen/Bathroom	79.400	1,1	-54
2	• Sealants Windows IG unit	56.700	27,7	-12.226
3	• Sealants Expansion Joints	38.900	0,9	16
4	• High Quality Sealants & Adhesives	10.100	11,7	-925
5	• Masonry Water Repellent - concrete	2.500	25,3	-378
6	• Masonry Water Repellent - bricks	10.100	13,2	-650
7	• PU Additives for Thermal Insulation in Construction	9.300	2,7	-80
8	• PU Additives for Thermal Insulation in Appliances	4.700	17,0	-371
9	• Cooling Liquid in Transformers	8.700	1,6	-28
10	• Electrical Isolators	9.600	2,4	-128
11	• Chlorosilane for Solar Grade Silicon	360.100	7,5	-9.228
12	• Anti-foaming in Paper Production	10.200	27,1	-2.488
13	• Paint Additives	1.900	6,8	-5
14	• Silanes for Glass Fiber Coating	1.900	27,1	-167
15	• Heat-Resistant Industrial Coatings	3.200	7,3	-112
16	• Adhesion Promoter for Coatings	1.900	170,1	-731
17	• Antifoaming in Detergents	7.800	12,7	-778
18	• Baby Teats	1.900	0,3	8
19	• Heat Resistant Coating of Personal Appliances	1.600	13,8	-142
20	• Bakeware	1.900	1,2	-3
21	• Rubber in Motor Construction	33.800	86,3	-19.162
22	• Green Tyres	6.400	66,5	-2.325
23	• Coating for Polycarbonate	1.800	2,9	-26
24	• Coating for Car Exhausts	500	9,2	-25
25	• Marine Coatings	100	182,2	-126
26	• Automotive Bonding	5.900	28,4	-1.076
	Sum of case studies	**670.900**	**13,7**	**-51.208**

Table 5

Absolute GHG net-benefits of investigated case studies; total GHG abatement realised by investigated case studies (about 51 Mt of CO_2e per year; benefits are shown with a negative sign, in contrast to impacts with a positive sign); average benefit: impactratio of investigated case studies (13.7)

Figure 3 shows the benefit/impact ratio of all case studies in ascending order.

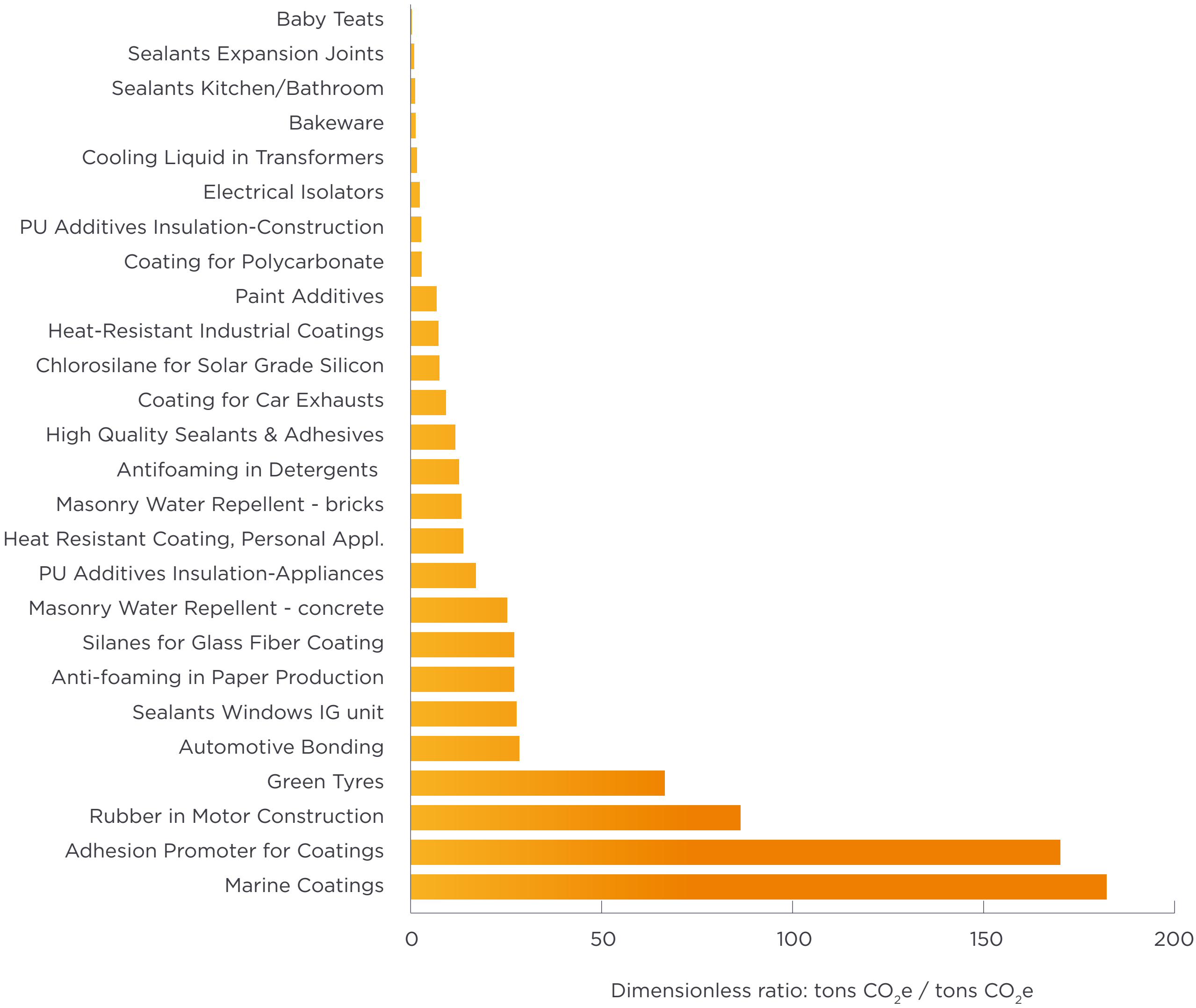


Figure 3

Benefit/impact ratios of all case studies (Ranges of results are listed in Table 7)

Table 6 shows absolute GHG emissions in the end-of-life-phase of the silicone and silane products investigated in case studies. On average the **end-of-life GHG emissions are 0.2 kg CO_2e / kg silicone or silane, which is only 3% of the GHG emissions of production**. The highest amounts of GHG emissions in the end-of-life-phase are related to products with high market volumes, which are either degraded in landfills or incinerated in MSWI plants (e.g. sealants), or which are dissipated during the use phase (e.g. masonry water repellents) or in the waste phase (e.g. antifoaming agents via sewage sludge utilisation). Negative GHG emissions stand for net benefits realised in waste management: as a result of energy recovery in industrial processes, fossil fuels and related GHG emissions are substituted, which are higher than the CO_2 emissions from burning silicone waste.

No.	Name of Case Study	Absolute GWP of silicones in waste phase (1,000 t CO_2e/a)
1	Sealants Kitchen/Bathroom	30,4
2	Sealants Windows IG unit	14,0
4	High Quality Sealants & Adhesives	-7,1
5	Masonry Water Repellent - concrete	5,1
6	Masonry Water Repellent - bricks	11,3
9	Cooling Liquid in Transformers	-9,3
12	Anti-foaming in Paper Production	12,2
17	Antifoaming in Detergents	9,3
	Sum of other case studies	1,7
	Total	67,4

Table 6

Absolute GHG emissions in the end-of-life-phase of silicone and silane products investigated in case studies. Case studies where absolute amount of end-of-life GWP is < 3 kt CO_2e/a are summarised in "sum of other case studies", where positive and negative values are partly compensating each other. Credits from recycling of solar grade silicon are not included.

The calculations performed for the 26 investigated case studies show that the use of silicone and silane products can contribute to GHG abatement by:

A | reduced consumption of fossil fuels, because silicone and silane products

- enable more efficient transport (green tyres; rubber in motor construction, marine coatings)
- contribute to lighter vehicles and related fuel savings (automotive bonding, polycarbonate coatings)
- contribute to savings in heating energy (high quality sealants and adhesives, masonry water repellents for brick facades, sealants for insulating-glass units of windows, paint additives)
- contribute to savings in electricity consumption (additives in PU foams for thermal insulation in electric appliances, antifoaming agents in detergents)
- help to increase the efficiency of processes (antifoaming agents in paper production)
- are used in production of photovoltaic electricity (chlorosilanes used for production of solar grade silicon)

B | saved production of other materials, because silicone products:

- contribute to extend the lifetime of materials coated with silicone (masonry water repellents for concrete surfaces, heat resistant coatings for car exhausts as well as industrial and personal appliances)
- contribute to a more efficient use of materials (paint additives, adhesion promoters, silanes for glass-fibre coating, antifoaming agents in detergents, cooling liquids in transformers)
- can render a certain function with less material and/or less carbon footprint in material production and recovery, compared to alternatives (sealants used in kitchens and bathrooms, cooling liquids in transformers, bakeware, electrical isolators, additives in PU foams for thermal insulation in the building sector)

Numerous silicone chemistry applications yield savings in the consumption of fossil fuels as well as greater efficiency in the use of other materials.

Effects directly related to savings of fuels or electricity lead to the most important contributions to GHG abatement, followed by effects related to increased efficiency of processes and materials. The results of the case studies are particularly influenced by the following case studies:

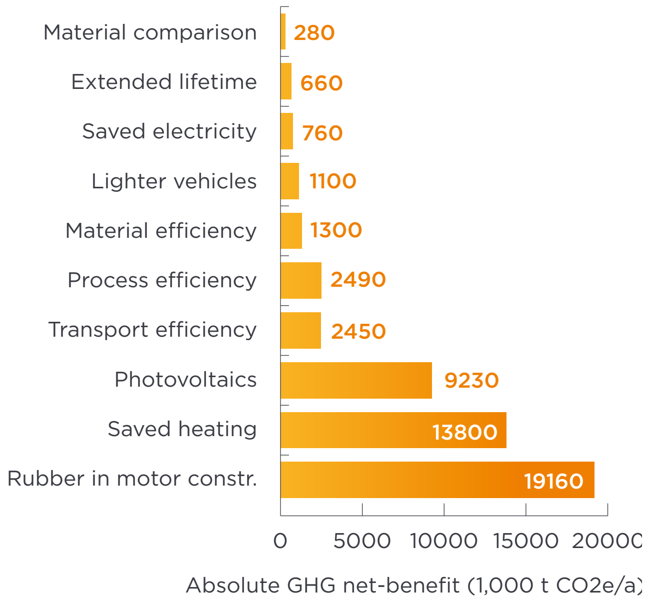
- "Rubber in Motor Construction" (contribution to higher efficiency of motors running at higher temperatures), which generates 38 % to the total GHG abatement realised by the investigated case studies;

- "Sealants Windows Insulating-Glass Units" (saved heating energy), 24 %;

- "Chlorosilane for Solar Grade Silicon" (photovoltaic power), 18%.

In Figure 4 and 5 the absolute GHG net benefits of investigated case studies were aggre-gated into classes according to the type of benefit and the type of substance involved.

Silicone rubber in motor construction generated about 40% of the total GHG abatement in the case studies investigated.



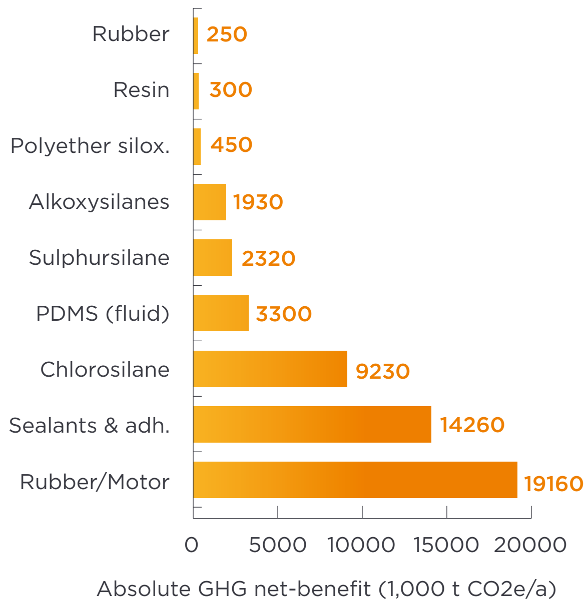
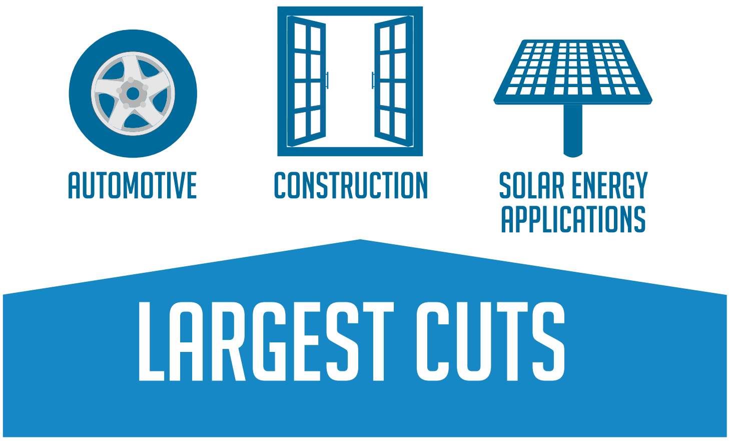


Figure 4
Absolute GHG net benefits as calculated in case studies, aggregated into classes regarding categories of benefits (Ranges of results are listed in Table 7)

Figure 5
Absolute GHG net benefits as calculated in case studies, aggregated into classes regarding different groups of substances (Ranges of results are listed in Table 7)



The following list summarises the benefits of using silicone and silane products for the 11 case studies that account for more than 95 % of the total GHG abatement identified in the study:

- **Rubber in Motor Construction**
  Modern, fuelefficient internal combustion engines run at higher temperatures than their predecessors. Silicone rubber is the only rubber that can endure very high temperatures over a long time without setting or becoming brittle. They are used to make isolators, sealants and for encapsulation (such as spark plug boots), and thereby contribute to fuel savings in the operation of passenger cars and commercial vehicle fleets.

- **Sealants Windows IG unit**
  Insulation glass (IG) units with sealants that are exposed to the sunlight are mostly sealed with silicone due to its good stability and resistance to ultraviolet light. Other sealants become brittle with time and the IG unit loses its air tightness, which leads to decreasing insulating properties. Silicone sealants keep their air tightness over the entire lifetime of the window and so maintain a constant U-value. As a consequence, energy used to heat and cool buildings is saved.

- **Chlorosilane for Solar Grade Silicon**
  Chlorosilane is a key compound for purifying silicon metal into solar- and semiconductor-grade silicon used to make photovoltaic chips and wafers. Although there are alternative technologies, solar grade silicon is the workhorse of photovoltaic power, which helps save fossil energy resources and the related GHG emissions.

- **Green Tyres**
  The use of silanes and precipitated silica in tyre manufacturing leads to reduced rolling resistance and therefore to fuel savings.

- **Anti-foaming in Paper Pulp Production**
  Silicone-based defoamers in pulp production are more efficient than mineral oil-based alternatives and thus allow to minimize water use during the washing process. Pulp production is more efficient; it requires less water and fewer chemicals.

- **Automotive Bonding**
  Lightweight materials, such as glassfibre reinforced plastics, cannot be spotwelded but must be glued together. Silicone adhesives thus contribute to a reduced car mass, which leads to fuel savings.

- **High Quality Sealants & Adhesives**
  In comparison with dryglazed window systems – where compressed rubber gaskets are used to seal the glass pane to the window frame –, structurally glazed systems – where glass panes are bonded with a silicone sealant – have better insulating properties and enable better air tightness. This leads to a reduced energy demand for heating and cooling.

- **Antifoaming in Detergents**
  Silicone based antifoam agents are very effective in a wide temperature range. They allow washing at lower temperatures even with small quantities of detergent and antifoam agents.

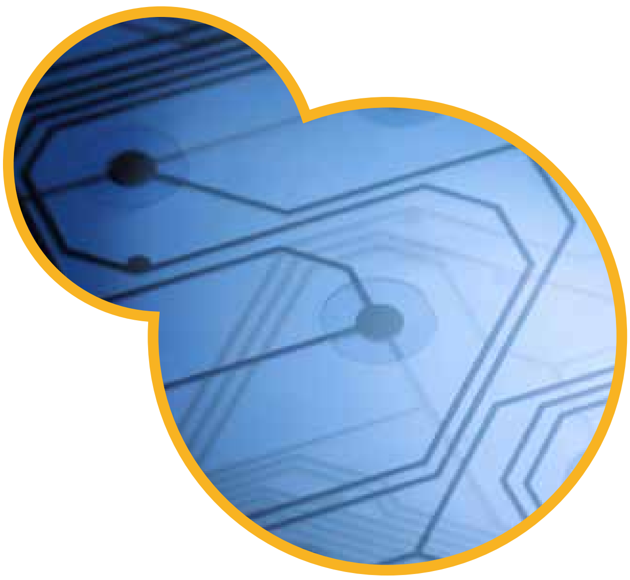
Adhesion Promoter for Coatings
Silane-based adhesion promoters allow for longer-lasting coatings. Less paint is required to protect the coated item over its lifetime, and less solvent will be used.

Masonry Water Repellent for Brick Facades
This silane product keeps brick facades dry, which improves insulating and thermal properties and saves heating energy.

PU Additives for Thermal Insulation in Appliances
In refrigerators and other appliances there is limited space for insulation. Polyether siloxanes allow for the manufacturing of highly efficient, finely calibrated polyurethane foams.
These have far better insulation properties than the historical alternative (mineral wool), which reduces electricity consumption.

When seals for insulation glass units are exposed to the sunlight, they are often made of silicone due to its stability and good resistance to ultraviolet light.

Silicone defoamers make it possible to wash clothes with reduced amounts of detergent and at lower temperatures.



4|2 UNCERTAINTY OF CASE STUDY RESULTS

The quality of data used for the calculations on the level of case studies is quite different for each of the investigated application sectors.

In Table 7 minimum and maximum values were calculated by varying the most uncertain input parameters within a sensitivity analysis.

No.	Name of Case Study	Market EU+ NA+JP	Benefit/ impact ratio - MIN	Benefit/ impact ratio - MAX	Absolute GHG net-benefits - MIN	Absolute GHG net-benefits - MAX
		tons/a			1,000 t CO_2e	1,000 t CO_2e
1	• Sealants Kitchen/Bathroom	79.400	1	2,7	211	-1.113
2	• Sealants Windows IG unit	56.700	14	41,4	-5.967	-18.486
3	• Sealants Expansion Joints	38.900	1	1,1	48	-24
4	• High Quality Sealants & Adhesives	10.100	9	14,7	-663	-1.187
5	• Masonry Water Repellent - concrete	2.500	13	36,6	-182	-574
6	• Masonry Water Repellent - bricks	10.100	8	21,1	-368	-1.071
7	• PU Additives for Thermal Insulation in Construction	9.300	3	36,3	-80	-1.625
8	• PU Additives for Thermal Insulation in Appliances	4.700	17	246,6	-371	-5.682
9	• Cooling Liquid in Transformers	8.700	1	2,4	9	-65
10	• Electrical Isolators	9.600	2	3,2	-56	-200
11	• Chlorosilane for Solar Grade Silicon	360.100	7	9,4	-8.183	-11.496
12	• Anti-foaming in Paper Production	10.200	21	37,0	-1.920	-3.434
13	• Paint Additives	1.900	4	10,1	-2	-7
14	• Silanes for Glass Fiber Coating	1.900	7	41,4	-38	-258
15	• Heat-Resistant Industrial Coatings	3.200	5	9,9	-66	-158
16	• Adhesion Promoter for Coatings	1.900	63	349,1	-250	-1.532
17	• Antifoaming in Detergents	7.800	7	20,3	-408	-1.239
18	• Baby Teats	1.900	0	0,7	10	4
19	• Heat Resistant Coating of Personal Appliances	1.600	11	17,0	-107	-178
20	• Bakeware	1.900	1	1,4	-2	-5
21	• Rubber in Motor Construction	33.800	43	129,3	-9.498	-28.827
22	• Green Tyres	6.400	40	92,5	-1.397	-3.252
23	• Coating for Polycarbonate	1.800	3	3,2	-23	-28
24	• Coating for Car Exhausts	500	7	11,4	-18	-31
25	• Marine Coatings	100	91	273,3	-63	-189
26	• Automotive Bonding	5.900	10	41,4	-357	-1.590
	Sum / average of case studies	670.900	8,7	21,7	-29.741	-82.246

Table 7

MINIMUM and MAXIMUM result values of case studies, based on sensitivity analyses.

It is important to note that due to various, conservative assumptions the range of minimum and maximum results is not symmetrically distributed around the standard result values for some case studies. On average, 40% of the total uncertainty range is between the standard result and the minimum results, and 60% of the total uncertainty range is between the standard result and the maximum results.

The total uncertainty range for the sum of all case studies (which was estimated with 27.2 Mt CO_2e [3]) is therefore distributed in the same way around the total GHG net abatement realised by all case studies.

This leads to the conclusion that the total GHG net abatement realised by all case studies is within a range of 40 Mt to 67 Mt of CO_2e per year, or within a range of 51 Mt minus 22% / plus 31 %.

[3] The uncertainty range of the sum of all case studies is smaller than the sum of the uncertainty ranges of the individual case studies due to prob-ability reasons; for details see full report.

05

RESULTS FOR TOTAL SI-CHEMISTRY MARKET

To calculate an estimated carbon balance (impacts compared to benefits) for the total market of silicone and silane products, 59 % of the total market amount could be covered by case studies. The case study results were extrapolated in a conservative way to an additional 10 % of the total market, leading to a further 5.5 Mt of net abatement of GHG emission.

For the remaining 31% of the total market, only the GHG emissions of production and end-of-life were taken into account. No GHG benefits were included when the final carbon balance of the total market was calculated. This led to the final results of this carbon balance study for the total market of silicone and silane products used in Europe, North America, and Japan.

The final results are the following:

The GHG benefits realised by all silicones, siloxanes and silane products are approximately 9 times greater (range: 7 – 12) than the GHG emissions from production and end-of-life treatment of these products.

The total net abatement of GHG emissions realised by all silicone products is approx. 54 Mt of CO_2e per year (within a range of 42 Mt to 71 Mt). The range results from combining the results presented in Table 8 with an uncertainty of -22 % and +31 % as discussed in Chapter 5.2.

The use of silicone chemistry products in the U.S., Europe and Japan yields GHG emission reductions equivalent to about 54 million tons of CO_2.

No.	Name of Case Study	Market EU+ NA+JP	Benefit/ impact ratio	Absolute GHG net-benefits
		tons/a		1,000 t CO_2e
1	• Sealants Kitchen/Bathroom	79.400	1,1	-54
2	• Sealants Windows IG unit	56.700	27,7	-12.226
3	• Sealants Expansion Joints	38.900	0,9	16
4	• High Quality Sealants & Adhesives	10.100	11,7	-925
5	• Masonry Water Repellent - concrete	2.500	25,3	-378
6	• Masonry Water Repellent - bricks	10.100	13,2	-650
7	• PU Additives for Thermal Insulation in Construction	9.300	2,7	-80
8	• PU Additives for Thermal Insulation in Appliances	4.700	17,0	-371
9	• Cooling Liquid in Transformers	8.700	1,6	-28
10	• Electrical Isolators	9.600	2,4	-128
11	• Chlorosilane for Solar Grade Silicon	360.100	7,5	-9.228
12	• Anti-foaming in Paper Production	10.200	27,1	-2.488
13	• Paint Additives	1.900	6,8	-5
14	• Silanes for Glass Fiber Coating	1.900	27,1	-167
15	• Heat-Resistant Industrial Coatings	3.200	7,3	-112
16	• Adhesion Promoter for Coatings	1.900	170,1	-731
17	• Antifoaming in Detergents	7.800	12,7	-778
18	• Baby Teats	1.900	0,3	8
19	• Heat Resistant Coating of Personal Appliances	1.600	13,8	-142
20	• Bakeware	1.900	1,2	-3
21	• Rubber in Motor Construction	33.800	86,3	-19.162
22	• Green Tyres	6.400	66,5	-2.325
23	• Coating for Polycarbonate	1.800	2,9	-26
24	• Coating for Car Exhausts	500	9,2	-25
25	• Marine Coatings	100	182,2	-126
26	• Automotive Bonding	5.900	28,4	-1.076
	Sum of case studies	**670.900**	**13,7**	**-51.208**
	GHG benefits not cov. by examplesstudies	114.000	8,7	-5.530
	Applications without GHG benefits	357.000	0,0	2.500
	Total market / weighted average	**1.141.900**	**8,9**	**-54.240**

Table 8

Calculation of the estimated carbon balance for the total market volume of siloxane and silane products.

Figure 6 summarises the final results of the carbon balance of the Si-chemistry in Europe, North America, and Japan.

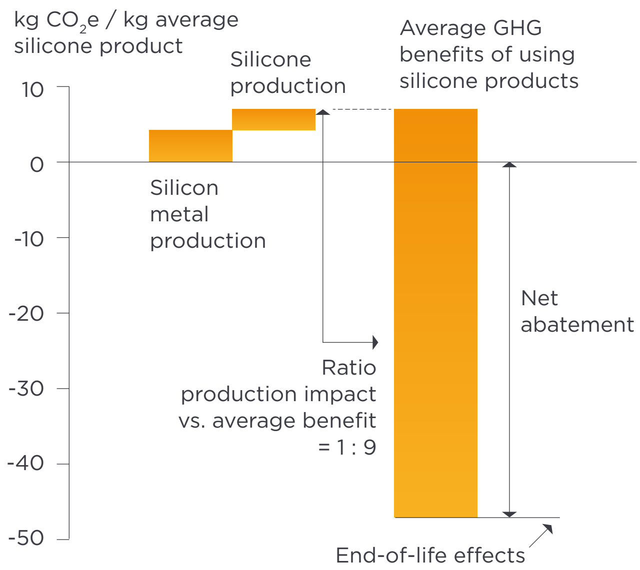


Figure 6

Carbon balance of the Si-chemistry in Europe, North America, and Japan. GHG emissions from silicon metal production and silicone production add up to total production impact. GHG benefits of using silicone & silane products are different for each application; figure shows average GHG benefit for total market. End-of-life GHG effects are very small.

06

CONCLUSION

The results presented above show that the use of silicones, siloxanes and silane products can generate GHG abatement effects which outweigh by far the impacts of production, even though the production GWP per kg of material is much higher than for many other materials (approx. 6.3 kg to 6.6 kg CO_2e compared to 2 to 4 kg for typical plastics or 0.5 to 4.5 kg for steel).

The efficiency of silicone usage in terms of GHG emissions is largely due to the substantial savings that they make possible in fossil fuel consumption, such as with the usage of silicone rubber in motor construction. In addition, in many cases a very small quantity of silicone or silane is sufficient to obtain a large increase in the efficiency of processes and use of materials - such as when used as antifoaming agent, paint additives, or for glass fibre coating.

Among the 26 investigated case studies only two applications (sealants for expansion joints and baby teats) showed a benefit/impact ratio below 1, meaning that the GHG emissions related to production, use and end-of-life phase of these silicone products are higher than the GHG emissions of the substituted product.

Silicon metal production is the most important process when calculating the carbon footprint of silicones such as PDMS. The overall footprint will largely reflect industrial conditions in the region where the silicon metal is produced. This is due to major differences in the electricity mix of countries producing silicon metal, as well as differences in the mix of reduction agents used in different regions of the world. Reducing the share of fossil fuels in electricity generation and in reduction agents therefore provides the most important path toward reducing the carbon footprint of silicone and silane products.

In theory, the recycling of silicone (for example the utilisation of Si in PDMS) could reduce its carbon impact. Establishing dedicated collection systems, however, is difficult in practice because waste quantities are comparably low, silicone products cannot be readily identified or form part of a multi material system – most of which are notoriously laborious to separate into individual components at end of life.

Cutting the share of fossil fuels in electricity generation and in reduction agents used in silicon metal production is the main path toward shrinking silicon chemistry's overall carbon footprint.

In summary, the following conclusions can be drawn from the study:

- Many silicone and silane products used on the market today enable a significant reduction of GHG emissions.

- The GHG benefits realised by all silicone and silane products used in Europe, North America, and Japan are approximately 9 times greater than the GHG emissions from production and end-of-life treatment of these products. This ratio is considerably higher than the respective average ratio (2.6) of all relevant products of the global chemical industry [ICCA 2009].

- The total net abatement of GHG emissions realised by all silicone products is in the range of 42 Mt to 71 Mt of CO_2e per year. The standard result value of 54 Mt of CO_2e per year is equivalent to the annual GHG emissions of small countries such as Norway, equivalent to 4.5 % of Japan's and 0.8 % of the United States' GHG emissions in 2009 [UNFCCC, 2012]. Own calculations based on energy consumption data of [ACC, 2012] and [INCPEN, 2004] as well as GWP-data from the Ecoinvent database [Ecoinvent, 2010] show that a saving of 54 Mt of CO_2e is equivalent to heating 10 million homes (7.8 million homes in Europe or Japan and 2.2 million homes in the U.S.); or taking 17 million cars off European roads.

- Calculations are based on available data and plausible assumptions, which are which are deliberately and cautiously conservative. Although there is substantial uncertainty in some case studies, there is no doubt that the sum of GHG benefits is significantly higher than the GHG emissions from production and end-of-life.

- Although the GWP of silicone production is greater than that of many other materials, many silicone and silane products do efficiently contribute to climate protection and resource conservation.

- In the majority of cases investigated, the use of silicones, siloxanes and silanes reduces the carbon footprint of many essential products and services. The greatest benefits are obtained through energy saving effects. In some cases, small amounts of silicones lead to considerable GHG benefits.

- A comparably low (or even no) benefit is obtained when silicone and silane products are simply compared to alternative materials without taking account of benefits during the use phase. In such cases the high GWP of silicones can only be compensated by considerably longer lifetime or less mass per functional unit.

- Silicon metal production is a very energy intensive process and has a major influence on the product carbon footprint of silicones, siloxanes and silanes. Local production conditions have a large influence on the overall footprint. A shift to more efficient, low GHG technologies in carbon-intense production areas provides the most important potential for optimization.

- Considering different life cycle phases it generally appears that the production and use phase are the most important, while end-of-life impacts are quite small.

- Transport impacts have a minor relevance in the product carbon footprint of silicones, siloxanes and silanes.

- The use of silicones, siloxanes and silanes will often enable functionalities that previously did not exist. While this demonstrates the innovative potential of these materials, the lack of any comparable alternative makes it difficult or meaningless to try and assess any GHG benefits.

The use of silicones, siloxanes and silanes reduces the carbon footprint of many essential products and services.

Future improvements of the quality of data used in this study are recommended for:

- electricity demand of silicon metal production
- regional source mix of purchased silicon metal
- electricity demand of methyl chloride production
- allocation approaches, especially for rubber used in motor construction
- allocation approaches for foam cell regulators for PU applications
- effects of silicone on air tightness and U-value of insulating-glass units
- fuel saving effect of green tires
- physico-chemical degradation in landfills.

The most important limitation of this study is that only GHG emissions are analysed. A more comprehensive environmental and sustainability assessment would require studying other environmental effects (such as relevant emissions and resource consumptions) as well as conducting further research into the economic and social implications of the use of silicones, silanes and siloxanes.

07

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ANNEX CRITICAL REVIEW STATEMENT

8|1 BACKGROUND

The study "Si-Chemistry Carbon Balance: Greenhouse Gas Emissions and Abatement Related to the Total Market of Silicones, Siloxanes and Silane Products in Europe, North America, and Japan" has been peer-reviewed by Professor Adisa Azapagic, based at the University of Manchester.

The study was carried out by denkstatt for the following clients:

- Global Silicones Council;
- Centre Européen des Silicones;
- Silicones Environmental Health and Safety Council of North America; and
- Silicone Industry Association of Japan.

The reviewer is independent of both the authors of the study and the clients who commissioned the study.

The criticalreview process involved the following steps and activities:

- a meeting with denkstatt and the clients, during which the scope of the study and the critical review were discussed;
- an iterative review of several draft study reports during which a number of recommendations for improvements were made by the reviewer and incorporated by the authors of the study;
- a review of the final study report, in which the authors of the study addressed the points as suggested during the critical review process; and
- the final critical review report (this review statement).

Although, due to the nature of the study, the international standards for Life Cycle Assessment (ISO 14040:2006 and 14044:2006) are not applicable, the critical review has followed the main guiding principles defined in these standards. It should be noted that it was not the role of this critical review to endorse or dispute the goal of the study and the related conclusions but rather the aim was to:

- examine that the methods used are scientifically and technically valid given the goal of the study;
- that the data used are appropriate and reasonable in relation to the goal of the study;
- that the interpretation reflects the goal of the study and the limitations identified; and
- that the study report is transparent and consistent.

The critical review did not involve a review of the data used in the study so that all the findings of the critical review are based solely on the reports and the discussions with the authors of the study.

The findings of the critical review based on the final report of the study are summarised below.

8 | 2 CRITICAL REVIEW FINDINGS

The study had the following two goals:

1 | to estimate the life cycle greenhouse gas (GHG) emissions and the related global warming potential (GWP) for different silicone, siloxane and silane products produced in Europe, North America and Japan; and

2 | to estimate any GHG abatement effect (benefits) from the use of the above products compared to a situation if they were not used or were replaced by their alternatives.

The scope of the study was from 'cradle to grave'. For the first goal of the study, the GHG emissions were estimated following broadly the ISO 14040/44 guidelines.

For the second goal of the study, the methodology for estimation of the GHG benefits followed that developed and used previously in other studies by denkstatt. In total, 26 different case studies were considered, covering a broad range of silicone, siloxane and silane products.

The data were sourced from Ecoinvent and other sources in the public domain as well as from manufacturers and industry experts.

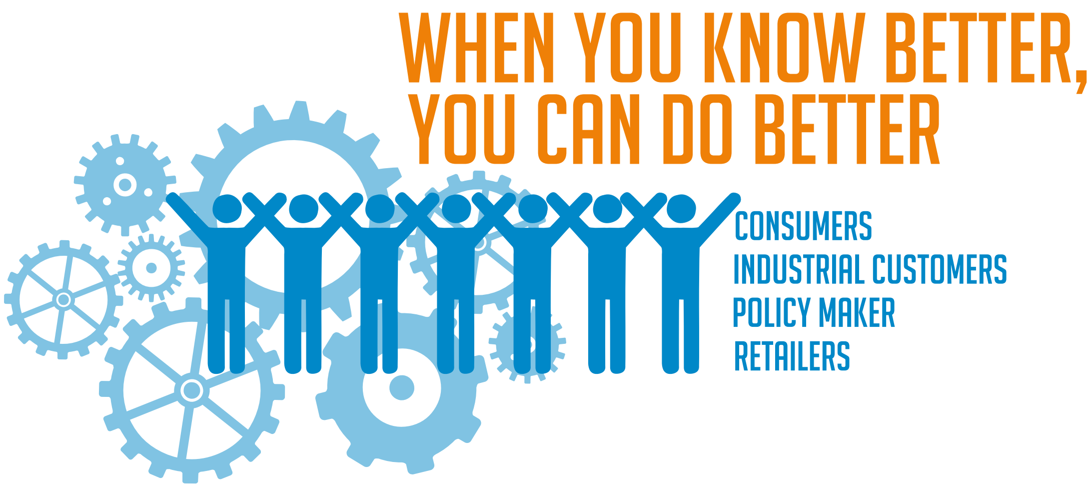
The critical review has found the following:

- This represents a thorough and competent study of the life cycle GHG emissions of silicone products currently available on the market in the areas covered by the study.
- The study assumptions are reasonable; in many cases conservative assumptions have been made to ensure that silicone products are not unduly favoured over their alternatives.
- The data sources are appropriate as far as possible, given the "80/20" approach and the other constraints of the study. In many respects the study goes beyond the "80/20" method and assumes a much more rigorous approach, as demonstrated by the depth of analysis in some cases as well as the range of sensitivity and uncertainty analyses carried out.
- The scope of the study is extensive so that a large number of assumptions and extrapolations had to be made. Nevertheless, while the results at the level of specific products may not be completely accurate, the overall results are sufficiently valid.
- The interpretation of the results is appropriate given the assumptions, limitations and the data used.
- The study report is very detailed, transparent, consistent and balanced.

However, it should be borne in mind that this is a broad-brush, sectoral-level analysis and that uncertainties exist, as demonstrated and discussed in the study. Moreover, there is no internationally accepted methodology for the estimation of GHG "benefits" of products. Nevertheless, the study uses a reasonable and transparent approach to enable scrutiny.

Finally, as this study considered only GHG emissions and GWP associated with the silicone-related products considered, the conclusions on any benefits from this class of products over their alternatives are only valid for this environmental impact and not necessarily for any other, wider sustainability issues. This is acknowledged in the report in the Summary and Conclusions section.

Professor Adisa Azapagic
April 2012



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ABBREVIATIONS

CES	European Silicones Centre Centre Européen des Silicones
CO_2e	Carbon dioxide equivalent(s)
EoL	End-of-Life
EPDM	Ethylene propylene diene monomer
EU	European Union
EU27+2	27 EU member states plus Norway and Switzerland
FU	Functional unit
GHG	Greenhouse gas(es)
GSC	Global Silicones Council
GWP	Global warming potential
HCR	High consistency rubber
HDD	Heating degree days
IG unit	Insulating glass unit
JP	Japan
kWp	Kilowatt peak
LCA	Life cycle assessment / analysis
MAX	Maximum
MIN	Minimum
MJ	Megajoule
MSWI	Municipal solid waste incinerator/ incineration
NA	North America
PCF	Product carbon footprint
PDMS	Polydimethylsiloxane
PMMA	Polymethylmethacrylate
PU	Polyurethane
PV	Photovoltaics
PVC	Polyvinyl chloride
RDF	Refuse derived fuel
SAS	Synthetic amorphous silica
SEHSC	Silicones Environmental Health and Safety Council of North America
SIAJ	Silicone Industry Association of Japan
UCTE	Union for the Coordination of Transmission of Electricity
U-value	Measure of the rate of heat loss through a material with given thickness, given in W/m2.K
UV	Ultra violet
XPS	Extruded polystyrene foam

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GLOSSARY

Carbon balance
In this study, the term "carbon balance" is used for the ratio of "GHG benefits resulting from the use of silicone and silane products" divided by "GHG emissions related to production, use and end-of-life of silicone and silane products"

CO_2e
Unit for comparing the radiative forcing of a GHG to carbon dioxide; the CO_2e is calculated by multiplying the mass of a given greenhouse gas by its GWP

Functional unit
Quantified performance of a product system for use as a reference unit

GHGs
Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds

GWP
Factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to an equivalent unit of CO_2 over a given period of time

Number format
In this report the comma is used as the 1000 separator and the full stop is used as separator for decimal numbers.

PCF
Total amount of GHGs emitted in the total life cycle of a product

Silicon (metal)
Elemental silicon

Silicone
Polymeric siloxanes

Siloxane
Cyclic and low molecular weight polydimethylsiloxanes

Silane
A reactive silicon-containing chemical intermediate or additive

Si-chemistry
Products of Si-chemistry include silicones, siloxanes and silanes

1 ton
1,000 kg

80/20 approach
In the present study "80/20 approach" means covering 80 % of the results with 20 % of the data required for a more comprehensive study. Under the 80/20 approach (also known as the Pareto principle), all working steps are focused on the most relevant effects and influences. Minor effects and influences that are assumed not to affect conclusions in any substantial way are not covered by this study.

www.siliconescarbonbalance.com