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Update of the Si-Chemistry Carbon Balance

Project SILICAB 2 Nutshell Report

Report 18/07/2024

Client Global Silicone Council (GSC)

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Abbreviations

CES .... CES – Silicones Europe
CO_2 .... Carbon dioxide
CO_2eq .... Carbon dioxide equivalent
EF .... Emission factor
EoL .... End of life
EPDM .... Ethylene propylene diene monomer
EU .... European Union
EV .... Electric Vehicles
GD .... Green Deal
GHG .... Greenhouse gas
GSC .... Global Silicone Council
GWP .... Global warming potential
HEV .... Hybrid electric vehicle
IG .... Insulating glass
LCA .... Life cycle assessment
LED .... Light-emitting diode
MeOH .... Methanol
PCF .... Product carbon footprint
PDMS .... Polydimethylsiloxane
PMMA .... Polymethyl methacrylate
PU .... Polyurethane
PV .... Photovoltaic
TIM .... Thermal Interface Material
U-value .... measure of thermal transmittance

Executive Summary

Recent focus on understanding product environmental impact, driven by global initiatives like the Paris Agreement, led the Global Silicone Council (GSC) to update a 2012 study on silicon-derived products. **The study, covering Central Europe, North America, and Japan, highlights 26 applications contributing positively to greenhouse gas reduction across industries. Key aspects include reduced fossil fuel consumption and extended material lifetimes due to silicon-based materials.**

In 2021, the cumulative market size of silicon-based products was estimated at 984 kt/a, with case studies covering 78% of this market. The absolute GHG benefits were scaled up for another 10 % of the market with GHG benefits not covered by the study. Notable market volume distinctions were observed among applications. **All case studies demonstrated a benefit-impact ratio >1, with cumulative annual GHG savings reaching 148 Mt CO_2eq. (-15%/+47%), marking an improvement from the 2012 study.** Absolute GHG benefits were extrapolated to cover 78% of the total silicone market, with conservative assumed benefits for the remaining 10% and GHG loss for the remaining 12% of the market were the application has no GHG benefits .

The study emphasizes that GHG benefits of silicone products are 14 times greater than production and end-of-life impacts. **The total result for the studied regions, -159.4 Mt CO_2eq., represents a significant portion of annual GHG emissions for countries like Japan and the US.** Acknowledging the need for data quality improvement and future exploration of broader environmental impacts, the report utilized conservative estimates to reduce overall uncertainty. Dr. Roland Hischier's critical scientific review ensured study validity, data appropriateness, goal reflection, and transparency. Only the main study was reviewed, the document at hand was not part of the review.

1. Scope and Method

1.1. Introduction

The Global Silicone Council (GSC) conducted a 2012 study on silicone and silane products' greenhouse gas (GHG) emissions, revealing significant benefits compared to production and EoL emissions. In 2021, the GSC updated this study to assess the impact of technological changes on GHG emissions of silicon applications. The study analyzes GHG emissions and benefits across 26 applications, comparing them through a "Si-chemistry carbon balance." Details on market shares, decision basis and evaluations can be explored in detail in Appendix. Dr. Roland Hischier's review ensures the scientific validity and transparency of the study's findings. Only the main study was reviewed, the document at hand was not part of the review.

In the 2012 Carbon Balance study, 26 applications were chosen based on GHG reduction potential, market size, and suitability. These applications covered various sectors, with market data indicating significant silicone product usage. Some applications were excluded due to the lack of alternatives or measurable GHG effects. The CES Green Deal 2021 report adds three applications and identifies new sectors based on qualitative analysis. The selection process prioritizes applications with high GHG net benefit-to-impact ratios from the 2012 study and considers alternative options. Benefits are calculated using insights from the previous study, with new applications following the same methodology. Overall, the study aims to cover a substantial market share and quantify the GHG benefits of silicones across different sectors.

The study follows a systematic approach, including lifecycle data collection, carbon balance calculation, and result presentation. Rigorous validation and sensitivity analyses are conducted for all case studies, with a focus on quantifying use phase benefits. Adopting a total market approach, the study considers the overall volume of silicone products within the defined region. To address uncertainties, a conservative approach is adopted, especially where data accuracy is less certain. **Key limitations and approximations include focusing solely on fossil GHG emissions, utilizing the 80:20 approach, allocating benefits by comparing results with alternative materials, defining use phase effects individually for each case study, basing waste management assumptions on the 2012 Carbon Balance study, and incorporating weighted average results for GWP or PDMS and selected precursors based on company-specific and market data.** These considerations collectively shape the study's goal and scope, offering an approximate assessment of impacts and benefits for the total silicone products market.

1.2. Method of environmental assessment

The study outlines the processes involved in producing siloxanes, silanes, and pyrogenic silica, focusing on product families such as fluid PDMS, sealants, rubbers, resins, alkoxysilanes, polyethersiloxanes, functional silanes, and trichlorosilane. It includes case studies related to each product category, detailing their formulations. Extensive data collection involved consultations and questionnaires with GSC experts to calculate PCFs for 26 silicone-based applications. Information on composition, function, and advantages/disadvantages was gathered and gaps filled using literature and databases. Following ISO guidelines for LCA, the study simplifies with an 80:20 approach, focusing on GHG emissions and comparing results with alternative materials. Use phase effects, waste management, and market data vary by case study, with benefits allocated individually.

The PCF calculation, based on the 2012 Carbon Balance study, adheres to ISO 14040/44 life cycle assessment guidelines. New data and member information were integrated, replacing old data where applicable. The model covers the entire production lifecycle, assessing eco-profiles, use phase, and end-of-life. For each case study, benefits from using silicone or silane products are defined and calculated as **net-benefits - calculated by subtracting the impacts of production and EoL from the benefits versus alternative applications, and benefit/impact ratios - calculated by dividing the benefits versus alternative applications by the impacts of production and EoL.**

The system boundary, set for one year (mostly 2019), covers global warming potential results for silicone and silane products in Europe, North America, and Japan. The geographic scope accounts for global silicon markets and averages production conditions across the mentioned regions. The 2012 Carbon Balance study extensively examined GHG emissions related to PDMS fluids, sealants, rubbers, resins, intermediates, and pyrogenic silica, covering over 90% of the market. The 2021 eco-profiles utilized diverse sources, including confidential silicon production data, the Ecoinvent database, Euroalliages, GSC member companies, and QYResearch's Global Basic Silicone Market Report. GHG emissions for PDMS, chlorosilanes, and pyrogenic silica are based on detailed company information, while data for special siloxane- or silane-based substances are estimated using GWP data for raw materials.

1.3. GHG emissions related to silicon and silicon derivatives

Production of silicon, PDMS and related substances

Silicon production, primarily from mined quartz, contributes 51% of GHG emissions, utilizing various reduction agents like coal, pet coke, and biomass. Electricity consumption for silicon production ranges from 11 to 14 kWh/kg, influenced by regional energy mixes. **In Europe, electricity usage yields 1.51 kg CO_2eq./kg silicon, while globally it reaches 5.1 kg CO_2eq./kg silicon.** Direct CO_2 emissions from reduction agents vary regionally, with a typical range of 6.0 to 7.0 kg CO_2eq./kg silicon, considering both fossil and biogenic sources. The total GHG emissions, including production and delivery of reduction agents, amount to 4.9 kg CO_2eq./kg silicon. **Silica fume, a byproduct, is allocated 3% of total production impact, resulting in a total GWP of 9.7 kg CO_2eq./kg silicon, with a slight decrease since 2012.** This study's GWP differs from available data due to regional variations in energy sources and reduction agents.

A thorough investigation examined the GHG emissions associated with PDMS-based silicone products, which dominate the siloxane and silane market. PDMS production involves several raw materials, including silicon, chloromethane, and methylchlorosilanes, with cross-links between polymers generating rubbers and resins. Confidential data from member companies informed the analysis, covering processes like transport, steam, and electricity production. The study assessed the cradle-to-gate GHG emissions of input raw materials and production stages for functional silanes and synthetic amorphous silica. Notably, fumed silica, produced through combustion, serves as a reinforcing filler. **Key findings reveal that silicon contributes to 67% of GHG emissions in methyl siloxanes, followed by steam, MeOH, HCl, and electricity. The study identified primary uncertainties in GHG emissions related to silicon and electricity/heat consumption, with an overall uncertainty of ±1.1 kg CO_2eq./kg methyl siloxane.** Reported CO_2eq. values varied between studies, with this analysis indicating higher energy efficiency and reduced emissions compared to previous data.

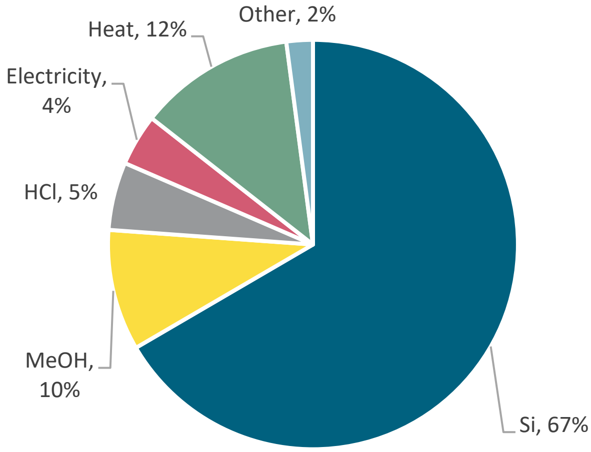

Figure 1: Shares of important raw materials, energy consumption, other inputs and waste to total GHG emissions of methyl siloxanes.

Use phase and EoL

Silicone products can offer significant GHG savings even with minimal usage, yet some comparisons only consider material aspects, suggesting no apparent GHG impact during use. Use phase benefits may stem from a blend of silicone and other products or technologies, requiring proportional allocation of benefits to silicones. Region-specific datasets address variations in factors like electricity mix and heating degree days across different regions. However, limited data on silicone product distribution and degradation in landfills complicates detailed EoL calculations. **While future projects may address these gaps, EoL impact is minor compared to production and higher use-phase effects, along with diverse waste management contributions.** Assumptions based on regional waste management data guide EoL calculations in this study·

Regarding energy recovery, incinerating silicone products in waste incineration plants transforms fossil carbon to CO_2, affecting the study's GHG balances. **Industrial energy recovery, substituting coal or oil with waste-derived fuels, contributes to GHG credits.** Estimates consider average global conditions and utilization rates of different plants across regions. Silicones in residual waste landfills undergo chemical degradation, releasing carbon as CO_2 emissions. **Approximately 50% of silicone sealants in landfills are assumed to degrade within 100 years and are factored into the carbon balance calculations.** Volatile siloxanes detected in landfill gas support this observation.

2. Results

2.1. Overview of the case studies

This chapter outlines 26 case studies, providing information on background, functional units, and data for production, use phase, and EoL management. Key findings from case studies are outlined in this chapter below. Supporting GHG assessments and sensitivity assessments are available in the Appendix section.

Table 1: Overview of studied applications depicting the market data, benefit-impact ratio and absolute GHG net-benefits.

No.	Name of Case Study	Share of silicone in silicone product	Net benefit of silicone product	Benefit/ impact ratio	Market volumes	Absolute GHG net-benefits
			kg CO2e/kg		t/a	1,000 t CO2e
1	Automotive Bonding	100%	-128	21,3	9.970	-1.272
2	Batteries/Energy Storage	100%	-413	28,3	3.312	-1.369
3	Chlorosilane for Solar Grade Silicon	100%	-23	9,9	787.020	-18.289
4	Energy efficient lighting – LEDs	100%	-11.196	2,0	2.158	-24.165
5	Engine Performance, Rubber in Motor Construction	100%	-834	130,8	31.550	-26.312
6	Green Tyres	3,5%	-229	38,7	49.000	-11.226
7	High Quality Sealants & Adhesives	45%	-43	12,2	120.570	-5.182
8	Industrial applications in pulp industry, Anti-foaming in Pulp Production	20%	-144	83,5	14.663	-2.107
9	Sealants Windows IG unit	58%	-333	49,8	109.886	-36.578
10	Wind Turbines	100%	-2.266	379,3	1.842	-4.174
11	PU Additives for thermal Insulation in Appliances	1,0%	-50	15,5	7.750	-4
12	Antifoaming in Detergents	0,15%	-106	3,6	842	-89
13	Masonry Water Repellent - bricks	10%	-60	104,1	11.317	-68
14	Masonry Water Repellent - concrete	100%	-58	11,6	15.332	-887
15	Conformal coatings in electronics	33%	-2	1,0	1.859	-1
16	Electrical Isolators & Insulations	57%	-5	2,5	11.000	-50
17	Heat-Resistant Industrial Coatings	25%	-104	2,6	3.450	-360
18	Silicone foam for thermal insulation	75%	-6	2,0	28.087	-180
19	Adhesion Promoter for Coatings	80%	-359	136,5	845	-243
20	Coating of means of transport, anti fouling coatings	100%	-456	60,8	24.371	-11.117
21	Electric transport (bycicle, electric and hybrid cars, train)	100%	-81	13,4	40.390	-3.258
22	Lighter automative parts, Coating for Polycarbonate	100%	-30	2,7	11.940	-360
23	Reflective roof coatings	25%	-12	2,4	68.320	-847
24	PU Additives Insulation-Construction	0,8%	-9	3,6	20.570	-1
25	Telecommunication	25%	-478	161,9	81	-39
26	Cooling Liquid in Transformers, LSR as insulating materials in cables	100%	-9	2,5	2.018	-18

As evident in Table 1, silicones offer significant environmental benefits across various industries. They contribute to durability, weather resistance, and emission reduction in automotive bonding processes. In battery technology, silicones extend battery lifespan and reduce energy consumption in electric vehicle batteries. They also play a vital role in solar grade silicon production, contributing to significant fossil energy savings in photovoltaic solar modules. Additionally, silicones enhance energy efficiency and longevity in LED lighting applications. They improve fuel efficiency and emissions reduction in engine performance, as well as reduce rolling resistance in tires, leading to fuel savings. Silicones provide thermal insulation with lower environmental impact and control foam in detergents, reducing water and energy usage. They also protect building materials, reduce heating energy demand, and offer corrosion protection with reduced environmental impact in various industrial applications. Furthermore, silicones contribute to aerodynamics and fuel efficiency in electric transport components, reduce vehicle weight and fuel consumption through polycarbonate coatings, and reduce cooling energy needs in buildings with reflective roof coatings. Overall, silicones play a crucial role in sustainability and efficiency across these applications, contributing to environmental protection and resource conservation.

2.2. Analysis of the silicon market

The study highlights the significant role of silicones in reducing greenhouse gas (GHG) emissions across various industries. **Market data reveals that chlorosilane for solar-grade silicone dominates in the EU, North America, and Japan, contributing to a doubling of market volume from 2012 to 2019. The benefit-impact ratio, a key metric, indicates the GHG savings per unit of emissions, with wind turbines showing the highest ratio due to low production and EoL emissions.** Other applications, such as adhesion promoters and engine performance in motor construction, also exhibit high ratios. Despite variations, **all 26 applications yield a benefit-impact ratio >1, signifying overall GHG benefits**.

Furthermore, understanding the net GHG benefits per unit volume of silicone product is crucial. Energy-efficient lighting, particularly LEDs, demonstrates the highest GHG benefits per kilogram of silicon product, followed by wind turbines. **The cumulative annual GHG savings from these case studies amount to 148 Mt CO_2eq., with an average benefit-impact ratio of 19.6, reflecting a significant increase compared to the 2012 study.** These savings result from reduced fossil fuel consumption and saved production of additional materials, driven by factors like market volume and net-benefit per unit volume of the product.

The 26 case studies represent 1.378 Mt of silicone products, while the total silicone market in Europe, Japan, and North America is estimated at 1,771,000 tons annually. Approximately 78% of this market is captured by the case studies, with the remaining 22% attributed to other applications. Extrapolating GHG benefits for 10% of applications not covered yields an additional -12.6 Mt CO_2eq. Additionally, 1.4 Mt CO_2eq. are added to account for applications with no GHG benefit. **This results in an overall -159.4 Mt CO_2eq. saving for the total market. The GHG benefits of silicones, siloxanes, and silanes exceed emissions from production and EoL treatment approximately 14-fold.**

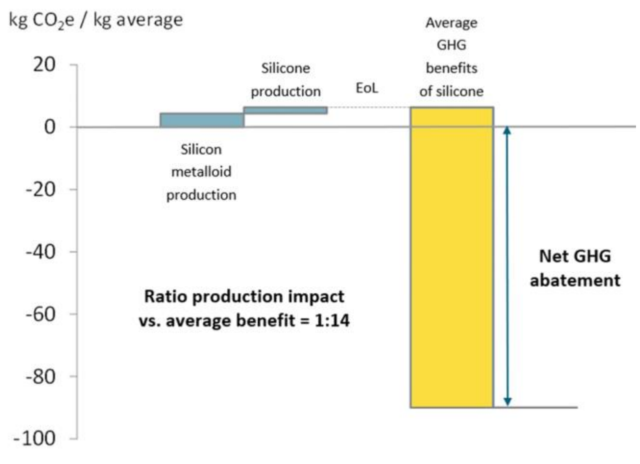

Figure 2: Carbon balance of the Si-chemistry in Europe, North America, and Japan.

As shown in Figure 2, emissions from silicone production are minimal (6.4 kg CO_2eq./kg) compared to the substantial GHG benefits from the use phase (-96 kg CO_2eq./kg). The EoL GHG impact is minor, totaling only 0.11 kg

CO_2eq./kg of product, constituting just 1.7% of the total GHG impact from production and waste management of silicone-based products.

Varying data quality among applications leads to uncertainties ranging from small to high. **The average benefit-impact ratio of 19.6 has an uncertainty range of 13.0 to 38.8, suggesting significant GHG benefits across studies. The absolute GHG abatement of -148 Mt CO_2eq. has an uncertainty range of -341 to -86 Mt CO_2eq.** For a more precise estimate, a 90% confidence interval was derived assuming deviations follow a Gaussian distribution. This results in a total uncertainty range of 45.5 Mt CO_2eq., leading to an absolute GHG savings range of between -217 to -126 Mt CO_2eq. or a symmetric uncertainty range of -148 ± 31% Mt CO_2eq. Limitations include the exclusive focus on GHG emissions and neglect of other factors. Future studies should focus on improving data quality and addressing these limitations.

3. Conclusion

The study assessed the life-cycle greenhouse gas emissions of silicone products in Europe, North America, and Japan, focusing on 26 case studies selected based on significant GHG savings potential. These silicon-based products offer benefits such as adhesion and heat resistance, resulting in reduced fossil fuel consumption and extended product lifetimes. **In 2019, these products accounted for 78% of the total market volume, with an average GHG potential of 6.36 kg CO_2eq./kg.** Energy-efficient lighting, notably LEDs, showed the highest net-GHG benefit, while conformal coatings for electronics exhibited the lowest**. The total GHG abatement ranged from -217 to -126 Mt CO_2eq., with significant contributions from applications like improved thermal isolation and more efficient transport. Extrapolating to the entire market yielded a net abatement of -159.4 Mt CO_2eq., reflecting a 1.5-fold increase in benefit-impact ratios since 2012.** Despite these findings, there are challenges in reducing carbon footprints, including fossil fuel dependency in production and recycling complexities. Future studies should aim to improve data quality and consider broader environmental and socioeconomic factors beyond GHG emissions.

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Appendix

Table 2: Chosen applications according to the sector classification incl. GHG net-benefits of 2012 study and reason of selection.

Application	Sector	Absolute GHG net-benefits ($ktCO_2eq$)	Selection reasoning
Automotive bonding	Transportation	-1,076.2	The SEE Study (2020) also points out that fuel can be saved due to silicone applications in vehicles (e.g., lower weight components).
Batteries/ energy storage	Transportation	N/A	Batteries are crucial for electric mobility and renewable energy. Focus in Green Deal and public attention.
Chlorosilane for solar-grade Si	Electricity	-9,228.4	Silanes essential for siloxane and silicone production, enabling high-purity silicon. Approximately 90% of PV cells are Si-based.[1]
Energy efficient lighting – LEDs	Electronics	N/A	LED lights are recognized for cost-effective GHG emission reduction. SEE study (2020) notes silicones' role in improving energy efficiency, extending LED lifetime, and enhancing brightness.[2]
Engine performance, rubber in motor construction	Transportation	-19,162	While individual transportation electrification is expected, the transformation extends beyond 2030. Combustion engines (biofuel-powered) will persist, particularly in freight, agriculture, mining, and construction, contributing promising GHG savings.
Green tires	Transportation	-2,324.5	SEE study (2020) confirms substantial GHG savings, attributing fuel savings to silicone additives in Green Tires.[3]
High quality sealants & adhesives	Construction	-924.9	Sealants, crucial in construction, bring substantial socio-economic value, ranking as the second most vital silicone sector by mass.[4]
Industrial applications in pulp industry, anti-foaming in pulp production	Industrial	-2,487.7	According to the SEE study from 2020, silicone fluids with fine powdered silica acting as an antifoaming and defoaming agents help increase production rates in the pulp industry.
Windows IG unit sealants	Construction	-12,226.1	Key application in construction[5] with significant socioeconomic value with very high GHG net benefits.[6]
Wind turbines	Electricity	N/A	Wind power is crucial in renewable electricity generation. Silicones boost efficiency, lifespan in wind power plants.

[1] Wood Environment & Infrastructure Solutions UK Limited. (2016). Socio-economic evaluation of the global silicones industry-Final Report. United Kingdom.

[2] See Footnote 1.

[3] See Footnote 1.

[4] See Footnote 1.

[5] Wood Environment & Infrastructure Solutions UK Limited. (2016). Socio-economic evaluation of the global silicones industry-Final Report. United Kingdom.

[6] Bernd Brandt, Evelin Kletzer, Harald Pilz, Dariya Hadzhiyska, Peter Seizov, (2012). Silicon-Chemistry Carbon Balance: An assessment of Greenhouse Gas Emissions and Reduction. Retrieved from www.silicones.eu/wp-content/uploads/2019/05/SIL_exec-summary_en.pdf (last accessed: 18.10.2021)

PU additives insulation appliances	Electronics	-371.0	Silicones in PU foam enhance stability, cut CO2eq, reduce heat use for improved insulation.[7]
Antifoaming in detergents	Industrial	-777.5	Silicones in detergents cut washing machine energy use, reducing GH emissions.[8]
Masonry water repellent – bricks	Construction	-650.5	Improved insulation cuts domestic energy use; water repellents for façades play a vital role.
Masonry water repellent – concrete	Construction	-377.6	Water repellents are crucial for ensuring the 100-year durability of concrete structures like bridges, following guidelines such as Eurocode.
Conformal coatings in electronics	Electronics	N/A	Growing demand for circuit boards and electronic devices has led to an increased need for Si-based conformal coatings, prompting a closer examination of their impact.
El. isolators & insulations	Electronics	-127.8	Silicone usage can cut the weight of high-voltage isolators by up to 90%, resulting in reduced GHG emissions.
Heat-resistant ind. coatings	Industrial	-112.3	Silicone coatings in industry extend product life, fostering a circular economy and saving resources.
Silicone foam for thermal insulation	Construction	N/A	Silicone foam, with superior temperature and fire resistance, is indispensable in unique insulation applications.
Adhesion promoter for coatings	Industrial	-730.9	The lifetime extension of materials to prevent waste flows becomes increasingly important.
Coating of means of transport, antifouling coatings	Transportation	-125.8	Antifouling coatings are crucial for modern marine shipping, reducing fuel consumption by preventing corrosion and organic growth on ships, thereby minimizing drag and optimizing fuel efficiency.
Electric transport	Transportation	N/A	Electromobility is a vital component of the GD, contributing to reducing the environmental impact of private transport.
Lighter automotive parts, coating for polycarbonate	Transportation	-25.5	Silicone resin-coated polycarbonate enables lightweight automotive glazing, protecting surfaces from abrasion. The use of polycarbonate replaces heavier glass parts, reducing fuel consumption.
Reflective roof coatings	Construction	N/A	Reflective roof coatings deflect harmful UV rays, preserving roofs and curbing premature aging, hence waste reduction.
PU additives insulation – construction	Construction	-80.0	Silicones in PU foam for buildings lead to a better insulation effect and reduces costs and CO_2eq emissions.[9]
Telecommunication	Electronics	N/A	Longer service life and decreased energy consumption during charging cycles reduce CO2eq emissions.[10]
Cooling liquid in transformers, LSR	Electronics	-28.1	Silicone cooling liquid in transformers has many advantages, e.g., fire retardant with high heat and fire resistance. These

[7] See Footnote 5.

[8] See Footnote 5.

[9] Wood Environment & Infrastructure Solutions UK Limited. (2016). Socio-economic evaluation of the global silicones industry-Final Report. United Kingdom.

[10] Horizon Telecom. (2017). Benefits of Mobile Telecommunication. Retrieved from https://www.horizontelecom.co.uk/blog/benefits-of-mobile-telecommunication/#:~:text=Mobile %20telecommunications %20allow %20you %20to,indeed %20taken %20over %20our %20lives. (accessed 02/22)

as insulation in cables			characteristics result in saved resources and less environmental risks.

Table 3: Use effect of a silicone-based component, the alternative component and system per application.

Application	Effect of a Silicone-based component	Alternative component and system
Automotive bonding	Enables reduction of weight, leading to fuel and energy saving.	Spot welding and heavier materials
Batteries/ energy storage	Silicones shield batteries, acting as TIM, ensuring safety and preventing fires, particularly in EV batteries.	Epoxy; 8 years lifetime
Chlorosilane for solar-grade silicone	Silicones crucial for solar-grade silicon in PV cells, enhancing energy efficiency in solar power production.	Electricity production (regional mix)
Energy efficient lighting – LEDs	Silicones enhance light performance and extend product life as encapsulants, adhesives, and reflector materials by prolonging service life compared to alternatives.	Optical grade epoxy as encapsulant material
Engine performance, rubber in motor construction	Contributes to more efficient motor technology, which leads to fuel savings.	Ethylene propylene diene monomer rubber (EPDM)
Green tire	Less rolling resistance leads to fuel savings (enabled by sulfidosilanes).	Conventional tires
High quality sealants & adhesives	A system with silicone demands less material and saves energy for heating and cooling.	Thermally improved dry glazing system
Industrial applications in pulp industry, anti-foaming in pulp production	Higher washer throughput makes pulp plants more efficient, less water is vaporized, less process chemicals are lost.	No defoamer, more detergent, more wash loads at 60°C
Windows IG unit sealants	Divergent insulation properties lead to different electricity demand, plus different GWP of foaming agents.	Insulation material made of mineral wool
Wind turbines	Difference in the air tightness leads to divergent U-values, which lead to different heating demand.	PU and polysulfide window sealant
PU additives insulation appliances	Silicones enhance durability, provide weather-resistant coatings, and improve energy production in turbines by up to 8%.	Synthetic lubricants
Antifoaming in detergents	Silicones in detergents reduce energy consumption and product dosage through improved foam control.	Non-silicone detergent
Masonry water repellent – bricks	Water repellent impregnation minimizes moisture entry, decreasing the U-value and heating demand of brick facades.	Brick wall without silicone-based water repellent
Masonry water repellent – concrete	Less moisture in the bridge pillar's concrete reduces cracks and weathering, extending the structure's lifespan.	Concrete bridge pillar without silicone-based water repellent
Conformal coatings in electronics	Silicones provide corrosion protection to electrical assemblies used in high-humidity or harsh environments.	Conformal coating with polyurethane and acrylic resins
El. isolators & insulations	Silicone isolators are much lighter and do not break during production or installation.	Isolators out of ceramic or EPDM
Heat-resistant ind. coatings	Silicone coatings have an extended lifetime and can harden at room temperature.	Zinc coating & enamelling

Silicone foam for thermal insulation	Silicone foam excels in insulating façades, pipelines, and household appliances due to its high temperature resistance, weatherability, and fire resistance.	EPDM in combination with PU foam
Adhesion promoter for coatings	Silicone coatings on marine vessels prevent corrosion and inhibit organic growth, reducing drag and optimizing fuel usage.	Alkyd paint coat without a Si-based adhesion promoter
Coating of means of transport, antifouling coatings	Anti-fouling coatings minimize organic growth on ships, reducing drag and optimizing fuel consumption for improved efficiency.	No/bad anti-fouling coatings, 6% increase in fuel usage
Electric transport	Silicone parts reduce aerodynamic drag, enhancing fuel efficiency and lowering CO2 emissions.	A PHEV with EPDM pipe hanger
Lighter automotive parts, coating for polycarbonate	Silicone resin-coated polycarbonate enables lightweight automotive glazing, replacing heavier glass parts and reducing fuel consumption through mass reduction.	Increase of fuel consumption due to automotive glazing made of glass
Reflective roof coatings	Silicone in reflective roof coating extends material lifetime by reflecting UV rays, offering superior protection.	Polyurethane polymer-based roof coating
PU additives insulation – construction	Silicone PU additives enhance building insulation, ensuring stability for improved efficiency and cost savings.	XPS and foam glass
Telecommunication	TIM improves heat transfer between interfaces, crucial for electronic device performance, stability, and lifespan.	A smartphone with epoxy-based TIM
Cooling liquid in transformers, LSR as insulation in cables	Silicone cooling liquid in transformers minimizes environmental risks and, with fire-retardant properties, reduces the need for an extra transformer building, saving resources.	Mineral oil coolant

Table 4: GWP of electricity used for production of silicon (for silicones) in Europe.

Region	Sources of silicon	GWP of electricity, supply mix, (kg CO2e/kWh)
Norway	35 %	0.02
France	52 %	0.08
Spain	0 %	0.32
Germany	13 %	0.56
Europe (w. avg.)	**100 %**	**0.12**

Table 5: GWP of electricity used for global production of silicon for silicones.

Global regions	Sources of silicon	GWP of electricity, supply mix (kg CO2e/kWh)
China	18 %	1.02
Brazil	21 %	0.22
North America	21 %	0.50
Europe	32 %	0.12

RoW	8 %	0.41
Global (w. avg.)	**100 %**	**0.41**

Table 6: Mix of reduction agents in different regions of the world, given in shares of carbon in different sources. Approx. 5 % of total carbon consumption is related to electrodes. The regional source mix is related to silicon used for production of silicones.

Region	Regional source mix	Coal	Coke	Pet coke	Charcoal	Woodchips	Total
China	18 %	8 %	9 %	51 %	26 %	7 %	100 %
Brazil	21 %	0 %	9 %	0 %	72 %	20 %	100 %
North America	21 %	37 %	6 %	0 %	0 %	57 %	100 %
Europe	32 %	49 %	7 %	1 %	3 %	40 %	100 %
RoW	8 %	16 %	7 %	1 %	33 %	43 %	100 %
Global mix	**100 %**	**27 %**	**7 %**	**10 %**	**23 %**	**33 %**	**100 %**

Table 7: GWP data of fuels.[11] *Values for coke and pet coke were derived from GWP of production and delivery incl. direct CO2 emissions.*

Fuel Type	GWP 100 a (kg CO_2e / MJ)
Woodchips	0.0226
Charcoal	0.0671
Hard coal	0.1105
Coke	0.1194
Pet coke	0.1080

Table 8: Calculation of GWP data for reduction agents used for silicon production.

	units	Coal	Coke	Petcoke	Charcoal	Woodchips	Total
Global mix	% C	27%	7%	10%	22%	33%	100%
Direct CO_2	kg CO_2/kg Si	1.77	0.48	0.67	1.45	2.14	6.50
Direct CO_2	kg CO_2 / GJ	93	105	93	98	105	
Red. agents	MJ / kg Si	19.1	4.6	7.2	14.8	20.3	65.9

[11] ecoinvent Version 3 Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Retrieved from http://link.springer.com/10.1007/s11367-016-1087-8. 06/2021.

GWP 100 a	kg CO_2e / MJ	0.1105	0.1194	0.1080	0.0671	0.0226	
GWP (CO_2eq)	kg / kg Si	2.10	0.54	0.78	0.99	0.46	4.9

Table 9: Average cradle-to-gate GWP data for PDMS, intermediates, and related substances, as well as average gate-to-gate GWP data for polymerisation, mixing, and transport of products as separate processes. All figures represent average global production.

	GWP data in kg CO_2e / kg product
Transport of raw materials	0.07
Methyl siloxanes production	+ 5.78
Methyl siloxanes	**= 5.85**
Polymerisation PMS to PDMS	+ 0.12
PDMS - silicon fluid / oil	**= 5.97**
Polymerization of PMS to rubber/resin	0.24
Mixing process	0.27
PDMS rubber/resin	**6.36**
Transport of products	**0.05**
Chlorosilane production	**2.31**
Methyl chlorosilane production	**3.25**
Pyrogenic silica production	**8.30**

Table 10: Use effects of case studies; details and sources are described in respective case studies.

Application	Use effect related to GHG emission reductions
Automotive bonding	Enables reduction of weight, which leads to fuel saving
Batteries/energy storage	Improved heat dissipation and reparability lead to extended battery life and thus offer GHG savings
Chlorosilane for solar grade silicon	Solar grade silicon is needed for PV plants, solar electricity production saves fossil energy resources
Energy efficient lighting – LEDs	The primary effect considered is the extension of the service life over a certain period of time due to the silicone encapsulant, compared to epoxy.
Engine performance, rubber in motor construction	Contributes to more efficient motor technology leading to fuel savings
Green tires	Less rolling resistance leading to fuel savings
High quality sealants & adhesives	System with silicone demands less material and saves energy for heating & cooling
Industrial applications in pulp industry, anti-foaming in pulp production	Higher washer throughput makes pulp plant more efficient, less water must be vaporised, less process chemicals are lost

Sealants windows IG unit	Improved air tightness leads to different U-values, which result in a reduced heating demand
Wind turbines	Si-based materials improve durability and weathering of composites through reduced friction and improved energy efficiency leading to energy savings
PU additives insulation-appliances	Improved insulation properties lead to reduced electricity demand, and differ-ent production GWP of foaming agents
Antifoaming in detergents	Less electricity for washing leads to reduced detergent consumption
Masonry water repellent – bricks	Silane product protects bricks against moisture, U-value is improved and heating energy is saved
Masonry water repellent – concrete	Silane product protects concrete infrastructure, less concrete and steel must be produced
Conformal coatings in electronics	no significant use effects
Electrical isolators & insulations	No GHG effects in the use phase compared to other materials; differences in leakage current could not be quantified
Heat-resistant industrial coatings	Saved enameling or reduced demand for iron and zinc coating
Silicone foam for thermal insulation	Lower emissions during production of insulation material, while retaining the same insulation and fire/temperature resistance
Adhesion promoter for coatings	Reduced demand for paint production, less evaporation of solvent
Automotive, anti-fouling coatings	Prevent fouling of ship bodies, which lead to fuel savings
Electric transport (bicycle, electric and hybrid cars, train)	Aerodynamic drag reduction, which results in increased fuel efficiency and therefore fuel savings
Lighter automotive parts, coating for polycarbonate	Contributes to lighter automotive parts, which leads to fuel saving
Reflective roof coatings	The extension of the service life of the roof over a certain period of time due to the silicone-based coating, compared to the PU based alternative
PU additives insulation-construction	Different GWP of foaming agents
Telecommunication	Enhanced heat transfer of the thermal interface material (TIM) results in increased energy efficiency with respect to the smartphone performance
Cooling liquid in transformers, LSR as insulating materials in cables	Silicone enables compact design and improves fire safety; both aspects help to protect electrical infrastructure

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*Table 11: EoL assumptions for silicone products used in **Europe**: 100 % of product mass is allocated to different waste collection routes or to dissipation or stays in ground; within collection routes, a split into final recovery/disposal options is given.*

	EU												
		residual waste			building rubble			seperate collection			not entering WM		
Nr.			MSWI	landfill		industrial en. Recov.	landfill		industrial en. Recov.	landfill		dissipation	stays in ground
1	Automotive Bonding							100%	80%	20%			
2	Batteries/Energy Storage in EV							100%	100%				
3	Chlorosilane for Solar Grade Silicon							100%	to recycling				
4	Energy efficient lighting – LEDs	50%	53%	47%				50%	80%	20%			
5	Engine Performance, Rubber in Motor Construction							100%	80%	20%			
6	Green Tyres							35%	70%	30%	65%	100%	
7	High Quality Sealants & Adhesives				50%		100%	50%	50%	50%			
8	Industrial applications in pulp industry, Anti-foaming in Pulp Production							100%	80%	20%			
9	Sealants Windows IG unit	25%	53%	47%	25%		100%	50%	50%	50%			
10	Wind Turbines							90%	100%		10%	100%	
11	PU Additives Insulation-Appliances	15%	53%	47%				85%	50%	50%			
12	Antifoaming in Detergents							90%	20%	80%	10%	100%	
13	Masonry Water Repellent - bricks				50%		100%				50%	100%	
14	Masonry Water Repellent - concrete				67%		100%				33%	100%	
15	Conformal coatings in electronics	100%		100%									
16	Electrical Isolators & Insulations	50%	53%	47%				50%	50%	50%			
17	Silicone foam for thermal insulation	20%	53%	47%	60%	20%	80%				20%		100%
18	Adhesion Promoter for Coatings	25%	53%	47%	25%		100%	50%	90%	10%			
19	Coating of means of transport, anti fouling coatings										100%	100%	
20	Electric transport (bycicle, electric and hybrid cars, train)							100%	80%	20%			
22	Polycarbonate Coatings; Lighter automative parts							100%	80%	20%			
22	Reflective roof coatings				100%	70%	30%						
23	Heat-Resistant Industrial Coatings							100%	90%	10%			
24	PU Additives Insulation-Construction	20%	53%	47%	60%	20%	80%				20%		100%
25	Telecommunication	50%	53%	47%				50%	80%	20%			
26	Cooling Liquid in Transformers, LSR as insulating materials in cables							100%	100%				

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*Table 12: EoL assumptions for silicone products used in **North America**: 100 % of product mass is allocated to different waste collection routes or to dissipation or stays in ground; within collection routes, a split into final recovery/disposal options is given.*

	NA												
		residual waste			building rubble			seperate collection			not entering WM		
Nr.			MSWI	landfill		industrial en. Recov.	landfill		industrial en. Recov.	landfill		dissipation	stays in ground
1	Automotive Bonding							100%	80%	20%			
2	Batteries/Energy Storage in EV							100%	100%				
3	Chlorosilane for Solar Grade Silicon							100%	to recycling				
4	Energy efficient lighting – LEDs	50%	19%	81%				50%	80%	20%			
5	Engine Performance, Rubber in Motor Construction							100%	80%	20%			
6	Green Tyres							35%	70%	30%	65%	100%	
7	High Quality Sealants & Adhesives				50%		100%	50%	50%	50%			
8	Industrial applications in pulp industry, Anti-foaming in Pulp Production							100%	80%	20%			
9	Sealants Windows IG unit	50%	19%	81%	50%		100%						
10	Wind Turbines							90%	100%		10%	100%	
11	PU Additives Insulation-Appliances	15%	19%	81%				85%	50%	50%			
12	Antifoaming in Detergents							90%	20%	80%	10%	100%	
13	Masonry Water Repellent - bricks				50%		100%				50%	100%	
14	Masonry Water Repellent - concrete				67%		100%				33%	100%	
15	Conformal coatings in electronics	100%		100%									
16	Electrical Isolators & Insulations	50%	19%	81%				50%	50%	50%			
17	Silicone foam for thermal insulation	20%	19%	81%	60%	20%	80%				20%		100%
18	Adhesion Promoter for Coatings	25%	19%	81%	25%		100%	50%	90%	10%			
19	Coating of means of transport, anti fouling coatings		19%	81%							100%	100%	
20	Electric transport (bycicle, electric and hybrid cars, train)							100%	80%	20%			
22	Polycarbonate Coatings; Lighter automative parts							100%	80%	20%			
22	Reflective roof coatings				100%	70%	30%						
23	Heat-Resistant Industrial Coatings							100%	90%	10%			
24	PU Additives Insulation-Construction	20%	19%	81%	60%	20%	80%				20%		100%
25	Telecommunication	50%	19%	81%				50%	80%	20%			
26	Cooling Liquid in Transformers, LSR as insulating materials in cables							100%	100%				

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Table 13: EoL assumptions for silicone products used in Japan: 100 % of product mass is allocated to different waste collection routes or to dissipation or stays in ground; within collection routes, a split into final recovery/disposal options is given.

	JP												
		residual waste			building rubble			seperate collection			not entering WM		
Nr.			MSWI	landfill		industrial en. Recov.	landfill		industrial en. Recov.	landfill		dissipation	stays in ground
1	Automotive Bonding							100%	100%				
2	Batteries/Energy Storage in EV							100%	100%				
3	Chlorosilane for Solar Grade Silicon							100%	to recycling				
4	Energy efficient lighting – LEDs	10%	90%	10%				90%	80%	20%			
5	Engine Performance, Rubber in Motor Construction							100%	100%				
6	Green Tyres							35%	100%		65%	100%	
7	High Quality Sealants & Adhesives				50%		100%	50%	80%	20%			
8	Industrial applications in pulp industry, Anti-foaming in Pulp Production							100%	80%	20%			
9	Sealants Windows IG unit				90%		100%	10%	100%				
10	Wind Turbines							90%	100%		10%	100%	
11	PU Additives Insulation-Appliances	10%	100%					90%	100%				
12	Antifoaming in Detergents							90%	20%	80%	10%	100%	
13	Masonry Water Repellent - bricks				50%		100%				50%	100%	
14	Masonry Water Repellent - concrete				67%		100%				33%	100%	
15	Conformal coatings in electronics	100%		100%									
16	Electrical Isolators & Insulations	50%	100%					50%	100%				
17	Silicone foam for thermal insulation	20%	100%		60%	80%	20%				20%		100%
18	Adhesion Promoter for Coatings	25%		100%	25%	100%		50%	90%	10%			
19	Coating of means of transport, anti fouling coatings										100%	100%	
20	Electric transport (bycicle, electric and hybrid cars, train)							100%	80%	20%			
22	Polycarbonate Coatings; Lighter automative parts							100%	100%				
22	Reflective roof coatings				100%	70%	30%						
23	Heat-Resistant Industrial Coatings	100%	100%										
24	PU Additives Insulation-Construction	20%	100%		60%	80%	20%				20%		100%
25	Telecommunication	10%	90%	10%				90%	80%	20%			
26	Cooling Liquid in Transformers, LSR as insulating materials in cables							100%	100%				

Table 14: Calorific values and fossil carbon contents of substances relevant in the waste management calculations of this study.

Substance	Net calorific value, MJ/kg	Fossil C-content[12], %
PDMS[13]	23.3	32 %
PMMA/acrylate[14]	27.4	60 %
Fuel oil light[1]	42.6	86 %
XPS[15]	45.6	92 %
PU[16]	26.0	50 %

[12] Denkstatt, (2021), internal expert knowledge

[13] Wacker, (2011), Retrieved from http://www.ambercomposites.com/downloads/datasheet/wacker-silicone-fluid-ak250-tds.pdf (02/2022)

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[15] Patel M., (1999), KEA für Produkte der organischen Chemie. Arbeitspapier im Rahmen des UBA-F&E-Vorhabens Nr. 10401 123. Erar-beitung von Basisdaten zum Ener-gieaufwand und der Umweltbelastung von energieintensiven Produkten und Dienstleistungen für ÖKO-Bilanzen und Öko-Audits. Fraunhofer-Institut für Sys-temtechnik und Innovationsforschung (FhG-ISI)

[16] Brandt, B., Kletzer, E., Pilz, H., Hadzhiyska, D., Seizov, P. (2012). Silicon-Chemistry Carbon Balance: An assessment of Greenhouse Gas Emissions and Reduction. Retrieved from www.silicones.eu/wp-content/uploads/2019/05/SIL_exec-summary_en.pdf. 08/2021.

EPDM[17]	44.0	87 %
Calcium carbonate filler[18]	5.2 – 5.9[19]	12 %
Epoxy resin[20]	31.7	42 %
Polycarbonate[21]	30.6	75 %
Synthetic lubricant[22]	42.1	86 %
Petrol coke[1]	35.0	100 %
Carbon black[23]	27.9	100 %
PS[24]	46.0	92 %
PVC[25]	41.0	38 %
PE[26]	43.0	86 %
PP[27]	44.0	86 %

Table 15: Processes for industrial energy recovery of RDF (refuse derived fuel) and the fuels which are typically substituted (in the same process or in an alternative process) by the use of RDF.

Process	Substituted fuels
Power plant (where RDF can be used)	Coal (or co-generation gas-turbine)
Cement kiln	Coal, heavy fuel oil, biomass, natural gas
Fluidised bed combustion process	Coal (or co-generation gas-turbine)
Blast furnace	Coke, heavy fuel oil

[17] denkstatt. (2021). Internal expert knowledge

[18] Brandt, B., Kletzer, E., Pilz, H., Hadzhiyska, D., Seizov, P. (2012). Silicon-Chemistry Carbon Balance: An assessment of Greenhouse Gas Emissions and Reduction. Retrieved from www.silicones.eu/wp-content/uploads/2019/05/SIL_exec-summary_en.pdf. 08/2021.

[19] M. Dabrowska, A. Swietochowski, A. Lisowski (2019). Physicochemical properties and agglomeration parameters of biogas digestate with addition of calcium carbonate

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[21] VDS (2000). Kunststoffe. Eigenschaften, Brandverhalten, Brandgefahren. Retrieved from https://shop.vds.de/download/vds-2516. (10/2021).

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[26] Panda, Achyut & Singh, Raghubansh Kumar & Mishra, Dhanada. (2017). Thermolysis of waste plastics to liquid fuel A suitable method for plastic waste management and production of value added products - A world prospective. 88. 13-18. Retrieved from Panda, Achyut & Singh, Raghubansh Kumar & Mishra, Dhanada. (2017). Thermolysis of waste plastics to liquid fuel A suitable method for plastic waste management and production of value added products - A world prospective. 88. 13-18. (10/2021)

[27] Ioelovich, M. (2018). Energy Potential of Natural, Synthetic Polymers and Waste Materials – A Review. Retrieved from https://juniper-publishers.com/ajop/pdf/AJOP.MS.ID.555553.pdf (10/2021)

Table 16: Assumption of substituted fuels by industrial energy recovery.

Substituted fuels	Assumed shares regarding MJ waste input
Substitution of heavy fuel oil	30 %
Substitution of coal	50 %
Substitution of gas	10 %
Substitution of biomass	10 %
Total	100 %

Table 17: Average fuel mix for district heating in the EU28, North America and Japan.

Average fuel mix for district heat	EU-28 2015[28]	North America 2019[29]	Japan 2015[30]
Waste	1 %	-	-
Biomass	19 %	7 %	-
Renewables	3 %	-	-
Gas	44 %	43 %	20 %
Oil	16 %	9 %	-
Coal	12 %	-	-
Nuclear	5 %	-	-
Electricity	-	41 %	17 %
Kerosene	-	-	63 %
Total	**100 %**	**100 %**	**100 %**

Table 18: Assumed chemical degradation rates for various substances in various environments within 100 years.

Substance class	Residual waste landfill	Rubble landfill	Separate collection landfill	Dissipation
Fluid	100 %	100 %	100 %	100 %
Sealant	50 %	0 %	50 %	100 %
Rubber	50 %	0 %	50 %	100 %
Resin	50 %	0 %	50 %	100 %
Inert	0 %	0 %	0 %	0 %
Organic	50 %	0 %	50 %	100 %
Acrylate	100 %	100 %	100 %	100 %

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[28] Bertelsen, N., & Vad Mathiesen, B. (2020). EU-28 residential heat supply and consumption: Historical development and status. Energies, 13(8), 1894.

[29] U.S. Energy Information Administration (2021). Monthly Energy Review. https://www.eia.gov/energyexplained/use-of-energy/homes.php (accessed 11/2021)

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Table 19: Aggregated market data per application for 2019 and for the market regions (EU, NA, JP) based on member estimates and market studies (information confidential). Market shares per region cannot be shared due to license reasons.

Case study	Total market volume 2019 (t/a)
Automotive bonding	9 970
Batteries/energy storage	3 312
Chlorosilane for solar grade silicon	787 020
Energy efficient lighting – LEDs	2 158
Engine performance, rubber in motor construction	31 550
Green tires	49 000
High quality sealants & adhesives	120 570
Industrial applications in pulp industry, anti-foaming in pulp production	14 663
PU additives insulation-appliances	7 750
Sealants windows IG unit	109 886
Wind turbines	1 842
Antifoaming in detergents	842
Masonry water repellent – bricks	11 317
Masonry water repellent – concrete	15 332
Conformal coatings in electronics	1 859
Electrical isolators & insulations	11 000
Heat-resistant industrial coatings	3 450
Silicone foam for thermal insulation	28 087
Adhesion promoter for coatings	845
Coating of means of transport, anti-fouling coatings	24 371
Electric transport (bicycle, electric and hybrid cars, train)	40 390
Lighter automotive parts, coating for polycarbonate	11 940
Reflective roof coatings	68 320
PU additives insulation-construction	20 570
Telecommunication	81
Cooling liquid in Transformers / LSR as insulating materials in cables	37 486 / 2 018

	D	E	
K	Factor FU/kg	3.33	
Name of case study Functional unit (FU): definition	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**	Abbrev. used in formula below:
Silicone application			
Production & Transport	9.2	30.7	Sil.Prod
Production of Silicone	1.8	6.1	pureSil.Prod
Production of other Components (F)	7.4	24.6	Rest.Prod
Use			Sil.Use
End of Life (G)	0.0	0.1	Sil.EoL
Total	9.2	30.8	
Alternative application			
Production & Transport	6.1	20.5	Alt.Prod
Use	829.5	2 764.8	Alt.Use
End of Life	3.6	12.2	Alt.Eol
Total	839.2	2 797.5	
Difference			
Production & Transport	3.1	- 14.4	
Use	-829.5	- 2 764.8	
End of Life	-3.6	- 12.1	
Total (- ... Net-Benefit of Product with Silicone)	-830	-2 767	H
Total (- ... Net-Benefit of Silicone)	-164	-547	I
Ratio Benefit / Impact	90		J

A: Silicone application rows; B: Alternative application rows; C: Difference rows.

Figure 3: Example of the results table explained.

Table 20: Explanation of result table.

A	Life cycle GWP data of the silicone product (or scenario with silicone)
B	Life cycle GWP data of alternative product or scenario.
C	Differences between both scenarios, calculated as A – B. A negative value indicates that the environmental impact of the silicone scenario is smaller than that of the alternative scenario and silicone shows a net-benefit.
D	Figures related to the functional unit (definition in the upper part of the table)
E	Figures related to one kg of the silicone product or to the equivalent mass of alternative product
F	Grey cells represent life cycle stages for which no GWP effects are identified or considered

G	"0,0" means that the GWP effects considered are negligible
H	The total of difference (same as the difference of totals) of both scenarios. A negative figure (less GWP impact, benefit for silicone product) is highlighted green, a positive figure - red.
I	(Optional line) When silicone is only a part of the product that is investigated, the results are also related to the contained silicone only. Depending on the GWP of the other components, it is possible that one figure is positive and the other one is negative. $\text{Total net benefit of silicone} = (\text{pureSil.Prod} + \text{Sil.EoL}) - (\text{Alt.Prod} + \text{Alt.EoL} + \text{Alt.Use}) * \text{pureSil.Prod}/(\text{pureSil.Prod} + \text{Rest.Prod})$ Thus the equation looks as follows: = (1.8 + 0) - (6.1 + 829.5 + 3.6) * 1.8 / (1.8 + 7.4) = 164.1
J	Benefit/impact ratio: relates the benefit of the silicone product/scenario to the impact of pure silicone. Depending on the kind of case study – product made of silicone only or silicone mixed with other components, there are two formulas which are used for the calculation of this indicator (GWP figures): Silicone only: $\text{Ratio} = \frac{\text{Alt.Prod} + \text{Alt.EoL} + \text{Alt.Use} - \text{Sil.Use}}{\text{Sil.Prod} + \text{Sil.Eol}}$ Silicone mix: $\text{Ratio} = \frac{(\text{Alt.Prod} + \text{Alt.EoL} + \text{Alt.Use} - \text{Sil.Use}) * \text{pureSil.Prod}/(\text{pureSil.Prod} + \text{Rest.Prod})}{\text{pureSil.Prod} + \text{pureSil.Eol}}$ With the numbers from above: = (6.1 + 829.5 + 3.6) * 1.8 / (1.8 + 7.4) / (1.8 + 0) = 89.8 The distinction of the EoL impact of pure silicone and other component may be omitted, where the impact is negligible and mainly caused by one of them.
K	The factor represents a quotient value where the divisor is the mass per FU of the Si-based material

Table 21: GWP effects of automotive bonding.

	Case study no.	1
	Factor FU/kg	1.25
Automotive Bonding Functional unit (FU): 1 car	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone automotive bonding		
Production & Transport	5.0	6.3
Use		
End of Life	-0.022	-0.138
Total	**5.01**	**6.15**
Spot welding and heavier materials		
Production & Transport	12.0	15.0
Use	95.0	118.7
End of Life		
Total	**107.0**	**133.7**
Difference		
Production & Transport	- 6.9	- 8.7
Use	- 95.0	- 118.7
End of Life	- 0.02	- 0.14
Total (- … Net-Benefit of Silicone)	**- 101.9**	**- 127.5**
Ratio Benefit / Impact	**21.3**	

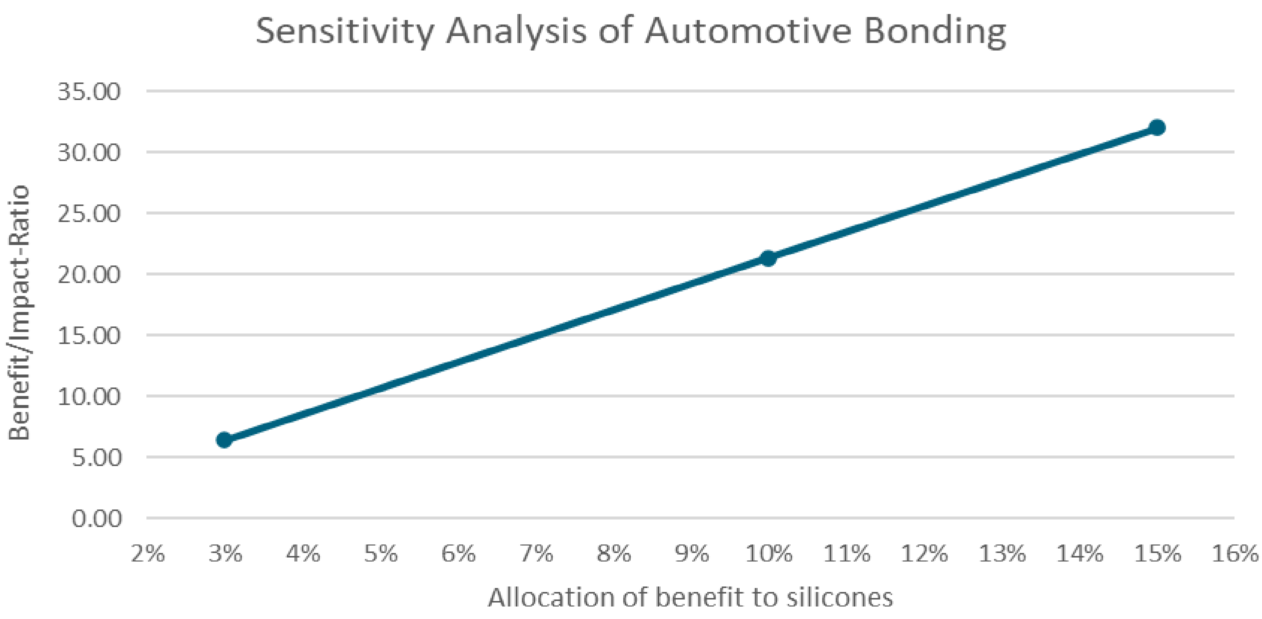

Figure 4: Sensitivity analysis for allocation of benefit of automotive bonding.

Table 22: Life cycle GWP of silicone and epoxy as Thermal Interface Material in batteries in EV.

	Case study no.	2
	Factor FU/kg	0.767884549
Thermal Interface Material (TIM) in batteries in electric v Functional unit (FU): TIM for 1 Battery 70 kWh; 10a	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product (TIM)**
Silicone application: Silicone TIM for 1 Battery 70 kWh; 10a life time		
Production & Transport	19.7	15.1
Production & Transport Silicone	19.7	15.1
Use	2 144.3	1 646.6
Production & Transport Batterycells	2 144.3	1 646.6
End of Life	- 0.0	- 0.0
Total	**2 164.0**	**1 661.7**
Alternative application: Epoxy TIM for 1 Battery 70 kWh; 8a life time of the battery		
Production & Transport	22.4	17.2
Production & Transport Epoxy	22.4	17.2
Use	2 680.4	2 058.2
Production & Transport Batterycells	2 680.4	2 058.2
End of Life	- 0.4	- 0.3
Total	**2 702.4**	**2 075.1**
Difference		
Production & Transport	- 2.7	- 2.0
Use	- 536.1	- 411.6
End of Life	0.3	0.3
Total (- ... Net-Benefit of Battery	**- 538.4**	**- 413.4**
Ratio Benefit / Impact	**28.3**	

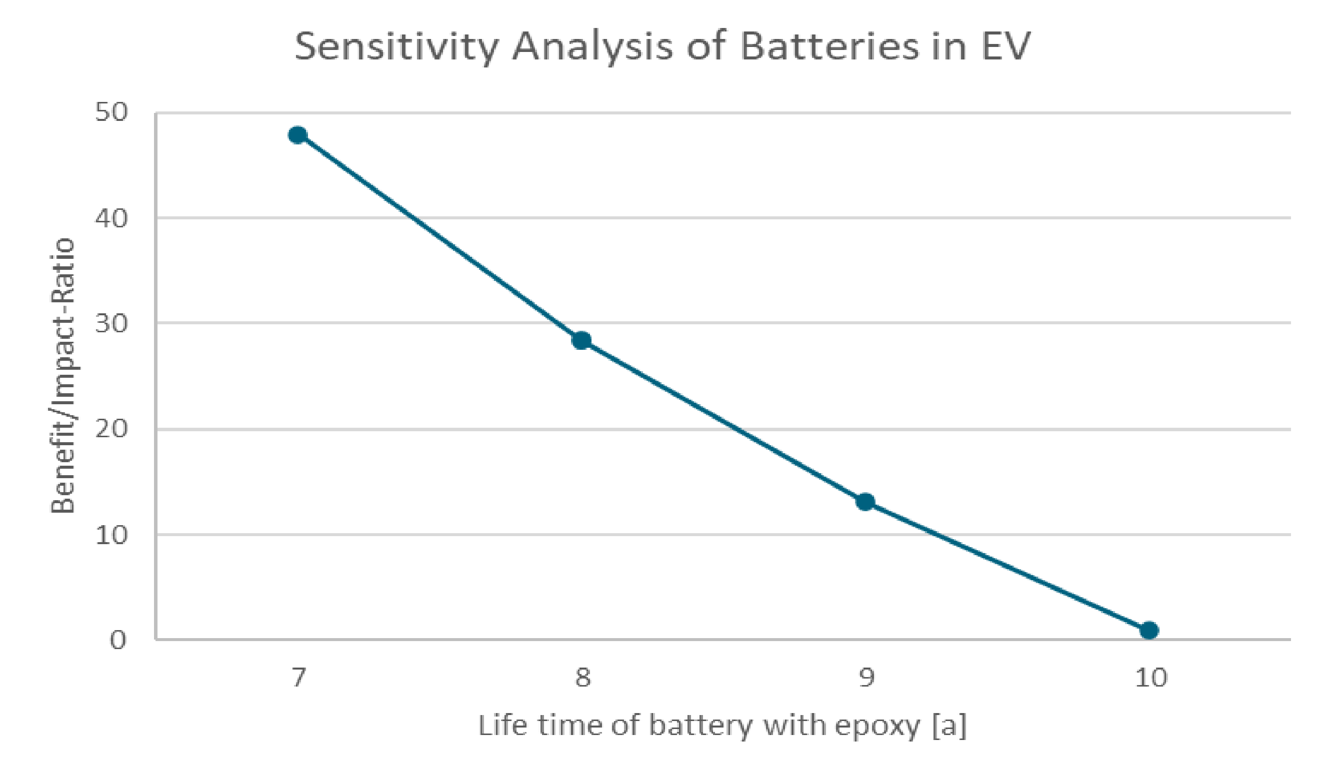

Figure 5: Sensitivity analysis: Batteries in EVs, silicone and epoxy as a Thermal Interface Material.

Table 23: Electricity produced by PV systems of 1 kWp in different regions EU and North America.

	Unit	FR	UK	ES	US	CA
Average yield rooftop	kWh/kWp.a	1,115	898	1,450	1,454	1,193

Table 24: Electricity produced by PV systems of 1 kWp in different regions.

	Unit	W. average	Europe	North America	Japan[31]
Average yield rooftop	kWh/kWp.a	N/A	1,100	1,444	1,051
Electricity produced over lifetime	kWh	30,793	30,715	31,060	30,666

[31] International energy agency. (2008). Analysis of PV system's values beyond energy- by country and stakeholder. Retrieved from https://iea-pvps.org/wp-content/uploads/2020/01/rep10_02.pdf (accessed 11/2021)

Table 25: GWP effects of a photovoltaic PV unit. The right column shows the GWP related to chlorosilane.

	Case study no.	3
	Factor FU/kg	0.081159597
Chlorosilanes Functional unit (FU): 1kWp installed capacity	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicon photovoltaic system		
Production & Transport	1 378	112
Silicon production and purification	29	2
Production of Solar systems	1 349	109
Use		
End of Life		
Total	**1 378**	**112**
Electricity production (regional mix)		
Production & Transport		
Use	14 955	1 214
End of Life		
Total	**14 955**	**1 214**
Difference		
Production & Transport	1 378	112
Use	- 14 955	- 1 214
End of Life		
Total (- … Net-Benefit of Product)	**- 13 576.7**	**- 1 101.9**
Total (- … Net-Benefit of Chlorosilane)	**- 286.3**	**- 23.2**
Ratio Benefit / Impact	**9.9**	

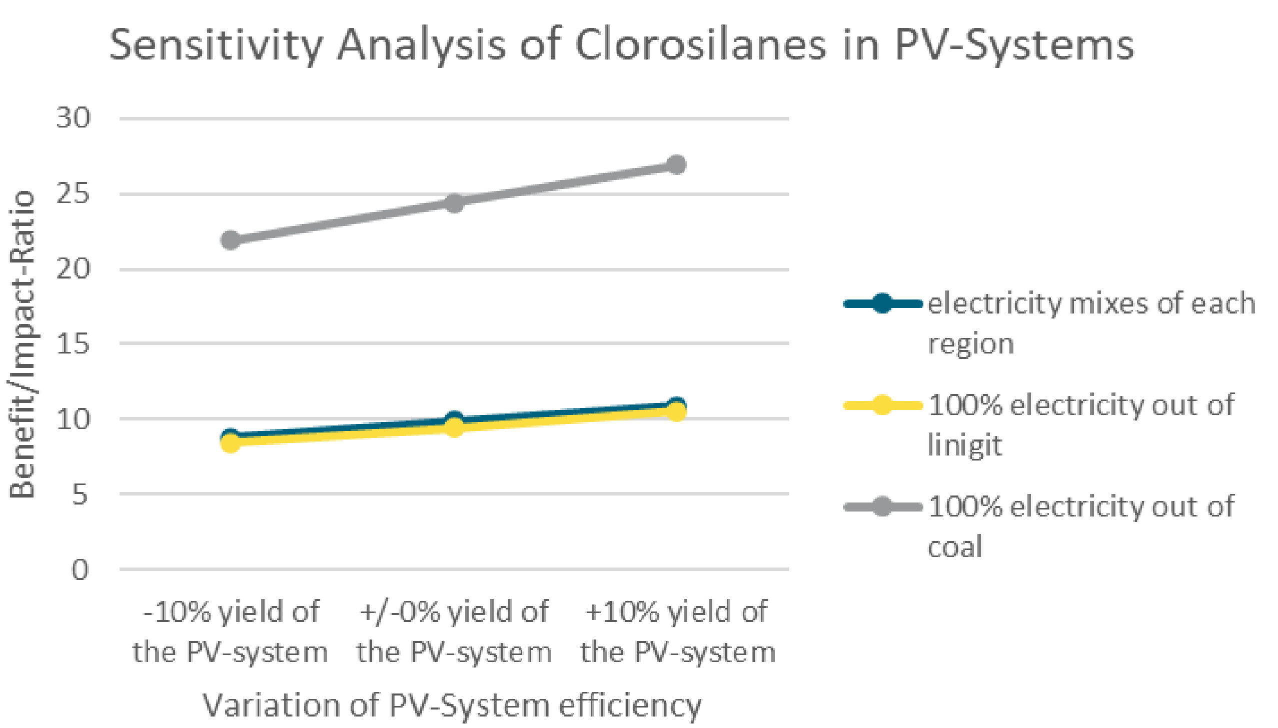

Figure 6: Sensitivity analysis of Chlorosilanes in PV-Systems.

Table 26: GWP effects of LED with silicone as encapsulant and LED with epoxy as encapsulant.

	Case study no.	4
	Factor FU/kg	3658
LED Functional unit (FU): light duration of 1500h	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone**
LED lamp with silicone encapsulant		
Production & Transport	3.06	11 197
LED lamp production excluding encapsulant	3.06	11 190
Silicone encapsulant production	0.0019	7
Use		
End of Life	0.0004	1.47
Total	**3.06**	**11 198.21**
LED lamp with epoxy encapsulant		
Production & Transport	6.12	22 391.52
LED lamp production excluding encapsulant	6.12	22 379.93
Epoxy encapsulant production	0.00	11.58
Use		
End of Life	0.0008	2.82
Total	**6.12**	**22 394.34**
Difference		
Production & Transport	- 3.06	- 11 194.78
Use		
End of Life	- 0.00	- 1.35
Total (- ... Net-Benefit of Silicone)	**- 3.1**	**- 11 196.1**
Ratio Benefit / Impact	**2.0**	

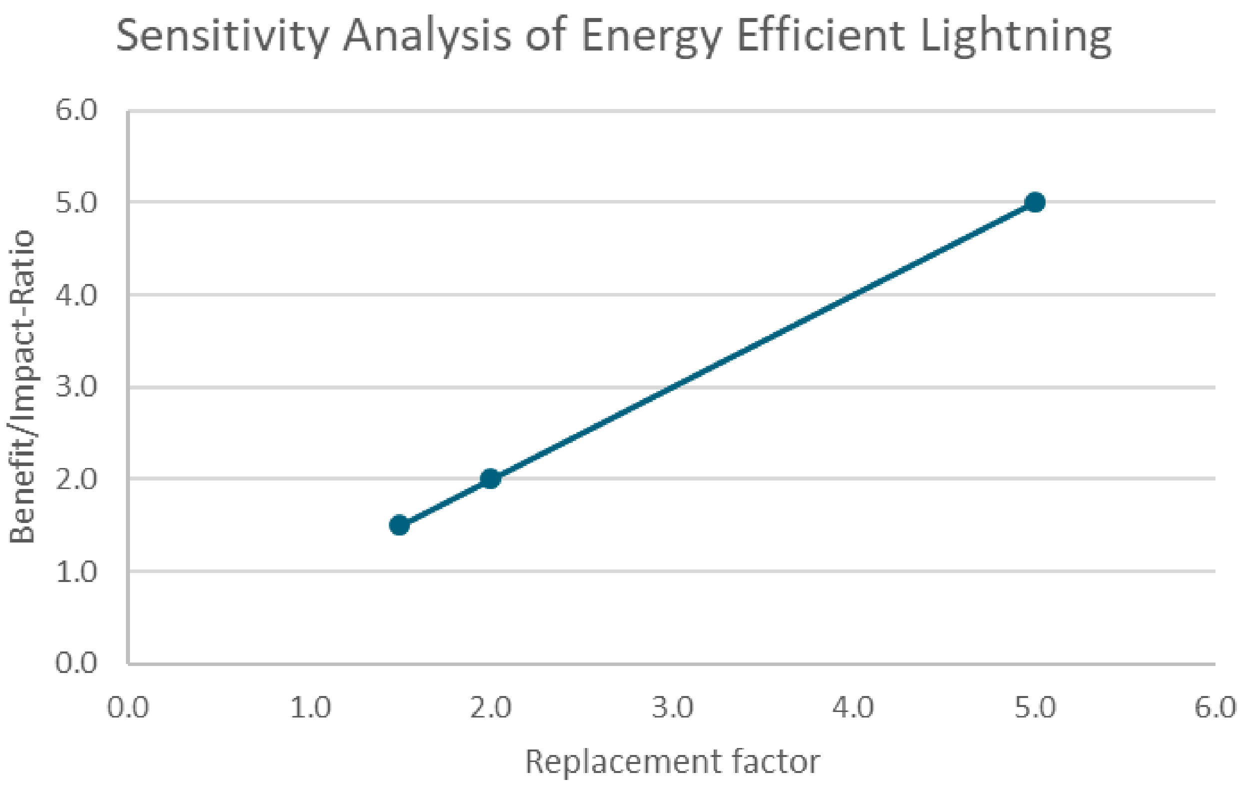

Figure 7: Sensitivity analysis of energy efficient lightning.

Table 27: GWP effects of silicone rubber and EPDM in motor construction.

	Case study no.	5
	Factor FU/kg	2.44
Rubber for Engines Functional unit (FU): 1 car, 150.000 km	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Silicone rubber		
Production & Transport	2.6	6.4
Use		
End of Life	0.0	0.1
Total	**2.6**	**6.4**
EPDM		
Production & Transport	0.7	1.8
Use	343.6	838.1
End of Life	0.2	0.6
Total	**344.6**	**840.4**
Difference		
Production & Transport	1.9	4.6
Use	- 343.6	- 838.1
End of Life	- 0.2	- 0.5
Total (- ... Net-Benefit of Silicone)	- 341.9	- 834.0
Ratio Benefit / Impact	130.8	

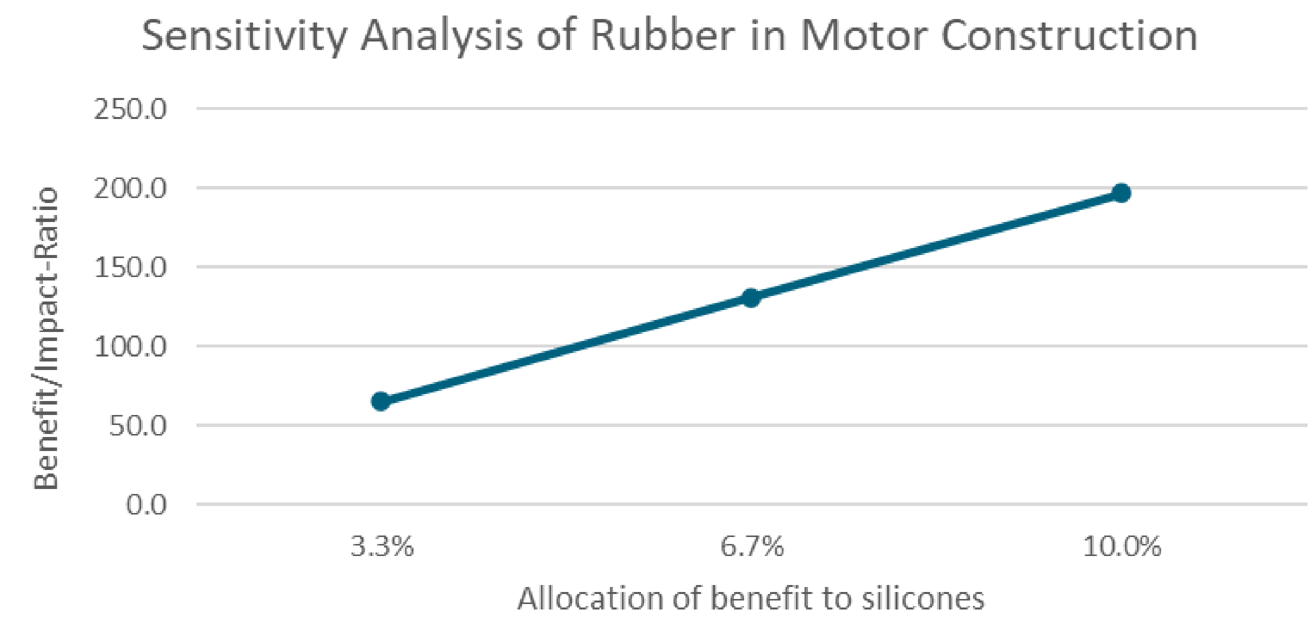

Figure 8: Sensitivity analysis for allocation of benefit of rubber in motor construction.

Table 28: Shares of petrol and diesel engine as well as passenger vehicles across studied regions.

2019	EU[32]	NA[33]	JP[34]
Share of petrol engine cars	53 %	96 %	96 %
Share of diesel engine cars	42 %	4 %	0.1 %
Passenger cars in use	326.8 Mio.	108.5 Mio.	61.7 Mio.

Table 29: GWP effects of green tires and conventional tires.

	Case study no.	6
	Factor FU/kg	2.86
Green Tires Functional unit (FU): set of 4 tyres for 1 car	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Green Tyres with silane		
Production & Transport	10.7	30.7
Silane Si 69	2.1	6.0
Silica	8.6	24.6
Use		
End of Life	0.01	0.0
Total	**10.7**	**30.7**
Conventional tyres		
Production & Transport	7.2	20.5
Use	407.6	1 164.6
End of Life	2.5	7.1
Total	**417.2**	**1 192.1**
Difference		
Production & Transport	3.6	- 14.5
Use	- 407.6	- 1 164.6
End of Life	- 2.5	- 7.1
Total (- … Net-Benefit of Green Tyres)	**- 406.5**	**- 1 161.5**
Total (- … Net-Benefit of Silicone)	**- 80.2**	**- 229.1**
Ratio Benefit / Impact	**38.7**	

[32] ACEA. (2021). Passenger car fleet by fuel type, European Union. Retrieved from https://www.acea.auto/figure/passenger-car-fleet-by-fuel-type/ 08/2021.

[33] U.S. Department of transportation. (2015). Diesel-powered Passenger Cars and Light Trucks. Retrieved from https://www.bts.dot.gov/sites/bts.dot.gov/files/legacy/DieselFactSheet.pdf (accessed 11/21)

[34] Kato, Y., Koyama, M., Fukushima, Y., & Nakagaki, T. (2016). Energy Technology Roadmaps of Japan: Future Energy Systems Based on Feasible Technologies Beyond 2030 (1st ed. 2016 ed.). Springer.

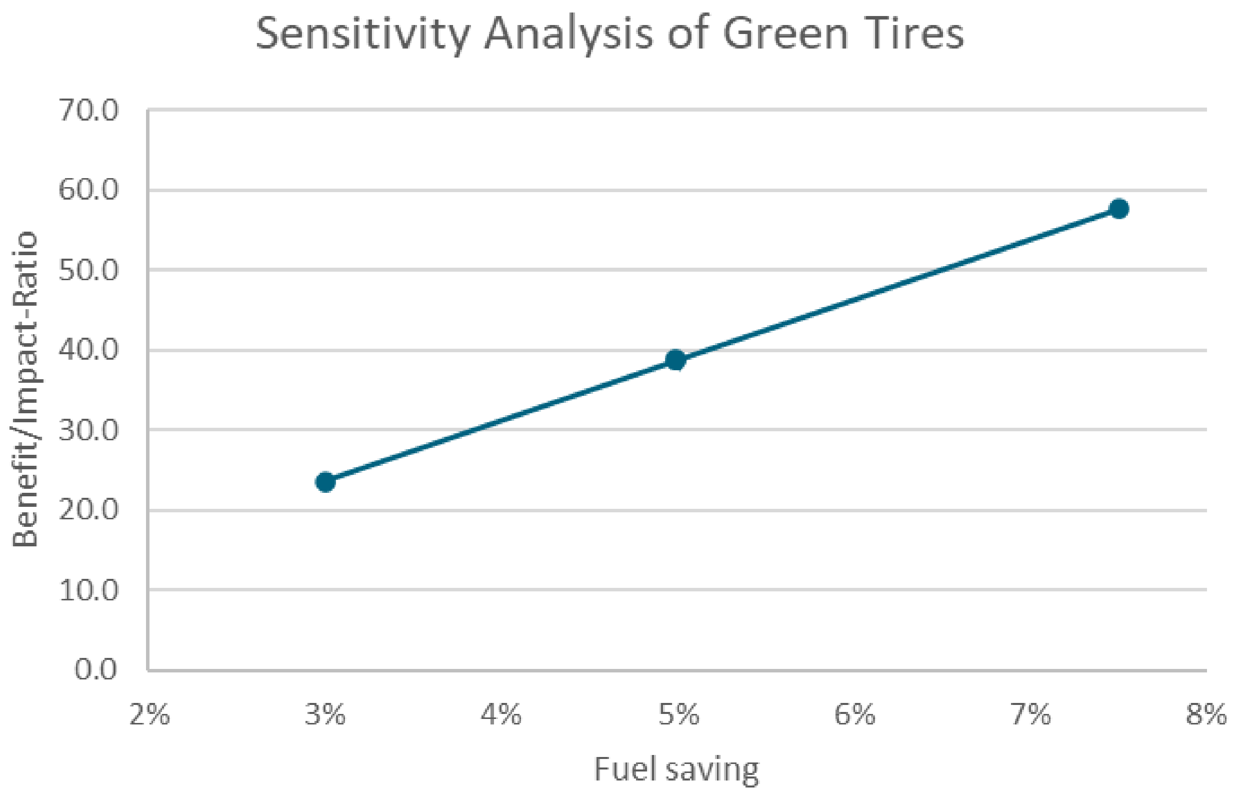

Figure 9: Sensitivity analysis of the fuel saving through green tires.

Table 30: Silicone components in structural glazing system.

Silicone sealing in structural glazing	Area	Density	Mass/FU
Unit	cm^2	g/cm^3	kg
12 x 16 mm structural silicone joint	1,92	1,45	3.214
20 x 8 mm silicone weather seal	0,80	1,45	1.339
12 x 8 mm silicone foam spacer	0,96	0,5	554

Table 31: Share of energy sources for residential heating in studied regions in 2015, with exception for North America (2019).

Share of energy sources for residential heating 2015	EU-28	North America	Japan
Waste	1%	-	-
Biomass	19%	7% (wood)	-
Renewables	3%	-	-
Gas	44%	43%	20%
Oil	16%	9%	-
Coal	12%	-	-
Nuclear	5%	-	-
Electricity	-	41%	17%
Kerosene	-	-	63%

Table 32: Average effect of different U-value and increased air infiltration in studied regions.

Average effect of different U-value (CO_2eq/FU.a)	Europe	North America	Japan
cold climate	1,627	3,700	3,140
hot climate	651	1,391	1,222
Average effect of increased air infiltration			
cold climate	23,353	53,992	45,398
hot climate	10,783	25,752	21,274

Table 33: Life cycle GWP of a silicone structural glazed system and a dry glazing thermally improved system.

	Case study no.	7
	Factor FU/kg	0.000196
HQ Sealants & Adhesives Functional unit (FU): 1 building	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone structural glazed system		
Production & Transport	19 871.8	3.9
Use		
End of Life	- 215.0	- 0.04
Total	**19 656.8**	**3.8**
Dry glazing thermally improved system		
Production & Transport	54 978.5	10.8
EPDM gasket	20 797.9	4.1
Aluminium frame	34 180.6	6.7
Use	179 718.8	35.2
effect of U-value	44 111.2	8.6
effect of air infiltration	135 607.6	26.6
End of Life	4 457.9	0.9
Total	**239 155.2**	**46.8**
Difference		
Production & Transport	- 35 106.8	- 6.9
Use	- 179 718.8	- 35.2
End of Life	- 4 672.9	- 0.9
Total (- ... Net-Benefit of Silicone)	**- 219 498.4**	**- 43.0**
Ratio Benefit / Impact	**12.2**	

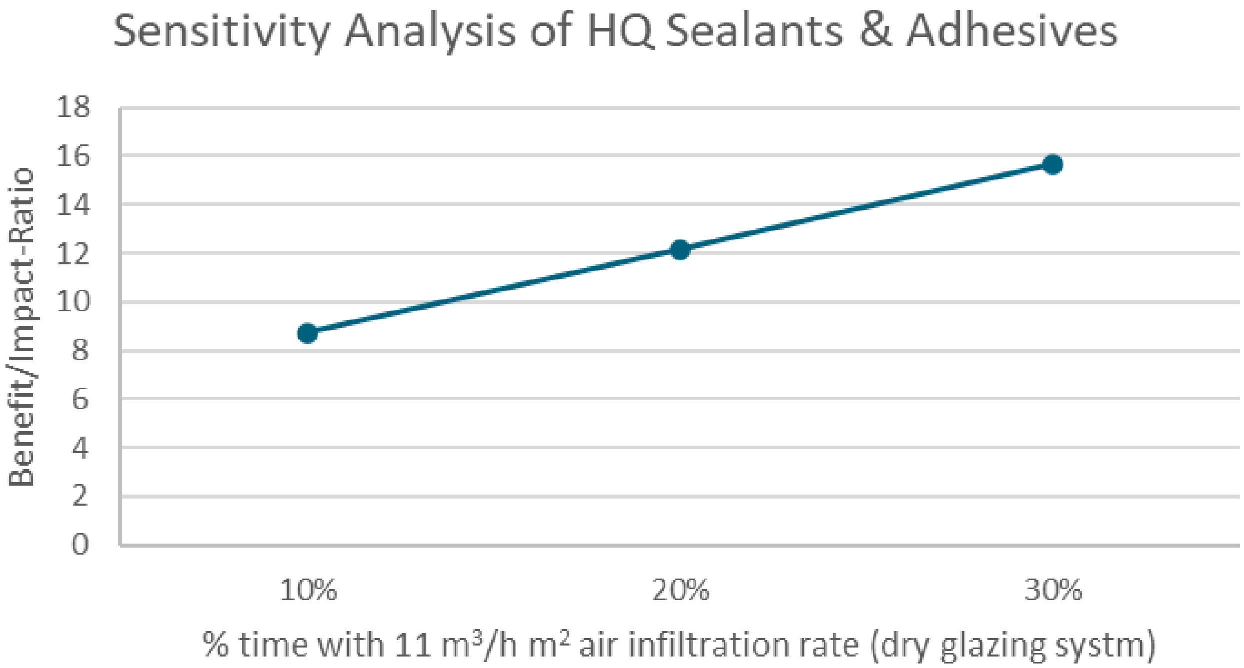

Figure 10: Sensitivity analysis of % of time with 11 $m^3/h\ m^2$ for the dry glazing system.

Table 34: GWP effects of pulp washing with silicone-based defoamers, compared to mineral oil-based defoamers.

	Case study no.	8
	Factor FU/kg	2.5
Anti-Foaming Pulp Production Functional unit (FU): 1 ton of dried pulp	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone application		
Production & Transport	0.6	1.5
Use		
End of Life	0.1	0.2
Total	**0.7**	**1.7**
Alternative application		
Production & Transport	3.6	9.1
Use	52.3	130.8
Worse production rate of pulp plant	1.3	3.2
Additional water (production)	0.5	1.4
Additional water to evaporate	46.4	116.1
Additional cauistic soda used	4.1	10.1
End of Life	2.2	5.5
Total	**58.2**	**145.4**
Difference		
Production & Transport	- 3.0	- 7.6
Use	- 52.3	- 130.8
End of Life	- 2.1	- 5.3
Total (- … Net-Benefit of Silicone)	**- 57.5**	**- 143.7**
Ratio Benefit / Impact	83.5	

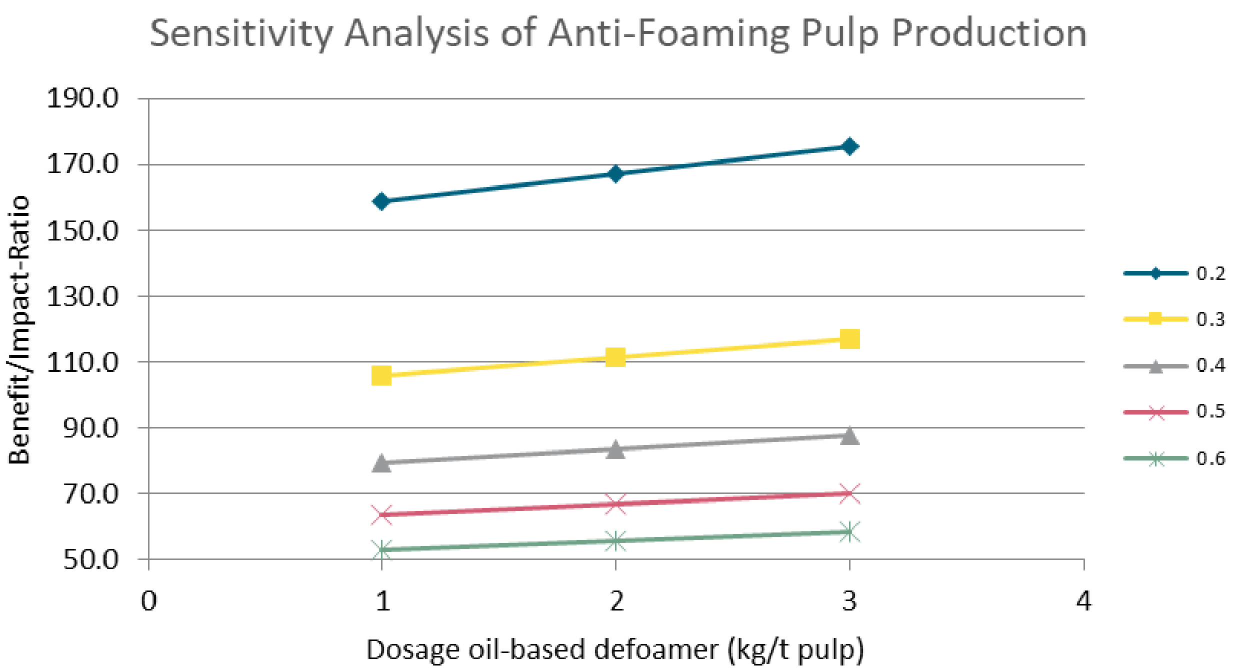

Figure 11: Dependency of benefit/impact ratio on the dosage levels of silicone defoamer and its alternative, oil-based defoamer.

Table 35: Life cycle GWP of window sealants for IG units, silicone is compared to polyurethane and polysulfide.

	Case study no.	9
	Factor FU/kg	2.6
Sealants Windows Functional unit (FU):	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone window sealant		
Production & Transport	2.6	6.6
Silicone	2.5	6.3
Filler	0.1	0.2
Use		
End of Life	0.1	0.2
Total	**2.7**	**6.8**
Polyurethane and poysulfide window sealant		
Production & Transport	1.1	2.7
Use	130.8	335.3
End of Life	0.7	1.7
Total	**132.6**	**339.7**
Difference		
Production & Transport	1.5	3.9
Use	- 130.8	- 335.3
End of Life	- 0.6	- 1.5
Total (- ... Net-Benefit of Silicone)	**- 129.9**	**- 332.9**
Ratio Benefit / Impact	**49.8**	

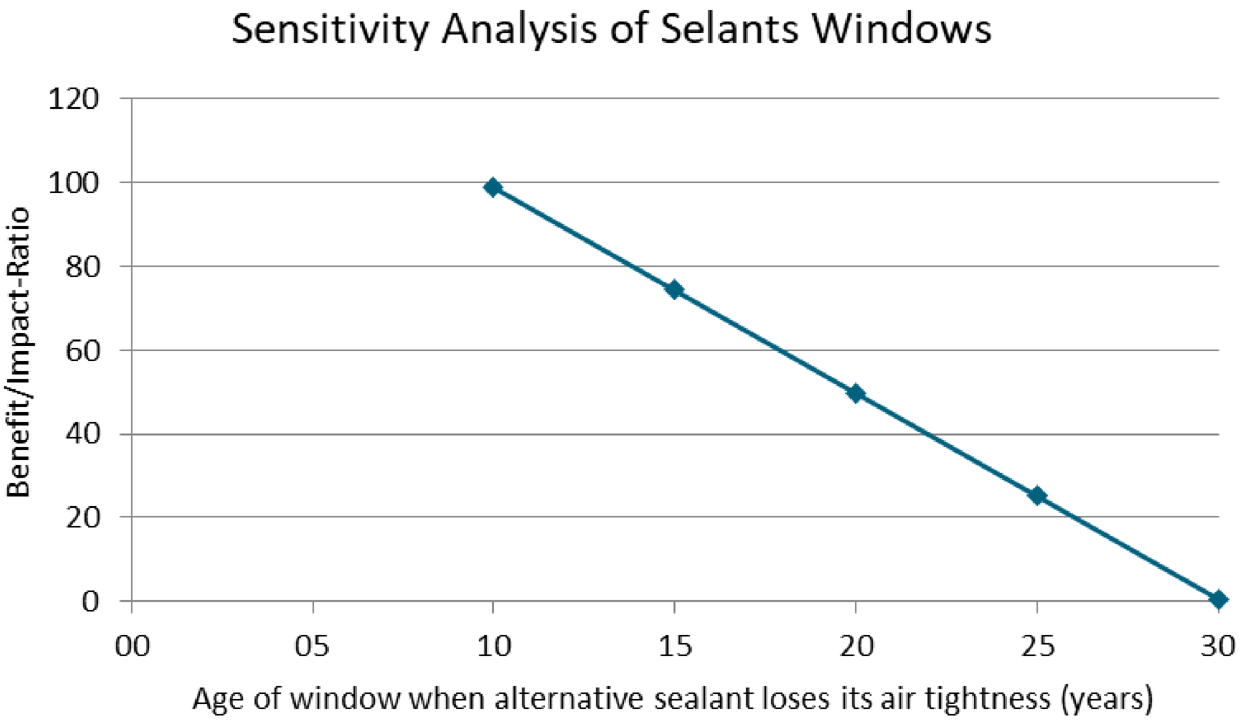

Figure 12: Benefit/impact ratio depending on the assumed lifetime of polysulfide sealant; The horizontal line shows the breakeven point at about 25.5 years.

Table 36: GWP effects of wind turbines with silicone and synthetic lubricants in 25 years of operation.

	Case study no.	10
	Factor FU/kg	0.0000851
Wind Turbines	**GWP** kg CO2 / FU	**GWP** kg CO2 / kg Silicone Product
Functional unit (FU): Functional unit: 8 MW capacity of wind power; 25 years of operation		
Silicone application: silicone lubricants		
Production & Transport	70 769	6.02
Use		
End of Life	- 385	- 0.03
Total silicone lubricants	**70 384**	**5.99**
Alternative application: synthetic lubricants		
Production & Transport	12 200	1.04
Use	26 678 200	2 270.31
End of Life	8 692	0.74
Total synthetic lubricants	**26 699 091**	**2 272.09**
Difference		
Production & Transport	58 569	4.98
Use	- 26 678 200	- 2 270.31
End of Life	- 9 077	- 0.77
Total (- … Net-Benefit of Silicone)	**- 26 628 707.3**	**- 2 266.1**
Ratio Benefit / Impact	**379.3**	

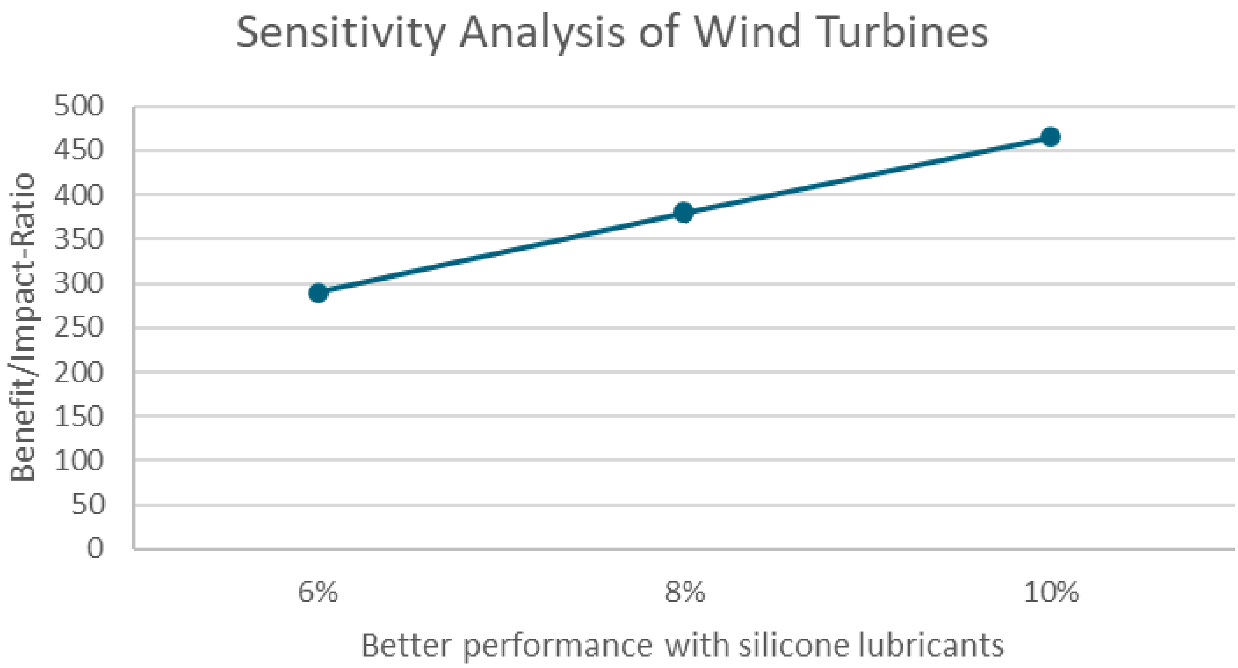

Figure 13: Sensitivity analysis of the benefit through better performance with silicone lubricants.

Table 37: Life cycle GWP of insulation material in appliances made of PU compared to insulation boards made of mineral wool.

	Case study no.	11
	Factor FU/kg	8.3
PU Additives in Appliances Functional unit (FU): 1 refrigerator with a volume of 272 litres (198l fridge, 74l freezer)	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone application		
Production & Transport	47.2	393.3
PU without Polyether Siloxane	46.1	383.8
Polyether Siloxane	0.4	3.5
Blowing Agent Pentane	0.7	6.0
Use	1 351.3	11 260.5
End of Life	3.8	31.4
Total	**1 402.2**	**11 685.2**
Alternative application		
Production & Transport	26.0	216.3
Use	2 040.6	17 005.2
End of Life		
Total	**2 066.6**	**17 221.5**
Difference		
Production & Transport	21.2	176.9
Use	- 689.4	- 5 744.7
End of Life	3.8	31.4
Total (- … Net-Benefit of PU foam slab)	**- 664.4**	**- 5 536.3**
Total (- … Net-Benefit of Silicone)	**- 6.0**	**- 50.2**
Ratio Benefit / Impact	**15.5**	

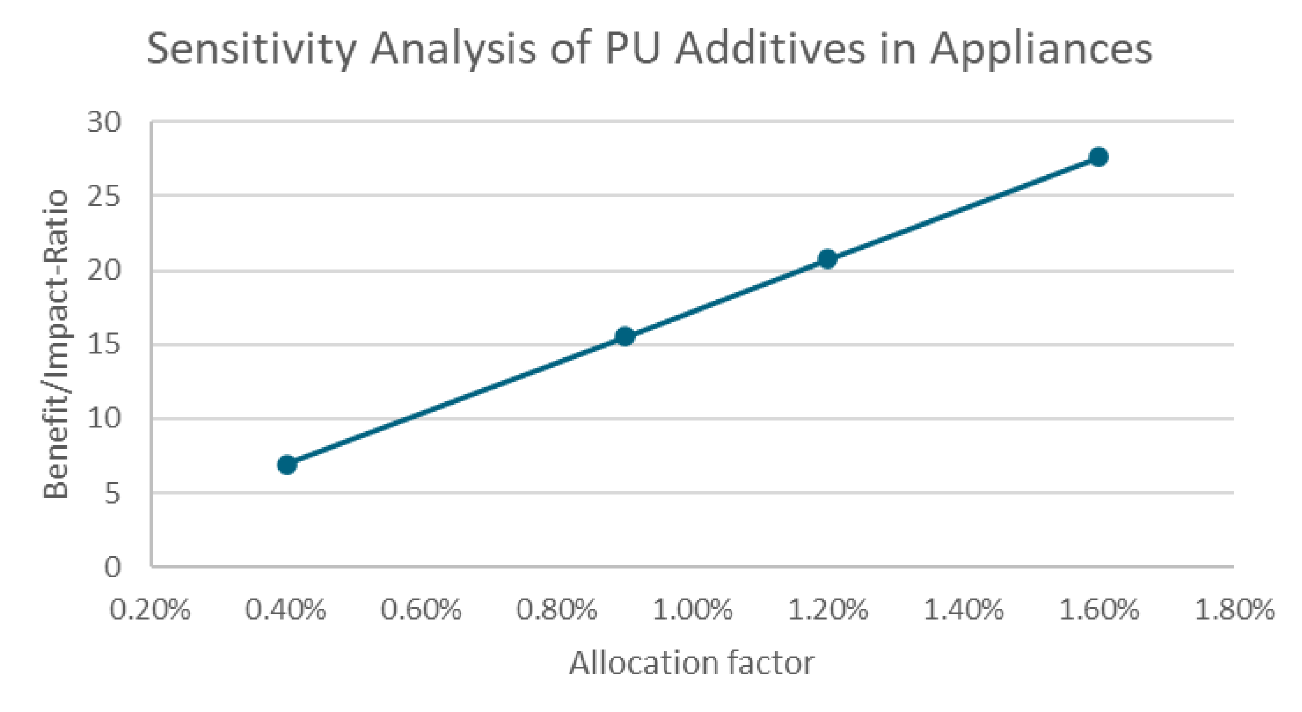

Figure 14: Sensitivity analysis of PU additives in appliances.

Table 38: Composition of silicone detergent (company data).

Silicone Detergent	Share
Organo-modified siloxane (PDMS)	0.15 %
Builders	40 %
Filler	35 %
Surfactants	9.85 %
Bleach	15 %

Table 39: Life cycle GHG emissions of silicone-based detergent compared to GHG emissions of alternative detergents.

	Case study no.	12
	Factor FU/kg	68.37606838
Antifoaming in Detergents Functional unit (FU): 100 washing cycles	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
PDMS (plus detergent)		
Production & Transport	22.3	1 521.9
Silicone defoamer (PDMS)	0.0	1.6
Surfactant = Detergent (without PDMS)	22.2	1 520.4
Use		
End of Life	2.3	158.9
Silicone defoamer (PDMS)	0.4	28.6
Surfactant = Detergent (without PDMS)	1.9	130.3
Total	**24.6**	**1 709.4**
No defoamer, more detergent, more wash loads at 60°C		
Production & Transport	33.1	2 262.2
Silicone defoamer (PDMS)		
Surfactant = Detergent (without PDMS)	33.1	2 262.2
Use	3.7	256.3
Electricity for washing	3.7	256.3
End of Life	3.2	221.0
Silicone defoamer (PDMS)		
Surfactant = Detergent (without PDMS)	3.2	221.0
Total	**40.1**	**2 739.5**
Difference		
Production & Transport	- 10.8	- 740.2
Use	- 3.7	- 256.3
End of Life	- 0.9	- 62.1
Total (- … Net-Benefit of Detergent)	**- 15.5**	**- 1 058.6**
Total (- … Net-Benefit of Silicone)	**- 1.2**	**- 105.9**
Ratio Benefit / Impact	**3.6**	

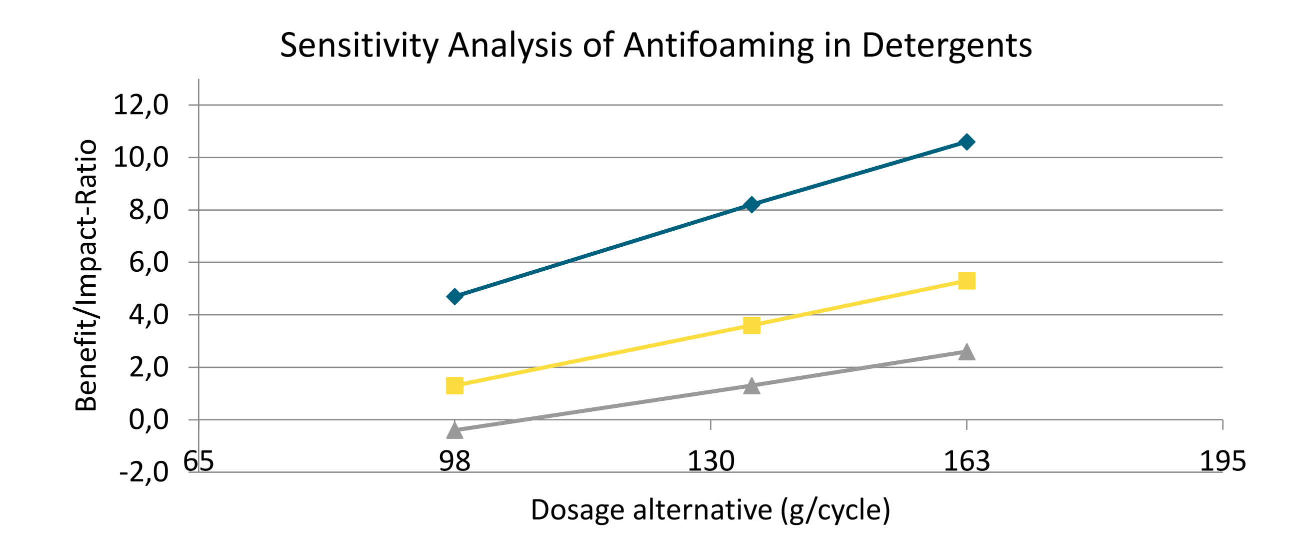

Figure 15: Benefit/impact-ratio variation with respect to the applied detergent dosage.

Table 40: Life cycle GHG emissions of silicone-based water repellent impregnation compared to GHG emissions of producing additional concrete and steel due to the shorter lifetime of bridge pillars without impregnation.

	Case study no.	13
	Factor FU/kg	0.008
Silicone-based water repellent - concrete Functional unit (FU): 1 exemplary typical bridge pillar	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Alkyl alkoxy silane impregnation		
Production & Transport	566.7	4.7
Production Silicone	566.7	4.7
Production Solvent		
Use		
End of Life	88.2	0.7
Total	**655.0**	**5.5**
Additional production of concrete and steel		
Production & Transport		
Use	7 598.5	63.3
End of Life		
Total	**7 598.5**	**63.3**
Difference		
Production & Transport	566.7	4.7
Use	- 7 598.5	- 63.3
End of Life	88.2	0.7
Total (- … Net-Benefit of Silicone)	**- 6 943.5**	**- 57.9**
Ratio Benefit / Impact	**11.6**	

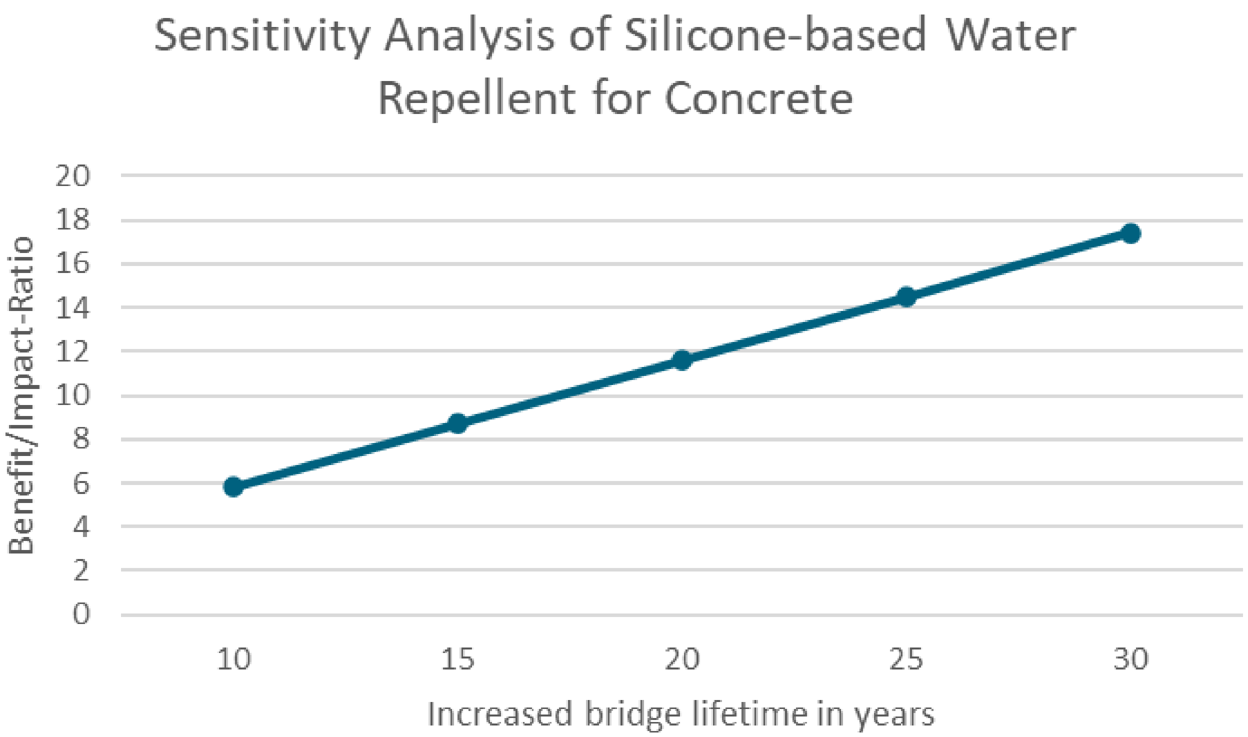

Figure 16: Variation of benefit/impact ration plotted against variable additional lifetime due to repellent impregnation.

Table 41: Life cycle GHG emissions of silicone-based impregnation for brick façades compared to GHG emissions of additional heating energy as a result of less thermal insulation without impregnation.

	Case study no.	14
	Factor FU/kg	0.05
Masonry water repellent - bricks Functional unit (FU): 100 m2 of brick facade	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone masonry water repellent for brick facades		
Production & Transport	19.2	1.0
Production Silicone	9.4	0.5
Production Solvent	9.7	0.5
Use		
End of Life	2.2	0.1
Total	**21.4**	**1.1**
No wall impregnation - additional heating energy		
Production & Transport		
Use	2 467	123.3
End of Life		
Total	**2 467**	**123.3**
Difference		
Production & Transport	19.2	1.0
Use	- 2 467.0	- 123.3
End of Life	2.2	0.1
Total (- … Net-Benefit of Masonry water repellent)	**- 2 446**	**- 122**
Total (- … Net-Benefit of Silicone)	**- 1 203**	**- 60**
Ratio Benefit / Impact	104.1	

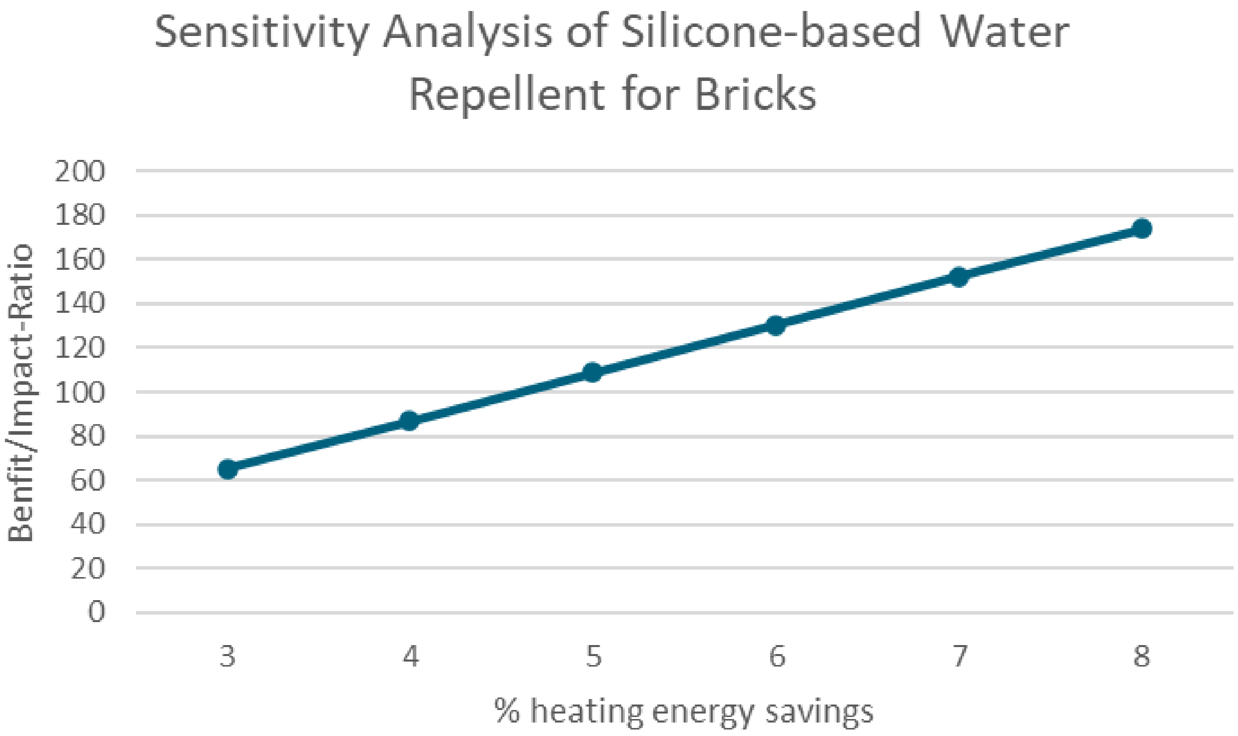

Figure 17: Variation of benefit/impact ration plotted against variable heating energy savings due to repellent impregnation.

Table 42: Life cycle GWP of conformal coatings in electronics with silicone compared to a combination of conformal coatings in electronics with acrylic and urethane components.

	Case study no.	15
	Factor FU/kg	2160.22
Conformal coatings for electronics Functional unit (FU): 100 m2 of coated surface	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone application		
Production & Transport	25.002	54 010.065
Use		
End of Life	0.000	0.586
Total	**25.002**	**54 010.651**
Alternative application		
Production & Transport	25.002	54 010.232
Use		
End of Life	0.001	2.060
Total	**25.003**	**54 012.292**
Difference		
Production & Transport	- 0.000	- 0.167
Use		
End of Life	- 0.001	- 1.473
Total (- ... Net-Benefit of Silicone)	**- 0.001**	**- 1.641**
Ratio Benefit / Impact	**1.000030**	

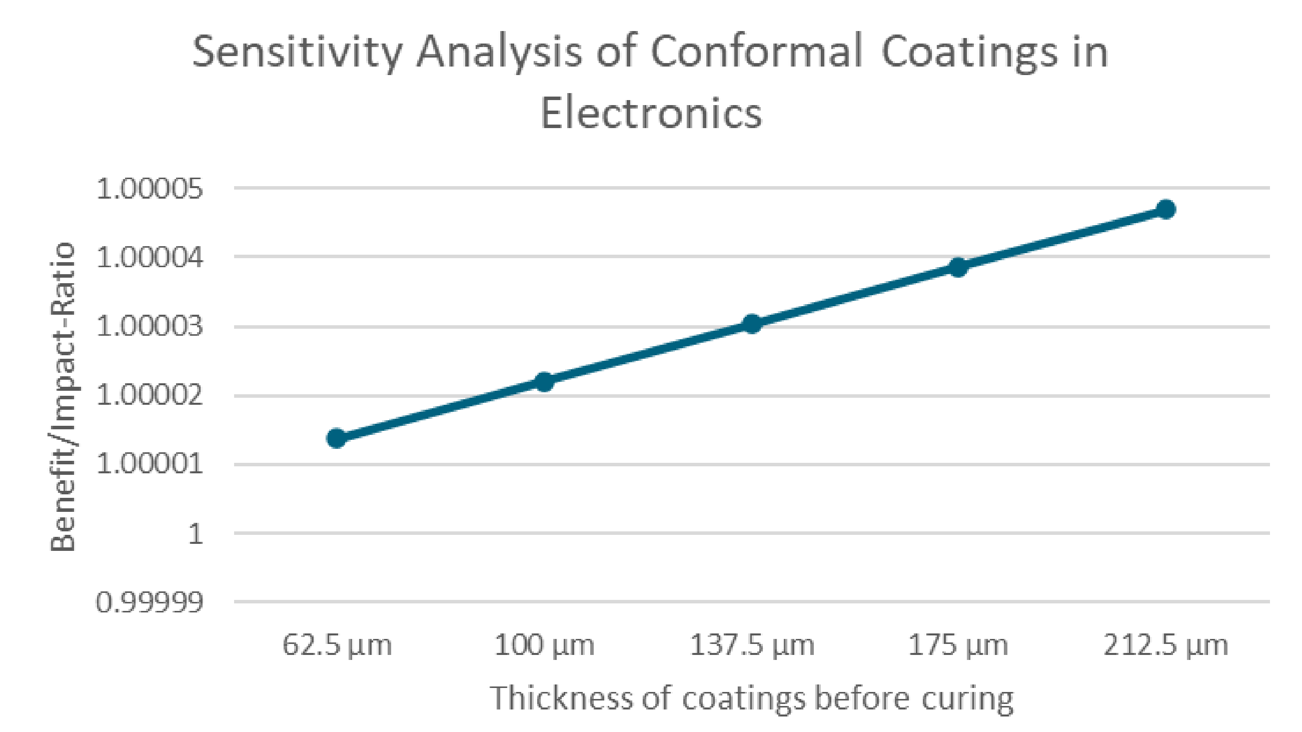

Figure 18: Sensitivity analysis of conformal coatings of electronics.

Table 43: Lifecycle GWP of silicone electrical isolators compared to a combination of ceramic and EPDM electrical isolators.

	Case study no.	16
	Factor FU/kg	0.125
Electrical Isolators Functional unit (FU): 1 isolator with 20 sheds	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Silicone isolator		
Production & Transport	20.6	2.6
Silicone	14.5	1.8
Filler	6.1	0.8
Core	10.2	1.3
Use		
End of Life	3.1	0.4
Total	**33.9**	**4.2**
Ceramic and EPDM isolator		
Production & Transport	57.4	7.2
Use		
End of Life	2.7	0.3
Total	**60.1**	**7.5**
Difference		
Production & Transport	- 36.8	- 4.6
Use		
End of Life	0.4	0.0
Total (- ... Net-Benefit of Silicone)	**- 36.4**	**- 4.5**
Ratio Benefit / Impact	**2.5**	

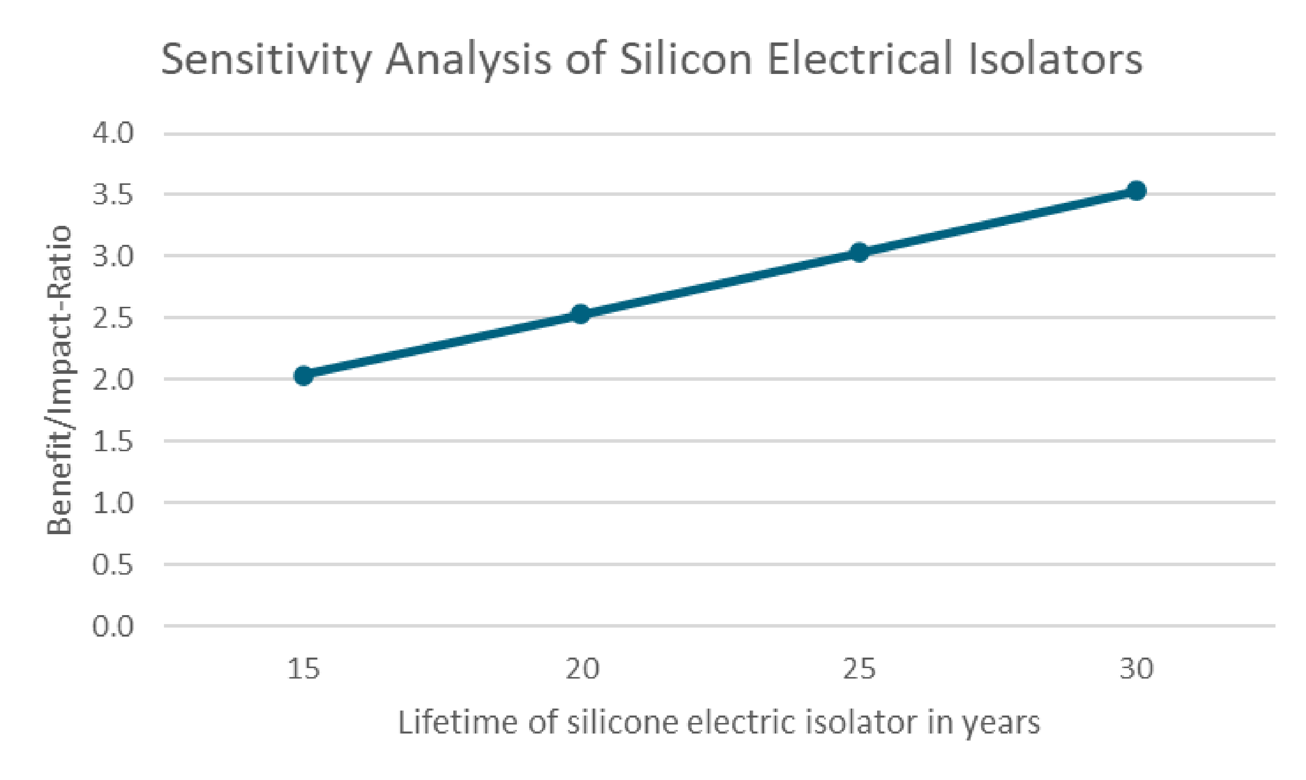

Figure 19: Sensitivity analysis of the benefit/impact ratio by lifetime expectancy.

Table 44: Life cycle GWP of heat-resistant silicone coating compared to a combination of enamelling and zinc primer.

	Case study no.	17
	Factor FU/kg	23.49
Heat-resistant industrial coatings Functional unit (FU): 1 m2 of coated surface	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Silicone resin coating for 1 m2 of steel		
Production & Transport	2.5	57.9
Use		
End of Life	0.3	6.2
Total	**2.73**	**64.10**
Zinc coating/enamelling for 1 m2 of steel		
Production & Transport	5.7	133.5
Use	7.3	171.6
End of Life	0.06	1.5
Total	**13.05**	**306.5**
Difference		
Production & Transport	- 3.2	- 75.6
Use	- 7.3	- 171.6
End of Life	0.20	4.7
Total (- … Net-Benefit of Silicone)	**- 10.3**	**- 242.4**
Ratio Benefit / Impact	**4.8**	

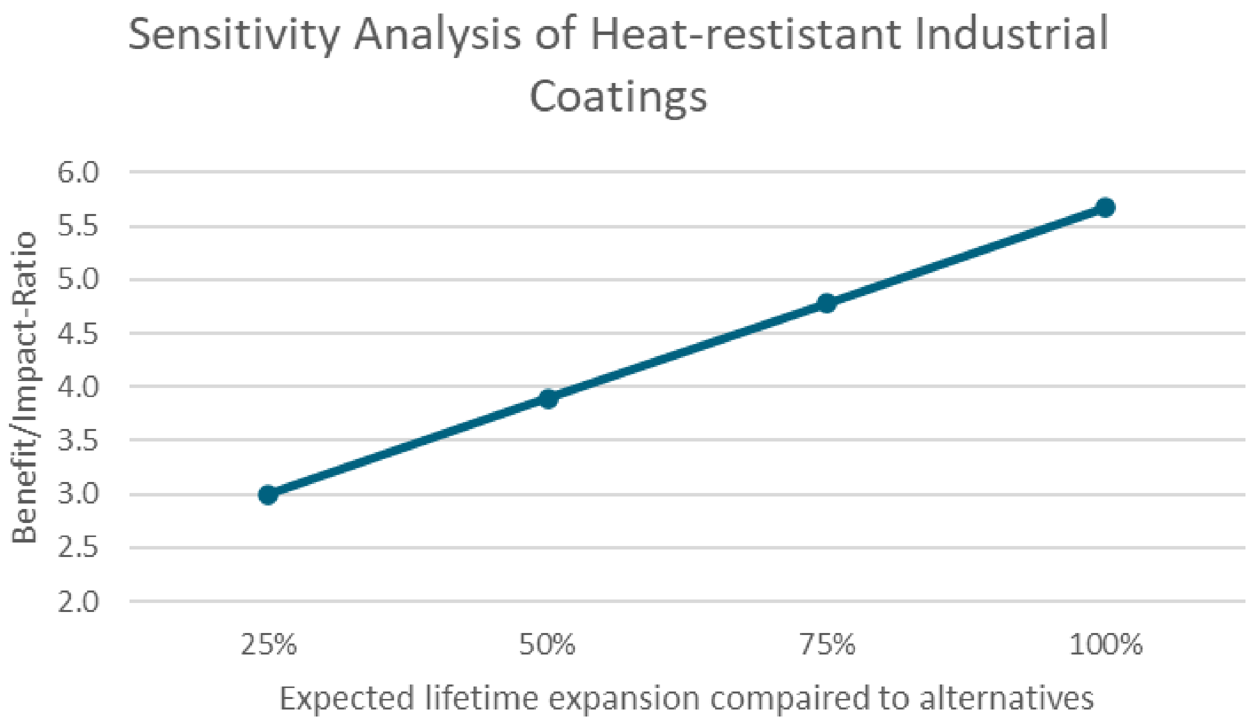

Figure 20: Sensitivity analysis of the benefit/impact ratio by expected lifetime expansion.

Table 45: Life cycle GWP of silicone foam compared to a combination of PU foam and EPDM.

	Case study no.	18
	Factor FU/kg	0.001
Silicone foam for thermal insulation Functional unit (FU):	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Silicone application		
Production & Transport	6 203.9	6.5
Use		
End of Life	63.6	0.1
Total	**6 267.5**	**6.5**
Alternative application		
Production & Transport	9 441.1	9.8
Use		
End of Life	2 971.53	3.10
Total	**12 412.6**	**12.9**
Difference		
Production & Transport	- 3 237.2	- 3.4
Use		
End of Life	- 2 907.93	- 3.03
Total (- … Net-Benefit of Silicone)	**- 6 145.2**	**- 6.4**
Ratio Benefit / Impact	**2.0**	

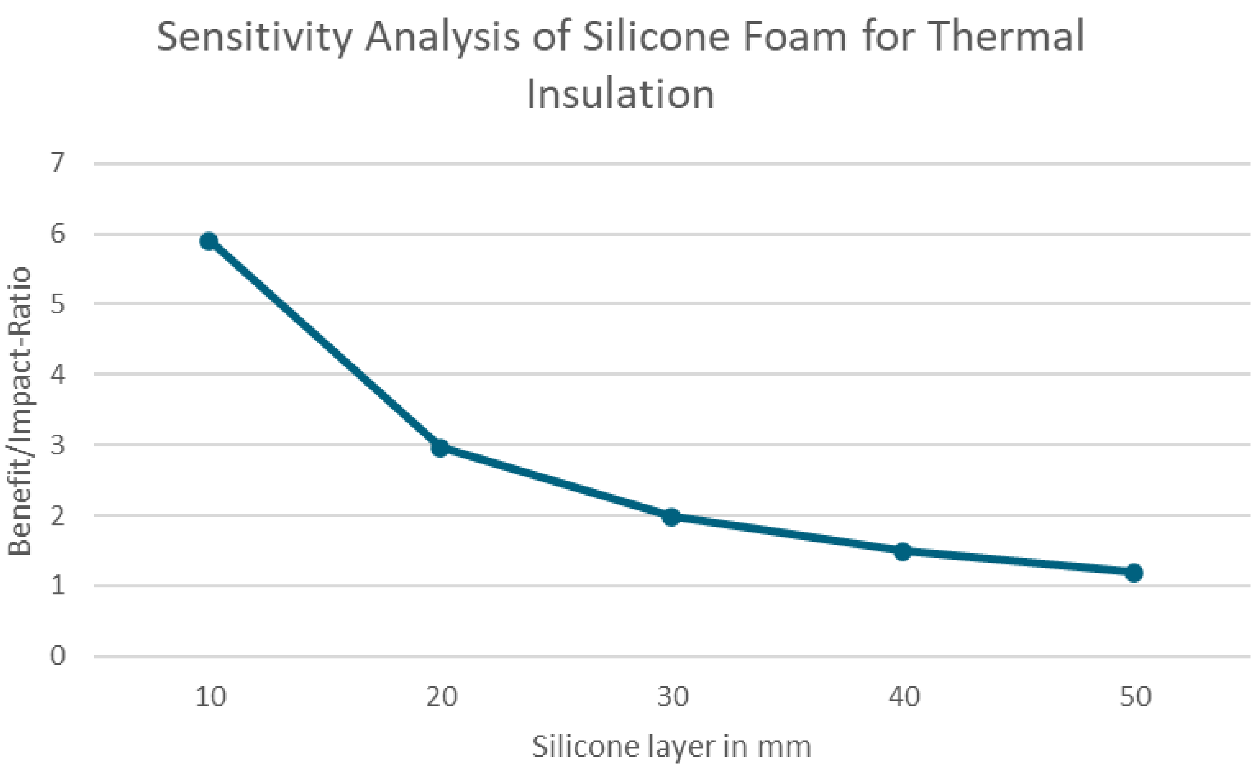

Figure 21: Sensitivity analysis of GHG-emission savings due to the use of silicone foam at variable layer thickness.

Table 46: Life cycle GWP of silicone-based adhesion promoter.

	Case study no.	19
	Factor FU/kg	10.0
Adhesion promoter for coatings Functional unit (FU): 100 m2 of coated substrate	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Adhesion promoter applied		
Production & Transport	0.3	2.8
Silicone adhesion promoter (Alkoxysilane)	0.3	2.7
Solvent (Methanol; without alkoxysilane)	0.0	0.2
Use	76.8	768.1
End of Life		
Total	**77.1**	**771.0**
No adhesion promoter, earlier repainting		
Production & Transport		
Use	115.3	1 153.2
End of Life		
Total	**115.3**	**1 153.2**
Difference		
Production & Transport	0.3	2.8
Use	- 38.5	- 385.1
End of Life		
Total (- … Net-Benefit of Paint with adhesion promoter)	**- 38.2**	**- 382.2**
Total (- … Net-Benefit of Silicone)	**- 35.9**	**- 359.4**
Ratio Benefit / Impact	**136.5**	

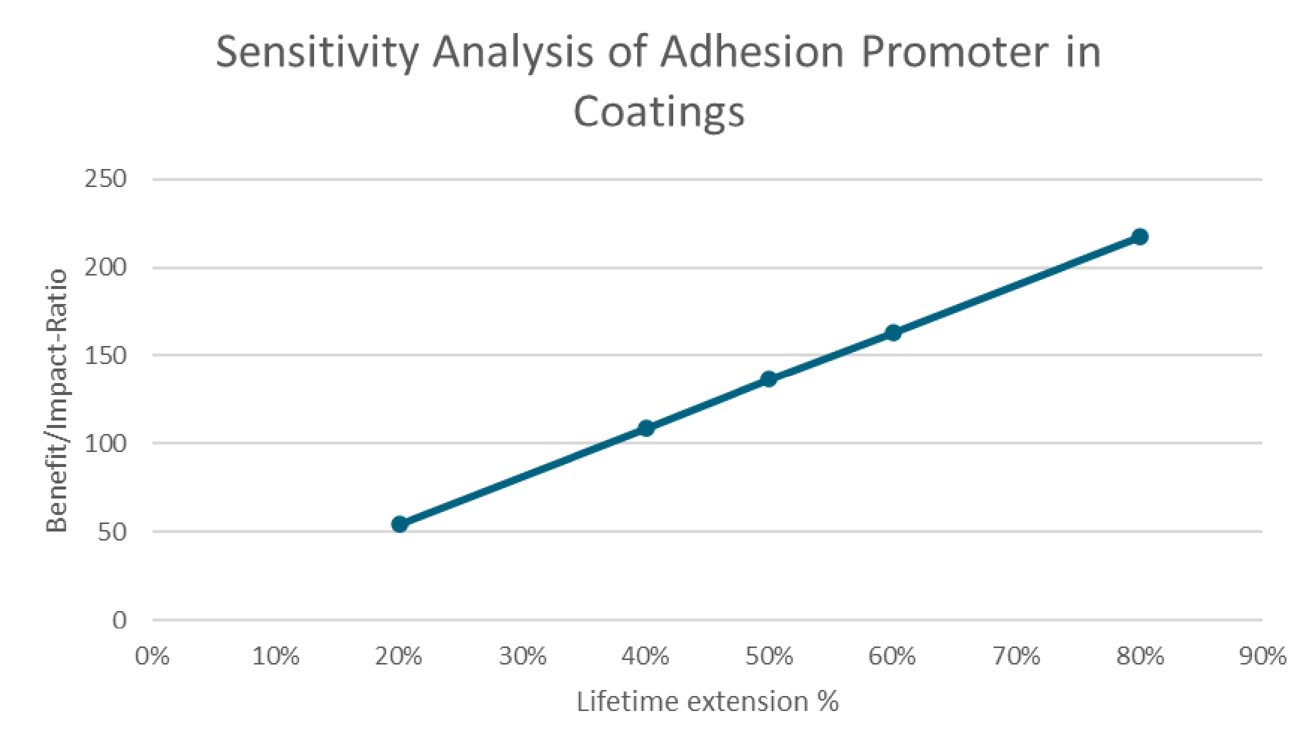

Figure 22: Sensitivity analysis of coating lifetime extension due to the application of a silicone-based adhesion promoter.

Table 47: GWP effects of marine antifouling coating made from silicone resin.

	Case study no.	**20**
	Factor FU/kg	0.00020
Coating of means of transport, anti fouling coatings	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Functional unit (FU): Silicone in anti fouling coatings applied to 5% of marine fleet, 1 year		
Silicone antifouling coating		
Production & Transport	92 999 777	8
Silicone	81 437 660	7
Solvent	11 562 118	1
Use		
End of Life		
Total	**92 999 777**	**8**
No antifouling coating		
Production & Transport		
Use	5 651 558 525	464
End of Life		
Total	**5 651 558 525.3**	**463.8**
Difference		
Production & Transport	92 999 777	8
Use	- 5 651 558 525	- 464
End of Life		
Total (- … Net-Benefit of Silicone)	**- 5 558 558 748.0**	**- 456.2**
Ratio Benefit / Impact	**60.8**	

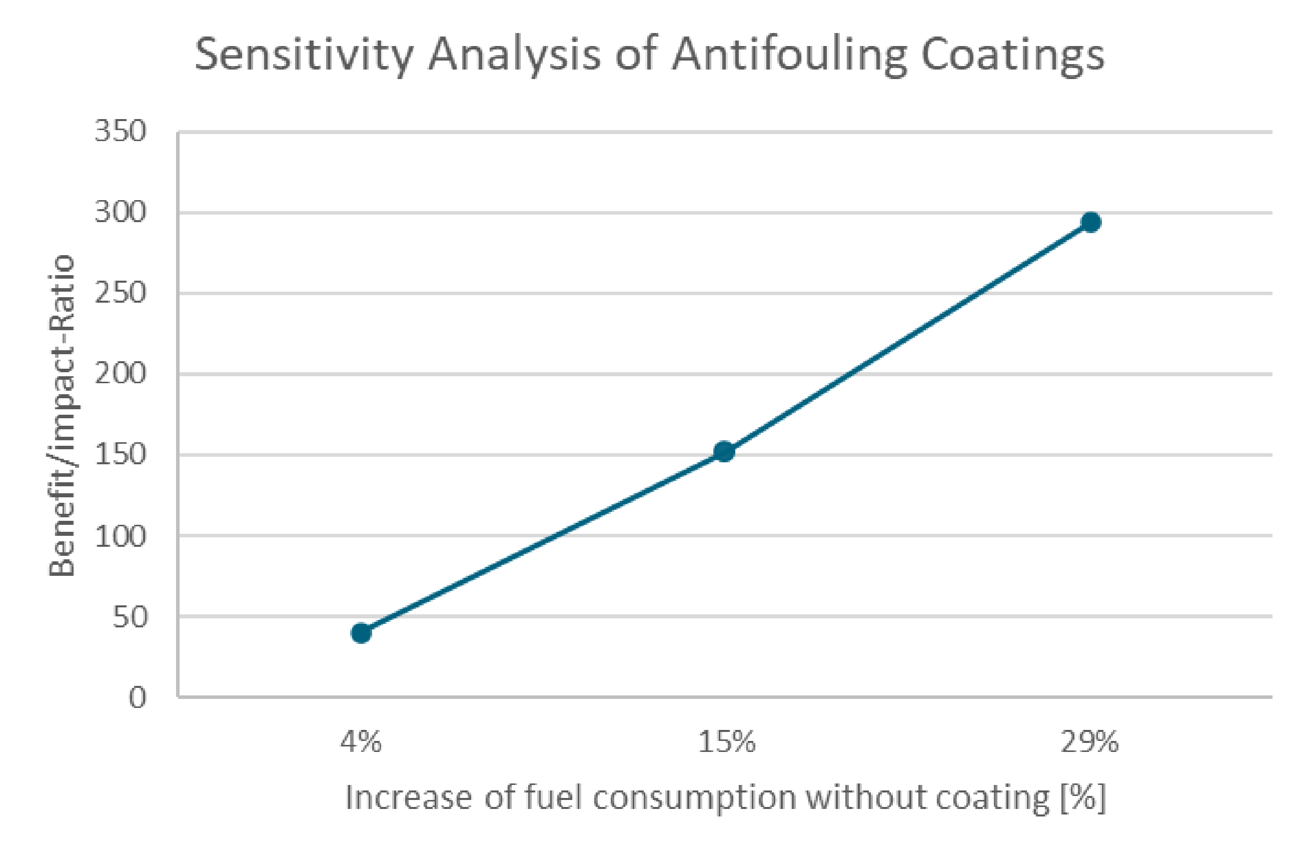

Figure 23: Sensitivity analysis of fuel savings due to the application of silicone antifouling coatings.

Table 48: Passenger cars in use and respective share of petrol and diesel fleet in studied regions.

2019	EU[35,36]	NA [37,38]	JP [39,40]
Passenger cars in use	326.8 mln.	108.5 mln.	61.7 mln.
Petrol car share	52.90 %	96.00 %	96.00 %
Diesel car share	42.3 %	4.00 %	0.10 %

[35] ACEA. (2021). Passenger car fleet by fuel type, European Union. Retrieved from https://www.acea.auto/figure/passenger-car-fleet-by-fuel-type/ 08/2021.

[36] Retrieved from https://www.acea.auto/files/ACEA_Report_Vehicles_in_use-Europe_2019.pdf (accessed 01/22)

[37] U.S. Department of transportation. (2015). Diesel-powered Passenger Cars and Light Trucks. Retrieved from https://www.bts.dot.gov/sites/bts.dot.gov/files/legacy/DieselFactSheet.pdf (accessed 11/21)

[38] Timmons, M. (2021). Car Ownership Statistics: How Many People Own a Car in the US?. Retrieved from https://www.valuepenguin.com/auto-insurance/car-ownership-statistics (accessed 01/22)

[39] Kato, Y., Koyama, M., Fukushima, Y., & Nakagaki, T. (2016). Energy Technology Roadmaps of Japan: Future Energy Systems Based on Feasible Technologies Beyond 2030 (1st ed. 2016 ed.). Springer.

[40] Statista. (2022). Number of passenger cars in use in Japan from 2012 to 2021. Retrieved from https://www.statista.com/statistics/911570/japan-passenger-cars-in-use-numbers/#:~:text=As %20of %20March %2031 %2C %202021,over %2082 %20million %20in %202021. (accessed 01/22)

Table 49: GWP impact of a PDMS based pipe hanger and underbody cover.

	Case study no.	21
	Factor FU/kg	5.03
Electric transport Functional unit (FU): 1 PHEV over the life time of 240000 km (8y)	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
PHEV with silicone pipehanger and underbody cover		
Production & Transport	55.8	280.9
Silicone	1.3	6.7
PP injection molded undercover	54.5	274.2
Use		
End of Life	19.3	96.9
Total	**75.1**	**377.8**
PHEV with EPDM pipehanger		
Production & Transport	0.5	2.7
Use	748.5	3 764.5
End of Life	0.2	1.0
Total	**749.2**	**3 768.2**
Difference		
Production & Transport	55.3	278.1
Use	- 748.5	- 3 764.5
End of Life	19.1	95.9
Total (- … Net-Benefit of Product)	**- 674.1**	**- 3 390.4**
Total (- … Net-Benefit of Silicone)	**- 16.5**	**- 80.7**
Ratio Benefit / Impact	**13.4**	

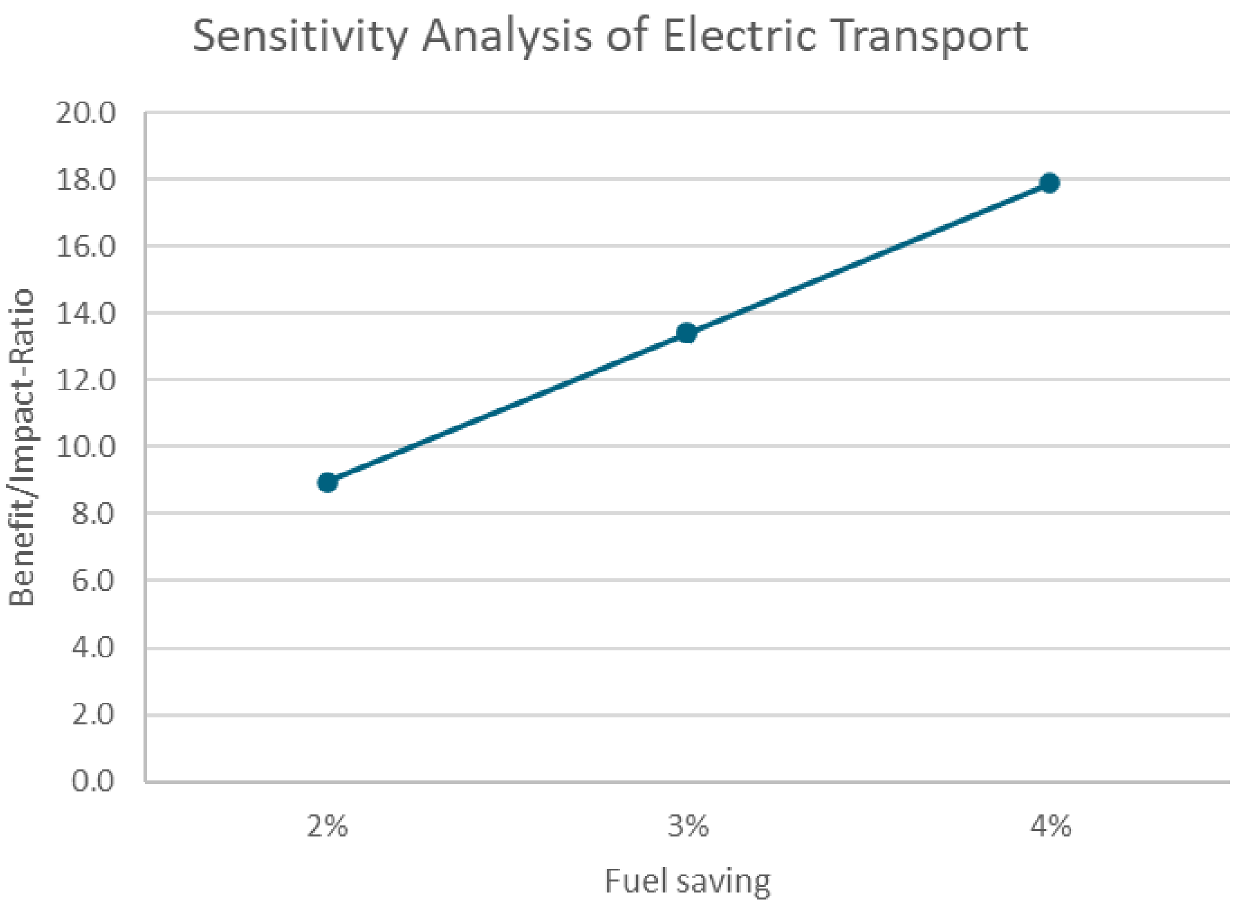

Figure 24: Sensitivity analysis of the benefit/impact ratio by percentage of saved fuel.

Table 50: Life cycle GHG emissions of automotive glazing made of polycarbonate and coated with silicone resin.

	Case study no.	22
	Factor FU/kg	240
Coating for polycarbonate	**GWP kg CO2 / FU**	**GWP kg CO2 / kg Silicone Product**
Functional unit (FU): Automotive glazing of 20,8 dm^2 (made from 1 kg polycarbonate) and lifetime		
PC automotive glazing + silicon resin coating		
Production & Transport	8.3	1 981.2
Production PC glazing	8.1	1 950.5
Silicone resin production + curing/baking of coating	0.1	18.1
Transport PC and Silicone	0.1	12.6
Use		
End of Life	1.4	344.3
Total	**9.7**	**2 325.6**
Glass automotive glazing of 20,8 dm^2		
Production & Transport	2.3	564.0
Production & Transport Glass	2.3	564.0
Use	19.6	4 712.8
End of Life		
Total	**22.0**	**5 276.8**
Difference		
Production & Transport	5.9	1 417.3
Use	- 19.6	- 4 712.8
End of Life	1.43	344.31
Total (- … Net-Benefit of Product)	**- 12.3**	**- 2 951.3**
Total (- … Net-Benefit of Silicone)	**- 0.1**	**- 30.1**
Ratio Benefit / Impact	**2.7**	

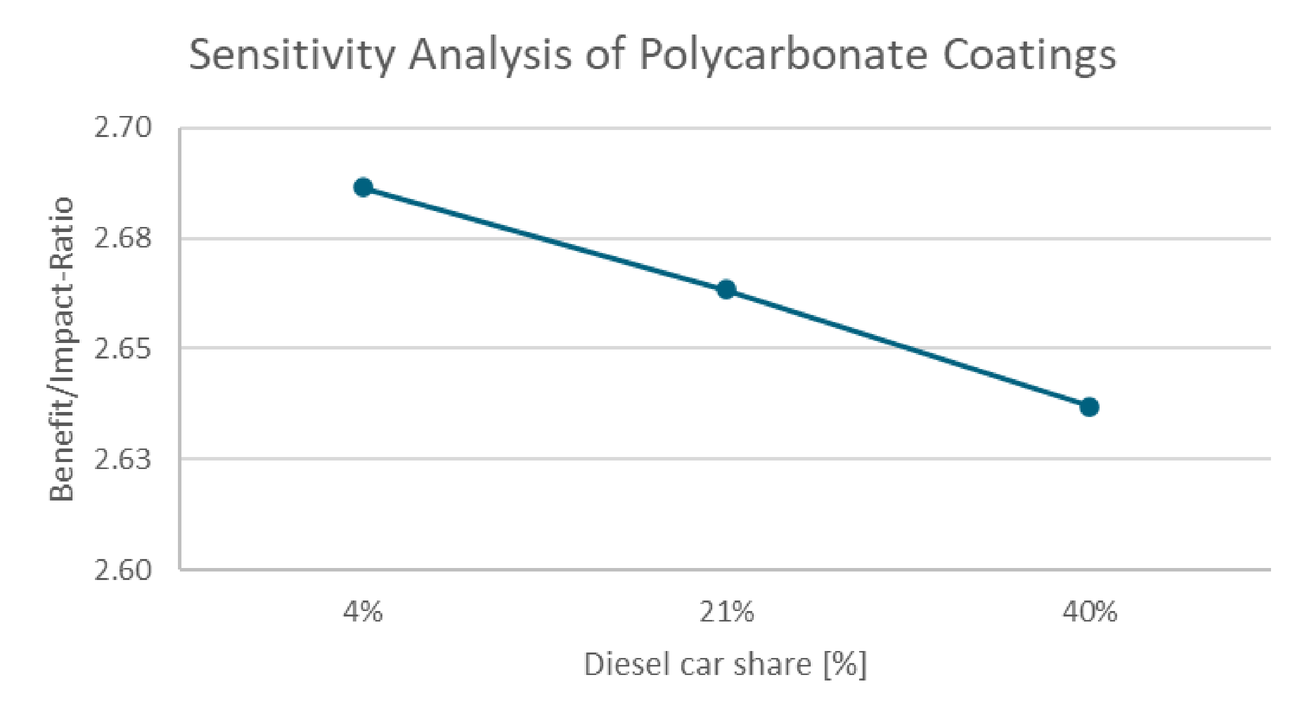

Figure 25: Sensitivity analysis of the share of diesel cars and the benefit of polycarbonate coatings.

Table 51: Mass of material input to primary construction.

Constructive Element	Material	Lifespan	Mass (t)
Insulation	Polystyrene	10	1.18
Prot. layer	Glass fiber	10	0.1
Membrane	PVC	10	0.9
Prot. layer	Glass fiber	10	0.1
Protection	Gravel	50	78
Vapour barrier	Polyethylene	10	0.7

Table 52: Life cycle GWP of a silicone based and a PU based reflective roof coating.

	Case study no.	23
	Factor FU/kg	0.01
Reflective Roof Coatings Functional unit (FU): 100 m2 of coated surface over 17 y	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Silicone based coating		
Production & Transport	500.4	4.5
Use		
End of Life	451.0	4.1
Total	**951.4**	**8.6**
PU based coating		
Production & Transport	675.2	6.1
Use	1 007.9	9.1
End of Life	638.9	5.8
Total	**3 289.4**	**21.0**
Difference		
Production & Transport	- 174.8	- 1.6
Use	- 1 007.9	- 9.1
End of Life	- 187.9	- 1.7
Total (- … Net-Benefit of Silicone)	**- 1 370.5**	**- 12.4**
Ratio Benefit / Impact	**2.4**	

Table 53: Replacement factor for sensitivity analysis of reflective roof coating.

Silicone application (yrs.)	Alternative application (yrs.)	Replacement factor	Benefit/Impact ratio
10	8	1.25	1.6
17	12	1.42	2.4
25	15	1.67	4.1

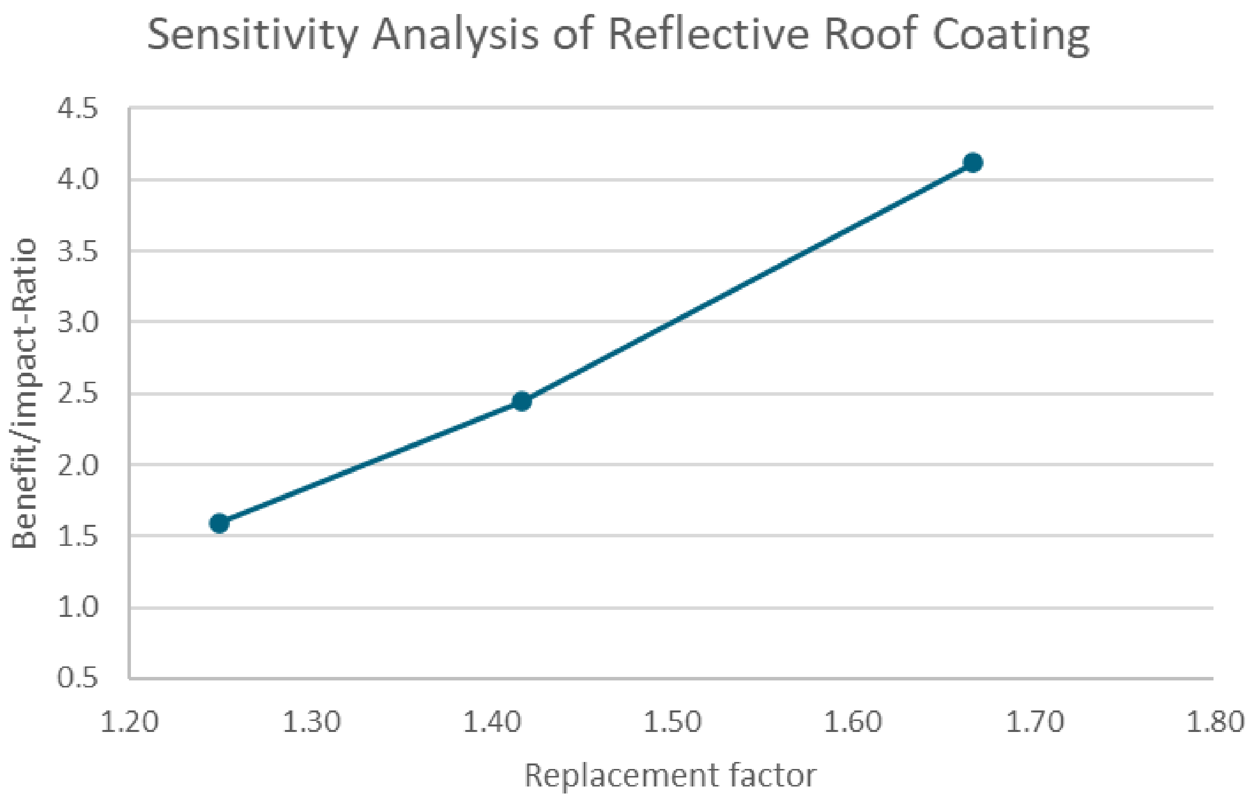

Figure 26: Sensitivity analysis of the lifetime (y) of reflective roof coating.

Table 54: Disposal of PU insulation panels in studied markets.

	EU	North America	Japan
Residual waste	20%	20%	20%
of which incineration	*53%*	*19%*	*100%*
of which landfill	*47%*	*81%*	*0%*
Building rubble	60%	60%	60%
of which incineration	*20%*	*20%*	*20%*
of which landfill	*80%*	*80%*	*80%*
Not entering waste management system (remain at site)	20%	20%	20%

Table 55: Lifecycle GWP of 100m² insulation equivalent to 8 cm PU.

	Case study no.	24
	Factor FU/kg	0.520833333
PU Additives for Thermal Insulation in Construction Functional unit (FU): 100m2 insulation equivalent to 8cm PU	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone**
Insulation boards made of PU		
Production & Transport	931.3	485.0
PU without Polyether Siloxane	925.0	481.8
Polyether Siloxane	6.2	3.3
Blowing Agent Pentane	20.1	10.5
Use	12.3	6.4
End of Life	193.9	101.0
Total	**1 137.4**	**592.4**
Insulation boards made of XPS and foamglass		
Production & Transport	1 939.4	1 010.1
Use	808.8	421.3
End of Life	618.2	322.0
Total	**3 366.4**	**1 753.3**
Difference		
Production & Transport	- 1 008.1	- 525.1
Use	- 796.5	- 414.9
End of Life	- 424.3	- 221.0
Total (- … Net-Benefit of PU foam slab)	**- 2 229.0**	**- 1 160.9**
Total (- … Net-Benefit of Silicone)	**- 16.3**	**- 8.5**
Ratio Benefit / Impact	**3.6**	

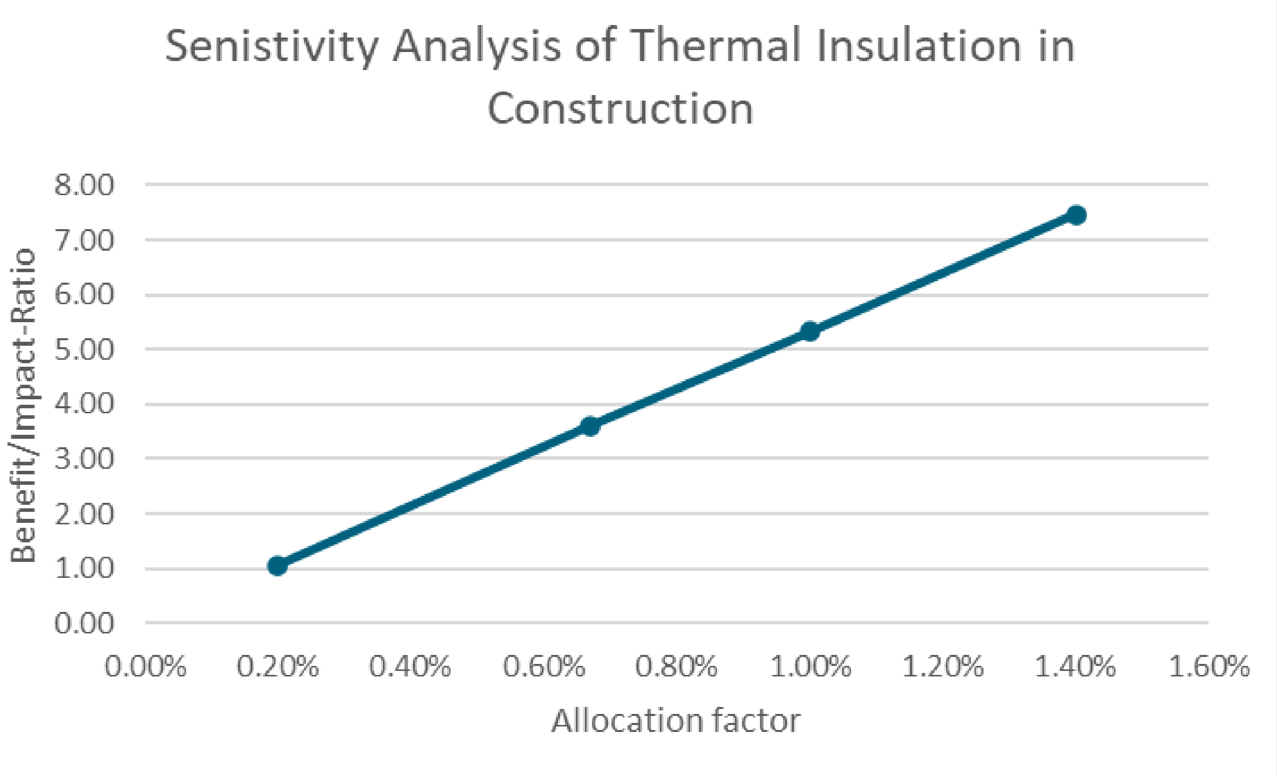

Figure 27: Sensitivity analysis of thermal insulation in construction.

Table 56: Lifecycle GWP of a silicone-based TIM and a polyolefin-based TIM.

	Case study no.	25
	Factor FU/kg	6666.7
Telecommunication Functional unit (FU): 1 piece smartphone over the lifetime of 3 y	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**
Silicone based TIM		
Production & Transport	0.00042	2.8
Use		
End of Life	0.00003	0.2
Total	**0.00045**	**3.0**
Polyolefin based TIM		
Production & Transport	0.00027	1.8
Use	0.07182	478.8
End of Life	0.00009	0.6
Total	**0.07218**	**481.2**
Difference		
Production & Transport	0.00015	1.0
Use	- 0.07182	- 478.8
End of Life	- 0.00006	- 0.4
Total (- … Net-Benefit of Silicone)	**- 0.07174**	**- 478.3**
Ratio Benefit / Impact	**161.9**	

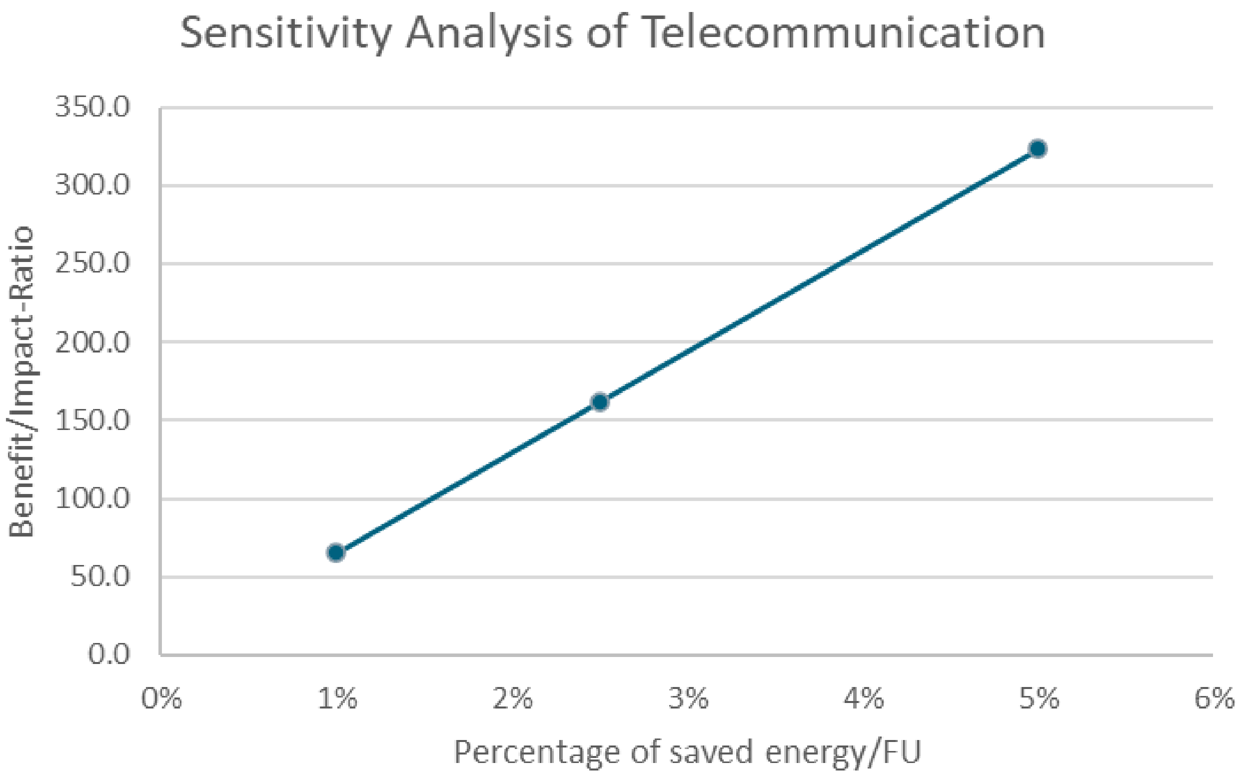

Figure 28: Sensitivity analysis of the benefit/impact ratio by percentage of saved energy.

Table 57: Lifecycle GWP of cooling liquid in transformers.

	Case study no.	26
	Factor FU/kg	0.001
Cooling Liquid in Transformers Functional unit (FU): Cooling liquid for 2.5 MW transformer, 60 years	**GWP** **kg CO2eq / FU**	**GWP** **kg CO2eq / kg Silicone Product**
Silicone fluid		
Production & Transport	6 022.4	6.0
Use		
End of Life	- 36.4	- 0.0
Total	**5 986.05**	**5.99**
Mineral oil, additional building		
Production & Transport	3 431.9	3.4
Use	9 088.4	9.1
End of Life	2 352.1	2.4
Total	**14 872.4**	**14.9**
Difference		
Production & Transport	2 590.6	2.6
Use	- 9 088.4	- 9.1
End of Life	- 2 388.5	- 2.4
Total (- ... Net-Benefit of Silicone)	**- 8 886.3**	**- 8.9**
Ratio Benefit / Impact	**2.5**	

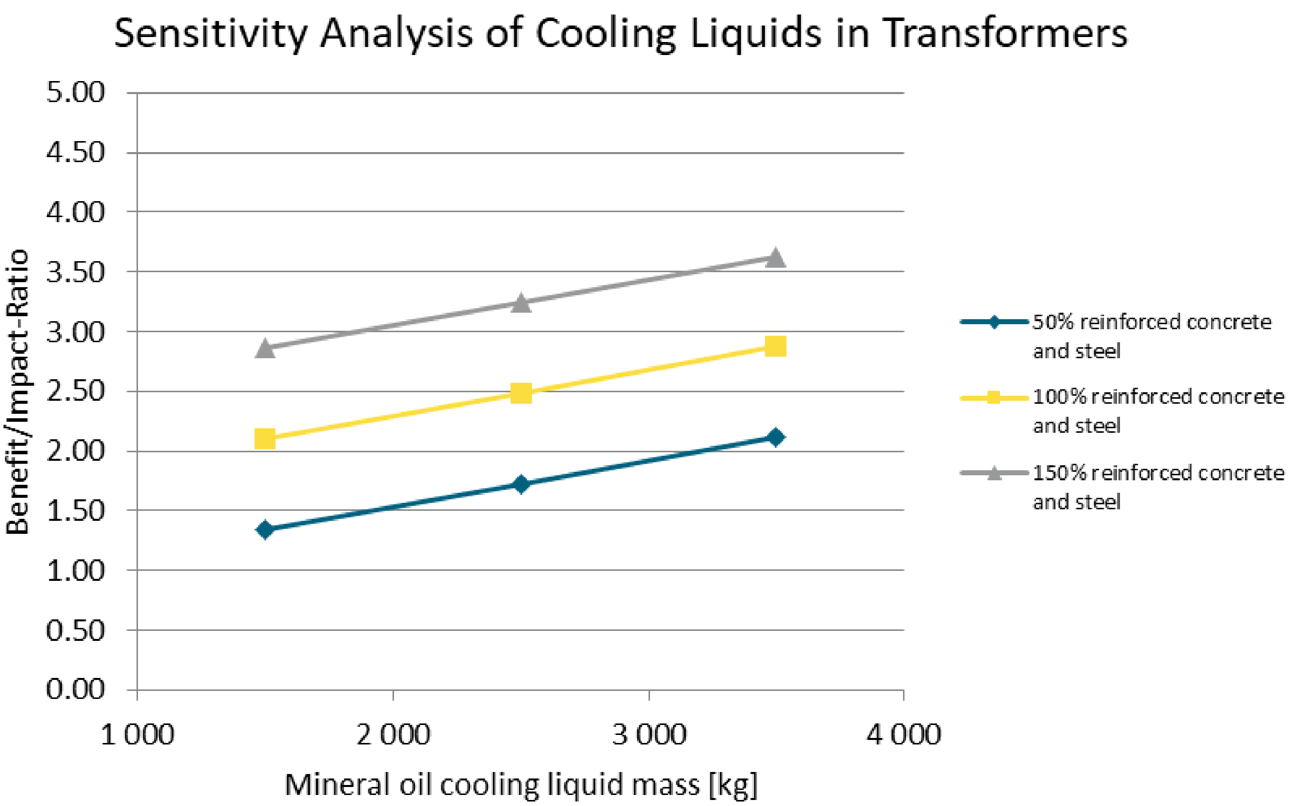

Figure 29: Sensitivity analysis of the benefit/impact ratio by mineral oil cooling liquid mass.

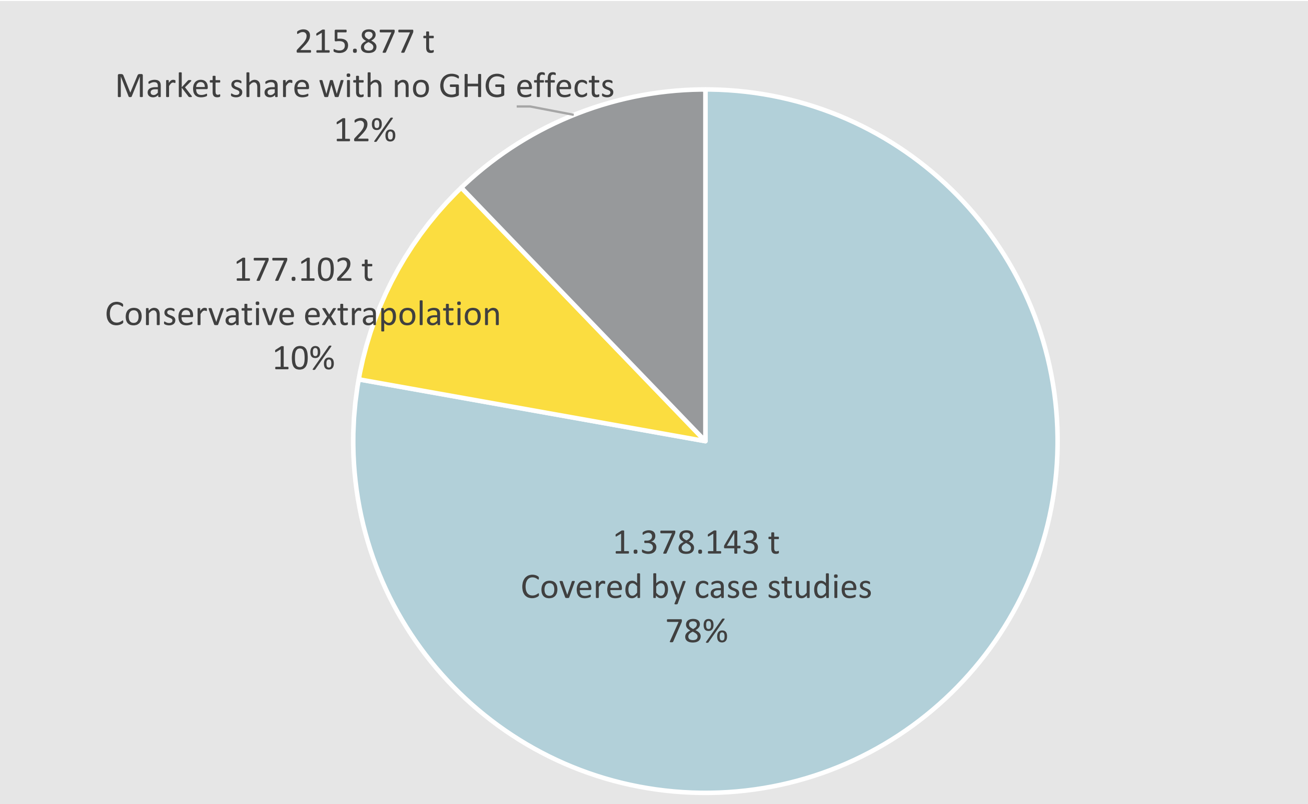

Figure 30: The share of silicon market covered by case studies.

Table 58: Extrapolation of carbon balance to the total market volume

Name of Case Study	Market volumes (t/a)	Benefit/ impact ratio	Absolute GHG net-benefits
Automotive Bonding	9.970	21,3	-1.272
Batteries/Energy Storage	3.312	28,3	-1.369
Chlorosilane for Solar Grade Silicon	787.020	9,9	-18.289
Energy efficient lighting – LEDs	2.158	2,0	-24.165
Engine Performance, Rubber in Motor Construction	31.550	130,8	-26.312
Green Tyres	49.000	38,7	-11.226
High Quality Sealants & Adhesives	120.570	12,2	-5.182
Industrial applications in pulp industry, Anti-foaming in Pulp Production	14.663	83,5	-2.107
Sealants Windows IG unit	109.886	49,8	-36.578
Wind Turbines	1.842	379,3	-4.174
PU Additives for thermal Insulation in Appliances	7.750	15,5	-4
Antifoaming in Detergents	842	3,6	-89
Masonry Water Repellent - bricks	11.317	104,1	-68
Masonry Water Repellent - concrete	15.332	11,6	-887
Conformal coatings in electronics	1.859	1,0	-1
Electrical Isolators & Insulations	11.000	2,5	-50
Heat-Resistant Industrial Coatings	3.450	2,6	-360
Silicone foam for thermal insulation	28.087	2,0	-180
Adhesion Promoter for Coatings	845	136,5	-243
Coating of means of transport, anti fouling coatings	24.371	60,8	-11.117
Electric transport (bycicle, electric and hybrid cars, train)	40.390	13,4	-3.258
Lighter automative parts, Coating for Polycarbonate	11.940	2,7	-360
Reflective roof coatings	68.320	2,4	-847
PU Additives Insulation-Construction	20.570	3,6	-1
Telecommunication	81	161,9	-39
Cooling Liquid in Transformers, LSR as insulating materials in cables	2.018	2,5	-18
Sum of case studies	**1.378.143**	**19,6**	**-148.196**
GHG benefits not covered by examples	177.000	13,0	-12.610
Application without GHG benefits	215.877	0,0	1.398
Total market	**1.771.020**	**16,5**	**-159.410**

Table 59: MIN and MAX result values of case studies benefit-impact ratio based on sensitivity analyses and the MIN and MAX values for net-benefit of silicone product and uncertainty in absolute GHG net-benefits.

Name of Case Study	Benefit/ impact ratio - MIN	Benefit/ impact ratio - MAX	Market volumes (t/a)	Benefit/ impact ratio	MIN Net benefit of silicone product (kg CO2e/kg)	MAX Net benefit of silicone product (kg CO2e/kg)	Absolute GHG net-benefits - MIN (1000 t CO2e)	Absolute GHG net-benefits - MAX (1000 t CO2e)
Automotive Bonding	6,4	32,0	9.970	21,3	-38,3	-191,3	-381	-1.907
Batteries/Energy Storage	13,1	47,9	3.312	28,3	-182,8	-709,9	-606	-2.351
Chlorosilane for Solar Grade Silicon	8,8	24,4	787.020	9,9	-20,7	-57,5	-16.274	-45.283
Energy efficient lighting – LEDs	1,5	5,0	2.158	2,0	-5.597,5	-44.787,5	-12.081	-96.666
Engine Performance, Rubber in Motor Construction	64,9	196,7	31.550	130,8	-413,9	-1.254,1	-13.057	-39.567
Green Tyres	23,6	57,6	49.000	38,7	-137,2	-391,6	-6.724	-19.188
High Quality Sealants & Adhesives	8,7	15,7	120.570	12,2	-29,8	-56,5	-3.593	-6.809
Industrial applications in pulp industry, Anti-foaming in Pulp Production	52,9	175,3	14.663	83,5	-90,4	-303,6	-1.325	-4.451
Sealants Windows IG unit	25,2	74,4	109.886	49,8	-165,2	-500,6	-18.157	-55.004
Wind Turbines	289,9	465,5	1.842	379,3	-1.730,7	-2.781,6	-3.188	-5.124
PU Additives for thermal Insulation in Appliances	6,9	27,6	7.750	15,5	-20,4	-91,9	-2	-7
Antifoaming in Detergents	-0,4	10,6	842	3,6	14,6	-318,0	12	-268
Masonry Water Repellent - bricks	65,2	173,9	11.317	104,1	-37,5	-100,9	-42	-114
Masonry Water Repellent - concrete	5,8	17,4	15.332	11,6	-26,2	-89,5	-402	-1.373
Conformal coatings in electronics	1,0	1,0	1.859	1,0	-1,6	-1,6	-1	-1
Electrical Isolators & Insulations	2,0	3,5	11.000	2,5	-3,1	-7,5	-34	-82
Heat-Resistant Industrial Coatings	2,6	5,7	3.450	2,6	-104,2	-299,6	-360	-1.034
Silicone foam for thermal insulation	1,2	5,9	28.087	2,0	-1,2	-32,0	-35	-900
Adhesion Promoter for Coatings	54,5	217,2	845	136,5	-142,5	-576,2	-96	-389
Coating of means of transport, anti fouling coatings	40,5	293,7	24.371	60,8	-301,6	-2.234,0	-7.349	-54.446
Electric transport (bycicle, electric and hybrid cars, train)	8,9	17,9	40.390	13,4	-50,8	-110,5	-2.052	-4.464
Lighter automative parts, Coating for Polycarbonate	2,7	2,6	11.940	2,7	-30,6	-29,7	-365	-354
Reflective roof coatings	1,6	4,1	68.320	2,4	-5,1	-26,8	-349	-1.834
PU Additives Insulation-Construction	1,1	7,5	20.570	3,6	-0,2	-21,1	0	-3
Telecommunication	65,2	322,9	81	161,9	-191,0	-851,9	-16	-69
Cooling Liquid in Transformers, LSR as insulating materials in cables	1,3	3,6	2.018	2,5	-2,0	-15,7	-4	-32

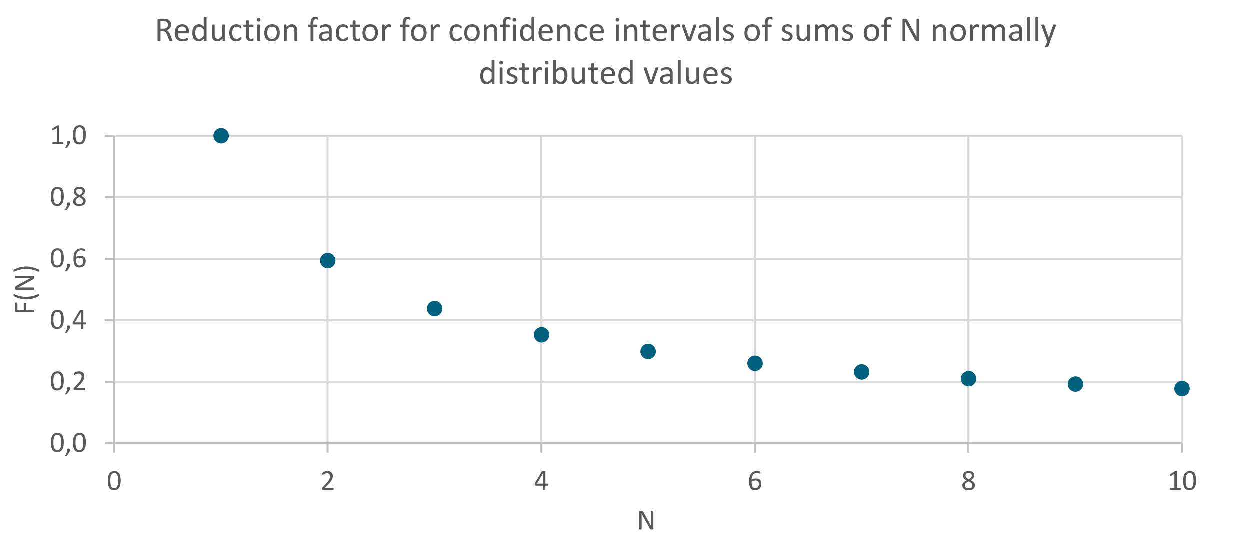

Figure 31: 90 % confidence interval for sum of N normally distributed values is sum of N 90 % confidence intervals of single values x reduction factor F(N).

Table 60: Calculation of adapted uncertainty for sum of case studies (± 45,500 kt CO_2eq.).

	Rounded average deviation (±) of GHG net-benefit results	Reduction factor for uncertainty of sum	Adjusted uncertainty for sum
	kt CO_2e		kt CO_2e
Energy efficient lighting – LEDs	42.292	0,50	21.100
Chlorosilane for Solar Grade Silicon	15.193	0,30	4.600
Engine Performance, Rubber in Motor Construction	15.193	0,30	4.600
Green Tyres	15.193	0,30	4.600
Sealants Windows IG unit	15.193	0,30	4.600
Coating of means of transport, anti fouling coatings	15.193	0,30	4.600
Automotive Bonding	1.103	0,22	200
Batteries/Energy Storage	1.103	0,22	200
High Quality Sealants & Adhesives	1.103	0,22	200
Industrial applications in pulp industry, Anti-foaming in Pulp Production	1.103	0,22	200
Wind Turbines	1.103	0,22	200
Electric transport (bycicle, electric and hybrid cars, train)	1.103	0,22	200
Reflective roof coatings	1.103	0,22	200
Total uncertainty range	125.978		**45.500**

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