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GSC
GLOBAL SILICONES COUNCIL

Update of the Si-Chemistry Carbon Balance

Project SILICAB 2 Summary Report

Report 18/07/2024

Client Global Silicone Council (GSC)

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Abbreviations

CEFIC .... European Chemical Industry Council
CES .... CES – Silicones Europe
CO_2 .... Carbon dioxide
CO_2eq .... Carbon dioxide equivalent
EBS .... Ethylene-bis-stearamide
EEA .... European Environment Agency
EF .... Emission factor
EoL .... End of life
EPDM .... Ethylene propylene diene monomer
EU .... European Union
EV .... Electric Vehicles
FEICA .... Association of the European Adhesive & Sealant Industry
FU .... Functional unit
GD .... Green Deal
GHG .... Greenhouse gas
GSC .... Global Silicone Council
GWP .... Global warming potential
HEV .... Hybrid electric vehicle
HP .... High power
IG .... Insulating glass
LCA .... Life cycle assessment
LED .... Light-emitting diode
MeOH .... Methanol
NEV .... Neighbourhood electric vehicle
OD .... Outer diameter
PCF .... Product carbon footprint
PDMS .... Polydimethylsiloxane
PMMA .... Polymethyl methacrylate
PU .... Polyurethane
PV .... Photovoltaic
RoW .... Rest of the world
$SiCl_4$ .... Tetrachlorosilane
$SiHCl_3$ .... Trichlorosilane
TIM .... Thermal Interface Material
U-value .... measure of thermal transmittance

Executive Summary

In recent years, organizations increasingly focus on understanding their products' environmental impact, driven by motives like aligning with global initiatives such as the Paris Agreement and addressing climate change. Silicon-derived products play a crucial role in the economy due to their versatile properties, finding applications in everyday items. The Global Silicone Council (GSC) mandated an update to a 2012 study, reflecting technological advancements and silicon products' contribution to decarbonizing global economies. The study, covering Central Europe, North America, and Japan, reveals **significant positive contributions to greenhouse gas reduction across industries through 26 applications**. Two key aspects highlighted the benefits of silicon-based products:

1. Reduced fossil fuel consumption: Enhanced efficiency in processes and transport.
2. Extended material lifetimes: Silicon-coated materials enhance weathering and heat resistance, optimizing material use.

Market dynamics in 2021 estimated **the cumulative market size of silicon-based products at 984 kt/a**. The absolute GHG benefits were scaled up for another 10 % of the market with GHG benefits not covered by the study. Noteworthy volume distinctions were observed, with chlorosilanes for solar-grade silicon leading and telecommunication applications having the lowest volume.

All case studies demonstrate a benefit-impact ratio >1, with cumulative annual GHG savings reaching 148 Mt CO_2eq. (-15%/+47%). This marks an improvement from the 2012 study, indicating an enhanced benefit profile and reduced lifecycle impacts. The case studies cover 78 % of the market. 10 % of the market applications were assumed to also have some benefits and conservatively estimated to bring additional savings of -12.6 MtCO_2eq. For the remaining 12 % market share, only the average impact (production and end-of-life) was considered, which adds 1.4 MtCO_2eq to the total result of -159.4 MtCO_2eq. Absolute GHG benefits were extrapolated to full market scale, thus adding an additional -12.6 MtCO_2eq. savings from the unquantified 10% of the market, while the remaining 12% of the market received a GHG loss of 1.4 MtCO_2eq.

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.,** is comparable to emissions from countries like the Czech Republic or the Philippines, representing 11% of Japan's and 2.7% of the US annual GHG emissions.

Acknowledging the need for data quality improvement and data gap bridging, the report notes the use of conservative estimates to reduce overall uncertainty. Future studies should explore broader environmental impacts, including water use, sustainable sourcing, biodiversity, and social and economic implications. Dr. Roland Hischier's critical scientific review aimed to ensure the study's validity, appropriateness of data, reflection of study goals, and transparency. Only the main study was reviewed, the document at hand was not part of the review.

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1. Introduction

In recent decades, the Global Silicone Council (GSC) addressed environmental concerns by conducting a 2012 study on the GHG emissions of silicone and silane products, which revealed GHG benefits to be around nine times higher than emissions from production and end-of-life. In 2021, the GSC updated the study to analyze technological changes' impact on GHG emissions.

This study examines GHG emissions, benefits, and impacts of 26 applications. The "Si-chemistry carbon balance" represents GHG benefits to emissions, and the GHG net-benefit is derived by subtracting impacts. The calculation involves market volume segmentation, GHG emissions computation, case study analysis, carbon balance calculation, and conservative extrapolation of benefits. This report focuses on GHG effects while providing a comprehensive view of non-GHG benefits. Roland Hischier's critical review examines scientific validity, data appropriateness, interpretation, and transparency. Only the main study was reviewed, the document at hand was not part of the review.

2. Methodology

2.1. Selection of the relevant applications

In 2021 Carbon Balance study[1] selected 26 applications, building upon 18 from the 2012 study and 3 from the CES Green Deal 2021 report. Five new applications were added based on GSC expert decisions and market relevance. Selection criteria included GHG reduction potential, current market size (GSC data), and screening for suitable Si-based product applications. In the 2012 study, the total silicone products market was estimated at 1.142 Mt/a in 2009 across sectors like Construction, Industrial, Transportation, Electronics, Personal & Lifestyle, and Special Systems. The Si-applications market share was estimated at 690 kt/a for Europe, 331 kt/a for North America, and 121 kt/a for Japan. Sectors were based on the socio-economic study published by CES[2].

The original aim was to cover a high market share (60–70%) through case studies, but some applications lacked comparable or quantifiable GHG effects, so they were excluded in 2012. The CES Green Deal 2021 report conducted a qualitative analysis to identify relevant sectors and screen silicone applications based on the SEE 2020[3] study. Previous applications were included due to a high GHG net benefit-to-impact ratio from the 2012 study, emphasizing the potential decrease in GHG emissions. The selection process clustered silicone applications by sector, evaluating the use effect and defining alternative options. Silicone benefits were determined using the

[1] 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)

[2] CES. (2007). A Socio-Economic Study on Silicones in Europe. European Silicones Centre – Centre Européen des Silicones (CES). Brussels, Belgium.

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

2012 Carbon Balance study insights[4]. New applications had comparable reference systems selected following the same methodology. The total benefits for the EU27 were calculated by multiplying the net benefits of silicones per kilogram with the market data.

2.2. Calculation of the PCF

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.

2.3. Methodology and limitations

Methodological steps for the study included lifecycle data collection, carbon balance calculation, and result presentation. Validation and sensitivity analyses were performed for all case studies. Special attention was given to quantifying use phase benefits. The study adopts a total market approach, considering the overall market volume of silicone products in the defined region for the carbon balance. A conservative approach was taken when dealing with uncertain or assumptive data. Limitations and approximations applied are:

- The calculation focuses on fossil **GHG emissions**.
- **The 80/20 approach** is applied, utilizing approximations for areas where data accuracy is less critical. [5]
- **Allocation of benefits** - results are compared with alternative materials for the same functional unit.
- **Use phase effects** are individually defined in each case study.
- **Waste management** considerations are based on assumptions from the 2012 Carbon Balance study.[6]
- **Weighted average results** for GWP or PDMS and selected precursors derived from company-specific, confidential data and other market data.

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[4] 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)

[5] Dunford. R., Su, Q., and Tamang, E. (2014) 'The Pareto Principle', The Plymouth Student Scientist, 7(1), p. 140-148.

[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)

These aspects collectively contribute to the study's goal and scope, providing an approximate ratio of impacts and benefits for the total silicone products market.

2.4. System definition for silicone products

Figure 1 describes the investigated products and processes in the life cycle of silicone products.

Table 1: Legend of objects for Figure 1.

Products	
	Silicone products in the focus of this study – Sealants, silicone rubber and silicone resin account for the highest market share of the products in the system.
	Other products, inputs and intermediates.
Processes	
+	Production processes in Si-industry; the four processes highlighted in yellow account for the main energy input in the production system.
	Production processes in Si-industry not considered in [Boustead 2003], but considered in this study because GWP data for additional products are needed.
	Processes in the use phase.
	EoL process - there is only little recycling of production waste (which is not considered in the study), but no EoL recycling.
	Substituted process in EoL phase, e.g. generation of heat from fossil fuels that is substituted by generation of heat from waste incineration.
	Transport processes - for clarity, not all transport processes considered are displayed (for example also transport of alternative materials is taken into account).

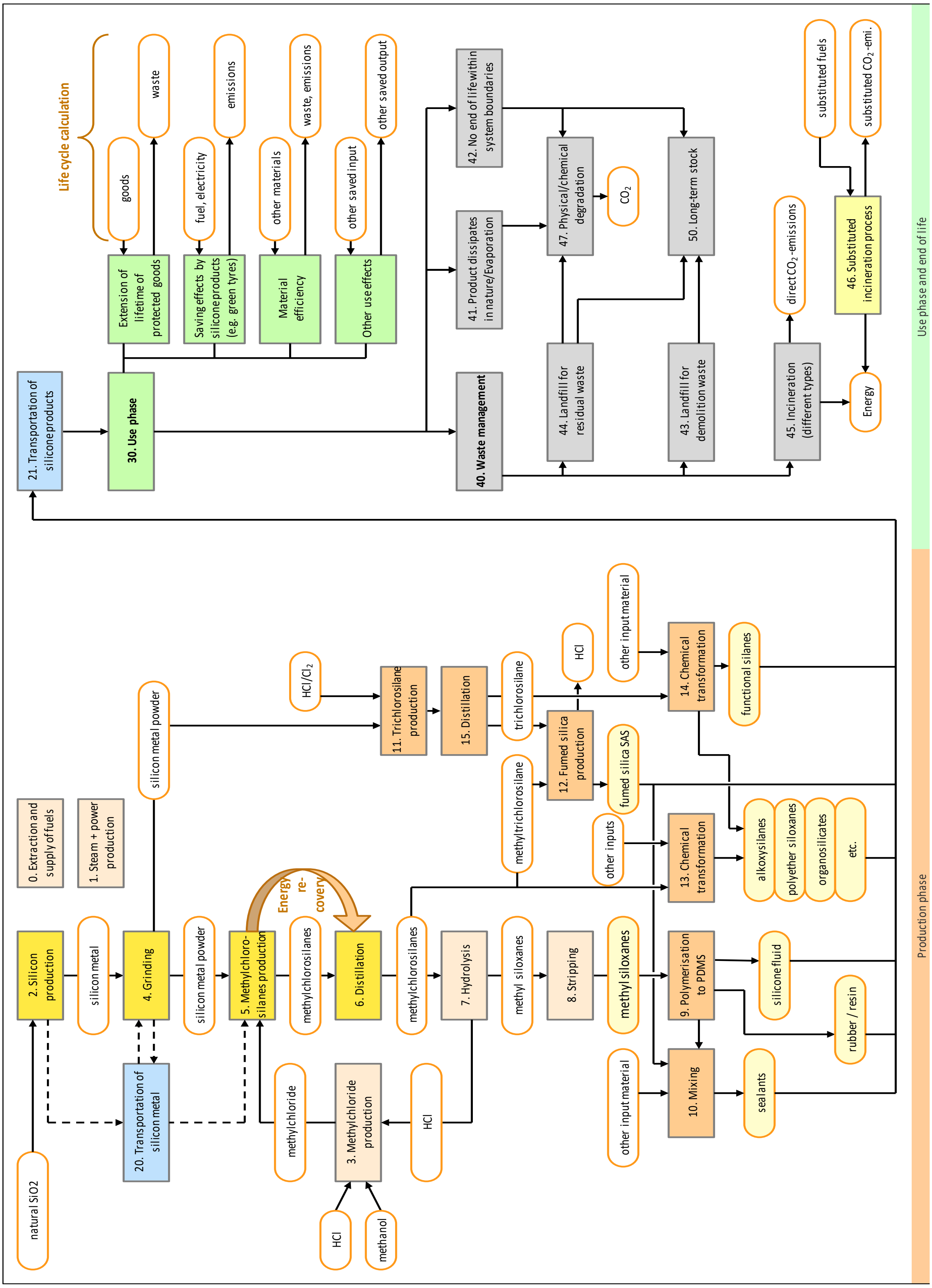

Figure 1: System definition overview and investigated processes for production of siloxanes, silanes and pyrogenic silica. The products shown in the figure above describe typical product families. 4 case studies are related to fluid PDMS, 5 to sealants, 2 to polyethersiloxanes, 1 to a functional silane, and one to trichlorosilane. Relevant, formulations of final products are described in the respective case studies. Processes 0 and 1 are not individual processes, but part of every process in the chart, but omitted there for better readability.

Eco-profile

The 2012 Carbon Balance study extensively examined GHG emissions related to PDMS fluids, sealants, rubbers, and resins, expanding eco-profiles compared to a 2002 CES study.[7, 8] The update included PDMS fluids, sealants, rubbers, resins, intermediates, and pyrogenic silica data based on 2010 data. These profiles cover over 90% of the 2012 market, focusing on cradle-to-gate GHG emissions. The 2021 eco-profiles used diverse sources, including confidential silicon production data, Ecoinvent database[9], Euroalliages, GSC member companies, and QYResearch's Global Basic Silicone Market Report[10]. Siloxane and silane production data quality varies, relying on Euroalliages, experts, literature, regional energy mixes, and regional reduction agents. 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.

2.5. GHG emissions for global silicon production

Primary materials for siloxanes/silanes are silicon, MeOH, and HCl, with silicon production contributing 51% to GHG emissions (see chapter 2.2). Silicon (or elemental silicon) is produced from mined quartz and various reduction agents in submerged electric arc furnaces. Reducing gas (CO, H_2) is produced from fossil materials like coal, pet coke and coke, and/or from biogenic materials like charcoal and woodchips. Silicon is used in production of aluminum compounds (50%), silicones (40%), and electronics (4%).[11] Emission calculations employ the "80/20 approach" and reasonable estimates, ensuring the result's magnitude order accuracy with approximately ±21% uncertainty.

Electricity consumption

Range of 11 – 14 kWh/kg silicon is considered typical for the electricity demand of silicon production processes.[12] Differences in electricity demand arise from varying energy efficiency among production sites and some plants utilizing 10 – 20% excess heat from electric arc furnaces. Uncertainty exists about whether the lower data range includes associated processes, leading to calculations based on an **average of 12.5 kWh/kg** silicon.

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[7] CES. (2002). Eco-profile of Silicones Executive Summary. European Silicones Centre – Centre Européen des Silicones (CES). Brussels, Belgium.

[8] Boustead, I. (2003). Eco-Profiles of Production Systems for Silicones. A report for Centre Européen des Silicones (CES), a Sector Group of Cefic, Brussels. Provided by CES. Unpublished.

[9] Ecoinvent Version 3.8. (2011). Competence Centre of the Swiss Federal Institute of Technology. Zürich, Switzerland. www.ecoinvent.org.

[10] QYResearch. (2021). Global Basic Silicone Market Report – History and forecast 2016 – 2027, Beijing, China.

[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. 02/2022.

[12] 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.

Electricity mix for silicon sourcing regions

Life cycle GHG emissions per kWh electricity vary based on the country of silicon production, significantly impacting silicon production's electricity-related emissions. Members provided regional source data, with weighted averages reflecting silicone production market shares.

GHG emissions related to electricity used in European silicon production is derived from the split of European silicon sources - Norway, France, Spain and Germany and the respective global warming potential (GWP) of the respective electricity mix ("market for electricity, medium voltage"[13]). The resulting GHG emissions related to electricity used in European silicon production are **1.51 kg CO_2eq./kg silicon**.

Applying the same procedure to derive GHG intensity of global silicone production based on the following sourcing regions – China, Brazil, North America and Europe, the resulting **GHG emissions related to electricity used in global silicon production are 5.1 kg CO_2eq./kg silicon**.

Direct CO_2 from reducing agents

Various reduction agents are used in the submerged electric arc furnaces to produce silicon: hard coal, pet coke, coke, charcoal and woodchips. In addition, the consumption of electrodes contributes to CO_2 emissions. Shares of reduction agents in different regions were derived from two confidential sources – Euroalliages and ecoinvent[13]. Based on these sources, we consider a **range of 6.0 – 7.0 kg CO_2eq./kg silicon** as the most typical range for the **direct CO_2 emissions incl. biogenic CO_2 emissions** for silicon production processes.

All further calculations are based on an **average value of 6.5 kg CO_2eq./kg** silicon. In this study, biogenic CO_2 emissions from wood and charcoal are counted as "carbon neutral" and are not included in the GWP data, following a standard LCA practice. Only fossil CO_2 emissions from production and delivery of biogenic fuels are included.

GWP related to reduction agents, including production and delivery of reduction agents

Carbon footprint analyses are related to the total lifecycle of products, hence the GHG emissions related to the production and delivery of reduction agents (both fossil and biogenic) must be included. GWP of the following fuel sources were included in the evaluation – **woodchips, charcoal, hard coal, coke and pet coke**. Thus, the GWP of reducing agents is derived as **4.9 kg CO_2eq./kg silicon**, where **2.86 kg CO_2 are direct emissions from the submerged electric arc furnace (see above) and 1.96 kg CO_2eq. are related to production and delivery**.

Estimated GHG emissions for global silicon production

Silica fume, a byproduct of silicon production (40-50% of silicon mass), is allocated 3% of the total production impact considering mass shares and market prices. Based on this, the GHG emissions related to electricity and reduction agents are 4.9 kg CO_2eq./kg silicon and 4.8 kg CO_2eq./kg silicon, respectively, resulting in a total GWP

[13] 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.

of 9.7 kg CO_2eq./kg silicon with an uncertainty of ±2 kg CO_2eq. (±21%). Changes since 2012 include reduced emission factors for electricity but an increased GWP for reduction agents, primarily due to higher emission factors for biogenic energy sources. Overall, the total GWP of silicon production has slightly decreased.

The GWP of global production of silicon used for siloxanes and silanes, as calculated in this study (9.7 kg CO_2eq./kg silicon), is much higher compared to available data sources[14, 15] since these refer to different regions, sources of electricity and mixes of reducing agents.

2.6. GHG emissions from producing PDMS and related substances

PDMS-based silicone products, constituting over 90% of the siloxane and silane market, underwent a detailed investigation into their production-related GHG emissions. PDMS production involves silicon, chloromethane, and methylchlorosilanes, leading to the formation of PDMS through hydrolysis and subsequent polymerization. Crosslinks between polymers yield rubbers and resins.[16] Methylchlorosilanes or chlorosilanes are employed in the production of various siloxanes, silanes, resins, or pyrogenic silica, while trichlorosilane is crucial for functional silanes. The cradle-to-gate GHG emissions of input raw materials for functional silanes and the production of synthetic amorphous silica were assessed. Confidential data from member companies was utilized for this comprehensive analysis.

Fumed silica, produced through the combustion of chlorosilanes or methylchlorosilanes, serves as a reinforcing filler. Companies provided confidential data on processes like transport, steam and electricity production, grinding of silicon, and various production stages. Some companies also shared data on chlorosilanes and pyrogenic silica production. Extracted information influenced a model for calculating cradle-to-gate GHG emissions of methyl siloxanes. All steps were separately assessed, and specific results per kg of product were averaged based on company market shares. Similar averaging was applied to chlorosilanes and pyrogenic silica production.

Remarks on the calculation process:

denkstatt and the companies engaged in discussions to clarify data issues. Data from different companies was examined to ensure comparability in process magnitude. Input masses below 1% in the hydrolysis process were excluded. Grid electricity consumption was combined with the country-specific GWP. Site-specific fuel mixes from companies were used for on-site electricity and steam production. GWP data were derived from Ecoinvent 2021, except for silicon. Simplifications were made, such as the neglect of differentiation between main and

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[14] 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.

[15] Eco-Profiles of Production Systems for Silicones. A report for Centre Européen des Silicones (CES), a Sector Group of Cefic, Brussels. Provided by CES; unpublished.

[16] European IPPC Bureau (2007): Reference document on best available technologies for the production of Speciality Inorganic Chemicals. European Integrated Pollution Prevention and Control (IPPC) Bureau. http://eippcb.jrc.es/reference/sic.html

byproducts in the Müller-Rochow synthesis, resulting in negligible effects on the GWP of PDMS. Recycling credits and benefits allocation followed specified approaches for simplification and precision.

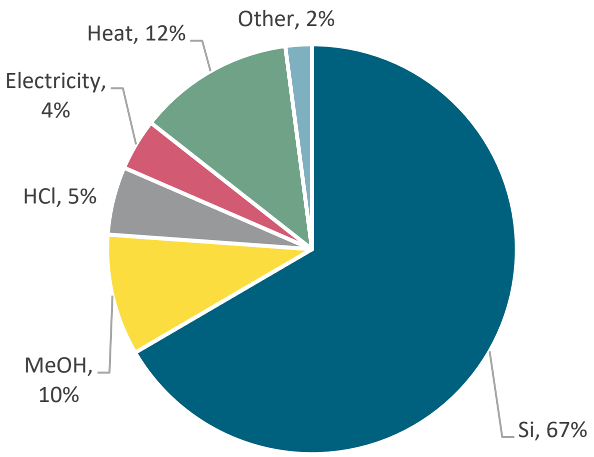

Figure 2: Shares of important raw materials, energy consumption, other inputs and waste to total GHG emissions of methyl siloxanes.

GHG emissions for substances with functional groups from siloxanes or silanes were estimated using GWP data from raw materials, assuming similar energy demand and emissions in final processing as PDMS. Figure 2 shows, that silicon accounts for 67% of GHG emissions in methyl siloxanes, followed by steam, MeOH, HCl, and electricity. Other contributions are minimal.

The primary uncertainties in the GWP of methyl siloxanes are attributed to silicon (± 2.0 kg CO_2eq.) and electricity/heat consumption (± 0.3 kg CO_2eq.), resulting in an overall uncertainty of ± 1.1 kg CO_2eq./kg methyl siloxane (± 20% or 4.7–7.0 kg CO_2eq./kg methyl siloxane). Boustead[17] reported 4.9 kg CO_2eq./kg PDMS and 5.2 kg CO_2eq./kg silicone fluid, contrasting with 5.97 kg CO_2eq./kg PDMS found in this study. The disparities are attributed to lower GWP of silicon in the Boustead model.

The Ecoinvent dataset for PDMS production indicates 15.86 kg CO_2eq./kg PDMS.[18] Discrepancies arise from additional subprocesses in Ecoinvent (e.g., potassium hydroxide) and the older, partly literature-based data. The current study, based on recent primary data, indicates higher energy-efficiency achieved, consuming two-thirds less energy along the value chain and emitting fewer pollutants like CO_2 and CH_4.

2.7. GHG emissions from use phase

Silicone products exhibit varied effects, with some cases showing substantial GHG savings from minimal usage. In certain comparisons, only material aspects are considered, leading to no apparent GHG impact during use. Use phase benefits may arise from a combination of silicone and other products or technologies, necessitating a proportional allocation of benefits to silicones, as detailed in chapter 3. Region-specific datasets address variations in electricity mix, heating mix, heating degree days, and automotive fuel consumption across Europe, North America, and Japan, detailed in relevant case studies.

[17] Boustead, I. (2003): Eco-Profiles of Production Systems for Silicones. A report for Centre Européen des Silicones (CES), a Sector Group of Cefic, Brussels. Provided by CES; unpublished.

[18] 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. 02/2022.

2.8. GHG emissions from EoL phase

Limited data on silicone product distribution, natural degradation, and chemical degradation in landfills hinders detailed End-of-Life (EoL) calculations. Future projects may address these gaps, but EoL's impact is minor due to significant 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**.

Distribution of silicone products in waste management

Initially, 100% of product mass is allocated to waste collection routes or dissipation, and subsequent allocation into recovery/disposal options is detailed for each collection route. Possible end-of-life routes are outlined in Figure 3 of the system definition. Estimates are based on sources and assumptions, including Eurostat[19] and Euwid[20] for Europe, EPA (2021) for the USA,[21, 22] and the Ministry of the Environment (2018) for Japan[23]. Additional details and case-specific calculations are explained in chapter 3.

Calculations related to energy recovery

Incinerating silicone products or alternatives in waste incineration plants transforms fossil carbon to CO_2, impacting the study's GHG balances. Utilizing waste calorific value for electricity or heat production, including replacing fossil fuels, contributes to GHG credits. Industrial energy recovery, involving RDF utilization in various processes like power plants and cement kilns, substitutes coal, heavy fuel oil, or gas.[24, 25] Assuming equal efficiency for waste and standard fuels, the calculation model assumes a certain share of fuels substituted by industrial energy recovery, aiming to represent average global conditions.

MSWI plants in Europe are estimated to have an average utilization of 18% for electricity and 20% for district heat, while all North American plants generate electricity (19%[26]). Japanese plants are assumed to produce 12%

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[19] Eurostat. (2021). Municipal waste statistics. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics#Municipal_waste_treatment. (accessed 10/2021)

[20] Eurostat. (2008). EoL vehicles (ELVs) Re-use and Recovery Rate. Retrieved from http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/elvs (accessed 10/2021)

[21] EPA. (2020). Advancing Sustainable Materials Management: Assessing Trends in Materials Generation and Management in the United States. Retrieved from https://www.epa.gov/sites/default/files/2021-01/docments/2018_ff_fact_sheet_dec_2020_fnl_508.pdf. (accessed 10/2021)

[22] EPA. (2011). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010. U.S. Environmental Protection Agency (EPA). Retrieved from www.epa.gov/osw/nonhaz/municipal/pubs/msw_2010_factsheet.pdf (accessed 10/2021)

[23] Ministry of the Environment. (2018). Emissions and Processing of Domestic Waste. An Introduction to Plastic Recycling. Retrieved from プラスチック基礎知識2019_本文_191223.indd (pwmi.or.jp) (accessed 10/2021)

[24] Pilz, H. (2007): Environmental assessment of feedstock recycling of plastic waste in the blast furnace process of voestalpine Stahl, compared to alternative recycling and recovery routes. Denkstatt GmbH, Vienna, Austria for voestalpine Stahl, Linz, Austria. Summary published in Karl J. Thomé-Kozmiensky (Publ.) "Produktverantwortung", TK-Verlag, 2008.

[25] Pilz, H., Brandt, B. & Fehringer, R. (2010): The impact of plastics on life cycle energy consumption and green-house gas emissions in Europe, Denkstatt GmbH, Vi-enna, Austria for PlasticsEurope - Association of Plastics Manufacturers, Brussels, Belgium.

[26] Kaplan, P. O., Decarolis, J., & Thorneloe, S. (2009). Is it better to burn or bury waste for clean electricity generation?

electricity and 68% steam. Credits for electricity are based on substituted regional mixes, using emissions data from Ecoinvent 2021[27].

Degradation of silicone in landfills and nature

Silicones in residual waste landfills undergo chemical degradation, converting carbon to CO_2. Volatile siloxanes detected in landfill gas support this. Silicones dissipating into nature convert to CO_2 within approximately 100 years. Approximately 50% of silicone sealants in landfills are assumed to degrade within 100 years, releasing carbon as CO_2 emissions, factored into the case study's carbon balance calculations.

2.9. Description of data collection and literature review for case studies

To calculate PCFs for 26 silicone-based applications and alternatives, extensive data collection involved questionnaires and consultations with GSC member experts. Information on composition, amount, function, replaceability, and advantages/disadvantages was gathered and iteratively incorporated. Data gaps were filled using literature and recognized databases. This study adheres to ISO guidelines for LCA but simplifies with an 80:20 approach, focusing on GHG emissions. Comparative results are based on alternative materials for the same functional unit. Use phase effects, waste management, and market data implementation vary by case study. Benefits are allocated individually based on specific considerations in each case.

[27] 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.

3. Case studies: silicone-based applications

This chapter outlines 26 case studies, providing information on background, functional units, and data for production, use phase, and end-of-life management, and thus discusses the results of silicon carbon balance for each application.

3.1. Automotive bonding

This chapter relies on the CES Green Deal (GD) 2021 report, adapting data from Europe, North America, and Japan. In automotive bonding, silicones outperform alternatives like spot-welding, offering energy efficiency, weight reduction, and lower GHG emissions[28]. **Functional unit considered is 1 passenger. car.**

Production, use phase and end of-life

FEICA[29] data compares automotive bonding to spot welding in production. Assumptions suggest 4500 saved spot welds per car, equivalent to 0.005 kWh saved energy per weld. Adhesive bonding requires ca. 800 g per car, with GWP data for silicone bonding estimated by combining PDMS data with mixing and transport information.

FEICA assumptions for use phase: Silicone bonding saves 52.2 kg per car, leading to energy savings of about 14,200 MJ for petrol cars and 13,100 MJ for diesel cars over a 10.7-year, 150,000 km car lifetime[30, 31, 32]. Only 10% of the use benefit is applied to silicone[33]. Emission data, based on Ecoinvent factors[34], assumes an average diesel car share of 21% and petrol car share of 68%[35, 36]. Future projections suggest a transition to electric

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[28] FEICA. (2021). FEICA's 5 Guiding Principles in support of a successful European Green Deal. Retrieved from: https://www.feica.eu/information-center/all-information-centre/preview/1214/five-guiding-principles-support-successful-european-green-deal?id=037118c0-a3f2-4891-8171-4be515ce85c8&filename=FMI-EX-K07-040_Five_Guiding_Principles_supporting_GD.pdf. 02/2022

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vehicles, altering use phase benefits[37, 38]. It is assumed, that in the EU27 and North America, 80% of bonding material is incinerated, 20% landfilled; in Japan, 100% is allocated to energy recovery.

Results

The definition of impact in the context of silicone adhesive bonding encompasses both production and end-of-life considerations. In terms of benefits, substituting energy for spot welding has resulted in fuel savings. The dominant life cycle GWP impact is from the use phase, considering the car's lifespan and fuel reduction (with only 10% attributed to bonding). The influence of silicone's proportion in the fuel-saving benefit, ranging from 3% to 15%, results in a **benefit/impact ratio between 6.4 and 32.0**.

3.2. Batteries/energy storage in battery-electric-vehicles

This chapter relies on the CES Green Deal 2021 report on Silicones' role in the EU Green Deal. Changes in data sources include a mix of European, North American, and Japanese data. Silicone is crucial in assembling EV battery packs, serving purposes like sealing, bonding, and thermal management. It extends battery life, and though the exact extension isn't quantifiable, it's believed to increase from 8 to 10 years. Silicone also facilitates easier cell detachment for better reparability. Epoxy is chosen as an alternative material[39]. **Functional unit considered is TIM (Thermal Interface Material) - silicone or epoxy – for 1 battery 70 kWh with 10 years of battery lifetime.**

Production, transport, use phase and end of life

The silicone-TIM, with 15% silicone and 85% inorganic filler at a density of 2.9 g/cm^3 [40], differs from epoxy with a density of 1.13 g/cm^3 [41]. GSC feedback suggests an average TIM value of 0.123 kg/kWh, or 0.042 dm^3/kWh, equivalent to 8.68 kg/Battery. GWP values are from Ecoinvent[42] and the silicone eco-profile, including emission factors for mixing and transport based on the 2012 eco-profile[43].

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[38] IEA. (2021). EV share of car sales in the European Union in the Sustainable Development Scenario, 2019-2050. Retrieved from https://www.iea.org/data-and-statistics/charts/ev-share-of-car-sales-in-the-european-union-in-the-sustainable-development-scenario-2019-2050. 08/2021.

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Manufacturers assure an 8-year[44] minimum battery lifespan. Epoxy batteries last 8 years, while silicon-TIM extends it by 2 years, yielding a 1.25 replacement factor. Emissions from battery manufacturing and transport are part of the use phase. In the end-of-life scenario, both silicone and epoxy batteries are assumed to be incinerated in pyrometallurgical waste treatment plants after separate collection in all three regions.

Results

Silicone's longer battery life, allowing individual cell replacement, yields a high benefit-impact ratio, reducing material and energy use. Calculations consider the entire battery during the use phase. The silicone-free battery has a shorter service life, requiring a different battery for the alternative application, with emissions multiplied by a 1.25 replacement factor for a 10-year service life.

Impact is defined as production and transport of silicone-TIM. Benefit is defined as total GWP of epoxy-TIM minus production, transport, and End-of-Life (EoL) expenses for silicone-TIM battery cells. Using silicone results in a net benefit, extending the battery's life and reducing raw material and energy use during replacements, considering the battery weighs about 300 kg in EVs.

The difference in battery lifespan determines the replacement factor, a crucial factor in comparing silicone and epoxy. With a fixed 10-year total life for silicone-TIM batteries, epoxy-based batteries vary from 7 to 10 years. Replacement factors for silicone-TIM are 1.25 for 8 years, 1.43 for 7 years, 1.11 for 9 years, and 1 for 10 years. Despite no documentation attributing a 10-year battery life solely to silicone, a slight advantage of 0.9 exists for silicone-TIM even with an equal 10-year service life.

3.3. Chlorosilane for solar grade silicon

This chapter relies on the CES Green Deal (GD) 2021 report, incorporating data from European, North American, and Japanese sources. Silicone's applications in PV systems, constituting 90% of the market[45], are explored, emphasizing its role in frame sealing, junction box adhesion, and encapsulation[46]. Traditional silicon PV systems, dominant due to efficiency compared to emerging alternatives like perovskite tandem cells, are not considered as a reference application[47].

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[47] Science. (2019). To amp up solar cells, scientists ditch silicon. https://www.science.org/content/article/amp-solar-cells-scientists-ditch-silicon. (accessed 12/2021)

The study considers solar grade silicon[48, 49], produced through the Siemens process, and analyzes the flow diagram of silicon PV systems, distinguishing between mono-Si and multi-Si production methods[50, 51]. The balance of system (BOS) is assessed, focusing on mounting system components and excluding lightning protection, inverters, and cables. Detailed process of PV system production is depicted in Figure 3.

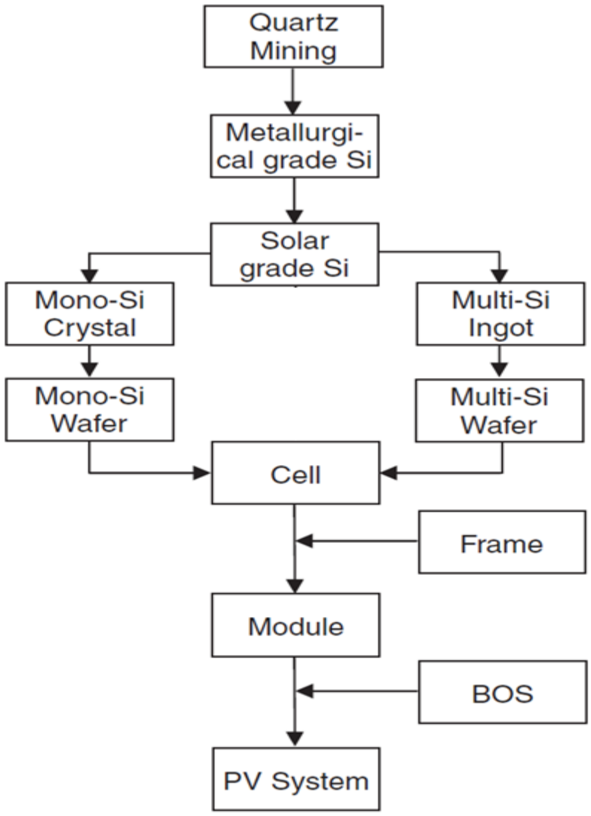

Figure 3: Detailed flow diagram from the raw material acquisition to manufacturing stage of PVs (ds modified from Fthenakis, V.M., Kim, H.C., Alsema, E. (2008)).

Functional unit considered is 1 kWp installed PV capacity. Kilowatt peak is the maximum output of an electricity generating system. Solar systems achieve this output under standard conditions (solar radiation of 1.000 W/m^2).

Production, use phase and end of life

Ecoinvent (2021) data for 1 kWp capacity in mono-Si (224 Wp) and multi-Si (210 Wp[52]) wafer systems, considering market shares (95% mono, 5% multi)[53], reveal that around 3 kg of silicon or 12 kg of chlorosilanes (90% tri- and 10% tetrachlorosilane)[53], are required to produce a 1 kWp system.

During the 30-year assumed lifetime of PV systems[54], with annual 0.5% degradation[55], the yield for rooftop

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[52] 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. 07/2021.

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installations is calculated[53, 56, 57] at a weighted European average of 1,100 kWh/kWp.a[58] as regional variations exist[59]. The North American average rooftop yield (1,444 kWh/kWp.a) is a weighted average of US[60] and Canadian[61] data. The electricity produced over the system's lifetime was produced based on installed market capacity in 2019. EoL waste management effects are considered in Ecoinvent datasets and are included in the production and transport processes.

Results

GWP effects considered are of silicone PV systems and regional electricity production mixes, with use phase differences assessed through electricity production over the PV system's lifetime. EoL is consolidated into the production and transport phase. **The impact definition covers solar-grade silicon production, and the benefit involves substituting the European electricity mix with solar power.**

Different approaches for CO_2eq. calculations are explored, considering renewable sources in regional electricity mixes and the marginal source (e.g., natural gas). Substituting with gas results in a 9.4 benefit/impact ratio, saving 13,000 kg CO_2eq. (compared to 13,577). Using coal increases savings to 33,616 kg CO_2eq., with a 24.4 benefit/impact ratio. In addition, variations in PV system efficiency prevail.

3.4. Energy efficient lighting – LEDs

This chapter is based on the CES Green Deal 2021 report, focusing on the role of silicones in LEDs. LEDs, comprising around 38% of the market in 2019[62], find extensive applications in street lighting[63], displays, and general lighting, offering longevity that can revolutionize the industry. Silicones play a crucial role in various LED components, enhancing performance and extending product life[62]. The study emphasizes the benefits of using silicone as an encapsulant or lens compared to optical-grade epoxy. Silicone's role in extending LED lifetime is highlighted, with a conservatively estimated replacement factor of 2, considering efficiency variations. Glass,

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[56] 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. 11/2021.

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[62] denkstatt. (2021). External expert interviews. 09/2021.

[63] Koh, S., Van Driel, W., & Zhang, G. Q. (2011). Degradation of epoxy lens materials in LED systems. In 2011 12th Intl. Conf. on Thermal, Mechanical & Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (pp. 1-5). IEEE.

although thermally stable, is disregarded due to its brittleness, weight, and challenging processing[62, 64]. **The functional unit considered is a HP-LED with luminous duration of 1.500 h at constant 350 mA.**

Production, use phase and end of life

Calculation considers a standard 1 g LED[65] with materials like metals, resin, and electronic grade silicon[66]. Encapsulant materials, epoxy, and silicone are crucial[67]. Additional materials for LED lamps are factored in[65] based on an OD of 10 mm and a thickness of 1 mm[64]. The original Ecoinvent dataset for LEDs (2007) was adapted, replacing the encapsulant material with epoxy and silicone to match high-power LED input materials.

Both LED types are assumed to be replaced once they malfunction, factoring in lifetime differences during production. In Europe and North America, 50% of encapsulant material is treated as residual waste, with 53% incinerated or sent to landfill in Europe and 19% in North America. The remaining 50% undergo separate collection, with 80% in Europe and North America going for industrial energy recovery or landfill. In Japan, 10% of the encapsulant mass is treated as residual waste, 90% of which is incinerated, and 90% of separate collection goes to energy recovery (80%) and landfill. The rest of the LED is treated as electronics scrap in the Boliden process recycling of metals phase by the Kaldo plant.

Results

The production phase has a significantly greater impact than the EoL phase. The total net benefit of silicone (-11,196 kg CO_2eq./kg silicone product) is relatively high due to the small mass of silicone as encapsulant material (0.3% of the total weight of the LED lamp) to which the benefit relates. By choosing a **replacement factor of 5** (for the production and EoL of the LED lamp, including epoxy encapsulants) with a light duration of 1,500 h for LED[68], the benefit/impact ratio would increase to 5 (instead of 2), and the **net benefit of silicone would be -44,787.5 kg CO_2eq./kg silicone product**.

3.5. Engine performance, rubber in motor construction

This chapter, primarily derived from the CES Green Deal (GD) 2021 report, assesses silicones' role in achieving the EU Green Deal's decarbonization objectives. Silicone rubber is crucial in motor construction, offering

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[64] Wang, J. S., Tsai, C. C., Liou, J. S., Cheng, W. C., Huang, S. Y., Chang, G. H., & Cheng, W. H. (2012). Mean-time-to-failure evaluations of encapsulation materials for LED package in accelerated thermal tests. Microelectronics Reliability, 52(5), 813-817.

[65] Casamayor, J. L., Su, D., & Ren, Z. (2018). Comparative life cycle assessment of LED lighting products. Lighting Research & Technology, 50(6), 801-826.

[66] Hischier R., Classen M., Lehmann M. and Scharnhorst W. (2007). Life cycle inventories of Electric and Electronic Equipment: Production, Use and Disposal. Ecoinvent report no. 18. Empa/ Technology & Society Lab, Swiss Centre for Life Cycle Inventories, Dübendorf, 2007

[67] Kim, J., Ma, B., & Lee, K. (2013). Comparison of effect of epoxy and silicone adhesive on the lifetime of plastic LED package. Electronic Materials Letters, 9(4), 429-432.

[68] Lin, Y. H., You, J. P., Lin, Y. C., Tran, N. T., & Shi, F. G. (2010). Development of high-performance optical silicone for the packaging of high-power LEDs. IEEE Transactions on Components and Packaging Technologies, 33(4), 761-766.

durability and fuel efficiency, with a 20% fuel saving attributed to silicone[69]. In the evolving automotive landscape, silicones contribute to gasket durability in new electric cars. The anticipated decline in combustion engine usage[70, 71] aligns with global strategies, projecting an EV share of 57% in 2030 and 97% by 2050 in the EU[72]. **The functional unit considered is 1 car covering 150,000 km**, with an average silicone mass of 2.13 kg per vehicle and appears plausible as per literature references[73]. The market shift towards electric vehicles impacts the benefit/impact ratio, emphasizing the role of silicones in battery and EV-related technologies.

Production, use phase and end of life

Silicone rubber in motor construction, consisting of 70% vinyl PDMS and 30% fillers, is treated for emissions as PDMS. EPDM, with a density of 0.82 g/cm^3 [74], is assumed for a silicone-free motor, using Ecoinvent data[75] for production. In the use phase, 20% of fuel savings are credited to silicones[76], with average car consumption from Ecoinvent. Benefits also involve 10 to 30 components contributing to fuel reduction, assigning an average 6.7% benefit to silicone rubber. In the EoL phase, with separate car collection, 80% of rubber material is incinerated in EU27 and North America, while Japan opts for 100% industrial energy recovery.

Results

Despite attributing only 6.7% of fuel savings to silicone rubber, its use effect surpasses the impacts from production and the EoL phase. Looking ahead, the benefit/impact ratio will decrease significantly as fuel savings can't be allocated to silicone. Impact is defined as the production & EoL of silicone rubber. Benefit is defined as the substituted production and EoL of EPDM rubber, saved fuel. Future benefits will shift towards EV technologies. Varying the allocation of fuel saving benefits to silicone, ranging from 3.3% to 10%, resulting in a **benefit/impact ratio range of 64.9 to 196.7**.

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[69] denkstatt. (2021). External expert interviews. 06/2021.

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[72] International Energy Agency (2021): EV share of car sales in the European Union in the Sustainable Development Scenario, 2019-2050. Retrieved from: https://www.iea.org/data-and-statistics/charts/ev-share-of-car-sales-in-the-european-union-in-the-sustainable-development-scenario-2019-2050

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[74] 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.

[75] 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. 08/2021.

[76] denkstatt. (2021). External expert interviews. 06/2021.

3.6. Green tires

This chapter relies on the CES Green Deal (GD) 2021 report, incorporating data from Europe, North America, and Japan. "Green tires" refer to those with lower rolling resistance, achieved by using specific silanes or silica in the rubber[76], resulting in a 5% fuel reduction. **The functional unit is one set of four tires for a car, assumed to last for 50,000 km**[76].

Production, use phase and end of life

Evaluated based on specific precursors, the GWP of silicone includes data from Ecoinvent (2021) multiplied by a safety factor of 1.5. Silica production GWP, precipitated from a sodium silicate solution, is estimated using Ecoinvent (2021). Carbon black data is directly from Ecoinvent (2021), with assumed equal mass substitution.

Fuel saving attributed to silicone is approximately 5%[76]. A weighted average dataset for European, North American, and Japanese car mix models diesel and petrol engine car shares. GWP data for burning petrol and diesel is from UBA[77] (2019), with Ecoinvent (2021) for upstream chain information. Reduced fuel consumption, enabled by Si and silica, allocates benefits using GWP for their production.

During a tire's life, 65% of tread material becomes worn-out[78, 79]. Tire abrasion, washed off roads, degrades in soil and water. The remaining 35% of tread, along with the tire, is collected for industrial energy recovery (70% in Europe and North America, 100% in Japan) and landfills.

Results

In the GWP assessment, the use effect surpasses production and EoL phases. Impact involves silicone Si and silica production & EoL, while benefit is substituted carbon black (incl. EoL) and saved fuel. The benefit/impact ratio considers silicone and silica proportions, dividing the benefit by the sum of their GWPs, then multiplying by silicone GWP. Varied fuel savings (3% to 7.5%) from green tires result in a **benefit/impact ratio between 23.6 and 57.6**. The next-generation silane rubber system, with developing market shares, can achieve savings up to 7.5%[80].

3.7. High quality sealants & adhesives

The chapter draws extensively from the CES Green Deal (GD) 2021 report, focusing on Silicones' role in supporting the EU Green Deal's decarbonization goal. The data sources include a mix of European, North American, and Japanese data.

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[77] Umweltbundesamt (UBA). (2019). Berechnung von Treibhausgas (THG)-Emissionen verschiedener Energieträger. Retrieved from https://secure.umweltbundesamt.at/co2mon/co2mon.html. 06/2021.

[78] denkstatt. (2021). External expert interviews. 06/2021.

[79] Krömer, S. (1999). Life cycle assessment of a car tire, Continental AG, Hannover.

[80] denkstatt. (2021). External expert interviews. 08/2021.

The study compares structural glazing, facilitated by silicone sealants, with a thermally improved conventional system using dry glazing as an alternative. The alternative system employs insulating glass (IG) units and serves as a reference in this case study. The standard thermally improved glazing system utilizes pressure bars mechanically attaching the glazing to the façade. In contrast, wet structural silicone sealant is applied in structural glazing, anchoring the glass to the frame and providing a continuous thermal barrier[81]. This silicone system absorbs movements, ensuring stability, and prevents air and water infiltration during thermal expansion[81], live load deflections, and various building dynamics. Figure 5 and Figure 4 illustrate the configurations of the standard thermally improved system and wet structural silicone sealant application, respectively.

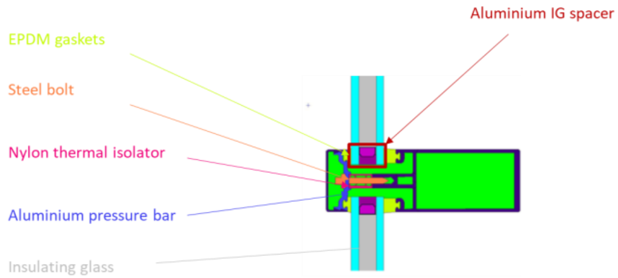

Figure 5: Dry glazed thermally improved system.

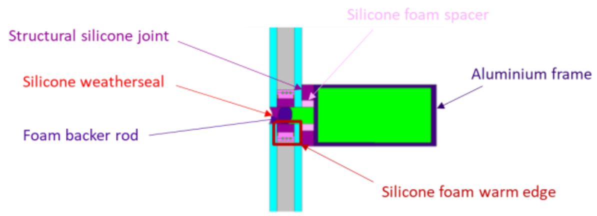

Figure 4: Silicone structural glazed system.

The functional unit considered is a 9-story model building, featuring a rectangular layout measuring 12 x 50 meters with a 4-meter ceiling height. This corresponds to 1,560 windows, each measuring 1.2 x 2.5 meters, totaling a length of 11.544 meters when arranged consecutively. The selection of a large glass area follows a conservative approach in the study, emphasizing the potential impact of the frame and silicone. **The assumed lifetime of the building is 50 years.**

Production, use phase and end of life

An average structural glazing **sealant** contains 45% silicone (PDMS), 50% calcium carbonate, and 5% unspecified additives. The **aluminum frame's** static part is excluded, and for the alternative glazing system, an estimated 4052 kg aluminum is used. EPDM **rubber gaskets** in the dry glazing system weigh approx. 3653 kg. Different climates are considered for the model, highlighting the **improved U-value** of the silicone system (2.01 W/m^{2}K vs. 2.30 W/m^{2}K) [82] and **lower air infiltration rates**, impacting heating and cooling energy demands. The GWP for heating is based on Bertelsen's study, using Ecoinvent (2021) data[83]. The GWP for residential heat supply in North America is based on the 2019 U.S. residential sector energy consumption[84] and Ecoinvent (2021) data. In

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[81] Carbary, L. et al. (2009). Comparisons of Thermal Performance and Energy Consumption of Facades Used in Commercial Buildings, in: Glass performance days 2009.

[82] denkstatt. (2021). External expert interviews. 06/2021.

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

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

Japan, it relies on the household sector's energy mix for specific heat categories[85], and the GWP for electricity mixes in Europe, North America, and Japan is sourced from Ecoinvent (2021).

The impact of U-value and air infiltration on GWP during the use phase in hot and cold climates is based on Carbary's study (2009), considering energy input for gas (heating) and electricity (cooling). Standard glazing for structural glazing facades is a triple low E system. The conservative approach averages use effects, assuming 25% of silicone leads to cold climate effects, another 25% to hot climate effects, and 50% causes no use effect. The air infiltration rate is assumed to be 5.5 $m^3/h\ m^2$ for both systems for 80% of the time and 11 $m^3/h\ m^2$ for the dry glazing system for the remaining 20% of the time.

Assuming 50% of all sealing materials are treated as building rubble, while the other 50% are separately collected. In Europe and North America, they go to incineration plants and landfills equally, while in Japan, the distribution is 80% incineration and 20% landfill.

Results

Differences in the use phase appear due to the higher air infiltration effect in the dry glazing system. A conservative assumption (20% of time with increased air flow for the dry glazing system) was made to maintain realistic silicone benefits. Impact is defined as the production & EoL of silicone sealant, while benefit is defined as the substituted production and EoL of EPDM and aluminium, along with saved heating and cooling energy. With an 11 $m^3/h\ m^2$ air infiltration rate for the dry glazing system, varying the % of time between 10% and 30% results in a range of the benefit/impact ratio between 8.7 and 15.7.

3.8. Industrial applications in pulp industry, anti-foaming in pulp production

This chapter, relying on the CES Green Deal (GD) 2021 report, explores silicones' vital role in supporting the EU Green Deal's decarbonization goals, drawing data from Europe, North America, and Japan. Silicones play a crucial role in brown stock washing during pulp production, aiding in the removal of dissolved substances. They enhance spent chemical recovery, reduce reagent consumption, and minimize effluent loads[86, 87].

In defoaming for brown stock washing, silicones have replaced oil-based defoamers, offering advantages such as improved foam control, lower chemical dosage, and cleaner pulp. **The functional unit is 1 ton of dry pulp.**

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[85] Agency for Natural Resources and Energy Ministry of Economy, Trade and Industry Japan. (2015). Effective use of heat

[86] Hoekstra, P.M. (2007). Improving Washing Efficiencies in the Kraft Pulp Mill with New Defoamer Technology - Hoekstra 2007 & TAPPI's 2007 Engineering, Pulping, and Environmental Conference held October 21-24, 2007, at the Hyatt Regency Jacksonville Riverfront in Jacksonville, Fla

[87] Hart, P.W and Santos, R.B. (2014). Brownstock washing – a review of the literature. Retrieved from: (PDF) Brown Stock Washing – A Review of the Literature (researchgate.net). 10/2021.

For silicones, a dosage of 0.4 kg/t dry pulp is assumed, with a silicone content of 0.08 kg/t[88, 89]. This slightly differs from the CES Green Deal (GD) 2021 report. Oil-based defoamers require an average of 2 kg/t pulp[90, 91].

Production, use phase and end of life

Oil-based defoamers primarily use mineral oils and EBS[92], with an average EBS share of 7.5%[93]. GWP data for production are from Ecoinvent 3.8[94]. The use of silicone-based defoamers reduces shower flow by approximately 10%, saving 800 l/t of dried pulp. This water-saving effect has a GWP impact of 0.54 kg CO_2eq./t pulp. The more significant impact is the saved energy from reduced evaporation during concentration, estimated at 46.5 kg CO_2eq./t pulp. Improved drainage and reduced shower flow enhance the recovery of process chemicals, reducing caustic soda loss by an average of 3.18 kg/t pulp, equivalent to 4.1 kg CO_2eq. The higher brown stock throughput and better recovery of process chemicals contribute to a 10% increase in pulp mill productivity, saving 1.2 kg CO_2eq./t pulp[93, 94].

Sewage residues in the pulp industry are assumed to be 80% incinerated and 20% landfilled for all regions. The GWP impact for oil-based defoamer is 2.22 kg CO_2eq./t pulp, while for silicone-based defoamer, it is 0.09 kg CO_2eq./t pulp.

Results

GWP impacts of silicone-based defoamer versus mineral oil-based defoamer show higher GWPs for the alternative product in production, transport, use, and end-of-life (differences: -3.0 kg CO_2eq./FU, -52.3 kg CO_2eq./FU, -2.1 kg CO_2eq./FU). The use phase has the most significant impact.

The benefit/impact ratio is 83.5, calculated by dividing the alternative product's total GWP by the silicone product's production and EoL. Impact is defined as production & EoL of the silicone application, and benefit is defined as the GWP ratio of silicone-based defoamer to oil-based defoamer over their lifetime. For oil-based defoamers, varying the dosage from 1 to 3 kg/t of dry pulp results in a benefit/impact ratio range of 79.3 to 87.6. In the sensitivity analysis for silicone-based defoamers, varying the dosage from 0.2 to 0.6 kg/t of pulp produces benefit/impact ratios from 166.9 to 55.6.

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3.9. Sealants windows IG unit

This chapter relies on the CES Green Deal (GD) 2021 report, emphasizing Silicones' role in supporting the EU Green Deal's decarbonization. The information integrates a mix of European, North American, and Japanese data. In the context of insulation glass (IG) units as shown in Figure 6[95], **the functional unit is one insulation glass window (123 x 148 cm, one sash)**. Sealants here play a crucial role, and the calculated amount is based on dimensions and densities (silicone: 1.5 g/cm^3, polysulfide: 1.6 g/cm^3, polyurethane: 1.3 g/cm^3). The assumed lifetime for all sealant types is 30 years, as per QKE & EPPA[96].

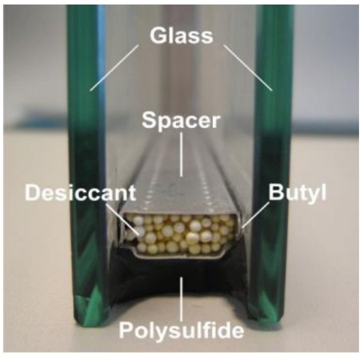

Figure 6: Cross-section of an IG unit.

Production, use phase and end of life

This study compares silicone, polysulfide, and polyurethane sealants for IG units. Silicone sealant considered in the study, constituting of 50% PDMS, 3% plasticizer, 5% cross-linker, and 42% filler, has a calculated GWP of 1.95 kg CO_2eq./kg[97]. Polysulfide (GWP: 1.95 kg CO_2eq./kg) and polyurethane (GWP: 3.85 kg CO_2eq./kg) are chosen as alternatives with a 60:40 market split[98], resulting in a 1.1 kg CO_2eq./FU average GWP. Silicone is used when the outside of IG unit is exposed to sunlight for superior UV stability. UV-exposed alternatives losing air-tightness raise the U-value by 0.3 W/m^{2}K after 20 years in a 30-year lifetime.

Higher U-values increase heating energy demand. Using market share-weighted[99] heating degree days per region[100,101,102] and the window area, the conservative calculation yields a **0.11 kg CO_2eq./MJ weighted heating energy mix**. At EoL, waste paths vary regionally, with Europe having 25% residual waste, 25% building rubble, and 50% separate collection; North America having 50% residual waste and 50% building rubble; and Japan having 90% building rubble and 10% separate collection.

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95 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. 10/2021

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98 Energiesparhaus.at. (2021). Fensterverglasung. Retrieved from: http://www.energiesparhaus.at/gebaeudehuelle/fenster-verglasung.htm. 10/2021.

99 denkstatt. (2021). External expert interviews. 10/2021.

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

101 U.S. Energy Information Administration (2021). Monthly Energy Review. Retrieved from https://www.eia.gov/energyexplained/use-of-energy/homes.php. 11/2021.

102 Agency for Natural Resources and Energy Ministry of Economy, Trade and Industry Japan. (2015). Effective use of heat.

Results

The production & transport phase of silicone emits 2.6 kg CO_2eq./FU, higher than the alternative's 1.1 kg CO_2eq./FU. However, the use phase (-130.8 kg CO_2eq./FU) and EoL phase (-0.6 kg CO_2eq./FU) differences result in a favorable benefit/impact ratio of 49.8. Impact is defined as the production & EoL of silicone, and benefit is defined as substituted production and EoL of polysulfide and polyurethane, along with saved heating energy.

In the original scenario, the alternative sealant loses air tightness after 20 years, initially showing no use effect. In a sensitivity analysis varying this point, the break-even point occurs around 25.5 weeks once the window starts losing air tightness (20 years). This suggests that, at this point, the benefit outweighs the burden of silicone's higher production GWP.

3.10. Wind turbines

This chapter relies on the CES Green Deal (GD) 2021 report, focusing on Silicones' role in supporting the EU Green Deal's decarbonization. Silicones, crucial in wind turbines, enhance durability, reduce friction, as transformer oil provide electrical insulation[103] and improve energy efficiency. The case study centers on silicone lubricants, aiming to increase energy generation by up to 8%[104]. Functional unit considered is an 8 MW wind turbine over its 25-year lifespan.

Production, use phase and end of life

Silicone lubricant is compared to a synthetic alternative over wind turbine's 25-year service life. Approximately 10 tons of lubricant are used during this period[105]. An 8 MW wind turbine with 4,000 annual full load hours with silicone lubrication yields 8%[104] more energy than one with synthetic oil, resulting in an annual benefit of 2.37 GWh of green energy. This equates to a CO_2eq. reduction based on an average electricity mix of 0.45 kg CO_2eq./kWh[106]. Both lubricants are assumed to undergo energy recovery in industrial plants (90%), with the remaining 10% dissipating into the environment during operation. The carbon content difference between both lubricants (32% vs. 86%) contributes to the emission benefit for the silicon-based lubricant, which is released as CO_2 upon combustion.

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[103] Shin-Etsu. (2010). Silicones for Wind Power Applications. Shin-Etsu Chemical Co. Ltd.

[104] Global Silicones Council. (2020). Socio-economic evaluation of the global silicones industry. In: Wood Environment & Infrastructure Solutions UK Limited

[105] Umweltbundesamt. (2021). Aktualisierung und Bewertung der Ökobilanzen von Windenergie- und Photovoltaikanlagen unter Berücksichtigung aktueller Technologieentwicklungen. In: CLIMATE CHANGE 35/2021.Dessau

[106] 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. 08/2021.

Results

Silicone lubricant demonstrates substantial benefits during the use phase, outweighing higher production efforts. Impact is defined as the production & EoL of silicone lubricant in an 8 MW wind turbine for one year, leading to an 8% increase in energy output. Benefit is defined as the substituted production and EoL of synthetic lubricant, combined with the generated green electricity in the use phase.

Varying the silicone lubricant's performance within +/- 2% results in a **benefit/impact ratio ranging from 289.9 to 465.5**.

3.11. PU additives for thermal insulation in appliances

This chapter, based on the CES Green Deal (GD) 2021 report, focuses on Silicones' role in supporting the EU Green Deal's decarbonization. Polyurethane (PU) in rigid foam for appliance insulation incorporates polyether siloxane to regulate foam cell size. The study hypothetically compares PU to mineral wool in a 272-liter refrigerator. This study is a hypothetic assessment since alternatives with higher U-values are no longer available due to increased energy demand. The assessment spans production, altered energy demand during use, and waste management. Polyether siloxane receives a share of the benefit. **The functional unit considered is a 272-liter refrigerator with a 12 kg[107] insulation space, favoring PU with a lifetime of 12 years.**

Production, use phase and end of life

Polyurethane (PU) for refrigerator insulation is characterized by a siloxane/polyether weight ratio of 30:70, with a GWP of 3.4 kg CO_2eq./kg[108]. PU density is 35 kg/m^3, thermal conductivity is 0.020 W/mK, and blowing agent GWP is 1.1 kg CO_2eq./kg. For PU in the production phase an average GWP of 3.8 kg CO_2eq./kg is used - based on Ecoinvent 3.8[108] and the information from experts. The alternative material, mineral wool[109], has a density of 50 kg/m^3, thermal conductivity of 0.035 W/mK, and a GWP of 1.46 kg CO_2eq./kg. The mass of mineral wool within one refrigerator is 17.1 kg.

During the 12-year lifetime, PU demands 824 $MJ_{el.}$/a[110], and mineral wool requires 1245 $MJ_{el.}$/a. A weighted average electricity mix for regions of 0.49 kg CO_2eq./kWh is applied. Blowing agents contribute to a GWP of 0.7 kg CO_2eq./kg for PU, while mineral wool has 0 kg CO_2eq./kg in the use phase.

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[108] 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. 08/2021.

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[110] Michel A., Attali, S., Bush, E. (2016). Energy efficiency of White Goods in Europe: monitoring the market with sales data – Final report. ADEME

Silicone benefits are allocated based on the GHG emissions ratio of polyether siloxane to polyurethane production. In waste management, mineral wool has no effects due to no fossil C-content, and polyether siloxane's contribution in the EoL phase is neglected in the 80:20 approach.

Results

Differences in insulating capacities lead to higher energy consumption in the use phase for the alternative material, dominating the GWP balance. The production and transport GWP for silicone (47.2 kg CO_2eq./FU) is higher than the alternative (26.0 kg CO_2eq./FU), with a higher EoL phase GWP (3.8 kg CO_2eq./FU) compared to the alternative's 0 kg CO_2eq./FU due to no C-content. The benefit/impact ratio is 15.5, favoring silicone despite its higher production and EoL phase GWP. Impact is defined as production & EoL of polyether siloxane. Benefit is defined as substituted production, use, and EoL of mineral wool insulation boards, saved energy due to substitution, with only the siloxane-related share considered (allocation based on GWP).

The benefits of silicone are allocated based on the GHG emissions ratio of polyether siloxane to polyurethane production (0.8%). In a sensitivity analysis, the benefit allocation factor varies from 0.4% to 1.6%, resulting in a **benefit/impact ratio ranging from 6.9 to 27.6**.

3.12. Antifoaming in detergents

The drive for resource efficiency[111] in personal hygiene focuses on making washing machines more efficient and reducing detergent usage. Densification, emphasizing lower detergent dosages, aligns with sustainability goals. Silicon optimizes detergent formulations, reducing the need for detergent per cycle[112]. This, along with modern washing systems, achieves comparable results with less water and energy. A comparison of silicone and non-silicone detergents considers factors like detergent quantity and surfactant usage. **The functional unit considered are 100 washing cycles.**

Production, use phase and end of life

The average composition of silicone-based detergents, as per experts, contributes to a total GWP of 2.23 kg CO_2eq./kg for production, resulting in 0.21 kg CO_2eq. per washing cycle and 21.73 kg CO_2eq. per functional unit (FU)[113]. In comparison, the alternative detergent, based on fatty acids, has a GWP of 0.31 kg CO_2eq. per washing cycle and 31.13 kg CO_2eq. per FU. The assumed dosage for silicone-based detergents is 97.5 g/washing cycle (9750 g/FU), while the non-silicone detergent is assumed to require 130 g/washing cycle (13,000 g/FU) to

[111] IKW (2017). Nachhaltigkeit in der Wasch-, Pflege- und Reinigungsmittelbranche in Deutschland 2015-2016. Retrieved from www.ikw.org/haushaltspflege/themen/nachhaltigkeit/ikw-nachhaltigkeitsbericht-aktuell/. 12/2021

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[113] 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 . 08/2021.

achieve comparable results. A sensitivity analysis considers variations in detergent dosage[114]. Waste management for all regions considered assumes 90% of waste is separately collected, with 80% landfill and 20% incineration, and 10% dissipated. Wastewater treatment is not considered in this study.

Results

The benefit/impact ratio is 3.6 for silicone anti-foaming in detergents for the functional unit of 100 washing cycles compared to the GHG emissions of a non-silicone antifoaming agents.

In a sensitivity analysis considering different consumer behaviors, the average dosage of detergents is varied. For silicone detergents, the average dosage is 97.5 g/washing cycle, ranging from 65 g/washing cycle (min) to 130 g/washing cycle (max). The alternative product has a calculated dosage of 130 g/washing cycle, varied from 97.5 g/washing cycle (min) to 162.5 g/washing cycle (max). **The benefit/impact ratio ranges from -0.4 to +2.6 with the maximum silicone dosage, and from +4.7 to +10.6 with the minimum silicone dosage**, compared to the average dosage.

3.13. Water repellents in construction – concrete

In construction, silicone-based water repellents are commonly used for impregnating concrete surfaces[115], offering protection against weathering, freezing, and thawing effects. The silicone penetrates the concrete, preventing moisture ingress and enhancing the structure's longevity (Figure 7)[116, 117]. The impregnation also shields against corrosion from deicing salts, extending the life of the structure[116]. The study focuses on a concrete bridge pillar treated with a silicone-based water repellent, comparing it to an untreated pillar.

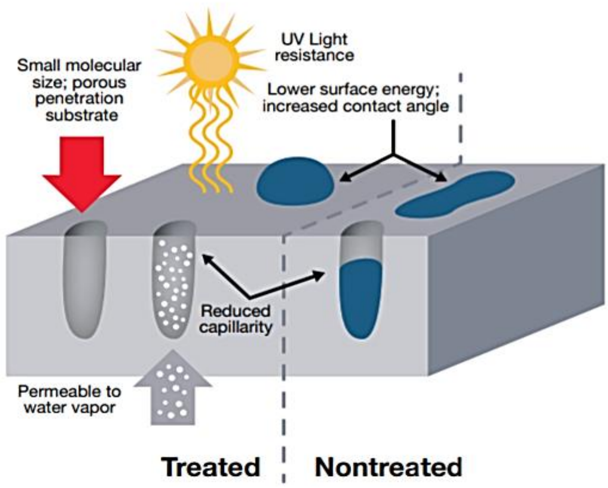

Figure 7: Mode of action of a silicon-based water repellent.

The functional unit is the impregnation of an average bridge pillar (1 x 4 x 10 m) with a 100 m^2 surface containing approx. 96 t of concrete and 8 t of steel . The impregnation, applied as a neat substance without solvents, is based on silanes/siloxane resins and is typically

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[114] denkstatt. (2022). External expert interviews. 02/2022.

[115] denkstatt. (2021). External expert interviews. 09/2021.

[116] McAuliffe, T., (2019). Concrete Protection with Silanes. DOW Performance Silicones. [online] Retrieved from https://www.dow.com/content/dam/dcc/documents/en-us/tech-art/62/62-15/62-1567-01-concrete-protection-with-silanes.pdf?iframe=true. 11/2021.

[117] DOW (2021) Limited silanes – bonding organic and inorganic materials. The Dow Chemical Company. [online] Retrieved from https://www.dow.com/content/dam/dcc/documents/en-us/mark-prod-info/26/26-2350-01-silanes-bonding-organic-inorganic-materials.pdf. 01/2022

used at a rate of 200 g/m^2. With an application renewal every 15 years, a pillar's 90-year lifespan requires six treatments, totaling 120 kg of repellent per functional unit[115].

Production, use phase and end of life

The silicone material used in water repellents contains siloxane resins and/or alkyl- or alkoxy-silanes with variable organic additives[116, 118]. An average GWP of 4.72 kg CO_2eq./kg of active ingredient is used for calculations. The lifetime extension of a bridge pillar due to a silicone-based water repellent is estimated to be approximately 20 years[119, 120, 121], resulting in a total assumed lifetime of 90 years[116].

GWP data for concrete and steel production is sourced from Ecoinvent 3.8. The degradation rate of the water repellent over time is considered, with trials indicating that after 15 years, 67% of a silane impregnation on concrete bridge elements remains[122]. For the 90-year lifespan of the bridge pillar, it is assumed that 33% of the impregnation dissipates and does not enter the waste management system, while the remaining 67% goes to landfills for building rubble or recycling, with all carbon in dissipation routes counted as CO_2 emissions and no further degradation during landfilling.

Results

GWP calculations indicate that the benefit of reduced concrete and steel consumption is 11.6 times higher than the additional impact of the impregnation from production and EoL. Impact is defined as production of silicone-based water repellent used to impregnate concrete surfaces. Benefit is defined as the increased lifetime of the ferroconcrete elements, i.e., reduced consumption of concrete and steel.

The lifetime extension of the concrete bridge pillar, attributed to the water repellent application, significantly influences the calculation of reduced steel and concrete consumption and, consequently, the benefits of the repellent. The benefit/impact ratio varies between 5.8 and 17.4, depending on the assumed extension of the bridge pillar lifetime (ranging from 10 to 30 years). With a conservative 10-year extension, the net benefit decreases to 26.2 kg CO_2eq./kg, while with a 30-year extension, the net benefit increases to 89.5 kg CO_2eq./kg.

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118 denkstatt. (2021). External expert interviews. 12/2021.

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3.14. Masonry water repellent – bricks

Silicone-based masonry water repellents are applied to brick façades for moisture protection, durability and preventing weathering[123, 124]. **Functional unit considered is a 100 m^2 brick façade treated with a silicone-based repellent, applied at a rate of 20 g/m^2 every 10 years.** Over a 10-year period, 2 kg of silicone is used per functional unit[125]. The impregnation aims to reduce thermal transmittance, leading to heating energy savings. The benefits of this treatment will be quantified and compared to an untreated brick façade[125].

Production, use phase and end of life

The study considers a silicone-based water repellent for brick façades, with an active ingredient GWP of 4.72 kg CO_2eq./kg. The paint solvent GWP of 0.54 kg CO_2eq./kg is used[126]. Energy savings from thermal insulation are conservatively estimated at 5%[127], resulting in a U-value reduction from 1.77[128] to 1.68 W/Km^2. The calculated energy savings over 10 years are approximately 19.4 GJ, equivalent to 2064 kg CO_2eq.[129, 130, 131]. The masonry water repellent is conservatively assumed to degrade by 50% after 10 years, with the remaining half going to landfills[132]. The benefit is allocated to the silicone-based component, accounting for 10% of the use benefits.

Results

The GHG benefit from saved heating energy due to impregnating a brick façade with a silicone-based masonry water repellent is 22 times higher than the GHG emissions from producing and disposing of the water repellent. Impact includes production of the silicone-based active ingredient and solvent, while benefit is the 5% reduction in heating energy consumption due to increased thermal insulation. **The benefit/impact ratio ranges from 65.2 to 173.9, depending on the variable heating energy savings between 3% and 8%. With a conservative 3%**

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[129] EEA. (2019) Indicator Assessment: Heating and cooling degree days. [online] Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/heating-degree-days-2/assessment. 12/2021

[130] Sönnichsen, N., (2021). Number of heating degree-days in the U.S. 1950-2020. [online] Retrieved from https://www.statista.com/statistics/245632/number-of-heating-degree-days-in-the-united-states/. 12/2021

[131] IEA (2021) Heating degree days in Japan, 2000-2020. [online] Retrieved from https://www.iea.org/data-and-statistics/charts/heating-degree-days-in-japan-2000-2020. 12/2021

[132] denkstatt. (2021). External expert interviews. 09/2021.

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reduction, the net benefit is 37.5 kg CO_2eq./kg, while an 8% reduction results in a net benefit of 100.9 kg CO_2eq./kg.

3.15. Conformal coatings in electronics

Conformal coatings, thin protective films applied to printed circuit boards (PCBs), safeguard electronic components from environmental factors. This study examines coatings based on acrylic resin (AR), silicone resin (SR), and urethane resin (UR). Each has distinct advantages: AR offers high dielectric strength and easy removal, SR excels in wide temperature ranges and chemical/moisture resistance, and UR provides excellent moisture and chemical resistance[133]. Despite their unique properties, this study assumes interchangeability for GWP comparison. **The functional unit considered is 100 m^2 of coated substrate.**

Production, use phase and end of life

Conformal coatings for printed circuit boards typically include base materials and solvents like xylene and acetone[134, 135]. In this study, coatings with solvents are compared. The assumed formulation for the silicone resin coating consists of silicone resin (33%), xylene (16.5%), acetone (16.5%), and dimethyl ether (33%). The urethane resin coating formulation is urethane resin (98%) and ethylbenzene (2%)[136]. The acrylic coating formulation assumes equal distribution of ethyl acetate, acetone, and propane (33% each). After coating, the PCB undergoes heating[136], and the baking energy is estimated based on an industrial bread baking process. The study compares silicone resin coating with a hypothetical mix of urethane and acrylic coatings. All GWP data, except for PDMS resins and ethyl acetate, is taken from Ecoinvent 3.8[137]. The assumed end-of-life scenario involves collecting coatings in residual waste with region-specific waste pathways. The study assumes coatings are interchangeable, and no GWP is calculated for the use phase.

Results

The GWP impact of silicone in the silicone conformal coating is 1.2%, with the heating process for drying being the primary contributor across all coatings. As the heating process is the same for all coatings, there is minimal difference between silicone and alternatives. Impact is defined as the production of the silicone-based active ingredient, while benefit is the increased lifetime of the coated surface.

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133 Techspray (2022) – The essentail guide to conformal coating (online). Retrieved from Essential Guide to Conformal Coating | Techspray

134 Brian Chislea, Erica J. Everett – Getting Started with Silicone Conformal Coatings (online). Retrieved from Getting Started with Silicone Conformal Coatings - EE Times Asia (eetasia.com)

135 MG Chemicals – Technical Data Sheet – Silicone Conformal Coating 422B. Retrieved from 0900766b8154a5b4.pdf (rs-online.com)

136 Google Patents – Conforaml coating formula and conformal coating usage method. Retrieved from CN103436154A - Conformal coating formula and conformal coating usage method - Google Patents

137 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. 07/2021.

The sensitivity analysis for different coating thicknesses shows a nearly equal benefit/impact ratio close to 1. Slight advantages for the silicone product suggest potential benefits in production and/or end-of-life phases, assuming interchangeability and equivalent coating lifetimes.

3.16. Electrical isolators & insulations

This chapter draws primarily from the CES Green Deal (GD) 2 report, focusing on Silicones' role in advancing the EU Green Deal's decarbonization objectives. It incorporates a mix of European, North American, and Japanese data, emphasizing a geographical shift. The case study explores isolators for high-power lines, assuming interchangeability between ceramic, EPDM rubber, and silicone rubber. Ceramic isolators, with a lifespan of around 30 years[138], currently dominate, and any shift in materials is expected to be gradual.

Silicone isolators offer advantages such as initial hydrophobicity, lightweight design, weather resistance, cost-effectiveness in installation, and improved leakage current control. **The functional unit considered is an isolator with 20 sheds ("layers").**

Production, use phase and end of life

A silicon isolator comprises a non-silicone core and silicone sheds, with the core made of glass fibre-reinforced plastic. Fictitious silicone isolator sheds consist of approximately 57% silicone high consistency rubber (HCR), 23% aluminium hydroxide, 14% silica filler, and 6% aluminium oxide. The mass of one silicone isolator is 8 kg[139], with 50% attributed to the non-silicone core[138], resulting in 4 kg for the silicone sheds. The core for all isolators, including EPDM and ceramic[140, 141, 142], is assumed to be identical. EPDM isolators are filled with 50% aluminium hydroxide[143], with a mass of 8 kg. Ceramic isolators use an average GWP value[143] for "ceramic tiles" and "sanitary ceramics," with a mass of 84 kg and 5% breakage rate.

The expected lifetimes are 40 years for ceramic[144], 30 years for EPDM, and 20 years for silicone isolators, with a market share assumption of 40% silicone, 50% ceramics, and 10% EPDM[145]. Pollution and humidity affect isolators, and silicone surfaces are known to reduce maintenance in high-voltage insulation[139].

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138 denkstatt. (2021). External expert interviews. 08/2021.

139 denkstatt. (2012). External expert interviews. 08/2012

140 Klebeprofi – GFK Kleben (online). Retrieved from Tipps zum GFK kleben | Der 3M™ Klebeprofi

141 Sattler-scm – EPDM (Ethylen-Propylen-Dien-Kautschuk) (online). Retrieved from Alles über das Material EPDM (Ethylen Propylen Dien Kautschuk) (sattler-scm.de)

142 r-g – Glasfasern (online). Retrieved from Glasfaser Wiki - Einsatzgebiete der Glasfasern - R&G Wiki (r-g.de)

143 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. 07/2021.

144 INMR – Testing Ageing of Porcelain Insulators (online). Retrieved from Testing Ageing of Porcelain Insulators - (inmr.com)

145 denkstatt. (2022). External expert interviews. 01/2022

The cleaning of isolators and electricity lost due to leakage current are challenging to quantify, and no use effect is considered. Worn and dismantled isolators are assumed to be collected, with 50% in residual waste and 50% following region-specific waste collection pathways.

Results

The production impact of ceramics, due to its high mass, is significantly higher than that of silicone, resulting in a clear GWP advantage for silicone isolators. The effects of better surface properties of silicone, not accounted for, would further enhance this advantage. Impact is defined as the production and end-of-life (EoL) of silicone for electrical isolators, while benefit is defined as the substituted production and EoL of ceramic and EPDM isolators.

The assumed lifetime of silicone isolators is a crucial factor in calculating the benefits of substituting ceramic and EPDM isolators. The **benefit/impact ratio ranges between 2.0 and 3.5** when varying the lifetime expectancies of isolators between 15 and 30 years. **Assuming a conservative 15-year lifetime, the net benefit of the silicone isolator is 3.07 kg CO_2eq./kg.** With a 30-year lifetime - 7.5 kg CO_2eq./kg.

3.17. Heat resistant industrial coatings

The information in this chapter is primarily derived from the CES Si-Chemistry Carbon Balance 2012 report, focusing on the role of silicones in supporting the EU Green Deal's decarbonization goal. Changes made for this application involve updated data inputs and methodological adjustments. Silicone resin serves as a critical component in heat-resistant industrial coatings, applied to surfaces like hot industrial steel and corrugated roofs. The coating process involves a zinc primer, which requires heating to cure, followed by the application of silicone resin paint, which, according to company information, does not necessitate additional heating[146].

The zinc-silicone coating is compared to a mean value of two alternatives, as described below:

- Silicone resin coating prevents corrosion of industrial, hot equipment for an extended period, resulting in a longer service life (assumption: 75% longer service life[146], leading to avoided steel production).
- Enameling - a historic alternative with no zinc coating before enameling; assumed identical lifetime as zinc primer plus silicone resin coating.

The functional unit considered is 1 m^2 of coated surface with a steel thickness of 2 mm and a silicone resin coating thickness of 125 µm.

Production, use phase and end of life

The coating process involves applying a zinc primer[147], followed by heating and curing at 200°C for 1 hour, and finally, adding silicone resin paint (25% silicone resin, 25% aluminium pigments, 50% solvent) without further

[146] denkstatt. (2021). External expert interviews. 08/2021.

[147] Zinep (2018) – technical datasheet. Retrieved from ZINEP (vmp-anticor.com)

curing. The GWP of PDMS resin is 6.36 kg CO_2eq./kg[148]. Curing energy is estimated based on an industrial bread baking process using a gas turbine (50% sour gas, 50% sweet gas). Coated steel with zinc-silicone resin is assumed to have a 75% longer lifetime than zinc coating alone, equivalent to enamelling-treated steel. In the waste management scenario, 90% of coated steel is assumed to be recycled, while 10% goes to landfill. The recycling share and the choice between incineration or landfill for residual waste depend on regional practices.

Results

Results are based on assuming a 25% extended lifetime for zinc-silicone resin-coated steel compared to an alternative (zinc coating and enamelling mix). The production, transport, and waste management of silicone resin coating result in 2.8 kg CO_2eq., while coating with zinc or enamelling leads to 5.8 kg CO_2eq.. Impact is defined as the production of silicone resin coating. Benefit is derived as an average of 2 approaches:

- silicone resin coating extends the coated steel lifetime, reducing the need for zinc-coated steel
- silicone resin coating substitutes enamelling.

The sensitivity analysis varies the assumed lifetime extension between 25% and 100% of the expected lifetime of enamelling and zinc coating. **With a conservative 25% extension, the net benefit of silicone coating is 128.1 kg CO_2eq./kg.** With a 100% extension, the net benefit reaches 299.6 kg CO_2eq./kg. Assuming the same 25% extension, **the benefit/impact ratio is 2.6, and the net benefit of silicone is 104.2 kg CO_2eq./kg.**

3.18. Silicone foam for thermal insulation

Silicone foam, known for its high thermal resistance and fire resistance, finds applications in various fields, particularly in pipeline insulation. This case study focuses on the insulation of a 100 m^2 pipeline surface, comparing silicone foam to a combined system of EPDM rubber[149] and PU foam[150]. While silicone foam is more expensive[151] and has higher thermal conductivity and resistance[149] than alternatives like PU foam, it offers superior fire resistance. In addition silicon foam does not produce toxic combustion gasses[151] in contrast to other materials[152].

[148] 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. 07/2021.

[149] KS. (2021) KS SIL F-230 SILIKONSCHAUM – Technisches Datenblatt. KS KNEISSL & SENN TECHNOLOGIE. [online] Retrieved from: https://ks-tech.at/wp-content/uploads/2021/09/KS-SIL-F230_Silikonschaum_Silicone-sponge_TBD_TDS_1KSA.pdf. 02/22

[150] Zhang, H., Fang, W. Z., Li, Y. M., & Tao, W. Q. (2017). Experimental study of the thermal conductivity of polyurethane foams. Applied Thermal Engineering, 115, 528-538.

[151] denkstatt. (2021). External expert interviews. 09/2021.

[152] McKenna, S. T., & Hull, T. R. (2016). The fire toxicity of polyurethane foams. Fire Science Reviews, 5(1), 1-27.

The functional unit considered is 100 m^2 of insulated pipeline surface with a 50-year lifespan[153, 154]. A common thickness for silicone foam insulation is approximately 20-30 mm, requiring 960 kg of silicone foam (density: 320 kg/m^3 [149]). The comparative system[155] combines 25 mm of EPDM (density: 1340 kg/m^3) and 7 mm of PU foam (density: 30 kg/m^3), resulting in a U-value[156] of about 1.68 W/m^2K, matching the silicone foam system.

In summary, for the same U-value, the silicone foam system demands 960 kg of material, while the combined EPDM and PU foam system requires 3350 kg of material. Despite the higher thermal conductivity, the benefits of silicone foam, especially in terms of fire resistance, make it a suitable choice for pipeline insulation.

Production, use phase and end of life

Silicone foam, as reported by GSC member experts, comprises approximately 75% silicone-based active ingredient and 25% silica filler. The active ingredient, vinyl-capped-polydimethylsiloxane[157], contains about 3% vinyl and 97% PDMS[158], with a resulting GWP[159] of 6.46 kg CO_2eq./kg for silicone foam. PU foam additives have a GWP[159] of 3.86 kg CO_2eq./kg, and EPDM has a GWP[159] of 2.79 kg CO_2eq./kg.

As both silicone foam and the combined EPDM and PU foam system offer equivalent thermal insulation and fire resistance, the use phase is deemed irrelevant for these calculations. Approximately 20% of the silicone foam used for pipeline insulation is assumed to end up in residual waste. Waste disposal paths for both systems involve landfill, industrial energy recovery, or no waste management, with specific percentages varying by geographic region.

Results

Benefit/impact calculations show that benefits of the silicone foam prevail over the life cycle GWP of silicone foam used for thermal insulation compared to a combined system, consisting of EPDM and PU foam. Impact is defined as the production and EoL of silicone foam. Benefit is defined as equal thermal insulation and fire/thermal resistance with lower GHG emissions. The benefit of silicone foam usage is twice as high as the impact of its production and EoL.

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[153] Najafi, M. (2011). Pipeline rehabilitation systems for service life extension. In Service life estimation and extension of civil engineering structures (pp. 262-289). Woodhead Publishing.

[154] denkstatt. (2021). External expert interviews. 01/2022.

[155] Brederoshaw (2015). PCP and EPDM – Rubber-Based Anti-Corrosion Systems. Bredero Shaw – a ShawCor Company. [online] Retrieved: https://www.yumpu.com/en/document/read/35512960/pcp-and-epdm-bredero-shaw. 02/22

[156] Grimm, R., (2019) Was ist der U-Wert. BaustoffWissen. [online] Retrieved from: https://www.baustoffwissen.de/baustoffe/baustoff-knowhow/bauphysik/was-sind-u-wert-und- %CE %BB-wert/. 02/22

[157] denkstatt. (2022). External expert interviews. 01/2022.

[158] Arkles, B. (2016). REACTIVE SILICONES: FORGING NEW POLYMER LINKS - Vinyl-Functional Silicones. Gelest, Inc. [online] Retrieved from: Vinyl-Functional Silicones - Gelest. 01/22

[159] 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.om/10.1007/s11367-016-1087-8. 08/2021.

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The thickness of silicone foam insulation can vary between 10 and 50 mm based on GSC member feedback[157]. A sensitivity analysis was conducted, resulting in a **benefit/impact ratio ranging from 5.9 for a thinner silicone layer (10 mm) to 1.2 for a thicker layer (50 mm)**. This variation in silicone foam thickness leads to net benefits ranging from 32.0 kg CO_2eq./kg to 1.2 kg CO_2eq./kg.

3.19. Adhesion promoter for coatings

Silane-based adhesion promoters, serving as effective coupling agents, enhance the adhesion of paints, inks, coatings, adhesives, and sealants to various surfaces[160]. These promoters not only improve adhesion but also enhance abrasion and UV resistance, thermal stability, and durability[161]. Their primary application is in enhancing adhesion between organic resins and metals, forming strong bonds with metal surfaces[162]. Silane-based adhesion promoters (Figure 8[163]), with modifiable organic functional groups (denoted as R-), are versatile and suitable for various substrates such as glass, wood, and construction materials.

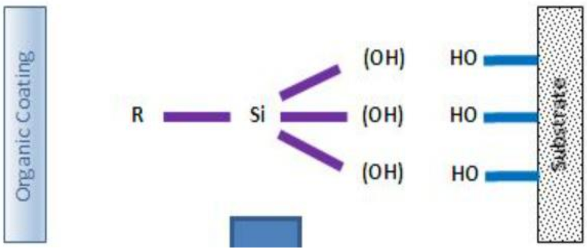

Figure 8: Bonding between adhesion promoter components, inorganic surface and coating.

These promoters can be used as primers applied before coating or as integral additives within the coating, enhancing adherence[164] by preventing flaking under adverse conditions. Approximately 10–15% of global adhesion promoters use silane as the functional ingredient[162]. The current study focuses on silane-based adhesion promoters blended into paints to improve adhesion and extend coating lifetimes, comparing them to coatings without promoters based on renewal durations. **Functional unit considered is 100 m² of coated substrate.**

Production, use phase and end of life

The active ingredient in silane-based adhesion promoters, assumed to be organosilanes[165, 166], is attributed a GWP of 2.60 kg CO_2eq./kg. Blended into paint coatings at a rate of 1%, the adhesion promoter consists mainly of organosilanes (approximately 80%) and MeOH (approximately 20%). The application rate is 0.1 kg of

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160 Pape, P. G. (2011). Adhesion promoters: Silane coupling agents. In Applied plastics engineering handbook (pp. 503-517). William Andrew Publishing.

161 DOW (2021) Limited silanes – bonding organic and inorganic materials. The Dow Chemical Company. [online] Retrieved from https://www.dow.com/content/dam/dcc/documents/en-us/mark-prod-info/26/26-2350-01-silanes-bonding-organic-inorganic-materials.pdf. 01/2022

162 denkstatt. (2021). External expert interviews. 09/2021.

163 Makala, V., (2018) Select Adhesion Promoters for Coatings. SpecialChem – The material selection platform. [online] Retrieved from https://coatings.specialchem.com/selection-guide/select-adhesion-promoters-for-coatings. 12/2021

164 Dow Corning. (2005). A guide to silane solutions. Dow Corning Corporation. Form No. 26-1328-01.

165 Pape, P. G. (2011). Adhesion promoters: Silane coupling agents. In Applied plastics engineering handbook (pp. 503-517). William Andrew Publishing.

166 Abel, M. L. (2011). 11 Organosilanes: Adhesion Promoters and Primers. Handbook of Adhesion Technology, 237.

organosilanes per 100 m^2 of paint[162]. The use of adhesion promoters increases coating durability, with an assumed extension of approximately 50% in coating lifetime[161]. A sensitivity analysis varies the lifetime extension between 20% and 80%. In the production phase, assuming an application rate of 14.9 kg paint per 100 m^2, the GWP of standard white alkyd paint is derived as 5.35 kg CO_2eq./kg[167].

Waste phase modeling considers the carbon content and calorific value of paint based on PMMA data, accounting for both production and waste in the use phase. Benefits are allocated to the promoter components, with 94% allocated to organosilanes. Approximately 25% of the silicone adhesion promoter ends up in residual waste, and disposal methods vary regionally. Around 25% is disposed with building rubble, going entirely to landfills. The remaining 50% is collected separately, with 90% incineration and 10% landfill.

Results

The overall benefits of using silicone adhesion promoters in paint coatings, considering their life cycle GWP, far exceed their environmental impact. The impact, defined as the production and end-of-life (EoL) of the silicone adhesion promoter, is outweighed by the benefit of reduced paint consumption due to a longer coating lifetime.

The benefit is 136.5 times higher than the impact, with a crucial parameter being the lifetime expansion of the coating. A realistic 50% lifetime expansion leads to a net benefit of 142.5 kg CO_2eq./kg. Sensitivity analysis shows that **with a conservative 20% lifetime extension, the benefit/impact ratio is 54.5, resulting in a net benefit of 142.5 kg CO_2eq./kg.** With an 80% lifetime extension, the benefit/impact ratio reaches 217.2, and the net benefit increases to 576.2 kg CO_2eq./kg.

3.20. Coating of means of transport, antifouling coatings

Antifouling coatings are vital for the global marine shipping industry, reducing fuel consumption[168] by minimizing drag. However, existing coatings often release biocides and copper-based materials into the sea, posing environmental concerns. A hypothetical case study explores the potential benefits of a biocide-free silicone antifouling coating, aiming to protect marine ecosystems. **Functional unit considered are 14,000 tons of silicone coating (market size in Europe, North America and Japan) applied to 5% of the global marine fleet over 1 year.**

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[167] 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.om/10.1007/s11367-016-1087-8. 08/2021.

[168] McKinsey (2009): Innovations for Greenhouse Gas Reductions A life cycle quantification of carbon abatement solutions enabled by the chemical industry.

Production, use phase and end of life

Globally, the marine industry annually produces anti-fouling coatings worth about US$ 2 billion[169], equivalent to 200,000 metric tons. The coatings contain 50% solids and 30% solvents[170], with assumed biocide and silicone application rates being equal. In the marine shipping industry, the annual fuel consumption is about 213 Mt, and it is estimated that without these coatings ship fuel consumption would be 15% higher. Assuming 5% of ships use silicone-based coatings, it leads to a conservative fuel saving of 6% with a marine footprint of 3.63 kg CO_2eq./kg fuel. The study disregards the production of the baseline product to maintain a conservative assessment. It's presumed that 100% of the coating washes off into the sea, degrading into non-GHG relevant CO_2.

Results

The use benefit of silicone antifouling product outweighs the impact from the production by far, due to the huge potential of fuel saving through a small amount of product. Impact is defined as the production of silicone resin. Benefit is defined as the saved fuel. The starting point for the sensitivity analysis is the value of 15 % based on information provided by GSC members[171]. The fuel saving of 29 % is used as the maximum as assumed by McKinsey[172]. 4 % is taken as the minimum value.

3.21. Electric transport (bicycle, electric and hybrid cars, train)

Silicone rubber, replacing traditional materials in plug-in hybrid electric vehicle (PHEV) exhaust hangers, enhances fuel efficiency[173] by preventing aerodynamic drag[174]. This is crucial, as a 10% reduction in drag (C_D) typically improves fuel economy by 2-2.5%[173]. With silicone's high-temperature resistance (up to 425-625°C[175]), it allows the exhaust system to be covered by the underbody panel, contributing to a more fuel-efficient design[176]. **Functional unit considered is a hybrid EV (PHEV) drive train over a 240,000 km (8 years)[177] lifespan.** This aligns

[169] imarc (2022) Global Antifouling Paints and Coatings Market: Industry Trends, Share, Size, Growth, Opportunity and Forecast 2021-2026.

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[175] Song, J., Huang, Z., Qin, Y., & Li, X. (2019). Thermal Decomposition and Ceramifying Process of Ceramifiable Silicone Rubber Composite with Hydrated Zinc Borate. Materials, 12(10), 1591.

[176] denkstatt. (2021). External expert interviews.

[177] Cascade collision. (2018). How Many Miles Can a Car Last?. Retrieved from https://cascadecollision.com/blog/what-is-the-average-life-of-a-car/ (accessed 12/21)

with industry standards, reflecting an average possession lifespan of new passenger cars in Japan of 7.2 years[178, 179].

Production, use phase and end of life

For the study, exhaust pipe hangers made of PDMS rubber were considered, replacing traditional EPDM. The assumed average volume of the PDMS rubber-based pipe hanger is 55 cm^3, weighing 0.1914 kg[180, 181]. The underbody cover, assumed to be polypropylene (PP) produced through injection molding[182], has a mass of 14.7 kg[173]. Fuel and energy input savings are estimated at 3%[183], considering a private PHEV with a utility factor (UF) of 69%[184], indicating the share of mileage on the electric motor versus the combustion engine.

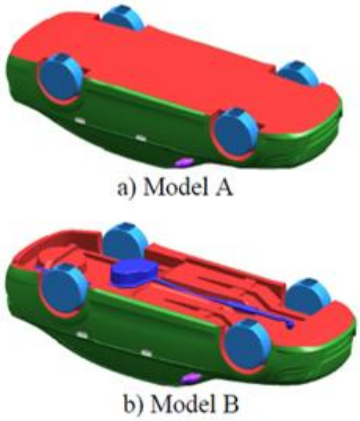

Figure 9: Chassis with (Model A) and without (Model B) underbody panel.

GHG emissions from burning petrol and diesel were calculated based on a weighted average dataset for European, North American, and Japanese PHEV car mixes. The resulting emission factor for petrol and diesel fuel combustion and supply is 0.16 kg CO_2eq./km. GHG emissions for used electric energy in HEVs were considered with input data of 0.15 kWh/km[185] and an average electricity mix GWP of 0.077 kg CO_2eq./km[186]. The allocation factor for use phase allocation is 0.025, derived from a GWP-based allocation approach. The end-of-life scenario assumes 100% of PHEVs are collected separately, with varying disposal shares (80% incineration, 20% landfill) based on regional differences in Europe, North America, and Japan[183].

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178 Nakamoto, Y., & Kagawa, S. (2021). A generalized framework for analyzing car lifetime effects on stock, flow, and carbon footprint. Journal of Industrial Ecology.

179 Automobile Inspection and Registration Information Association of Japan. (2019). Passenger carmarket trends. Retrieved from: https://www.airia.or.jp/publish/statistics/trend.html

180 Kang, D. H., Seo, M. Y., Gimm, H. I., & Kim, T. W. (2009). Determination of shock absorption performance and shear modulus of rubbers by drop impact test. Transactions of the Korean Society of Mechanical Engineers A, 33(4), 321-328.

181 Shin-Etsu.(2022). Silicone Rubber: Performance Test Result. Retrieved from https://www.shinetsusilicone-global.com/catalog/pdf/rubber_et.pdf (accessed 12/21)

182 Röchling. (2022). Unterbodenverkleidungen. Retrieved from https://www.roechling.com/de/automotive/produkte-loesungen/aerodynamics/unterbodenverkleidungen (accessed 12/21)

183 denkstatt. (2021). External expert interviews.

184 International Council on Clean Transportation. (2020). Real-world usage of plug-in hybrid EVs fuel consumption, electric driving, and CO2 emissions. Berlin.

185 Verivox. (2020) .Verbrauch beim Elektroauto. Retrieved from https://www.verivox.de/elektromobilitaet/themen/verbrauch-elektroauto/#:~:text=Nach %20Herstellerangaben %20liegt %20der %20durchschnittliche,circa %2015 %20kWh %2F100 %20km. (accessed 11/21)

186 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.

Results

The effect of the production of PDMS based pipe hanger and underbody cover is greater than the effect from the use or the EoL phase. **The benefit/impact ratio changes between 8.9 and 17.9 with the fuel saving varied between 2-4% achieved by a silicone-based pipe hanger system**.

3.22. Lighter automotive parts, coating for polycarbonate

Lightweight automotive glazing, composed of polycarbonate parts coated with a silicone resin layer, provides benefits in reducing fuel consumption due to mass reduction compared to heavier glass alternatives. The functional unit considered is 1 kg of polycarbonate automotive glazing with an average thickness of 4 mm. The silicone resin coating on both sides, with a thickness of 10 µm, contributes a mass of 4.2 grams of silicone resin coating per kg of polycarbonate. The allocation of the total benefit between polycarbonate and the silicone resin coating is determined based on their respective shares of the global warming potential (GWP) in both production and end-of-life (EoL) phases.

Production, use phase and end of life

Silicone resin, with a GWP of 6.7 kg CO_2eq./kg product, includes additional energy consumption during curing (0.7 MJ natural gas per kg polycarbonate) and transportation (0.19 kg CO_2eq./kg product). The equivalent glass part has a 2.1 times higher mass than the polycarbonate part.

GWP data for white glass, polycarbonate production, and baking gas is from Ecoinvent 3.8[187]. A weight saving of 52.2 kg per car over an assumed 11.5-year lifetime leads to fuel savings of about 14,200 MJ for petrol cars and 13,100 MJ for diesel cars[188]. Emission factors for petrol and diesel from Ecoinvent 3.8 are applied[189], considering the average share of diesel cars of 14% in the EU27, North America, and Japan[190] and 18.3 kg CO_2eq./kg saved weight. For automotive plastic part disposal, industrial co-incineration is assumed.

Results

The production of 1 kg of PC automotive glazing parts emits 8.1 kg CO_2eq., while silicone resin production, including baking, only contributes 0.1 kg CO_2eq. due to the thin coating. The equivalent glass parts have lower GHG emissions during production (2.3 kg CO_2eq. lower), but the use phase results in a net-benefit of 12.3 kg

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[187] 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. 11/2021.

[188] ACEA. (2021). Average age of the EU vehicle fleet, by country. Retrieved from https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/. 08/2021.

[189] 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. 08/2021.

[190] 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.

CO_2eq./kg of PC. Impact is defined by the production and end-of-life of the silicone resin coating, while benefit includes the substituted glass glazing (production, transport, end-of-life) and the reduced fuel demand due to the lighter PC. The weight saving from using PC, leading to fuel efficiency, is the primary benefit. The varying share of diesel cars in different regions has a minimal impact on the benefit/impact ratio.

3.23. Reflective roof coatings

A standard flat roof is constructed with "filtron tiles," comprising 4 cm extruded polystyrene insulation covered by gray gravel with a reflective paint coating on the external surface. The tiles utilize a PVC membrane attached to the structural deck of the roof[191]. Gravel, while absorbing sunlight and retaining heat, can reduce the roof's flexibility and lifespan due to the depletion of asphaltic oils[192]. This study considers a polyurethane (PU)-based reflective roof coating as an alternative to Si-based coatings, given a similar market size. Acrylic coatings were excluded due to a lack of data for benefit quantification. The lifetime of a silicone-based coated roof varies between 10-25 years, while a conservative estimate of 17 years was considered for this study. A polyurethane (PU) based coating has an assumed lifetime of 12 years, resulting in a roof replacement factor of 1.4[193]. **The functional unit is 100 m^2 of coated roof surface over a 17-year lifespan.**

Production, use phase and end of life

For coating 100 m^2, about 140 liters (212.52 kg) of reflective roof coating is needed over 20 years[193], with a density of 1.518 g/cm^3 [194]. The coating includes polymers, calcium carbonate filler, solvent, additives, adhesion promoter, and catalysts[193]. Silicone coatings can be low solids (around 67%) or high solids (around 98%)[195]. The GWP for silane is based on Ecoinvent 3.0 data[196], using methyl chlorosilane as a reference. The GWP for PU production is multiplied by a replacement factor of 1.4.

Over 17 years, the alternative roof surface (12-year lifetime) needs to be produced new, with GWP based on inventory data for a 677 m^2 roof over a 10-year lifetime[197], scaled to 100 m^2 for a 17-year lifetime. The replacement factor of 1.42 allocates 42% of the total roof GWP to the alternative system's environmental impact in the use phase. Gravel, with a 50-year lifetime, is not considered in EoL. Insulation materials can be incinerated with

[191] Saiz, S., Kennedy, C., Bass, B., & Pressnail, K. (2006). Comparative life cycle assessment of standard and green roofs. Environmental science & technology, 40(13), 4312-4316.

[192] ITW Polymers Sealants North America. (2014). How-To: Coat Gravel Roofs. Retrieved from https://elastek.com/news/how-to-coat-gravel-roofs/ (accessed 01/22)

[193] denkstatt. (2021). External expert interviews.

[194] Jasim, H. H. (2018). Evaluation the Effect of Vibration on the Corrosion Rate of Automotive Paints, J. Engineering, 24(4), 41-57.

[195] Daisey, G. (2019). Roof Coatings Review: How Chemistry Impacts Quality. Retrieved from https://wsrca.com/blog-post/1648950/316795/Roof-Coatings-Review-How-Chemistry-Impacts-Quality (accessed 02/22)

[196] 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.

[197] Saiz, S., Kennedy, C., Bass, B., & Pressnail, K. (2006). Comparative life cycle assessment of standard and green roofs. Environmental science & technology, 40(13), 4312-4316.

heat recovery[198]. All coated surfaces are assumed to be collected as building rubble, with 70% and 30% going to incineration plants and landfills, respectively, depending on the region[199].

Results

The overall performance differences, up to 74%, are primarily due to the use phase, driven by additional roof production in the alternative scenario without silicone over a 17-year lifetime. Impact is defined as production and EoL of the silicone-based coating and roof. Benefit is defined as substituted production and EoL of the PU-based coating and roof (excluding gravel). **The benefit/impact ratio ranges between 1.6 and 4.1**, depending on the replacement factor for the roof surface concerning the PU-based reflective roof coating.

3.24. PU additives insulation-construction

If PU were unavailable, thicker alternative insulation boards with higher U-values (XPS, foam glass) would be used. A lifecycle comparison of PU, XPS, and foam glass applied on a cellar wall is made for the same functional unit, assuming the same insulating properties but different board thickness. The differences in GHG emissions from production (thicker boards), use (foaming agents), and waste management are considered, and a portion of the benefit is allocated to the polyether siloxane. The functional unit considered is insulation for a 100 m^2 building (cellar) wall below ground level with the same insulation performance as an 8 cm PU board.

Production, use phase and end of life

Assumptions on polyurethane[200]

GWP data for polyether siloxane in rigid PU foam applications is derived from company member information and Ecoinvent 3.8, resulting in a GWP of 3.86 kg CO_2eq./kg[201]. Experts from member companies suggest that the final production step, hydrosilylation, has a negligible influence on the product's carbon footprint. The content of polyether siloxane foam stabilizers in rigid PU foam typically ranges from 0.5% to 1.5%, with an average of 0.8% used for calculations. PU insulation panels typically have a foam density of 30 kg/m^3. Most producers specify a thermal conductivity of 0.023 W/m.K for PU insulation panels with gas-tight facers, representing an average value for 50 years of usage. These key figures guide the analysis of the environmental impact of PU foam applications.

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198 Contarini, A., & Meijer, A. (2015). LCA comparison of roofing materials for flat roofs. Smart and Sustainable Built Environment.

199 denkstatt. (2021). Internal expert knowledge

200 denkstatt. (2021). External expert interviews. 10/2021.

201 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.

Assumptions on alternative materials

XPS insulation panels typically have a density of 32 kg/m^3 [202] and a thermal conductivity of 0.037 W/mK. Their GWP in the production phase is 4.03 kg CO_2eq./kg. Foam glass insulation panels, on the other hand, have a density of 115 kg/m^3 [203] and a thermal conductivity of 0.043 W/m.K. Their GWP in the production phase is 1.45 kg CO_2eq./kg[204]. Both XPS and foam glass insulation panels have a lifespan of 50 years, similar to PU. Additionally, the market share ratio between XPS and foam glass is 80:20[199], respectively. These key figures inform the analysis of environmental impacts associated with XPS and foam glass insulation panels.

The benefits of silicone are distributed based on the GHG emissions of polyether siloxane production compared to polyurethane production, resulting in an allocation factor of 0.67%. In the 80:20 approach, individual consideration of polyether siloxane in the EoL phase is disregarded. PU insulation panels are assumed to follow these waste paths: 20% residual waste, 60% building rubble, and 20% remaining in the ground at the local site without entering the waste management system.

Results

Variations in the use phase reflect the effects of different blowing agents utilized for PU and XPS. No other usage effects are considered, assuming all boards possess identical insulation capacities (differing only in thickness). The benefit/impact ratio is 3.6, primarily attributed to the reduced GHG emissions during the production phase of the silicone application.

The benefits of silicone are determined by the relationship between the GHG emissions of polyether siloxane and polyurethane production, which stands at 0.67%. Even slight changes in production methods and calculation approaches significantly impact the benefit/impact ratio. To ensure accurate comparisons, the allocation factor was directly varied in the sensitivity analysis, ranging from 0.2% to 1.4%. **At the minimum, silicone's benefit/impact ratio is 1.1, while it reaches 7.5 with a 1.40% allocation factor.**

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[202] Danny Harvey, L.D., (2007). Net climatic impact of solid foam insulation produced with halocarbon and non-halocarbon blowing agents, Building and Environment, Volume 42, Issue 8. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360132306003337. 12/2021.

[203] 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. 10/2021

[204] IBU (2021). Umwelt-Produktdeklaration nach ISO 14025 und EN 15804+A2. Retrieved from: https://www.heinze.de/pdfdownload/?pdf=/m2/09/61309/pdf/73/14555173px595x842.pdf. 12/2021.

3.25. Telecommunication

The rapid increase in smartphone usage has heightened the need to reduce energy consumption and GHG emissions in telecommunication networks[205]. Thermal Interface Materials (TIM) are essential for enhancing heat transfer in electronic devices[206]. They fill air gaps between solid interfaces[207], such as between heat-generating components and heat sinks[206] (Figure 10). TIM types include greases, phase change materials (PCM), gels, and adhesives, with common formulations containing 60-90% thermally conductive fillers[206]. Silicone-based TIMs, despite higher coefficients of thermal expansion, offer more stable heat dissipation for processors in smartphones, ensuring reliability throughout the product's lifespan[208, 209]. **Functional unit is 1 piece smartphone over the lifetime of 3 years[205].**

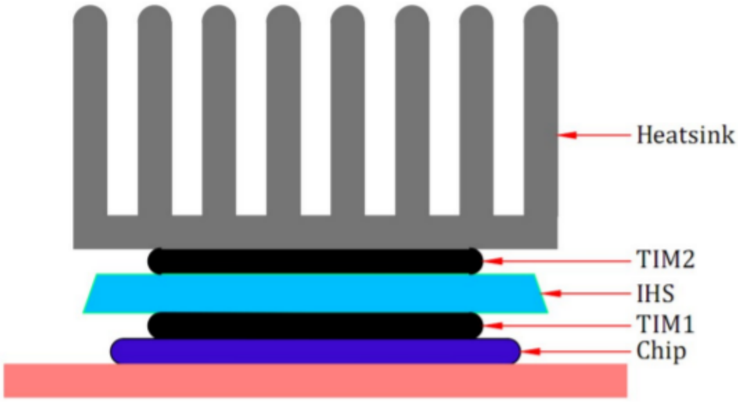

Figure 10: Schematic illustration of a typical electronic package with two TIMs.

Production, use phase and end of life

The silicone-TIM consists of 25% silicone polymer and 75% inorganic filler, weighing 0.15 g/FU[210]. Polyolefins are chosen as an alternative TIM for smartphones based on expert opinion[210]. While smartphones typically last 3 years, the TIM choice has minimal impact on their lifespan. Lower operating temperatures save approximately 0.05 kWh per smartphone annually (based on 5 charges)[210]. Waste treatment varies by region: in Europe[211] and North America[212], 50% is residual waste. For the remaining 50%, 80% is subject to energy recovery and 20% to landfill. In Japan[213] 10% treated as residual waste, while remaining 90% collected separately are destined for 80% energy recovery and 20% landfill.

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205 Ercan, M., Malmodin, J., Bergmark, P., Kimfalk, E., & Nilsson, E. (2016). Life cycle assessment of a smartphone. Proceedings of the ICT for Sustainability, Amsterdam, The Netherlands, 29-31.

206 Zhou, Y., Wu, S., Long, Y., Zhu, P., Wu, F., Liu, F., ... & Guo, Z. (2020). Recent advances in thermal interface materials. ES Materials & Manufacturing, 7(7), 4-24.

207 Sarvar, F., Whalley, D. C., & Conway, P. P. (2006, September). Thermal interface materials-A review of the state of the art. In 2006 1st electronic systemintegration technology conference (Vol. 2, pp. 1292-1302). IEEE.

208 Dembowski, K. (2015). Die Computerwerkstatt: Für PCs, Notebooks, Tablets und Smartphones. Dpunkt.Verlag GmbH.

209 denkstatt. (2021). External expert interviews.

210 denkstatt. (2021). External expert interviews.

211 Eurostat. (2021). Municipal waste statistics. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics#Municipal_waste_treatment. (accessed 10/2021)

212 EPA. (2020). Advancing Sustainable Materials Management: Assessing Trends in Materials Generation and Management in theUnited States. Retrieved from https://www.epa.gov/sites/default/files/2021-01/docments/2018_ff_fact_sheet_dec_2020_fnl_508.pdf. (accessed 10/2021)

213 Plastic Waste Management Institute. (2019). Emissions and Processing of Domestic Waste. An Introduction to Plastic Recycling. Tokyo.

Results

Comparison of the environmental impact of a smartphone over 3 years with silicone or polyolefin-based TIMs reveals use phase having a greater impact than production or EoL phases. Impact is defined as silicone production and EoL, while benefit is defined as saved electricity due to the Si-based TIM, substituting the weighted average European, North American, and Japanese electricity mix.

According to experts, varying energy savings achieved through silicone based TIM between 1% and 5% [214] leads to a range of the benefit/impact ratio between 65.2 and 322.9.

3.26. Cooling liquid in transformers, LSR as insulating materials in cables

Transformers convert input AC voltage to output AC voltage, requiring cooling systems for heat removal from the iron core and coils. Liquid cooling, such as silicone fluids, is more efficient than air-cooling, especially in dry-type cast resin transformers. Most liquid-filled transformers use mineral oil, but its risks near buildings[215] prompt consideration of silicone cooling fluid. Silicone fluids offer stability, fire resistance, and potential for compact designs with higher temperatures[216]. Accelerated aging tests show silicone fluids remain stable even after 500 h at 160°C [217], unlike mineral oil, which oxidizes and turns into sludge. Retrofilling with silicone fluid is common during maintenance, offering extended lifespan and cost savings, particularly for small transformers.

The GHG benefits of silicone cooling liquids versus mineral oil were assessed across four aspects: longer lifetime (mineral oil: 30 years, silicone fluid: 60 years), potential for more compact transformers (reducing cooling liquid volume by 20%), infrastructure advantages (e.g., reduced concrete use), and compact design benefits. For instance, a standard transformer requires 2.5 times more mineral oil over 60 years compared to silicone fluid for a compact transformer. Sensitivity analysis varied the mass ratio of mineral oil to silicone fluid between 1.5 and 3.5. No quantitative data was available for improved electrical efficiency. **Functional unit considered is a 2.5 MW transformer, 60 years of operation with 1,000 kg of PDMS fluid or 2,500 kg of mineral oil.**

Production, use phase and end of life

PDMS - fluid silicon oil: 6.6 kg CO_2eq./kg; mineral oil: dataset for lubricating oil is used (1.37 kg CO_2eq./kg) [218]. During use, no external building is needed (2.6 x 3 x 5 m) for the transformer, saving 43 tons of concrete and 1.8

[214] denkstatt. (2021). External expert interviews. 02/2022

[215] denkstatt. (2012). External expert interviews. 08/2012.

[216] Athanassatou et al. 2010

[217] Dow Corning, 2006

[218] 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. 08/2021.

tons of steel. At the end of its service life, cooling liquids are mainly used as alternative fuels in industrial processes, with 100% industrial energy recovery assumed for both mineral oil and silicone fluid. Additionally, for concrete and steel used exclusively for mineral oil transformer buildings, 90% industrial energy recovery and 10% landfill are assumed.

Results

Silicone transformer cooling liquid has a higher production-related GWP compared to mineral oil. However, the benefits of silicone cooling liquid outweigh this. In this study, the benefits of substituting mineral oil and avoiding additional buildings are estimated to be 1.6 times higher than the impact of silicone oil production and EoL management. Nevertheless, the result can vary significantly due to different input data and the uncertainty in the assumptions made.

In sensitivity analysis, two parameters were varied: the mineral oil to silicone fluid mass ratio (1.5 to 3.5) and the saved reinforced concrete mass (± 50%). **This resulted in benefit/impact ratios ranging from 1.3 to 3.6.** The saved infrastructure mass had a greater impact on the ratio than the oil to silicone ratio.

4. Results and discussion

4.1. Overview silicone industry

Table 2: 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

Market volume of applications in the EU, North America and Japan

Market data is crucial for estimating the GHG benefits of various applications. In the EU, chlorosilane for solar-grade silicone dominates the market, comprising 67.8% with 570,440 t/a. Sealant windows IG unit and high-quality sealants & adhesives each exceed 50,000 t/a market share (Table 2). In North America, chlorosilane for solar-grade silicon holds a 40% market share (151,700 t/a), followed by high-quality sealants & adhesives at 41,017 t/a. In Japan, chlorosilane for solar-grade silicon captures 41.2% (64,880 t/a). Across regions, chlorosilane for solar-grade silicone leads with 787,020 t/a market share. **Overall, the market volume has more than doubled from 2012 to 2019, reaching 1,378,143 t/a[219].** It is however important to note, that case studies investigated are not equivalent and while a majority of applications were investigated in both studies, some of the

[219] 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.

lower impact applications have been replaced by new applications due to technological development, which meanwhile achieve a greater GHG impact.

Benefit-Impact Ratio

Benefit-impact ratio is a key result of the study and depicts the amount of GHG savings for each unit of emissions from production and EoL thus allowing a comparison of case studies for their relative GHG reduction potential.

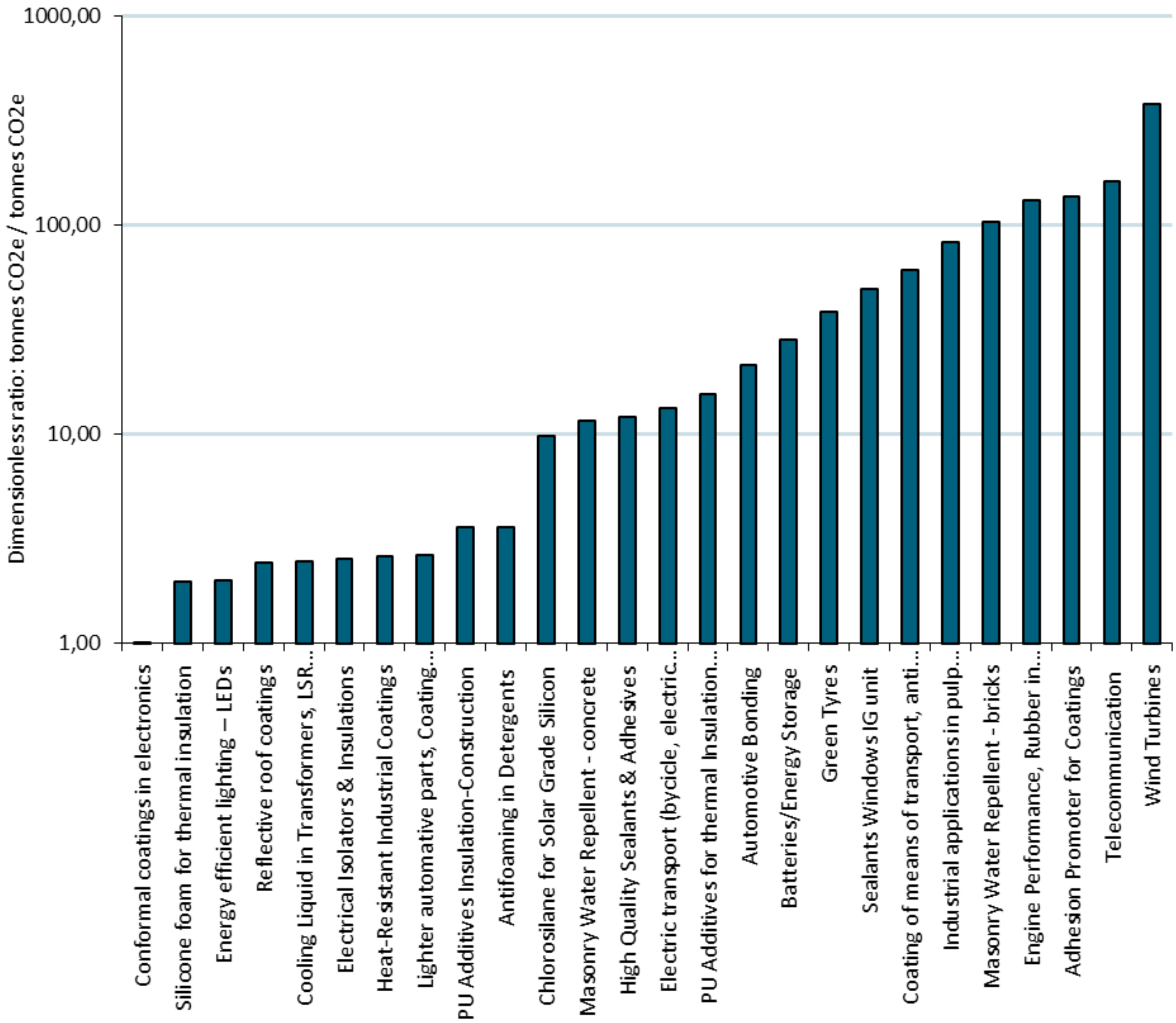

Figure 11: Benefit-impact ratios for all case studies ordered from lowest to highest values.

It is evident form Figure 11, **that the wind turbines application achieves the highest benefit-impact ratio**, mainly due to its low production and EoL emissions compared to the GHG savings it delivers. It surpasses other applications by over 2-fold, such as the next highest - telecommunication. 3 other applications also exceed benefits over impacts by more than 100: adhesion promoter for coatings, engine performance - rubber in motor construction, and masonry water repellent – concrete. 10 applications have a benefit-impact ratio between 10 – 100, while 11 applications have a ratio of <10. **It's crucial to note that while a high benefit-impact ratio indicates efficiency and environmental friendliness, it doesn't necessarily reflect the size of opportunity. Overall, all 26 applications achieve a benefit-impact ratio >1, indicating an overall GHG benefit of silicone application.**

Net benefit of silicone product

In addition to the benefit-impact ratio, understanding the net GHG benefits per unit volume of silicone product is crucial. **Energy-efficient lighting, specifically LEDs, demonstrates the highest GHG benefits per kilogram of silicon product at -11,196 kg CO_2eq./kg,** nearly five times greater than the next application, wind turbines, at -2,266.1 kg CO_2eq./kg. Among others, one application falls within the range of -1,000 to -800 kg CO_2eq./kg, six applications range from -500 to -200 kg CO_2eq./kg, and the rest show a net benefit lower than -200 kg CO_2eq./kg, with five of them ranging from -10 to -1 kg CO_2eq./kg. **It's important to note that all values mentioned are absolute, and limitations and uncertainties have been discussed previously.**

Absolute GHG net-benefits

The GHG net-benefits for all 26 case studies are calculated by scaling up the net-benefits per kilogram of silicone product to the market volumes (Table 2). **Overall, these case studies yield a cumulative annual GHG saving of 148 million metric tons of CO_2 equivalent, with an average benefit-impact ratio of 19.6. This represents more than a twofold increase in absolute GHG savings compared to the 2012 Carbon Balance Study (51 Mt CO_2eq.) and a 1.4-fold increase in the benefit-impact ratio (13.7).** Despite a decrease in market volume compared to the previous study, the reduced environmental impact and improved performance of the studied applications have led to significant additional GHG savings in 2019, reflected in the increased average benefit-impact ratio. The GHG savings from these case studies can be broadly classified into two categories:

1. **Reduction in fossil fuel consumption** through various means such as more efficient transport, reduced weight, improved thermal and electrical isolation, and the use of PV panels.
2. **Saved production of additional materials** due to the extended lifetime of silicone-coated materials, protection against weathering and heat, and the efficient use of silicon-based materials as additives.

The highest absolute GHG savings are achieved by applications such as improved thermal isolation (Sealants Windows IG unit, -36,578 kt CO_2eq.), more efficient transport (Engine performance, Rubber in Motor Construction, -26,312 kt CO_2eq.), and energy-efficient lighting (LEDs, -24,165 kt CO_2eq.). Other significant contributors include Chlorosilane for Solar Grand Silicone (-18,289 kt CO_2eq.), Green Tyres (-11,226 kt CO_2eq.), and Coatings in means of transport (-11,117 kt CO_2eq.).

The drivers for absolute GHG net-benefits in these high-performing applications include the distinctively high estimated market volume (e.g., Sealants Windows IG unit), relatively high net-benefit per unit volume of the product (e.g., Engine performance, Rubber in Motor Construction), and the highest net-benefit of silicone product per unit volume (e.g., Energy efficient lighting -LEDs). It is important to note that all values mentioned are absolute, and uncertainties and limitations have been discussed previously.

4.2. Results for total Si-chemistry market

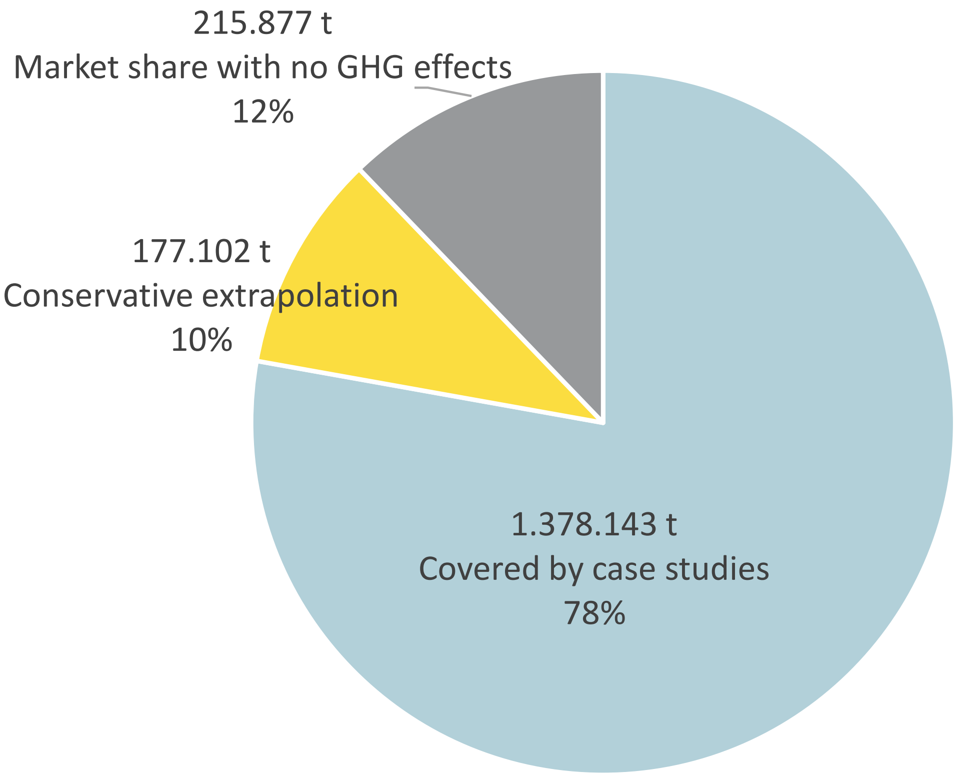

Figure 12: The share of silicon market covered by case studies.

The combined market volume of the 26 case studies amounts to 1.378 Mt of silicone products. When considering the total silicone market in Europe, Japan, and North America, reported as 984 kt/a in the Global Basic Silicone Market Report[220], it's important to note that this figure excludes chlorosilanes for solar grade silicone, which adds an additional 787,000 tons. Thus, the total silicone market is estimated at 1,771,000 tons annually. As depicted in Figure 12, in the updated carbon balance study, approximately 78% of this total market in 2019 could be captured by the case studies, with the remaining 22% attributed to other applications not suitable for study or those with no tangible GHG benefits.

[220] Jing L. (QYResearch), *Global Basic Silicone Market Report, History and Forecast 2016-2027*, pp. 29 – 33.

Table 3: 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**

Using the conservative assumptions from the 2012 Carbon Balance study, the minimum benefit-impact ratio of each case study (13.0) was averaged to extrapolate GHG benefits for 10% of applications not covered by the study, resulting in an additional -12.6 Mt CO_2eq. Additionally, 1.4 Mt CO_2eq. were added to the overall market balance to account for the GWP of applications with no GHG benefit (estimated GHG life cycle impact of 1 kg silicone product = 6.50 kg CO_2eq./kg), as outlined in Table 3. **This yields an overall -159.4 Mt CO_2eq. saving for the total market, including applications not covered by this study.** The absolute value has an uncertainty range associated with it of -15% / +47%, as detailed in the following chapter. **The GHG benefits achieved by all**

silicones, siloxanes, and silane products exceed the GHG emissions from production and EoL treatment approximately 14-fold.

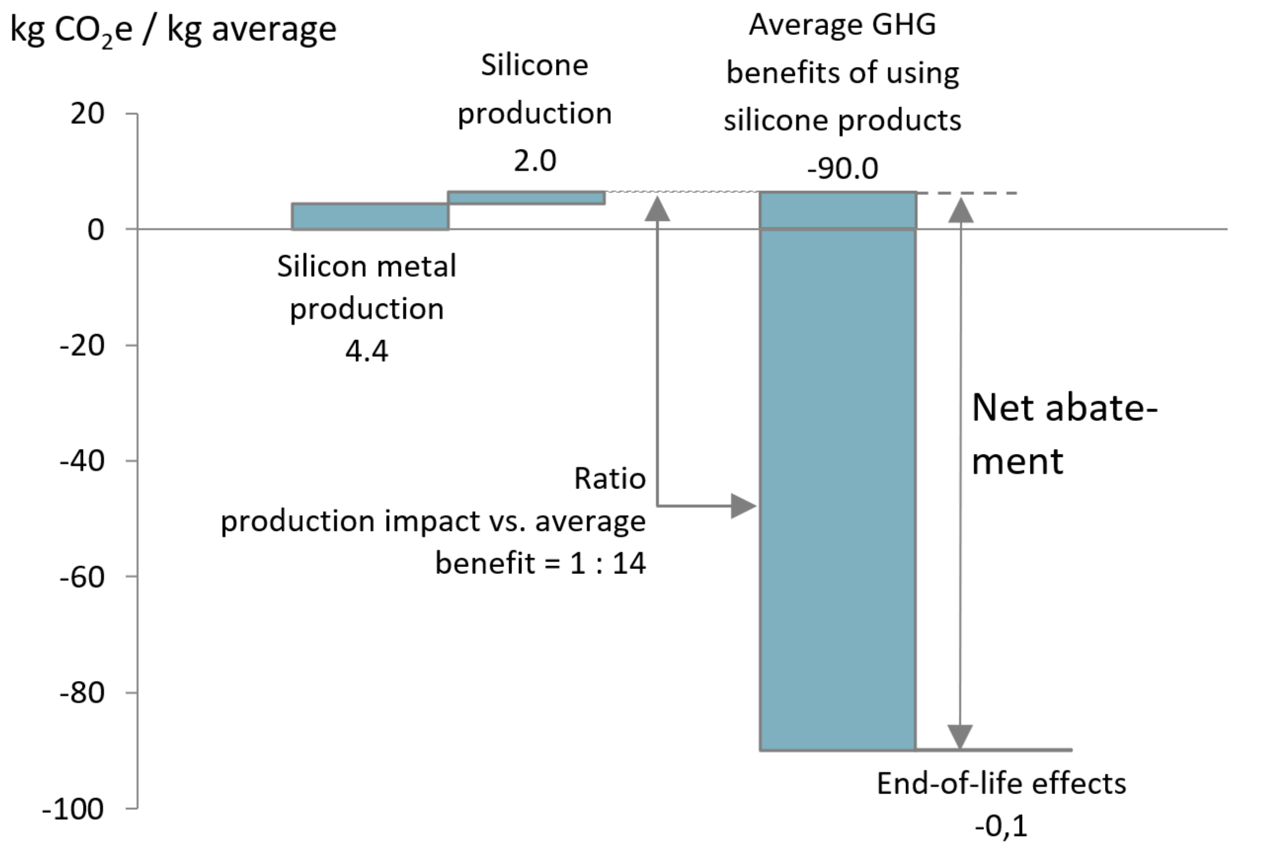

Figure 13: Carbon balance of the Si-chemistry in Europe, North America, and Japan. GHG emissions from silicon metal production and silicone production add up to total production impact. GHG benefits of using silicone & silane products are different for each application; figure depicts average GHG benefit for total market. EoL GHG effects are comparatively very small.

As shown in Figure 13, 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, in contrast, is very minor compared to both production and net abatement. Specifically, the EoL GHG impacts amount to only 0.11 kg CO_2eq./kg of product, constituting a mere 1.7% of the total GHG impact from production and waste management of silicone-based products. This negligible EoL impact is attributed to significant impacts in production and the use phase, as well as varied contributions from waste management, which offset each other to a certain extent.

4.3. Assessment of uncertainties

Table 4: 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

As shown in Table 4, there is a significant variation in the quality of data among different applications, resulting in a range of uncertainties from small to high, as elaborated in detail for each case study in Chapter 3. The average benefit-impact ratio of 19.6 comes with an associated uncertainty ranging between 13.0 and 38.8. Despite conservative selection of input parameters to avoid overestimation or bias, the weighted average minimum value for the benefit-impact ratio remains substantial, around 13, indicating significant GHG benefits across all case studies. This suggests an improvement in the efficiency of studied applications compared to the 2012 Carbon Balance Study[221] (average benefit-impact ratio of 8.7), even with conservative estimates.

[221] 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.

Regarding the absolute GHG abatement figure of -148 Mt CO2eq., the uncertainty range spans between -341 and -86 Mt CO2eq. The largest contributors to the overall uncertainty are the case studies with the four highest GHG net-benefits. However, considering that it's unlikely for all errors to occur simultaneously in one direction, the actual uncertainty range is expected to be smaller.

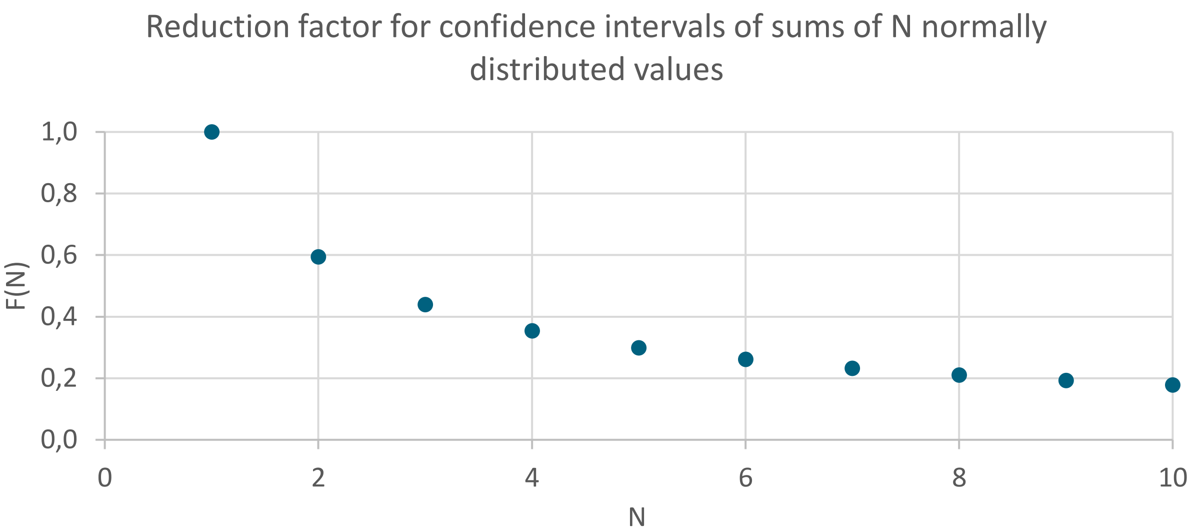

Figure 14: 90 % confidence interval for sum of N normally distributed values is sum of N 90 % confidence intervals of single values x reduction factor F(N).

To produce a more precise estimate of the uncertainty for the sum of the case study results, we assume that the deviations for each case study follow a Gaussian distribution, and the min-max ranges provided above represent a 90% confidence interval.

If each of the N equal values follows a standard normal distribution, then the 90% confidence interval of the sum of the values is smaller by a factor F (Figure 14) than the sum of the 90% confidence intervals of the individual values. The values for F(N) are determined by:

- Calculating P from the equation (1 – P)^N < 0.1, where P is the probability that a single value is within the range of ± z in the Gaussian distribution.
- Dividing z by 1.65 (the 90% confidence interval in the Gaussian standard normal distribution is ± 1.65).

Figure 14 describes the grouping of case studies, which cover 99 % of total uncertainty on the basis of similar uncertainty ranges. Thus, for case studies with the same rounded average uncertainty factor, the reduction factor was used to calculate the estimated total for all case studies.

Table 5: 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**

Due to variations in assumptions, uncertainty around the absolute value for some case studies is not evenly distributed in both positive and negative directions. About 24% of the total uncertainty range lies between the absolute value and the minimum result, with the remaining 76% between the value and the maximal absolute GHG uncertainty threshold. **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.**

Another limitation is the exclusive focus on GHG emissions, neglecting other environmental, economic and social factors. A comprehensive analysis should consider sustainable forest management, repairability, circular economy contribution, and impacts on local ecosystems and biodiversity. EoL aspects, like environmental degradation and bioaccumulation impacts, should also be investigated, given the durability and weatherability of silicones. While based on extensive research and expert collaboration, the accuracy of results depends on input data quality, leading to potential error margins. Future studies should aim to improve data quality and bridge gaps to reduce reliance on conservative assumptions.

5. Conclusion

The study aimed to estimate the product carbon footprint or life-cycle greenhouse gas emissions associated with the total market of silicones, siloxanes, and silane products in Europe, North America, and Japan, and to assess any potential GHG benefits of silicone products. Case studies were selected based on various criteria, including market data, significant GHG savings potential, and other advantages of silicone applications compared to alternatives. Calculations were conducted for 26 case studies, contrasting production, use phase, and end-of-life emissions with estimated GHG savings compared to reference applications without silicone.

Overall, the benefits of silicon-based products stem from their versatile physical and chemical properties, such as adhesion, heat resistance, and weatherability, attributed to the generally inert nature of Si-based materials. **These benefits are mainly driven by reduced fossil fuel consumption and saved production of additional materials through extended product lifetimes or improved efficiency. The cumulative market volume of silicon-based products in 2019 was estimated at 1.378 Mt/a, with the 26 case studies representing 78% of the total market. The study revealed that the greenhouse gas potential (GWP) for silicon metalloid production averages 4.39 kg CO_2eq./kg, while silicone production contributes an additional 1.97 kg CO_2eq./kg, resulting in a total average GWP of 6.36 kg CO_2eq./kg per average silicon-based product.** Notably, regional differences in energy sources for silicon extraction and generation significantly impact these values.

To assess the carbon balance for the entire market of silicon-based products, the net-benefit per unit of produced silicon product was calculated. This involved balancing production, use phase, and end-of-life emissions with GHG abatement per unit of the silicon product. The analysis indicated that energy-efficient lighting, specifically LEDs, yielded the highest net-GHG benefit, while conformal coatings for electronics exhibited the lowest net benefit. To determine the absolute GHG net-benefits, the net benefit of silicone products was scaled up to the estimated market value for each application. **Consequently, the total GHG abatement achieved ranged from -217 to -126 Mt CO_2eq., with a symmetric uncertainty range of -148 ± 31% Mt CO_2eq.** Notably, applications such as improved thermal isolation (Sealants Windows IG unit) and more efficient transport (Engine performance, Rubber in Motor Construction) accounted for the highest absolute GHG savings. Additionally, silicone-coated products that extended product lifetimes demonstrated significant GHG benefits, representing a noteworthy shift from the findings of the 2012 Carbon Study.

Extrapolating absolute GHG net-benefits for the entire market, using conservative assumptions, resulted in a net abatement of -159.4 Mt CO2eq. This is a significant improvement from the 2012 Carbon Balance study and is supported by a nearly 1.5-fold increase in benefit-impact ratios since then. **The GHG benefits realized by all silicone products are approximately 14 times higher than the GHG emissions from their production and end-of-life treatment.** This amounts to about 11% of Japan's and 2.7% of the United States' GHG emissions [EDGAR, 2015].

The estimated EoL GHG impact compared to both production and net abatement is very small. Specifically, the EoL GHG impacts correspond to 0.11 kgCO_2eq/kg of product, which constitutes 1.7 % of the total GHG impact from production and waste management of silico-based products. This influence is even smaller considering the total GHG net abatement (0.1 %). Although, waste management emissions can play an important role for applications with high market volumes in overall GHG balance, compared to the lifecycle emissions this impact is minimal. This is similar for transport, which tends to add a rather minor impact to the overall GHG balance.

Overall, the study shows that all 26 applications received a GHG benefit that outweigh the emissions in the lifetime of the product (benefit-impact ratio >1). In other words, for all studies the GHG emissions related to production, use phase and EoL of silicone alternatives are overall lower compared to the substituted product in reference application. With an average benefit-impact ratio of 19.6, the study indicates that for every unit of emissions generated in silicon-based product generation 19.6 units of CO_2 equivalent emissions are saved, which is indicative of an overall positive GHG effect of the use of silicon-based products. This is despite the higher GHG benefit of average silicon products (6.36 kgCO_2eq/kg) compared to common plastics (2-4 kgCO_2eq/kg) or steel (0.5–4.5 kgCO_2eq/kg) resulting due to the fact that silicon-based material production is rather energy intensive per unit output generated. These savings generally are due to savings of fossil fuels (e.g., when used as rubber in motor construction) or through extending the lifetime of other materials on which these are applied (e.g., water repellent for masonry and concrete). Furthermore, often small quantities of silicones and silanes are sufficient to increase the efficiency of processes and materials used (e.g., as antifoaming agent, paint additives) thus reducing the demand for additional materials to be produced.

To mitigate the carbon footprint of silicone and silane products, **reducing fossil fuel dependency in electricity generation and manufacturing processes is crucial, particularly in silicon metalloid production. Outsourcing production to countries with lower reliance on fossil fuels could also help. However, this must be carefully evaluated to avoid unintended environmental and economic consequences.** Recycling offers potential to reduce carbon footprint by decreasing reliance on virgin materials, though implementation challenges exist due to the complexity of separating silicon-components from multi-component products and the relatively low product volumes considered in this study.

While this study benefited from extensive research and collaboration with experts, the accuracy of results is contingent upon the quality of input data, leading to notable error margins in absolute GHG net-benefits. Future studies should prioritize improving data quality and addressing data gaps with conservative assumptions. **An important limitation of this study is its focus solely on GHG emissions. For a comprehensive environmental assessment, factors such as water use, waste management, biodiversity, and socioeconomic criteria should be considered.**

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