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Silicones' role in supporting the EU Green Deal's decarbonization goal

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Abbreviations

BECCS ... Bioenergy with carbon capture and storage
BEV ... Battery electric vehicle
BL ... Baseline scenario
BOM ... Bill of material
BOS ... Balance of system
CCS ... Carbon capture and storage
CEFIC ... European Chemical Industry Council
CES ... CES – Silicones Europe
CO_2 ... Carbon dioxide
CO_2eq ... Carbon dioxide equivalent
DU ... Downstream user
EBS ... Ethylene-bis-stearamide
ECV ... Electrically chargeable vehicle
EEA ... European Environment Agency
EF ... Emission factor
EGS ... Electronic-grade silicon
EoL ... End-of-life
EPDM ... Ethylene propylene diene monomer
ETS ... Emissions Trading Scheme
EU ... European Union
EV ... Electric vehicles
FEICA ... Association of the European Adhesive & Sealant Industry
FU ... Functional unit
GD ... EU 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
LULUCF ... Land Use, Land-Use Change and Forestry
NEV ... Neighborhood electric vehicle
OD ... Outer diamter
PCF ... Product carbon footprint
PDMS ... Polydimethylsiloxane
PU ... Polyurethane
PV ... Photovoltaic
$SiCl_4$ ... Tetrachlorosilane
$SiHCl_3$ ... Trichlorosilane
SMEs ... Small and medium-sized enterprises
TESPT ... Bis(triethoxysilylpropyl)tetrasulfide
TIM ... Thermal Interface Material

Executive Summary

The last two decades have shown a slow, but steady increase in perception of the importance of climate change across the world. Especially the sphere of financial industries started to anticipate climate-related risks as relevant for their long-term investments and thus triggered developments requiring market participants of all industries to report their CO_2eq-emissions.

It still needed almost twenty years for regulations to come into effect and to demand serious reports from enterprises. One of these reports has been published by the European Commission in December 2019: the EU Green Deal. This regulatory basket contains a number of programs dedicated to the thoroughly pursuit of targets for "greening the industry" as a paradigm to strengthen the European economy in an international context.

A core target is the decarbonization of European society – which is meant to become a role model for other economic regions. This target is supported by additional goals such as biodiversity and ecosystem protection.

The European Union plans to be carbon-neutral by 2050 in all facets and, evidently, industry plays a crucial role in this project. The political program is and will be accompanied by numerous regulatory requirements meaning that all industrial sectors are now challenged to engage in strategic investigations for their future prosperity. They have to seriously scrutinize their products, services, and business models for opportunities and potential hazards due to the new regulations and societal demands worldwide.

The silicone industry has accepted this challenge and proactively investigated whether applications and products using silicones support the main goal – decarbonization – of the EU Green Deal and, if so, how much. The study analyses the current greenhouse gas (GHG) contribution of silicone-containing applications to a climate-neutral economy.

This is not the first time a report of this kind has been published. Back in 2012, the Global Silicone Council (GSC) commissioned a study on GHG-emissions and impacts of silicones, silanes, and siloxanes. The benefits of these Si-based materials and applications, which are defined as materials that consist of silicon backbones and surface-capped atoms or pendants, were investigated and presented in comparison to non-Si-based applications. To show the potential future contribution of the silicone industry with respect to reaching a net-zero carbon society, a new study was mandated by the European Silicone Center – Silicones Europe (CES) based on the methodology of the study from 2012. For this purpose, 11 relevant applications were selected and their contribution to decarbonization was calculated.

In general, the results of this new study confirmed the conclusions of 2012: selected silicone-containing applications show CO_2eq savings potential throughout their lifecycle in comparison with their non-silicone alternatives. Especially applications in the energy industry and mobility sector were found to significantly contribute to the decarbonization of the European economy. The results are depicted and described in detail in this study.

For the calculation of the GHG-balances and -benefits, information was collected through intensive collaboration with CES members, industry experts, a comprehensive survey among downstream users, and literature research. The final results represent the situation for 2019 and the projections for 2030 and 2050.

Overall, it can be stated that for many technologies relevant for the energy and mobility transition, silicone-containing applications are of crucial importance. It is recommended to apply them in a reasonable manner according to their potential to support the decarbonization target of the EU Green Deal.

The diagram below summarizes the key results of all investigated silicone applications studied in this report. It shows the total absolute EU GHG net benefits of the investigated applications for 2019 (blue) and potentials that might be achieved in 2030 (yellow) and 2050 (grey). The presented results show emission savings, achieved by the respective silicone application compared to its alternative product, considering corresponding market volumes and share of silicone in the silicone product. To be more specific, the absolute EU27 GHG net benefits per year of all investigated silicone applications change from about -52,5 Mt CO_2eq in 2019, to -96,4 Mt CO_2eq in 2030, and to -42,6 Mt CO_2eq in 2050. The result for 2019 accounts for approximately 6,6 % of Germany's total emissions for the same year, which is equivalent to about 810 Mt CO_2eq in absolute terms. These are the emissions that are being avoided due to the application of silicones in different areas.

Whereas silicone applications in the area of fossil fueled engine performance or chlorosilanes show the highest GHG benefits in the present, the future potential lies in applications such as batteries/energy storage and LEDs. Those applications show the biggest potential towards future savings and can make a significant contribution to reducing CO_2eq emissions in the EU through the use of silicones. Out of all applications, the future GHG benefits for batteries are the highest. In addition, the mobility sector also shows great potential due to the share of electromobility in the passenger car market which is expected to increase to 90 % by 2050, leading to an almost complete substitution of fossil fuels and decrease of emissions in the private mobility sector.

The decrease of absolute EU GHG net benefit of some applications over time is mainly related to the energy mix shifting towards the renewables. This is based on an assumption, that due to the broad decarbonization of various sectors, a significant reduction in the emission factors for electricity and heat in the EU27 will result until 2030 and 2050. Further influencing factors are described in the individual chapters.

Overall, every application under study shows an emissions savings potential compared to alternatives without silicones indicating the importance of the silicone industry to support “decarbonization” one major goal of the EU.

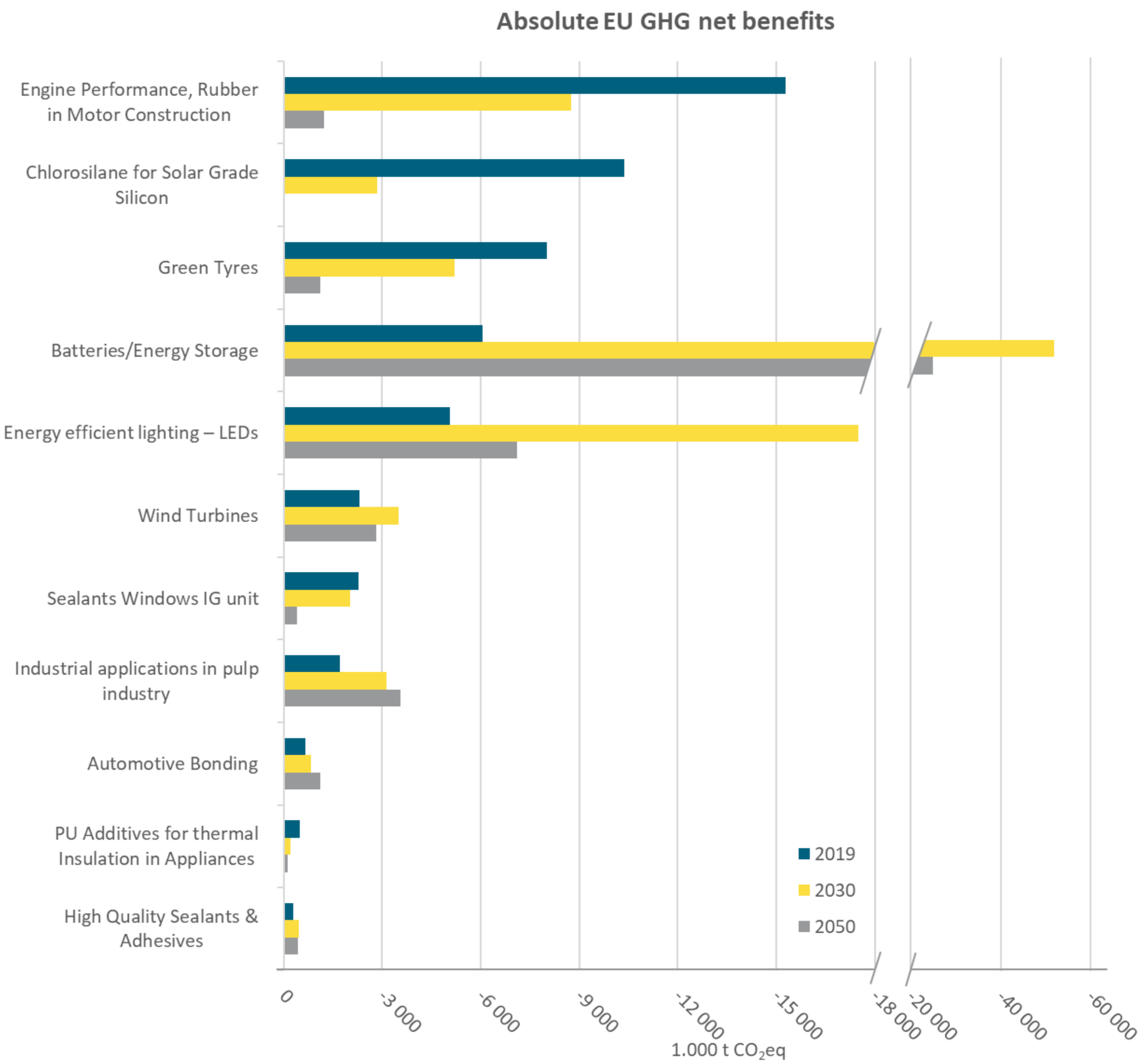

Figure 1: Results of the absolute GHG net benefits of all studied silicone applications for the EU27

1. Introduction

1.1. Background, aim, and chosen approach of the study

The current president of the European Commission Ursula von der Leyen has announced a major change in Europe's economic policy: the EU Green Deal (abbreviated with GD) shall serve as an engine to promote strengthening business in Europe but, at the same time, safeguarding the environment with major emphasis on carbon reduction.

The Green Deal's general building blocks are

1. Increasing the EU's climate ambition for 2030 and 2050
2. Supplying clean, affordable, and secure energy
3. Competitive industry and circular economy
4. Energy and resource efficient building and renovating
5. Sustainable and smart mobility
6. Fair, healthy, and environmentally-friendly food system
7. Preserving and restoring ecosystems and biodiversity
8. Zero pollution / toxic free environment

Within these building blocks, numerous opportunities arise and remain to be discovered. To show the importance of silicones in achieving the targets of the GD - especially the ambitious goal of carbon neutrality by 2050 – European Silicone Center – Silicones Europe (CES) provides this study looking into the greenhouse gas (GHG) emissions, benefits, and impacts of 11 silicone-based applications. The use of silicones, silanes, and siloxanes is broad, ranging from the mobility sector, to energy production, and includes various applications such as batteries, wind turbines or photovoltaic panels.

In close cooperation with industry experts, CES members, and with the help of other internal experts, having substantial experience with special applications, the role and importance of the silicone industry in the GD and the CO_2eq reduction pathway till 2050 were elaborated.

The aim of this project is to show the importance of silicones and their benefits in comparison to their non-silicone alternatives. In this report, 11 key GD silicone applications including their GHG emissions, which play a crucial role to achieve climate neutrality for Europe, are described. The mechanism, by which different silicone-based products support the GD with emphasis on carbon neutrality is depicted in the study. In order to reflect reality as accurately as possible, a downstream user survey on silicones being essential for achieving carbon neutrality was being conducted and its results incorporated into the calculations (details see Chapter 4.3).

In this report, silicones are being matched with the GD and the carbon neutrality target. To precisely steer the central project activities into directions, targeted by the European policy, the GD will be scrutinized for its potential beneficiary fields of activity. This phase is also characterized by reviewing information from silicone industries and their clients to match technologies with GD-activity fields. The main CO_2-reducing applications and technologies are being identified. Thus, an 80:20 comprehensive methodology was developed and applied. In addition, selection criteria have been defined in cooperation with CES. To support the technological assumptions and the expected CO_2eq benefits, a downstream user (DU) survey is conducted as a broad-range feedback loop. To support political discussions, this study provides crucial information about validity of the assumptions and sensitivity of the chosen parameters.

A critical scientific review of this study was performed by Dr. Roland Hischier, based at EMPA, Swiss Federal Laboratories for Materials Science and Technology. The review report is attached to this study.

The aim of the critical review was to examine:

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

2. The EU Green Deal

2.1. Introduction and analysis of the Green Deal

The Green Deal (hereinafter referred to as "**GD**"), presented by the European Commission on December 11, 2019[1], reaffirms[2] the political ambition to achieve climate neutrality, i.e., the reduction of net GHG emissions to zero on the European continent by 2050.

The GD contains a roadmap of main strategies and action plans. The measures of this roadmap promote the efficient use of resources by moving towards a clean circular economy, halting climate change, tackling biodiversity loss, and reducing pollution. As a new strategy for growth, the GD covers all sectors of the economy. It outlines the investments needed, the financial instruments available, and how to ensure a fair and inclusive transition[3]. The key message of the GD is that, in order to achieve the ambitious climate targets, the economic system must be redefined and transformed for a sustainable future. The key elements of the GD are illustrated below:

Figure 2: Key elements of the European Green Deal (Source: European Commission, 2021)

[1] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. 09/2021.

[2] European Commission. (2018). A Clean Planet for all. COM(2018) 773 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773. 09/2021.

[3] European Commission. (2019). The European Green Deal. Press release. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691. 09/2021.

In the following chapters, the key elements of the GD will be introduced. While the GD covers various areas, the focus of this study will be on CO_2eq reduction.

2.1.1. Increasing the EU's climate ambition for 2030 and 2050

In addition to climate-neutrality by 2050, the EU announced the adaption of the reduction target for 2030 from 50 % to 55 % of the GHG emissions compared to 1990[4]. The setting of new targets is necessary because, while already "leading one of the most modern and climate-friendly economies", current policies[5] will only reduce GHG emissions by 60 % by 2050[6].

Therefore, the Commission reviewed all relevant **climate-related policy instruments** by July 2021. The Emissions Trading Scheme (ETS) stood out as a main point of consideration with a possible extension to new sectors[7]. Member states' emission reduction targets for industries not covered by the ETS and the Regulation on Land Use, Land Use Change and Forestry have also been updated[8]. These political and regulatory reforms are also intended to help ensure effective CO_2 pricing throughout the economy.

In order to make the *political* goal of the GD legally binding, the EU has as well passed the **European Climate Law**[9], which will be discussed later (see 2.3).

2.1.2. Supplying clean, affordable, and secure energy

Since 75 % of the EU's GHG emissions are caused by the energy production and consumption in all sectors of the economy, further **decarbonization** of the energy system is crucial. This includes extensive expansion of the

[4] The previous target was at least 40 %.

[5] European Commission. (2020). EU Emissions Trading System, Effort Sharing Regulation, Land use, land use change and forestry Regulation

[6] European Commission. (2019). Annex to the Communication on the European Green Deal. 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2. 02/2021.

[7] European Commission. (2021). Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union. COM(2021) 551 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)551&lang=en. 08/2021.

[8] European Commission. (2021). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review. COM(2021) 554 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)554&lang=en. 08/2021.

[9] European Commission. (2018). Regulation establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119&from=DE. 10/2021.

renewable energy sources, phasing out of coal, and decarbonization of the gas sector. To this end, the European energy market must be fully integrated, networked, and digitalized[10].

One of the main objectives is to create an intelligent infrastructure and strengthen cooperation between member states. Innovative technologies and infrastructures are to be promoted and sector integration made possible. Therefore, the Commission will review all relevant energy and energy infrastructure legislation and propose a revision in order to adapt to the new climate targets by 2023[11]. As a result, there should be a framework for the deployment of innovative technologies and infrastructures such as smart grids, hydrogen networks, carbon capture, storage and utilization as well as energy storage.

In July 2020, the Energy System Integration Strategy was adopted by the EU[12]. The main characteristics are:

- a more efficient and "circular" system, where waste energy is captured and re-used,
- a cleaner power system, with more direct electrification of the end-use sectors such as industry, heating of buildings, and transport, and
- a cleaner fuel system, for hard-to-electrify sectors such as heavy industry or transport[13].

To speed up the transition to renewable electricity, the EU aims to increase production of electricity from renewable energy sources, convert industry, transport, and buildings to renewable electricity, and create the necessary infrastructure for it. Regarding the aim of a cleaner fuel system, low carbon fuels (including hydrogen) will be promoted for sectors where decarbonization is difficult. Carbon capture, storage, and use shall be enabled to support large-scale decarbonization[14]. Silicones are also playing their part in the renewable energy transition, particularly in applications such as PV systems and wind turbines. They serve as the basis for both the construction and operation of such applications.

However, the strategy notes that EU member states have different starting positions. Implementation in national energy and climate plans will therefore take place according to respective circumstances.

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[10] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. 09/2021.

[11] European Commission. (2021). Factsheet. Decarbonising our energy system to meet our climate goals.https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6723. 09/2021.

[12] European Commission. (2020). Powering a climate-neutral economy: An EU Strategy for Energy System Integration. COM(2020) 299 final. Retrieved from https://ec.europa.eu/energy/sites/ener/files/energy_system_integration_strategy_.pdf. 09/2021.

[13] European Commission. (2020). Factsheet: EU Energy System Integration Strategy. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/fs_20_1295; https://ec.europa.eu/commission/presscorner/detail/en/fs_20_1297. 09/2021.

[14] See 12

2.1.3. Mobilizing industry for a clean and circular economy

As already mentioned, the entire industry must be mobilized to achieve a climate-neutral economy. According to the Commission this transformation will take 25 years – a whole generation, therefore a rapid implementation of measures is required within the next five years[15].

Worldwide, around a half of the total GHG emissions and more than 90 % of the biodiversity loss and water scarcity are due to the extraction and processing of raw materials, fuels, and food. Within the EU industry is responsible for 20 % of the GHG emissions and uses only 12 % recycled materials[16]. Therefore, accelerated development and promotion of low-emission technologies, sustainable products, and services is to be pursued. In addition to circular economy, decarbonization and modernization of energy-intensive industries such as steel, chemicals, and cement industries play a decisive role.

The EU Industrial Strategy[17], published in March 2020, aims to create a European industry that is greener and more digital, while remaining competitive on a global scale. This will facilitate the transformation and growth of traditional and new industries across the EU and support small and medium enterprises (SME) sustainable competitiveness. In particular, industries need a secure, clean and affordable supply of energy and raw materials.

Although all industrial value chains have a key role to play, the strategy addresses mostly energy-intensive industries such as steel, chemicals, and cement as these are vital to the European economy. Therefore, decarbonization and modernization of these sectors is crucial - industrial processes have to be redefined and clean technologies - developed. The following are given as examples: a zero-carbon steel making process and a new chemicals strategy for sustainability. Furthermore, CO_2-intensive regions in particular should be supported financially during the transition period.

The EU Circular Economy Action Plan[18], published in March 2020, focusses on resource-intensive sectors such as textiles, construction, electronics, and plastics. It contains new initiatives along the entire life cycle of products in order to modernize and transform the economy while protecting the environment[19]. The Action Plan includes a strategy for "sustainable products" which will support a circular and life-cycle-oriented design of all products based on common methods and principles. Silicon and Si-derived materials are readily applied across the sectors mentioned in the EU Circular Economy Action plan. Due to the tailorable conductivity silicon is used as a semi-conducting material in computing chips, while Si-derived polymers owing to their diverse physical properties are applied as lubricants, rubbers and as electric insulation materials. These applications directly support

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[15] See 6

[16] Eurostat. (2021). Circular material use rate. Retrieved from https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=cei_srm030&plugin=1. 10/2021.

[17] European Commission. (2020). A New Industrial Strategy for Europe. COM(2020) 102 final. Retrieved from https://ec.europa.eu/info/sites/info/files/communication-eu-industrial-strategy-march-2020_en.pdf. 09/2021.

[18] European Commission. (2020). A new Circular Economy Action Plan For a cleaner and more competitive Europe. COM(2020) 98 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN. 09/2021.

[19] European Commission. (2020). Factsheet: Circular Economy Action Plan. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/fs_20_437. 09/2021.

advancement in technology and towards electrification, as well as extend the lifetime and durability of other materials and structures in line with the EU Circular Economy Action Plan.

The Action Plan promotes new business models and sets minimum requirements in order to prevent environmentally harmful products from reaching the EU market. Extended producer responsibility will also be strengthened. Companies shall be encouraged to offer reusable, durable, and repairable products, ensuring consumers are able to choose such products. The Commission will develop requirements which ensure that all packaging placed on the EU market is reusable or recyclable in an economically viable way by 2030. Additionally, the Commission will develop a legislative framework for biodegradable and bio-based plastics, while implementing measures against the distribution of disposable plastics.

In order to reduce the risk of "green washing", companies will be required to provide environmental information using a standard method for assessing their environmental impact. The Commission will step up its regulatory and non-regulatory efforts to address inaccurate environmental claims.

2.1.4. Building and renovating in an energy and resource efficient way

Given that significant amounts of energy and mineral resources which are required for construction, use, and renovation of buildings and that buildings account for 40 % of energy consumption, a "renovation wave" is being worked on to achieve energy efficiency and affordability. Furthermore, the annual rate of renovation is only between 0,4 and 1,2 % across the EU[20]. As a result, member states are to be obliged to renovate at least 3 % of the total area of all public buildings[21]. In addition to new legislation on the overall energy efficiency of buildings, emissions from buildings are to be included in the European ETS. The design of new and renovated buildings in all phases must meet the requirements of circular economy and lead to an increased digitalization and ensure the climate compatibility of existing buildings.

In October 2020, a corresponding strategy was announced: A Renovation Wave for Europe - Greening Our Buildings, Creating Jobs, Improving Lives[22]. The main message of the Strategy is the promotion of energy efficient building renovation. In this course of this action, renewable energies, especially from local sources, should be integrated and the use of waste heat increased.

According to the impact assessment for the 2030 Climate Target Plan, the residential building sector will require the largest reduction in energy demand for heating and cooling: between -19 % and -23 % compared to 2015. About 4 % of heating systems in both residential and tertiary sectors would need to be replaced each year. At

[20] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. 09/2021.

[21] European Commission. (2021). Factsheet: Buildings. Retrieved from https://ec.europa.eu/commission/presscorner/api/files/attachment/869476/Buildings_Factsheet_EN_final.pdf.pdf. 01/2021.

[22] European Commission. (2020). A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. COM(2020) 662 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662. 02/2021.

the same time, the share of renewable energies and waste heat would have to increase to 38-42 % to reach the target. For this purpose, the EU will revise the relevant legislation[23] by 2021.

Silicones also contribute to improving the energy efficiency of buildings and thus support this goal of the Green Deal. Applications such as sealants for windows improve the insulating properties of buildings, meaning that less energy is needed for heating and cooling.

2.1.5. Accelerating the shift to sustainable and smart mobility

The transport sector accounts for a quarter of the GHG emissions in the EU and this share continues to rise. To achieve climate neutrality, transport-related emissions must be reduced by 90 % by 2050[24,25].

The Commission is about to adopt a roadmap for sustainable and intelligent mobility to address this challenge in relation to all emission sources[26].

Multimodal transport must be given a strong impulse so that the transport system becomes more efficient. Priority should be given to shifting a substantial part of the 75 % share of internal freight transport, currently moved by road, to rail and inland waterways.

The price of transport services must reflect their impact on the environment and human health. Subsidies for fossil fuels should be abolished and the Commission will closely examine the current tax exemptions, including for aviation and maritime transport fuels, and consider how best to close any legal loopholes. The Commission will also propose to extend European emissions trading to maritime transport and to reduce the number of free allowances allocated to airlines under the EU ETS.

In parallel, the EU will promote the production and distribution of sustainable alternative fuels. The goal for 2025 is, to have 1 million public charging stations and petrol stations constructed for 13 million emission-free and low-emission vehicles.

The Commission plans to revise the legislation on CO_2eq emission performance standards for cars and vans, with a focus on ensuring the transition towards zero emission mobility from 2025. In addition, consideration is being

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[23] European Commission. (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, L 140, 5 June 2009, pp. 16–62.

[24] See 20

[25] European Commission. (2019). Factsheet: Sustainable Mobility. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6726. 02/2021.

[26] European Commission. (2020). Initiative: Sustainable and Smart Mobility Strategy. Retrieved from https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12438-Sustainable-and-Smart-Mobility-Strategy. 02/2021.

given to applying European emissions trading to road transport to complement existing and future CO_2eq emission performance standards for vehicles[27].

In this study, applications in the mobility sector likewise play an important role in supporting the Green Deal. Silicones contribute to more efficient mobility through weight reduction, their good sealing properties, heat resistance, durability, etc., and consequently reduce emissions from fossil fueled transportation. As the share of electric cars in the EU is expected to increase to up to 90 % by 2050, the use of silicone in batteries in particular will make a significant contribution to the ongoing decarbonization of the mobility segment[28].

2.1.6. From 'farm to fork': designing a fair, healthy and environmentally-friendly food system

Despite the already high standards of European food products, food production remains a big factor when it comes to air, water and soil pollution, biodiversity loss, and climate change. It contributes to an excessive consumption and waste of natural resources[29].

The 'farm to fork' Strategy for a fair, healthy, and environmentally-friendly food system[30] aims to establish a circular economy – from producer to consumer – including the following key points:

- better informed citizens,
- healthy food consumption and reduction of food losses, and food waste,
- more efficient food production systems,
- improved storage and packaging, and,
- more sustainable processing and sustainable rural transport[31].

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[27] European Commission. (2021). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2019/631 as regards strengthening the CO_2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition. COM(2021) 556 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)556&lang=en. 08/2021.

[28] 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

[29] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. 09/2021.

[30] European Commission. (2020). A Farm to Fork Strategy. COM(2020) 381 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381. 02/2021.

[31] European Commission. (2019). Factsheet: From Farm to Fork. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6727. 02/2021.

2.1.7. Preserving and restoring ecosystems and biodiversity

A new EU Biodiversity Strategy for 2030 was published in May 2020[32]. It aims to establish additional protected areas for land and sea and to restore degraded ecosystems by increasing organic farming, halting, and reversing the decline of pollinators, reducing the use of pesticides, restoring rivers to a free-flowing state, and planting 3 billion trees by 2030. For this purpose, subsidies will be established and provided for biodiversity[33].

Since forest ecosystems in particular are under increasing pressure as a result of climate change, the EU's forest area must be improved both qualitatively and quantitatively to achieve climate neutrality and a healthy environment. Sustainable afforestation and reforestation and the restoration of damaged forests can increase the absorption of CO_2eq while improving the resilience of forests and promoting circular bio-economy.

Following the Biodiversity Strategy, the Commission will prepare a new EU Forestry Strategy covering the whole forest cycle and promoting the many services provided by forests. The main objectives of the new EU Forestry Strategy are to ensure effective afforestation, conservation, and restoration of forests in Europe, to increase CO_2eq absorption, reduce the frequency and extent of forest fires, and promote bio-economy, while also respecting ecological principles that favor biodiversity.

2.1.8. A zero-pollution ambition for a toxic-free environment

The GD encourages the EU and the member states to review and strengthen policies and regulations regarding monitoring, reporting, preventing, and remedy of pollution from air, water, soil, and consumer products. Air quality standards should be revised to align them more closely with the recommendations of the World Health Organization[34].

Large industrial installations will be given closer attention. Further measures to address pollution and to prevent industrial accidents will be reviewed.

In October 2020, the Commission published a Chemicals Strategy for Sustainability Towards a Toxic-Free Environment[35]. It sets out requirements for the chemicals industry which aim to ensure the production of safe and sustainable chemicals. Chemicals should be produced and used in ways which maximize their contribution to society, including achieving the green and digital transition, while avoiding harm to the planet.

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[32] European Commission. (2020). EU Biodiversity Strategy for 2030. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380. 02/2021.

[33] European Commission. (2020). EU Biodiversity strategy for 2030. Retrieved from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu/EU-biodiversity-strategy-2030_en#why-do-we-need-to-protect-biodiversity. 02/2012.

[34] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. 09/2021.

[35] European Commission. (2020). Chemicals Strategy for Sustainability Towards a Toxic-Free Environment. COM(2020) 667 final. Retrieved from https://ec.europa.eu/environment/pdf/chemicals/2020/10/Strategy.pdf. 02/2021.

Promoting safe and sustainable-by-design chemicals will include the application of relevant criteria, in addition to the establishment of an EU-wide support network and financial aid, but also the adaption of legislation on industrial emissions.

Furthermore, the EU will prioritize the shift to a toxic-free material cycle and the reduction of substances of concern in products, while not only supporting recycling but also the research and development of advanced materials. Further development of chemical and material production processes that have a low-carbon and low environmental impact shall be encouraged.

While there are already successful legal frameworks especially for hazardous substances in the EU[36], the aim is to go one step further in order to respond more quickly and effectively to challenges posed by hazardous chemicals. Specific draft laws are to follow within the fourth quarter of 2021.

2.2. The EU Green Deal roadmap

The annex to the GD contains a roadmap of key actions[37]. Apart from what was already described, the following actions were planned for 2021:

- *Proposals for revisions of relevant legislative measures to deliver on the increased climate ambition, following the review of Emissions Trading System Directive; Effort Sharing Regulation; Land use, land use change and forestry Regulation; Energy Efficiency Directive; Renewable Energy Directive; CO_2eq emissions performance standards for cars and vans* [38]
- *Proposal for a revision of the Energy Taxation Directive*[39]
- *Proposal for a carbon border adjustment mechanism for selected sectors*[40]
- *New EU Strategy on Adaptation to Climate Change*[41]

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[36] European Commission. (2008). Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). L396. 30.12.2006. pp. 1–849. Regulation on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (CLP). L353. 31.12.2008. pp. 1–1355.

[37] European Commission. (2019). Annex to the Communication on the European Green Deal. COM(2019) 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2. 02/2021.

[38]European Commission. (2021). Better regulations initiatives. Retrieved from https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives_en. 09/2021.

[39] European Commission. (2020). Amended proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). COM(2020) 563 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2020)563&lang=en. 03/2021.

[40] European Commission. (2019). REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL Preparing the ground for raising long-term ambition EU Climate Action Progress Report 2019. COM(2019) 564 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2019)559&lang=en. 03/2021.

[41] European Commission. (2021). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change. COM(2021) 82 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)82&lang=en. 08/2021.

- *Revised proposal for a Directive on Combined Transport (not published yet)*
- *Proposal of the Alternative Fuels Infrastructure Directive and the Trans European Network – Transport Regulation*[42]
- *Initiatives to increase and better manage the capacity of railways and inland waterways*[43]
- *Proposal for more stringent air pollutant emissions standards for combustion-engine vehicles (expected in the 4th quarter of 2021)*
- *Examination of the draft national strategic plans, with reference to the ambitions of the European Green Deal and the Farm to Fork Strategy*
- *Measures, including legislative, to significantly reduce the use and risk of chemical pesticides as well as the use of fertilizers and antibiotics*
- *Measures to address the main drivers of biodiversity loss*
- *Zero pollution action plan for water, air, and soil*
- *Revision of measures to address pollution from large industrial installations (expected in early 2022)*
- *Review of the relevant State aid guidelines, including the environment and energy State aid guidelines*

2.3. The legal framework

In order to legally establish the GD and its aim to become climate neutral by 2050, the **European Climate Law** was published in the Official Journal on 9 July 2021 and entered into force on 29 July 2021[44].

It constitutes a framework for the irreversible and gradual reduction of GHG emissions and enhancement of removals by natural or other sinks in the EU. Climate neutrality by 2050 is set out as a legally binding target[45]. The regulation lays the foundations for the definition of a roadmap leading the EU to climate neutrality. The Commission set a new EU target for 2030 to reduce GHG emissions by at least 50 to 55 % compared to 1990 levels.

EU institutions and member states are primarily addressed to take the necessary (legislative) measures at the EU and national level to achieve climate neutrality. Regular assessment of the progress and actions of the Union

[42] European Commission. (2021). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council. COM (2021) 559 final. 08/2021.

[43] European Commission. (2020). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. COM(2020) 324 final. Retrieved from https://ec.europa.eu/info/sites/default/files/brexit_files/info_site/com_2020_324_2_communication_from_commission_to_inst_en_0.pdf. 08/2021.

[44] European Commission. (2018). Regulation establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119&from=DE. 02/2021.

[45] European Commission. (2020). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). COM(2020) 80 final Article 1. Retrieved from https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vl6ooocjp2z5. 09/2021.

and the member states shall be undertaken to ensure the compatibility of actions with the target path and to ensure that progress is maintained[46]. This will also allow improvement measures to be enforced or recommended where necessary.

In addition, an essential and constant element of a climate strategy is adaptation to climate change[47]. The aim is to continuously improve adaptability, strengthen resilience, and reduce vulnerability to climate change. Member states are encouraged to develop and implement adaptation strategies and plans that provide frameworks for comprehensive risk management.

In accordance with the Treaties, necessary measures will be taken in order to reach these ambitious goals, including the adoption of legislative proposals and further delegated acts[48]. Specific obligations for companies therefore only arise under the context of these legislative changes.

In conclusion, the goal of the GD, i.e., climate neutrality by 2050, has been made legally binding by the European Climate Law since 29 July 2021.

2.4. Targeted savings of the Green Deal

The GD itself does not contain precise information on the targeted CO_2eq savings per sector. However, as the GD is based on the EU's 2018 vision "A Clean Planet for All"[49], it makes sense to use the information provided therein as a guide. In this guide and the GD it is highlighted that under current climate and energy policies and goals, a transition to a net-zero GHG-emission economy cannot be attained by 2050. Nevertheless, the document also sets out a clear vision of how to reach climate neutrality by the middle of this century and thereby complies with the clear objective of the GD and the newly proposed Climate Law[49].

As already mentioned, without the GD and the setting of the new targets for 2030, current policies, such as the ETS, the Effort Sharing Regulation and the Land Use, Land Use Change, and Forestry Regulation, will only reduce

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[46] European Commission. (2020). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). COM(2020) 80 final Article 6. Retrieved from https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vl6ooocjp2z5. 09/2021

[47] European Commission. (2020). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). COM(2020) 80 final Article 4. Retrieved from https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vl6ooocjp2z5. 09/2021

[48] European Commission. (2020). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). COM(2020) 80 final Article 3. Retrieved from https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vl6ooocjp2z5. 09/2021.

[49] European Commission. (2018). A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM(2018) 773 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2018)773&lang=en. 08/2021.

GHG emissions by 60 % by 2050, which is not sufficient to contribute to the Paris Agreement's temperature goal[50].

2.4.1. Savings based on different scenarios

The vision of a climate-neutral society was translated into several scenarios described in the "A Clean Planet for All" document[51]. The 1,5TECH scenario for example is illustrated in the following graph and depicts the emissions trajectory for several sectors:

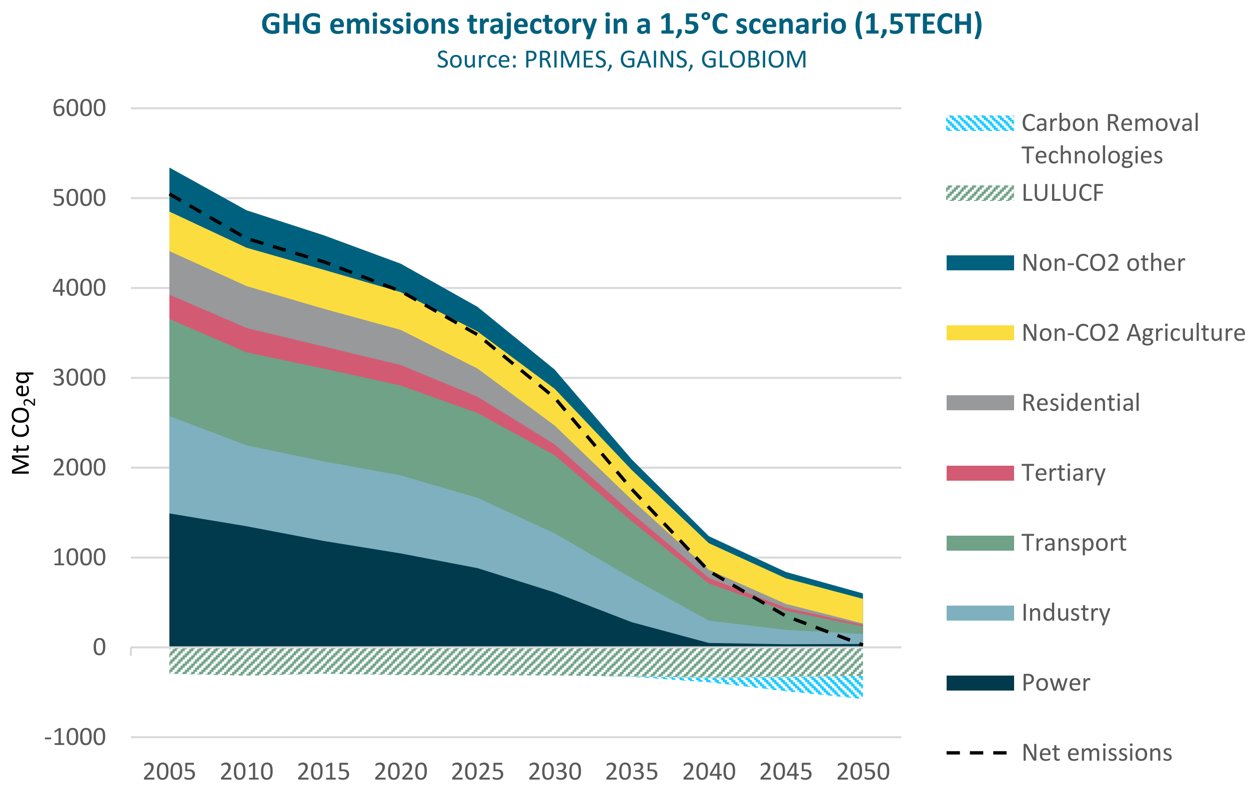

Figure 3: GHG emissions trajectory in a 1,5°C scenario. (Source: A Clean Planet for All – Supplementary Information[52])

All scenarios have been obtained from the PRIMES-GAINS-GLOBIOM model suite. The results were supported by a literature review and the corresponding macroeconomic analysis which is based on the models GEM-E3,

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[50] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. 09/2021.

[51] See 49

[52] European Commission. (2018). A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM(2018) 773 final. Retrieved from https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2018)773&lang=en. 08/2021.

E3ME, and QUEST. Consequently, eight economy-wide scenarios have been developed, aligning with the temperature objectives of the Paris Agreement, namely to keep global warming well below 2°C or to limit it to 1,5°C. Various mitigation measures and technological options explain the different results for each scenario. Emission abatements for all scenarios range from 80 % to 90 % and 100 % in comparison to 1990[53].

All pathways are compared with the baseline scenario (BL) which illustrates the current decarbonization trajectory of the EU in light of current climate and energy policies and goals. The previously mentioned scenarios are grouped into three categories with the first one responding to the "Well below 2°C" ambition and thus envisioning an 80 % decrease of emissions in comparison to 1990. This category encompasses five distinct scenarios that strongly improve energy efficiency and transport efficiency, as well as the use of renewable energy. Within this category, a total of three scenarios takes a closer look at specific energy carriers to replace fossil fuels in order to decarbonize the economy. The corresponding energy carriers and corresponding scenarios are electricity (ELEC), hydrogen (H2), and e-fuels (P2X). The remaining two scenarios study the effect of more stringent energy efficiency measures (EE) or the transition to a more circular economy (CIRC)[53].

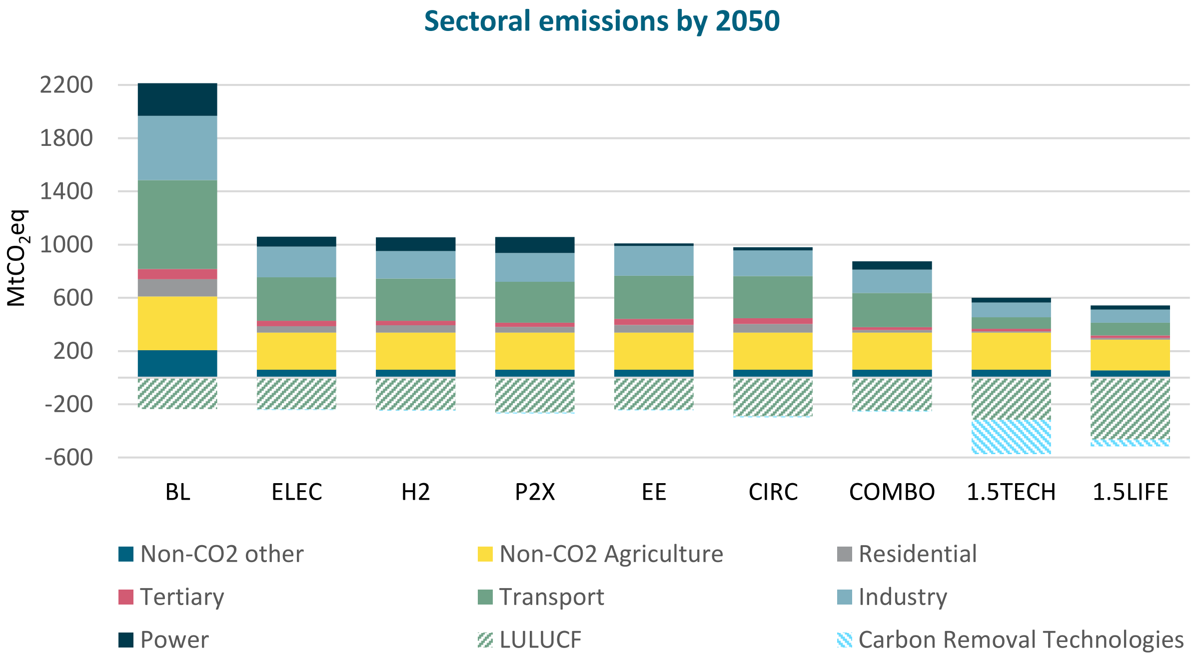

Figure 4: Sectorial emissions by 2050. (Source: A Clean Planet for All – Supplementary Information[54])

The second group consists of only one scenario (COMBO), which combines the actions and technologies of the five previous scenarios, without reaching the same level of deployment for each technology. It can also be

[53] See 49
[54] See 52

considered a hybrid scenario that combines elements of Category one and three pathways. By contrast to the two previous categories, the last one comprises two scenarios that reach net-zero GHG emissions by 2050 and thus comply with the efforts to achieve a 1,5°C increase in temperature. All emissions that cannot be abated by 2050 need to be balanced out through negative emissions. Hereby, Scenario 1,5TECH increases the contribution of the technologies mentioned in Category one, while simultaneously relying on biomass and the subsequent carbon capture and storage (BECCS)[55].

In addition to different reduction trajectories for every developed scenario, every sector is expected to accomplish different emission cuts dictated by several factors. As pointed out in the "A Clean Planet for All" document, no sector will achieve full decarbonization, but all of them require major progress early on in order to achieve the target of net-zero GHG emissions. The highest potential for significant progress lies in power generation and district heating. Consequently, the residential and tertiary sectors will cut their emissions rapidly. However, industry and transport are expected to achieve net-zero at a slower pace. Non-CO_2 GHGs emissions remain the most difficult ones to abate[55].

In the following graph, differences in annual emissions per sector are illustrated:

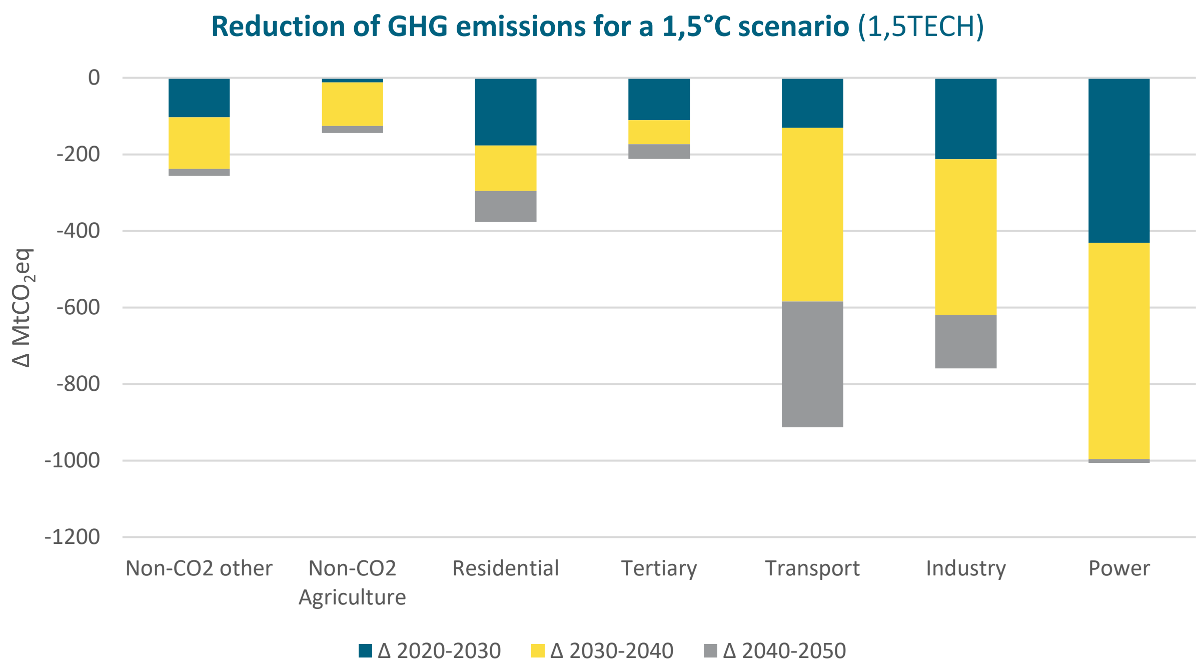

Figure 5: Reduction of GHG emissions for a 1,5°C scenario. (Source: A Clean Planet for All – Supplementary Information[56])

[55] See 49
[56] See 52

Taking a special look at the combined emissions trajectories of all sectors, as described in the 1,5TECH scenario, the initial emissions of 3,96 Gt CO_2eq in 2020, have to be reduced to 0,6 Gt CO_2eq in 2050. Land Use, Land Use Change, and Forestry (LULUCF), and carbon capture and storage (CCS) will abate the remaining emissions in order to comply with the net-zero GHG emissions objective. According to the model and more specifically to the 1,5TECH pathway, in 2020 the power sector emitted 1 Gt CO_2eq which is planned to be reduced to zero by 2050. As stated in the European GD, the production and use of energy amount to more than 75 % of the EU's GHG emissions. Consequently, the increased deployment of renewable energy sources plays a key role in building a climate-neutral Europe until the mid of this century[57].

2.4.2. Silicones and the Green Deal

Silicones and their precursor compounds can directly contribute to both the energy transition and the implementation of the GD by providing essential products for wind turbines and photovoltaic (PV) power plants. Such products include liquids for transformers of wind turbines and silanes for the production of solar grade silicon for PV panels[58].

Another sector specifically mentioned in the "A Clean Planet for All" document and the GD, is the industry sector, which accounts for 20 % of the EU's emissions[57]. The industry includes many silicone applications, for example silicone as a coating material to prolong the longevity of products or as an additive to reduce the quantity of material while maintaining the same end result. In this context, silicones as additives reduce paint use due to different product formulations or enable lowering the loss of process chemicals as an antifoaming agent in pulp production[58]. With such applications silicones contribute to the required reduction as described in the 1,5TECH pathway, from 0,9 Gt CO_2eq to 0,1 Gt CO_2eq in 2020 and 2050, respectively[57].

Furthermore, the residential sector receives special attention in the GD, as buildings are responsible for 40 % of energy consumption in the EU. GHGs emitted by buildings are approximately 0,4 Gt CO_2-eq in 2020 and should be completely eliminated by mid-century. Silicones contribute directly in this regard, as their application supports the energy efficiency of renovated and newly constructed buildings. In particular, different types of seals, such as the ones applied for windows, and brick coatings stand out due to their insulation properties.

The transport and mobility sector are responsible for 25 % of the EU's emissions and requires a drastic 90 % GHG reduction in order to accomplish the objectives of the GD[59]. In the context of the 1,5TECH Scenario, this translates to significant emission cuts from 1 Gt CO_2eq in 2020, to 0,1 Gt CO_2eq in 2050. Applications of silicone in the mobility sector can, for example, lead to fuel reduction when used in motor construction. In general, silicones are used as seals, isolators, and for encapsulations in motor construction. Another solution leading to

[57] See 49

[58] 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.

[59] See 50

reduced fuel consumption are the so-called “green tyres”, which are characteristic for their reduced rolling resistance attributed to silane additives. Also, silicone applications for batteries and energy storage for electric vehicles can contribute to longer lifetimes, larger ranges and faster recharging[60]. In addition, silicones protect batteries from heat, cold, and dirt as well as seal, cushion, and reduce the risk of battery fires. Furthermore, the application of silicone resin coatings in the production of lightweight automotive glazing enables the replacement of heavier glass parts and thereby reduces fuel consumption[60].

In this report, 11 silicone-based applications are analysed in the context of their contribution to the EU’s net-zero GHG goals. It is important to highlight that while this study reviews a limited number of 11 relevant silicone applications, silicones in general have multiple other uses that can play a crucial role in the Green Deal’s objective of a climate-neutral economy. These applications, while equally relevant, have been excluded on the basis of quantitative and qualitative criteria for project selection, elaborated in subsequent sections.

[60] See 52

3. Identification of the relevant applications

The following Chapters 3.1 and 3.2 describe the identification of the relevant silicone application case studies in detail. The methodical approach was developed in coordination with the CES members. In total, 11 relevant applications have been identified for this study, and 11 alternative components or systems have been chosen to present divergences in a differentiated manner and to quantify the benefit. The benefit of silicone applications is thus contrasted versus the GHG performance of these comparison products, which do not contain silicone but are otherwise identical. In many cases, these are applications that have been used before the widespread adoption of silicones on the market, or are still used in parallel with silicones. The use of silicone is the basis for choosing the alternative production option. Therefore, the alternative systems are referenced to a specific functionality, described in Chapter 5 in more detail as functional unit per application.

3.1. Selection of the relevant applications

The selection of relevant applications was based on qualitative and quantitative factors influencing the contribution to the GHG net benefit based on the following criteria:

1. Definition of a portfolio of applications for selection based on the Carbon Balance Study of 2012, the SEE study 2016 and market research
2. Relevance for achieving the objectives of the GD (qualitative assessment)
3. CO_2eq reduction potential (based on existing estimates) & Current market size (data CES)
4. Expected growth until 2030 & 2050 (literature research, denkstatt internal sources see Chapter 4.2)

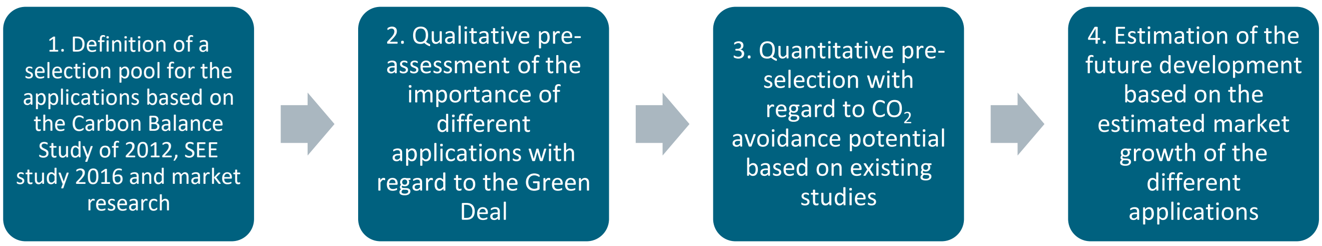

Figure 6: Selection process of the silicone applications.

As a first step, a qualitative analysis was conducted for the purposes of identifying sectors relevant for the Green Deal and the screening of silicone applications in different sectors. The global silicones council conducted a study, namely the socioeconomic evaluation of the global silicones industry (SEE study)[61], which evaluates and highlights the socioeconomic importance of the silicones industry for the global economy, served as the basis for this undertaking.

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

Secondly, from a multitude of applications a selection was made based on the Silicon-Chemistry Carbon Balance Study from 2012[62]. The key argument for including previous applications in the new study was a high GHG net benefit to impact ratio in the forgoing study of 2012, showing the importance of the potential decrease of GHG emissions. In this process, current market sizes and expected growth until 2030 & 2050 were also taken into account. The net benefit to impact ratio is described in more detail in Chapter 5. New applications were included in the selection based on the relevance for the GD and the decisions of the CES experts. Further reasons why a specific application was included in this study can be found in chapter 3.2.

In the end, the applications were finally selected by the members of CES based on their expertise in the different industry field as well as the qualitative and quantitative pre-selection described above.

Even though an attempt has been made to screen as many applications as possible in the selection process, it was not possible to screen the entire range of silicone products available on the market. Therefore, limitations had to be accepted. In this study, the 11 most promising applications were selected for the Green Deal in terms of their CO_2 benefit potential. It should be mentioned, that there are probably dozens to hundreds of other silicone applications that may also show a CO_2 benefit, but could not be considered within the scope of this study.

Then the selection of silicone applications was clustered through sector classification (transportation, electricity, electronics, construction, industrial). The use effect was evaluated and the alternative options were defined accordingly.

Finally, based on a qualitative assessment conducted by experts of the CES members, the following applications were chosen, elaborated in the next section.

[62] 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)

3.2. The 11 selected applications

The following Table 1 shows the selected applications according to their classified sector, and including their absolute GHG net benefits and the benefit/impact ratio based on the Carbon Balance study from 2012 – serving as part of the basis for selection. The reason for selection is further elaborated herein.

Table 1: Chosen applications according to the sector classification incl. GHG net-benefits and benefit/impact ratio of 2012 study and reason of selection

Application	Sector classification	Absolute GHG net-benefits (Carbon Balance study 2012) [1.000 tCO_2eq]	Benefit/Impact Ratio	Selection reason
High Quality Sealants & Adhesives	Construction	-924,9	11,7	The SEE study (2016) highlights sealants as a key construction application with significant socio-economic value. Calculated by mass, construction is the second most important sector for silicone applications. In addition, according to the Carbon Balance study (2012) this application is on the seventh position among twenty-six applications regarding the GHG net benefits.
Sealants Windows IG unit	Construction	-12.226,1	27,7	The SEE study (2016) highlights sealants as a key construction application with significant socioeconomic value. Calculated by mass, construction is the second most important sector for silicone applications. In addition, GHG net benefits are exceptionally high according to the Carbon Balance study from 2012.
Chlorosilane for Solar Grade Silicon	Electricity	-9.228,4	7,5	Silanes are indispensable input materials and intermediates in the production of siloxanes and subsequently silicones. Without silanes it would not be possible to produce silicon of sufficient purity for solar grade silicon. Around 90 % of solar (photovoltaic) cells are based on silicon (SEE 2016). In addition, GHG Net benefits are exceptionally high according to the Carbon Balance study from 2012.
Wind Turbines	Electricity	n.d.	n.d.	Wind power is seen by many recognized authorities as an essential element for the production of 100 % green electricity. With regard to the GD, the applications of silicones in the wind power industry are highlighted for the increased efficiency and lifetime of wind power plants.
Energy Efficient Lighting – LEDs	Electronics	n.d.	n.d.	LED-lights are seen by many recognized authorities as a cost-effective and efficient way to reduce CO_2eq emissions. The SEE study (2016) highlights the benefits of silicones among others in increased energy efficiency improvements for lighting, extend the lifetime of each unit, and enable enhanced brightness of LEDs.
PU Additives Insulation-Appliances	Electronics	-371,0	17,0	According to the SEE study (2016), silicones as additives in PU foams for insulation contribute to foam stabilization, reduced CO_2eq emissions, reduced heat consumption and better foam insulation.

Industrial applications in pulp industry, Anti-foaming in Pulp Production	Industrial	-2.487,7	27,1	According to the SEE study from 2016, silicone fluids with fine powdered silica acting as an antifoaming and defoaming agents help increase production rates in the pulp industry. Their pronounced positive impacts are also confirmed by the 2012 Carbon Balance study as they are the fourth most relevant application regarding GHG net benefits.
Automotive Bonding	Transportation	-1.076,2	28,4	The Carbon Balance study from 2012 revealed high GHG net benefits. The SEE Study (2016) also points out that fuel can be saved due to silicone applications in vehicles (e.g., lower weight components).
Batteries/Energy Storage	Transportation	n.d.	n.d.	Powerful and safe batteries are an essential part of the transformation from conventional fuel-based to electric mobility. In addition, stationary batteries will play a crucial role in a future energy system based on renewable energies. As a result, this application is receiving a great deal of attention within the GD as well as from the public.
Engine Performance, Rubber in Motor Construction	Transportation	-19.162,4	86,3	According to the Carbon Balance study from 2012, this application achieved the highest GHG net benefits. This aspect is not explicitly addressed in the SEE study (2016). Although it is expected that a large part of individual transportation will be electrified, this transformation will continue well beyond 2030. In addition, combustion engines (powered by biofuels) will continue to play an important role in the future, especially in sectors such as freight transport, agriculture, mining, and construction. Therefore, this is included in the study due to the promising GHG net benefit potential.
Green Tyres	Transportation	-2.324,5	66,5	In the Carbon Balance study from 2012 the GHG net benefits were the fifth most relevant regarding absolute GHG net-benefits. This is confirmed by the SEE study (2016) highlighting that great amount of fuel savings that can be achieved due to silicone additives in Green Tyres.

3.2.1. Definition of silicone-based use effect and comparable alternatives

To define the benefit of the silicone-based material, the use effect was evaluated based on the insights of the Carbon Balance study from 2012[63]. For the three added applications - Batteries/Energy Storage, Energy Efficient Lighting – LEDs and Wind Turbines - a comparable reference system was chosen in accordance with the methodology of the Carbon Balance study from 2012[64]. In Table 2 the alternative component and systems are also presented – chosen to have an identical use effect as their silicone-based counterparts.

Table 2: Use effect of a silicone-based component, the alternative component and system per application and sector

Application	Sector classification	Effect of a Silicone-based component	Alternative component and system
Automotive Bonding	Transportation	Enables reduction of weight, which leads to fuel and energy saving.	Spot welding and heavier materials
Batteries/Energy Storage	Transportation	Silicones protect batteries from heat, cold and dirt, seal and cushion internal components, and reduce the risk of battery fires. After consulting with manufacturing experts, a wide variety of applications were identified. Herein we focus on silicones as TIM (Thermal Interface Material), identified as a core application in batteries for electric vehicles.	Epoxy; 8 years lifetime[65]
Chlorosilane for Solar Grade Silicon	Electricity	Solar grade silicon is needed for photovoltaic cells; solar electricity production saves fossil energy resources. Silanes are essential for the production of solar grade silicon.	Electricity production (regional mix)
Energy Efficient Lighting – LEDs	Electronics	Silicones serve as encapsulant, die-bonding adhesive, and reflector material. Silicones provide improved light performance and extended product life. The primary effect considered is the extension of the service life over a certain period of time due to the silicone encapsulant, compared to an alternative material.	Optical grade epoxy as encapsulant material

[63] 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)

[64] 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)

[65] Tabusse, R., Bouquain, D., Jemei, S., Chrenko, D. (2020). Battery aging test design during first and second life. 1-6. 10.1109/VPPC49601.2020.9330977. Retrieved from https://www.researchgate.net/publication/349461290_Battery_aging_test_design_during_first_and_second_life. 09/2021.

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Engine Performance, Rubber in Motor Construction	Transportation	Contributes to more efficient motor technology, which leads to fuel savings.	Ethylene propylene diene monomer rubber (EPDM)
Green Tyres	Transportation	Less rolling resistance leads to fuel savings (enabled by sulfidosilanes).	Conventional tyres
High Quality Sealants & Adhesives	Construction	A system with silicone demands less material and saves energy for heating and cooling.	Thermally improved dry glazing system
Industrial Applications in Pulp Industry, Anti-foaming in Pulp Production	Industrial	Higher washer throughput makes pulp plants more efficient, less water is vaporized, less process chemicals are lost.	Mineral oil-based defoamer
PU Additives Insulation-Appliances	Electronics	Divergent insulation properties lead to different electricity demand, plus different GWP of foaming agents.	Insulation material made of mineral wool
Sealants Windows IG unit	Construction	Difference in the air tightness leads to divergent U-values, which lead to different heating demand.	Polyurethane and polysulfide window sealant
Wind Turbines	Electricity	Durability improvement for composite materials, high weatherability coatings, adhesion & sealing, heat dissipation for generator components. In addition, silicones are used in electrical insulation, protection & covering of connection cables and as a transformer oil. Silicone lubricants are selected from this wide range of applications as these can increase energy production per turbine by up to 8 %.	Synthetic lubricants

4. Data collection and calculations

The following chapter describes the calculation of the product carbon footprint (PCF) in terms of implemented methodology, general limitations, and assessment of the Eco-profile in terms of the production of polydimethylsiloxane (PDMS) fluids, sealants, rubbers, and resins as well as market data.

4.1. Calculation of the PCF

The calculation of the PCF is based on the Carbon Balance study of 2012, which broadly follows the methodological guidelines for life cycle assessments (LCA) given in ISO 14040/44. New data was inserted (e.g. on base of member information and research) and old data replaced (e.g. emission factors) where necessary and possible. The model is developed on the basis of case studies and covers calculations concerning the entire life-cycle of production including the assessment of Eco-profiles, use phase, and end-of-life. For each case study, the benefits resulting from using the silicone or silane products are defined and calculated:

- **Net-benefits** are calculated by subtracting the impacts of production and end-of-life from the benefits versus alternative applications.
- **Benefit/impact ratios** are calculated by dividing the benefits versus alternative applications by the impacts of production and end-of-life.

System definition

The temporal system boundary of the silicone-carbon balance is defined as one year (mostly 2019). The regional system boundary and therefore geographic scope is the final global warming potential (GWP) results for silicone and silane products under average production conditions in Europe.

The specific methodology, general limitations as well as the Eco-profile evaluation are described in the following chapters.

4.1.1. Methodology and limitations

In order to obtain useful results, the following steps were followed:

- Data collection (Life cycle inventory based on the 2012 study, updated with new data from industry experts, literature research and downstream user information (obtained via DU surveys))
- Calculation of carbon balance and presentation of the results
- Data validation, sensitivity analyses (for all case studies)

The quantification of the use phase benefits was a particular focus of the process. These benefits can for example be assigned to material efficiency (in comparison to competing materials) or fuel and electricity savings. In particular, these include:

- Extension of lifetime of materials enhanced by silicone applications (e.g. LED)
- Fuel and electricity saving/ substitution effects via use of silicone-containing products (e.g. green tyres, chlorosilane for solar grade silicon used in the photovoltaic industry)
- Material efficiency (substitution effects are accounted when comparing with competing materials, e.g., automotive bonding)

The study follows a total market approach, which means that the total market volume of silicone products consumed in the defined region is considered when calculating the overall carbon balance.

Where data is uncertain or requires assumptions, a conservative approach has been taken, whereby assumptions are such that attribute lesser benefits to silicones compared to their alternatives. This is to ensure that results are robust and not unduly biased toward silicones.

Due to the goal and scope of this study, the following limitations, simplifications and additional elements in the methodology are used:

- The calculation is limited to **GHG emissions**; no other environmental impacts are considered.
- **Pareto principle - 80/20 approach**: Due to the intended character of the results (approximate ratio of impacts and benefits for the total market of silicone products, not accurate LCA results of single products), many estimations and simplifications are utilized in cases where the influence of the simplification on the result is small, or where research for more accurate data is not feasible within the agreed project scope and time frame.
- **Allocation of benefits**: In some case studies, other materials or effects contribute to the realized benefits in addition to the use of silicone. To calculate results per kg silicone, it is necessary to allocate a certain share of the total use to the silicone product. Allocation approaches are defined individually in each respective case study.
- **Comparative results**: Each case study is based on a comparison with alternative materials or alternative ways to provide the same service. The comparison always refers to the same functional unit.
- **Use phase:** Effects are defined individually in each case study. Generally, the methodological standards do not regulate the calculation of use phase effects, as these effects and quantification options differ from product to product.
- **Waste management**: End-of-life effects usually do not influence results significantly in comparison with other life phases. Only limited amount of detailed data regarding waste flows, natural degradation rates and the behavior of silicones in residual waste landfills is available. If no current and reliable source has been found for some case studies, data on waste management is based on the assumptions of the Carbon Balance study of 2012. The transport after the use-phase to the EoL treatment was not taken into consideration and is therefore out of the scope as the influence on the overall impact is considered negligible.

- **Use of market data**: Results per kg of silicone material are combined with estimated market volumes to calculate absolute annual effects of each product, and to enable the calculation of aggregated results for the total market of silicones for the years 2030 and 2050.

4.1.2. Eco-profile

The GHG emissions related to the production of polydimethylsiloxane (PDMS) fluids, sealants, rubbers, and resins were investigated in detail in the Carbon Balance study of 2012 as Eco-profiles.

In 2002, CES published an Eco-profile of silicones which provides data on raw material usage, and emissions from the production of basic silicone material, polydimethylsiloxane, silicone fluids, and silicone sealants[66]. Data were derived from the Boustead study (2003)[67].

The Study from 2012 extended the scope of eco-profiles in comparison to the original study from Boustead from 2003[68], also including: PDMS fluid (= silicone oil), and PDMS used for sealants (the GWP data for sealants is calculated in the respective case studies for different formulations). Additionally, data for several other components were generated: GWP data for silicone rubbers and resins, intermediates such as methylchlorosilanes and chlorosilanes as well as GWP data for pyrogenic silica. The Eco-profile update is based on data from 2010.

PDMS-based silicone fluids, sealants, rubbers, and resins or with a chemical composition which is very similar to PDMS covered more than 90 % of the total market amounts of siloxane and silane products in 2012 and therefore were chosen for detailed investigation. Regarding environmental impacts, these eco-profiles are limited to cradle-to-gate GHG emissions

2012 data from different sources were considered for this Eco-profile calculations and estimations:

- Detailed data of specific silicon production plants (confidential)
- Dataset on silicon production included in the Ecoinvent database (2011)[69]
- Information received from Euroalliages (Association of European ferro-alloy producers)
- Information received from various CES member companies
- Information from the "Silicon Industry" Magazine (http://www.simuch.com)

Data for production of siloxanes and silanes is of differing quality due to different availability of data sources: GHG emissions to produce silicon metal are not based on primary data from single plants, but on information from Euroalliages (Association of European ferro-alloy producers), experts, literature, and on regional electricity

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

[67] 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.

[68] See 67

[69] Ecoinvent Version 2.2. (2011). Competence Centre of the Swiss Federal Institute of Technology. Zürich, Switzerland. www.ecoinvent.org.

mix and regional mix of reduction agents. GHG emissions resulting from the production of PDMS, chlorosilanes, and pyrogenic silica are based on detailed information from five companies. GHG data for special siloxane- or silane-based substances, which contain certain functional groups with relevant mass shares, were estimated based on the GWP data of the raw materials used.

4.2. The calculation of market data & extrapolation for 2030/2050

The aim of this study is to assess the impact of silicones for the achievement of the European Green Deal targets. Market data comparable to the Carbon Balance study from 2012 was collected for EU27.

Market volumes estimates were based on the 2012 study and downstream user surveys which were further specified by literature research. For each application these data sets are total market value assumptions for the EU27. As most of the data is confidential, only the sources of the literature research are disclosed (see Table 3).

All market data only refer to silicones and alkoxysilanes as pure substances (not formulated silicones or silanes). "Silicone" covers only silicone (PDMS) and its functional derivatives, including organosilicons, cyclic and linear siloxanes, but no fillers, solvents, and additives. Chlorosilanes for the production of solar and electronic grade silicon are also included, but not other silanes, which are used to produce silicones or alkoxysilanes. All market data refer to consumption, not to production, as there is a considerable trade of products.

Table 3: Aggregated market data per application for 2019 and market projections for 2030 & 2050.

Name of case study	Market volumes 2019 (t/a)	Market volumes 2030 (t/a)	Market volumes 2050 (t/a)	Additional sources	Data quality
Automotive Bonding	3.050	3.763	5.061	[70], [71]	High
Batteries/Energy Storage	1.838	28.358	74.739	[72]	High
Chlorosilane for Solar Grade Silicon	352.116	416.137	560.184	[73]	Medium

[70]ACEA. (2021). EU passenger car production. Retrieved from https://www.acea.auto/figure/eu-passenger-car-production/. 08/2021.

[71]Gao, P., Kaas, H.W., Mohr, D., Wee, D. Automotive revolution – perspective towards 2030. How the convergence of disruptive technology-driven trends could transform the auto industry. Retrieved from https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/disruptive-trends-that-will-transform-the-auto-industry/de-DE. 07/2021.

[72] European Commission. (2020). Batteries Europe Strategic Research Agenda. Retrieved from https://ec.europa.eu/energy/sites/default/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf. 09/2021.

[73]. Huangluolun, Z. (2021). EU Energy Outlook 2050 – Wie entwickelt sich Europa in den nächsten 30 Jahren?. Energy BrainBlog. Retrieved from https://blog.energybrainpool.com/eu-energy-outlook-2050-wie-entwickelt-sich-europa-in-den-naechsten-30-jahren-3/. 09/2021.

Energy Efficient Lighting – LEDs	450	2.801	6.306	[74]	Medium
Engine Performance, Rubber in Motor Construction	17.000	20.682	27.645	[75]	High
Green Tyres	31.500	39.998	56.858	[76]	Medium-high
High Quality Sealants & Adhesives	22.000	49.973	100.118	[77]	Low-medium
Industrial Applications in Pulp Industry, Anti-foaming in Pulp Production	6.000	10.858	11.950	[78], [79]	High
PU Additives for Thermal Insulation in Appliances	4.100	5.862	11.065	[80]	Low-medium
Sealants Windows IG unit	24.000	36.376	73.256	[81]	Medium
Wind Turbines	1.116	5.405	13.807	[82]	Medium

Using the data from Table 3, the total benefits for the EU27 were calculated by multiplying the net benefits of silicones per kilogram with the market data. For the years 2030 and 2050, the same methodology was applied with one minor modification – we take into account that the benefit of one equivalent of substituted or saved energy (primarily electricity and heat) decreases over time.

[74] Vision Research Reports. (2021). LED Lighting Market – Global Industry Trends and Forecast 2021 to 2030. Retrieved from https://www.mynewsdesk.com/se/newswire/pressreleases/led-lighting-market-global-industry-trends-and-forecast-2021-to-2030-3122474#:~:text=The%20global%20LED%20Lighting%20market,forecast%20period%202021%20to%202030. 09/2021.

[75] See 47

[76] Kords, M. (2018). Prognose der Anzahl der Neuzulassungen von Personenkraftwagen (Pkw) in Europa nach Art der Fahrzeugnutzung im Zeitraum der Jahre 2018 bis 2030. Statista. Retrieved from https://de.statista.com/statistik/daten/studie/875198/umfrage/prognostizierte-pkw-neuzulassungen-in-europa-nach-art-der-pkw-nutzung/. 08/2021.

[77] FEICA. (n.d.). Value of the adhesive and sealant industry in Europe. Retrieved from https://www.feica.eu/our-industry/markets. 08/2021

[78] Berg,P., Lingqvist, O. (2019). Pulp, paper & packaging in the next decade: Transformational change. Retrieved from https://www.mckinsey.com/~/media/McKinsey/Industries/Paper%20and%20Forest%20Products/Our%20Insights/Pulp%20paper%20and%20packaging%20in%20the%20next%20decade%20Transformational%20change/Pulp-paper-and-packaging-in-the-next-decade-Transformational-change-2019-vF.pdf. 10/2021.

[79] De Galembert, B. (2021). Wood Supply for the growing European pulp and paper industry. Retrieved from http://www.fao.org/3/XII/0904-C1.htm. 10/2021.

[80] Pavel, C. C., Blagoeva, D. T. (2018). Competitive landscape of the EU's insulation materials industry for energy-efficient buildings, EUR 28816 EN. Publications Office of the European Union. Luxembourg. 2018. ISBN 978-92-79-96383-4, doi:10.2760/750646, PUBSY No. JRC108692.

[81] See 52

[82] IEA. (2018). Installed capacity of offshore wind by region and scenario, 2018-2040. IEA. Paris

It was assumed that due to the broad decarbonization of various sectors, a significant reduction in the emission factors for electricity and heat in the EU will occur until 2030 and 2050. Table 4 provides an overview of the assumed emission factor reductions. As a basis, the emission factors (EF) for 2019 were used.

A decarbonization factor of 90 % was used for electricity and heat for 2050. Thereby, it is assumed that a small share of the electricity and heat is still utilized via fossil fuel power plants in 2050. A 90 % decarbonisation rate can be considered conservative, as even the EU Commission's reference scenario assumes that around 13 % of electricity in the EU will continue to be supplied by gas-fired power plants in 2050. This is similarly the case for heat supply[83].

In addition, for the applications energy efficient lighting – LEDs and battery/energy storage, it was assumed that the GHG intensity of the production of a functional unit would decrease by 44 % by 2030 and 90 % by 2050.

Table 4: Assumed changes in emission factors for the year 2030 and 2050.

	EF 2019 [g CO_2eq/kWh]	2030 Change in [%]	EF 2030 [g CO_2eq/kWh]	2050 Change in [%]	EF 2050 [g CO_2eq/kWh]	Sources
Elec-tricity	411,9	-68,5 %	129,8	-90,0 %	41,2	[84], [85]
Heat	242,7	-40,0 %	145,6	-90,0 %	24,3	[77], [86], [87]

4.3. Data collection via downstream user survey

To gather more data on previously made assumptions regarding the use of silicones, their advantages and disadvantages as well as future projections on regulations and market developments, a downstream user survey (DU-survey) was conducted.

[83] Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., ... & Kesting, M. (2020). EU Reference Scenario 2020-Energy, transport and GHG emissions Trends to 2050.
[84] EEA. (2021). Overview of the electricity production. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment-1. 09/2021.
[85] Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., ... & Kesting, M. (2020). EU Reference Scenario 2020-Energy, transport and GHG emissions Trends to 2050.
[86] EEA. (2021). Final energy consumption by sector. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-12/assessment. 09/2021.
[87] Mathiesen, B. V., Bertelsen, N., Schneider, N. C. A., García, L. S., Paardekooper, S., Thellufsen, J. Z., & Djørup, S. R. (2019). Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. Aalborg Universitet. Retrieved from https://www.euroheat.org/wp-content/uploads/2019/12/Towards_a_decarbonised_H_C_sector_in_EU_Final_Report.pdf. 08/2021.

4.3.1. Goal and purpose of the survey

In an intensive dialog with experts from CES, the data and assumptions used from 2012 were updated. For this purpose, factsheets of the known applications were prepared and sent to the nominated experts of members. For the three new applications (batteries in electric vehicles, energy-efficient lighting – LED, and wind turbines), basic and detailed information and data were obtained in interviews and questionnaires with internal experts from CES.

Additionally, a DU-survey was conducted as a broad-ranged feedback loop to support the technological assumptions and the expected CO_2eq-benefits. DUs are the customers of silicone manufacturers and have detailed knowledge on the practical application of silicones: from application-specific issues, to deep insight into the development of the market and technologies up to 2050.

4.3.2. Set up of the questionnaire

An online survey was used to collect data from downstream users on the following topics: applications, composition of silicone-based materials, professional estimations of the current market situation, and future market development of specific products. In addition to this, the survey contained questions aimed at generating a brief assessment of possible future changes in technologies and regulations concerning the use of silicon-based products in the DU's business segment.

The survey was conducted as a general questionnaire which was adapted to each of the 11 applications and expanded with additional questions. In addition, a separate survey was created for each application. DU survey subjects were chosen by the lead CES members.

The content of the basic questionnaire contains the following:

Part I: Use of silicon-based materials

1. Composition of the used silicon-based material
2. Amount of silicon-based material per functional unit
3. Function of the application/product and the silicone used in the product
4. Replaceability of the silicon-based material in the application
5. Alternative, non-silicon-based materials for the application
6. Advantages of silicon-based materials compared to alternatives
7. Disadvantages of silicon-based materials compared to alternatives

Part II: Current market situation and market development

8. Assessment of the size and the growth of the market in the EU27 for the product of the DU in 2019, 2030, and 2050
9. Expected upcoming innovations that will influence the use of silicone and silicon-based materials

10. Expected changes in framework conditions (legal requirements, bans, standards, trade of raw materials, …) that will change the use of silicon-based materials and their impacts

4.3.3. Results of the questionnaire

The questionnaires were sent to the DUs over a period of several months. The feedback was evaluated and included in the calculations of the applications and market data. Where necessary, individual consultations were held with the contact persons via email or calls. Altogether, the results of the individual survey categories showed similarities to the previously collected information from research and feedback from CES members.

5. Case studies on 11 silicone-based applications

This chapter presents the 11 case studies selected and elaborated in this report. Description of background information, functional units, and data used for production, use phase, and end-of-life (EoL) management is included.

The results of all case studies are presented in the same table format. The structure of the table, the formulas used to calculate results, and the meaning of colors are explained in the figure below and Table 5.

	D	E	
K	Factor FU/kg	3,33	
Name of case study Functional unit (FU): definition	**GWP** **kg CO2 / FU**	**GWP** **kg CO2 / kg Silicone Product**	Abbrev. used in formula below
Silicone application (A)			
Production & Transport	**9,5**	**31,8**	Sil.Prod
Production of Silicone	2,1	**7,2**	pureSil.Prod
Production of other Components (F)	7,4	**24,6**	Rest.Prod
Use			Sil.Use
End of Life (G)	**0,0**	**0,1**	Sil.EoL
Total	**9,6**	**31,9**	
Alternative application (B)			
Production & Transport	**6,6**	**22,0**	Alt.Prod
Use	**829,5**	**2 764,8**	Alt.Use
End of Life	**3,6**	**12,2**	Alt.Eol
Total	840	2 799,0	
Difference (C)			
Production & Transport	3	- 14,9	
Use	-829	- 2 764,8	
End of Life	-4	- 12,1	H
Total (- … Net-Benefit of Product with Silicone)	-830	-2 767	
Total (- … Net-Benefit of Silicone)	-189	-629	I
Ratio Benefit / Impact	87		J

Figure 7: Example of result table

Table 5: Explanation of result table

A	Life cycle GWP data of the silicone product (or scenario with silicone)
B	Life cycle GWP data of alternative product or scenario.
C	Differences between both scenarios, calculated as A – B. Therefore, a negative value means that the environmental impact of the silicone scenario is smaller than that of the alternative scenario and silicone shows a net-benefit.
D	Figures related to the Functional unit (definition in the upper part of the table)
E	Figures related to one kg of the silicone product or to the equivalent mass of alternative product
F	Grey cells represent life cycle stages for which no GWP effects are identified or considered
G	A zero means that there are GWP effects considered, but turned out to be zero
H	The total of difference (same as the difference of totals) of both scenarios. A negative figure (less GWP impact, benefit for silicone product) is highlighted green, a positive figure - red.
I	(Optional line) When silicone is only a part of the product that is investigated, the results are also related to the contained silicone only. Depending on the GWP of the other components, it is possible that one figure is positive and the other one is negative. $$\text{Total net benefit of silicone} = (\text{pureSil.Prod} + \text{Sil.EoL}) - (\text{Alt.Prod} + \text{Alt.EoL} + \text{Alt.Use}) * \text{pureSil.Prod}/(\text{pureSil.Prod} + \text{Rest.Prod})$$
J	Benefit/impact ratio: relates the benefit of the silicone product/scenario to the impact of pure silicone. Depending on the kind of case study – product made of silicone only or silicone mixed with other components, there are two formulas which are used for the calculation of this indicator (GWP figures): Silicone only: $$\text{Ratio} = \frac{\text{Alt.Prod} + \text{Alt.EoL} + \text{Alt.Use} - \text{Sil.Use}}{\text{Sil.Prod} + \text{Sil.Eol}}$$ Siliconemix: $$\text{Ratio} = \frac{(\text{Alt.Prod} + \text{Alt.EoL} + \text{Alt.Use} - \text{Sil.Use}) * \text{pureSil.Prod}/(\text{pureSil.Prod} + \text{Rest.Prod})}{\text{pureSil.Prod} + \text{pureSil.Eol}}$$ The distinction of the end-of-life impact of pure silicone and other components is sometimes omitted, when the impact is very small and mainly caused by one of them.
K	The factor represents a quotient value where the divisor is the mass per FU of the Si-based material

5.1. Automotive bonding

5.1.1. Description of the case study

In the automotive industry, silicones are used for a wide variety of applications. One of these applications is automotive bonding, which, due to its weight-saving properties, leads to a reduction in fuel consumption and thus CO_2eq emissions. As an alternative to the silicone application, there is the spot-welding method, in which two steel or metal parts are welded together. The welded parts have to be thicker and heavier to meet the same requirements to their stability, whereas thinner steel parts can be used when they are glued together with an adhesive. Thus, this method consumes more energy and is more sensitive to external influences than silicone-based adhesive bonding.

Other options to reduce additional weight are the use of lighter materials, such as reinforced plastics or aluminum. Altogether, bonding is the most energy efficient joining technique.

5.1.2. Data basis and assumptions

Functional unit

1 passenger car

Production

For the production phase, data was taken from FEICA, the Association of the European Adhesive & Sealant Industry[88], where automotive bonding is compared with spot welding. The assumptions state that the number of saved spot welds per car is 4.500 which revealed that the saved energy per one substituted spot weld equals approximately 0,005 kWh.

Regarding the amount of adhesive bonding needed for one car, FEICA assumes around 800 g per car. The GWP data for the silicone adhesive bonding was estimated by combining the data for PDMS with mixing and transport data, based on the eco-profile from 2012.

[88] FEICA. (2011). Moving more with less CO_2 - Bonding in the Automotive Industry. Retrieved from: https://www.feica.eu/application/files/6016/1539/0295/FEICA_BS_Moving-more-with-less-CO2.pdf. 06/2021

Use phase

Assumptions from FEICA were also used for the use phase. There, a weight saving of 52,2 kg per car on average is assumed due to the use of silicone-based adhesives. This leads to a saving of about 14.200 MJ for petrol cars and 13.100 MJ for diesel cars over the lifetime of a car, which is assumed to be around 11,5 years[89].

To calculate the emission data, factors from Ecoinvent[90] were used. The average share of diesel cars in the EU27 was assumed to be around 42 %, whilst the share of petrol cars was estimated at 53 %[91]. Looking at future developments in the automotive sector, the share of fossil-fuel vehicles will be drastically reduced. Forecasts point to an increase in the share of e-cars of up to 57 % by 2030 and 97 % by 2050. Accordingly, the benefits from the use phase will be allocated differently in the future, since technology is moving towards electrically powered engines[92].

End of life

In the end-of-life phase, it was assumed that cars would be collected separately. In this scenario, 20 % of the bonding material is incinerated and the remaining 80 % is assumed to be landfilled.

5.1.3. Results

Table 6 shows the life cycle GWP effects of automotive bonding in cars. The use effect is much greater than the effects from production or the end-of-life phase, as the life of the car and the fuel reduction are taken into account here (even if only 10 % is attributed to bonding).

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[89] 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.

[90] 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.

[91] 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.

[92] 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.

Table 6: GWP effects of automotive bonding

2019	Case study no.	1
	Factor FU/kg	1,25
Automotive Bonding Functional unit (FU): 1 car	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product**
Silicone automotive bonding		
Production & Transport	5,3	6,7
Use		
End of Life	-0,0005	-0,0034
Total	**5,34**	**6,67**
Spot welding and heavier materials		
Production & Transport	9,3	11,6
Use	172,7	215,9
End of Life		
Total	**182,0**	**227,5**
Difference		
Production & Transport	-3,93	-4,91
Use	-172,72	-215,90
End of Life	-0,0005	-0,0034
Total (- ... Net-Benefit of Silicone)	-176,6	-220,8
Ratio Benefit / Impact	34,07	

Definition impact: Production & EoL silicone adhesive bonding

Definition benefit: Substituted energy for spot welding, saved fuel

5.1.4. Sensitivity analysis

Figure 8 shows the influence of the silicone proportion of the fuel saving benefit. The percentage of allocated benefits to silicone is varied from 3 % to 15 %, which leads to a range of the benefit/impact ratio between 10 and 51.

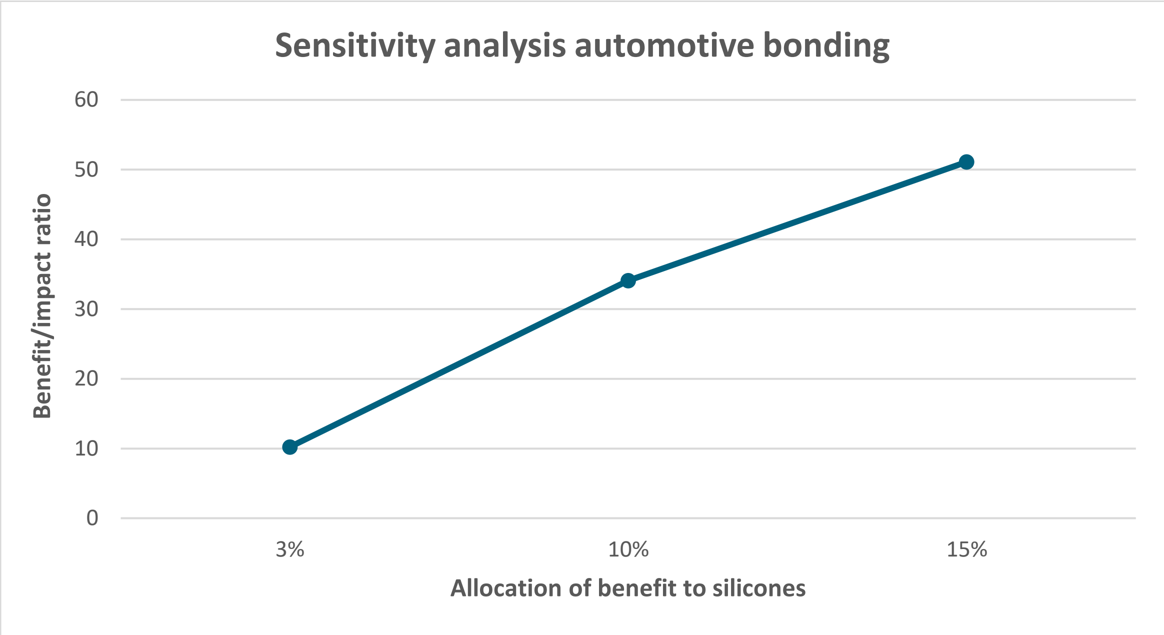

Figure 8: Sensitivity analysis for allocation of benefit of automotive bonding

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

5.2.1. Description of the case study

By assembling battery cells to a battery pack for EV, silicone is used for sealing and bonding, thermal management and electric insulation. Among these applications, utilization as TIM (Thermal Interface Material) is considered essential. Heat dissipation and thermal management are growing issues in the design of electric vehicles (EV) as well, silicones tend to put much lower stress on components. Lithium-ion batteries change their structure and dimensions during charging and discharging, known as "swelling". Therefore, structural flexibility and long lasting softness (very low moduli even for several thousand hours of service) are key requirements for TIM materials. Highly filled thermally conductive silicones have very low moduli and will not show thermooxidative hardening during the service life of a battery. Organic polymer based TIMs undergo thermal aging as the hydrocarbon chemistry is generally limited in heat resistance. This aging leads to irreversible structural changes of the macromolecular network and will as such cause a hardening of the material over time. Due to well-known silicones excellent heat resistance, no degradation is observed in batteries environment, therefore physical and thermal performance is guaranteed at least for the car's life time.[93] [94]

The extend of service life of a battery due to silicone may be not quantifiable at this time due to lack of long-term experience. However, the main advantage of silicone based TIMs is that they do allow a future extension of the battery lifetime by optimizations in the lithium-ion battery technology itself as they are not a limiting factor for the service lifetime.

A range of 5-50 % lifetime extension by using silicones as TIM was indicated in expert interviews[95]. Therefore, it is assumed that silicones as TIM extend the life of batteries from 8 to 10 years on average because high priced EV producers already guarantee this longer life[96].

Another advantage of using silicone is a better reparability due to eased detachment of individual cells. All manufacturers launching EVs are building capacity for battery repairs in the so-called "Battery Refurbishment Centers". Within these centers, individual defective modules or battery cells are replaced to make the battery operational again[96].

There are a number of incumbent materials used in EV batteries including epoxy and PU. For the purpose of this study, the focus was placed on epoxy. Epoxy is chosen as the alternative material to silicone.

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[93] Chowdhury, ASMR.; Rabby, M.M.; Kabir, M.; Das, P.P.; Bhandari, R.; Raihan, R.; Agonafer, D. (2021) A Comparative Study of Thermal Aging Effect on the Properties of Silicone-Based and Silicone-Free Thermal Gap Filler Materials. Materials 2021, 14, 3565. https://doi.org/10.3390/ma14133565

[94] Walter, P. Silicone-Based Thermal Interface Materials for Electric Vehicles. *adhesion ADHESIVES+SEALANTS* **19**, 22–25 (2022). https://doi.org/10.1007/s35784-022-0387-6

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

[96] ADAC. (2021). Elektroauto-Batterie: Lebensdauer, Garantie, Reparatur. Retrieved from https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/info/elektroauto-batterie/. 10/2021.

5.2.2. Data basis and assumptions

Functional unit (FU)

1 dm^3 of TIM (Thermal Interface Material) - silicone or epoxy

10 years of battery lifetime

Production and Transport

The silicone-TIM consists of 15 % silicone polymer (PDMS) and 85 % inorganic filler (Al_2O_3) with a density of 2,9 g/cm^3 [97].

The density of epoxy is 1,13 g/cm^3 [98].

The battery pack of an average BEV weights approx. 330 kg and contains 1,11 kg of insulation[99]. Due to the facts that the bill of material (BOM) lists various plastics with the exception of silicone, and TIM has both insulating and heat dissipating properties, it is assumed the amount of "insulation" in modules and packs corresponds to the amount of TIM. This gives a volume of 0,38 dm^3 silicone-TIM per battery pack. So, with 1 dm^3 of silicone-TIM a battery pack with 856 kg could be manufactured.

The specific values for GWP of inorganic filler (Al_2O_3), epoxy, and the production of the Li-ion battery originate from Ecoinvent[100]. The values for silicone polymer have been obtained from the eco-profile of silicones[101] C.

Emission factors for mixing and transport are based on the Eco-profile from 2012.

Use phase

Almost all manufacturers guarantee a minimum battery lifetime of 8 years[102]. Therefore, the lifetime of a battery with epoxy is assumed to be 8 years. In the case of the use of silicon-TIM an additional lifetime of 2 years is assumed because EV producers of high-priced EVs are already guaranteeing this longer life. This results in a

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97 Wacker. (2017). Datenblatt Semicosil 961 TC 7399-EN.pdf

98 Moosburger-Will, J., Greisel, M., Sause, M., Horny, R., Horn, S. (2014). Physical properties of partially cross-linked RTM6 epoxy resin. 16th European Conference on Composite Materials, ECCM 2014.

99 Winjobi, O., Dai, Q., Kelly, J.C. (2020). Update of Bill-of-Materials and Cathode Chemistry addition for Lithium-ion Batteries in GREET� 2020

100 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.

101 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.

102 Tabusse, R., Bouquain, D., Jemei, S., Chrenko, D. (2020). Battery aging test design during first and second life. 1-6. 10.1109/VPPC49601.2020.9330977. Retrieved from https://www.researchgate.net/publication/349461290_Battery_aging_test_design_during_first_and_second_life. 09/2021.

replacement factor of 1,25. The use phase also includes emissions from the manufacturing and transport of the batteries.

End of life

In the end-of-life scenario, once a battery is deposed as waste, both the silicone and epoxy models are assumed to be incinerated in a pyrometallurgical waste treatment plant.

5.2.3. Results

Table 7 compares the life cycle GWP for batteries in EVs which utilize silicone or epoxy as an alternative TIM. The reason for the difference and the benefit is primarily owed to the longer battery life when using silicone. This is possible because silicone allows individual cells to be replaced, thus extending the service life and lifetime of batteries. Small amounts of silicone-TIM lead to a high benefit-impact-ratio. The benefit is expressed through reduced use of materials and energy. Therefore, use phase calculations take into consideration the entire battery, not just the very small proportion of silicone that makes this service life extension possible.

The functional unit includes a life time of 10 years of the battery, regardless it is made with or without silicone. The difference between the silicone and alternative application is a shorter lifetime for the silicone free battery. In case of the alternative application another battery has to be manufactured to fulfil the demand of 10 years lifetime. This is accounted for by a replacement factor (10 years / lifetime of the silicon free battery; see “Use phase” above) by which the emissions of one alternative battery are multiplied. The results of the alternative application in Table 7 thus refer to the 10-year service life of the functional unit.

Table 7: Life cycle GWP of silicone and epoxy as Thermal Interface Material in batteries in EV

	Case study no.	2
	Factor FU/kg	2,298850575
TIM in batteries in electric vehicles Functional unit (FU): 1 dm^3 TIM; 10 a	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product (TIM)**
Silicone application: TIM; 10 a life time of the battery		
Production & Transport	6,8	15,6
Production & Transport Silicone	6,8	15,6
Use	5.731,2	13.175,1
Production & Transport Batterycells	5.731,2	13.175,1
End of Life	0,0	0,0
Total	5.738,0	13.190,7
Alternative application: Epoxy; 8a life time of the battery		
Production & Transport	7,5	17,3
Production & Transport Epoxy	7,5	17,3
Use	7.164,0	16.468,9
Production & Transport Batterycells	7.164,0	16.468,9
End of Life	-0,1	-0,3
Total	7.171,4	16.485,9
Difference		
Production & Transport	-0,7	-1,7
Use	-1.432,8	-3.293,8
End of Life	0,1	0,3
Total (- ... Net-Benefit of Battery	-1.433,4	-3.295,2
Ratio Benefit / Impact	211,7	

Impact definition: Production & Transport of silicone-TIM

Benefit definition: Total GWP of the epoxy-TIM minus expenses for the production, transport, and end-of-life processes of silicone-TIM battery cells.

The benefit of using a small amount of silicone in batteries is to extend the life of the entire battery, which in EVs weigh about 300 kg. This longer life causes the benefit in the form of reduced use of raw materials and energy when replacing used batteries. This saving of material and energy, not the replacement of the alternative material with silicone brings the high net benefit in this application.

5.2.4. Sensitivity analysis

The difference between battery lives of products with and without silicone determines the size of the replacement factor. This is the crucial factor for the level of benefit in the comparison of the two materials.

Starting from a total life of 10 years, the life of the battery with silicone TIM is varying from 9 to 11 years. In the case of epoxy, the duration of use is fixed at 8 years. This results in replacement factors of 1,25 for 10 years, 1,13 for 9 years, and 1,38 for 11 years of life time.

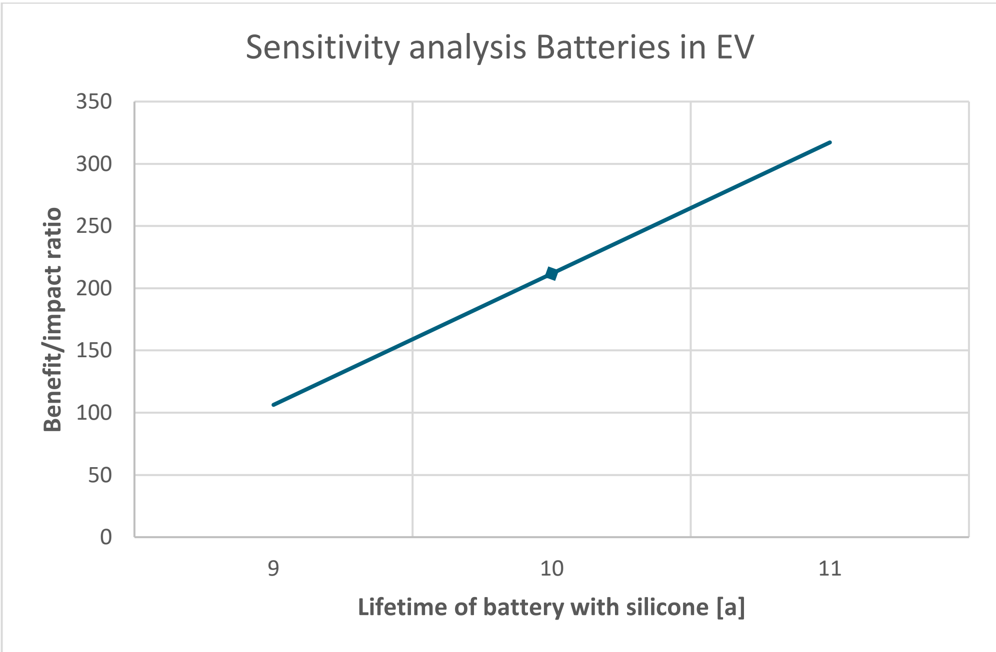

Figure 9: Sensitivity analysis: Batteries in EVs, silicone and epoxy as a Thermal Interface Material

5.3. Chlorosilane for solar grade silicon

5.3.1. Description of the case study

In addition to monocrystalline and polycrystalline silicon as the products from the silicon industry, silicone is also used as a frame sealant, junction box adhesive, junction box potting agent, and encapsulant for microinverter in the fabrication of PV systems[103].

90 % of the PV modules on the market are based on silicon[104]. Alternative materials such as perovskite tandem cell need to overcome significant deficits in order to achieve the same efficiency as silicon-based PV modules and are therefore not considered as reference application[105].

Formerly, silicon for photovoltaic (PV) applications came partly from off-grade material in the electronic grade silicon production[106,107]. The share of off-grade electronic grade silicon in 2006 was about 5 %[108], with a downward trend to 0 % in 2021[109].

Almost the entire amount of solar grade silicon is purified from metallurgical grade silicon through a "Siemens" process[110]. This involves tetrachlorosilane ($SiCl_4$) and trichlorosilane ($SiHCl_3$) as an intermediate[111].

Therefore, solar grade silicon is regarded as a product of silicone industry and is examined within the context of this study.

Figure 10 shows a flow diagram of silicon PV systems, including the two ways of producing solar cells (mono-Si, multi-Si). These are also included in the calculation based on their respective market shares. BOS (mentionend in the figure below) means "balance of system" and refers to the mounting system. It includes the production of the additional components necessary for the mounting but excludes lightning protection, inverters, and cables, which are not considered in this study. The datasets, which are referring to the BOS system, are derived

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

104 Andreani, L. C., Bozzola, A., Kowalczewski, P., Liscidini, M., & Redorici, L. (2019). Silicon solar cells: toward the efficiency limits. Advances in Physics: X, 4(1), 1548305.

105 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)

106 Fthenakis, V.M., Kim, H.C. (2010). Photovoltaics: Life-cycle analyses. Center for Life Cycle Analysis. Columbia University, New York, NY, USA. Photovoltaic Environmental Research Center, Brookhaven National Laboratory. Upton, NY, USA. In: Science Direct, Solar Energy 85 (2011) p. 1609–1628

107 Ecoinvent Version 2.2 (2011), Competence Centre of the Swiss Federal Institute of Technology, Zürich, Switzerland. www.ecoinvent.org.

108 Ecoinvent Version 2.2 (2011), Competence Centre of the Swiss Federal Institute of Technology, Zürich, Switzerland. www.ecoinvent.org.

109 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.

110 Dazhou Y. (2018). Siemens Process. In: Yang D. (eds) Handbook of Photovoltaic Silicon. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-52735-1_4-1

111 Maurits JEA. (2014). Silicon production. In: Seetharaman S (Ed) Treatise on process Metallurgy, (Vol 3): industrial processes. pp 919–948 https://doi.org/10.1016/B978-0-08-096988-6.00022-5

from Ecoinvent 2021. An average of two datasets (flat-roof installation and slanted-roof installation) and an average of two datasets (flat-roof installation and slanted-roof installation) was formed.

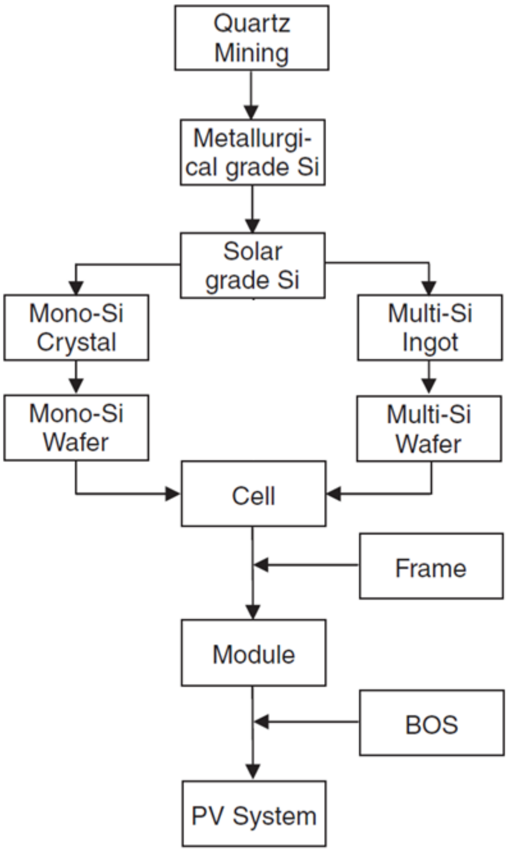

Figure 10: Detailed flow diagram from the raw material acquisition to manufacturing stage of PVs (ds modified from Fthenakis, V.M., Kim, H.C., Alsema, E. (2008)[112])

5.3.2. Data basis and assumptions

Functional units

1 kWp installed capacity

Kilowatt peak is the unit for maximum output of an electricity generating system. Solar systems achieve this output under standard conditions (solar radiation of 1.000 W/m^2).

[112] Fthenakis, V.M., Kim, H.C., Alsema, E. (2008). Emissions from photovoltaic life cycles. Environmental Science & Technology 42, 2168– 2174.

Production

Production data are taken from Ecoinvent (2021). Ecoinvent data are available for a capacity of 224 Wp for mono-Si wafer systems and 210 Wp[113] for multi-Si wafer systems in reference to 1 m^2 of active surface, with their current market shares taken into consideration (95 % mono and 5 % multi)[114]. The active surface was scaled accordingly to the functional unit of 1 kWp.

For the production of a system with 1 kWp, around 3 kg of silicon are required, which equals around 12 kg of chlorosilanes (90 % of tri- and 10 % tetrachlorosilane)[115].

Use phase

The only environmental effect in consideration during the use phase of PV systems is the production of electricity and substitution of other electricity sources.

The lifetime of a PV system is assumed to be 30 years[116]. Every year the system performance deteriorates by 0,5 % (due to the degradation of components)[117]. The yield is calculated for rooftop installation only, as the fraction of façade installations is less than 1 % [118]. Electricity produced from photovoltaic systems is considered as a primary substitute for conventional energy sources in the European electricity mix.

Table 8: Electricity produced by photovoltaic systems of 1 kWp in different regions

	Weighted average EU	FR	UK	ESP	Unit
Average yield rooftop	1.100	1.115	898	1.450	kWh/kWp.a
Electricity produced over lifetime	30.715				kWh

The weighted European average rooftop installation yield is 1.100 kWh/kWp.a[119]. The country specific rooftop yield varies along the table data above[120]. (Table 8)

[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 http://link.springer.com/10.1007/s11367-016-1087-8. 07/2021.

[114] denkstatt. (2021). External expert interviews. 07/2021.

[115] denkstatt. (2021). External expert interviews. 07/2021.

[116] Ito, M. (2011). Life cycle assessment of PV systems. Crystalline silicon properties and uses, 297.

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

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

[119] EU Commission. (2018). Energy statistical datasheets for the EU countries. Retrieved from https://data.europa.eu/data/datasets/information-on-energy-markets-in-eu-countries-with-national-energy-profiles?locale=en. 08/2021.

[120] Leloux, J., Taylor, J., Moretón, R., Narvarte, L., Trebosc, D., Desportes, A., & Solar, S. (2015). Monitoring 30,000 PV systems in Europe: performance, faults, and state of the art. In 31st European photovoltaic solar energy conference and exhibition (pp. 1574-1582).

End of life

Waste management effects are considered in Ecoinvent data; hence, they are included in the "production and transport" processes listed in the results table.

5.3.3. Results

Table 9 shows the life cycle GWP effects of both systems (silicone photovoltaic system and regional mix of electricity production). Differences in the use phase appear as a value in the alternative system, hence the amount of electricity produced over the lifetime of a PV-system is evaluated via a regional energy mix. EoL is not shown separately as it is included in the production and transport phase of this specific dataset.

Table 9: GWP effects of a photovoltaic unit. The right column shows the GWP related to chlorosilane, the intermediate product in the purification process.

	Case study no.	3
	Factor FU/kg	0,081159597
Chlorosilanes Functional unit (FU): 1 kWp installed capacity	**GWP kg CO_2eq / FU**	**GWP kg CO_2eq / kg Silicone Product**
Silicon photovoltaic system		
Production & Transport	1.377	112
Silicon production and purification	44	4
Production of Solar systems	1.332	108
Use		
End of Life		
Total	2.753	223
Electricity production (regional mix)		
Production & Transport		
Use	12.654	1.027
End of Life		
Total	12.654	1.026,994
Difference		
Production & Transport	1.377	112
Use	-12.654	-1.027
End of Life		
Total (- ... Net-Benefit of Silicone)	-11.277	-915
Total (- ... Net-Benefit of Chlorosilane)	-363	-29
Ratio Benefit / Impact	8,2	

Impact definition: production, transport, and EoL of solar grade silicon for a PV system

Benefit definition: Substitution of the average European electricity mix by solar power electricity

5.3.4. Sensitivity analysis

Substitution of conventional energy sources with renewable energy sources in electricity mixes of each region is a usual method for calculating the CO_2eq of a specific electricity production system. A different approach is considering natural gas which is the only marginal source for electricity consumption in the EU.

With gas as the substituted source of electricity, a 1 kWp PV plant would save 13.576 kg CO_2eq during its lifetime (instead of 11.477), the benefit/impact ratio would increase to 11,5 (instead of 9,8). With coal as the substituted source of electricity a 1 kWp PV plant would save 33.295 kg CO_2eq during its lifetime. The benefit/impact ratio would increase to 24,2.

5.4. Energy efficient lighting – LEDs

5.4.1. Description of the case study

LEDs are widely applied in various fields, such as traffic lights, display media, and general lighting systems[121]. Due to their long lifetime, they have the potential to transform the illumination industry, in particular - automotive applications and street lightning[122]. It is estimated that high power (HP) LEDs contribute to the market with a share of approx. 38 % in 2019[123].

Silicones can be found in the reflector, the encapsulating material or the lens, the thermal interface material, and as a bonding adhesive. Silicones provide improved light performance and extended product life[124].

In this study the focus lies on the benefits of the extended product life through the usage of silicone as an encapsulant or a lens compared to optical grade epoxy as the lens-material, due to the proportionally large quantity of utilized encapsulant material compared to the amount of used thermal interface material or bonding adhesive and lack of data for quantifying the benefit of silicone as reflector material.

HP LEDs encased with epoxy encapsulants face several problems such as material yellowing and shorter lifetime due to the large amounts of heat generated and accumulated in the package. It can be stated that the useful lifetime with silicone encapsulants is higher than with an epoxy encapsulant, as the lumen output for the epoxy encapsulant drops about 81 % (for 350 mA constant current for 1.500 h) in comparison to a drop of 1-5,5 % for the silicone encapsulant[125]. Useful lifetime is defined as the timespan from first-time use to a drop in the luminous flux beneath 70 %[126]. This “failure time” of the silicone encapsulated LED and the alternative epoxy-encapsulated LED can be compared.

The timespan is extended due to the use of silicones, leading to a replacement factor of 5 for the epoxy encapsulated LED[127]. This replacement factor is generated on the basis of only one publication (to the knowledge of the author there are no other publications available) and specific laboratory trials under artificial conditions. A replacement factor of 2 was applied in order to not overestimate the benefit since it can be assumed that in practice the efficiency of silicone is likely to be lower.

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121 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.

122 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.

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

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

125 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.

126 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.

127 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.

This approach has been chosen due to the lack of specific data for the benefit quantification of silicones as bonding adhesives or reflector materials.

Furthermore, glass can be seen as an alternative to epoxy with superior thermal stability compared to silicone[128]. However, glass possesses several disadvantages as well - a brittle and heavy material which is difficult to process into the desired design and requires a higher temperature and energy consumption for processing[129]. Therefore, it was not considered as an alternative.

5.4.2. Data basis and assumptions

Functional unit

The functional unit was chosen as the luminous duration of 1.500 h at constant 350 mA provided by a HP LED.

Production

A typical LED with an average weight of 1 g was considered for the calculation[130]. LEDs consist of various inputs, for example, metals such as copper, nickel or tin, resin, and electronic grade silicon (EGS)[131]. Epoxy and silicone are widely used as encapsulant materials in LEDs[132]. For a LED lamp several additional input materials are needed such as e.g., metal threads, plastic structures or joint rings[133]. The masses for the encapsulants are calculated based on outer diameter (OD) of 10 mm and a thickness of 1 mm[134]. The encapsulant component material (funnel glass) of the original Ecoinvent dataset for LED[135] has been replaced by epoxy and silicone to fit the input materials for HP LED. The original Ecoinvent dataset dates back to 2007.

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128 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.

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

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

131 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

132 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.

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

134 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.

135 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

Use phase

It is assumed that both kinds of LEDs are replaced once they lose their function. The different lifetimes are considered within the production phase. There are no differences between the studied scenarios considered in the use phase.

End of life

50 % of the encapsulant material mass was assumed to be treated as residual waste and incinerated as such. The other 50 % are separately collected and sent for industrial energy recovery (100 % in Europe). The rest of the LED is treated as electronics scrap[136] introduced in the recycling of metals phase of the Boliden process by the Kaldo plant.

5.4.3. Results

Table 10 shows the life cycle GWP impacts of energy efficient lighting – LEDs. The production phase has a considerably greater impact than the end-of-life phase.

[136] 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. http://link.springer.com/10.1007/s11367-016-1087-8. 07/2021.

Table 10: GWP effects of LED with silicone encapsulant and LED with epoxy encapsulant

	Case study no.	4
	Factor FU/kg	3658
LED Functional unit (FU): light duration of 1500 h	GWP kg CO_2eq / FU	GWP kg CO_2eq / kg Silicone Product
LED lamp with silicone encapsulant		
Production & Transport	3,07	11.237
LED lamp production excluding encapsulant	3,07	11.230
Silicone encapsulant production	0,0019	7
Use		
End of Life	0,00044	2
Total	3,07	11.238
LED lamp with epoxy encapsulant		
Production & Transport	6,1	22.472
LED lamp production excluding encapsulant	6,1	22.460
Epoxy encapsulant production	0,0032	12
Use		
End of Life	0,0009	3
Total	6,1	22.475
Difference		
Production & Transport	-3,1	-11.235
Use		
End of Life	0,000	-2
Total (- ... Net-Benefit of Silicone)	-3	-11.237
Ratio Benefit / Impact	2,0	

Impact definition: Production & EoL of LED lamp with silicone encapsulant.

Benefit definition: Substituted production and EoL of LED lamp with epoxy encapsulant due to extended life-times related to the use of silicones.

The total net benefit of silicone (-11.237) measured as kg CO_2/kg silicone product is relatively high due to the factor [FU/ kg] of 3.658, which is defined by the small mass of silicone as encapsulant material (0,3 % of the total weight of the LED lamp) to which the benefit relates.

5.4.4. Sensitivity analysis

The benefit/impact ratio would increase to 5 (instead of 2) and the net benefit of silicone to -44.949 kg CO_2eq/kg silicone product by choosing a replacement factor of 5 (for the production and EoL of the LED lamp including epoxy encapsulants) referring to a light duration of 1.500 h[137] for LED.

[137] 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.

5.5. Engine performance, rubber in motor construction

5.5.1. Description of the case study

Silicone rubber is used in motor construction as an isolator, sealant and for encapsulations, e.g., as spark plug boots, turbo charger hoses, seals and gaskets, vibration dampers for noise reduction, or NEV cables. Silicone rubber is the only rubber material that endures very high temperatures over a long period of time without becoming brittle or breaking. Due to the increased downsizing of engines in recent years, a higher temperature resistance is required from the used materials. Modern motor management requires direct ignition per cylinder, high temperatures, and a high voltage ignition spark, which can only be reached with silicone encapsulating and isolation. In addition to the described optimal engine conditions, the use of silicone also leads to a fuel saving of about 20 % [138].

For new electric car generations, silicones play a major role as well by increasing the durability of gaskets through a higher temperature resistance. Every gasket has its own requirements (tightness or temperature resistance, self-adhesion to different substrates) that need to be tackled during production. For the current study, EPDM is considered as an (historical) alternative material, which doesn't enable such high temperature levels and resulting fuel saving.

However, the market for combustion engines will decrease drastically in the future, as different legislations at the EU level and in national resolutions are supposed to lead to a decrease of the use of fossil fuels[139]. Additionally, car manufacturers are committing to the electrification of their portfolios in their future strategies. Projections foresee the e-car share rising up to 57 % in 2030 and 97 % by 2050 in the EU[140]. Therefore, the benefit/impact ratio of the application will be significantly reduced, as the fuel savings can no longer be allocated to silicone use. The benefits will shift towards the use of batteries and other EV-relevant technologies to save electric energy instead of fossil fuel resources (see Chapter 5.1.2).

5.5.2. Data basis and assumptions

Functional unit

1 car, 150.000 km

The mass of silicone parts in cars varies between 1 and 4 kg, depending on the model, region, and the manufacturer. The value of the average mass of silicone was calculated by dividing the total silicone market volume for the European Union by the total number of vehicles produced in the EU27. Considering that not all rubber parts

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

[139] European Commission (2021). European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541 (accessed 09/2021)

[140] International Energy Agency (2021): EV share of car sales in the European Union in the Sustainable Development Scenario, 2019-2050. Taken 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

of a car are used for the motor construction, but also for gaskets, seals or mounts, the resulting average mass calculation of 2,36 kg silicone per vehicle is a plausible value compared to the values referred in Moutney[141]. The average amount of silicone used in motor construction was estimated at 0,7 kg/car, taking into account the silicone market mass for automotive applications and the number of produced vehicles in the EU27.

Production

A mixture of 70 % vinyl PDMS and 30 % fillers is assumed for the silicone rubber used in motor construction. In the calculation of emissions, vinyl PDMS was treated as PDMS.

It is assumed that the same volume of EPDM is needed for a similar motor without silicone rubber. The density of silicone rubber is 1,15 g/cm^3; the density of EPDM is 0,82 g/cm^3 [142]. Production data for EPDM is taken from Ecoinvent[143].

Use phase

In the use phase, 20 % of the fuel savings are allocated to all silicones used in the engine[144]. Emission data for the operation of the cars was taken from Ecoinvent[145]. An average consumption of 5,2 liters/100 km for diesel and 6,8 liters/100 km for petrol cars is assumed. The Ecoinvent values are considered a good conservative assumption, avoiding an overestimation of the use effect.

However, the benefits from the use phase cannot be solely attributed to the silicone rubber, but also depend heavily on other engine technologies and components. Therefore, it was assumed that between 10 and 30 functional components also contribute to the overall fuel reduction. The allocation factor to applications with silicones therefore varies between 1/30 and 1/10, whereby the arithmetic mean of 6,7 % can be assigned as a benefit to this particular rubber application.

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[141] Mountney, A. (n.d.). Silicones in Transportation: Automotive and Aviation. Dow Corning Ltd. Barry (Wales).

[142] 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.

[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. 08/2021.

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

[145] See 139

End-of-Life

In the end-of-life phase, it was assumed that cars would be collected separately. In this scenario, 20 % of the rubber material is incinerated and the remaining 80 % is assumed to be landfilled.

5.5.3. Results

In Table 11 the life cycle GWP effects of silicone rubber in motor construction are shown. Despite the allocation of the fuel saving of only 6,7 % attributed to silicone rubber, the use effect outweighs the impact from production and the end-of-life phase. Looking at the future, the benefit/impact ratio of the application will be significantly reduced, as the fuel savings can no longer be allocated to the use of silicone. The benefits will shift towards the use of batteries and other EV-relevant technologies.

Table 11: GWP effects of silicone rubber and EPDM in motor construction

2019	Case study no.	5
	Factor FU/kg	1,43
Rubber for Engines Functional unit (FU): 1 car, 150.000 km	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product**
Silicone rubber		
Production & Transport	4,61	6,58
Use		
End of Life	-0,0004	-0,0006
Total	**4,60**	**6,58**
EPDM		
Production & Transport	1,25	1,78
Use	632,1	903,0
End of Life	0,09	0,13
Total	**633,437**	**904,911**
Difference		
Production & Transport	3,4	4,8
Use	-632,10	-903,00
End of Life	-0,09	-0,13
Total (- … Net-Benefit of Silicone)	-628,8	-898,3
Ratio Benefit / Impact	**137,6**	

Impact definition: Production & EoL of silicone rubber

Benefit definition: Substituted production and EoL of EPDM rubber, saved fuel

5.5.4. Sensitivity analysis

Figure 11 shows the influence of how much of the fuel saving benefit is allocated to silicone. The percentage is varied from 3,3 % to 10 %, which leads to a range of the benefit/impact ratio between 68 and 206.

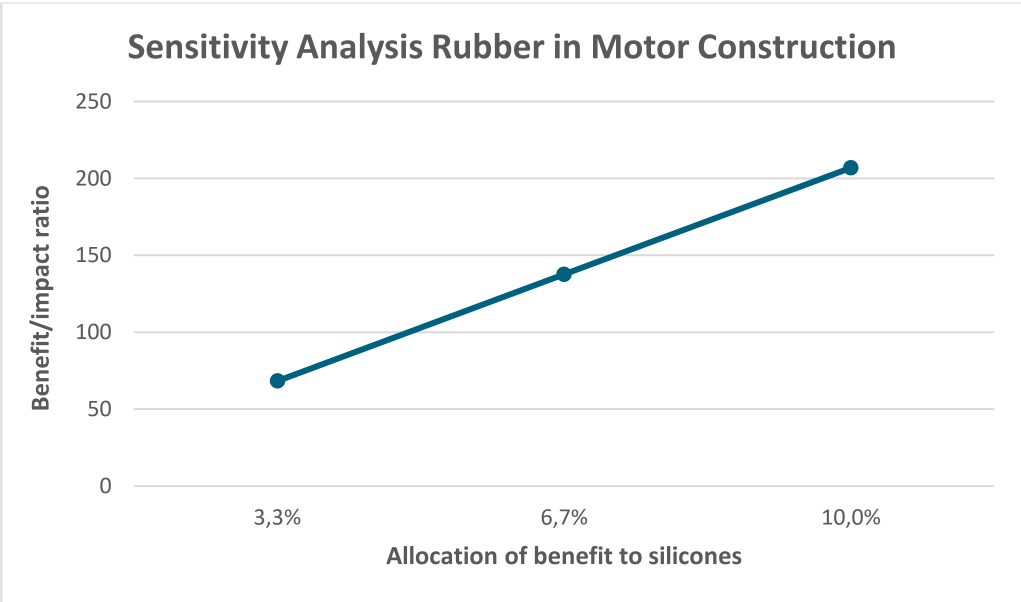

Figure 11: Sensitivity analysis for allocation of benefit of rubber in motor construction

5.6. Green tyres

5.6.1. Description of the case study

Green tyres are a term for tyres with lower rolling resistance which consequently leads to fuel saving. The reduction of rolling resistance is realized by adding certain silanes (such TESPT silane), also called bis(triethoxysilylpropyl)tetrasulfide – a standard silane in silica tyres[146]), and precipitated silica instead of carbon black to the rubber of the tyre tread. The derived fuel reduction is about 5 % [147].

However, it is assumed that different legislations at the EU level and in national resolutions will lead to a significant reduction of fossil fuels use in the future. Projections foresee the e-car share to rise up to 57 % in 2030 and 97 % by 2050 in the EU[148]. Therefore, the benefit/impact ratio of the application will be reduced, as the market share of internal combustion engines declines and, due to the ongoing decarbonization of electricity generation, the CO_2 intensity per passenger kilometer of electric vehicles will decrease significantly.

Nevertheless, it was taken into account that Green Tyres contribute to energy efficiency of e-cars via reducing the rolling resistance and the reduction of overall CO_2 emissions, as long as the electricity used for e-cars is not carbon-neutral.

5.6.2. Data basis and assumptions

Functional unit

1 set of 4 tyres for 1 car. A set of tyres is assumed to last for 50.000 km [149].

Production

Similar to the 2012 study, the GWP of the TESPT silane was evaluated on the basis of specific precursors (trichlorosilane, ethanol, propanol, sodium persulfate, and sulphur) and the data from Ecoinvent (2021) was multiplied with a safety factor of 1,5 to avoid underestimating the GWP.

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146 denkstatt. (2021). External expert interviews. 06/2021.

147 denkstatt. (2021). External expert interviews. 06/2021.

148 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.

149 denkstatt. (2021). External expert interviews. 06/2021.

The GWP of the Silica production, which is precipitated from an aqueous solution, was estimated through a combination of a dataset for the solution of sodium silicate, sulphuric acid, and a dataset for a drying process similar to paper recycling[150]. These data are also taken from Ecoinvent (2021).

Data for carbon black is directly taken from Ecoinvent (2021). The amount of substituted carbon black is assumed to have the same mass as TESPT silane and silica in total.

Use phase

Fuel saving attributed to silane use is about 5 % [151]. GWP data for the burning of petrol and diesel is taken from UBA (2019)[152] and information for the upstream chain is taken from Ecoinvent (2021). They are based on a petrol fuel consumption of 6,8 liters/100 km and a diesel fuel consumption of 5,2 liters/100 km[153]. Ecoinvent values are considered a good conservative assumption, which enables avoiding use effect overestimation.

An average dataset for a European car mix was modelled assuming that the average share of diesel cars in the EU27 is around 42 %, while the share of petrol cars is approximately 53 %[154]. The remaining 5 % fuel types are hybrid electric (HEV), electrically chargeable (ECV), and alternative fuels, which are not considered due to the conservative approach.

Allocation

The reduced fuel consumption is enabled by the use of TESPT silane and silica. For the allocation of this benefit, the GWP for the production of both substances was used.

End of life

The quantity of worn-out material produced during the life of a tyre amounts to approx. 1 kg per tyre[155], which correlates to 50 % of the tyre tread. Tyre abrasion is temporarily spread on the road and then washed off by the rain water to soil and water bodies, where degradation occurs. The other 50 % of the tyre tread are separately collected together with the rest of the tyre, and go to industrial energy recovery (70 % in Europe) and landfills.

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[150] 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.

[151] denkstatt. (2021). Personal information from experts of the project steering group.

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

[153] 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.

[154] 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.

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

5.6.3. Results

Table 12 shows the life cycle GWP effects of green tyres. The use effect is much greater than any effect from the production or the end-of-life phase.

Table 12: GWP effects of green tyres and conventional tyres

	Case study no.	6
	Factor FU/kg	2,86
Green Tyres Functional unit (FU): set of 4 tyres for 1 car	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silane Product**
Green Tyres with silane		
Production & Transport	**11,1**	31,7
Silane TESPT	2,5	7,1
Silica	8,6	24,6
Use		
End of Life	0,03	0,1
Total	**11,1**	**31,8**
Conventional tyres		
Production & Transport	7,7	22,0
Use	394,0	1 125,8
End of Life	3,5	10,1
Total	**405**	**1 158,0**
Difference		
Production & Transport	3	-15
Use	-394	-1 126
End of Life	-4	-10
Total (- … Net-Benefit of Green Tyres)	**-394**	**-1 126**
Total (- … Net-Benefit of Silicone/Silane)	**-89**	**-254**
Ratio Benefit / Impact	**36**	

Impact definition: Production & EoL of TESPT silane and silica.

Benefit definition: Substituted carbon black (incl. EoL), saved fuel.

The benefit/impact ratio was only calculated for the benefit of silane, taking into account the proportions of TESPT silane and silica. That is to say, the benefit was divided by the sum of the GWP of TESPT silane and silica and multiplied by the GWP of TESPT silane.

5.6.4. Sensitivity analysis

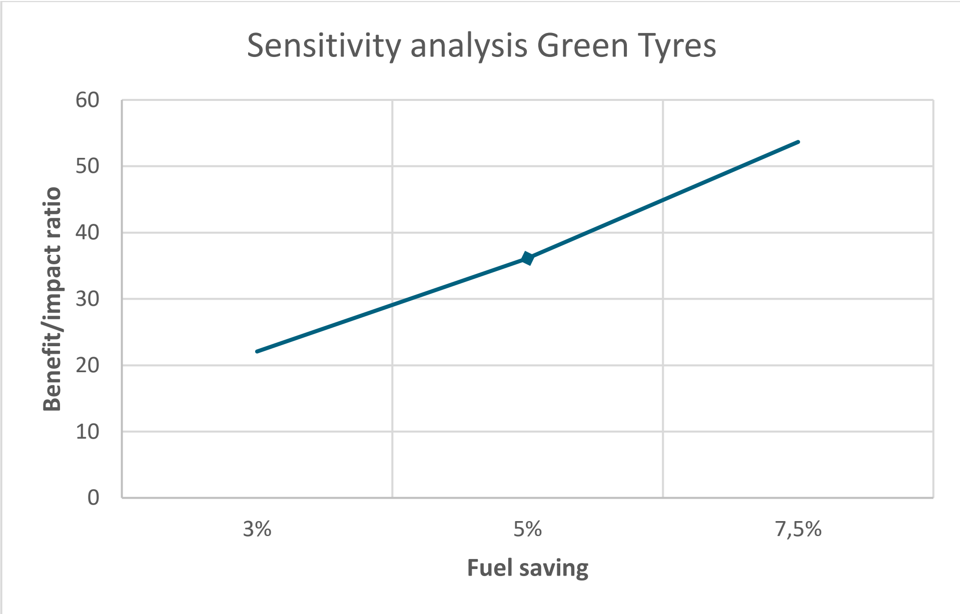

Figure 12: Sensitivity analysis of the fuel saving through green tyres

Figure 12 shows how the benefit/impact ratio changes with the fuel saving achieved by green tyres. It varies between 3 % and 7,5 %, which leads to a range of the benefit/impact ratio between 22 and 54.

5.7. High quality sealants & adhesives

5.7.1. Description of the case study

Structural glazing, an innovative way to design glass facades, is compared to a dry glazed thermally improved conventional system as alternative. Structural glazing is only attainable through the use of silicone sealants. The alternative was chosen, because it also uses insulating glass (IG) units (which are considered in the Chapter 5.10 and excluded in this case study) and provides a good thermal barrier[156].

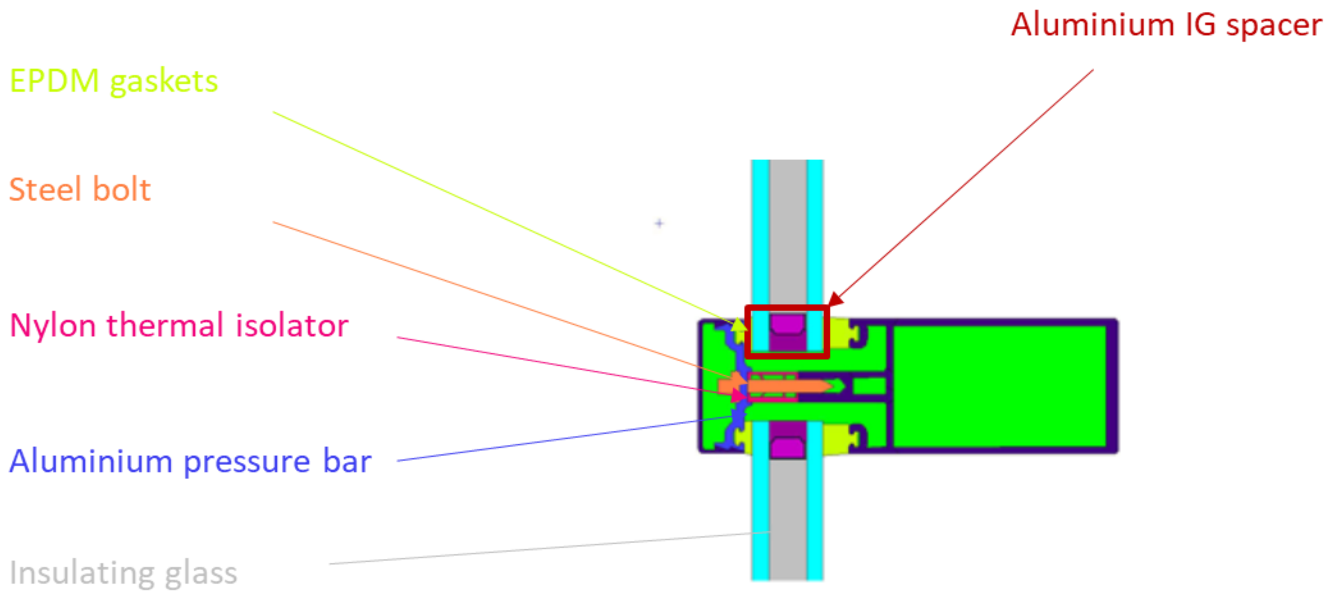

Figure 13: Dry glazed thermally improved system[157]

[156] Carbary, L. et al. (2009). Comparisons of Thermal Performance and Energy Consumption of Facades Used in Commercial Buildings, in: Glass performance days 2009.
[157] See 139

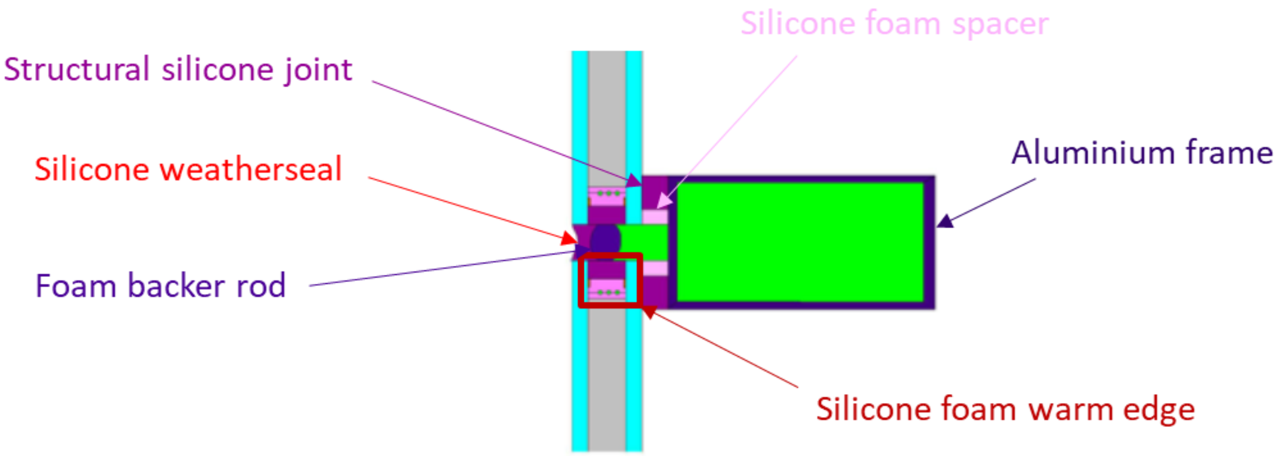

Figure 14: Silicone structural glazed system[158]

The standard thermally improved glazing system (Figure 13) operates with pressure bars mechanically attaching the glazing to the façade. The exterior aluminum glazing stop is attached to the interior frame every 236 mm with a steel bolt and a spacer of high-performance plastic separating the interior frame from the exterior frame. The glazing is able to move within the gaskets during thermal expansion and contraction and during movement due to live loading on the building. The gaskets perform the role of weather seals.

Figure 14 demonstrates the application of wet structural silicone sealant as an adhesive that anchors the glass to the frame, sealing the glazing from air and water infiltration. The structural silicone absorbs differential movements between glass and frame arising from thermal expansion and contraction, live load deflections from the building due to wind sway, seismic events, and occupant generated loads. These positive key attributes of the silicone structural glazing system are further enhanced by the fact that silicone is a continuous thermal barrier. During these quotidian movements over many years, silicone keeps the glazing in place and eliminates air and water infiltration[159].

5.7.2. Data basis and assumptions

Functional unit

A model building, 9 stories high with a rectangular layout, 12 x 50 meters with a 4-meter ceiling height was chosen as a functional unit[160]. A window size of 1,2 x 2,5 m induces to a number of 1.560 windows and a length of as much as 11.544 m window edge. It should be noted that the choice of a large glass area of the windows

[158] See 139
[159] See 139
[160] See 139

follows a conservative approach of this study as a low glass/frame rate would make the effects of the frame (and thus of silicone) more predominant.

The lifetime of the building is assumed to be 50 years.

Production

Silicone

Based on the company information from 2012, the structural glazing system consists of[161]: (Table 13)

Table 13: Silicone components in structural glazing system

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

An average, high-quality sealant for structural glazing consists of 45 % silicone (PDMS), 50 % calcium carbonate, and 5 % pigments and adhesion promoters[162] (the 5 % are not specified and are treated as silicone (PDMS) in the environmental assessment). This applies to all three components (silicone joint, silicone weather seal and silicone foam spacer).

Aluminium frame

Since the static supporting part of the aluminium frame is composed of the same amounts of material in both scenarios, it is excluded from the model, as it would not cause any differences. For the alternative glazing system, an aluminium pressure bar on the outside of the building is required. This bar is estimated as an object with a rectangular cross section, 4 x 2 cm, with 3 mm wall thickness at the side facing the glass, and 2 mm wall thickness else, which leads to a weight of about 4,025 kg aluminium per functional unit. Production data of the aluminium frame is a combination of “aluminium alloy production, AlMg3” and “section bar extrusion, aluminium”, originating from Ecoinvent (2021).

[161] 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)

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

Gaskets

The dry glazing system requires gaskets at either side of the IG unit, produced from EPDM (ethylene propylene diene monomer) rubber. The quantity of EPDM is estimated with a total area of 3,62 cm^2 per FU, which equals the area of all silicone components (silicone joint, silicone weather seal and silicone foam spacer) used for structural glazing[163]. This leads to a total mass of 3,635 kg EPDM per FU. Production data of EPDM is taken from Ecoinvent (2021).

The lifetime of EPDM gaskets is assumed to be 15 years. It is assumed that in mild climate regions they are replaced later than in hot or cold climates. With these assumptions in consideration, as well as the usage of a correct sliding agent during installing, an average of 2 sets of EPDM gaskets are needed[164] within the life time of a building. This is considered as a conservative approach.

Use phase

The building described above was modelled in different locations, one location with cold and one with hot climate to model the effects of structural glazing silicone on the European market[165].

The advantage of structural glazing is based on two effects, the U-value of the frame and air infiltration, which are considered separately in order to see how much they influence the total result.

Energy consumption due to different U-value of the frame

Structural glazing facades with the same IG units have a better U-value than dry glazed systems (2,01 W/m^2K for a silicone system vs. 2,30 W/m^2K for a dry glazed system with triple low E insulating glass)[166].

Energy consumption due to air infiltration

A genuine, low air infiltration rate can be attained when a building is wet sealed with silicone as a durable sealing material. Air infiltration rates can increase over time if the original glazing material (e.g., EPDM) is susceptible to degradation due to weathering[167].

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[163] Carbary, L. (2012). External expert interviews.

[164] denkstatt. (2021). Personal information from experts of the project steering group.

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

[166] See 153

[167] See 153

Both effects influence the demand of heating energy and electricity for cooling. The GWP for heating is taken from Bertelsen´s and Vad Mathiesen´s study regarding the EU-28 residential heat supply and consumption (2015), with reference to the following fuel shares (Table 14)[168].

Table 14: Fuel share of residential heating 2015 EU-28

Fuel share of residential heating 2015 EU-28	
Waste	1 %
Biomass	19 %
Renewables	3 %
Gas	44 %
Oil	16 %
Coal	12 %
Nuclear	5 %

The GWP for the European Electricity mixes were taken from Ecoinvent (2021).

Table 15: Effects of U-value and air infiltration on the GWP for hot and cold climate

Average effect of different U-value (CO_2eq/FU.a)	Europe
cold climate	1.627
hot climate	651
Average effect of increased air infiltration	
cold climate	23.353
hot climate	10.783

Table 15 shows the effects of the U-value (thermal transmittance) and air infiltration on the GWP for hot and cold climate, influencing the use phase. The calculations are based on data regarding energy input for gas (heating) and electricity (cooling) for the assumed building from Carbary´s study (2009)[169] and the GWP for heating and electricity as mentioned above. The values for the triple low E system regarding energy input for gas (heating) and electricity are used for the calculation here, because this is the standard glazing for structural glazing

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

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

facades[170]. The air infiltration rate was assumed to be 5,5 $m^3/h\ m^2$ [171] as a base case, and 11 $m^3/h\ m^2$ [172] in case of an increased air infiltration.

As a conservative approach to average the use effects of structural glazed systems considering locations with moderate climate, it was assumed that 25 % of silicone used for structural glazing led to the same effects as the cold climate model, another 25 % of silicone cause the effects occurring in hot climate, and 50 % cause no use effect at all. 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.

End of life

It is assumed that 50 % of all sealing materials are handled as building rubble and the other 50 % are collected separately and go to incineration plants and landfills in equal shares[173].

[170] See 165
[171] See 165
[172] See 165
[173] denkstatt. (2021). Internal expert knowledge

5.7.3. Results

Table 16 shows the life cycle GWP effects of both facade systems. Differences in the use phase appear as effects of the dry glazing system as consequences of a higher air infiltration effect. Still a conservative presumption (20 % of time with increased air flow rate for the dry glazing system) was made to keep the benefits of silicone realistic.

Table 16: Life cycle GWP of a silicone structural glazed system and a dry glazing thermally improved system

	Case study no.	7
	Factor FU/kg	0,000195807
HQ Sealants & Adhesives Functional unit (FU): 1 building	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product**
Silicone structural glazed system		
Production & Transport	21.298	4,2
Use		
End of Life	-132	-0,026
Total	**21.166**	**4,1**
Dry glazing thermally improved system		
Production & Transport	52.066	10,2
EPDM gasket	18.784	3,7
Aluminium frame	33.282	6,5
Use	113.810	22,3
effect of U-value	28.471	5,6
effect of air infiltration	85.340	16,7
End of Life	4.565	0,9
Total	**170.441**	**33,4**
Difference		
Production & Transport	-30.768	-6
Use	-113.810	-22
End of Life	-4.696	-1
Total (- ... Net-Benefit of Silicone)	-149.275	-29
Ratio Benefit / Impact	8	

Impact definition: Production & EoL of silicone sealant

Benefit definition: Substituted production and EoL of EPDM and aluminum, saved heating and cooling energy

5.7.4. Sensitivity analysis

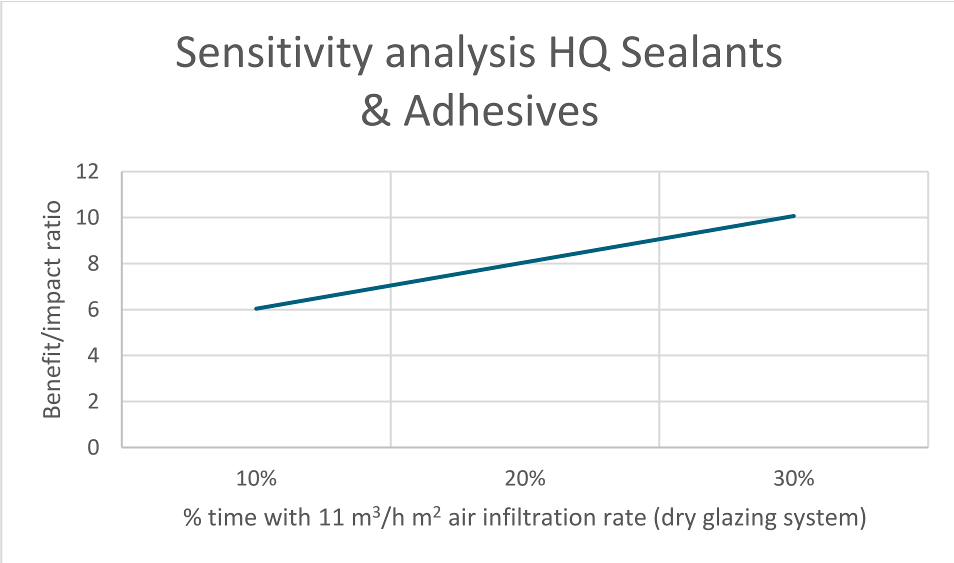

Figure 15: Sensitivity analysis of % of time with 11 $m^3/h\ m^2$ for the dry glazing system

Figure 15 shows how the benefit/impact ratio changes with 11 $m^3/h\ m^2$ air infiltration rate for the dry glazing system. The time span with a worse air infiltration rate of 11 $m^3/h\ m^2$ varies between 10 % and 30 %, which leads to a range of the benefit/impact ratio between 6 and 10.

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

5.8.1. Description of the case study

Silicones are used in several processes within the process chain of pulp production. The vast majority of silicone products are used in brown stock washing. In this procedure dissolved organic and inorganic substances are removed from the wash water. It is important to recover the maximum amount of spent chemicals in order to operate an efficient pulp mill. Thus, efficient washing improves the recovery of spent chemicals, reduces the consumption of reagents in the subsequent bleaching, and limits effluent load from the plant[174,175].

Defoaming chemicals (wash aids) are used in brown stock washing to increase productivity. For many years, oil-based defoamers were used – a technology developed from kerosene and pig fat to mineral oils and ethylene-bis-stearamide (EBS). Today, the vast majority of brown stock washing is done using silicone-based defoamers, which have a series of advantages over their oil-based alternatives[174]. Some of the benefits derived from this technology include:

- Higher production rate through better foam control
- Lower defoaming chemical dosage requirements
- Enhanced drainage of process chemicals
- Minimized loss of process chemicals
- Minimized bleaching chemical requirements
- Reduced shower flow
- Increased evaporator capacity
- Cleaner pulp
- Fewer pitch deposits
- Delivered as water dispersible emulsion

5.8.2. Data basis and assumptions

Functional unit

1 ton of dry pulp

[174] 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

[175] 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.

Dosage

The amount of defoamer needed greatly depends on the kind of wood used for pulp production. Softwood pulp requires a higher dosage of defoaming chemicals as opposed to hardwood pulp[176]. According to experts, the dosage of silicone antifoaming agents varies greatly. For this study, a silicone-based emulsion with an active silicone part of 30 % is assumed. Only silicone oil (PDMS) and silica are included in the calculation. Experts state that the average amount of silicone in antifoaming agents varies between 0,01 and 0,4 kg/t pulp. This results in a dosage of **0,2 kg silicone-based antifoaming agent** per ton of dry pulp which varies from 0,1 to 0,4 in the sensitivity analysis.

Defoaming with oil-based products requires an amount between 0,5 and 3,5 kg/t pulp[177,178]. For the calculation, an average value of **2 kg/t pulp** is used, which varies from 1 to 3 in the sensitivity analysis.

Production

Production data

Oil-based products are mainly based on mineral oils and EBS [179,174]. Vegetable oils, composites of oil, and hydrophobic silica are not taken into account - the first two due to their small shares of the market, the third because hydrophobic silica is mostly a product of the silicone industry and thus not a suitable alternative to silicones. The share of EBS in defoamers varies between 5 and 10 % in this study an average of 7,5 % is used[180]. Production GWP data are taken from Ecoinvent 3.7.1[181].

Use phase

Shower flow

One main goal of defoaming is to use as little water as possible for washing the pulp. The use of silicone-based defoamers leads to a reduced shower flow in comparison to oil-based defoamers. According to experts, the

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[176] Pekte, H., Wang, M. (2019). Select the Right Brown Stock Defoamer for your Washing Operations. Retrieved from https://www.tappi.org/content/Events/19PEERS/19PEE18.pdf. 10/2021.

[177] Habermehl, J. (2005). Silicone Foam Control Technology for Kraft Bownstock Washing. Dow Corning.

[178] McGee, J. (1990). Water-based Brownstock Antifoams. Michigan, Dow Corning

[179] Cao, T., Liu, Y. and Zhang, Z. (2017). Non-Silicon Defoamer. European Patent Application published in accordance with Art. 153(4) EPC. European Patent Office.

[180] 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

[181] 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.

reduced shower flow is about 10 %. An average of 8.000 l water/t of dried pulp is used, saving 800 l/t of dried pulp with a silicone anti-foaming agent.

In terms of GWP, this water saving is not a big effect and amounts to only 0,31 kg CO_2eq/t pulp.

The much higher effect is the saved energy from the evaporation of the washing water in the subsequent process, where the liquor is concentrated. Due to the lack of data, the GWP effect was estimated by using the evaporation enthalpy of 2,26 MJ/kg and the specific heat capacity of 4,19 kJ/kg*K of water which results in an energy supply for the temperature increase of 0,25 MJ/kg. The production of heat in a pulp plant is not very CO_2eq-intensive due to the extensive use of renewable energy resources (black liquor, bark, wood residues). A GWP of 0,02 kg CO_2eq/MJ was derived[182]. The GWP effect of the reduced evaporation effort amounts to 46,5 kg CO_2eq/t of pulp.

Process chemical loss

Reduced shower flow and better drainage also lead to an increased recovery of process chemicals[174]. The average reduction of caustic soda loss is estimated at 7 pounds per ton (3,18 kg)[174], which equals 4,1 kg CO_2eq.

Production rate

Higher brown stock throughput in the washer and better drainage, as well as the better recovery of process chemicals, lead to an overall increased performance of the pulp mill. According to expert opinions, this improvement amounts to at least 10 %. It is assumed that the total pulp production over the lifetime of a pulp mill is 20.000.000 t[183]. The GWP of the plant (without operational effects) is about 260 kt CO_2eq based on the data from Ecoinvent 3.7.1[184]. An increase in productivity of 10 % leads to a saving of 1,2 kg CO_2eq/t of pulp.

End of life

In the pulp industry, sewage residues are usually used for energy recovery. In this study, a share of incineration of 80 % is assumed, and 20 % are landfilled. The GWP effect for oil-based defoamer is 1,9 kg CO_2eq/t of pulp. The GWP effect for silicone-based defoamer is 0,07 kg CO_2eq/t pulp.

[182] Franklin Associates. (2012). Documentation for the Paper Calculator Version 3.2. Retrieved from: https://s3.amazonaws.com/EPNPaperCalc/documents/Paper_Calculator_Documentation.pdf. 10/2021.

[183] 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

[184] 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.

5.8.3. Results

Table 17 shows the GWP effects of the use of silicone-based defoamer, compared to a mineral oil-based defoamer. The use effects are described as disadvantages of the alternative product. The alternative product accounts for a higher GWP than the silicone product for production and transport (difference: -2,71 kg CO_2eq/FU), use (difference: -52,05 kg CO_2eq/FU) and EoL (difference: -1,84 kg CO_2eq/FU). Within the total life cycle, the effect in use is the biggest.

The benefit/impact ratio is calculated by dividing the sum of the GWP emissions of the alternative product by the sum of production and the end-of-life of the silicone product, and amounts to 108.

Table 17: GWP effects of pulp washing with silicone-based defoamers, compared to mineral oil-based defoamers

	Case study no.	8
	Factor FU/kg	5
Anti-Foaming Pulp Production Functional unit (FU): 1 ton of dried pulp	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product**
Silicone application		
Production & Transport	0,46	2,30
Use		
End of Life	0,07	0,35
Total	0,53	2,65
Alternative application		
Production & Transport	3,17	15,84
Use	52,05	260,25
Worse production rate of pulp plant	1,18	5,91
Additional water (production)	0,31	1,53
Additional water to evaporate	46,45	232,24
Additional cauistic soda used	4,11	20,57
End of Life	1,91	9,53
Total	57,13	285,63
Difference		
Production & Transport	-2,71	-13,55
Use	-52,05	-260,25
End of Life	-1,84	-9,18
Total (- … Net-Benefit of Silicone)	-56,60	-282,98
Ratio Benefit / Impact	108	

5.8.4. Sensitivity analysis

The dosage of oil-based defoamers is quoted in the range of 0,5 to 3,5 kg/t of dry pulp. If the average value of 2 (which is used in the calculation) is varied from 1 to 3, the GWP burden from defoamer production varies from 1,7 to 4,7 kg CO_2eq/t of pulp. As a result, the benefit/impact ratio varies between 106 and 110.

The dosage of silicone-based defoamer also varies in the sensitivity analysis. If only 0,1 instead of 0,2 kg/ton of pulp were needed, the benefit/impact ratio would increase to 220, if the dosage was 0,3 kg/ton of pulp, this ratio would decrease to 73. With a dosage of 0,4 kg/ton of pulp, the benefit/impact ratio would be 55. All considered sensitivity analyses are shown in Figure 16.

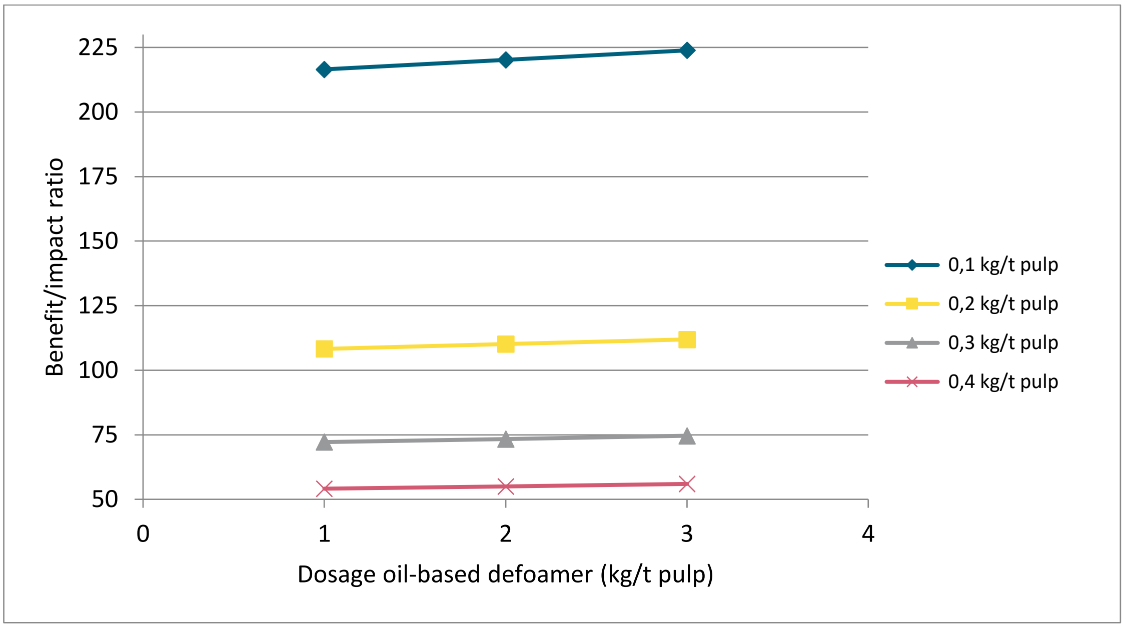

Figure 16: Dependency of benefit/impact ratio on the dosage levels of silicone defoamer and its alternative, oil-based defoamer.

5.9. PU additives for thermal insulation in appliances

5.9.1. Description of the case study

Polyurethane (PU) is used to produce rigid foam for thermal insulation in appliances like refrigerators and freezers. As a component of PU foam, polyether siloxane is used as an additive to regulate the size of foam cells.

If PU could not be produced, alternative materials for thermal insulation with higher U-values would be used (e.g., mineral wool). The higher U-value results in a higher energy demand due to the predetermined thickness of the insulation material in the appliances. Due to this disadvantage these alternative products actually are no longer available on the market. Hence, the case study is a hypothetical comparison of a modern and a historic product.

A life cycle comparison of PU and mineral wool applied in an average refrigerator (volume 272 l) is made. The differences in GHG from production, use (different energy demands due to different insulation properties), and waste management are accounted for and a part of the benefit is allocated to the polyether siloxane.

5.9.2. Data basis and assumptions

Functional unit

As a functional unit one refrigerator with a volume of 272 liters (198 l fridge, 74 l freezer) and an available space for insulation material, equal to 5 kg, PU is chosen. The lifetime considered is 12 years.

Polyurethane

Based on information given from experts the following assumptions are made:

- Polyether siloxanes for rigid PU foam applications have a siloxane/polyether weight ratio of 40:60.
- GWP data of polyether siloxane for rigid PU foam applications are calculated based on company member information and Ecoinvent 3.7.1[185]. The result is a GWP of 3,5 kg CO_2eq/kg.
- The influence of the final production step for attaching the polyethers to the siloxane backbone (hydrosilylation) on the product's carbon footprint can be neglected.
- The content of polyether siloxane foam stabilizers in rigid PU foam has an average share of 0,8 %, which is used for calculations.
- Density of rigid PU is 30 kg/m^3
- Thermal conductivity of PU is 0,020 W/m*K
- The mass of PU insulation material within one refrigerator is 5 kg.

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[185] 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.

- The production of blowing agents, which are mostly pentane, is considered to have a GWP of 1,1 kg CO_2eq/kg [185].

For PU in the production phase an average GWP of 3,35 kg CO_2eq/kg is used - based on Ecoinvent 3.7.1 and the information from experts[186].

Alternative material

For the alternative, competitive insulation material, the following assumptions are made based on the information from experts and Pilz et al.[187]:

- Density of mineral wool is 50 kg/m^3
- Thermal conductivity of mineral wool is 0,033 W/m*K
- GWP of mineral wool in the production phase is 1,46 kg CO_2eq/kg
- The mass of mineral wool within one refrigerator is 8,3 kg (assuming the same available space regarding volume for both PU and mineral wool insulation material).

Use phase

For the comparison of different insulation materials for refrigerators and freezers it is assumed that the inner and outer volume of the appliances remain the same, reflecting a given available space and a constant performance in terms of volume.

Due to the different insulating capacity of the materials the difference in cooling energy demand is considered as an effect during the use phase. The following assumptions are made:

- Energy demand of PU insulation is 824 MJ_{el}/a [188]
- Energy demand of mineral wool insulation is 1,245 MJ_{el}/a [187]

The values are multiplied with a lifetime of 12 years leading to the energy demand of the insulation material per functional unit.

An electricity mix of 0,41 kg CO_2eq/kWh is used based on the dataset for electricity in Europe[186]:

a) market group for electricity, low voltage

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[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. 08/2021.

[187] 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, Vienna. Austria for PlasticsEurope - Association of Plastics Manufacturers, Brussels, Belgium.

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

Another effect considered is the escape of blowing agents migrating from plastic foams over timer. According to experts, blowing agents have an average share of 5 % in the PUR foam. The vast majority of foams are currently blown with cyclo-pentane or isopentane. For the calculation, a GWP of 0,76 kg CO_2eq/kg PU foam is assumed, resulting from the release and degradation of pentane during the use phase.
For mineral wool, no blowing agent is needed, which results in a GWP in the use phase of 0 kg CO_2eq/kg.

Allocation

The benefits of silicone are allocated according to the relation between the GHG emissions of polyether siloxane production and polyurethane production.

End of life

Mineral wool has no effects in the waste management stage due to no fossil C-content.

The individual contribution of polyether siloxane in the end-of-life phase is neglected in the 80/20 approach.

5.9.3. Results

Table 18 shows the life cycle GWP effects of thermal insulation materials for appliances. Differences in the use phase are shown as the effects of different insulating capacities of the considered materials (under the assumption that there is no available space within the appliances for additional insulation material). This results in higher energy consumption for the alternative material, which dominates the GWP balance. The production and transport of the silicone application (179 kg CO_2eq/FU) accounts for a higher GWP than the alternative application (13,8 kg CO_2eq/FU). Also, the End-of-Life phase of the silicone application has a higher GWP (2,8 kg CO_2eq/FU) than the alternative application, which results in 0 kg CO_2eq/FU because of no C-content. Nevertheless, the benefit/impact ratio amounts to 33 because the disadvantages of the alternative material's use phase outweigh the advantages of the production and transport, and EoL phases.

Table 18: Life cycle GWP of insulation material in appliances made of PU compared to insulation boards made of mineral wool

	Case study no.	9
	Factor FU/kg	25
PU Additives in Appliances Functional unit (FU):	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product**
Silicone application		
Production & Transport	17,9	448,2
PU without Polyether Siloxane	17,4	436,2
Polyether Siloxane	0,1	3,7
Blowing Agent Pentane	0,3	8,4
Use	1.135,9	28.398,0
End of Life	0,02	0,6
Total	1.153,9	28.846,8
Alternative application		
Production & Transport	13,8	345,1
Use	1.709,7	42.742,4
End of Life	-	-
Total	1.723,5	43.087,5
Difference		
Production & Transport	4,1	103,1
Use	- 573,8	- 14.344,4
End of Life	0,0	0,6
Total (- ... Net-Benefit of PU foam slab)	- 569,6	- 14.240,7
Total (- ... Net-Benefit of Silicone)	- 4,7	- 117,4
Ratio Benefit / Impact	33	

Impact definition: Production & EoL of polyether siloxane

Benefit definition: Substituted production, use, and EoL of insulation boards made of mineral wool, which can be substituted by PU foam boards; saved energy due to substitution; only the siloxane-related share (allocation based on GWP) of the benefit was considered.

5.9.4. Sensitivity analysis

The benefits of silicone are allocated according to the relation between the GHG emissions of polyether siloxane production and polyurethane production, which is 0,8 %.

In a sensitivity analysis, the benefit allocation factor varies from 0,4 to 1,6 %. The minimum benefit of silicone has a benefit/impact ratio of 16. With a 1,6 % allocation factor, the benefit/impact ratio would be 64.

5.10. Sealants windows IG unit

5.10.1. Description of the case study

IG unit = insulating glass unit

An IG unit consists of 2 (or 3) glass panels, gas (e.g., argon) in between, seal around: spacer (mainly aluminum filled with desiccant, a primary seal made of polyisobutylene for gas tightness and a secondary seal made of polysulfide, polyurethane or silicone.

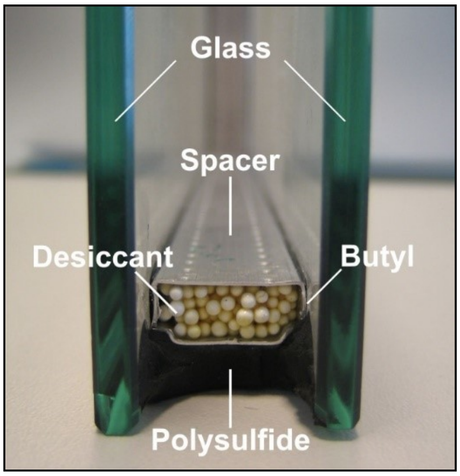

Figure 17: IG unit (section)[189]

5.10.2. Data basis and assumptions

Functional unit

1 insulation glass window, 123 x 148 cm, one sash

The amount of sealant is calculated via the volume (12 mm width, 4 mm depth, 542 cm length) and the density of the different sealant materials: silicone 1,5 g/cm^3, polysulfide 1,6 g/cm^3, polyurethane 1,3 g/cm^3).

According to the QKE & EPPA, the lifetime was assumed to be 30 years for all types of sealants[190].

[189] 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

[190] QKE & EPPA. (2011). Plastic windows made of PVC-U, 2-pane insulating glazing, construction depth 70 mm. Environmental product declaration. Environmental Product Declaration (EPD). Published by Qualitätsverband Kunststofferzeugnisse e.V. (QKE) and European PVC Window Profiles and Related Building Products Association (EPPA). Bonn, Germany. Brussels, Belgium.

Production

Based on the company information from 2012, following formulation for a silicone sealant is assumed[191]:

Table 19: Composition of silicone sealant (Company data)

Silicone Sealant Compound	Share
Polydimethylsiloxane polymer	60 %
Plasticizer	27 %
Cross-linker	25 %
Filler	10,5 %

Polysulfide and polyurethane were chosen for this study as alternative materials to silicone. Based on Ecoinvent 3.7.1, a GWP of 1,7 kg CO_2eq/kg for polysulfide production was used for the calculation[192]. The GWP data for the production of polyurethane was taken from the application "PU Additives for Thermal Insulation in Appliances" (see Chapter 5.9) which is based on the company information and Ecoinvent 3.7.1.

The market split between polysulfide and polyurethane as alternative materials to silicone is 60:40[193]. An average GWP of 1,1 kg CO_2eq/FU (based on the market split combined with the GWP data) was used for the alternative material.

Use phase

Most IG units are sealed with polysulfide or polyurethane due to their excellent sealant properties. Silicone is only used when the outside of the IG unit is exposed to sunlight, because of its better UV-stability. If polyurethane or polysulfide seals are exposed to UV radiation, they can lose their tightness over time (company information). If that is the case, the isolating gas (mostly argon) is exchanged with air, which leads to a slight increase of 0,2 W/m^2*K of the U-value of the glass unit[191]. It is assumed that the deterioration of the U-value occurs after 20 years of the 30 years lifetime.

A higher U-value leads to a higher demand for heating energy. The heating energy needed per year is calculated on the basis of average heating degree days for a certain region and window area, through which the energy is

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[191] 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

[192] 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.

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

lost. The weighted average of heating degree days for Europe is 2055 Kd/a according to EEA[194]. Using this value leads to a conservative calculation, as it can be assumed that IG windows are preferably used in cold climates, so the average heating degree days for all installed IG units would probably be higher.

The heating energy mix is taken from Bertelsen et al. which is 0,07 kg CO_2eq/MJ [195] referring to the fuel share of residential heating (EU-28, year 2015) stated in Table 14.

End of life

At the end-of-life phase, the following mix of waste paths is assumed for Europe: 25 % residual waste, 25 % building rubble, 50 % separate collection.

[194] EEA. (2021). Heating and cooling degree days. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/heating-degree-days-2/assessment. 10/2021.

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

5.10.3. Results

Table 20 shows the life cycle GWP for the outside-facing IG window sealants exposed to sunlight. The production & transport phase of the silicone material amounts to 3,2 kg CO_2eq/FU, which is higher than the GWP of the alternative material with 1,1 kg CO_2eq/FU. The difference of the use phase (-43,6 kg CO_2eq/FU) and EoL phase (-0,1 kg CO_2eq/FU) outweigh the disadvantage in production & transport, resulting in a benefit/impact ratio of 13.

Table 20: Life cycle GWP of window sealants for IG units, silicone is compared to polyurethane and polysulfide

	Case study no.	10
	Factor FU/kg	2,6
Sealants Windows Functional unit (FU):	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product**
Silicone window sealant		
Production & Transport	3,2	8,2
Silicone	2,6	6,7
Filler	0,4	1,0
Use	-	-
End of Life	0,2	0,5
Total	3,4	8,7
Polyurethane and poysulfide window sealant		
Production & Transport	1,1	2,7
Use	43,6	111,6
End of Life	0,3	0,8
Total	44,9	115,2
Difference		
Production & Transport	2,1	5,5
Use	- 43,6	- 111,6
End of Life	- 0,1	- 0,3
Total (- ... Net-Benefit of Silicone)	- 41,5	- 106,5
Ratio Benefit / Impact	13	

Impact definition: Production & EoL of silicone

Benefit definition: Substituted production and EoL of polysulfide and polyurethane, saved heating energy

5.10.4. Sensitivity analysis

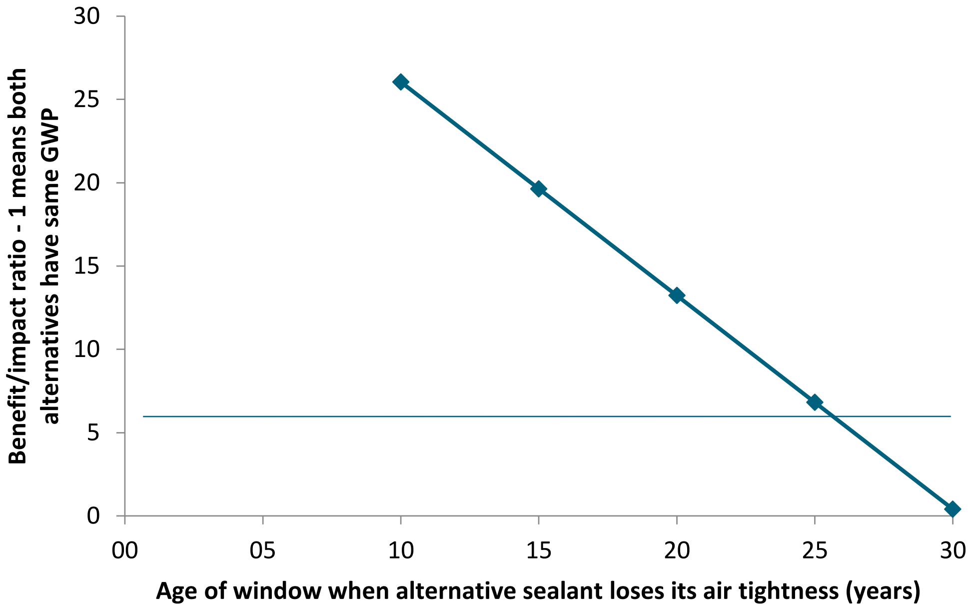

Figure 18: Benefit/impact ratio depending on the assumed lifetime of polysulfide sealant; The horizontal line shows the breakeven point at about 25,5 years.

In the original scenario, the alternative sealant loses its air tightness after 20 years (which means that there is no use effect for the first 20 years). In a sensitivity analysis this point of time was varied. Figure 18 shows how the benefit/impact ratio depends on the year when the seal loses its air tightness.

Once the window starts losing air tightness (20 years), the break-even point is at about 25,5 weeks, which means that at this point, the benefit now outweighs the burden of the higher production GWP of silicone.

5.11. Wind turbines

5.11.1. Description of the case study

Silicones are advanced functional materials which are designed for use in a variety of applications in wind turbines. Silicones are used for durability improvement in composite materials, high weatherability coatings, adhesion and sealing, and heat dissipation in generator components. In addition, silicones are used in electrical insulation, protection, and covering of connection cables and as transformer oil[196].

In this case study, silicone lubricants are selected as the focus. This is attributed to the fact that silicone lubricants reduce friction between wind turbine components (gearboxes, hydraulic circuits and brakes) improving energy efficiency and reducing wear and tear in components. These efficiency gains may increase energy generation by up to 8 % per turbine[197].

5.11.2. Data basis and assumptions

Functional unit

Wind turbine with 8 MW capacity of wind power, one year of operation

Production

The silicone lubricant consists of a base oil of silicone fluid (e.g., ShinEtsu G-30M).

A synthetic lubricant is chosen as the alternative option (e.g., MOBIL SHC GEAR 320 WT)

Over a service life of 25 years, approx. 10.000 kg of lubricant are consumed for maintenance and operation[198].

Use phase

A wind turbine produces 32.000 MWh of electricity in one year of operation given an 8 MW production capacity and 4.000 annual full load hours[198]. In comparison, a wind turbine with silicone lubrication produces 8 %[197] more energy than a wind turbine with synthetic oil. This results in an annual benefit of 2.370 MWh/a through the use

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

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

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

of silicone. An electricity mix of 0,41 kg CO_2eq/kWh is used based on the dataset for electricity in Europe from Ecoinvent[199] “market group for electricity, low voltage”.

End of life

It is assumed that 90 % of both lubricants are treated in an industrial plant for energy recovery in Europe. The remaining 10 % are dissipated into the environment during operation.

The silicone-based lubricant contains 32 % carbon, but the alternative lubricant contains 86 %. This difference in carbon content is the reason for the emission benefit, which is released as CO_2 during combustion and cannot be offset by the included savings from substitution of primary energy.

5.11.3. Results

Table 21 shows the life cycle GWP for wind turbines with different kinds of lubricants. The advantages of silicone related to the use phase far outweigh the higher efforts in production.

[199] 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.

Table 21: GWP effects of wind turbines with silicone and synthetic lubricants in 25 years of operation

	Case study no.	11
	Factor FU/kg	0,0000851
Wind Turbines	**GWP** **kg CO_2eq / FU**	**GWP** **kg CO_2eq / kg Silicone Product**
Functional unit (FU): Functional unit: 8 MW capacity of wind power; 25 years of operation		
Silicone application: silicone lubricants		
Production & Transport	76.482	7
Use	-	-
End of Life	993	0,08
Total silicone lubricants	77.475	7
Alternative application: synthetic lubricants		
Production & Transport	12.232	1
Use	24.413.323	2.078
End of Life	11.843	1
Total synthetic lubricants	24.437.398	2.080
Difference		
Production & Transport	64.250	5
Use	- 24.413.323	- 2.078
End of Life	- 10.850	- 1
Total (- ... Net-Benefit of Silicone)	- 24.359.923	- 2.073
Ratio Benefit / Impact	315	

Impact definition: Production & EoL of silicone lubricant in an 8 MW wind turbine during one year of operation, leading to an increased energy output of 8 %.

Benefit definition: Substituted production, use, and EoL of synthetic lubricant

5.11.4. Sensitivity analysis

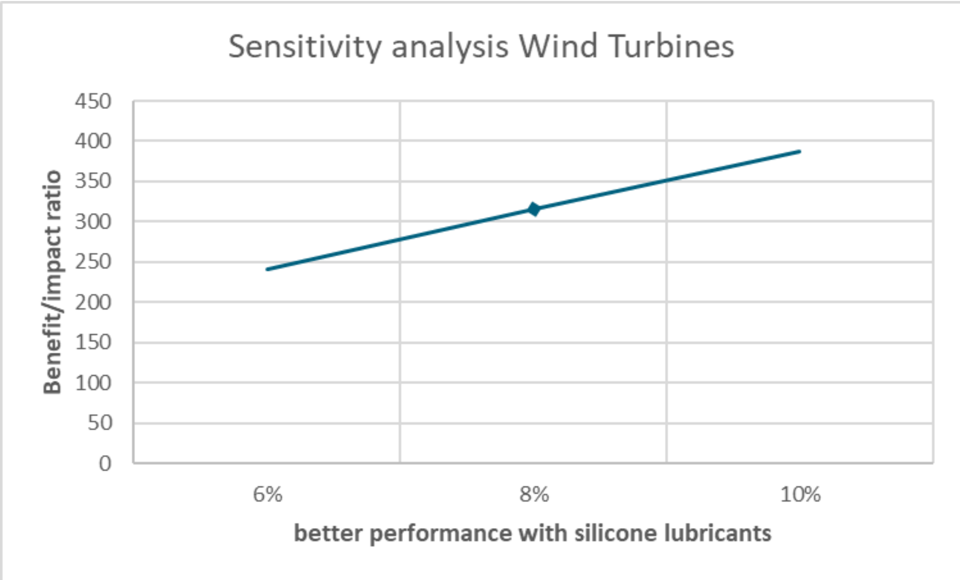

Figure 19: Sensitivity analysis of the benefit through better performance with silicone lubricants

Figure 19 shows how the benefit/impact ratio changes with the increased performance achieved by silicone lubricants. It is varied between 6 and 10 % (+/- 2 % of the given 8 % from [197]), which leads to a range of the benefit/impact ratio between 241 and 387.

6. Results and discussion of case studies

6.1. Overview

The goal of this study is to estimate the importance of silicones for the GD and their benefits in comparison to non-silicone alternatives. For this reason, 11 silicone-based applications which are essential for achieving the goals of the GD were selected. On one hand, the selection was based on the applications from the 2012 Carbon Balance Study and, on the other hand, on the GHG benefits and the potential contribution to CO_2 neutrality. For the purposes of the latter goal, the GHG emissions related to production, use-phase, and end-of-life phase of these applications are being compared with absolute EU27 GHG net-benefits resulting from the use of silicones, siloxanes, and silane applications. This analysis is carried out for a baseline scenario in 2019 and two projections for the years 2030 and 2050 for the EU27. Results will be discussed in the following chapters.

6.1.1. Overview base scenario 2019

Table 22 shows the results of all case studies summarised for the base scenario 2019. 7 out of 11 applications show a share of 100 % silicone content regarding the silicone-based components, meaning that the material or component considered in the application consists of 100 % silicone, silane, etc. This is the case for the following applications: automotive bonding, batteries/energy storage, chlorosilane for solar grade silicon, energy efficient lighting – LEDs, engine performance, rubber in motor construction, green tyres, and wind turbines. The share of silicone is below 100 % when, for example, the silicone is mixed with fillers or with other materials in the formulation of the final product. For each case study, the benefits were allocated according to the proportion of silicone in the components under consideration.

Table 22: Overview of results for baseline scenario 2019 of all investigated case studies with a total value for net benefit of silicone product, market volumes, and absolute EU GHG net benefits. "Silicone product" refers to "silicone, siloxane and silane products"

2019						
No.	**Name of Case Study**	**Share of silicone in silicone product**	**Net benefit of silicone product**	**Benefit/ impact ratio**	**Market volumes**	**Absolute EU GHG net benefits**
			kg CO_2eq/kg		t/a	1.000 t CO_2eq
1	Automotive Bonding	100 %	-220,8	34,1	3.100	-673
2	Batteries/Energy Storage	100 %	-3.295,2	211,7	1.800	-6.055
3	Chlorosilanes for Solar Grade Silicon	100 %	-29,4	8,2	352.100	-10.369
4	Energy Efficient Lighting – LEDs	100 %	-11.236,6	2,0	500	-5.056
5	Engine Performance, Rubber in Motor Construction	100 %	-898,3	137,6	17.000	-15.272
6	Green Tyres	100 %	-254,2	36,1	31.500	-8.006
7	High Quality Sealants & Adhesives	45 %	-29,2	8,1	22.000	-289
8	Industrial Applications in Pulp Industry, Anti-foaming in Pulp Production	30 %	-283,0	107,9	6.000	-1.698
9	PU Additives for Thermal Insulation in Appliances	0,8 %	-117,4	32,8	4.100	-481
10	Sealants Windows IG unit	90 %	-106,5	13,2	24.000	-2.287
11	Wind Turbines	100 %	-2073,0	315,4	1.100	-2.314
	Total		-18.543,6		463.200	-52.501

The **net benefit of silicone products** is one of the crucial results of every case study. Negative values represent a benefit in terms of emissions savings and positive results would mean that there is no benefit. Table 22 shows the GHG benefit achieved by the silicone product reduced by the GHG emissions from the production and EoL phases of the silicone product. This table is a summary of all case studies discussed in Chapter 5. All of the investigated silicone applications show a negative net benefit of silicone per kilogram which indicates a positive GHG benefit.

The **benefit/impact ratio** is another essential result of each case study, which can be found at the bottom of every result table in Chapter 5. It is calculated by dividing the benefit (achieved by the silicone product) by the GHG emissions from the production and EoL-phases of the silicone product. In general, if the value is larger than zero the benefit is bigger than the impact of production and EoL. The higher the value, the greater is the advantage of silicones compared to the alternative in each case study.

The **market volume** is the sum of pure silicone/siloxane/silane market volumes of the products consumed in the EU27 for each case study in tons per year. For the year 2019, the total market volume of the investigated silicone and silane applications was approximately 463.200 tons in the EU27.

The **absolute GHG net-benefit** of the investigated case studies is calculated in the following way: the net-benefit listed above (in kg CO_2eq per kg silicone product) is multiplied with the respective market volume, considering the share of silicone in the silicone product.

For the base year 2019, the average benefit/impact ratio of all investigated studies is about 82,5 with the highest ratio obtained for wind turbines. As discussed in Chapter 5.11, this high benefit/impact ratio is mainly due to the, 8 % increased performance in the use phase, when using silicon lubricants instead of the alternative application, synthetic lubricants. However, the sum of all absolute EU GHG net-benefits is about -52,5 Mt CO_2eq per year which is about 30 % related to the engine performance and rubber in motor construction application. This can be explained by the fact that the silicone product generates a major net benefit in the use phase compared to the alternative product, and at the same time has a comparably large market volume. LEDs show the highest net benefit of silicone product with a value about -11.000 kg CO_2eq/kg silicone. Here, a replacement factor of 2 was applied, which already represents a very conservative assumption based on publication results[200]. Nevertheless, the net benefit of silicone product stands out in comparison to other applications, which is due to the fact that the proportion of silicones used in the application is low (0,3 % silicones of the total weight of the LED lamp compared to the assumption of 100 % silicones of the total weight of the encapsulant). On this basis a very high benefit is feasible due to the extension of the lifetime.

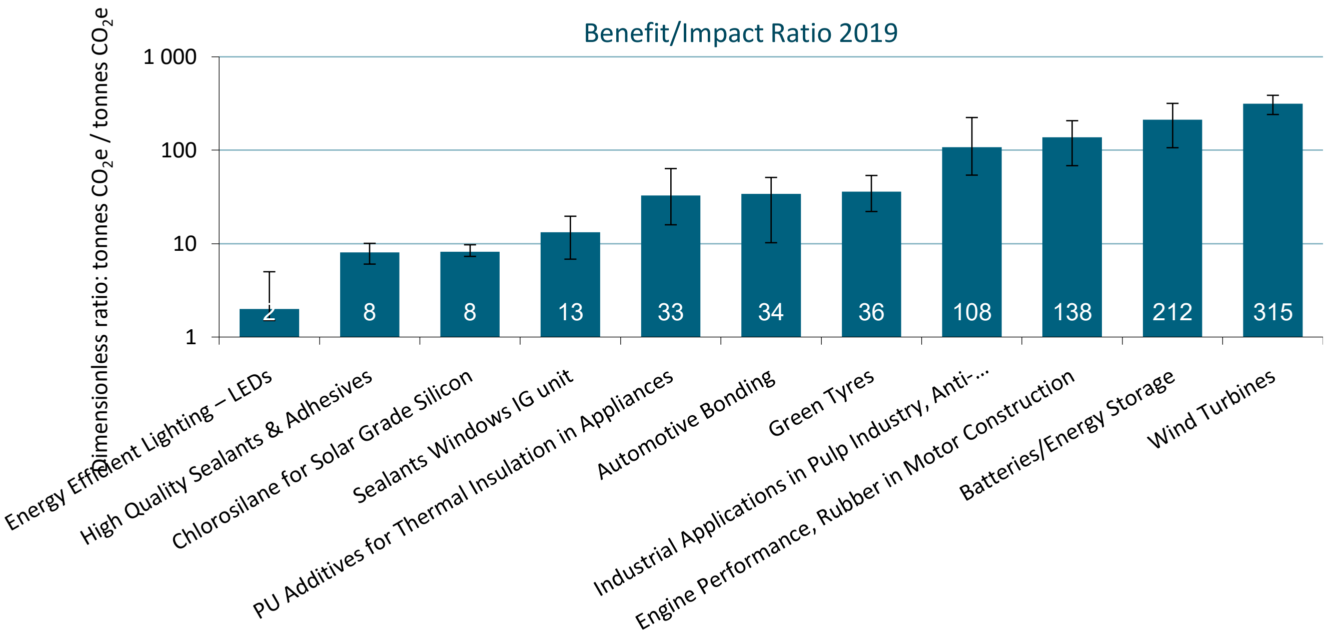

Figure 20: Logarithmic representation of the benefit/impact ratios for all case studies for the base scenario 2019 with error bars. Minimum and maximum values are taken from Table 24.

200 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.

Figure 20 shows the benefit/impact ratio results from Table 22 for each case study in ascending order. The Y-axis is displayed in logarithmic scale to aid the representation of all data. In general, all case studies show a positive benefit/impact ratio which indicates that the benefit of the investigated application is bigger than the respective impacts of production and EoL phase. The highest benefit/impact ratios are shown by the silicone applications for wind turbines and batteries/energy storage, which means that these applications show the highest benefits of silicones compared to their alternatives.

The **absolute GWP of silicones in the End-of-Life phase (EoL)** for each investigated case study is shown in Table 23. Overall, the emissions associated with the EoL-phase amount to 18 kt CO_2eq/a, with the highest GWP value related to the sealants windows IG unit application. This is due to the high market volume and the effects of EoL. In general, the EoL emissions result mainly from direct emissions generated during incineration.

Negative values of absolute GWP in the EoL phase represent the net benefits resulting from waste management and energy recovery in industrial processes. Fossil fuels and related GHG emissions, which are higher than the CO_2eq emissions from burning silicone waste, are substituted. This is the case for the following applications: automotive bonding, batteries/energy storage, engine performance - rubber in motor construction, and high-quality sealants & adhesives. The highest negative value regarding the absolute GWP of silicones in the waste phase shows the high quality sealants & adhesives application which is related to the high market volume and the benefits from substitution of primary energy.

Table 23: Absolute GWP of silicones in EoL-phase for all case studies. Negative values are highlighted in yellow.

No.	Name of Case Study	Absolute GWP of silicones in waste phase
		1.000 t CO_2eq/a
1	Automotive Bonding	-0,01
2	Batteries/Energy Storage	-0,07
3	Chlorosilane for Solar Grade Silicon	0,00
4	Energy Efficient Lighting – LEDs	0,73
5	Engine Performance, Rubber in Motor Construction	-0,01
6	Green Tyres	2,37
7	High Quality Sealants & Adhesives	-0,26
8	Industrial applications in Pulp Industry, Anti-foaming in Pulp Production	2,11
9	PU Additives for Thermal Insulation in Appliances	2,35
10	Sealants Windows IG unit	10,58
11	Wind Turbines	0,09
	Total	17,89

6.1.2. Uncertainty of case study results

The quality of data, used for the calculations of each case study, is quite different for each of the investigated application sectors. Table 24 shows an estimated qualitative description of the uncertainty and the minimum and maximum benefit/impact ratio as well as the minimum and maximum net benefit of silicone products for each case study for the base year 2019.

The three classes of uncertainty (low, medium, high) correspond with the quantitative ranges of uncertainty, as presented in Figure 20. The listed minimum and maximum values are based on uncertainties originating from input data and respective sensitivity analyses. Consequently, a range is calculated for the weighted average results of the case studies, as described in Chapter 5.

Table 24: Qualitative description of uncertainties of data used in case studies. Low: good data, no major uncertainty; medium: one/several uncertain estimations with relevant influence on the study, but conservative calculation; high: weak input data, substantial lack of information. MIN and MAX result values of case studies, based on sensitivity analyses.

No.	Name of Case Study	Estimated uncertainty	MIN Benefit/ impact ratio	MAX Benefit/ impact ratio	MIN Net benefit of silicone product	MAX Net benefit of silicone product
					kg CO_2eq/kg	kg CO_2eq/kg
1	Automotive Bonding	high	10,22	51,11	-66,24	-331,21
2	Batteries/Energy Storage	medium	106,3	317,2	-1.646,6	-4.943,8
3	Chlorosilane for Solar Grade Silicon	low	7,30	9,72	-26,14	-34,93
4	Energy Efficient Lighting – LEDs	high	1,50	5,00	-5.617,84	-44.948,92
5	Engine Performance, Rubber in Motor Construction	high	68,27	206,87	-445,79	-1.350,88
6	Green Tyres	medium	22,07	53,67	-152,53	-381,20
7	High Quality Sealants & Adhesives	medium	6,04	10,07	-20,87	-37,58
8	Industrial Applications in Pulp Industry, Anti-foaming in Pulp Production	medium	54,13	223,86	-140,64	-589,99
9	PU Additives for Thermal Insulation in Appliances	medium	15,90	63,62	-55,06	-231,34
10	Sealants Windows IG unit	medium	6,82	19,64	-50,64	-162,29
11	Wind Turbines	medium	241,10	387,04	-1.583,04	-2.545,21
	Midpoint				-891,40	-5.050,66

Based on the uncertainty results shown in Table 24, the theoretical maximum range of the average MIN and MAX benefit/impact ratio achieved by the investigated case studies is about 49 – 123 in 2019 which can be related to the sensitivity analyzes, differing per application (see Chapter 5).

6.1.3. Overview projected scenarios 2030 and 2050

In a similar fashion as for the baseline 2019 scenario, projected calculations of the environmental impact/benefit of the studied applications, as detailed in Chapter 5, were conducted. As discussed in Chapter 4.2, the major difference to the baseline 2019 scenario calculations is the use of projected market volumes in 2030 and 2050 for each of the discussed applications are based on the 2012 study, denkstatt internal sources, and DU surveys.

An additional, minor model adaptation in order to calculate the 2030 and 2050 projections takes into account that the benefit of one equivalent of substituted or saved energy will decrease over time due to the energy mix shifting towards the renewables. This is based on an assumption, that due to the broad decarbonization of various sectors, a significant reduction in the emission factors for electricity and heat in the EU27 will result until 2030 and 2050. Due to the lack of data availability for 2050 it is assumed that 10 % of electricity and heat is still derived from fossil fuel combustion in 2050.

Table 25: Overview of results for projected scenario 2030 of all investigated case studies studies with a total value for net benefit of silicone product, market volumes, and absolute EU GHG net benefits.

2030						
No.	**Name of Case Study**	**Share of silicone in silicone product**	**Net benefit of silicone product**	**Benefit/ impact ratio**	**Market volumes**	**Absolute EU GHG net benefits**
			kg CO_2eq/kg		t/a	1.000 t CO_2eq
1	Automotive Bonding	100 %	-220,3	33,6	3.800	-829
2	Batteries/Energy Storage	100 %	-1.832,2	211,9	28.400	-51.957
3	Chlorosilane for Solar Grade Silicon	100 %	-6,8	1,9	416.100	-2.835
4	Energy Efficient Lighting – LEDs	100 %	-6.244,0	2,0	2.800	-17.488
5	Engine Performance, Rubber in Motor Construction	100 %	-423,5	64,4	20.700	-8.759
6	Green Tyres	100 %	-130,1	18,2	40.000	-5.205
7	High Quality Sealants & Adhesives	45 %	-20,5	5,8	50.000	-460
8	Industrial Applications in Pulp Industry, Anti-foaming in Pulp Production	30 %	-289,6	110,4	10.900	-3.145
9	PU Additives for Thermal Insulation in Appliances	0,8 %	-35,9	10,7	5.900	-210
10	Sealants Windows IG unit	90 %	-61,8	8,1	36.400	-2.012
11	Wind Turbines	100 %	-650,1	93,5	5.400	-3.514
	Total		-9.914,8		620.400	-96.414

Table 26: Overview of results for projected scenario 2050 of all investigated case studies studies with a total value for net benefit of silicone product, market volumes, and absolute EU GHG net benefits.

2050						
No.	**Name of Case Study**	**Share of silicone in silicone product**	**Net benefit of silicone product**	**Benefit/ impact ratio**	**Market volumes**	**Absolute EU GHG net benefits**
			kg CO_2eq/kg		t/a	1.000 t CO_2eq
1	Automotive Bonding	100 %	-219,6	33,0	5.100	-1.112
2	Batteries/Energy Storage	100 %	-333,0	214,0	74.700	-24.888
3	Chlorosilane for Solar Grade Silicon	100 %	0,3	-0,1	560.200	163
4	Energy Efficient Lighting – LEDs	100 %	-1.126,9	2,0	6.300	-7.106
5	Engine Performance, Rubber in Motor Construction	100 %	-44,0	7,5	27.600	-1.217
6	Green Tyres	100 %	-19,5	3,4	56.900	-1.107
7	High Quality Sealants & Adhesives	45 %	-9,6	3,2	100.100	-434
8	Industrial Applications in Pulp Industry, Anti-foaming in Pulp Production	30 %	-297,9	113,5	12.000	-3.560
9	PU Additives for Thermal Insulation in Appliances	0,8 %	-10,3	3,8	11.100	-114
10	Sealants Windows IG unit	90 %	-6,0	1,7	73.300	-393
11	Wind Turbines	100 %	-203,7	27,9	13.800	-2.813
	Total		-2.270,3		941.100	-42.580

In a similar fashion to Table 22, which shows the results for base year 2019, Table 25 and Table 26 display the results for the 2030 and 2050 projections. The total market volume of the investigated silicone and silane products used in the EU27 region is expected to increase from 463.200 tons in 2019 to 620.200 tons in 2030, and to 941.000 tons in 2050. Compared to 2019 this represents an increase of market volume of about 34 % by 2030 and 52 % by 2050 compared to 2019 and 2030 respectively.

The absolute EU27 GHG net-benefits of all investigated silicone applications changes from ca. -52,5 Mt CO_2eq in 2019 to -96,4 Mt CO_2eq in 2030 and to -42,6 Mt CO_2eq in 2050. The result for 2019 accounts for approximately 6,6 % of Germany's total emissions for the same year, which is equivalent to about 810 Mt CO_2eq in absolute terms[201]. These are the emissions that have been avoided due to the application of silicone in the investigated areas. To put the results in context, to achieve the 1,5°C target by 2050, total EU GHG emissions would need to be reduced by approximately 3.668,7 Mt CO_2eq from 2020 to 2050 in the EU (also shown in Figure 3).

[201] Umweltbundesamt. (2021). Treibhausgas-Emissionen in Deutschland. Retrieved from https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland. 10/2021.

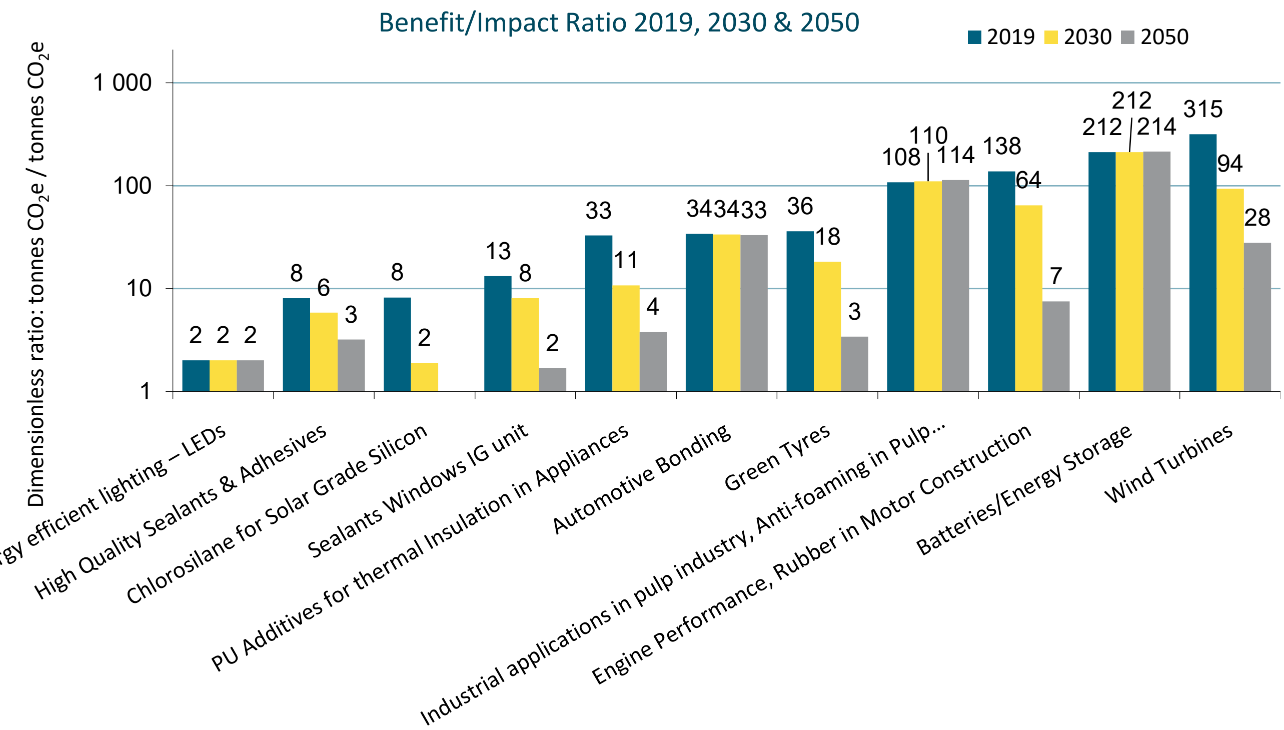

Figure 21: Logarithmic representation of the benefit/impact ratios for all case studies for base scenario 2019 and projected scenarios 2030 and 2050

Figure 21 depicts that the benefit/impact ratios for almost all investigated applications decrease over time. This decrease can be explained by the foreseen decarbonization of electricity and heat generation and production processes by 2050. The exceptions, which show an increase in 2050's benefit/impact ratio compared to 2030, are industrial applications in pulp industry, anti-foaming in pulp production and batteries/energy storage. The higher benefit of both silicone applications is justified by the credits in the EoL scenario of the alternative material. The latter records credits from industrial energy recovery due to the substitution of fossil energy fuels. In 2030 and 2050, the energy sources are increasingly decarbonized, which causes fewer credits for the alternative material. Therefore, the benefit for the silicon applications increases.

Overall, all but one results show positive benefit/impact ratios which indicates that the benefit is bigger than the impact of production and EoL. The exception is the chlorosilane for solar grade silicone application which shows a benefit/impact ratio of about -0,08 in 2050 which is also due to the expected decarbonization of the EU electricity mix.

6.2. Potential contribution to the Green Deal and associated carbon neutrality

Recent regulatory changes in the EU climate and environmental policy making point to a climate-neutral economy and challenge various sectors to contribute to the net-zero emissions roadmap. In this context, the following chapter will focus on how the silicone industry can play a crucial role in meeting the GD targets and to achieve a climate-neutral economy. Although the GD covers various areas, as shown in Chapter 2, the focus of this study is on CO_2eq-reduction for the following four GD building blocks:

1. Supplying clean, affordable, and secure energy
2. Competitive industry and circular economy
3. Energy and resource efficient building and renovating
4. Sustainable and smart mobility

6.2.1. Supplying clean, affordable, and secure energy

One of the GD's building blocks relate to the supply of clean, affordable, and secure energy. Since 75 % of the EU's GHG emissions are caused by energy production and consumption in all sectors of the economy, further decarbonization of the overall energy system is crucial[48]. This includes the extensive expansion of renewable energy sources including electricity and heat generation, for example, from solar and wind power plants. In this study, two silicone applications are directly linked to this sector, namely chlorosilane for solar grade silicon, which is needed for photovoltaic plants, and the use of silicone for wind turbines. These two silicone applications in total lead to an annual absolute EU GHG net benefit of around -12,7 MtCO_2eq of silicone in 2019 which is a consequence of reduced consumption of fossil fuels. In more detail, around 90 % of solar cells are based on silicon[202]. In this study, it is assumed that electricity production will emit around 68,5 % less CO_2eq emissions between 2019 and 2030 in relation to the GWP data for 2019, leading to decreased net benefits of the silicone product. In 2050, it is assumed that electricity production will emit around 90 % less CO_2eq emissions regarding the GWP data for 2019 which consequently leads to an overall decrease of absolute GHG net benefits.

Another positive effect of silicone applications shows increased efficiency and lifetime of wind power plants (wind turbines). Silicone-based components offer several benefits when applied to wind turbines such as improved durability of composite materials, high weatherability through coatings, adhesion, and sealing, and heat dissipation for generator components. In addition, silicones are used as electrical insolation, protection and covering of connection cables, and as transformer oil. These silicone applications lead to the replacement of synthetic lubricants. Wind turbines have gained considerable importance in the past decade and it is foreseen by the GD that they will have a crucial role in the decarbonization of our energy system. The silicone industry expects the market in this segment to grow significantly - by a factor of 5 during the 2019-2030 period and by a factor of 2,5 between 2030 and 2050. The reason for the decrease of the GHG benefit, despite growth in the second segment, is the increasing decarbonization of production, the energy industry, and waste disposal. The relatively moderate contribution of wind turbines, compared to other applications, is owed to the fact that the

[202] Andreani, L. C., Bozzola, A., Kowalczewski, P., Liscidini, M., & Redorici, L. (2019). Silicon solar cells: toward the efficiency limits. Advances in Physics: X, 4(1), 1548305.

total contribution of the wind turbine was not presented, but only the difference of 8 % performance increases due to the use of silicone lubricants.

6.2.2. Mobilizing industry for a clean and circular economy

The entire industry sector must be mobilized in order to achieve a climate-neutral economy. Worldwide, about half of total GHG emissions are caused by the extraction and processing of raw materials, fuels, and food[16]. Within the EU, the manufacturing industry is responsible for 20 % of the GHG emissions. To reach the GD's goal, it is necessary to further develop, promote, and accelerate low-emission technologies, as well as sustainable products and services. Although the industry sector is very diverse, there are many opportunities for the silicone industry to reduce its emissions. In this study, applications in the pulp industry, on the one hand, and applications in the electronics sector, on the other hand, were analysed.

Starting with the electronics sector: the investigated case studies include applications like energy efficient lighting – LEDs and PU additives for thermal insulation in appliances. Both electronic sector applications show a potential for an absolute EU GHG net benefit of silicone products of around -5,4 Mt CO_2eq of silicone in 2019. The absolute GHG net benefits of silicone products for the PU additives for thermal insulation in appliances applications is being predicted to decrease over time. This study shows that different insulation properties lead to different electricity demand, in addition to different GWP of foaming agents.

Between 2019 and 2030, absolute EU GHG net-benefits of silicones in LEDs will increase due to the forecasted expansion of the market volume from around 500 to 2.800 tons, as expected by industry experts. Data show a wide range of forecasted market volumes which is why a rather conservative assumption was used for this study – still the savings potential is quite high since the market is expected to grow in a large scale. The decrease of the absolute EU GHG net benefits from 2030 to 2050 is based on the reduced net benefits of the silicone product from -6.244 to -1.127 kg CO2eq/kg. The cause for this decrease is attributed to the expected decarbonization of the production process. In general, when it comes to LEDs, silicones provide improved light performance and extended product life. In particular, they can be found in the lens, the reflector, the encapsulating material, the thermal interface material, and the die-bond material.

Looking at the potential for industrial applications in the pulp industry, i.e., as anti-foaming detergents in pulp production, the absolute EU GHG net benefit changes from -1,7 Mt CO_2eq in 2019 to -3,1 Mt CO_2eq in 2030 and -3,6 Mt CO_2eq in 2050. This potential is based on higher washer throughput, since the anti-foaming silicone application makes pulp plants more efficient, less water must be vaporized, and less process chemicals are lost. Therefore, the consequence is a reduced consumption of fossil fuels, because silicone and silane products help to increase the efficiency of processes. The benefit/impact ratio for 2019 amounts to 108, which indicates the application has a relatively high benefit due to the high efficiency of silicone in comparison to the alternative material in the use phase.

6.2.3. Building and renovating in an energy and resource efficient way

Given that significant amounts of energy and mineral resources which are required for the construction, use and renovation of buildings and that buildings account for 40 % of energy consumption, it is of utmost importance to decarbonize this sector[20]. According to the impact assessment for the 2030 Climate Target Plan, the residential building sector will require the largest reduction in energy demand for heating and cooling of 19 % to 23 % compared to 2015[23]. The silicone applications used in this study, specifically, high quality sealants & adhesives and sealants for windows IG unit, can contribute to reach this target in the residential building sector.

With respect to the investigated case studies, both applications can lead to an annual, absolute EU GHG net benefit of about -2,6 Mt CO_2eq in 2019, -2,5 Mt CO_2eq in 2030, and -0,8 Mt CO_2eq in 2050. On one hand, this can be attributed to the reduced consumption of fossil fuels, since silicone products contribute to savings in heating and cooling energy and, on the other hand, to saved energy from production of other materials. The decrease of absolute GHG net benefit over time is attributed to the assumed high decarbonization of electricity and heat energy production in the future.

In general, silicone products can render a certain function with less material and/or lower carbon footprint in material production and recovery, compared to alternatives for example, when it comes to sealants for windows. Looking at the effects of silicone structural glazed systems, the differences in air infiltration rates and U-values compared to dry glazing thermally improved systems leads to a decreased heating demand regarding the silicone product.

6.2.4. Accelerating the shift to sustainable and smart mobility

The transportation and mobility sectors are responsible for 25 % of the EU's emissions and require a drastic reduction of 90 % by 2050 in order to accomplish the GD's goal[203,204]. In order to achieve climate neutrality, the EU will promote the production and distribution of sustainable alternative fuels. The aim is to provide about 1 million public charging stations and to build petrol stations for 13 million emission-free and low-emission vehicles, which are expected to be available on European roads by 2025. In this study, four applications which are directly linked to the transportation sector, are being analysed for their potential to contribute to a net-zero roadmap, namely automotive bonding, batteries/energy storage, engine performance, rubber in motor construction, and green tyres.

These silicone applications can lead to an annual absolute EZ GHG net benefit of about -30,0 Mt CO_2eq in 2019, -66,7 Mt CO_2eq in 2030 and -28,3 Mt CO_2eq in 2050 which is a consequence of

a) reduced consumption of fossil fuels, because silicone and silane products

[203] See 20
[204] See 25

- enable more efficient transport through more efficient motor technology and less rolling resistance (engine performance, rubber in motor construction and green tyres)
- contribute to lighter vehicles and related fuel savings (automotive bonding)

b) saved production of other materials
- in general silicones protect batteries from heat, cold and dirt, seal and cushion the batteries, and reduce the risk of battery fires. The TIM under consideration improves thermal management and enables repairs, thus extending service life.

It is important to note that the benefit/impact ratios of automotive bonding, rubber in motor construction, and green tyres decrease over time. This is due to the fact that fuel savings can no longer be allocated to the use of silicone. Furthermore, for green tyres, the absolute EU GHG net benefits are expected to decrease due to reduced net benefit of silicone product from -254,2 kg CO_2eq/kg silicone in 2019 to -19,5 kg CO_2eq/kg silicone in 2050 in relation to the expected increase of electromobility.

However, batteries/energy storage in EV show a relatively high benefit/impact ratio which increases from 212 in 2019 to around 214 in 2050. This can be mainly attributed to the longer battery life when using silicone. More precisely, silicone allows individual cells to be replaced, thus expanding the service life of the vehicle and avoiding the production of new batteries. This saves raw materials and energy and results in the great benefit of using silicone. Beyond that, the stationary use of EV batteries in a second life is an intensively discussed and recommended way to save resources and related CO_2 emissions. Therefore, benefits will shift towards the use of batteries and other EV-relevant technologies. In general, the silicone industry expects the market in this segment to grow strongly - by a factor of 15 in the 2019-2030 period and 2,5 times during the years between 2030 and 2050. The fact that growth in the second segment has little impact on the GHG benefit is attributed to the increasing decarbonization of production, energy management, and waste disposal.

6.3. Future improvements

One of the major limitations of this study concerns the limited selection of only 11 applications. In order to get a complete picture of the GHG impacts of silicone applications, this type of study should be extended to a whole range of silicone applications as this study tries to reflect only a small part of the reality.

In addition, further improvements of the data quality in this study are recommended for

- allocation approaches
- market growth until 2030 and 2050
- chemical degradation in landfills
- Decarbonization rates of electricity and heat generation as well as of the production of different applications (e.g. LEDs, batteries, etc.) by 2030/2050
- More precise reflection of future benefits & burdens of an application that occur during its lifetime (e.g. The benefit of many applications with a lifetime of +5 years will decrease significantly due to the decarbonization of heat generation and electricity production.)

Furthermore, additional improvements for each silicone application are described below:

Automotive Bonding

- Allocation approaches, especially with regard to future changes in car production and composition of car parts
- Weight/fuel saving effects of automotive bonding

Batteries/Energy Storage

- Quantification of the extension of service life of EV batteries through the use of silicone
- Quantification of the various applications of silicone in an EV battery (thermal management, gap filler, sealing, bonding, insulation, …)
- Investigating the promotion of reuse of used EV batteries in stationary applications through silicone (second life of used EV batteries in stationary applications)
- The importance and advantages of silicone in electromobility: connectors, cable sheathing, seals, improved fire resistance

Chlorosilane for Solar Grade Silicon

- Inclusion of mounting systems such as lightning protection, inverters, and cables for the PV panel
- Adjustment of energy output regarding transformer losses
- Availability of production and use phase data for non-silicon-based PV modules as alternative reference application

Energy Efficient Lighting – LEDs

- Input data regarding the composition of the encapsulant materials, e.g., percentages of filler, additives, etc.
- Mass of encapsulant
- More data (publications) regarding the lifetime differences of an LED consisting of an encapsulant based on silicone or alternative materials
- Market growth until 2030 and 2050 for energy efficient lightning (HP LED)
- Market share of HP LED

Engine Performance, Rubber in Motor Construction

- Allocation approaches and shifts towards other applications such as batteries
- Fuel saving effects of rubber in motor construction
- Future market shares and market growth of fossil fuelled and electric vehicles

Green Tyres

- Future fuel saving effect of green tyres
- Fuel savings potential when green tyres are used in freight transport

High Quality Sealants & Adhesives

- Effects of silicone on air infiltration rate and U-value
- Re-adjustment of EoL-assumptions regarding the shares of building rubble and separate collection divided between energy recovery and landfilling
- Future market growth of high-quality sealants & adhesives

Industrial applications in pulp industry, Anti-foaming in Pupl Production

- More data (publications) on quantifying advantages for silicone antifoaming during the use phase
- Future market shares and market growth of pulp industry up to the year 2050
- More input data for alternative material and its impact

PU Additives for thermal Insulation in Appliances

- Readjustment of EoL-assumptions of PU foam for thermal insulation in refrigerators
- More input data for alternative material and its impact

Sealants Windows IG unit

- Effects of silicone on air tightness and U-value of IG units
- Updated input data regarding composition of sealants

Wind Turbines

- In addition to lubrication, silicones are used in almost all parts of wind turbines. Investigate where and to what extent silicones are an essential component to increase the performance of wind turbines.
- Contribution of silicone in the bonding of rotor blades to increase the size and performance of wind turbines.

The most important limitation of this study is that only GHG emissions are being analysed. For a more comprehensive environmental and sustainability assessment, other relevant environmental impacts as well as economic and social criteria should be considered (e.g., repairability, contribution to circular economy, saving critical raw materials). Furthermore, as silicones are highly durable materials with high weatherability, any adverse end-of-life aspects, e.g., degradation related environmental contamination and thus health implications, and the ways in which these can be reduced or eliminated, must be investigated. Although the calculations in this study are based on extensive research and collected information through intensive collaborations with the experts from CES, the results are only as accurate as the input data the model is using. Moreover, the scope of this study is limited by the select 11 applications deemed most significant from the background research and expert insight. Thus, a broader study across the entire range of silicone applications may offer additional insights and scope for future studies to be even more representative, comprehensive and accurate.

7. Summary

The goal of this study was to estimate the importance of silicones and their benefits for the European Green Deal in comparison to their non-silicone alternatives. For that reason, 11 specific silicone applications have been selected which play a crucial role in accomplishing the 2050 targets for carbon neutrality. Many silicone and silane applications, which are already being used on the market today, can contribute significantly to the reduction of GHG emissions. Calculations performed in this study show that the use of specific silicone and silane products can contribute to a GHG reduction through:

a) **reduced consumption of fossil fuels**, because silicone and silane products
- enable more efficient transport (green tyres, engine performance, rubber in motor construction)
- contribute to lighter vehicles and related fuel savings (automotive bonding)
- contribute to savings in heating energy (high quality sealants & adhesives, sealants windows IG unit)
- contribute to savings in energy consumption (PU additives in thermal insulation - appliances)
- help increase the efficiency of industrial processes (industrial applications in pulp industry, anti-foaming in pulp production)
- are used in production of green electricity (chlorosilane for solar grade silicon, silicone lubricants in wind power plants)

b) **saved production of other materials**, because silicone products
- contribute to extended product lifetime (batteries/energy storage, energy efficient lighting – LEDs)

The **total output market volume across the 11 investigated silicone and silane applications** in the EU is assumed to increase from about 463.200 tons in 2019 to about 620.000 tons in 2030, and about 941.000 tons in 2050.

In general, all investigated case studies show a **negative net benefit of silicone product** results which indicates a GHG benefit achieved by each of the silicone products compared to its alternative product. The highest net benefits of silicone product for the base year 2019 are associated with the silicone applications energy efficient lighting – LEDs, batteries/energy storage, wind turbines, engine performance, and rubber in motor construction. Whereas in 2050 the highest net benefits are shown by the applications energy efficient lighting – LEDs followed by batteries/energy storage and industrial applications in pulp industry, anti-foaming in pulp production and automotive bonding.

In addition, the advantageous effect of silicone applications for the reduction of GHG emissions is also shown through the **benefit/impact ratio**. Starting with the results for 2019, the average benefit/impact ratio of all investigated studies is 83 within an average MIN/MAX range of 48 to 127, which can be related to the applied sensitivity analysis. In 2030, the average benefit/impact ratio for the investigated silicone applications decreases to about 51 and in 2050 to about 37. The highest benefit/impact ratio in 2019 is shown by wind turbines, batteries/energy storage, and engine performance, rubber in motor construction.

The **absolute EU27 GHG net benefits** per year of all investigated silicone applications change from about -52,5 Mt CO_2eq in 2019, to -96,4 Mt CO_2eq in 2030, and to -42,6 Mt CO_2eq in 2050. The result for 2019 accounts for approximately 6,6 % of Germany's total emissions for the same year, which is equivalent to about 810 Mt CO_2eq in absolute terms. These are the emissions that are being avoided due to the application of silicones in different areas. To put the results in context, to achieve the 1,5°C target by 2050, total EU GHG emissions would need to be reduced by approximately 3.668,7 Mt CO_2eq each year from 2020 to 2050 (also see Figure 3).

Calculations are based on the available data and plausible assumptions, which are kept conservative in terms of the silicone's performance. Some input data are rather uncertain and change the benefit/impact ratio considerably if adjusted. Although there are large uncertainties in some case studies, there is no doubt that the sum of GHG benefits is significantly higher than the GHG emissions from suitable alternatives.

Considering different life cycle phases, it becomes apparent that the production and use phases generally show the greatest impact and that the EoL effects are relatively small in comparison. Transport effects have minor relevance in the product carbon footprint of silicones, siloxanes and silanes.

As an overall result it may be stated that for many relevant technologies used for the energy and mobility transition silicone-containing applications can serve as crucial elements. It appears important to apply them in a reasonable manner according to their potential to support the decarbonization target of the EU Green Deal.

8. Conclusions

The study concludes that, considering solely the reduction of GHG emissions in line with the aims set out by the EU Green Deal, the utility of silicon derived compounds is advantageous with respect to comparable alternatives. Among other, key properties of silicone include high thermal and chemical resistance, wide-ranging viscosity, mechanical durability and hydrophobicity, making these extremely useful for industrial applications.

The study identifies and investigates the emissions benefits and impacts of 11 key applications of silicones across 4 key areas set out in the EU Green Deal:

- **Accelerating the shift to sustainable and smart mobility**
  automotive bonding, batteries/energy storage, engine performance and rubber in motor construction, green tyres
- **Supplying clean, affordable and secure energy**
  chlorosilane for solar grade silicon, energy efficient lighting – LEDs, PU additives for thermal insulation - appliances, wind turbines
- **Building and Renovating in an energy and resource efficient way**
  high quality sealants and adhesives, sealants windows IG units
- **Mobilizing industry for a clean and circular economy**
  anti-foaming in pulp industry

Based on the conducted research, developed model calculations and conservative approximations the study demonstrates a net positive contribution of each application with respect to their comparable alternatives and an absolute GHG net benefit of approx. -52,5, -96,4 and -42,6 Mt CO_2eq p.a. for the EU27 market in 2019, 2030 and 2050 respectively. The result for 2019 accounts for approximately 6,6 % of Germany's total emissions for the same year, which is equivalent to about 810 Mt CO_2eq in absolute terms. These are the emissions that are being avoided due to the application of silicones in different areas. The biggest emissions savings are shown to be attained in the production and use lifecycle phases of each application. In the context of the necessary emissions reduction of 3.668,7 Mt CO_2eq p.a. until 2050 for the EU27 market in line with the 1,5°C ambition this saving is deemed significant and demonstrates the utility of silicones in reaching the EU Green Deal targets.

The report acknowledges that some silicone applications may not offer greenhouse gas saving compared to commercially available alternatives e.g., exchanging wooden tools, such as kitchen utensils or manual labour tools, by their silicone counterparts. As silicone production requires multiple stages of chemical processing and may involve synthetic methods that utilise fossil hydrocarbon feedstocks, silicone application in these cases is likely to have a greater environmental footprint compared to the wood. It is, however, important to note that only the most industrially significant identified applications of silicone were considered in this study and thus an overarching study across a whole range of silicone applications may offer additional insights and further improve the accuracy of this report.

The study recognizes the errors associated with the used approximations and identifies the availability of comprehensive data and detailed studies as the limiting factors on the precision of forecasted emission savings. In line with the EU Green Deal further assessment of social, environmental and health related impacts of silicone derivatives is required.

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10. Appendix

10.1. Results critical review

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The Role of Silicones for the EU Green Deal (CES GD)

Critical Review Report

by

Roland Hischier

for

CES – Silicone Europe
(a sector group of the European Chemical Industry Council, Cefic)
Brussels (Belgium)

Date

December 20, 2021

Status

Final Version

1 Origination and Course of Action

The herein described critical review process, commissioned by CES – Silicone Europe (a sector group of the European Chemical Industry Council, Cefic), took place in December 2021. Although the examined study is not a traditional life cycle assessment (LCA) study according to the ISO EN DIN 14040 series [1a+b], a critical review process in the spirit of the terms of ISO series [1a] has been established. This on hand critical review report is based on the **version 2.0 of the study report** [2], **dated December 16, 2021**, and will be integrated into the very final version of this report. The study has been established by collaborators of Austrian company denkstatt GmbH, Wien, Austria.

The critical review can be seen as **'a posteriori' survey**, as the review took place in the very last stage of the study. The reviewer got a first (draft) final report in November 2021, and then in Mid of December 2021 the final report [2], dated December 16, 2021, by e-mail. This final version of the report was the basis for this final, overall (i.e. including resource and emission saving factors) critical report here. Within the framework of the complete review process, no actual meetings took place due to the limitations in time. Instead, exchanges via e-mail and telephone during the whole review time took place between the reviewer and Mr. Strobl, the key contact of the reviewer for this study within "denkstatt". A list with specific questions and comments on the draft final report (dated November 26, 2021) was sent to denkstatt by the reviewer. Denkstatt answered all questions in a detailed way and revised the report where necessary.

2 Comments about the report

2.1 Criteria

The review process is based on the review work done in the framework of previous studies from denkstatt resp. GUA (the former name of denkstatt) for PlasticsEurope, dealing with the contribution of plastics in general to resource efficiency [3-4], as well as the criteria mentioned in ISO EN DIN 14040 [1a]. In details, the following criteria have been examined here:

- *Is the chosen method scientifically sounded & reasonable within the goal of the study?*
- *Are the used data sufficient & appropriate in respect of the goal of the study?*
- *Does the conclusion take into account the recognized limitations of the study, especially in the framework of the original aim of the study?*
- *Is the report transparent and coherent?*

2.2 Scientific background and practicability of the used method

This study had never the aim of establishing a complete "classical" LCA study according to the international ISO standards [1a+b] and thus cannot be compared with those standards in the framework of the critical review process. According to the commissioner, the here reviewed study shall show "the role and importance of the silicone industry in the GD (= Green Deal) and the CO2eq reduction pathway till 2050". The aim of the project is to show the importance of silicones and their benefits in comparison to their non-silicone alternatives with a special focus on the goal of carbon neutrality by 2050.

Hence, this is a study that does not represent a full LCA (according to [1a+b]) in the field of the covered impact assessment factors, but represents only the climate change impact category. Otherwise, the applied methodology follows in large parts the LCA approach, similar as the former study in 2012 [5], study that has been judged by its respective reviewer as to represent "a thorough and competent study". The reviewer agrees with this judgment – and validates in that sense that this is a valid approach also for the present study. Such a focus on a single indicator is valuable, especially as it is clearly indicated already in the introduction of the report, and that this – according to the conclusion section – may could be seen simply as a first step towards a more comprehensive assessment of these materials in a later phase.

Thus, in summary, the chosen method can be qualified as scientifically adequate and reasonable in the context of the objectives and the timeframe of this study.

2.3 Appropriateness of data

As important as the methods for the calculation of the examined resource indicators are adequate data for their calculations. The on-hand report from denkstatt presents in a rather clear and, whenever possible, transparent manner how the various values have been collected and/or calculated in order to be able to come to the individual net benefits. An entire chapter of the report (i.e. chapter 4) is dedicated to the way, how calculations have been done. Starting point for all calculations is the former study (i.e. [5]) by denkstatt – looking at the greenhouse gas (GHG) emissions of silicone and silane products from “cradle to grave” and its updated LCI data for silicones production. Those data have been updated punctually in the frame of the present project (as described in details in chapter 4.1.2).

In the subsequent chapter 5, stepwise and detailed descriptions of the applied data, together with uncounted limitations are reported in a rather detailed and transparent manner – allowing to the reader to clearly understand for each of the examined sectors how the benefits have been calculated. Therefore, the authors applied a 80/20 approach in a conservative manner along the study. Due to the high degree of transparency and the detailed explanations for each of the case studies, it could be concluded that the study goes actually beyond this “80/20” method, showing a much more rigorous approach with the depth of analysis as well as the range of sensitivity and uncertainty analyses carried out at the various levels of the study (i.e. the individual cases, the various time horizons, …). This gets e.g. visible in the comprehensive discussion of the overall results and their link back to the starting point, i.e. the Green Deal of the European Commission (shown in chapter 6 or the report).

Overall, the quality of the used data is more than sufficient for this type of study, and the appropriateness of the data is given. For the reviewer it was however not possible to ensure the correctness and validity of all calculations within such a review process.

2.4 Conclusions of the report

The chapters covering results, discussion and conclusion summarize in a comprehensive, and most of the time adequate, manner the results of this study – and thus the content of the report.

The authors structured the result part (i.e. chapter 6) in a rather logical manner – starting with an in-depth discussion of the results for the reference year (i.e. 2019), followed in the second part by the outlook towards 2030 and 2050, respectively, before in a last part all these results are put into the context of the Green Deal (and thus the objectives of the study). The entire result & discussion section reads thus like a story-line. Within a dedicated section (i.e. chapter 6.3), the authors considers all the limitations due to the goal and scope of the study.

This described, logical sense is even continued by a section then summarizing the results (i.e. chapter 7), before in the concluding part (chapter 8) they are put into the context of the initial question, i.e. the influence/effects on the Green Deal.

As it is a "carbon footprint" study, the only impact category covered is GWP – from the point of view of an overall and comprehensive assessment (according to the ISO 14'040 standard) this is obviously not sufficient. However, the authors clearly stipulate this limitation several times a cross the report.

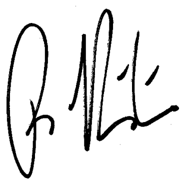
2.5 Transparency and coherence of the report

Overall, the report is clear and logically structured, most of time easily understandable and properly designed. All chapters (methodology, case studies, results and discussion, as well as conclusions) are transparent and aligned in a logic manner (first the methodology, then from an individual and detailed description of each examined case study to an overall presentation of the results) build up. Hence, the report fulfils all the requirements concerning transparency and coherence.

3 Summary and Conclusion

The complete study has been established in a rather transparent and logic manner. For the presented case studies – not covering all the aspects of using silicones – the authors of this study make clear statements in favour of the use of silicones. In the same time, limitations of the study (e.g. due to fact that there are numerous further application areas) are documented in the report. Overall, the study can be recommended for a publication in its present form.

St. Gallen, December 20, 2021



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