Gesellschaft für
Tribologie e.V.

Effects of tribology on CO_2-emissions in the use phase of products

Contributions of tribology to defossilization

Tribology in Germany

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Contributions of tribology to defossilization

An expert study by the Gesellschaft für Tribologie e.V.
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ABOUT THIS STUDY

Mankind claims natural resources by free withdrawal of raw materials and subsequent use of nature as a sink for residual materials. Tribological aspects are only indirectly perceived as consequence of human activities occurring anywhere and anytime. This lack of knowledge could explain why friction and wear occurring during the use phase of moving systems have yet not made inroads in greenhouse gas protocol, taxonomy and emission trading.

Both growth and prosperity of mankind have significant impact on the resource demand from nature. Here, the offerings of tribology, such as longevity through resource efficiency and conservation, and friction reduction through energy efficiency, come into play. Energy is not only expended to overcome friction, the resulting stress on the contacting surfaces leads to irreversible wear, ultimately requiring the replacement of parts or the overhaul of the equipment. As an irreversible loss or energy conversion to heat, friction is currently still largely proportional to carbon dioxide emissions. Longevity, either achieved through wear protection or through condition monitoring, extends the use phase of goods and equipment, reduces the extraction of natural resources and the associated embedded CO_2 of these resources and is consistent with material efficiency and resource conservation.

The studies published by the Gesellschaft für Tribologie e.V. (German Society for Tribology)

- “Tribology in Germany: Cross-cutting technology for reducing CO_2-emissions and conserving resources“ (2019) and

- „Wear protection and sustainability as cross-cutting challenges“ (2021),

indicated medium to long-term savings of 3.9 - 11.3 gigatons of $CO_{2eq.}$ annually. Hence, tribology should be essential for every portfolio of environmentally compatible technologies aiming to net mitigations of greenhouse gas emissions and should also be incorporated in emissions trading because CO_2 saved in the use phase (downstream) does not have to be generated in the generation phase (upstream).

Friction and wear occur all along the value chain. Therefore, tribology is an easy-to-implement technical option for the removal of CO_2 from the atmosphere – the CO_2 saved in the use phase (downstream) need not be generated in the extraction phase (upstream).

Reducing friction and extending longevity provide “industrial strategies for defossilization“ or „societal CO_2-sequestration“ because $CO_{2eq.}$-savings generated by tribology occur anywhere and anytime, and less energy needs to be generated to move machine elements upstream. Friction reduction and longevity are thus „negative emission technologies“ (NET) producing less or saving CO_2 during operation or are easy-to-implement as drop-in solutions.

Tribology is both engineering and science based on a very diverse industrial platform and a key interdisciplinary technology for mitigating the CO_2-overhang expected by 2050.

This third GfT study presents specific solution approaches, estimates the CO_2-value of selected tribological solutions and specifies the particular working axes based on the technologies available. The figures presented predominantly refer to the year 2019 and consider the last „regular“ business year prior to the Covid19 pandemic.

[The previous GfT studies „CO_2 and Friction“ and „Sustainability and Wear Protection“, published in 2019 and 2021, are also available online in German and French.]

RESEARCH TOPIC OF THIS STUDY

Before bits, bytes, bitcoins and artificial intelligence will drive the transformation into a completely virtual next century, the remaining 21st century will continue to be „material“.

Until then, machines and equipment with moving elements made of materials requiring lubrication to lower friction and to increase longevity will ultimately lower downstream $CO_{2eq.}$-emissions. The striving for prosperity of a growing population will fuel the hunger for energy and materials. Consequently, there is no alternative to adopting the offerings of tribology in order to mitigate energy demand and to increase longevity, as tribology provides the only solution capable of generating more value from the resources available for free from nature. $CO_{2eq.}$-emissions, not generated, required or mitigated downstream, will no longer need to be generated upstream. Hence, tribology can make a significant contribution to restoring the balance between the offerings of nature and the responsible extraction of resources based on anthropological values.

THE VAST OCEANS, THE OPEN ATMOSPHERE, AND THE EARTH‘S CRUST
ARE FREELY ACCESSIBLE RESOURCES!

MANKIND MUST APPRECIATE, VALUE AND HIGHLY VALORIZE THESE FREE OFFERINGS
WITHOUT COMPROMISING NATURE.

1. Interaction of Friction with CO_2-Emissions

The global total primary energy (TPES) consumption will increase from 584 exajoules in 2019 [1] to more than 700 exajoules in 2040 [2]. Furthermore, the U.S. Energy Information Administration (EIA) estimates that the annual energy consumption will increase by up to 50% by 2050 [3]. In 2019, the fossil CO_2-share accounted for 84% of the global primary energy generation.

Resolutions of the US Congress (not adopted!) [4] and studies by Holmberg et al. [5, 6] assume that 20-33% (absolute) of the total primary energy consumption is lost to friction with an estimated long-term savings potential of 30-40%. The various studies presented in Table 1 show a range of absolute potentials for reducing primary energy consumption generated by friction [7, 8]:

Jost[1] 1966: 5%; Holmberg 2019: 8%; Holmberg 2017: 8.6%; A.S.M.E. 1977: 10.9%; U.S. Congress 2016: 12%; A.R.P.A.-E 2017: 24%.

These studies reached a consensus with regard to the long-term savings potential of the friction share in primary energy consumption by means of tribological measures, which is estimated between 30-40%. In 2019, the fossil (i.e. anthropogenic), direct or energy-related CO_2-emissions[2] cumulated to 33.6 gigatons of CO_2 [9] plus 4.4 gigatons for process-related CO_2-emissions (non-energy related). This results in a calculated and absolute CO_2-reduction potential in the range of 2.7 gigatons to 8.1 gigatons, or 8-24% of global and direct CO_2-emissions. Regardless of the use of "green" energy generation, savings induced by the reduction of friction will be beneficial in any event. Either climate neutrality (net zero) will be achieved earlier, or more useful value will be generated from the same amount of primary energy.

It must be considered that incorporating non-energy CO_2-emissions, such as cement and brick production to the 33.6 gigatons of CO_2 will add an extra +4.4 gigatons of CO_2. Emissions of other greenhouse gases (GHGs), such as methane (CH4), nitrous oxide (N2O), sulfur hexafluoride (SF6), partially fluorinated hydrocarbons, fluorinated ethers, and perfluorinated compounds, as well as land use change (LUC), are converted as

Table 1: Saving potentials in primary energy through friction reductions [7, 8]

Study	Year of Publication	Saving potentials in primary energy	
		In % of primary energy consumption	In EJ related to the primary energy consumption of the said year
Jost (G.B.)	1966	5	0.4 EJ
A.S.M.E. (USA), Pinkus & Wilcock	1977	10.9	10 EJ (93 EJ)
Holmberg et al.	2017	8.6	
A.R.P.A.-E (USA)	2017	24	24.1 EJ (of 102.9 EJ)
Holmberg et al.	2019	8.0	

1 Exajoule (EJ)= 10^{18} Joules; A.S.M.E.= The American Society of Mechanical Engineers; Primary energy consumption (Total primary energy supplies (TPES)) in 2019: global= 584 EJ. USA= 105.7 EJ. Germany= 13.1 EJ; A.R.P.A.-E= U.S. Advanced Research Projects Agency-Energy.

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[1] The study by Sir Peter Jost ignores potentials from friction reduction and focused on wear protection, maintenance and service life extension.

[2] It should be noted that CO_2-emissions are composed of different values. Point of departure in 2019, for example, are direct or energy-related CO_2-emissions of 33.6 gigatons. This quantity increases by another +4.4 gigatons of CO_2 from non-energy related CO_2-emissions or CO_2-emissions generated by non-combustion processes, such as cement and brick manufacturing, amounting to fossil anthropogenic CO_2-emissions of 38.0 ± 1.9 gigatons. On top are other greenhouse gases (GHG), such as methane (CH4), nitrous oxide (N2O), sulfur hexafluoride (SF6), partially fluorinated hydrocarbons, fluorinated ethers, and perfluorinated compounds amounting to 14.4 gigatons of $CO_{2eq.}$ as well as land use change (LUC). In 2019, global $CO_{2eq.}$-emissions added to a total of 59.1 ± 5.9 gigatons $CO_{2eq.}$ See United Nation's Emission Gap Report 2020.

CO_2-equivalents and added on top, bringing total GHG emissions in 2019 to 59.1 ± 5.9 gigatons $CO_{2eq.}$ [9].

Even in a digitized world, friction in moving parts and machine elements will continue to irreversibly convert energy into heat. As often seen from a layman's point of view, reducing friction is not only a general issue or applicable only for internal combustion engines (ICE), but also for electric and fuel cell vehicles, because reducing friction in electric drives extents the range of electric vehicles.

Altogether, friction reduction is a dominant subset of energy efficiency, and, as such, well embedded in the United Nations Sustainable Development Goals (SDGs) [10].

Energy efficiency is found in SDG #7.3: "Double the global rate of improvement in energy efficiency by 2030," and in SDG #13: "Take urgent action to combat climate change and its impacts."

Article 2(17) in the EU Taxonomy Regulation EU/2020/852 explicitly emphasizes energy efficiency, which relates to CO_2-emissions through friction reduction (See chapter 3.1):

"Energy efficiency", a more efficient use of energy along the entire energy supply chain from generation to end use.

2. WEAR PROTECTION AND SUSTAINABILITY

Longevity is not linked to the technosphere of the circular economy, but the extension of the product life cycle decouples material consumption from economic growth, thus reducing waste streams and mitigating resource consumption and their embedded CO_2.

The concept of the term sustainability is widely perceived and often diffuse. The seventeen Sustainable Development Goals (SDG) and 169 targets adopted by the United Nations General Assembly [10] in October 2015 depict all aspects of sustainability. In the future, CO_2- or CO_2-equivalents ($CO_{2eq.}$) will be the currency for sustainability or the "gold standard" to compare human activities and assess their consequences.

Wear protection is embedded in SDG #12 "Ensure sustainable consumption and production patterns", and material efficiency and resource conservation in included SDG #8.4 as "Resource efficiency in consumption and production" and SDG #9.4 "More efficient use of resources".

2.1. EMBEDDED CO_2 IN MATERIAL RESOURCES

Every type of resource consumption during the process steps "mining, extraction, smelting, affination, refining and processing" inevitably leads to CO_2-emissions. Until today, the issue of resources has been circumstantial to the issue of CO_2-emissions. Global material flows provide the point of departure for assessing the impact, which resources have on embedded CO_2-emissions from primary resources. The global material consumption or total "first" extraction of 92.1 gigatons (= billion tons) in 2017 (plus + 8.6 gigatons of recyclates) will increase to 167 - 190 gigatons [11, 12] in 2060, of which fossil fuels accounted for only 15% of global material flows or a total of 15 gigatons in 2017. Such projections will inevitably drive the consumption of metals and minerals used in mechanical engineering, mobility or household appliances, if sufficiently available, as well as $CO_{2eq.}$-emissions embedded therein.

Table 2 lists consumptions and direct CO_2-equivalents for selected metals and materials. Table 2 is based on figures provided by international industry associations, which derive their statistics from qualified information available through member companies. The nature of the used ores and processing methods explain the ranges of equivalent CO_2-emissions ($CO_{2eq.}$) in Table 2.

Table 2: Mean $CO_{2eq.}$-emissions from the extraction of one ton of primary metal/material[3] *[*13, 14*]*

Primary metal or material	CO_{2}-equivalent in tons/per ton of metal or material	Global production 2018/2019 [10^3 tons]	Calculated $CO_{2eq.}$-emissions of primary metals or material [10^3 tons]
Special metals			
Neodymium	12-60	35	420-2,100
Lithium	5-16	80	400-1,280
Niobium	7.6	100	760
Tungsten	33.6	146	4,905
Molybdenum	3.4-14.8	259	881-3,788
Magnesium	20-26	1,100	>22,000
Nickel	13-42	2,330	30,290-97,860
Titanium	45	7,200	324,000
Silicone	10	8,400	81,000
Lead	3.2	1,.640	37,248
Chrome	25	12,300	307,500
Zinc	9.8	13,400	131,320
Manganese#	1.9-6.2	16,630	31,597-103,106
Subtotal	**–**	**73,620**	**972,321-1,116,867**
Significant engineering materials			
Copper*	5.5-9.5	23,600	129,800-224,200
Aluminum	16.6	64,800	1,075,680
Steel (iron)	>1.8	1,808,000	>3,254,400
Subtotal	**–**	**1,896,400**	**>4,459,880**
Non-metallic engineering materials			
Bitumen	0.30-0.75	90,000	27,000-67,500
Plastics+	~3.4	368,000	~1,251,000
Cement	0.6-1.3	4,200,000	2,520,000-5,460,000
Total	**–**	**6,620,020**	**9,228,401-12,422,711**
For comparison			
Germany 2019[4]	–	–	805,000
Global, energy-generated CO_2-emissions 2019[5]	–	–	37,900,000

*From concentrates, "open pit" mine; +Plastics= thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants as well as polypropylene fibers.

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[3] Further CO_{2eq}-emissions from the subsequent process steps of affination and further processing (rolling, stamping, heat treatment, etc.) are not included.

[4] In 2018 in Germany, greenhouse gas emissions amounted to 858.3 megatons of CO_2-equivalents, or 755.3 megatons of CO_2 (about 88%), and 888.3 megatons of CO_2-equivalents, when including air traffic. In 2019, greenhouse gas emissions decreased to 805 megatons of CO_2-equivalents, when excluding air traffic, or 683.8 megatons of CO_2. A further decrease to 739 megatons of $CO_{2eq.}$ or 644.5 megatons of CO_2) occurred in 2020. Greenhouse gas emissions amounted in 2022 to 746 megatons of CO_2-equivalents. Altogether, greenhouse gas emissions in Germany decreased by -40.4% since 1990.

[5] There are different compositions of greenhouse gas emissions (See Footnote 2).

In 2018 and 2019, the average gross ratio of mining, extraction and processing of one ton of primary metal or material to the corresponding $CO_{2eq.}$-emissions ranged between 1.36 and 1.82 tons of $CO_{2eq.}$ per ton of material. The overall ratio of $CO_{2eq.}$ and extracted tonnages of metals/materials was calculated 1.38:1 for 2015, if based on 11.5 gigatons of $CO_{2eq.}$ GHG emissions[6], as reported in the 2019 U.N. Emissions Gap Report [15, p. XXV & p. 57, ibid], and divided by the material footprint of 8.3 gigatons of metal ores, as reported in the United Nation Environment Report [16].

Irrespective of the efforts of the steel and aluminum industries to reduce specific CO_2-emissions in the long term, measures to improve lifecycles and longevity will reduce raw material consumption and waste streams, and help lower CO_2-emissions.

From a socio-ecological viewpoint, wear protection can contribute to doubling the utility value, all at the same resource consumption or stagnation of the embedded CO_{2eq-} emissions, i.e. twice as many people on earth can participate in the value of resources, thus satisfying the global "hunger" for material.

2.2. ALLOCATING MATERIAL FLOWS TO TRIBOLOGY

When extracting resources from nature that flow into various applications, the question arises as to their individual relationship to tribology. The material flows shown in Table 2 raise the questions for the potential resource pool whose service life can be extended by wear protection, or whose material flows go into applications and end uses with tribosystems or into applications with „functional profiles" determined by tribosystems. General findings or data records are not available to provide the answers. The material flow analysis illustrates which applications or material groups use the material flows of inflowing virgin material. Generally, there are no detailed or up-to-date Sankey[7] material flow diagrams available for the various material groups.

Extracted resources make inroads into various applications. In individual proportions, each material category is incorporated in mobility, machinery, equipment, installations, household appliances, etc., all of which contain tribosystems. Materials flowing in catalytic converters, packaging applications and static structures have no relevance for tribology, except when low-friction tribosystems reduce the energy consumption required for their production. Plastics and aluminum are the prime materials used in packaging applications, both having short life cycles of less than 2 years. The average life of smartphones also spans over less than 2 years. Buildings have a longer life cycle and also contain components with tribological systems, such as heating, ventilation, and air conditioning (HVAC), pumps and fans. Road surfaces and rails of transportation infrastructure are both subject to wear. Other than expected, 33% (2015) [17] of the total cement consumption in the U.S. and 22.4% (2019) [18] in China are used for roads and highways.

About 5% of asphalt pavements consist of bitumen, the other 95% are made of mineral aggregates and the most frequently recycled material. Approximately 85% of the 90 million tons of globally produced bitumen is used as a binding agent in various types of asphalts pavements for roads, airports and parking lots [19].

Steel, aluminum, copper or plastics are predominantly incorporated in vehicles, consumer goods and machinery containing tribosystems. The functionalities of automobiles, trains, airplanes and ships of the global transport sector depend on tribosystems. In 2018, they emitted 8.2 gigatons of CO_2 from energy sources [20] - a figure which does not account for the material resource footprint for the construction of transport technologies, vehicles and transport infrastructures (roads, railways, airports, ports).

In 2012, steel construction within the EU27 accounted for 64.7% of the 4.21 gigatons of iron and steel [21], whereas a study conducted by the Joint Research Center (EU-JRC) identifies 49% of the finished steel products used for construction

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[6] The 11.5 gigatons of $CO_{2eq.}$-emissions in 2015 also mean that the material footprint of metals/materials is responsible for 23.2% of the greenhouse gas emissions (CO_{2eq}) of the 49.85 gigatons of CO_2-emissions (2015).

[7] A Sankey diagram is a visualization used to represent flows of any type from a set of initial values to a set of final values along a value chain, whereby the width of each represented partial flow corresponds to a quantitative value.

in the EU [22]. Only 15% of the annually produced 1.87 gigatons of steel are used for cars, trucks and ships, 20% are used for machinery and 15% for consumer goods [23]. For the remaining 50%, especially for buildings and infrastructures, tribology is only indirectly related to buildings and infrastructure, whereas packaging itself shows no discernible link to tribology at all.

In 2019, global consumption of plastics amounted to 368 megatons. The EU28 (plus Switzerland and Norway) consumed 61.7 megatons of plastics, of which 43 megatons (69.7%) were used for packaging and in buildings [24]. 30.3% remained for transportation, machinery and consumer goods. 29.1 megatons (47.2%) of the 61.7 megatons were collected and only 9.32 megatons (15.1%) were physically recycled. 45% of the aluminum consumed worldwide goes into transportation equipment, machinery, and long living consumer goods [25]. 48% of the end-use of copper in 2019 [26] accounted for motors, drives, equipment in industry and transportation, and household appliances.

In a wide range of modern technologies, all special metals are of crucial importance and they cover a broad spectrum of technological applications. However, they have not found practical applications in packaging and construction. Some of them are used as catalysts. Nickel, chromium, molybdenum or manganese are invaluable alloying elements in metallurgy and materials science. They are also used for coatings in wear and corrosion protection.

Hard metals made of tungsten carbide consume 64% of the primary tungsten [27], compared to the 16% consumed by superalloys and steels. About half of the rare earth tonnage is used as catalyst, in glass and illuminants. Permanent magnets and engineering ceramics use the remaining volume of rare earths [28]. Particularly wind power and electric motors rely on neodymium, but also dysprosium and praseodymium [29]. In 2019, the global consumption of rare earth oxides attained 158,500 tons [29].

Table 3 gives an estimate of the $CO_{2eq.}$-emissions proportionate of material flows entering products which contain or depend on any type of tribosystems by means of multiplying the calculated emissions of metals and/or materials from Table 2 with an appropriate proportion of the metals/materials used in mobility, machinery, equipment, installations, household appliances, etc., all containing tribosystems or depending on this functionality. 32% to 42% of the calculated

Table 3: Estimates of $CO_{2eq.}$-emissions from material flows[8] entering products containing tribosystems

Primary metal or material	Mean, global dwell time [years]	Calculated $CO_{2eq.}$ emissions from primary metals [10^3 tons]	Proportion of tribosystems or depending thereof	Calculated $CO_{2eq.}$ emissions of material flows related to tribology [10^3 tons]
Special metals				
Nd, Li, W, Mn, Si, Ti, Ni, Mg, Zn, Pb, Mo	–	>1,039,131	<70	727,307
Distinct engineering materials				
Copper	41	129,800-224,200	48	61,020-107,520
Aluminum	21.1	1,075,680	45	484,056
Steel (iron)		>3,254,400	35-50	1,138,900-1,627,000
Subtotal	**–**	**4,459,880**	**–**	**1,688,976-2,218,576**
Non-metallic engineering materials				
Bitumen	~20	27,000-67,500	95	25,650-64,125
Plastics		~1,251,000	30	375,300
Cement	>30	2-520,000-5,460,000	22-33*	55,.400-1,801,800
Total	**–**	**9,297,011-12,371,911**		**3,371,633-5,187,108**

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[8] Note: Mitigated material/substance flows due to life-extending wear protection and condition monitoring are currently difficult to assess, as the tonnages saved cannot yet be quantified or directly be attributed to the applications and end uses containing or depending on tribosystems (See Chapter 2.1).

$CO_{2eq.}$-emissions from primary metals or materials can be attributed to material flows, which enter into or depend on applications and end-uses with tribosystems. This reduces GHG-emissions generated by the potential material flows in Table 2 from 9.2 - 12.4 gigatons of embedded $CO_{2eq.}$ to 3.4 - 5.2 gigatons in Table 3 for those related to tribology, particularly for life cycle extension. Assuming a medium to long-term doubling of service life induced by tribological measures, GHG-emissions decrease by 1.8-2.6 gigatons $CO_{2eq.}$ annually.

2.3. MATERIAL FLOWS RELEVANT TO $CO_{2EQ.}$-MITIGATIONS THROUGH WEAR PROTECTION

Sources of international organizations provide different volumes of material flows. For 2017, the UN Resources Outlook 2019 [12, p. 49] reports the extraction of 9.1 gigatons of „metal ores“, whereas the Circularity Report 2020 [30, p.18, ibid] states 10.1 gigatons. The various material resource pools result from the data available:

a. >6.620 gigatons of „engineering materials“ (See Table 2),

b. 9.120 gigatons of „metal ores“ (for 2017, U.N. Resources Outlook 2019) [12],

c. 10.1 gigatons of „metal ores“ (for 2017, Circularity Report 2020) [30] and

d. 17.720 gigatons (See for 2015 figures in Table 4 derived from U.N. Resources Outlook 2019).

Table 4: Global raw material extraction in 2017

Extraction acc. to material group	Gigatons	Relevance for tribology
Global raw material extraction	92.063	Mining is subjected to wear, including the equipment
Recycled materials	8.600	Re-refining of used oils
Total material flow	**100.663**	–
Mineral raw materials (non-metallic)	-43.834	Life cycle extensions of road pavements
Bio masses of any type	-24.062	Lubricants and additives based on renewable raw materials
Fossil energy sources	-15.047	Friction mitigation reduces general primary energy consumption
Potential resource pool for measures on wear protection	**17.720**	**A doubling the use phase of machinery, equipment and consumer goods halves the resource consumption**

In Table 4, the Circularity Gap Report 2020 subsumes the total resource consumption of 100.6 gigatons for 2017 and the potential resource pool applicable for tribological measures inducing service life extension. Non-recyclable and non-regenerable materials, such as the 15.047 gigatons of fossil fuels and the 24.062 gigatons of biomass, have been subtracted from the global material consumption or material flow of 100.663 gigatons (including recyclates). From the remaining 61.554 gigatons, further material flows, non-related to tribology, such as the 43.834 gigatons of non-metallic minerals (construction materials, sand, gravel and limestone, etc.) must be subtracted. In this group of materials, however, their use in road surfaces must be taken into account. The resulting 17.720 gigatons[8] represent the potential resource pool applicable for tribological measures extending service life.

Regardless of the considered resource pool, potential savings from wear protection remain significant in terms of the total global GHG-emissions of 51.8 gigatons $CO_{2eq.}$ or the 37.9 gigatons of direct CO_2-emissions in 2017.

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[8] The discrepancy between the 9.120 gigatons of „metals“ from the U.N. Resources Outlook 2019 and the 17.657 gigatons is due to the 8.6 gigatons of recycled materials from the Circularity Report 2020. These 8.6 gigatons (cycled sources) are not allocated to material groups or applications in the Circularity Gap Report 2020. Recycled materials must be included in the considerations of the potential resource pool, since these materials consist mainly of engineering materials and are returned to the manufacturing process. They also represent an additional material flow of engineering materials with CO_2-equivalents contained therein.

2.4. HIERARCHICAL ALLOCATION OF MATERIAL FLOWS TO TRIBOLOGY

Irrespective of the material flow, the question arises as to which hierarchical level this material flow can be allocated to tribology. The following methodologies can be identified:

A. **Focus only on the triboelements**
   This approach only considers the mass of the worn or failed triboelement, such as the plain bearing shell, piston ring or rolling bearing, regardless of its effect on subsystem or overall product.

B. **Focus on subsystems or components**
   Even if only one distinct triboelement causes wear or failure, the mass of the subsystem or component, such as transmission or engine, is crucial because as being unemployable it requires overhaul, and complete replacement would cause additional material consumption. This approach includes the mass of other triboelements, from housing and peripherals, even though they remain functional because the entire subsystem and/component was replaced and scrapped or dismantled, and the material quantity will hopefully be recycled.

C. **Focus on products or entire product mass**
   The entire machine or product (e.g. the vehicle) is scrapped, although many subsystems, interiors, drivetrains, and housings remain functional, so that all inherent masses are allocated to the material flow relevant to tribology, because

   - a technical obsolescence[10] occurred (so-called "stranded assets[11]") and/or

   - a subsystem or main component failed to such an extent that repair or replacement would economically not be feasible, especially late in the use phase.

When being scrapped or dismantled and recycled, all the various different materials of the total product mass are taken into account. This approach considers the overall consequences of a failed or worn tribological system.

Furthermore, awareness must be raised to the rapid technological and legal developments rendering products obsolete (functional obsolescence). As a result, longevity and the reuse of completely restored products through reconditioning no longer make sense.

2.5. REFURBISHMENT OF WORN COMPONENTS

One obvious benefit of extended product life is the reduction of waste streams, but another is the mitigation of greenhouse gas (GHG) emissions because use extension longer valorizes embedded GHG inherent in resource consumption. It appears that environmental sustainability requires longer product life cycles. One strategy for extending product life is to address the notion of quality in terms of intrinsic durability, condition monitoring, repairability, and reuse to the customer prior to the purchase so that replacement is only the last resort.

In times of recession, governmental economic development programs promote the exchange of products, thus directly shortening the life of still functional or repairable products. Business models in an affluent society are based on an early exchange of goods, for which there are various motivations. Companies must reap profits to survive, and a shift from quantity to quality clearly threatens a purely volume-oriented business model. Alternatively, more complex business models are conceivable selling the product not just for one life, but for further life cycles after refurbishment, performance enhancements or „restoration."

The „Ecodesign Directive" 2009/125/EC [31], last amended by 2021/341/EC, refers to a possible "life cycle extension resulting from minimum guaranteed life, minimum period of availability of spare parts, modularity, upgradability, repairability". The Ecodesign Directive aims at the envi-

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[10] Terms of obsolescence:

a. Technical or physical wear, material obsolescence: Material obsolescence is due to the poor performance of materials and components, but also due to extensive or intensive use.

b. Functional obsolescence, moral wear: functional obsolescence is caused by the rapidly changing technical and functional requirements to a product or caused by the technical progress outdating the product.

[11] "Stranded assets" have become prematurely obsolete or no longer generate income and must therefore be depreciated.

ronmentally compatible design of products relevant for energy consumption, i.e. products requiring energy to perform their intended function. The EU Ecodesign legislation encompasses 31 product groups, most of them for daily use (business-to-consumer (B2C)), such as refrigerators, air conditioners, vacuum cleaners, pumps, television sets, washing machines, street lighting or PCs, etc. An expansion to business-to-business (B2B) products is envisaged.

In addition, the Framework Directive 2008/98/EC „Waste Framework Directive“ [32] addresses product life extension as a waste reduction measure, only reinforced by amendments in EU Directive 2018/851/EC [33].

Life cycle extension is a sub-strategy of resource efficiency. Resource efficiency is one focus of the 2016 Toyama Framework [34] elaborated by the G7 industrial nations on material cycles to implement resource efficiency (RE), circular economy (CE), avoiding, reducing, improving (3R[12]), and sustainable material management (SMM[13]). Product life extension[14] policies incorporate the measures remanufacture, refurbishment, repair and direct reuse (RRRDR[15]). The Toyama framework aims at promoting a sustainable, low-emission global economy which conserves, restores and sustainably uses natural resources while providing economic opportunities, such as competitiveness, supply reliability, innovation, economic growth and job creation.

Refurbishment of worn components can reduce CO_2-emissions. An example of a successful implementation is the refurbishment of rolling bearings in rail, mining and cement industries, as well as in aircraft turbines.

Compared with the production of new bearings, resources are saved. Refurbishing wheelset bearings can reduce CO_2-emissions by over 95 percent, energy consumption by 94 percent and water consumption by 96 percent. For example, for a freight train with 80 wagons, two locomotives and thus a total of 1,296 wheelset bearings, 133 tons of CO_2 alone, 481 MWh of energy and 1,767 m^3 of water can be saved [35].

Data Matrix Code as the basis for digitized and condition-based maintenance

An important element of the SCHAEFFLER 100 percent return services is an individual Data Matrix Code (DMC) applied to each wheelset bearing during the manufacturing process. This code enables continuous recording of manufacturing and operating data as well as maintenance information for the individual product. The result is a digital twin of the product with a comprehensive service life record. Due to their design, wheelset bearings have a high potential for extending maintenance periods, employable with the evaluation of the service life record. In addition to the reduced CO_2-footprint, this condition-based maintenance improves operational reliability and safety at reduced costs.

Monitoring functional effectiveness of lubricants is another component ensuring optimum machine operation. Particular focus is on the correct lubrication of bearings, which can prevent multiple application problems and machine failures. Insufficient knowledge of the actual lubricant quantity and the condition of common automatic lubrication systems often cause maintenance personnel to continue lubricating manually instead of relying on automatic lubrication systems. As a result, up to 60% more lubricants are used than necessary. A smart and well-linked lubrication system, such as OPTIME C1 by Schaeffler, not only allows condition monitoring of hundreds of lubrication points, but also assists in setting the optimal lubricant quantity and when remote monitoring the lubricators. This digital service reduces grease consumption, the required lubrication effort and also increases machine availability, all of which have a positive overall impact on the conservation of resources.

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[12] 3R= Replace, Reduce, Refine

[13] SNM= Sustainable Materials Management

[14] Life extension R-strategies are: R3= reuse, R4=repair, R5= refurbish, R6= remanufacture, R7= repurpose.

[15] RRRDR= Remanufacture, Refurbishment, Repair and Direct Reuse (RRRDR).

3. INCORPORATING TRIBOLOGY IN CLIMATE REPORTING

3.1. TRIBOLOGY AS SUSTAINABLE ECONOMIC ACTIVITY WITHIN THE TAXONOMY

The „EU Taxonomy[16] Regulation" is a set of rules using a uniform classification framework to assess the sustainability of economic activities. It defines which projects and companies in the EU are considered as "green" or "environmentally sustainable" and are eligible for funding. The EU Taxonomy Regulation represents a seal of approval for climate-friendly investments and primarily affects financial and energy-intensive economic sectors, such as transport, housing, energy, and chemicals and steel. Since item (24) of the regulation states that an economic activity pursuing the environmental objective of climate protection must contribute significantly to stabilizing greenhouse gas emissions by avoiding or reducing them or by increasing the storage of greenhouse gases, the question arises as to which scope the Regulation EU/2020/852 is applicable.

Article 2(17) explicitly emphasized energy efficiency, which is related to CO_2-emissions through friction[17] mitigation: *"energy efficiency, a more efficient use of energy along the entire energy supply chain from generation to final consumption;".*

According to Article 10(1b), an economic activity makes a significant contribution to climate protection, if it increases energy efficiency. Table 5 links the targets of the taxonomy with attributes and contributions of tribology.

Table 5: Excerpts from Article 13 in EU/2020/852 „Substantial contribution for the transition to a circular economy".

Targets	Attributes and contributions to tribology
(1) An economic activity shall make a significant contribution to the transition to a circular economy, including **waste prevention**, reuse and recycling, if it:	Wear protection = technical longevity and service life extensions mitigate waste production.
a) **makes more efficient use** of **natural resources**, including procured biobased and other raw materials of sustainable origin, in production, including by	Bio-lubricants and lubricants from biogenic resources.
(i) **reduced use of primary raw materials** or increased use of by-products and secondary raw materials; or	Wear protection = material efficiency and resource conservation.
(ii) **resource and energy efficiency measures**;	Energy efficiency through friction reduction means a direct CO_2-reduction, Resource efficiency through wear protection means e.g. life extension of wind turbines.
b) Improves **durability**, repairability, upgradeability or reusability of products, especially in development and manufacturing activities;	Longevity through wear protection mitigates waste volumes and resource consumption.
e) extends the use of products, including through reuse, **design for longevity**, re-functioning, disassembly, remanufacturing, modernization and repair, and sharing product use;	Low-wear tribological systems and their remanufacturing conserve resources with their embedded CO_2-footprint.
k) **prevents or reduces waste**;	Longevity, repairability and remanufacturing reduce waste volumes. Re-raffinates substitute primary resources.

Article 17(1d(i)) classifies **"inefficiency in the use of materials"** as a significant impairment of environmental objectives. Therefore, lack of wear protection and repairability are no longer sustainable economic activities. Wear protection or increased longevity represent the core strategies for waste avoidance by means of reduced material flows and for the mitigation of embedded CO_2.

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[16] The taxonomy differentiates between activities and technologies beneficial („green") and problematic for the climate („brown").

[17] Friction is the worst enemy to efficiency.

3.2. Pricing of CO_2-emissions

Today, it is not possible to predict which specific technological innovations will be triggered by a higher CO_2-price. However, it can be assumed that a higher CO_2-price will drive energy-saving technological progress (see chapter 4) [36]. Consequently, higher CO_2-prices raise customer prices for emission-containing products resulting in a lower demand for such products. These additional costs can be mitigated by the offerings of tribology reducing emissions, and thus promoting product sales.

CO_2-pricing offers guidance for appropriate negative emission technologies (NETs) and can be regulated upstream or downstream at the emission source. CO_2-pricing gives general incentives reducing energy consumption or friction reduction. In the long term, EU Carbon Pricing (EU-ETS) provides the economic basis for the evaluation of tribological "CO_2-reduction pathways" solutions either by economic measures or through avoided CO_2-penalties.

In 2020, the CO_2-price corridor in the European Emissions Trading Scheme (EU-ETS) for the compensation of CO_{2eq}-emissions amounted between 40 and 80 US-\$/t CO_2 [37]. In early 2022, the EU-ETS emissions trading price corridor ranged from 75 €/t CO_{2eq} to 99 €/t $CO_{2eq,}$ with a peak of 105.30 €/t$CO_{2eq.}$ on 27.02.2023.

Projections on the economic value of GHG-avoidance costs expect a price corridor of 175 to 300 €/tCO_{2eq} in Europe by 2032 [38]. In February 2021, the interagency working group [39] on macro-economic costs of greenhouse gas emissions of the United States Government assessed [40] the value of social or macro-economic[18] costs of carbon dioxide emissions (SCC[19]= social costs of carbon dioxide) for 2020 at \$51/ tCO_2 followed by a projection to \$56/tCO_2 for 2025 and to \$63 for 2030. In a later study, Rennert et al. [41] estimated a mean SCC value of \$185/CO_2 (or \$44-\$413/tCO_2: range of 5 - 95%, in U.S. dollars for 2020) using a preferred discounting scheme[20]. This value is 3.6 times higher than the present, most commonly cited mean value of the U.S. government of \$51 per tCO_2 at a constant discount rate of 3%.

The German Federal Environment Agency (UBA) estimates the environmental damage costs (an indicator of the benefits lost to nature) for electricity, heat generation and road transport at €202.7 billion in 2019. Taking into account the greenhouse gas emissions of these sectors, it would result in 372 €/t$CO_{2eq.}$. The UBA [42] recommends the use of a cost rate of 195 €^{2020}/tCO_{2eq} for 2020 with a higher weighting of the welfare of current versus future generations and a cost rate of 680 €^{2020}/tCO_{2eq} with an equal weighting of the welfare of current and future generations.

The SCC cost can vary significantly, because there is no consensus among experts about how to value the marginal climate damages generated by CO_2.

3.3. Economic price tag for defossilization

In the 14th Five-Year Plan [43] 2021-2025, China expects CO_{2eq}-emissions to peak around 2030 and eventually aims for carbon neutrality in 2060. Where the GDP is concerned, CO_2-emissions are expected to be lowered by -18%. Since the GDP is projected to increase by 6% per year over the period from 2021 to 2025, a +12% expansion in CO_2-emissions is expected, although the increase turns out smaller than in the past. By 2030, the share of non-fossil energy sources in the energy mix shall be increased to "around 25%".

The International Monetary Fund (IMF) [44] identified a required annual investment for China of 1.5 to 2.0% of the gross domestic product or ¥2,200 billion or >US\$265 billion) until 2030 and a higher financial investment requirement for the period from 2030 to 2050 of more than ¥3,900 billion per year in order to achieve climate neutrality.

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[18] These estimates of social or economic damage should not be confused with estimates of the cost to achieve a particular emission or warming limit.

[19] SCC is an estimated monetary measure of the economic costs (i.e. climate damage) resulting from emitting one additional ton of carbon dioxide (CO_2) into the atmosphere. Conversely, it represents the benefit to society from the reduction of CO_2-emissions by one ton – a figure which can be compared to costs of reducing emissions.

[20] The discount rate translates the cost of future climate damage into present money (present value). Thus, the value of future climate damage is compared to today's monetary values.

In 2006, the Chinese Tribology Institution (CTI) concluded [45] that tribological measures in eight selected industries (metallurgy, energy, railroads, automobile, petrochemicals, agriculture, and shipping) could save at least 1.55% of China's GDP.

This information leads to the conclusion that savings generated by tribological measures alone allow China to counter-finance their decarbonization efforts.

3.4. SCOPE 4 „AVOIDED EMISSIONS" - TRIBOLOGY AS A CO_2 PREVENTION TECHNOLOGY

Achieving the Paris Climate Protection Agreement demands drastic emission reductions by 2050 at the latest, whilst China advertising climate neutrality by 2060 and India by 2070.

In a best-case scenario, the associated greenhouse gas neutrality requires no more greenhouse gases are emitted into the atmosphere that can be removed from the atmosphere by other means. An essential prerequisite for achieving this goal would be the extensive defossilization of today's material flows. This will not be realistic for many sectors. Consequently, the unavoidable residual emissions must be completely compensated in order to prevent an increase in the concentration of greenhouse gases and to achieve so-called „net zero emissions". Finding technologies and methods for ecosystems removing CO_2 from the atmosphere are designated as "negative emission technologies", which are limited to natural, biological or geochemical sinks (separations). Well-known buzzwords for the capture of CO_2 are CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilization).

3.4.1. CO_2-REDUCTION PATHWAYS

The Intergovernmental Panel on Climate Change (IPCC) [46] has prescribed carbon dioxide removal[21] (CDR) in the order of 100 to 1000 gigatons of carbon dioxide for the 21st century, and the National Academies of Science [47] and The Royal Society [48] have suggested that 8 - 10 gigatons of carbon dioxide per year must be removed by 2050 and 20 gigatons of carbon dioxide per year by 2100, but the world cannot rely on just one approach to achieve this magnitude.

Natural approaches, such as landscape restoration, could remove 5 - 6 gigatons of CO_2, if efforts will be significantly intensified. But technological approaches, such as direct separation from the air and storage of carbon, will also be required, if we want to remove and store as much carbon as latest scientific findings suggest [49].

Here, the savings of 3.9 - 11.3 gigatons $CO_{2eq.}$ tribology (see Chapters 1, 2 and 4) is offering come into play and should be included in the portfolio of carbon reduction pathways (see Table 6). Friction reduction and longevity represent "industrial carbon removals" or "societal carbon removals" because $CO_{2eq.}$-savings from tribology occur anywhere and anytime. Friction reduction and longevity are to be considered as "CO_2-reduction pathways" as less CO_2 is released by the operation of tribological systems, and especially as they are often relatively easy to implement in the form of drop-in solutions. In other words, CO_2-emissions not required downstream will not have to be generated upstream.

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[21] Synonymous terms: "carbon dioxide removal" or "anthropogenic activities removing CO_2 from the atmo-sphere", **IPCC's 1.5°C report (2018)**. "Greenhouse Gas Removal (GGR)", The Royal Society report (2018). "negative emissions technologies", **The National Academies report (2019)**.

Anthropogenic carbon dioxide (CO_2) emissions are redistributed between atmosphere, oceans, and terrestrial biosphere. Removal of carbon dioxide from the atmosphere naturally occurs through biological and geochemical sinks, such as forests and soil ecosystems, geological mineralization, and oceans. Of the global anthropogenic CO_2-emissions in 2019, 9.5 ± 2.2 gigatons CO_2 were sequestered in oceanic sinks, 11.4 ± 4.4 gigatons of CO_2 were sequestered in terrestrial sinks, and 19.8 ± 0.7 gigatons of CO_2 were sequestered as a sink in the atmosphere [50, p. 3292].

d. Oceans absorb about 23 - 30 percent of the carbon dioxide, or 9 - 12 gigatons CO_2/year that humanity emits to the atmosphere through direct chemical exchange. The ocean contains about 38,000 gigatons of dissolved carbon, primarily in the form of bicarbonate ions (HCO3-) and in smaller amounts in the form of carbonate ions (CO32-). Oceans serve as an important sink for anthropogenic CO_2 entering the atmosphere [51, 52, 53, 54].

e. Land plants absorb about 25 - 30% of the carbon dioxide released into the atmosphere by humans [55]. Worldwide, terrestrial biotic carbon stocks encompass about 600 gigatons of carbon in plant biomass (mainly in forests) and about 1,500 gigatons of carbon as organic matter in soil to a total depth of about 1 meter (or about 2,600 gigatons of carbon for up to 2 meters) [56].

f. The global geological storage capacity of saline aquifers and hydrocarbon reservoirs amounts to 5,000 to 25,000 gigatons of CO_2 [57, p. 252]. However, current storage rates are only in the magnitude of tens of megatons of CO_2/year. Natural sources of alkalinity (e.g., serpentine group minerals, basalt, or peridotite) are abundant in the earth crust and could store about 10 gigatons of CO_2 per year.

In August 2019, the IPCC announced several measures to create new CO_2-sinks sequestering carbon dioxide in addition to reducing greenhouse gas emissions (see Table 6). The mitigation potentials estimated by the IPCC by 2050 were [58, Chapter 2.6 ibid]:

1. enhanced weatherization between 0.5-4.0 gigatons CO_2/year,
2. reforestation/forest restoration: 0.5-10.1 gigatons CO_2/year, and
3. sequestration of soil carbon on cropland and grassland: 0.4-9.3 gigatons CO_2/year.

The literature available on carbon dioxide sequestration by plants yields a potential of 1 - 7 gigatons CO_2/year for the year 2050 [59, 60]. The German Society for Tribology (GfT e.V.) estimated the long-term $CO_{2eq.}$-mitigation potentials as follows:

a. friction reduction (= energy efficiency) between 2.3 - 4.5 gigatons $CO_{2eq.}$/year, and

b. longevity (= resource efficiency and conservation) between 1.7 - 6.8 gigatons $CO_{2eq.}$/year,

based on total fossil (anthropogenic) $CO_{2eq.}$-emissions in 2019. Tribology offers untapped and previously overlooked carbon dioxide removal potentials in a gigaton scale and in the same order of magnitude as the aforementioned mitigation measures identified by the IPCC.

Table 6: Estimated mitigation potential of different options for action for the mitigation of carbon dioxide in the atmosphere. [58]

CO_2-reduction pathways	**Avoidance potential up to 2050 [gigatons CO_2/yr.]**	
	Min.	**Max.**
Carbon dioxide removal sinks		
Enhanced geological weathering	0,5	4,0
Reforestation and forest restoration	0,5	10,1
Carbon absorption by cropland and grassland		10,0
CO_2-sequestration in geological formations	0,4	9,3
CO_2-prevention through tribological measures		
Reduction of friction*	**2,3**	**4,5**
Longevity*	**1,7**	**6,8**

*$CO_{2eq.}$

Friction and wear occur everywhere along the value chain. Since tribology is particularly effective during the use phase, it is a technical option for the removal of CO_2 from the atmosphere with good implementation opportunities.

Many believe that technological approaches to carbon removal are still in their „infancy“ and will only become marketable through significant scaling effects. On the other hand, sufficient tribological offerings with a technological readiness level of >6 (Technology Readiness Level, TRL) are available and only need find their way into practice. Superficially of non-functional nature, the resulting additional costs, however, must be valorized through monetary CO_2-savings.

Longevity affects the existing business models of growth, as they have been dependent on the regular exchange of goods and the frequent replacement of spare parts. The offerings of tribology will deliver just the required CO_2-savings without being particularly disruptive for the business models adapted to them!

3.4.2. ALLOCATION OF CO_2-CREDITS.

The technical guideline for Scope 3, Category 11, (see Chapter 4) only requires giving account of the use phase of sold (complete) products, as for vehicles. The GHG-protocol does not address savings, but only gives account of the use phase. The amount of GHG-emissions avoided through friction reduction and resource savings through longevity is not subtracted from the total carbon inventory of an organization. Given the impact of tribology on GHG-emissions, reductions should be part of the carbon trading system. The Greenhouse Gas Protocol has not yet addressed avoided emissions. Initial proposals for „avoided emissions“ (Scope 4) were made by the World Resources Institute back in November 2013 [61] in a commentary on the fifth report of the Intergovernmental Panel on Climate Change (IPCC). The proposed definition was:

> *„Emission mitigations occurring outside the life cycle or value chain of a product, but resulting from the use of that product.* **Fuel-efficient tires, energy-efficient ball bearings***, etc. are examples of products (goods and services) avoiding emissions.“*

The substitution of products and materials by those with lower embedded $CO_{2eq.}$-emissions is a challenging goal, as they must meet the functional requirements for longevity, strength, and low friction, as well as for safe operation. Again, the questions arise: who will be rewarded for such efforts with CO_2-certificates or credits and who owns the CO_2-savings in monetary terms?

Over the course of a year, dynamic seals or bearings generate unavoidable friction losses. Who will obtain the emission credits or will benefit from the friction reduction derived from CO_{2eq}-savings?

a. The seal or bearing manufacturer; or
b. the OEM as the purchaser of this solution or
c. the end user or operator as the bearer of additional costs, or
d. the actors along the value chain who appropriately share CO_{2eq}-savings from the use phase.

Established energy efficiency measures often require significant investment efforts. Friction reduction, as a technology to improve energy efficiency and sustainability in the use phase, saves rebuilds and investments. The transition to low-friction lubricants is often retroactive, and also applicable during the product life cycle and for low-friction materials or coatings during redesign. Energy savings or friction reductions can pay off twice (See Table 9):

a. directly in the cost of electricity or primary energy, but also
b. indirectly in climate reporting (scopes, GRI) through reduced CO_2-footprint and improved sustainability.

3.4.3. ESTIMATION OF EMISSION MITIGATIONS

Sustainable products should be understood as products whose production, transport, use or disposal release fewer CO_2-emissions than comparable products (see Figure 1). The reduction of the CO_2-footprint begins in an integrated way in the product development process, for example in product design and material selection. The decisive factor, however, is the entire life cycle, from raw material extraction and production to product use and possible circular economy concepts at the end of life. Avoided emissions can be calculated as the difference between accumulated GHG-emissions from a Business-As-Usual[22] (BAU) baseline scenario and from a scenario to mitigate GHG-emissions[23]:

**Avoided Net Emissions =
BAU Baseline Emissions –
technology emissions with mitigated emissions.**

The life cycle assessments (LCA) according to ISO 14040 and ISO 14044 serve as central instruments for recording the sustainability performance of products and processes and, by means of the product carbon footprint (PCF), take into account in particular the CO_2-balance from the provision of the products. The impact of improvement can occur at different phases of the life cycle, and avoided emissions should be considered as the total of changes along the value chain. Comparative impacts are estimated as the difference between the total attributable life cycle GHG-inventories of a corporate product ("evaluated" product) and an alternative product (or "reference" product) which performs an equivalent function (Figure 1) over the entire life cycle. This approach not only applies for the reduction of friction during the use phase, but also encompasses savings in material flows induced by longevity measures and from material production with regard to their embedded $CO_{2eq.}$-emissions. The methodology used to determine avoided GHG-emissions is in line with the cradle-to-grave approach in life cycle analyses.

During product development, the product carbon footprint (PCF) must be taken into account at an early stage of the design. First LCA software solutions are available for determining the PCF,

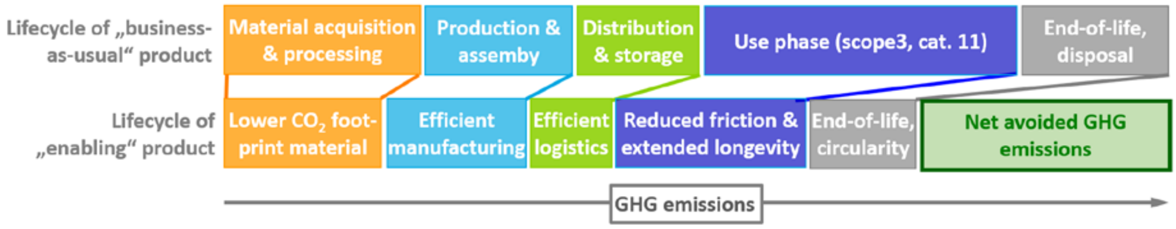

Figure 1: Methodology for the calculation of impacts on GHG-emissions using the technology with mitigated emissions [adapted from [62].

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[22] The BAU baseline emissions are GHG emissions, which would have occurred without the corresponding improvements.

[23] The positive benefit is replacing BAU with the lower-emission solution thus avoiding emissions.

such as an automated calculation option in the product configurator for rolling bearings (Medias® from Schaeffler).

For tribological products, such as lubricants, the GHG-emission benefits in the use phase are significantly larger than the embedded CO_2 or carbon intensity of raw or basic material.

The increase in efficiency[24] or the reduction in friction must be verifiable, especially over the life cycle. "Analytical sciences" on oil samples do not deliver any useful information. Tribological tests provide the tribological parameters representing functional system properties. Consequently, condition monitoring can only periodically verify the maintenance of the low friction coefficient level by means of application-oriented tribometry - unless the application implicitly provides information on ongoing energy efficiency (e.g. by recording the power consumption of pumps or actuators).

4. SCOPE 3, CATEGORY 11, DOWNSTREAM EMISSIONS

Scope-3-emissions, or emissions generated along the value chain, are defined as a result of downstream activities like all other indirect emissions occurring along the value chain of an organization. Scope-3-emissions are divided into 15 specific categories [63], of which Scope 3 of category 11 (Scope 3.11) is most relevant to tribology (see Table 7). The GHG-Protocol methodology classifies categories 1 - 8 to upstream and categories 9 - 15 to downstream areas.

Scope-3-emissions[25] are the result of activities from equipment not owned or controlled by the reporting organization. However, the organization has little influence on reducing these emissions. This is exactly where tribology offers savings downstream which do not have to be generated upstream. The importance of Scope-3-GHG-emissions for specific products, services, and industry sectors is summarized in [64].

It is only obvious that „products directly consume energy (fuels, electricity, resources) during their use" in order to keep operating. Lubricants are chemical products that influence the functional profile of other technologies in a way that reduces $CO_{2eq.}$-emissions. As long as they are not combusted, they have significant impact on $CO_{2eq.}$-emissions expected over lifetime from irreversible friction losses and they also have impact on the longevity of machinery, as they hopefully avoid premature failure of machinery and thus the consumption of additional metal/mineral resources with embedded $CO_{2eq.}$

This also applies to plain and ball bearings and seals, which are important machine elements for the operation of equipment and machinery (see also chapter 5).

Table 7: Scope 3, category 11, emissions from the use of products sold [63]

Type of emission	Types	Examples
From the use of sold goods	Includes emissions from the use of sold goods and services, by end customers, i.e. from the use phase.	Automobiles, aircrafts, engines, motors, power plants, buildings, appliances, electronics, lighting, data centers, web-based software
	Fuels and feedstocks	Petroleum products, natural gas, coal, biofuels, and crude oil

4.1. SCOPE-3-EMISSIONS FROM VEHICLES

Toyota applied a life cycle analysis (LCA), assessed the total CO_2-emissions of its vehicles, and found that the use phase of its vehicles accounted for 81.8% (fiscal year 2019) [65, p. 23, ibid] and 80.5% (fiscal year 2020) [66, p. 37, ibid]

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[24] In the understanding of U.S. Federal Trade Commission (FTC), only "voluntary consensus standard bodies" have the authority to develop and maintain standards for green claims [section III in FTC green guide, 2012]. These are ''organizations, which plan, develop, establish, or coordinate voluntary consensus standards using agreed-upon procedures". ASTM D7721-22 "Practice for determining the effect of fluid selection on hydraulic system or component efficiency" is such an example. Similar requirements are being developed in the EU (COM(2022)143) Green Guide Directive.

[25] Scope 3 emissions of category 11 are part of the GRI sustainability reporting standards (GRI= Global Reporting Initiative) and are disclosed under topic 305-3 „Other, indirect (Scope 3) GHG emissions".

of all indirect emissions (Scope 3, Category 11). The fuel consumption of vehicles with internal combustion engines is responsible for the largest share of greenhouse gas emissions during the use phase. Therefore, optimized tribological systems with low-friction surfaces and coatings [67], as well as low-friction engine and transmission oils reducing fuel consumption directly impact these CO_2-emissions.

As depicted in Table 8, about 80±5% of cradle-to-grave emissions from road vehicles during their use phase were emitted through fossil fuel combustion or, alternatively, electricity generation for electric/hybrid powertrains.

Table 8: Ratio of scope-3-GHG emissions from category 11 to all other 15 categories in scope 3.

Year	BMW [68]	RENAULT^{+} [69]	GM [70]	NISSAN [71]	Mercedes* [72]	TOYOTA	Volkswagen$^{\#}$ [73]
2020		83,2			79,6	80,5	76,2
2019	71,2	84,2	75,7	88,6	80,5	81,8	77,0

*Use phase (200,000 km); # Well-to-wheel; +Tank-to-wheel

The cross-industry research consortium „Low-Friction Powertrain“ of the Research Association for Drive Technology (FVA) and the Research Association for Combustion Engines (FVV) found a maximum possible reduction [74] in fuel consumption of 12.1 % (or 0.945 l/100km) by means of various measures for friction reduction in vehicles (M271 KE, gasoline engine, 1.8 L).

The forecasted savings of 0.945 liters of gasoline/100 km correspond to 2.249 kg CO_2/100 km. Here, the monetary CO_2-value of the tribological measures for friction reduction over a use phase of 200,000 km amounts to € 449.80, assuming a minimum price of € 100/t CO_2. See chapter 3.2 for other price assessments. The research cluster “Low-Friction Powertrain” has not taken into account the impacts of lubricants with low viscosity and/or high viscosity index.

Combining both leads to the conclusion that an average of 9.6±0.6% of Scope-3-category-1 life-cycle CO_2-emissions from road vehicles can be saved through friction reduction. The range of life cycle GHG-emissions of road vehicles ranges between 30-65 tons of $CO_{2eq.}$ during 200,000 km [75, 76]. When assuming a minimum price of 100 €/t CO_2, the monetary value of CO_2-emission reductions of 2.88-6.24 tCO_2 anticipated by tribological measures to reduce friction amounts to 288-625 €.

According to EU/2019/631, the Commission levies a charge of €95 per gram of CO_2 per kilometer from the manufacturer – by using NEDC, if the target value of 95 g of CO_2/km applicable to the entire EU fleet is exceeded for passenger cars. The maximum possible saving from the FVA/FVV project of about 12.1% combined with the average CO_2-emissions of new passenger cars registered in Europe of 122.3 g of CO_2 /km in 2019 would result in calculated savings of 14.8 g of CO_2/km and thus a significantly higher monetary benefit of 1,406 €.

4.2. A HOLISTIC CONTRIBUTION TO SUSTAINABILITY THROUGH STATE-OF-THE-ART SEALING TECHNOLOGY

Everywhere around the world, machines and vehicles of all types are operated and wherever machine elements move relative to each other, friction occurs, namely in rolling bearings, plain bearings and dynamic seals.

Wherever friction can be reduced, energy and ultimately CO_2 are saved. Particularly with dynamic seals, the reduction in friction goes along with reduced wear, thus resulting in a longer service life and ultimately in a lower consumption of resources [77].

That is why dynamic seals, such as Simmer® rings and mechanical seals, can significantly contribute to saving energy. Static seals can also make a contribution. Designing them to achieve their sealing effect with the lowest possible sealing force allows for less rigid and weight-saving structures.

Sustainability aspects must already be considered during product development [78]. In the end, the customer should be offered the best possible functionality while minimizing the consumption of resources and carbon emissions. In addition to materials and production technologies, the product design and infrastructure required for product manufacture are also taken into account.

4.2.1. CLIMATE-NEUTRAL PRODUCT DEVELOPMENT AS OBJECTIVE

The „Green Index“ developed by FREUDENBERG Sealing Technologies (FST) serves as an example to illustrate the methodology for climate-friendly development of seals. Here, climate-relevant emissions and also the hazard potential from raw materials are taken into account in order to internally compare and evaluate alternative materials and processes. Since state-of-the-art seals often consist of material mixes, all individual components are considered to avoid setting false incentives for the selection of certain materials.

The „Green Index“ ultimately represents a key indicator assigning sealing materials to a specific internal sustainability class. FST has not yet decided how and to what extent sustainability factors beyond the GWP will be considered in the future, however, it is crucial for an optimization that is not one-dimensional.

FST has elaborated on how the energy required for the production of seals can be correctly allocated to individual material batches or products. One prerequisite is the knowledge of the actual amount of energy specifically consumed in individual process steps, i.e. in relation to weight, volume or surface area. For this purpose, various manufacturing processes and options are investigated in detail early during the product development phase in order to fully exploit design scopes with regard to the CO_2-footprint. Fig. 2 shows the core processes which significantly impact the CO_2-footprint on the process side.

Waste avoidance is a major lever for a more climate-friendly component production and for a reduction of resource consumption. This is why FST consistently opts for waste-avoiding production technology. In addition to minimizing organization-related material losses, for example due to storage beyond the minimum shelf life of preliminary products and quality-related scrap, process-related material losses have been recorded for years and systematically reduced. In addition to minimizing material losses during material changes (start-up scrap, cleaning cycles), focus is directed on reducing so-called „engineered waste“, i.e. waste inherent in the processing of sprue gates, piping manifolds and waste generated by burrs. For this purpose, innovative mold concepts, sprueless cold runner processes and other concepts for net shape molding are being implemented.

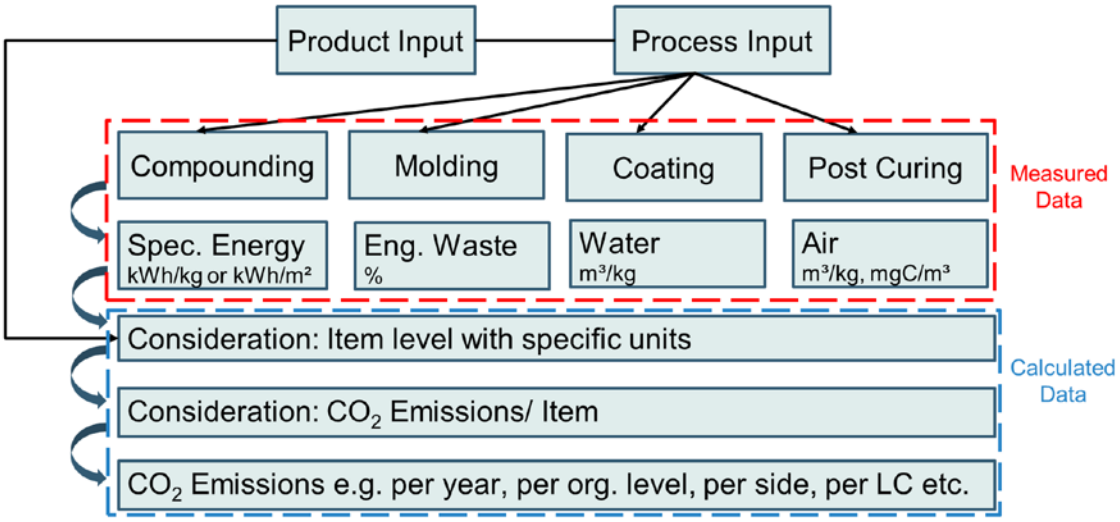


Figure 2: System of Key Performance Indicators (KPI) in product development

4.2.2. DYNAMIC “PREMIUM PRESSURE SEAL - PPS“

After this approach, dealing with the sustainability aspects of „cradle-to-gate“ (Scope 1-3), i.e. all the aspects seal manufacturers can influence, focus should also be directed on energy saving during the use phase. The contribution to sustainability where customers benefit from savings in monetary CO_2-credits resulting from friction reductions is designated as “handprint.”

Figure 5 shows the result of a test, during which at constant speed, the pressure to be sealed is increased and the friction caused by the seal is measured: the PPS using a slightly shorter and thus less pressure-responsive sealing lip and inverse sealing edge profile shows significantly lower friction compared to the other sealing rings.

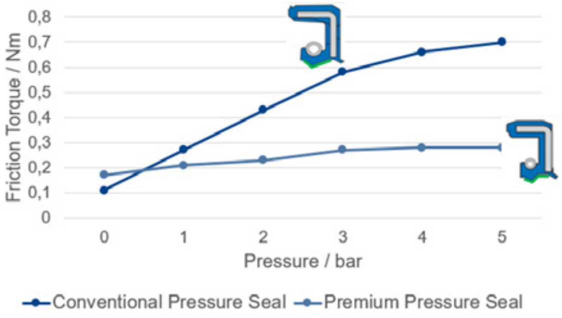


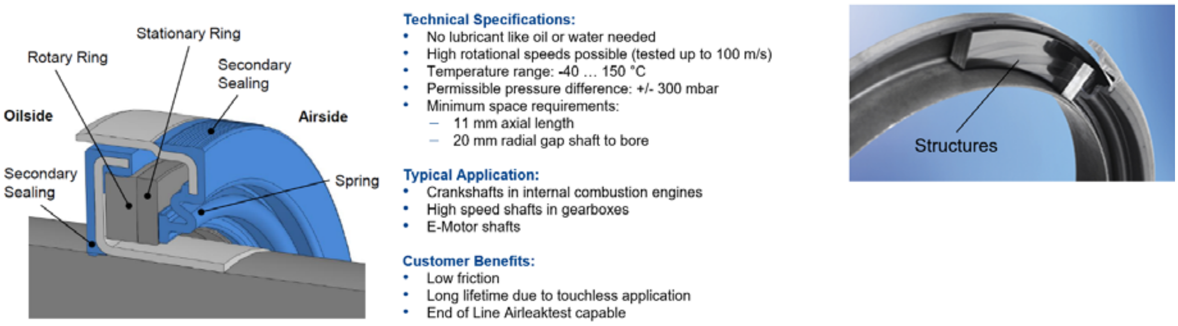
Figure 3: Friction of the different solutions in comparison

A direct comparison with the standard radial shaft seal shows that a PPS-Simmerring® for a 25mm shaft in a hydrostatic drive unit at 3 bar and 4,000 min^{-1} saves 160 kWh/year at 2,000 operation hours, corresponding to 64.2 kg of CO_2 for the German energy mix of 2019. In continuous operation (8,760 hours) PPS-Simmerring® would correspond to 700.8 kWh/year or approx. 281 kg of CO_2/year for the German energy mix of 2019. Approx. 1.3 million PPS are installed annually. At 2,000 operating hours, more than 200 GWh of energy or 55,000 tons of CO_2 respectively 80,200 tons of CO_2 are saved using a greenhouse gas intensity of a total electricity generation in the EU27 in 2019 of 275 g of $CO_{2eq/}$kWh and in Germany of 401 g of $CO_{2eq/}$kWh.

4.2.3. FRICTION-OPTIMIZED, GAS-LUBRICATED MECHANICAL SEAL

The Levitex® gas-lubricated mechanical seal reduces the seal friction at the rear crankshaft end of the internal combustion engines by around 90%, resulting in CO_2-savings of 0.5 - 1.0 grams per kilometer driven [79].

In operation, sliding rings and mating rings both sliding on each other are separated by means of gas grooves, i.e. aerodynamically effective structures on the sealing surface of the mating ring (see Figure 4). Cross-sectionally viewed, the gas groove is designed decreasingly into flow direction. It is only a few micrometers deep and opens exclusively to the air side. When rotating, air in the gas groove drags against a sealing dam. The resulting drag pressure separates the sealing surfaces and the seal runs largely without friction. Merely shear stress occurring in the air film causes friction losses [80, 81]. Compared to a standard PTFE crankshaft seal [82], this friction-optimized mechanical seal reduces friction by 0.5 to 1.0 g of CO_2/km in a 1.6-liter passenger car with dual clutch.



Technical Specifications:
- No lubricant like oil or water needed
- High rotational speeds possible (tested up to 100 m/s)
- Temperature range: -40 … 150 °C
- Permissible pressure difference: +/- 300 mbar
- Minimum space requirements:
  - 11 mm axial length
  - 20 mm radial gap shaft to bore

Typical Application:
- Crankshafts in internal combustion engines
- High speed shafts in gearboxes
- E-Motor shafts

Customer Benefits:
- Low friction
- Long lifetime due to touchless application
- End of Line Airleaktest capable

Figure 4: Gas-lubricated mechanical seal Levitex® in a sectional view

The examples below assume a conservative saving of 0.5 g of CO$_2$/km:

a. at an average annual driving distance of 15,000 km/year and a vehicle with one million seals installed, the savings amount to approximately 7,500 t of CO$_2$/year.
b. assuming an average vehicle life in the EU of 160,109 km for gasoline vehicles and 208,476 km for diesel vehicles [83], the cumulative savings per seal over the vehicle lifecycle amount to approximately 80 kg of CO$_2$ or respectively 104 kg of CO$_2$.

4.2.4. MONETARY CO$_2$-VALUE

Additional costs for tribological innovations mitigating CO$_2$-emissions must be considered as an investment in climate-neutral products and compared to a monetary CO$_2$-benefit. It is still unclear how the "CO$_2$-price" is divided up between component manufacturers, OEMs and/or end customers. Following, CO$_2$-savings achieved through state-of-the-art sealing technology are converted into CO$_2$-prices assuming 50 €/tCO$_{2eq}$ (see also chapter 3.2).

The calculated, monetary CO$_2$-value provides an indication of whether a tribological solution developed to improve the CO$_2$-footprint can achieve future market penetration, because an improved CO$_2$-footprint in itself does not represent a technical requirement for functionality, but offers extra benefits whose additional costs are valorized through CO$_2$-pricing. Before assessing monetary CO$_2$ values, it must be specifically clarified where they are accounted for:

» at the product manufacturer or

» at the end consumer via effectively lower energy or fuel costs.

Alternatively, the acquisition of a CO$_2$-emission right could be more favorable. Comparing the monetary CO$_2$-value in Table 9 with the actual energy costs saved impressively shows that today's CO$_2$-value is set far too low.

If the levy of €95 per gram of CO$_2$ and kilometer mentioned in Chapter 4.1 is taken as a basis, the additional savings amount to between € 47.50 and € 95 per vehicle assuming, that the vehicle fleet on average exceeds the current limit of 95 g of CO$_2$/km.

4.3. ESTIMATION OF THE GLOBAL ENERGY CONSUMPTION OF ROLLING BEARINGS

Rolling bearings transmit forces between surfaces moving in relation to each other and are among the most important machine elements. They prove to be reliable and are designed for a long service life. The about 8 billion electric motors in operation in the EU consume almost 50% of the electricity generated by the EU [84]. IEA estimated that electric motors consume 43 - 46% of the total global electrical energy [85, 86]. Of this share, 20 - 30% can be saved [87]. Electrified drive concepts increasingly use rolling bearings. The reduction of bearing friction in rolling bearing translates into range extension. High motor speeds and minimized bearing friction allow for increasing the efficiency of electric motors, whereby the proportion of bearing friction gains in importance with increasing speed.

However, no extensive studies exist describing the benefits of energy-efficient components over their complete life cycle. Although there are general guidelines covering production and transport [88, 89, 90], only scarce research is available

Table 9: The monetary value of CO$_2$-reduction by means of tribological measures (for 50 €/tCO$_{2eq}$) or actual energy costs saved

Sealing type	Marginal conditions	CO$_2$-savings [kg CO$_2$]	Monetary CO$_2$-value	Energy costs (0,3 €/kWh or 2 €/l fuel)
PPS-Simmerring	Hydrostatic drive unit, energy mix, Germany	64,2 (2.000 h/p.a.)	3,21 €/p.a.	48,- €/p.a.
		281 (7.860 h/p.a.)	14,05 €/p.a.	210,24 €/p.a.
Friction-optimized, gas-lubricated mechanical seal	Average life cycle of 160.109 km for gasoline and 208.476 km for diesel vehicle	80 kg (gasoline)/ 104 kg (diesel) per seal	4 € or. 5,20 €	69,- € or 76,4 €

and capable of shedding light on the carbon footprint during the remaining service life, i.e. the time period the component is in use, or the potential energy consumption required for disposal or recycling.

Various studies have been published on the calculation of global energy consumption [5] or on the energy consumption of individual industrial sectors, such as mining [91], the paper industry [92] or global CO_2-emissions from vehicles [6,93]. Authors of these studies defined an average proxy for each respective industry sector, for example an average car, and calculated the emissions of the sector based on this proxy. Furthermore, they could determine the potential effect of CO_2-savings of novel technologies by calculating the energy losses of the respective application.

Thorough studies on the contribution of specific but widely used components to global energy emissions have not yet been conducted. Rolling bearings are used in almost all types of machines. However, due to their high efficiency, their energy consumption is usually not focus of optimization (bearings are also designated as „antifriction bearings“). Nevertheless, because of the huge number of bearings used, their total consumption must not be neglected. In recent years, many energy-efficient bearings have been developed that feature specific designs or new materials to reduce losses without sacrificing load-bearing capacity. The effect of these changes on global energy consumption has not yet been quantified.

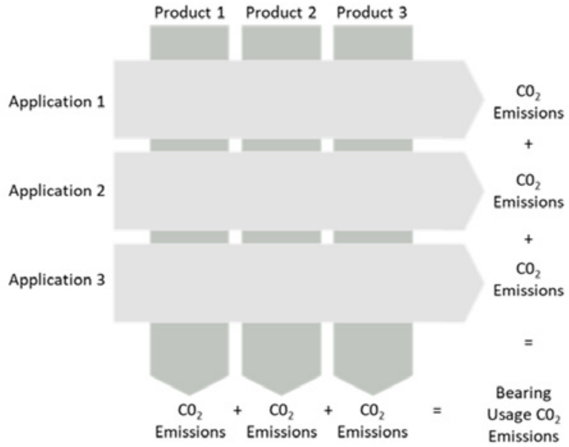


Figure 5: Comparison of the product-based with application-based approach.

Two feasible approaches, supposedly yielding similar results (Fig. 5), are available to calculate the total energy loss of rolling bearings during their operation. For the product-based approach, an ensemble of representative operating conditions is defined for a specific bearing type and the energy loss of each bearing type is determined using up-to-date calculation methods. Subsequently, the calculation results can be related to global sales figures to estimate the global emissions of a type.

The other application-based approach by Holmberg et al. [5, 6, 94] examines component by component the energy loss of a proxy application in a specific application area until the energy consumption of the rolling bearings can be estimated. However, the large scope and diversity of industrial applications and designs make this approach cumbersome. Although easy to apply in large industrial sectors, such as automotive, aerospace, wind energy, mining, or paper industry, for an accurate assessment, however, many other sectors should be incorporated. As this approach is very time consuming, it is not part of this study.

Only recently, a method using the product-based approach for estimating energy losses of rolling bearings has been presented [94]. The authors of this study demonstrate the influence of friction calculation methods on the results and the conditions under which the effect of friction-optimized designs could be quantified. Based on the findings of Bakolas [94], the authors calculated the global energy consumption of all catalog bearings using two different parameters.

In recent years, numerous bearing manufacturers have introduced bearings with various different internal designs aiming to reduce friction. Meanwhile, they have also presented improved calculation methods based on theoretical models for determining the frictional energy of bearings, both as catalog methods (SKF) [95] and also as specialized computer programs (SCHAEFFLER) [96]. However, these new calculation methods take into account significantly more factors affecting friction. They incorporate internal design either implicitly, as in catalog methods, or explicitly, as in the framework of computer programs. For the reasons given in [94], this study only uses the Schaeffler analysis method.

Schaeffler makes its friction model available in the form of the Bearinx Easy Friction computer program. This model relies on physical algorithms taking into account load, bearing ring tilt, lubricant viscosity, temperature, exact internal bearing geometry and bearing clearance. This model has been validated by a series of experiments and relies on the frictional force of each contact point within the bearing, generated by the lubricant shear and the friction between roughness peaks [96].

$$F_{sl} = \lambda \cdot F_{sl,asp} + (1 - \lambda) \cdot F_{sl,fl} \qquad (1)$$

with the dynamic frictional force F_{sl}, the dynamic frictional force of the roughness peak contacts $F_{sl,asp}$, the dynamic frictional force of the lubricant shear $F_{sl,fl}$ and the load-bearing component λ of the roughness peaks.

The specific frictional force of a surface element ΔA and the local frictional velocity u_s ultimately results in:

$$q = \frac{|F_{sl} \cdot u_{sl}|}{\Delta A} \qquad (2)$$

The total of specific friction losses on bearing contact surfaces yields the total friction loss. The product-based approach shall define an ensemble of operating conditions applicable to all bearing types. Standard ISO281 [97] mostly refers to rolling bearing life cycles. Therefore, it does not offer any guidance. Standard ISO/TS 16281 [98] provides a set of reference geometries useful to create reference types for the calculation.

Standard ISO15312 [99] dealing with the thermal reference speed provides the only source for specific operating conditions. Accordingly, the reference conditions stated in this standard predominantly rely on the operating conditions of the most commonly used bearing types and sizes. Since it includes a method for calculating friction losses in bearings, this standard is suitable for the present study. The operating conditions are selected in such a way that a bearing experiences an increase in temperature of 50°C (from 20°C to 70°C) in an oil bath lubrication, if the oil features an operating oil viscosity of 12mm²/s at 70°C. The operating conditions of this bearing are summarized in Table 10.

In a ball bearing, as shown in Fig. 6, tribosystems (frictional contacts) form the contacts between balls, raceways and cage, and, in addition, they are the sealing contact. Since the standard requires oil bath lubrication, which implies seal-free operation, the influence of the seal can be neglected. By choice of lubrication, the standard seems to ignore all rolling bearings which are typically lubricated with grease. It is the objective of this study to propose a generally applicable

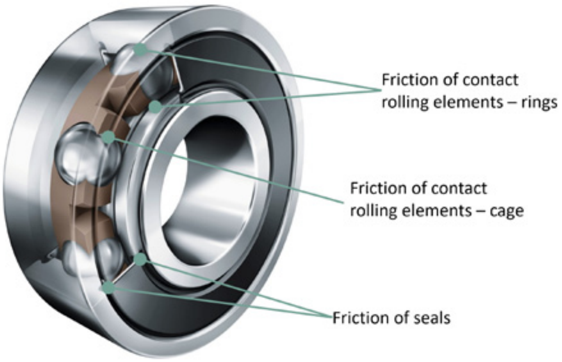


Figure 6: Frictional contacts in a typical radial deep groove ball bearing.

Tabelle 10: Operating conditions

	ISO 15312 Approach	Lh10 Approach
Bearing reference temperature	70°C	70°C
Radial reference load	5% C_{0r}	Calculated from nominal life cycle
Speed	Thermal reference speed according to ISO 15312	50% of thermal reference speed according to ISO 15312
Lubricant viscosity at 70°C	12 mm²/s	12 mm²/s
Type of lubrication	Oil bath	Oil bath
Hole diameter	< 1000mm	< 1000mm
Bearing clearance	N (ISO 5753-1)	N (ISO 5753-1)
Bearing axis	horizontal	horizontal
Stationary ring	Outer ring	Outer ring

method based on existing standards for the calculation of energy losses. That is why these standards also specify the estimates to be calculated. However, they predict significantly lower friction for grease-lubricated bearings compared to oil-lubricated bearings. Seals offset this lower friction, so that the two opposing effects level the friction of grease-lubricated and oil-lubricated bearings at the same order of magnitude. The estimates presented in Table 9 are therefore acceptable.

Speed is the only operating condition lacking verification. An examination of the bearing catalogs of various manufacturers shows that thermal reference speeds can vary immensely. This is due to (a) the individual internal bearing design and (b) to the method used to calculate friction losses. Hence, a set of speeds must be selected to evaluate the energy losses of all bearings. This study uses the reference speeds according to the ISO15312 calculation method.

The time during which energy losses occur is another important variable for the calculation of energy losses. This study assumes a life of 5,500 hours for all bearings regardless of their type and dimension. This number seems to be a good compromise between the short life of small bearings, typically running for 1,000 - 2,000 hours, and larger bearings, typically reaching or even exceeding 40,000 - 50,000 operating hours.

The operating conditions defined in ISO 15312 correspond to rolling bearings under light load and operating at very high speeds. Such high speeds increase the influence of centrifugal forces. The effect may be rather insignificant for ball bearings, but becomes the driving factor especially for roller bearings. In addition, churning losses are also proportional to the operating speed, which means that using such a condition leads to an overestimation. Therefore, an alternative set of operating conditions was chosen. Since the bearing life has already been prescribed, the operating load was selected for a nominal life of each bearing equivalent to 5,500 hours. In addition, the operating speed was set at 50% of the thermal reference speed to better match the speed in normal bearing operation. This set of conditions was designated as the Lh10 approach.

The frictional energy of most catalog bearing types was determined for both operating conditions. Table 11 shows the bearing types examined in this study together with their representative series.

Table 11: Bearings examined in the study

Type	Series	Type	Series
Deep groove ball bearing	62	**Cylindrical roller bearing**	NU3
Angular ball bearing	72	**Taper roller bearing**	303
Four-point bearing	QJ3	**Spherical roller bearings**	222
Self-aligning ball bearing	22	**Needle bearing**	NA49
Axial cylindrical roller bearing	812	**Axial spherical roller bearing**	294

In order to estimate energy losses of bearings during their projected service life, a number of bearings sold worldwide and their distribution in different sizes had to be assessed. Using data available on the magnitude of the bearing market and prices specified by various manufacturers in 2019, the distribution of bearings sold was determined using an iteration process. First, a statistical distribution was selected to allocate the sales per bearing size. Based on the price information, the statistical distribution of bearings sold was determined. Depending on the bearing type, an estimate was calculated regarding the final distribution of the units sold. The procedure was reiterated until the statistical distribution of sold bearings for each bearing type met the expectations. The statistical distribution of grooved ball bearings sold is shown in Figure 7.

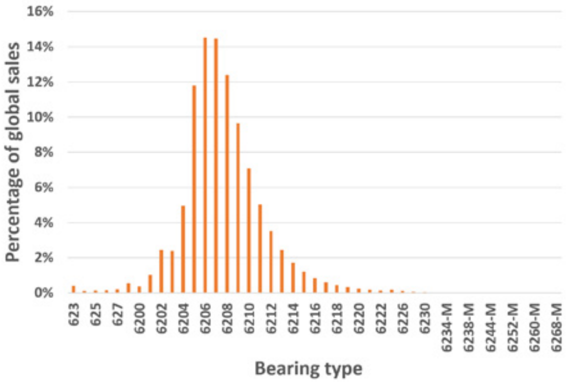


Figure 7: Percentage of bearing sales per bearing size

Figure 8 depicts a comparison of the results that friction calculations yielded. As expected, the friction force predicted by the ISO15312 approach exceeds the friction force of the Lh10 approach. Causes for this difference can be attributed to the higher speeds used by the ISO-approach, which in turn lead to higher energy losses.

There is another reason why the high speeds of the ISO-approach negatively impact energy losses in bearings. Churning losses also contribute to frictional losses and ISO 15312 prescribes oil bath lubrication immersing half of the lower rolling element in oil, proving that churning losses must not be neglected. Figure 9 shows the different results in applications where churning losses were neglected. Quite obviously, such losses can amount to 25% - 30% of the total friction losses, although this percentage varies distinctly depending on the bearing type.

The first conclusion drawn from the result that ball bearings cause the lion share of all energy losses and attain 50% of the total losses was to be expected given the size of the ball bearing market. Depending on the approach, needle bearings add another about 20% - 30% of the losses.

Ball bearings seem to be more affected by churning losses[26] than any other type of rolling bearing. This could stem from the thermal reference speed of ball bearings being typically higher than that of roller bearings. Since churning losses are proportional to speed, ball bearings are more affected by churning due to the selected operating conditions.

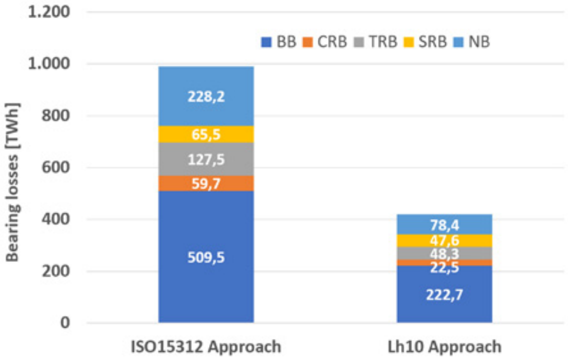


Figure 8: Global energy losses of rolling bearings

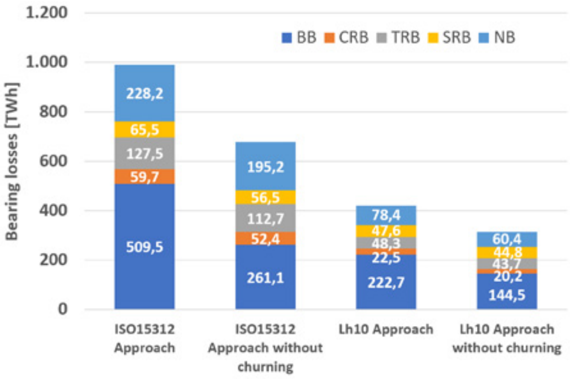


Figure 9: Influence of „churning“ on global energy losses in bearings

As a major benefit of such results, manufacturers and users of rolling bearings can evaluate the impact of new friction-optimized designs on energy consumption. Focus on such designs are the contacts between rolling elements and raceways or cages. Reducing roughness is an obvious measure to reduce friction. Furthermore, the osculation of the inner and outer rings significantly affects friction by reducing contact area and thus micro-slip in the contact. Specific cage designs and materials can also have a large impact on bearing friction. The number of rolling elements also affects friction for the obvious reason that it determines the number of frictional contacts. The use of bearings with ceramic rolling elements has also demonstrated the positive effects different material pairings have on friction. Finally, surface coatings can significantly reduce friction, which, in addition to their application in bearings, must have appropriate rollover resistance and wear resistance [100].

4.3.1. POTENTIAL CO_2-SAVINGS THROUGH ROLLING BEARINGS

Calculations by Bakolas et al [94] yielded that annual energy savings resulting from the use of friction-optimized standard ball bearings could amount to up to 90 TWh per year [94]. Assuming a German market share in the global ball bearing business of around 7% [101], this would translate into energy savings of 6.2 TWh per year.

With an average emission factor in Germany for an energy generation of 0.401 $kgCO_{2eq/}kWh$ in 2019, emission savings for Germany would be

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[26] There is a software CoDaC available from the professors Sauer and Schwarze in order to estimate churning losses.

2.486 megatons of CO_{2eq} per year. At a price of 50 €/$tCO_{2eq,}$ the monetary savings in CO_2-certificates for Germany then amount to 124 million € per year.

The average global carbon intensity of electricity generated is 0.475 kg CO_2/kWh [102]. From the 90 TWh saved, friction-optimized rolling bearings deliver a global mitigation of 42.750 megatons CO_{2eq} per year.

The aforementioned energy savings for Germany of 6.2 TWh in conjunction with an average electricity price for industrial customers of €0.18/kWh and €0.22/kWh for commercial customers result in economic savings of €1.11 and €1.36 billion per year – significantly more important than the monetary savings in form of CO_2-certificates. However, the total savings generated by low-friction standard bearings are composed of the monetary values of mitigated energy consumption and CO_2-certificates saved.

4.3.2. FRICTION REDUCTIONS IN ROLLING BEARING ELEMENTS USED IN MOBILITY

Rolling bearings play a key role in the safety and efficiency of future vehicles (see chapter 4.1). In commercial vehicles, for example, they offer great saving potentials - both in conventional and electrified drive systems. When developing innovative bearing solutions for efficient powertrains of light and particularly heavy commercial vehicles, focus is not only on minimizing friction, but also on reducing wear and weight in order to lower embedded CO_2 from resource consumption. The Schaeffler Group has developed a wheel bearing unit reducing frictional power which is specifically designed for commercial vehicles. In a 13-ton rear axle, this results in 56% less friction, ultimately yielding friction loss power savings of up to 600 W. For a commercial vehicle with an electric range of 500 km, this would translate into energy savings of up to 11 kWh for each charging process, thus enabling a significant range extension at identical battery size. Alternatively, the same range can be achieved with fewer resources and at lower costs [103].

Another bearing innovation with significant impact on sustainability is a high-performance ball bearing featuring an integrated centrifugal disc. This worldwide unique bearing of the Schaeffler Group replaces the rubber seals otherwise firmly attached to the outer sides of sealed bearings by a specifically designed centrifugal disc located inside the inner ring. This disc prevents contaminations similar to conventional bearing seals. However, since the disc can rotate freely, this bearing generates around 80% less friction compared to bearings using seals. The result is a CO_2-reduction of up to 0.3 g per kilometer and vehicle. Reduced losses of up to 30 W per bearing can also increase the range of electric vehicles by up to 1%. In addition, centrifugal disc bearings last significantly longer: compared with open-style bearings, the service life is increased by a factor of up to ten, ultimately yielding sustainable resource conservation. Compared with conventionally sealed ball bearings, the service life cycle doubles, allowing both bearings and gears to be dimensioned smaller in the future, which in turn saves material and weight [103].

4.4. ENERGY LOSSES IN HYDRAULIC SYSTEMS

Hydraulic fluids account for 9 - 12% of the total lubricant volume. Compared to electric drives, hydraulic systems are a powerful mechanical solution for moving components and machines. Highly shear-stable multigrade hydraulic fluids with a high viscosity index[27] (VI) have proven to be most effective to increasing productivity and reducing energy consumption. For excavators in particular, numerous field trials have demonstrated improvements over monograde oils. That is why major global manufacturers of construction equipment use such hydraulic fluids for initial fillings and prescribe their use for aftermarket service. In addition to the increase in productivity, the significantly extended oil change intervals due to longer service life and the elimination of oil changes between summer and winter make a significant difference. Despite all these benefits, most construction machines still use monograde oils.

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[27] The viscosity index (VI) measures the viscosity stability with increasing oil temperature. For any lubricant, the viscosity decreases by powers of ten as the oil temperature rises. A high VI means that the reduction in viscosity with increasing oil temperature is lower.

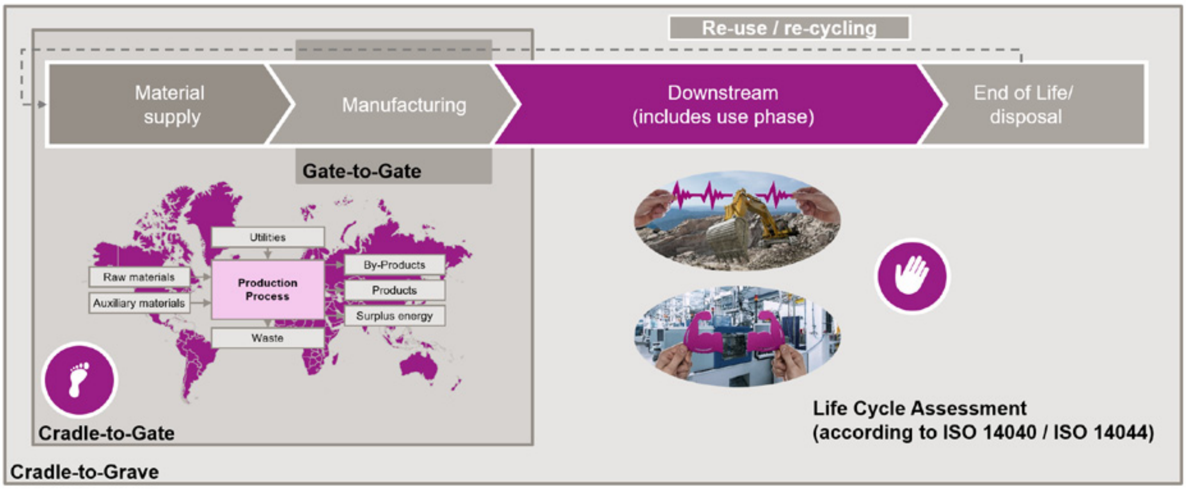

Figure 10: The assessment of the whole life cycle provides a holistic view on emissions [104]

The following life cycle analysis (LCA) according to ISO 14040/14044 describes two applications of energy-efficient hydraulic fluids using the example of mobile machinery and stationary production machinery. Figure 10 depicts the oil life cycle, whose CO_2-emissions are observed in various areas.

4.4.1. APPLICATION CASE EXCAVATOR

A conventional monograde hydraulic fluid HLP 46 serves as comparison to determine the CO_2-emissions saved when using a highly shear-stable multigrade hydraulic fluid with a high viscosity index (> 180) in a life cycle analysis. The high viscosity index enables lowering the viscosity grade while maintaining the viscosity at 100 °C compared to the monograde oil HLP 46. That is why the thinner-viscosity HVLP 32 was also considered in addition to the monograde oil HVLP 46.

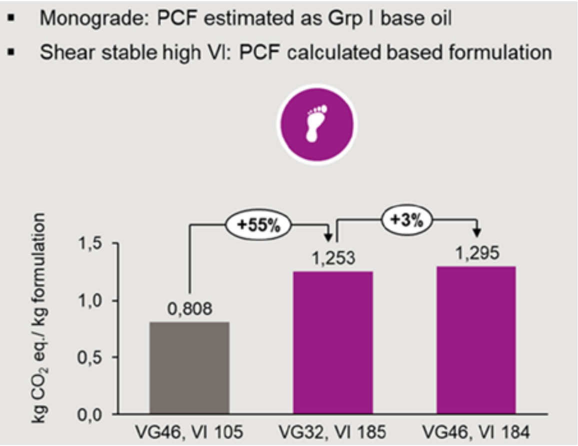

Figure 11: CO_2-footprint of hydraulic fluids (cradle-to-gate[28]; manufacturing phase) [104].

The CO_2-footprint of monograde oil HLP 46 is significantly lower in production than for both HVLP formulations because the used VI-improver yields a higher CO_2-footprint compared to the base oil of monograde oil HLP 46 (see Figure 11). Due to a higher content of VI-improvers, the CO_2-footprint of HVLP ISO 46 is slightly higher than that of HVLP 32.

For the application phase, based on statistically evaluated field tests, the work performed was used as a benchmark, i.e. one million tons of mass transported by the excavator type ZX 290, manufactured by Hitachi. The required amount of fuel and hydraulic fluid including disposal was determined for each fluid.

The oil life for monograde fluid HLP 46 was set at the 2,000 hours typically specified by excavator manufacturers, and at 4,500 hours each for HVLP 32 and HVLP 46 multigrade oils, reducing waste stream and resource requirements. Hydraulic fluids optimized for energy efficiency can save 8% or 13.6 t of CO_{2eq} with an HVLP 46, and 12% or 21.1 t of CO_{2eq} with an HVLP 32 with further lowered viscosity (See Figure 12). The significant effect of viscometric measures can be explained by the large phase of 99.5-99.7% in the total CO_{2eq}-emissions.

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[28] Cradle-to-gate only evaluates a product until it leaves the factory gate and before it is transported to the consumer/user.

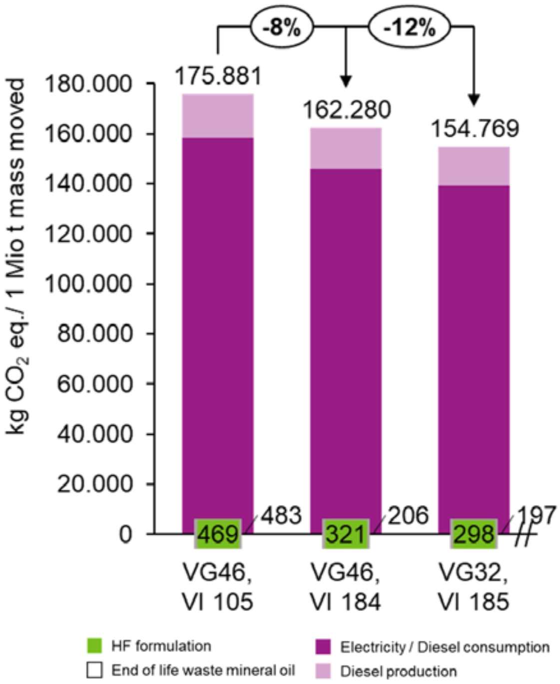
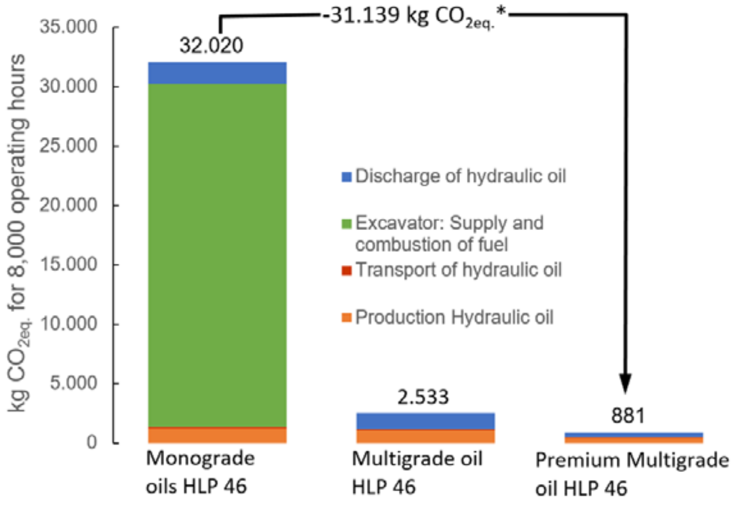


Figure 12: Service life analysis for the excavator application for the reference oil HLP 46 and the two highly shear-stable HVLP 32 and HVLP 46 [104]

In a large-scale excavator field test, the carbon footprint was drawn up for the hydraulic fluids used [105]. Environmental properties and costs of three mineral oil-based hydraulic lubricants were individually analyzed over the entire life cycle. Three different hydraulic fluids were used (See Figure 13): HLP 46 monograde oil, HVLP 46 multigrade oil and HVLP 46 premium multigrade oil, all with the objective to gain understanding of the factors influencing the carbon footprint starting from raw materials to production, over use and eventually disposal. The field test ran for 8,000 hours. Fig. 13 summarizes the savings potential, the premium multigrade hydraulic oil can offer. CO_2-emissions generated by diesel fuel consumption dominate the use phase. For a better overview: the monograde oil HLP46 only contains additional diesel consumption compared with the most efficient oil “Premium HVLP 46” (multigrade oil). Taking only one excavator for 8,000 operating hours, the “Premium Multigrade Oil HVLP 46” yields savings of 31.1 tons of $CO_{2eq.}$ In other words, the monetary value of the diesel saved exceeds the additional filling costs with “Premium Multigrade Oil HVLP 46” by powers of ten. The savings of 31.1 tons of CO_{2eq} currently correspond to approx. 3,100 € in CO_2-certificates. Major benefit of this oil compared to “Standard HVLP 46” is the significantly longer service life reducing resource consumption and waste streams.

The most striking result of the findings in Figure 13 is that the use phase clearly dominates the product carbon footprint[29] (PCF) - a reduction in



* of which 29.000 kg $CO_{2eq.}$ came from combustion of 9,600 L Diesel.

Figure 13: Life cycle analysis „hydraulic fluids“ - eco-efficiency analysis by FUCHS and BASF. Differential representation: Fuel dominates CO2-emissions with >99% [105]

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[29] The PCF records of CO_2- and greenhouse gas emissions of a product or service in the individual phases of the product life cycle, such as raw materials, production, transport, use and disposal, i.e. over the entire life cycle (cradle-to-grave).

friction during the use phase can more than compensate for the monetary investment in low-friction designs and high-performance lubricants.

4.4.2. Application case injection molding machine

Based on a long-term test with a KraussMaffei GX 550-4300 injection molding machine, a life cycle analysis was conducted for 8,100 operating hours [106]. The monograde fluid HLP 46 was compared with the HVLP 32 described above. The relevant factors for the service life were the power consumption and the oil disposal. The service life was assumed to be 8,100 hours for both, although the HVLP allows a significantly longer service life. In the final result, Fig. 14 illustrates efficiency increases of approx. 3%, with a range of 2.4% to 4.4% depending on the operating cycle. In the lifetime analysis, this resulted in CO_{2eq}-savings of 1 to 5%.

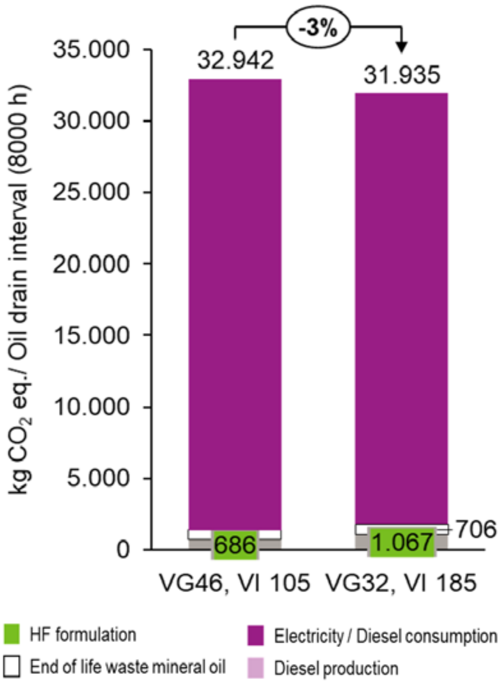

Figure 14: Service life analysis for HLP 46 monograde oil and a highly shear-stable HVLP 32 with very high viscosity index in injection molding machine application over 8,100 operating hours [104,106]

The CO_{2eq}-savings after 8,100 hours by HVLP32 compared to HPL46 amounts to 1.007 tons of $CO_{2eq.}$ (see Figure 14) with a monetary value based on EU ETS of approximately €90. On the other hand, HVLP32 saved about 1,600 kWh, whose monetary value is a multiple of current CO_2-certificates.

4.4.3. Potential, economic CO_2- and energy savings in hydraulic systems

Currently, only the purchase price of the hydraulic fluid is crucial. The results of both examples show that CO_{2eq}-emissions are clearly generated by energy losses during the use phase, thus making the CO_{2eq}-footprint of highly shear-stable multigrade hydraulic fluids with high viscosity index and their disposal less significant. The distinctive reductions in CO_{2eq} due to energy-efficient and highly shear-stable multigrade hydraulic fluids with high viscosity index justify the higher procurement costs through significant monetary savings in energy costs and costs saved for CO_2-certificates. Such efficient hydraulic fluids also provide backward compatibility for older, more inefficient machines, where they can unfold even greater energy consumption reduction and/or CO_2-mitigation potentials.

Generally, higher efficient hydraulic systems feature lower energy losses or significantly reduced power consumption and thus lower heat generation ultimately resulting in a lower operating temperature. Subsequently, stationary production equipment requires significantly less water for cooling. The lower heat dissipation makes for more comfortable operating conditions in warm environments. This not only reduces the risk of operating the system in a state of insufficient lubricant film thickness, which would force wear and the consumption of resources, but also reduces ageing of both oil and polymer seals. As a further consequence, the service life of oil and machine is improved and the risk of leakages is minimized. This significantly reduces costly repairs, e.g. due to oxidative deposits on control valves, which can lead to complete machine failure.

Examinations of injection molding machines from various manufacturers as well as other types of machines and equipment, such as presses, kneaders and machine tools have revealed that highly shear-stable multigrade hydraulic fluids can yield average savings of 3 - 10% [106, 107]. In stationary applications, virtually no efficient hydraulic fluids have been used to date, thus providing an additional savings potential of 1.3 TWh for stationary hydraulics.

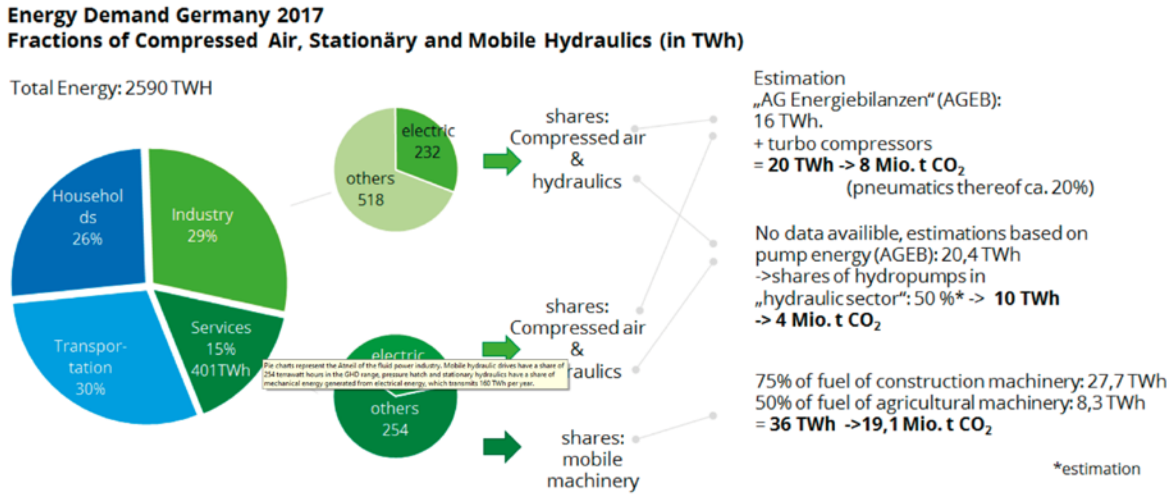

Figure 15: Proportionate energy demand of fluid technology and compressed air in hydraulics in Germany and the resulting CO_2-emissions [108]

In 2017, approximately 29.5 megatons of CO_2 were released from the operation of fluid power systems (see Figure 15) [108]. Mobile machines using large amounts of hydraulic energy for travel and work drives, consumed approx. 62 TWh of fuel in Germany [108]. The order of magnitude of the energy demand of machines and plants operated with fluid power systems lies in the higher double-digit TWh range, annually corresponding to about 10% of Germany's gross electricity consumption of 600 TWh (2017). In a variety of field tests with mobile construction machinery of different sizes and manufacturers [106, 109], the efficiency gain by switching to an energy-efficient hydraulic fluid, as described above, was assessed at an average of 10%. However, some mobile machinery already operates using efficient fluids, so only 80 % of the fuel consumption is taken as a basis. Since savings also apply to harvesters, but not to tractors making up the majority of agricultural machinery, the consumption of agricultural machinery is not taken into account. Ultimately, this results in a savings potential of 2.2 TWh for mobile machinery.

The study of ORNL [110] found, that 2008 fluid powered systems in USA consumed between 1.52 and 2.42 Quads[30] (1.60 to 2.55 ExaJoules) of energy producing between 259 and 317 megatons of CO_2, of which

a. mobile hydraulics consumes between 0.4 and 1.3 Quads/year producing between 26 and 92 megatons of CO_2,
b. industrial hydraulic equipment consumes approximately 1.1 Quads/year producing 196 megatons of CO_2 per year and
c. transportation of embedding hydraulic equipment in aerospace applications consumes approximately 0.02 Quads/year producing 1.7 megatons of CO_2.

The shares in 2008 of fluid powered systems in USA were 1.5 - 2.6% of 98.7 quads of primary energy consumption and 4.5 - 5.5% of the energy-related CO_2-emissions of 5.745 gigatons. Thus, the studies by ORNL and the German Federal Environmental Agency [108] revealed a comparable share of fluid power systems between 4.4% - 5.4% of total CO_2-emissions.

4.5. OPTIMIZED LUBRICANTS FOR FRICTION REDUCTION

With a sales volume of 225,000 tons, engine oils in Germany still represent by far the largest domestic sales quantity of the total 930,000 tons of lubricants sold in 2022.

In recent years, the reduction of friction and the increase efficiency has been the driving force behind the further development of engine oils.

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[30] Quad= Quadrillion (10^{15}) BTU. BTU is the abbreviation for British Thermal Unit(s). 1 quad = 1.0550559 Exajoules

A look at friction losses in gasoline engines can provide examples for optimization potentials, however, the figures may vary considerably depending on the engine design:

Piston group	25-30 %
Connection rod bearings	15-20 %
Crankshaft bearings	12-18 %
Cylinder head (valves + camshaft)	5-10 %
Pump losses	5-10 %
Auxiliary units	15-35 %

Overall, mechanical friction losses amount to about 15 - 20% of the engine performance. These figures were determined using electrically driven engine components in drag mode. The sum of all losses at each individual friction contact strongly depends on the operating conditions, ultimately yielding the total loss.

The tribocontacts mentioned here rely on different material pairings, surface pressures and contact geometries. When optimizing a lubricant towards increased energy efficiency, the focus will therefore be on the most significant loss points. For internal combustion engines, the following rough breakdown applies: 1/6 to 1/3 of the friction losses are located in the area of mixed friction and 2/3 in the area of liquid friction thus demonstrating the importance of viscosity as “adjusting screw“ for more consumption reduction.

4.5.1. RHEOLOGICAL APPROACHES TO FRICTION REDUCTION

The classical approach to increasing lubricant efficiency is therefore viscosity reduction. When interpreting viscosity as „internal friction“, it becomes quite clear why reducing viscosity offers important potentials. Reducing viscosity in hydrodynamic lubrication applications directly lowers power loss, but may lead to increased mixed friction and to increased wear at higher loads or lower speeds. The rheological parameters influencing elasto-hydrodynamic (EHD) and hydrodynamic friction are:

- Low viscosity (e.g. engine oil grades[31] SAE 0W-20, 0W-16, 0W-12)
- High viscosity index (160 to >200)
- Low shear viscosity HTHSV (e.g. < 2 mPa•s for passenger car engine oils)

High-temperature-high-shear viscosity (HTHSV) represents the essential viscosimetric parameter for improving fuel economy. In ASTM Standards D4683 and D4741, the dynamic viscosity is measured at 150°C and at a high shear rate of 10^6 s^{-1}. Ahead of the trend, viscosity-lowered SAE grades have long been specified in SAE J300:

SAE Grade	Kin. viscosity @ 100°C [mm^2/s]		HTHS viscosity @ 150°C [mPa•s]
SAE 20	≥ 6,9	< 9,3	≥ 2,6
SAE 16	≥ 6,1	< 8,2	≥ 2,3
SAE 12	≥ 5,0	< 7,1	≥ 2,0
SAE 8	≥ 4,0	< 6,1	≥ 1,7

Lowering the viscosity reduces the minimum lubricant film thickness, especially under shear gradient and for structurally viscous, non-Newtonian fluids. This results in two relationships: direct impact on frictional losses and increased wear rates in tribological systems. However, the lubricant film thickness not only depends on the shear viscosity, but also on other fluid parameters, e.g. the pressure-viscosity coefficient.

In addition to viscosity at a given temperature, the viscosity-pressure coefficient a describes the thickness of a hydrodynamic lubricating film [h_{min}] under high static pressures occurring in the lubrication gap. The viscosity of fluids displays a strong dependence on the pressure.

For the assessment of the hydrodynamic load-bearing capacity, the HTHS alone is insufficient, but $\alpha(T)$ must be considered as additional parameter [111]. As the pressure-viscosity coefficient a decreases, the temperature rises. This decrease, however, is less pronounced for synthetic esters as it is for hydrocarbons. Liquids with identical kinematic viscosity (V) can therefore pro-

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[31] Where will be the lower threshold for viscosity reduction? Firstly, the SAE 8 has a HTHS-viscosity (HTHS150°C) of >1.7 mPa•s, which is close to the dynamic viscosity of water with 1 mPa•s at 20°C. Secondly, the lower the viscosity, the lower the molar mass of the base oil molecule, and, in turn, the physical NOACK evaporation increases. Recently, a new viscosity grade SAE 4 with a HTHS viscosity of > 1.4 mPa•s has been proposed.

duce very different lubricant film thicknesses, which depend on

- pressure-viscosity coefficient (→ V(p) behavior)
- shear gradient (HTHSV)
- viscosity index (→ V(T) behavior).

When using synthetic esters or polyglycols, their tendency to have lower a-values (compared with hydrocarbons) can lead to a reduction in lubricant film thickness, which in turn is compensated at high oil temperatures by high viscosity indices.

However, increasing mixed friction and wear limit the viscosity reduction in a given tribological regime. When lowering the a-value, a material-based strategy must be provided, compensating for increased wear rates caused by a reduced lubrication gap height resulting from increased mixed friction. By using certain additives, however, the transition to mixed friction can be offset (within certain limits) thus alleviating the conflict of objectives, ultimately enabling wear reduction and lowering power loss.

In order to be able to push the viscosity limits even further, the perspective must be directed to the overall system, understood as the interaction of the design elements body - lubricant - counterbody.

Figure 16 clearly shows the impact of viscosity reduction on fuel consumption. Various base oil settings with identical additives were tested in a full vehicle (BMW 320d, engine: N47) according to the New European Driving Cycle (NEDC). Based on a SAE 10W-40 oil grade, a fuel consumption reduction of approx. 4% requires lowering the shear viscosity (HTHSV) by 1 mPa•s (or about three SAE viscosity classes). Lowering the HTHSV by 1 mPa•s from 5W-30 to 0W-12 reduces fuel consumption by another 2%. It is apparent that only reducing the viscosity would impose a design limit, i.e. further reduced consumption is only feasible through internal engine measures and adjusted additivation of the engine oil.

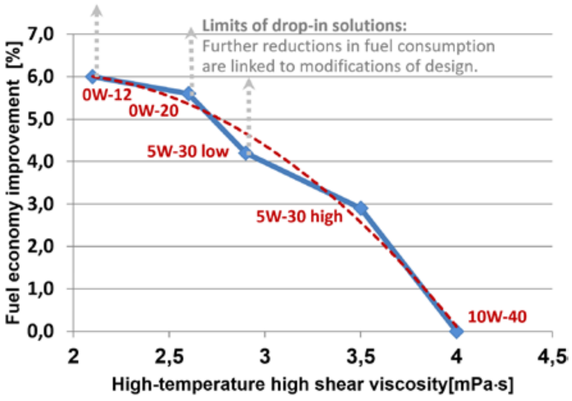

Figure 16: Fuel economy as a function of viscosity (HTHSV) with identical additivation - measurements according to NEDC, using a BMW 320d on the chassis dynamometer; engine: N47 [112]

In spite of the low friction level of modern low-viscosity engine oils, more fuel savings can be achieved: between 2% and 4% in WLTP (World-wide harmonized Light Vehicles Test Procedure) compared with an SAE 0W-20 oil are considered realistic by using state-of-the-art lubrication technologies [113]. However, further potentials of consumption-optimized engine oils are specific to each individual engine.

4.5.2. CONTRIBUTION OF ENGINE OILS TO THE CARBON FOOTPRINT

The average CO_2-emissions of all new vehicles in the EU28 as of 2019 was 122.3 g CO_2/km. Driving 30,000 km requires an oil change, emits 3,669 kg of CO_2 and consumes 10 liters of engine oil. Using a higher-grade engine oil allows for an oil change interval of 30,000 km. Engine oils with very low viscosity and high viscosity index can save >1% fuel compared to a 0W-30 engine oil. Engine oils with particularly thin viscosity and high viscosity index allow even more savings. For a mileage of 30,000 km, CO_2-emissions can be reduced by 36.69 kg CO_2, assuming a fuel saving of 1% while doubling the oil change interval for 5 liters of engine oil (~4 kg).

According to a study conducted by NESTE Oyj [114], the CO_2-footprint of engine oil production from fossil resources (Group I-III, PAO, GTL) amounts to 1.63 kg CO_{2eq}/kg plus 3.2 kgCO_{2eq}/kg, if thermally recycled. These values are to be regarded as indications only; in individual cases, commercially available engine oils may deviate considerably.

Based on the figures listed, a doubled oil change interval for 5 liters of engine oil (~4 kg) per 30,000 km results in savings of about 6.52 kgCO_{2eq} (without thermal recycling). Using an engine oil with 2% fuel saving and doubling the oil change interval can thus save an average of min. 79.9 kgCO_2 over 30,000 km.

The 2% fuel savings assumed here correspond to 73.4 kg of CO_2-emissions. When using the emission factors for fuels, this translates into a total savings of 31.6 l gasoline or 27.0 l diesel. These figures are to be multiplied by the local fuel prices. On top comes the monetary CO_2-value of low-friction engine oils with extended oil change intervals (5 l, ~4 kg) and 2% FE), which is calculated at >€7.34 (excluding thermal recycling), assuming a CO_2-price in the EU-ETS of €100/t CO_2. Wages and secondary savings are not considered here. Attraction and market penetration of fuel-efficient engine oils with extended operating times depend largely on the monetary value of the fuel quantity saved and the respective CO_2-pricing. Currently, direct fuel costs are dominant. The monetary value of the associated CO_2-emissions is therefore less significant.

On a societal level, the total reduction of CO_2-emissions, generated by 342 million passenger cars (EU, EFTA, UK) in 2019 with a mileage of 15,000 km p.a., would translate into savings of minimum 12.5 megatons of CO_2-emissions, when assuming fuel savings of 2% by viscometric measures only.

Since the research cluster „Low Friction Power Train“ [74] of FVA/FVV did not take into account the effects of viscometric measures of lubricants with low viscosity and/or high viscosity index, the maximum possible reduction [74] of fuel consumption of 12.1 % (or 0.945 l/100km, the several measures for friction reduction in vehicles (see chapter 4.1) determined by the research cluster need to be added on top.

5. CONCLUSIONS

Friction reduction and longevity are „industrial strategies for defossilization“ or „societal CO_2-sequestration” because CO_{2eq}-savings through tribology occur anywhere and anytime, since less energy generation is required to move machine elements upstream. Tribology can annually deliver global medium- to long-term carbon dioxide mitigations of 3.9 - 11.3 gigatons $CO_{2eq.}$ during the use phase (downstream). Therefore, tribological measures should be classified as “negative emission technologies” (NET) because they generate less CO_2 during operation and avoid emissions as easy to implement drop-in solutions. Friction, as practically irreversible loss, is proportional to carbon dioxide emissions. Technologies for friction mitigation are available and their implementation to mitigate CO_2 is an objective which is easy to achieve (low hanging fruits). Technologies for service life extension and wear protection are also available and can significantly reduce the hunger for material with its embedded CO_2 footprint.

Hence, tribology offers both technical and political solutions for the avoidance of CO_2 from the atmosphere - CO_2 saved in the use phase (downstream) does not have to be generated in the extraction phase (upstream)! That is why politics and society should direct their focus on the offerings of tribology and demand their implementation.

Prosperity and population growth fuel the hunger for energy and materials. Consequently, there is no alternative to embracing the offerings of tribology in order to mitigate energy demand and increase longevity, as it is essential to generate more value for everyone from the free resources nature is offering.

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