Climate and Monetary Benefits of Tribology

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Abstract: The consequences of friction are abundantly present in today's world. Friction produced from any interacting surfaces in motion wastes energy. It is apparent that energy not consumed downstream does not need to be produced upstream - thus the energy being simply released into the environment. While friction can be employed resourcefully, too much of the force may prove detrimental to the products involved and can cause damage to their surfaces. This nuisance of wear generates waste and fuels material hunger, further straining limited resources. Any resource consumed has an embedded carbon footprint. The proper application of tribology, or the careful selection of lubricated surfaces to reduce the amount of friction, can be utilized to save CO_2 without losing functional values in use. Subsequently, this reduction would proportionally reduce wear on the surfaces involved - allowing for increased longevity of the products and goods involved. Taking both together, friction reduction and longevity help to limit or reduce CO_2 emissions by getting out more from the same amount of resources. Proper lubrication, condition monitoring, reparability or wear resistant materials/coatings all help to minimize friction and to extend longevity. This paper deals with the general question, what will be the monetary values for investments in reducing friction and extending longevity?

1. Introduction

The interplay of friction, wear, and lubrication known as tribology is an important, but hidden aspect of human activities. The growth in the human population and its wealth have significant implications for our resource demands on nature, including for future patterns of global consumption. If we are to avoid exceeding the limits of what Nature can provide while meeting the needs of the human population, consumption and production patterns must be fundamentally re-structured as well.

Friction and wear occur everywhere and anytime along the value chain. According to Holmberg and Erdemir [1] out of all total primary energy, 20% are absolutely lost due to friction. The total savings in Table 1 are based on a level of friction reduction of at least 40%.

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[1] K. Holmberg, A. Erdemir, The impact of tribology on energy use and CO_2 emission globally

Here comes the offers of tribology into play through longevity (resource efficiency and resource conservation) and friction reduction (energy efficiency). The cause-root relationship between friction and CO_2 emissions as well as between durability/ longevity and sustainability so far have not reached politics and society.

2. Relationship between CO_2 emissions and friction

With friction present in any mechanical system, wear on the engine would inevitably follow. As such, there would be less power available to move the machinery, thus requiring more oil-based lubricants needed in order to combat friction and run the equipment smoothly [2]. Consequently, the more energy the engine or any machine uses, the more CO_2 emissions are released into the atmosphere which negatively impacts the environment with climate damage. Operational costs also drastically increase as reduced efficiency hurts productive output.

8-24% of total primary energy consumption can be saved by reducing friction (see Table 1).

Irrespective of the usage of "green" energy production, savings through reducing friction helps anyhow either upstream (generation of energy) or downstream (use of energy). Positive flows from anthropogenic activities represent upstream GHG emissions to the atmosphere and negative flows are downstream GHG removals from the atmosphere. Friction reductions can help to save 2.3-4.5 gigatons of CO_2 p.a. [3], while longevity through wear protection and condition monitoring can save 1.7 to >6.8 gigatons of CO_{2eq} p.a. as indirect contribution to reducing CO_2 Emissions [4].

Table 1: Potentials of economical savings by reduced friction [3,4]

Study	**Year of publication**	**Savings on Energy**	
		in % of primary energy consumption	in EJ of primary energy consumption in 2017

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and in combustion engine and Electric Cars, Tribology International. 135 (2019) 389–396. https://www.sciencedirect.com/science/article/abs/pii/S0301679X19301446

[2] MicroTribo Dynamics, Automobile Engines, n.d., https://microtribodynamics.tamu.edu/tribology_intro/examples/engines.htm

[3] M. Woydt, The importance of tribology for reducing CO_2 emissions and for sustainability, WEAR, Vol. 474–475, 15 June 2021, 203768

[4] M. Woydt, Material efficiency through wear protection – The contribution of tribology for reducing CO_2 emissions, WEAR, Vol. 488–489, 15 January 2022, 204134

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. (global)	2012	**8.6 %**	—
A.R.P.A.-E (USA)	2017	**24 %**	24.1 EJ (out of 102.9 EJ)
Holmberg et al. (global)	2017	**8 %**	—

1 Exajoule (EJ)= 10^{18} Joules; A.S.M.E.= The American Society of Mechanical Engineers; 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.

3. Longevity and CO_2 emissions of material streams

Excessive wear on any object ultimately reduces its longevity and operational lifespan. Longevity has no connection to the technosphere of the circular economy, but the extension of the product life cycle consequently decouples material consumption from economic growth and reduces waste streams, as well as mitigates resource consumption and their CO_2 backpack. The extraction of resources and their further processing is inevitably associated with CO_2 emissions. A hypothetical doubling of the general service life through wear protection and condition monitoring saves approximately >9.0 gigatons of resources per year combined with an equivalent of 1.39-1.86 tons of CO_{2eq} per ton of resource [4]. These considerations are oriented on the sustainable development goals of the United Nations from Fall 2015.

The extracted resources flow into various applications. Each material category flows in individual proportions into mobility, machinery, equipment, installations, household appliances, etc., which contain tribosystems. Material flows in catalysts, packaging and static constructions are not related to tribology. Table 2 estimates the proportional $CO_{2eq.}$ emissions from material streams that enter in products containing or depending on tribosystems of any kind by multiplying the calculated emissions of metals/materials from Table 2 by an appropriate proportion of the metals/ materials used in mobility, machinery, equipment, installations, household appliances, etc., that contain or depend on the functionality of tribosystems [4]. Depending on the absolute amount of material stream considered, its portions allocated to tribology and assuming doubling the service life result in average savings of embedded 1.65 to 2.56 gigatons $CO_{2eq.}$ per year.

Table 2: Estimates of the $CO_{2eq.}$ emissions of material streams going into products containing tribosystems [4]

Primary metal or material	**Global, average residential time [years]**	**Calculated $CO_{2eq.}$ emissions of primary metals or materials [10^3 tons]**	**Portion with tribosystems or affected by these**	**Estimated $CO_{2eq.}$ emissions of material streams with tribo-systems [10^3 tons]**
Specialty metals				
Nd, Li, W, Mn, Si, Ti, Ni, Mg, Zn, Pb, Mo	—	>1,039,131	<70	727,307
Major engineering metals				
Copper	41	129,800-224,200	48	61,020-107,520
Aluminum	21.1	1,075,680	45	430,272
Steel (Iron)		>3,254,400	35-50	1,138,900-1,627,000
Subtotal	—	4,251,152	—	1,608,816-2,142,760
Non-metallic, engineering materials				
Bitumen	~20	27,000-67,500	95	25,650-64,125
Plastics		~1,224,000	30	367,200
Cement	>30	2,520,000-5,460,000	22-33*	554,400-1,801,800
Total	—	**9,270,011-12,344,911**		**3,304,749-5,125,224**

* Transportation infrastructure (roads, tracks, airports (taxiing and runways), ports)

From a socio-ecological perspective, friction reduction and longevity expansion help to double the utility value while consuming the same amount of resources resulting in an overall reduction in $CO_{2eq.}$ and GHG emissions.

4. Scope 4 - Avoided emissions

The economic balance sheet for investments in "low carb tribology" depends on the value of saved energy and/or CO_2, which are monetary valorized as savings.

The Greenhouse Gas (GHG) Protocol does not yet address avoided emissions, even the World Resources Institute emphasized in November 2013 scope 4 emissions [5] in a commentary to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC). The proposed definition was:

> “Avoided emissions are emission reductions that occur outside of a product’s life cycle or value chain, but as a result of the use of that product. Examples of products (goods and services) that avoid emissions include fuel-saving tires, energy-efficient ball-bearings etc. Other terms used to describe avoided emissions include climate positive, net-positive accounting and scope 4.”

This definition clearly includes “fuel-saving tires and energy-efficient ball-bearings” tribological actions. It is an entire new category that falls outside current agreed protocols. It is also a relatively new concept. Scope 4 emissions describe emissions that can be avoided through a product or a service. Avoided emissions are often referred to as being caused by the enabling effect of a technology or solution, e.g., low friction lubricants or coatings. A solution enables the same function or performance with significantly less GHG emissions. Conversely, a lubricant offers the same anti-wear and extreme pressure functionalities with significantly reduced friction, which saves in the use phase GHG emissions.

Such Scope 4 reporting is of considerable importance for tribology and lubricants to develop and promote low carbon, e.g., low friction and long lasting, products. At the company level, we need to distinguish between two different concepts, emission reductions and avoided emissions:

- **Emission reduction:** an actual decrease in GHG emissions between two dates within a given scope and
- **Avoided emission** (or decarbonization): the difference in the level of emissions induced by a solution compared to a baseline scenario or current situation.

The big issue of such claims is that avoided emission claims are often unverifiable or inaccurate, because by cherry-picking the system boundaries, methodological approaches vary leading to the accusation of “greenwashing”. The GHG Protocol Product Life Cycle Accounting and

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[5] L. Draucker, Do We Need a Standard to Calculate “Avoided Emissions”? , 05.11.2013, https://www.wri.org/insights/do-we-need-standard-calculate-avoided-emissions

Reporting Standard ("Product Standard"), World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) as well as ISO 14064-2019, parts 1-3, and ISO 14069-2013 outline requirements and guidelines for quantifying, that goods and services reduce GHG emissions. A globally harmonized consensus is highly awaited.

5. Negative Emission Technology

IPCC [6] has disclosed in August 2019 several actions to create new CO_2 sinks removing carbon dioxide in addition to reducing GHG emissions. The mitigation potentials estimated until 2050 by IPCC were (see section 2.6 in [6]):

1. Enhanced weathering between 0.5–4.0 gigatons of CO_2/yr.,
2. Afforestation/reforestation: 0.5–10.1 gigatons of CO_2/yr. and
3. Soil carbon sequestration in croplands and grasslands: 0.4–9.3 gigatons of CO_2/yr.

The full literature range on plant-based carbon dioxide removal gives for 2050 potentials of 1–7 gigatons CO_2/yr. [7,8].

The German Society for Tribology (GfT e.V.) estimated the long-term mitigation potentials by

a. Friction reduction (= energy efficiency) between 2.3-4.5 gigatons of $CO_{2eq.}$/yr. [9] and
b. Longevity (= resource efficiency and resource conservation) between 1.7-6.8 gigatons of $CO_{2eq.}$/yr. [10],

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[6] P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.), Climate Change and Land. An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, August 2019, https://www.ipcc.ch/srccl/

[7] Strengthening and implementing the global response, Chapter 4, section 4.3.7. In: Global Warming of 1.5°C. An IPCC Special Report, 2018, https://www.ipcc.ch/sr15/chapter/chapter-4/

[8] T. M. Lenton, The Global Potential for Carbon Dioxide Removal, Environmental Science and Technology, 2014, 38, p. 52-79

[9] M. Woydt, T. Gradt, T. Hosenfeldt, R. Luther, A. Rienäcker, F. Wetzel and C. Wincierz, Interdisciplinary technology for the reduction of CO_2-emissions and the conservation of resources, publisher: German Society for Tribology, September 2019, https://www.gft-ev.de/wp-content/uploads/GfT-Study-Tribology-in-Germany.pdf

[10] M. Woydt, M. Bäse, T. Hosenfeldt, R. Luther, Chr. Scholz, J. Schulz, Chr. Wincierz, Wear protection and sustainability as cross-sectional challenges, publisher: German Society for Tribology January 2021, https://www.gft-ev.de/en/tribology-in-germany-wear-protection-and-sustainability-as-cross-sectional-challenges/

in relation to fossil (anthropogenic) CO_2 emissions in 2019 of 33.6 gigatons of CO_2 or in total of 59.1±5.9 gigatons of $CO_{2eq.}$ Tribology offers hidden gigatons-scale of carbon dioxide removal in the same orders of magnitude as the mitigations identified by IPCC.

Friction and wear occur everywhere along the value chain. Tribology and lubrication technologies are therefore strong technical options for removing CO_2 from the atmosphere with high implementation potential. Friction reduction and longevity are “industrial carbon removal” or “societal carbon removal” technologies, because $CO_{2eq.}$ savings by tribology occurs everywhere and anytime. Friction reduction and longevity must be seen as “negative emissions technologies” (NET), because they create less or save CO_2 during operation or are easy-to-avoid emissions as a drop-in solution.

6. The monetary value of CO_2 reductions by friction in the use phase

The Avoided Emissions Framework [11] reinforces the importance of the use phase. Offsets or carbon credits are generic terms used to assign a value to a reduction or avoidance of GHG emissions achieved by a certified project. A carbon credit can be traded or used to compensate for the carbon footprint.

The carbon pricing is an orientation on suited Negative Emissions Technologies and can be regulated at the point source of emissions, upstream or downstream. The carbon price corridor in Europe ranged in 2020-2021 between 40-80 €/tCO_2 [12] with an all-time high on 8 February 2022 with 98.88 €/tCO_2 for European Carbon permits (ETS). The price of the 2022 California carbon allowance price ceiling sale is 72.29 US-\$/tCO_2 but ranged in 2021-2022 between 17-32 US-\$/tCO_2. The think tank “France Stratégie” projects values of costs for abating greenhouse gases (GHG) by enabling technologies for 2030 at around 250 €/tCO_2 and at 500 €/tCO_2 for 2040.

In a long-term perspective and for investments in the future, NETs with costs of \$100 per ton of CO_2 or slightly above should be considered. The additional costs of tribological NET solutions must compete with these economical figures.

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[11] A. Stephens and V. Thieme, Towards >60 Gigatons of Climate Innovations. Module 2 – The Avoided Emissions Framework (AEF), September 2020, https://www.misolutionframework.net/pdf/Net-Zero_Innovation_Module_2-The_Avoided_Emissions_Framework_(AEF)-v2.pdf

[12] World Bank. State and Trends of Carbon Pricing 2021. Washington, DC: World Bank, May 2021. https://openknowledge.worldbank.org/handle/10986/35620

Lubricants are basically petrochemical, non-energy products and so long as they are not burned will significantly impact the total expected lifetime CO_{2eq} emissions from irreversible frictional losses and limited longevity of machineries.; With properly functional lubricants, premature failures of the machinery would be avoided allowing for the equipment to hold a longer lifespan - and thus would prevent excess consumption of metal/mineral resources with embedded CO_{2eq} from frictional losses.

6.1 Vehicles

Around 80±5% of cradle-to-grave emissions for road vehicles [13] were emitted during the use phase by combusting fossil fuels or in the case of electric/hybrid drivetrains from electricity generation.

The cross-sector research consortium "Low Friction Power Train" [14] of the Research Associations for Power Transmission Engineering (FVA) and Research Associations for Combustion Engines (FVV) determined various combinations of measures, which achieved 12.1% as the maximum possible reduction in fuel consumption through friction reduction for a gasoline engine (Mercedes C-Class with mechanically supercharged 1.8-liter gasoline internal combustion engine (M271 KE) and manual transmission). The potential fuel savings were 0.945 L/100 km (or range extension of 3.6 miles) out of 7.81 L/100 km (30.1 mpg). The projected savings of 0.945 liters of gasoline/100 km are the equivalent of 2.249 kg CO_2/100 km. The monetary CO_2 value of these tribological measures to reduce friction over 160,100 km (mean gasoline car life in EU27) calculates in this case to 180 € when taking a price floor of 50 €/tCO_2. On the other hand, the monetary value of the saved fuel is 1,512 Liters times the fuel prices, which is more than ten times of the actual monetary CO_2 value.

For passenger cars, a 10% reduction in friction of the powertrain can result in savings of 340 liters of petrol throughout the car's lifetime or $350 per car. When considering the 1.3 billion IC engine cars available worldwide, the savings would make a grand impact on the climate by preserving 442 billion liters of petrol and $455 billion in financial savings [15]. The "Low Friction Power Train" research cluster did not consider the impact of low viscosity lubricants.

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[13] M. Woydt, E. Bock, V. Bakolas, C. Wincierz, T. Hosenfeldt, R. Luther, "Effects of tribology on CO_2 emissions in the use phase of products - Contributions of tribology to decarbonization", publisher: German Society for Tribology, December 2022

[14] K. Michaelis, J. Geiger, K. Moser, Stahl. K., J. Beulshausen, S. Pischinger, Low Friction Powertrain, final report of the research cluster, "Low Friction Powertrain", FVV Heft 1000, 2013, Frankfurt am Main, Germany

[15] R. Shah, A. Kumar, M. Woydt, N. Aragon, Tribology's contribution to CO_2 Reduction and Sustainability, Fuels and Lubes, 2020. https://www.fuelsandlubes.com/fli-article/tribologys-contribution-to-co2-reduction-and-sustainability/

Combining both estimates comes to the conclusion that 9.6±0.6% of the use-phase scope 3 CO_2 life-cycle emissions of category 11 of road vehicles can be saved on average by reducing friction. The span in lifecycle GHG emissions of road vehicles range between 40-65 tons CO_{2eq}. during 200,000 km. The monetary value of a tribological measure to reduce friction calculates to 192-312 € when taking a price floor of 50 €/tCO_2.

6.2 Deep groove ball bearings

Bakolas et al. [16] estimated the energy losses during the use phase of the widely used deep groove ball bearings and by assuming 20% of savings in energy from lowering friction, estimated that with the use of friction-optimized standard ball bearings as high as 96 to 152 TWh of electricity per year could be saved out of 23.845 TWh globally (2019).

Now, by using the global emission factor for electricity (2019) of 475 grCO_{2eq}/kWh or 275 grCO_{2eq}/kWh for EU27 calculate with a monetary CO_2 values with 50 €/tCO_2 to a range of 1.237 to 2.137 billion € p.a., whereas with a price for electricity of 0.30 €/kWh, the monetary savings reach globally 28.8 to 45.6 billion €!

6.3 Dynamic seals

A friction-optimized mechanical face seal cuts the friction by 0.5 to 1.0 grCO_2/km [17] in a 1.6-liter passenger car with double-clutch versus a standard PTFE crankshaft seal. Assuming a lifetime operation during 200.000 km results in CO_2 savings between 100-200 kgCO_2. The monetary value per seal in the use phase calculates to 5-10 € when taking a price floor of 50 €/tCO_2. With emissions factors of 2.317 kgCO_2/L gasoline and 2.714 kgCO_2/L Diesel results in 43.1-73.7 L fuel times the national fuel price, which is visibly significantly higher than the savings in CO_2 allowances.

6.4 Low rolling resistance tires

The life cycle analysis by Michelin shows that more than 92.6% of the environmental impacts come from the use phase of the tire through rolling resistance. A rolling resistance optimized summer tire

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[16] V. Bakolas, P. Roedel, O. Koch and M. Pausch, A First Approximation of the Global Energy Consumption of Ball Bearings, Tribology Transactions, 2021, Vol. 64, No. 5, p. 883–890, https://doi.org/10.1080/10402004.2021.1946227

[17] N.N., Gas-lubricated mechanical face seals reduce CO_2 emissions, White paper, Freudenberg Sealing Technologies GmbH & Co. KG, D-69465 Weinheim, Germany https://www.fst.com/de/services/downloads/whitepaper/ https://www.fst.com/de/sealing/maerkte/automobil-lkw-bus/

saves up to <0.21 L/100 km or 4.872 g CO_2/km in a passenger car (VW Golf VII, MY2020, 1.5 TSI) [18]. During the tire's 35,000 km life, up to 170 kg less CO_2 is emitted. The monetary value of a low rolling resistance tire in the use phase calculates to 8.50 € when taking a price floor of 50 €/tCO_2. The reduction in rolling resistance of up to 27% improves the energy efficiency also of an electric vehicle, thereby increasing its range by up to 7%, or about 30 km for a VW e-Golf with a range of 400 km compared with a comparative tire of EU efficiency class "A".

170 kg less CO_2 is emitted for a gasoline vehicle times the emission factor for gasoline of 2.317 kgCO_2/L results in 73.4 liters of gasoline savings. Again, this monetary benefit, depending on the national fuel prices, is around one order of magnitude higher than the savings in European carbon permits.

6.5 The monetary value of savings through tribological measures

The aforementioned examples can be condensed in a general way by comparing the tribological enhanced savings from electrical energy savings compared to the associated monetary values of avoiding carbon allowances.

The prices for EU Carbon Permits in 2022 ranged between 60-98 €/tCO_2 times the emission factor of the energy mix of 0.275 tCO_2/MWh in EU27 and 0.401 tCO_2/MWh in Germany calculate to a monetary CO_2 value between 16.5 to 39.3 €/MWh. If one looks at the savings in electrical energy, the average costs for electricity in the 1st half of 2022 in Germany were for industry 330.2 €/MWh and households 371.4 €/MWh.

As for the aforementioned examples, the general approach also comes to the conclusion that efforts in reducing the consumption in electrical energy are 10-20 times more economic than in saving costs for CO_2 allowances.

The cost of charging Electric vehicles (EVs) can vary by region, type of charger and time of day, as well as the driving range of each specific model. To properly compare prices and savings between EVs and gasoline vehicles, one could compare the ratio of car range in miles over range per kilowatt hour (kWh) of electricity multiplied by the cost of electricity in kWh, or (car range (CR) / range per kWh (RPK)) * cost per kWh (CPK) = cost to charge [19]. Given a national average cost of

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[18] Michelin e.primary, eco-responsible, made to last, January 2021, https://www.michelin.com/en/press-releases/the-eco-responsible-michelin-e-primacy-tire-made-to-last/

[19] J. Rodriguez, How Much Does It Cost To Charge an Electric Car?, November 2022,

\$0.14 per kWh and conventional range of 360 miles with each kWh persisting for 3 miles, (360-mile range / 3 miles per kWh) * \$0.14 kWh would indicate that the average EV costs \$16.80 to fully charge, whereas a corresponding estimate for a small gasoline vehicle with a 12-gallon tank at a national average of \$3.39 per gallon of gasoline would calculate to \$40.68 for a full tank. Furthermore, if one considers the superior range of gasoline vehicles at about 403 miles compared to the 360 mi of an EV, the cost of gasoline vehicles would be around \$36.38. This calculation changes, when considering average costs for electricity in 1. half 2022 in Germany of 0.330 €/kWh for industry and 0.371 €/kWh for consumers.

Even though gasoline vehicles present the highest cost, especially as larger tank sizes that run on more expensive diesel fuel are more common, completely switching to EVs would not be very helpful as EVs are not free from releasing CO_2, given the grid used to produce electricity is mechanical and has associated frictional related emissions. Proper tribology in every area in industry is key to savings in emissions in operational costs. According to USA industry estimates from 2019 [20], as shown in Table 3, 10% of tribological contacts resulted in approximately 773 billion kilowatt-hours of energy wasted due to overcoming friction. According to the US Environmental Protection Agency [21], one kWh of energy emits 0.707 kg of CO_{2eq} and thus with further analysis correlates the wasted energy to release nearly 546 million metric tons (MT) of CO_2. Using the 2021 US social cost of carbon at \$51 per MT of CO_{2eq} [22], it can be determined that friction resulted in at least \$27.9 billion worth of environmental damage in the US in 2019 - and the value only continues to grow when considering multiple countries and the increasing annual rate of emissions.

With proper tribology, even a 7.5% reduction in friction could make a significant impact on the climate by reducing nearly 41 million MT of CO_{2eq} from being emitted into the environment, as seen in Table 4 [20]. This would correlate to saving 58 billion kWh of energy and allowing \$2 billion of GHG to be saved from damaging climate. If manufacturers are able to properly utilize tribology to reduce increasing amounts of friction, then the climate will have a bright future ahead. Additionally, as the friction that creates the wear, degradation, and ultimate failure of electro-mechanical systems is minimized, the lifetime of the various machines could be doubled or even tripled - further reducing

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https://finance.yahoo.com/news/much-does-cost-charge-electric-130009449.html

[20] D. Troyer, Look to tribology to reduce climate change impact, The RAM Review, 2020, https://theramreview.com/look-to-tribology-to-reduce-climate-change-impact/

[21] US Environmental Protection Agency, Greenhouse Gases Equivalencies Calculator, June 2022, https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[22] K. Rennert et. al, The social cost of carbon, September 2021, https://www.brookings.edu/bpea-articles/the-social-cost-of-carbon/

costs allowing for more money to be reinvested into the company, increasing manufacturing output and thus more income and available jobs. Reducing friction by proper employment of tribology is necessary to protect our environment and preserve resources.

Table 3: 2019 estimates of USA energy consumption and expenses due to friction presence

Energy Industry Types	Total BTU quads used (2019)	kWh -Eq Consumed by Tribological Systems	MT CO_{2eq}	Social Cost of Carbon Loss ($)
Coal	1.12	32,823,959,859	23,206,540	$1,183,533,540
Renewables	2.50	73,267,767,543	51,800,312	$2,641,815,912
Electricity	3.25	95,248,097,806	67,340,405	$3,434,360,655
Petrol	8.87	259,954,039,243	183,787,506	$9,373,162,806
Natural Gas	10.63	311,534,547,593	220,254,925	$11,233,001,175
Total	**26.37**	**772,828,412,044**	**546,389,687**	**$27,865,874,037**

Social Cost of Carbon Loss estimated with a US 2021 value of $51 per MT CO_2-eq [20].

Table 4: Estimated savings by reducing friction by 7.5% with proper tribology

Industry	7.5% friction reduction savings (MT CO_2-eq)	Reduction in kWh -Eq	Social Cost of Carbon Savings ($)
Coal	1,740,490	2,461,796	$88,764,990
Renewables	3,885,023	5,495,082	$198,136,173
Electricity	5,050,530	7,143,607	$257,577,030
Petrol	13,784,063	19,496,553	$702,987,213
Natural Gas	16,519,119	23,365,091	$842,475,069

Total	**40,979,227**	**57,962,132**	**$2,089,940,577**

Social Cost of Carbon Savings estimated with a US 2021 value of $51 per MT CO_2-eq [20].
Reduction in kWh-Eq determined by dividing MT CO_2-eq by 0.707 MT CO_2-eq/kWh-eq.

7. Conclusions

Friction reduction and longevity avoid greenhouse gas emissions in the use phase (Scope 3). Tribology and lubrication sciences shall be considered as carbon dioxide removal sinks and compete by GHG savings with other carbon dioxide removal sinks or Negative Emission Technology (NET). The prices for carbon allowances are far too low in order to justify investments in NET, like reducing friction and extending longevity. In light of rising energy costs, investments in tribological solutions represent a hidden business case when targeting savings in costs for energy.

Friction reduction and longevity can compete with all mitigation potentials for carbon dioxide removal expressed by IPCC with the difference that friction reduction and longevity are effective downstream in the use phase. Tribology and lubrication are both technology-based approaches to eliminate carbon dioxide and greenhouse gases, respectively, friction reduction and longevity must be seen as "negative emissions technologies" (NET) of downstream (scope 4 "avoided emissions"). Measures to reduce friction and extend service life must be included in the emissions trading system and tribology must be eligible for CO_2 allowance allocations. The strategic employment of tribology, the efficiency of involved components would increase tremendously as wear is reduced and longevity lengthens; ultimately protecting the environment from harmful CO_2 emissions and conserving resources as well as helping the economy by cutting costs to the benefit of consumers and vendors alike.

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