SUSTAINABILITY AS IT RELATES TO CARBON DIOXIDE EMISSIONS, FRICTION AND WEAR

Following the growing world population and demands of energy as well as amenities, many studies have proved the use of fossil-based fuels as the main contribution of climate change and global warming. The consequences are evident from rising temperatures, sea levels and an increase in the intensity and frequency of extreme weather conditions. Therefore, immediate actions, including limitations on CO_2 and fine particulate emissions in internal combustion engines, need to be taken to reduce energy-consumption levels and pollution. Transportation, power generation and manufacturing are essential industrial activities in modern societies that will generate a great amount of carbon dioxide and greenhouse gases. These activities involve many different forms of machinery and mechanical systems with numerous moving parts and contacting surfaces [1]. Tribology is the science of interacting surfaces in relative motion under relative loads and encompasses the study of friction, wear, lubrication and related design aspects [2]. Smooth, reliable, and long-lasting operations of these machines heavily depend on how well friction and wear can be controlled in these systems [1]. Material efficiency and resource conservation can be achieved through products with a longer life cycle [1]. Since tribology has become a key factor in developing sustainable technologies, this contribution aims at exploring the global impact of tribology in terms of CO_2 emissions.

Tribology has become a cross-sectional technology involving biology, chemistry, engineering, materials science and mathematics of economic importance. It combines economic aspects and sustainability in terms of correlating CO_2 emissions and friction. As a result, tribology has both direct and indirect effects on certain global sustainable development goals (SDG) as outlined in Table 1 [3]. Table 1 emphasizes the tremendous impact tribology can make from energy efficiency through wear protection and lubrication. Wear protection and condition monitoring help to extend service life and functionality of components. Therefore, fewer replacement parts are required for production and handling operations, reducing overall materials, energy and work [3]. Another fundamental aspect of tribology is lubrication. Lubrication is essential for optimizing friction in sliding surfaces, minimizing direct surface contact, and reducing tool wear and power requirements. Lubricants consisting of base oils and additives synthesized from biomasses are the most suitable options, as they are made of renewable raw materials [3]. The tonnage of lubricants corresponds to about 1% of the fuel volume [3]. Moreover, there is enough biomass tonnage available to feed the synthesis of chemicals needed for formulating about 38-42 million metric tons of lubricants consumed annually.

Furthermore, the correlation between energy efficiency and CO_2 emissions is evident in Figure 1, which shows the estimation of key scenarios for reducing CO_2 emissions to limit global warming by 2°C in 2050. As opposed to carbon capture and storage and renewables, the largest impact is expected to come from end-use energy efficiency (38%), which includes energy generated in industry, services, agriculture and households. A 2017 analysis of earlier studies calculated that approximately 23% of the world's total energy consumption is related to tribological contacts [1]. 20% is used to overcome friction and the remaining 3% is connected with remanufacturing worn parts and spare equipment due to wear and wear-related failures [1]. Assuming that friction losses can be reduced by 30-40%, the medium and long-term global savings potentials, the potential for reducing primary energy by reducing friction has a wide range of predictions: 8.6% (Holmberg, 2017) [1], 8% (Holmberg, 2019) [5], 10.9% (ASME, 1977) [6], 13% (US Congress, 2016) and 24% (ARPA-E, 2017) [7]. In consequence, based on 33.3 gigatons of CO_2 emissions in 2017, about 2.66-4.93 gigatons of CO_2 per year could be avoided by reasonable and appropriate measures to reduce friction and wear.

Thus, a large emphasis has been placed on tribological research. This progress includes the development of new materials and coatings, surface engineering (surface treatments, modifications and texturing), and lubricants and additives (nanomaterials and solid lubricants), as well as innovative technical solutions such as new component designs [8]. The coefficient of friction (COF) in the "milli-range" is en vogue in research and will greatly reduce CO_2 emissions, if widely applied in practice. Some of the solutions for friction and wear reduction can be directly applied to existing machines, but some may only be compatible with newer or more

Table 1: Effect and impact of tribology on the sustainable development goals (SDG) [3].

Global sustainability goal	Attributes and contributions
#3: Ensure healthy lives and promote well-being for all at all ages	• Biolubricants: reduction of particulate emissions using more wear-resistant materials (tires, brakes, roads, rails)
#6: Ensure availability and sustainable management of water and sanitation for all	• Conservation of resources & energy efficiency through biolubricants or environmentally acceptable lubricants, which limit pollution of waters
#7: Ensure access to affordable, reliable, sustainable and modern energy for all	• Energy efficiency through the reduction of friction effects, resulting in long-life transmissions and bearings in wind turbines and exhaust heat recovery systems
#8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	• Resource efficiency through wear protection, adaptive condition monitoring and tribotronics. • Hydraulic fluids used to increase the productivity of construction machinery
#9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	• Wear protection, material efficiency, resource conservation and reduction of fine dust due to fewer wear particles
#12: Ensure sustainable consumption and production patterns	• Lubricants and additives based on renewable raw materials • Bio-lubricants, low-wear braking systems and tires, reprocessing of tribosystems • Wear protection = long-life technology and extended service life cycles, reducing the amount of waste
#13: Take urgent action to combat climate change and its impacts	• Energy efficiency through the reduction of friction effects • The use of lubricants from renewable or recycled resources

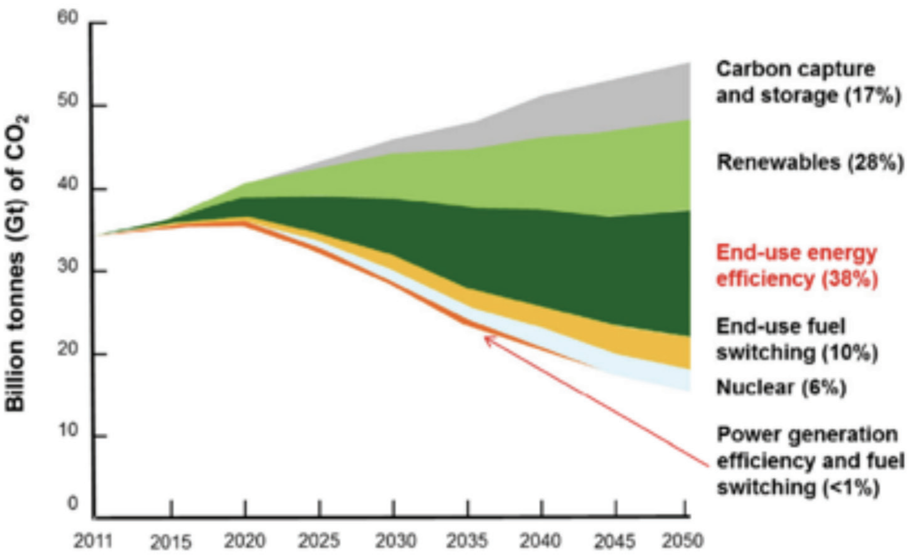

Figure 1: Key technologies for reducing CO_2 emissions to limit global warming to 2°C, estimated by International Energy Agency (IEA) [4].

advanced instruments [1]. Many industries also aim at synthesizing lubricants with the focus on biodegradable and eco-friendly characteristics [9].

Within the scientific community, there is an increased awareness of tribology and its impact on sustainability with more efforts into investigating this field. Table 2 shows the potential average friction and wear reduction rate in 2017 as well as levels estimated to be possible to achieve in 2030 [1,8]. These estimations are based on the average friction and wear levels of today's devices compared to the relative friction and wear reduction in today's new commercial devices, the lowest levels measured in research laboratories and the levels estimated to be possible to achieve up to 2030. This data focuses on the transport, energy, industrial and residential sectors.

Table 3 displays the estimated potential energy and savings and CO_2 emissions reduction in some geographic regions in the long term (15 years), as a result of better tribological performance [1]. The figures are calculated as related to the total primary energy supply (TPES). Due to people's improved understanding of tribology and its implementation, friction and wear reduction rates are expected to increase in the future (Table 2) and can ultimately improve cost and energy savings as well as CO_2 emission reduction (Table 3).

In conclusion, following the population growth that leads to higher energy demand on a global scale, tribology plays a key role in reducing CO_2 emissions related to energy-consumption levels. Tribology has both direct and indirect effects on various SDGs through energy efficiency, in terms of friction and wear protection. Hence, a lot of efforts must be undertaken to implement the pre-existing knowledge and develop new business models. However, it needs to be emphasized that sustainability is not limited to environmental friendliness. By taking advantage of new materials, lubrication technologies and condition monitoring in many machinery and other equipment, energy losses may be significantly reduced, which can be estimated to be about 3.1 gigatons of CO_2 emissions or ~9% of the total direct CO_2 emissions in 2017.

Table 2: Relative friction and wear reduction rate in 2017 to 2030 [1].

	Relative friction and wear reduction		
	From Average 2017 to New 2017	From Average 2017 to Lab 2017	From Average 2017 to Future 2030
	%	%	%
Friction reduction			
– Transport and energy industry	40	70	80
– Industry and residential	40	80	90
Wear reduction			
– Transport and energy industry	30	40	50
– Industry and residential	40	60	70

Table 3: Estimated potential energy and cost savings, CO_2 emission reduction on long term (15 years) by region [1]

	TPES	Share of global TPES	Energy savings	Cost savings	CO_2 emission reduction
Unit	Mtoe	%	PJ/a	Million Euro/a	Million tonnes/a
World	13,700	100	46,000	973,000	3,140
Industrialized countries	8,220	60	27,600	583,800	1,884
Industrially developing countries	4,800	35	16,100	340,550	1,099
Agricultural countries	685	5	2,300	48,650	157
China	3,066	22.4	10,304	217,952	703
USA	2,216	16.2	7,452	157,626	509
EU-28	1,606	11.7	5,382	113,841	367
India	825	6.0	2,760	58,380	188
Russia	710	5.2	2,392	50,596	163
Japan	442	3.2	1,472	31,136	100
Brazil	303	2.2	1,012	21,406	69
Canada	280	2.0	920	19,460	63
UK	180	1.3	598	12,649	41
Finland	34	0.25	115	2,433	8

References:

[1] Holmberg K., Erdemir A, "Influence of tribology on global energy consumption, costs and emissions", FRICTION, 2017; 5(3);264-284. Doi: 10.1007/s40544-017-0183-5.

[2] Jin Z., Fisher J., "Tribology in joint replacement", Joint replacement technology, 2008

[3] Woydt M., Hosenfeldt T., Luther R., Scholz C., Bäse M., Wincierz C., Schulz J., "Wear protection and sustainability as cross-sectional challenges", German Socity for Tribology (www.gft-ev.de), 2021, https://www.gft-ev.de/en/tribology-in-germany-wear-protection-and-sustainability-as-cross-sectional-challenges/

[4] IEA Energy Technology Perspectives 2008, "Scenarios & Strategies to 2050", IEA International Energy Agency, Paris, France 2010. ISBN 978-92-64-04143-1

[5] K. Holmberg and A. Erdemir, "The impact of tribology on energy use and CO_2 emission globally and in combustion engine and electric cars.", Tribology International, 2019, Vol. 135, pp. 389-396

[6] O. Pinkus and D.F. Wilcock, "Strategy for Energy Conservation through Tribology", 1977, The American Society of Mechanical Engineers, New York, NY 10016-5990, USA; www.asme.org

[7] P.M. Lee and R. Carpick (eds.), Tribology Opportunities for Enhancing America's Energy Efficiency – A report to the Advanced Research Projects Agency, 14th February 2017, U.S. DoE, https://alliance.seas.upenn.edu/~carpickg/dynamic/wordpress/wp-content/uploads/2012/03/TribologyARPAE_FINAL.pdf

[8] Holmberg K., Kivikytö-Reponen P., Härkisaari P., Valtonen K., Erdemir A. "Global energy consumption due to friction and wear in the mining industry", Tribology International, 2017;116–139

[9] Saini V., "Aspects of green-sustainable tribology and its impacts on future product development: A Review", Ecology, Environment and Conservation. 25, 2019;146-157

[10] Shah R., Woydt M., Huq N., Rosenkranz A., "Tribology meets sustainability", Industrial Lubrication and Tribology, 2020, DOI: 10.1108/ILT-09-2020-0356

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