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Perspective

The Effects of Energy Efficiency and Resource Consumption on Environmental Sustainability

Raj Shah [1,*], Rui Chen [2,*] and Mathias Woydt [3,*]

[1] Koehler Instrument Company, Inc., 85 Corporate Drive, New York, NY 11742, USA
[2] Department of Materials Science and Chemical Engineering, Stony Brook University, New York, NY 11794, USA
[3] MATRILUB, D-12203 Berlin, Germany
[*] Correspondence: rshah@koehlerinstrument.com (R.S.); rui.chen.2@stonybrook.edu (R.C.); m.woydt@matrilub.de (M.W.)

Abstract: Primary energy has become a vital part of society—from mobility, heating, and cooling to refrigeration to preserve food as well as for simple communication methods, such as texting. As such, pollution and environmental concerns regarding the impact of human activities have become mainstream and efforts have been made to reduce solid wastes as well as CO_2 and greenhouse gas emissions. Renewable energy is almost synonymous with environmentally friendly. While energy conversion from fossil fuels and natural gases is responsible for most of the pollution (CO_2, NO_x, SO_2, particulate matter (PM), etc.) in modern society, these processes also generated 86% of global primary energy in 2019. Furthermore, as humans become more dependent on energy, power demands will only increase with time. Material hunger represents another little perceived dependency of human prosperity. The longevity of products and goods is crucial to limit CO_{2eq} emissions associated with material streams. This paper will focus on two relationships: that of CO_2 and friction, and that of sustainability and wear protection.

Keywords: energy efficiency; CO_2; wear; environmental sustainability; greenhouse gases; tribology

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1. Introduction

As the human population continues to grow, along with individual wealth, it is without a doubt that energy demands and resource consumption will increase with it. Total primary energy consumption is predicted to increase from 584 Exajoules in 2019 [1] to above 700 Exajoules in 2040 [2]. In addition, the U.S. Energy Information Administration (EIA) estimates that annual energy consumption will increase by as much as 50% by 2050 [3]. In 2019, 5130 megatons [4] of CO_2 produced in the U.S. was energy related, of which 94% was from fossil fuels. Fossil use for primary energy in the United States is estimated at 74% [5] and 84% globally compared to other sources. It is commonly agreed worldwide that reducing fossil fuel usage and decreasing GHG emissions are of vital importance [6–9]. Today, the public and political scene recognize only CO_2 and GHG emissions from energy production and do not consider CO_2 and GHG emissions embedded in material and resource consumption.

Renewable energy alternatives are on the rise and can be seen as long-term alternatives to fossil energy carriers (oil, coals and natural gases). Although there are still many obstacles to overcome, there are also many possible solutions to these issues. For one, a complete overhaul of the current energy system for a renewable alternative is extremely costly, but methods such as government subsidies can increase the incentive for populations to install solar panels. However, while these topics are equally important, the focus of this paper is to discuss the potential improvements that can be made in the petroleum and natural gas industry. Societal discussions mainly consider the consumption of fuels and its estimated impact on CO_2 emissions. The climate discussion is limited mainly to mobility.

The transportation industry accounts for 16.2% and energy use in buildings for 17.5% of global CO_2 emissions.

The consumption of resources and their impact on climate and sustainability has so far not found inroads into societal discussions, NGOs and politics. The 2020 circularity gap report states that in 2017 [10], global total material consumption or flow of materials amounted to 100.6 gigatons, including 8.6 gigatons of cycled products. Conversely, 15.047 gigatons were fossil fuels and non-recyclable and non-regenerable materials, and 24.062 gigatons were of biomass of any kind. There is consequently a remaining 61.491 gigatons that is disregarded. The question is, how much embedded CO_2 is linked to the consumption of the remaining 61.491 gigatons of resources? Are there engineering materials included with a direct or indirect link to friction, wear, and lubrication?

It was recently illuminated that as high as 23% [6] of total primary energy consumption is due to friction! Irrespective of the usage of "green" energy production, savings through reducing friction helps. Either the transformation of net zero arrives faster or we are able to provide more for all from the same amount of primary energy. Here, one must distinguish electricity from green technologies and primary energy from renewables. This paper will discuss the relationship between tribology and energy efficiency plus embedded CO_2 in the consumption of material resources, which is a hidden use of CO_2 generation Higher production and consumption efficiency will inevitably lead to lower production of GHGs as less energy is utilized. As aforementioned, humanity as consumers, NGOs, policy makers and industry are not only not aware of the total annual consumption of resources, but are also unaware of societal stocks! In 2020, the global in-use stock exceeded 1100 gigatons [11] or 1200 gigatons [12]. If we consider a societal stock for Germany of ca. 62 gigatons having a population of 82 million or approximately ~1% of the global population, assuming that the rest of the world intends to reach Germany's societal stock, we reach the conclusion that we operate in a resource crisis, irrespective of the associated CO_2 emissions, because the global societal stock will theoretically grow to 6200 gigatons. Therefore, material efficiency and conservation of resources are hidden and high-priority topics. Another aspect of material streams is embedded CO_{2eq} emissions.

2. Tribology and Environmental Sustainability

2.1. Friction

2.1.1. Energy Costs of Friction

Tribological processes and frictional contacts make up approximately 23% of total primary energy consumption worldwide. Holmberg et al. [6] estimated that 23% energy usage worldwide results from friction, 20% of which was for overcoming friction and 3% for replacing worn out parts [6]. An improvement within this field will also greatly reduce the rate at which fuel is consumed, thereby indirectly reducing GHG production. Furthermore, tribology is everywhere and exists in multiple sectors worldwide. In the past, the studies on the impact of tribology were focused on monetary issues. They concluded on a range of savings on total primary energy consumption [13,14] from 5% to 12%, even up to 24% [9]. There are approximately 1.6 billion vehicles (encompassing land, water, and air) [6,15], with those on land using 75% of the total energy for this sector. In the industrial sector, the petrochemical and iron and steel industries account for almost 50% of all energies consumed in that sector. The energy sector contains a multitude of moving parts that has tribological contacts, such as mining drills, gas turbines, and pumps [6,9]. The residential and service sector mostly use energy for heating systems, appliances, and lighting. It is estimated that the amount of energy needed to overcome friction for each sector is approximately 10% for the residential, 20% for the services, 30% for the energy, and 20% for the transportation and industrial sectors [6].

The aforementioned percentages that are required to overcome friction were by no means small. When total energy usage worldwide in 2017 is taken into account, the effects of friction and wear are approximately 119 EJ, 2.54 trillion Euros, and 8120 MT of CO_2 emission [6], as shown in Figure 1. The amount of CO_2 emission caused globally by tribology was 60% higher than energy-related CO_2 emissions in the USA, i.e., 5.14 gigatons. Total CO_2 and GHG emissions in 2017 emitted by the United States of America was 6.448 gigatons of CO_{2eq} in the same year. When loss due to friction is compared to loss due to wear, frictional loss is 6-fold greater than wear loss for energy and CO_2, but only 3-fold greater for monetary costs [6]. It is clear that a reduction in friction and wear will greatly decrease not only needless energy consumption, but also consumption, which contains embedded CO_{2eq} emissions.

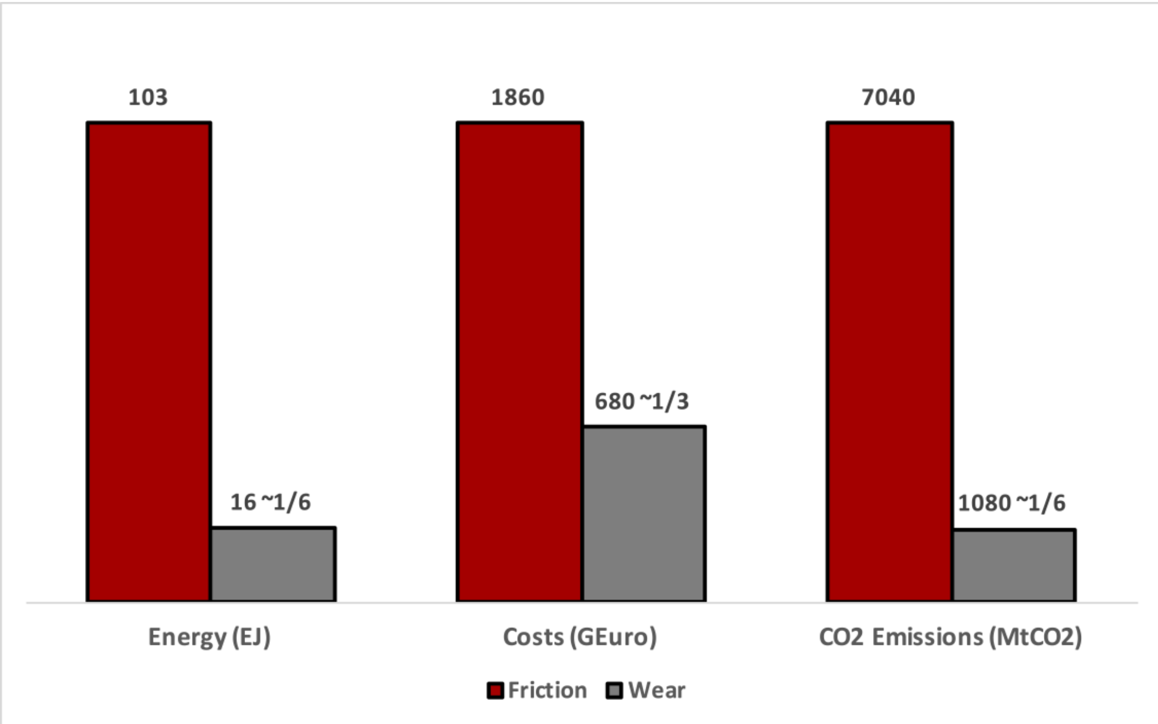

Figure 1. Global friction and wear effects on energy, costs, and CO_2 emissions (2017) (adapted from [6]).

Figure 2 shows a schematic that depicts the division of the usage of fuel energy in the transportation sector in 2009. Over 50% of energy usage in this sector can be attributed to light road vehicles; similarly, most energy usage is for transporting people. The other division is freight transport, where freight trucks and maritime shipping account for the vast majority of the energy consumption in this area [16]. Within this, international shipping has been revealed to produce approximately 2% of global CO_2 emissions in 2020 from fuel consumption [17]. It can be seen that only approximately one-third of the energy usage goes toward actually making the vehicle move while the rest is wasted as heat due to friction. However, some of this is necessary for operation of the car—such as braking and rolling resistance. A similar Sankey-type diagram was presented by the National Lawrence Livermore Laboratory [18].

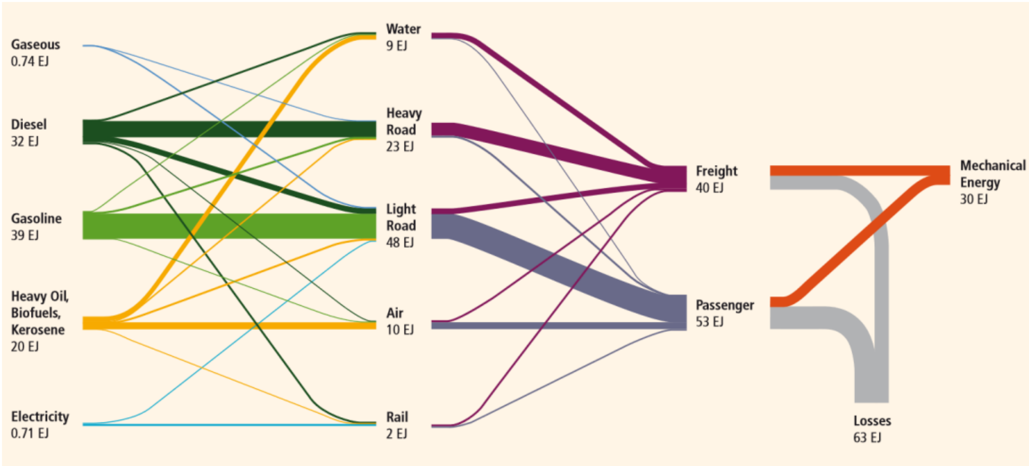

Figure 2. Final energy consumption of fuels by transport subsectors in 2009 [19].

2.1.2. Reducing Friction

It was found that reducing friction by 50% will enhance fuel efficiency by 5–7% [20] in new vehicles. The research into developing friction has been ongoing and significant improvements have been seen in the past decade, including large reductions in the coefficient of friction for trucks and buses [6,21,22]. One of the most common ways to reduce friction is through the use of lubricants wherever there exists contact of moving parts. Lubricants have a myriad of applications for different parameters and situations. Studies have shown that less viscous lubricants tend to have a lower fuel intake than lubricants with higher viscosity, but the specifics will be dependent on individual engine models and technologies. Through these observations, it can be estimated that a decrease in viscosity of 1 mPas will result in CO_2 savings of over 1.64 Mts in Germany alone [15]. Higher-viscosity engine oils are preferred when driving shorter distances due to the nature of these brief trips of fluctuating driving profiles. In these scenarios, lubricants with a high viscosity index are preferred in transient driving profiles as they remain stable even at varying temperatures, providing optimal protection. Current research into new engine oils such as ionic liquids can potentially increase the mechanical efficiency of ICEs by 10% without causing side effects. New additives to lubricants can prove to be extremely beneficial in enhancing their performance. Additionally, friction reduction can also be achieved through improvements in the tribological contact of moving parts, such as in an internal combustion engine (ICE). Enhancement of ICEs in smaller vehicles can lead to over a 30% decrease in energy usage [23]. When paired with additional modifications such as engine weight reduction and a more flexible construction, the benefits will be noticeably greater [23,24].

Reductions in friction will reduce energy usage, costs, and even CO_2 emissions globally [6]. A breakdown of potential savings is shown in Table 1. These values indicate the amount of potential savings for energy, costs, and CO_2 emission reduction over a 15-year period (using data from 2014) if solutions for reducing friction and wear in different sectors are implemented. An estimated amount of 573.6 EJ of total primary energy supply (TPES) can be saved over 15 years with the aforementioned implementation. Furthermore, different studies estimated absolute savings in primary energy through friction reduction between 8 and 12% [13,14], even up to 24% [9]. Global savings for others are estimated based on 2014 to be 46 EJ for energy, 973 billion €, and a reduction of 3.14 billion tons in CO_2 produced. However, since it is impossible to eliminate friction (and it is necessary for the proper functioning of items such as transportation vehicles), these approximations are based on possible reductions in friction and wear using current and near-future technologies. Energy and cost savings will allow focus onto improvements in other sectors instead of the resources being put to waste; reduced CO_2 emissions will greatly help the climate while technologies advance and move onto the path of environmental sustainability.

Table 1. Projected savings over a 15 year period (based on 2014 data) for energy, costs, and CO_2 reduction with the implementation of new technology (adapted from [6]).

Unit	Total Primary Energy Supplies [EJ]	Share of Global TPES [%]	Energy Savings [PJ/a]	Cost Savings [Million €/a]	CO_2 Emission Reduction [Megatons/a]
World	573.6	100	46,000	973,000	3140
Industrialized countries	344.1	60	27,600	583,800	1884
Industrially developing countries	201.0	35	16,100	340,550	1099
Agricultural countries	28.7	5	2300	48,650	157
China	128.4	22.4	10,304	217,952	703
USA	92.8	16.2	7452	157,626	509
EU-28	67.2	11.7	5382	113,841	367
India	34.5	6.0	2760	58,380	188
Russia	29.7	5.2	2392	50,596	163
Japan	18.5	3.2	1472	31,136	100
Brazil	12.7	2.2	1012	21,406	69
Canada	11.7	2.0	920	19,460	63
Finland	1.4	0.25	115	2433	8

1 EJ = Exajoules = 10^{18} Joules; total primary energy supplies (TPES).

2.2. CO_2 from Resource Consumption and Its Relationship to Wear Protection

If materials wear down and prematurely fail due to tribocontacts, then it is obvious that those materials need to be replaced for the machine to continue working as intended. This fuels material consumptions. This is obvious for tires, roads, brake pads and disk rotors [14,15] and especially for the mining industry supplying resources to the world, where abrasive or severe wear is predominant. In Finland, the maintenance costs in the mining industry in 1997 amounted to 15.2% of the annual sales revenues [25]. Globally, the mining industry contributed to 6.2% of the CO_2 emissions in 2014 [21]. The mining and extraction of minerals lead to high water and land consumption, referred to as additional CO_{2eq} emissions.

Not only will global total primary energy consumption grow, but global material consumption will also increase from 92.1 gigatons in 2017 (+8.6 gigatons of cycled products) to 167 gigatons in 2060 [25], or 190 gigatons (O.E.C.D.) [26]. The CO_{2eq} emissions associated with the consumption of metals and minerals used in engineering and in general remain so far out of the focus of societal discussion. At this point, it is clear that doubling the longevity of goods will halve the resource consumption of material hunger. Wear protection and condition monitoring here improve on sustainability and CO_2 emissions, because one can output more utility from the same amount of consumed resources.

Table 2 compiles the global consumption of important specialty metals, major engineering metals, and non-metallic engineering materials times their range in CO_2 equivalent emissions (CO_{2eq}) per ton of primary metal or material. These data were sourced from industry associations or from the literature. The gross and average ratio between mining, extraction and processing of one ton of primary metal or material to CO_2 emissions in 2018/2019 ranges between 1.38 and 1.83 tons of CO_{2eq} per ton of material [27]. It is clear that CO_2 emissions embedded in resource consumption have to be taken into account separately to energy-related CO_2 emissions.

In relation to materials, the emissions factors for fuels are as follows. The 2020 regulation sets the average EU fleet-wide CO_2 emission targets to 95 gr·CO_2/km (regulation (EU) 2019/631), which corresponds to 4.09 L gasoline per 100 km and 3.49 L diesel per 100 km. By introducing the densities from EN16528, the tons of CO_2 emissions per ton of fuel range from 3.032 to 3.494 t CO_2/t fuel [28].

Table 2. Average CO_{2eq} emissions from the primary production of one ton of selected primary metal or material [14,27,29].

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 Metal or Material [10^3 tons]
Specialty metals			
Neodymium	12–60	35	420–2100
Lithium	5–16	80	400–1280
Tungsten	33.6	146	4905
Molybdenum	3.4–14.8	259	881–3788
Manganese #	1.9	16,630	31,597
Titanium	45	7200	324,000
Nickel	42	2330	97,860
Chromium	25	12,300	307,500
Magnesium	20–26	1100	>22,000
Lead	3.2	11,640	37,248
Zinc	9.8	13,400	131,320
Subtotal	—	65,120	>958,131
Major engineering metals			
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	—	1,908,299	4,459,880
Non-metallic, engineering materials			
Bitumen	0.30–0.75	90,000	27,000–67,500
Plastics +	~3.4	360,000	~1,224,000
Cement	0.6–1.3	4,200,000	2,520,000–5,460,000
Total		**6,623,419**	**9,189,011–12,269,378**
For comparison			
Global direct or energy related CO_2-Emissions 2019	—	—	37,900,000

* from concentrates, "open pit" mining; + Plastic = thermoplastics, polyurethanes, duroplastics, elastomers, adhesives, coatings/paints and sealants as well as fibers in polypropylene; # metal content.

3. Conclusions

The consequences of human activities of total primary energy consumption and the embedded CO_2 emissions in the consumption of materials/resources are interwoven through CO_2 emissions. While current energy usages are creating environmental problems such as global warming and increased consumption of non-renewable resources, it will be decades until renewable alternatives can completely replace fossil fuels and natural gases. Therefore, the reduction in friction and the longevity of goods will reduce energy requirements and CO_{2eq} emissions so that impacts on the environment can be realized on short notice. On the other hand, more usages can be offered from the same amount of energy and material streams. Energy usage has become an integral part of today's society at the expense of harming the environment and climate. One way or another, the speed at which GHGs are produced, and resources are consumed, must be addressed for a sustainable future.

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