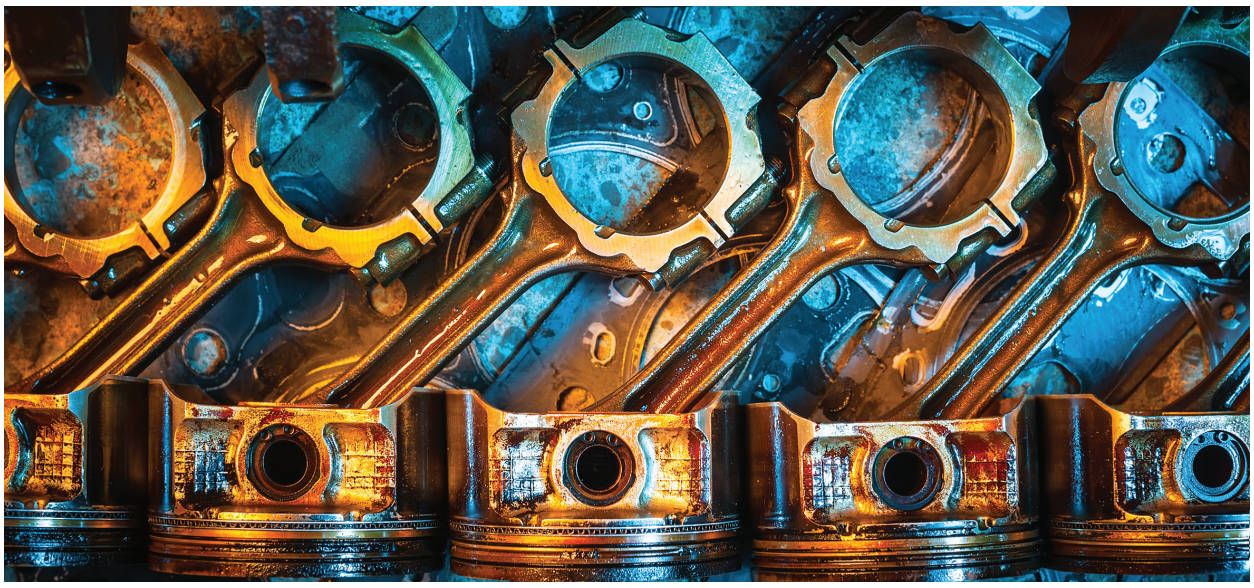
THE INTERSECTION OF SUSTAINABILITY AND TRIBOLOGY

The field of tribology has the potential to impact and provide for sustainable practices in a large way. By using tribology to change the way that we design industrial machinery and engines, we can save much energy and thus CO_2 that would otherwise be lost and would contribute to increased emissions of CO_2 and other greenhouse gases. A study [1] funded by the U.S. Advanced Research Projects Agency – Energy (2016) estimated that advances in tribology can help to save around 23.3% of the total primary energy consumed in the combined transportation, industrial, and utilities sectors in the United States. Some advancements that have already been made towards sustainability using tribology will be highlighted here.

To fully understand and redesign mechanical systems, it is necessary to have a fundamental understanding of the engineering and science that provides the foundation for their operation. This is the knowledge that draws on the science of tribology - which concerns the complex interaction between surfaces in relative motion. The spectrum of technology that we use today is affected by the notion of tribological interactions, making the potential environmental and economic benefits of tribological analysis tremendous. The application of tribology to mechanical systems can help reduce global carbon emissions by decreasing friction [2], reducing wear, and increasing the longevity of resources. By creating technology through a tribological lens, machinery can run more efficiently by lowering energy loss and the reduction of wear lowers the frequency of machine replacement, which saves cost, resources, and time.

In 2015, the United Nations established 17 sustainable development goals (SDGs) and 169 targets to try and bring more attention to the emissions issues and more sustainable practices that can be used to combat these issues. The goals and targets are explained in reference [3]. Much tribological design has been carried out with these goals in mind. The organization ASTM International, which issues industrial standards to a global audience, has a committee known as D02. This committee is focused on petroleum products and lubricants and is a primary standards organization in the fields of tribology and lubrication engineering. D02 has issued several standards, such as D5798 on ethanol fuel blends and D6751 on biodiesel fuel blend stock, which contribute to the development of environmentally friendly fuels [4]. A subcommittee of D02, called D02.96, provides a large amount of reference information for testing and condition monitoring of lubricants, which test for effects of friction and wear (D02.L. and D02.G.). This contributes to economic growth and SDG #8, because systems last longer and save resources. Additionally, subcommittee D02.12 is dedicated to various environmental standards for lubricants such as toxicity, environmental persistence, and biodegradation, which helps reduce contamination from harmful chemicals and leads to proper management of spilled and leaked lubricants [5].



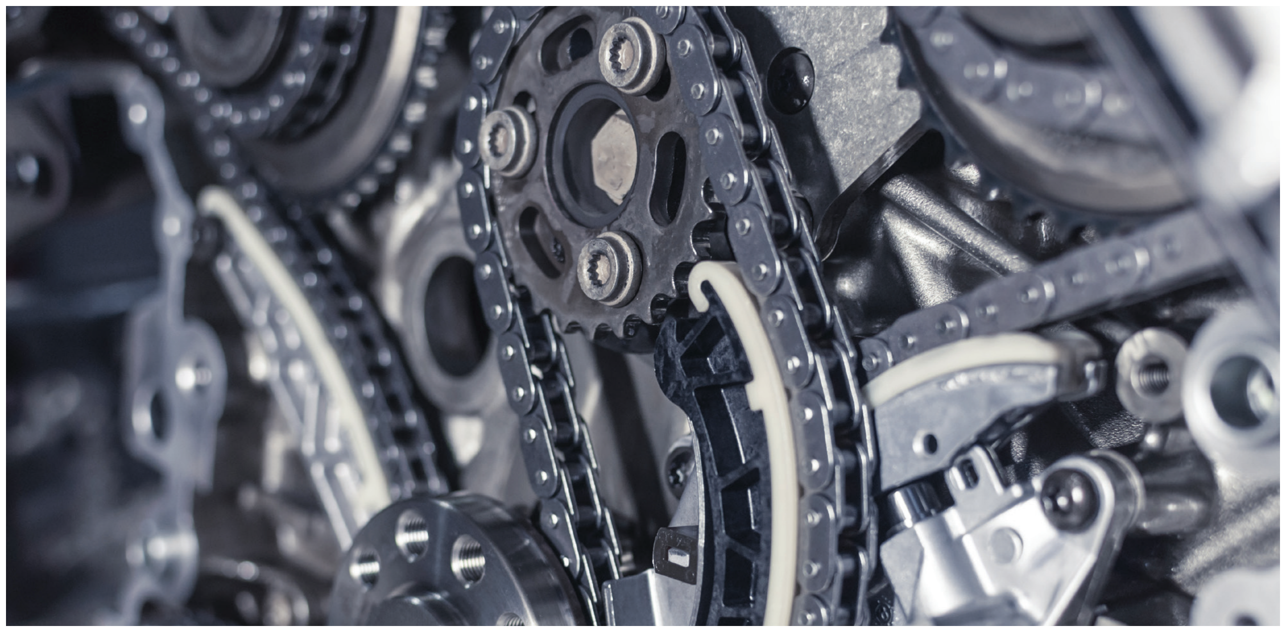
In recent years, much research and development has been aimed towards developing bio-lubricants that are usually made from vegetable oil feedstocks and are almost completely biodegradable. Scientists have investigated how these bio-lubricants compare in performance with mineral oils derived from petroleum.
The main drawback of vegetable oil-based lubricants is that they were found to have lower hydrolytic and oxidative stability and inferior low-temperature performance compared to mineral oils due to their unsaturated bonds. Typically, saturated esters dominate the market [6].

The good news is that the vegetable oil-based bio-lubricants have numerous advantages over the mineral oils, such as more biodegradability, low toxicity, high viscosity indices, and high flash points. Research has shown an improvement to low-temperature performance and oxidative stabilities by converting the unsaturated vegetable oils to polyesters via epoxidation and transesterification.

TMP esters (tri-esters) are widely used. They are a reaction product of trimethylolpropane (TMP) with long chain alcohols, mostly a mixture of C8-C10 [7]. The alcohol can be derived from renewables, like oleic acid ($C_{18}H_{34}O_2$), which is cleaved at the double bond into two C9 fragments. A content of renewables from vegetable resources can be integrated also in di-esters and tetra-esters. The introduction of a renewable content in PAGs can be achieved by the starter molecule, e.g. bio-butanol, and by using ethylene oxide derived from bio-ethanol and/or propylene oxide derived from bio-glycerol.

Another field in which sustainability and tribology meet is power generation from wind turbines. Compared to other renewable energy technologies, wind power generation is the most sustainable, has the lowest greenhouse gas emissions, the lowest water consumption, and the most favorable social impact [9]. Wind turbines can benefit directly from tribological innovation because one of the biggest problems they face is failure due to white etching cracks (WECs). A study was done in 2018 that confirmed lubricants can be an issue which leads to WECs. The study found that some additives in lubricants used in the bearings promote WEC formation very often. Additionally, it was found that lubricants with a high water content led to increased WEC formation due to the extra hydrogen produced by arcing [10]. Synthetic lubricants, such as esters, poly alpha olefins (PAOs), and polyalkalene glycols (PAGs), have also entered the lubrication regime for wind turbine bearings. They offer increased operating lifetimes which allow for a lower amount of maintenance and routine oil changes. They also provide some extra protection against micro pitting and have wide ranges of operating temperatures. Their downside is that some may have issues with compatibility with other materials in the bearings and they can also suffer from instability caused by hydrolysis [11]. There is room for continued improvement regarding lubrication in wind turbine bearings but with the proper treatment, years and possibly decades can be added to the lifetime of wind turbines.

Tribology will play a significant role in the mainstream implementation of electric vehicles (EVs) as well. EVs have the potential to provide a form of transportation that has a significant reduction in emissions and battery electric vehicles (BEVs) in particular can be powered using sustainable sources of energy. By the end of 2019, ~7.5 million BEVs/PHEVs were running around the world, so the potential for EVs looks very bright [12]. There are some challenges with EV lubrication that tribology can address, such as the requirement for lubricants which address noise and efficiency and have good dielectric properties. Lubrication for EVs will most likely be quite similar to that for standard internal combustion engine (ICE) vehicles, but proper additives need to be included that will allow for better electrical properties and reduced corrosion. Many of the bio-lubricants mentioned above can potentially be applied well to EVs with the proper additives to increase their thermal and oxidative stability, but they would have to be analyzed with regard to their compatibility with electric components. Similarly, many nanoparticle additives, such as silicon dioxide [13] or magnesium, phosphorus, and sulfur acting together [14], have shown a large improvement in coefficients of friction and reduction of wear. Still, these also need to be tested with electrical systems. Once well-known and dedicated lubricants for EVs are established, the potential of this highly sustainable and environmentally friendly form of transportation is limitless and unless sufficient resources are available for batteries and electrified powertrains, but more research needs to be done first.



As previously discussed, tribology can play a very large role in the implementation of sustainable practices. We have seen organizations like ASTM International spending much effort on promoting the SDGs of the United Nations and lubrication engineers have worked to develop breakthroughs in the barrier to widespread incorporation of bio-lubricants. Tribology can also help to develop sustainable power generation from wind turbines and can help in the global distribution of EVs. Tribology is very tightly linked with sustainability and will likely be a driving force towards using our resources in a more efficient and safe manner.

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About the Authors

Dr. Raj Shah is a Director at Koehler Instrument Company in New York, where he has worked for the last 25 years. He is an elected Fellow by his peers at IChemE, CMI, STLE, AIC, NLGI, INSTMC, The Energy Institute and The Royal Society of Chemistry An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at https://www.astm.org/DIGITAL_LIBRARY/MNL/SOURCE_PAGES/MNL37-2ND_foreword.pdf

A Ph.D in Chemical Engineering from The Penn State University and a Fellow from The Chartered Management Institute, London, Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. An adjunct professor at the Dept. of Material Science and Chemical Engineering at State University of New York, Stony Brook, Raj has over 300 publications and has been active in the petroleum field for 3 decades. More information on Raj can be found at https://www.petro-online.com/news/fuel-for-thought/13/koehler-instrument-company/dr-raj-shah-director-at-koehler-instrument-company-conferred-with-multifarious-accolades/53404

Dr. Mathias Woydt is managing director of MATRILUB Materials I Tribology I Lubrication, with more than 34 years of experience in R&D and with more than 340 publications and 51 priority patents filed. He is also board member of the German Society for Tribology. He is recipient of the ASTM award of Excellence. He can be reached at m.woydt@matrilub.de

Mr. Nathan Aragon is a senior in Chemical Engineering at SUNY, Stony Brook University, where Dr. Shah is an adjunct professor and the chair of the external advisory Committee in the Dept. of Material Science and Chemical Engineering.


Mr. Nathan Aragon


Dr. Mathias Woydt

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsville, NY 11742 USA • Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com

David Phillips, Content Editor, Petro Industry News, david@pin-pub.com