TRIBOLOGY OPPORTUNITIES FOR ENHANCING AMERICA'S ENERGY EFFICIENCY

A Report to the Advanced Research Projects Agency-Energy at the U.S. Department of Energy

February 14, 2017

Workshop held May 19-20, 2016
Las Vegas, NV
under Contract number DE-AR00282

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EXECUTIVE SUMMARY

Surfaces in interacting motion are at the foundation of the critical energy-efficiency properties of friction, lubrication and wear, and these are found throughout all energy systems with moving parts. Tribology, a branch of engineering, is relatively unmapped and uncharted for energy technologies in recent times; not since the 1980s has any comprehensive study been conducted in the United States (U.S.) to assess the impact of tribology and potential benefits of tribology research across energy technologies. Experts have estimated that over 30% of the approximately 26 quads of energy currently consumed in the U.S. by the transportation sector alone is spent to overcome losses due to friction and wear. Further, they estimate that tribological advances may save nearly 11% (or 10.7 quads) across the transportation, industrial and utilities sectors' combined energy use in the U.S. Yet tribological science and engineering approaches to modern energy efficiency issues remain underexplored, with few dedicated funding programs, an aging and shrinking workforce, and many open fundamental, applied and commercially-driven questions.

In support of the Advanced Research Projects Agency-Energy (ARPA-E) mission to overcome long-term and high-risk technological barriers in the development of energy technologies that ensure America's energy security and technological lead, a workshop titled 'Tribological Opportunities' was held on May 19-20, 2016 following the 71st Society of Tribologists and Lubrication Engineers (STLE) Annual Meeting and Exhibition in Las Vegas, NV. The purpose of the workshop was to explore opportunities in advanced tribological science and engineering for energy technologies across a wide range of application sectors. Enabled by funding from Department of Energy (DOE) (Prime Contract Number DE-AR00282 through subcontract 2300-004 with the Von Braun Center for Science & Innovation, together with the DOE, the workshop organizers convened 31 experts from industry, academia and national laboratories, as listed in Appendix B. Attendees met over a two-day period to discuss industry needs, and where new tribological science and engineering principles may accelerate technological advances in how surfaces and lubricants interact during relative motion for energy savings. The workshop was augmented by an on-line survey called "Can Tribology Save a Quad" distributed to the broader community and in consultation with STLE and other professional societies. Over 100 industry and academicians responded to the survey. The synthesized results and findings are assembled here.

The ARPA-E workshop created the unique opportunity for best-in-class scientists and engineers from across the nation to discuss and assess new unexplored paths to accelerate tribology advances for energy efficiency, security and sustainability.

The following key technical requests were made to workshop contributors:

1. Identify technology ideas in tribology that could save large amounts of energy in the U.S. if implemented, and which require research to be accelerated to market.

2. Explain what the idea is, including how it is a tribology problem, and why research funding is needed to get it to market. Explain what research problem/scientific question/technological barrier would be tackled using the funding.
3. Provide an estimate of the amount of U.S. primary energy saved by this new technology (in quads), and show a simple 'back of the envelope' calculation with citations or sources that justify such savings.
4. List examples of what companies would be the adopters of the technology if successful, and state if there are policy or regulation issues that are necessary to implement or incentivize the technology.

The attendees assessed potential energy impacts of tribology and tribological systems engineering across numerous key industrial sectors, including: *Transportation*, incorporating automotive, aviation, marine and rail; *Power Generation*, incorporating turbomachinery, high temperature gas nuclear reactors, turbines and wind and solar technologies; and *Industrial and Advanced Manufacturing*, incorporating materials, metals, mining, machining and wear. They considered the influence on other supply-chain or crosscutting sectors such as nano-mechanical switch devices, HVAC systems, vapor-phase lubrication, energy auditing programs and others.

A summary of the resulting discussions is provided in this report. A total of 20 quads of energy was identified that could be saved annually through technologies enabled by targeted research support in tribology. More broadly, recommendations are made to expand the topic of tribology to a national 'Call-to-Action' that will take an entirely new approach to reducing energy use and improving energy management or generation systems. The report also identifies energy efficiency stretch goals to challenge the tribology research community at large and the extended industrial network. The long-term goal includes finding solutions, measurement and characterization tools, and new technologies to change how we deploy advanced energy technologies across all energy sectors. Example breakthroughs in tribology or tribological systems that are needed include:

- Reduced viscosity lubricants, including 'Intelligent' oils that incorporate novel additives such as 'on-demand' microencapsulation nanotechnology that releases supplemental additives as depleted, or as a function of temperature or ultra-low elastohydrodynamic shear.
- Computationally-aided design to develop on-demand, self-healing, ultra-thin, fluid/solid tribofilms with desirable friction and wear properties across the load, speed and temperature ranges of the engine and drivetrain to reduce the current 33% parasitic engine losses by half.
- Advanced sensors and actuators in engines and drivetrains that actively modulate the lubricant delivery rate or the bearing surface area in real-time to optimize lubricant efficiency and extend life.
- Innovative nanomaterial fillers to reduce automotive tire rolling resistance by 20% while maintaining regulated tread, at low cost for U.S. light duty vehicle fleet.

- A new generation of high-temperature stable bearing lubricants and seals to increase the efficiency in the harsh environment of steam and gas turbines used in electricity generation.
- Transformed reliability and efficiency of wind turbine drivetrains, including novel materials-based solutions for bearings and gear boxes as well as utility-scale technologies enabling of higher-efficiency harvesting at lower wind speeds.
- Nanoelectromechanical (NEMS) switches to selectively replace solid-state transistors in computers and consumer electronics, as these have orders of magnitude better energy efficiency over transistors, whose efficiency is getting increasingly worse as they are made smaller and faster.
- New materials, environments and processing methods for scaled-up, efficient manufacturing of triboelectric nanogenerators (TENGs) that capture and store mechanical energy with high efficiency.
- Vapor phase lubrication methods to enable large energy gains through higher operating temperatures of heat engines and turbines.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1
Introduction and Overview

1.1 INTRODUCTION

Access to affordable, reliable and clean energy is the cornerstone of America's prosperity and economic growth. Our energy use in the twenty-first century must be sustainable and focused on our Nation's energy security. Water-, solar- and wind-based energy generation combined with conventional oil, gas, coal, nuclear and hydroelectric energy generation are helping to achieve this. Continuing efforts to improve energy efficiency also play a pivotal role in the long term continued prosperity of the U.S. Considering that friction and wear can lead to the failure of most energy systems components, related machines and devices, and the inefficient use of them, better understanding and control of friction and wear has the potential to offset large energy savings, while benefiting safety and industrial productivity. Improved friction and wear—tribology—can save the embodied energy of systems required to manufacture and replace parts.

Over the last decade, annual energy consumption in the U.S. has hovered near 100 quads (1 quad = 1 x 10^{15} Btu = 1.055 x 10^{18} J) [1]. Most recently, increased demand from population and economic growth has been offset by higher energy efficiency. However, reducing the production of CO_2 and managing its accumulation are increasingly urgent challenges with the potential to positively shape the future of our ecosystem and improve quality of life [2,3]. Reducing energy consumption globally will have a direct impact on CO_2 production. A substantial amount of energy is not put to useful purposes, but rather it is lost due to friction and wear. For instance, the transportation sector consumed over 26 quads of energy in 2015, one third of which was used simply to overcome frictional losses [4] (Figure 1). It has been previously estimated that almost 11% of the energy used by the transportation sector, the industrial sector and the utilities sector can be saved by new developments in tribology [5].

1.2 WHAT IS TRIBOLOGY?

Tribology is the study of interacting surfaces in relative motion and the resulting phenomena of friction, adhesion, lubrication and wear. Tribological interactions literally provided the spark of life–being the first "technology" to enable the production of fire, and are at the heart of the origins of culture, with cave scratchings being the first known expression of art. Historical records demonstrate the practical use of tribology in the related technologies of the day. For example, ancient Egyptian depictions of the transportation of hallowed statues show men pouring a liquid (likely water) in front of the heavy sledge carrying the colossus to lubricate the path [6]. In the 1700s, Leonardo da Vinci conducted experiments probing how friction forces depend on load and apparent interfacial contact area; modern replicates of his experiments were recently conducted, and validated the quantitative accuracy of his work [7]. Amontons in 1699 [8] and Coulomb in 1821 [9] quantified the basic "laws" of friction (proportional to normal force and independent of apparent area and sliding speed), and decades of subsequent science and engineering then proceeded. A renaissance emerged in the 1950s thanks in large part to the fundamental approach and the innovations in instrumentation of Bowden and Tabor [10,11].

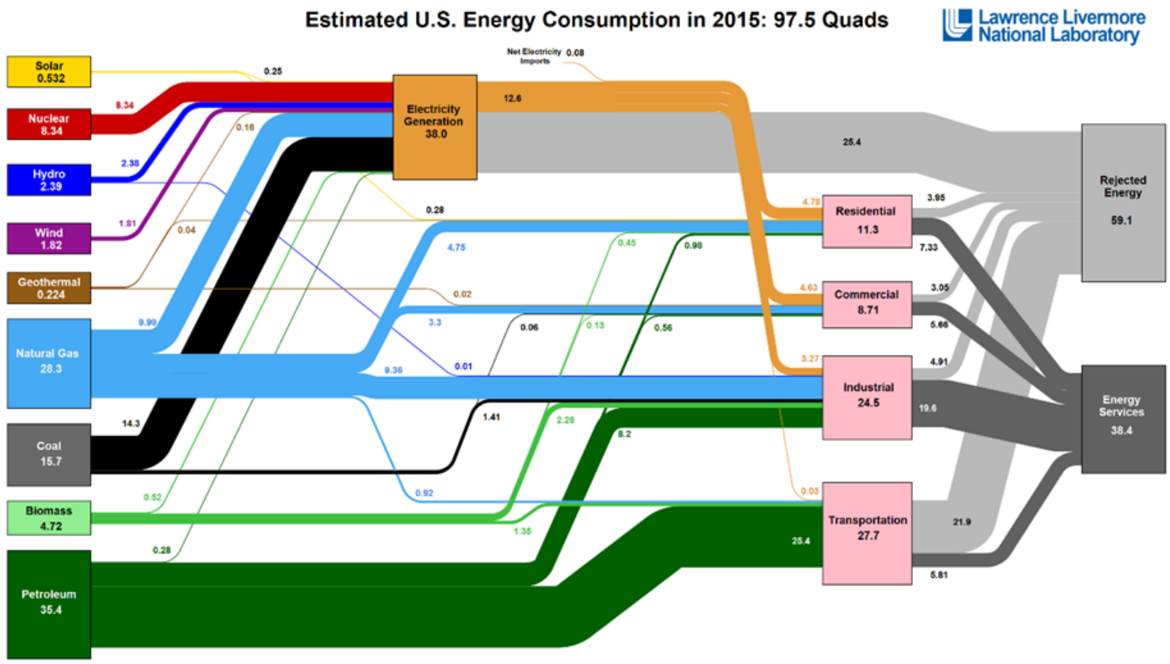

Figure 1. Flowchart showing estimated U.S. energy use in 2015 [35], from primary energy on the left to energy services on the right. Note that less than 40% of the primary energy provides energy services while over 60% is rejected as losses. Most losses are thermodynamic conversion losses, but other inefficiencies, including tribological losses, are significant. Tribology plays a direct role in the equipment used in energy conversion and end-use in 75% of the 97.5 quads of primary energy and an average efficiency improvement due to improved tribology of 1.3% would result in 1 quad of primary energy savings.

A turning point occurred in March 1966 when the findings of an investigation by the Lubrication Education and Research working group were published by the United Kingdom (UK) Department of Education and Science. This report, known as the Jost Report, concluded that more attention to and application of tribology could lead to annual savings of over £500 million [12]. The Jost Report catapulted the newly-coined field of tribology to the forefront of government-funded research. This helped usher in an era of modern tribology research.

The study and optimization of tribology is intrinsically challenging because the action takes place at a buried interface that is normally hidden from view. Moreover, the interactions that occur require insights at intersections of physics, chemistry, mechanics, thermal science, materials science and, in the case of biological interfaces like knee joints and eyelids, biology and biomedicine. Phenomena involve inherently coupled behavior, such as the mechano-chemical response seen in wear processes [13,14], and physio-chemical- thermal responses for additives in lubricants that form sliding-induced tribofilms [15]. This interplay renders tribological studies extremely challenging due to the frequent need for scientific literacy in multiple domains. Regardless, tremendous progress has been made in the recent years. The development of nanotribology has yielded numerous atomic-scale insights into the origins of tribological phenomena [16-20], and biotribology has emerged as a discipline that has been crucial for enabling important medical technologies [21,22]. Relatively recent breakthroughs and high impact developments relying on tribology include: non-stop improvement in advanced lubricant performance for fuel economy of passenger vehicle engines (Chapter 2); progressive Moore's Law-scaling of storage density of computer hard disks (Chapter 5); successful deployment of microelectromechanical systems devices with contacting surfaces like air bag accelerometers and digital light projector micromirror arrays (Chapter 5); innovative coatings for dynamic components in aerospace applications, like space antennae that survive the harsh and varying environments of space missions [23]; and improved orthopedic implants that have massively proliferated with ever-increasing lifetime [18,24]. As numerous in situ methods have now opened up the opportunity to view tribological interfaces in real space and real time, the stage is set for major advances [11,25]. Advances in atomistic and multi-scale computation methods, enabled by advances in computational power and the development of advanced algorithms, are now matching experimental length and time scales [26-29] and accelerating the ability to explore and optimize the impact tribology to our nation.

1.3 THE ECONOMIC AND ENERGY IMPACT OF TRIBOLOGY

The Jost Report triggered a number of investigations over the following decade in the U.S., Germany, Canada and China, which concluded that tribology had a major economic impact on energy and economic prosperity [30]. Consensus was that industry and government savings between 1.0 to 1.4% of a country's gross domestic product (GDP) may be achieved through research and development expenditure on the order of 1/50th of the savings (i.e., one dollar toward research saves fifty dollars over the course of the following year), a figure considered still valid [30-33]. To achieve this, these reports suggested the need to increase research activity by establishing tribology-focused national research and development (R&D) centers and laboratories in these countries, and broaden awareness of the potential impacts of tribology between both the academic and industrial research communities. Additional studies by the American Society of Mechanical Engineers (ASME) [5,34] identified opportunities for energy and economic savings across several industrial sectors, namely road transportation, power generation, turbomachinery and industrial machinery.

These studies were followed up in 1985 by a set of six comprehensive reports by the Energy Conversion and Utilization Technologies (ECUT) Program in the U.S. Department of Energy (DOE) [36], which are summarized by Dake et al. [32]. The six reports focused on:

1. Identifying typical tribology energy sinks in six major industries (mining, agriculture, primary metals, pulp and paper, chemicals/refining and food processing).
2. Reducing tribological losses in the electric utility and transportation sectors.
3. Identifying tribology research needs for advanced heat engines.

4. Determining the energy conservation potential in metalworking using new surface modification methods.
5. Assessing government tribology programs.
6. Assessing industrial attitudes toward research needs in tribology.

These reports collectively estimated that annual direct and indirect losses due to friction and wear amounted to over 4 quads of primary energy in 1978. Simply compounding to 2016 (i.e., for 38 years) assuming 3–5% growth results in 12.3–25.5 quads lost. However, accounting for technology improvements such as higher efficiency vehicles, turbines and machinery would slightly reduce this figure. The first report (on major industries impacted by tribology) found that energy losses from material wear in these industries were greater than energy losses from friction by nearly a factor of 2, suggesting that reducing both friction and wear should be considered.

Very recent work by Erdemir, Holmberg and co-workers [4,37] has highlighted the substantial losses in vehicles due to friction, and this work was cited in a Perspective by former DOE Secretary Steven Chu and founding U.S. Advanced Research Projects Agency-Energy (ARPA-E) Director Arun Majumdar [38]. Most recently, the importance and potential beneficial impacts motivated U.S. Congressman Tim Ryan (OH-13) and Dan Lipinski (IL-03) to introduce a House of Representatives resolution on September 28th, 2016 (H.Res.916) to emphasize the impact of tribology on the U.S. economy and competitiveness, and to highlight the need for increased R&D investment in tribology [39]. As this report highlights, by considering the impact across multiple sectors and systems, the magnitude of energy lost to friction and wear is massive, and a 1 quad annual saving through tribological improvements is readily attainable.

The U.S. government has funded tribology R&D programs over the years through federal agencies including DOE, the National Science Foundation and the Department of Defense's research programs and contracting laboratories. A prior evaluation can be found in 'Assessment of Government Tribology Programs' [40]. Many of these programs have focused on the very important basic science of tribology, and many others were directed toward solving tribological problems in existing applications or in advancing innovative technologies that required tribology research to be successful. As noted in the past, this federal funding has had significant impact across a wide range of application areas as well as in basic research [40]. Despite these investments, there remain critical gaps in tribology basic knowledge, and many applications like wind power, low viscosity vehicle lubricants and microelectromechanical systems suffer from tribology-related challenges and failures. Such barriers prevent the deployment of innovative technologies, which could save large amounts of energy and provide economic benefit through better efficiency and reduced wear.

1.4 THE PURPOSE OF THIS REPORT

Part of DOE's and ARPA-E's mission is to support high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E projects have potential to radically improve U.S. economic, national and energy security, and environmental well-being by providing America's energy researchers with funding, technical assistance and market readiness. This report is the outcome of a joint study funded by the ARPA-E [41] and led jointly by the University of Pennsylvania, the University of Florida, Argonne National Laboratory, Sandia National Laboratories, the Southwest Research Institute and the Society of Tribologists and Lubrication Engineers (STLE) with the intent of identifying pathways and recommending research directions to reduce the energy consumed in the U.S. by 1 quad annually through tribology.

The report is not intended to be a comprehensive accounting of all areas where tribology can have impact, or where opportunities to apply tribology research and technology exist. Rather, it is deliberately focused on a set of technologies in major economic and industrial sectors where the largest potential impact on energy efficiency, energy security and environmental benefits exist, particularly those that could potentially benefit from focused investment by ARPA-E over a period of approximately three years. The absence of any specific technology from this report is not a statement of a lack of potential benefit for that technology. We have attempted to be as broad as possible while remaining focused on technologies whose commercial advancement could be substantially addressed through ARPA-E support.

The process began in 2015 with informal consultations amongst several tribology researchers and professionals spanning industry, academia and national labs to start identifying technologies and developing the process for formulating the research needed for this report. To publicize the effort and invite broad input, an article was published in the May 2016 STLE's TLT Magazine, entitled "Can Tribology Save a Quad?" [42]. The article described the effort and invited comments and ideas from the community through completion of a free online survey. Approximately 100 survey responses from respondents in industry, academia, national labs and government were collected through the end of 2016 and were assessed and analyzed. This helped select ideas in this report. Input was also directly sought from the Independent Lubricant Manufacturers Association (ILMA) and the ASME.

We then organized the ARPA-E Tribology Opportunities Workshop, a 2-day workshop held in May 2016 just after the conclusion of the 71st STLE Annual Meeting and Exhibition in Las Vegas. The workshop brought together tribologists from industry, government and academia who shared their ideas for saving one quad of energy through innovations in tribology. The attendees at this workshop are listed in an Appendix B. These discussions formed the core material of this report and were supplemented by additional research by members of the tribology community who collectively shared in contributing to this report, as identified in the Acknowledgments.

Along the way, research literature and several reports on tribology's economic and industrial impact were compiled. Many of these are cited throughout this report. For completeness, a full bibliography of these collected articles is included in Appendix A

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Chapter 2
Opportunities in the Transport Sector

2.1 INTRODUCTION

There are key opportunities for reducing energy consumption and greenhouse gas emissions in automotive vehicles, planes, boats and trains. Figure 2 shows the global breakdown of energy consumption by transportation vehicles. Collectively, we estimate roughly 2.136 quads of energy can be saved annually in the U.S. through the development of technologies supported by tribology research. At today's gasoline fuel prices, 1 quad is equivalent to roughly $1.6 billion. In passenger vehicles alone, there were 260.4 million registered light duty vehicles [1] in the U.S. in 2014. This number has risen steadily since 1960, and both the median and mean age of automobiles has increased with an average age of 11.4 years in 2014, an increase from 5.1 years in 1969 [2]—a trend likely to continue. This combination of new and used vehicles presents differing challenges in reducing vehicle energy losses. Older vehicles are currently limited to retrofitting with improved lubricants, fuels and tires, whereas new vehicles can be designed with more substantial energy saving technologies. These technologies can be used across the vehicle power platforms: liquid-fueled, alternative-fueled, electric and hybrid vehicles.

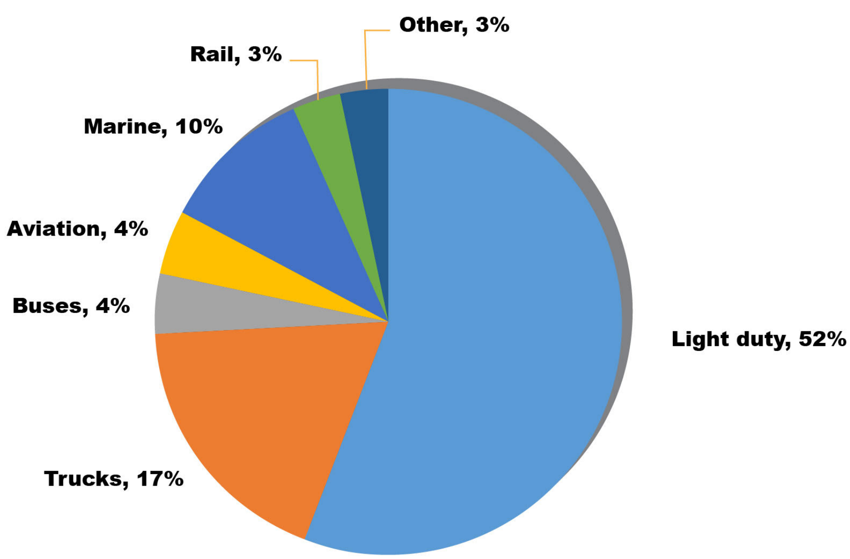

Figure 2. Global breakdown (%) of the energy consumption by transportation vehicles [3].

There are Environmental Protection Agency (EPA) regulations in place to control the fuel economy of new vehicles, with a current requirement of 54.5 mpg for passenger cars and light trucks by the year 2025 [4] as Corporate Average Fuel Economy (CAFE) standards, i.e., the fuel economy across the fleet of vehicles sold by any one manufacturer in that year. However, there are currently no strategies in place to control energy consumption in used vehicles, whose energy usage per mile may increase as their component wear increases. CAFE standards are driven by emissions, not energy efficiency. Therefore, investment has been in meeting emissions regulations rather than making design choices focused on improved engine and drivetrain efficiencies [5].

Government policy can have strong effects on investment in technology for improved fuel economy, and can result in significant changes in countries' vehicle fleets. Examples include the current EPA fuel economy requirements highlighted above and the $2.877 billion 'scrappage program' run by the U.S. Government in 2009, which offered over market value when trading in older vehicles and resulted in 690,411 transactions [6]. There is little question that the 2025 CAFE value has driven research budgets in original equipment manufacturers (OEMs), lubricant companies and lubricant additive companies (AddCos). However, most of this research is based on iterative, incremental developments in fuel, additive and component design; none are disruptive technology changes that require significant funding. A new approach, where transformative ideas for efficiency are based on tribological issues, could have significant impact.

The typical current passenger car uses only 21.5% and heavy duty vehicle only 34% of their fuel energy to move the vehicle (Figures 3 and 4). The remainder is lost in overcoming parasitic losses such as pumps and friction in the engine, transmission, tires, brakes and heat [7,8]. By using new technologies, it is predicted that friction losses could be reduced by 18% in cars and 14% in trucks in the short term (4–8 yrs) and 61% in cars and 37% in trucks in the long term (8–12 yrs) [7,8]. Such new technologies include improved component designs for tribological optimization, component coatings and finishes, and new low-viscosity, low-shear lubricants and additives as well as improved combustion strategies.

DOE's Office of Vehicle Technologies and Advanced Manufacturing Office are both actively investing in automotive component light weighting incremental research and development as an energy efficiency strategy. The MY2015 Ford F150 reduced its overall weight by 700 pounds using a high strength steel frame and a military grade aluminum alloy body [9]. However, further research is required to consider the energy balance between the benefits of lighter vehicles and potential additional energy used in their manufacturing process—where tribology also plays a role. Tribological opportunities in the Industrial and Manufacturing sector, which are pertinent to achieving energy efficient manufacturing of lightweight materials, are covered in Chapter 5.

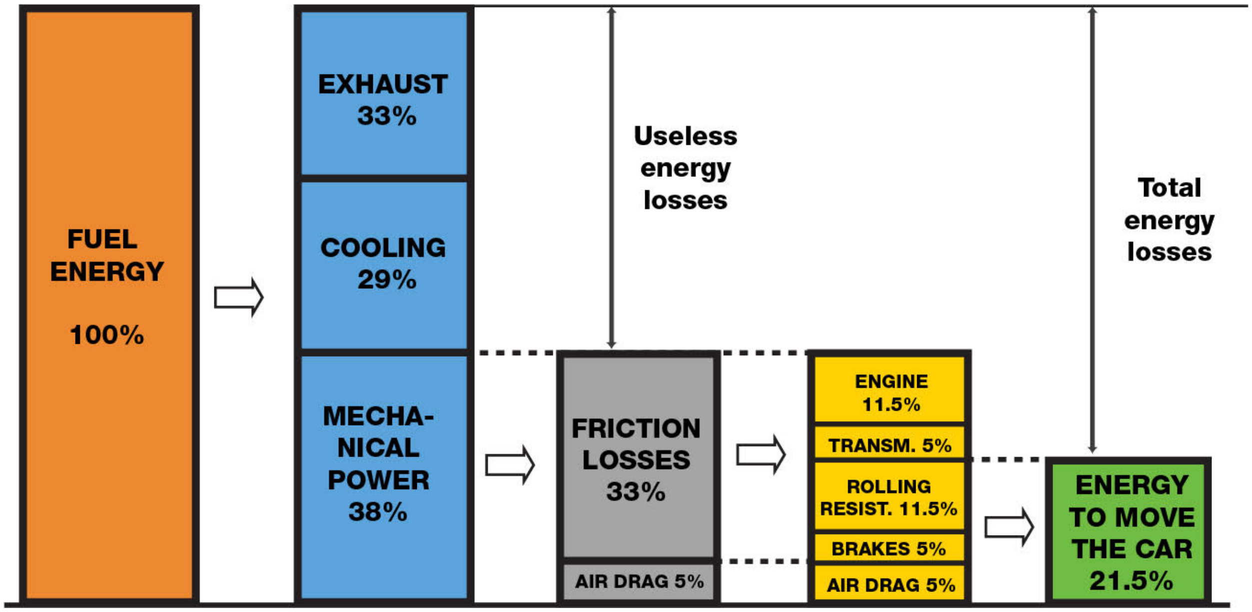

Figure 3. Breakdown of passenger car energy consumption showing % frictional loss in passenger cars [7].

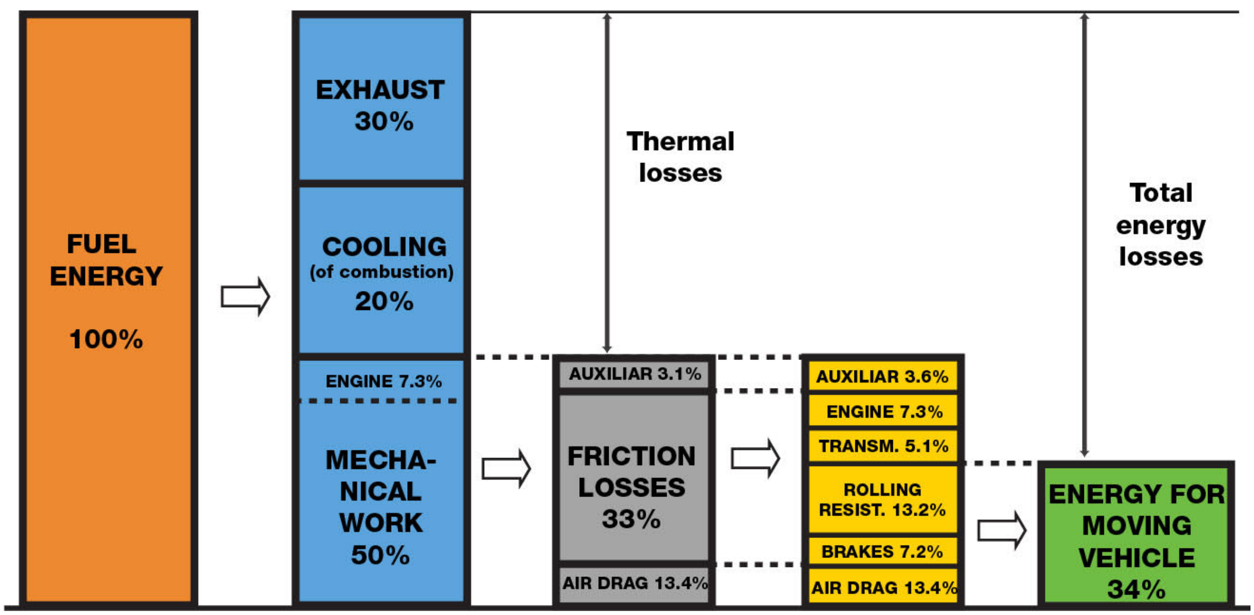

Figure 4. Breakdown of average energy consumption showing % frictional loss in heavy duty vehicles [8].

In November 2016, the EPA reported that the average U.S. fuel economy for new passenger vehicles was 24.8 mpg [10]. If we assume that all 190.6 million registered drivers [11] each use new vehicles with these improved fuel economy capabilities and the average annual vehicle mileage is taken to be 13,467 miles per year [12], this equates to 103.5 billion gallons of fuel used. A 0.5% saving would yield an annual saving of 517 million gallons of fuel (0.062 quads of

Energy[1]). As this ignores the older, less fuel-efficient vehicles, the actual savings have the potential to be considerably higher. Therefore, even small improvements from tribology in vehicle energy conservation can have profound effects on both energy consumption and overall vehicle emissions. Below we discuss the barriers and opportunities to achieving such improvements.

2.2 ENGINE AND DRIVETRAIN LUBRICANTS

Oils and greases (lubricants) are used to reduce wear and frictional energy loss in vehicle engines and drivetrains. The lubricants include additive packages to improve the operating lifetime and keep them within specifications defined by the Society of Automotive Engineers (SAE), American Petroleum Institute (API), American Society for Testing and Materials (ASTM) and OEMs. Lubricants also experience internal energy losses when they are under shear conditions, and for this reason there is currently a motivation within the automotive industry to develop lower viscosity lubricants that give physically thinner films resulting in lower shear losses. This trend will almost certainly spread across other industries and will be increasingly used in small engines, trains, generators and marine applications. SAE has introduced new categories of lubricants to the SAE J300 specifications to allow for these lower viscosity lubricants [13]. However, as lubricant films become thinner, the opportunity for contact between interacting surfaces of the components becomes greater. This interaction, without tribological consideration, increases wear of both engines and drivetrains. Engine oil sludge control and high temperature piston deposit control also becomes an issue when using these lower viscosity grades [14].

There are three primary sets of moving parts in an engine: piston/ring/liner; valvetrain and plain bearings; and three in the drivetrain—clutches, gears and roller/ball bearings. As the lubricant becomes thinner, some of these components are more prone to contact while others have savings from reduced lubricant shear losses. It has been shown that the energy saving advantages from lower viscosity lubricants, primarily the bearings, reach a point where the viscosity is too low and is outweighed by the increased frictional contacts in engines, particularly the piston assembly [15]. The viscosity level at which this occurs depends on the engine architecture and design. This is also true for gears and hydraulic systems. New additive packages will be required to meet these increasing demands where the lubricant acts as a transport mechanism for the additives rather than the lubricant directly protecting the components in contact. Disruptive technologies need to be developed to produce additives, coatings and engine designs that work in synergy such that lubricant viscosities can be reduced further. This is something being considered by Industry, but it has not yet been researched in depth due to the complexity of systems at play.

Automotive lubricant research and development is made more complex as the additive requirement for the piston assembly is significantly different from that for the valvetrain and bearings. Exhaust after treatment systems such as catalysts and stipulated emissions regulations

[1] 1 gallon gasoline = 120,000 BTU; 1×10^{15} BTU = 1 quad

also have an impact on the choice of additives. Significant fuel economy savings have already been achieved through the use of lower viscosity lubricants. We estimate that continued efforts in this area as well as the proposed changes in additive technology discussed above could easily achieve 2–5% additional fuel economy gains, equivalent to 0.25–0.62 quads per year.

2.3 COMPONENT AND DESIGN OPTIMIZATION

The modern engine is a finely tuned package of moving parts. Much iterative research has been invested by every OEM in refining and developing the current technology. However, few significant hardware changes have been made in the drive towards improved fuel economy. Some evolutionary changes that have occurred in recent years include engines with rolling element bearings instead of plain bearings in the overhead valvetrain systems with a 2% fuel economy gain per vehicle [16]. This reduces frictional losses and permits use of lower viscosity lubricants. However, it can increase noise and negatively impact durability. If this technology was used throughout the vehicle fleet, a saving of 0.25 quad would be achieved. Camless valvetrain systems have also been suggested with an anticipated 10% fuel economy gain, 1.24 quads if achieved across the entire vehicle fleet [17]. Stop-start technology has been introduced to reduce energy waste when idling and is suggested to save 5–10% of fuel economy, depending upon driving cycles (urban vs. city) [18]. If the 5% mark were taken across the entire vehicle fleet, this would translate to saving 0.62 quads. However, there are durability concerns with plain bearings in the connecting rods. Roller bearings may be an option, but the cyclic loading due to combustion forces threatens durability. Maintaining lubrication in this region by using variable speed electric oil pumps prevents contact in the bearings at stop start and can help reduce friction and wear, but it has not yet realized its full potential. Reduced overall piston mass, piston skirt sizes and use of coatings on a piston skirt are strategies currently used by many manufacturers to reduce reciprocating engine mass and improve fuel economy. However, strong lighter materials combined with piston and ring coatings could make significant improvements. This is discussed in Section 2.5.

Another significant energy loss in vehicles comes from parasitic losses from the oil pump, air conditioning (AC) compressor, power steering pumps and water pumps. Variable speed electric pumps reduce parasitic losses in engines as can improved AC compressor designs. Electric cooling fans operating only when required have been used for many years for this reason. Novel methods of delivering lubricating oil to the engine, e.g., when and where it is required based on engine operating conditions, would vastly reduce parasitic losses from the oil pump. Use of electric AC would remove parasitic losses due to the AC system [19].

For significant improvements to occur in fuel economy, significant technology changes need to be made in engine design and optimization. Such ideas include use of hydrostatic/hydrodynamic gas bearings for engines, dimpling and textured surfaces for optimization of lubricant supply and pressure controls, redesign of components to work in tandem with this dimpling technology, consideration of using the lubricating oil as the engine coolant with improved heat extraction design and active bearing pressure control using actuators. Estimates of annual energy savings are challenging to determine since the design space for these ideas is very wide, but could potentially be as high as 20% (2.48 quads).

2.4 DESIGNING ENGINE/DRIVETRAIN AND LUBRICANT IN TANDEM

The current situation in the automotive market is that OEMs will design and build an engine with little consideration for the potential improvements that could be made if a tribologist was consulted throughout the design process. Lubricants end up being designed for the engine, whereas the engine could be instead designed with the known lubricant's capabilities and limitations in mind. The impact of this is likely to be significant, with a projected 15–20% fuel improvement. Such an idea is analogous with the DOE's current Co-Optimization of Fuels and Engines (Co-Optima) initiative [20]. This unique $7M initiative is jointly sponsored by DOE's Bioenergy Technologies Office (BETO) and Vehicle Technologies Office (VTO). The initiative involves collaboration between DOE national laboratories and industry stakeholders to conduct coordinated R&D into fuels and engines.

This fundamental change, if applied to lubricant-engine co-development, would permit greater consideration of materials, coatings, component form and lubrication throughout the design process, yielding a potentially large impact. Much work is undertaken on after-market improvements to overcome unanticipated problems in engines. There are also many considerations in not just additive packages and coatings, but also lubrication strategies that could be incorporated. For example, not all interacting engine components require the same quantity of lubricant, even bearings require different levels of 'support' at different points in their rotation. Specifically, the connecting rod big end bearing requires more support when under combustion loads than during the intake and exhaust cycles.

Current lubricant and coating technologies are restricted by the stipulation that they be backward-compatible—i.e. today's lubricants can be run in previous generations of cars [21]. Only recently has the market begun to move away from this stipulation with the introduction of SAE J300 0W–8, 0W–12 and 0W–16 engine lubricants [22]. If this trend away from backward compatibility continues, lubricant and additive manufacturers will have greater scope to develop lubricant blends specifically for new generation engines. All Japanese car manufacturers have small engines that work with the new lowest viscosity 0W–8 SAE J300 engine lubricants. However, the U.S. manufacturers do not have the lead in this technology, and wear is of considerable concern for them. More design optimization needs to be undertaken both in coping with lower viscosity lubricants and designing engines for improved fuel economy.

Many light duty vehicles are used for short journeys, with an average trip length of less than 11 miles [23]. When vehicles are cold, the engines, drivetrain and lubricants do not perform optimally, thereby increasing fuel consumption. Heating of lubricants and coolants to bring the systems to full operating temperatures more quickly has the potential to save significant amounts of fuel. Another option is to insulate the engine and drivetrain so as to maintain oil at operating temperatures for significant time periods when vehicles are not in use. A third option is to use low viscosity lubricants, but again, the problem of wear arises. If this could be solved, for example through the use of much better anti-wear additives including those that form protective anti-wear tribofilms even at low temperatures, vehicle fuel economy gains of 3% (0.372 quads) could be achieved.

A number of these options are being considered, and some have been brought to market recently. Table 1 shows a cost assessment made of the savings vs. the costs of implementation, Many of these options could become more cost effective with suitable investment in improved technology that incorporates tribology research efforts. A potential fuel economy impact of up to 10% (1.3 quads) is predicted.

Table 1. Cost of fuel efficient technologies to be used in vehicles (Baseline: V6 engine with 4-speed automatic transmission). [Adapted from 18]

TECHNOLOGY	COST PER VEHICLE	MPG GAIN	COST PER 1% MPG GAIN	QUAD EQUIVALENT*
Start-Stop	$1800-$2000	5-10%	$200	0.62-1.3
Cylinder Deactivation	$200-$230	4.5-6%	$38	0.558-0.744
Engine Accessory Improvements (electric pumps for coolant/oil, electric alternator)	$125-$165	1-2%	$83	0.124-0.248
Gasoline Direct Injection	$120-$525	1-2%	$263	0.124-0.248
Electric Power Steering	$120-$200	1.5-2%	$99	0.186-0.248
Turbo + Smaller Displacement	$120-$810	1.5-2%	$110	0.186-0.248
6-speed Automatic Transmission (upgrade)	$160-$265	3-6%	$52	0.372-0.744
Aggressive Shift Logic	$40	1-2%	$85	0.124-0.248
Reduce Engine Friction	$21/cylinder	1-3%	$42	0.124-0.372
Low Rolling Resistance Tires	$6	1-2%	$3	0.124-0.248
Low Friction Lubricants (low viscosity fluids: 5W-20, 0W-20)	$3	0.5%	$6	0.062

*Based on Section 2.1. 103.5 billion gallons of fuel used per year. 0.5% saving = 0.062 quads)

2.5 ADVANCED COATINGS, FINISHES AND LUBRICANTS

It has been shown in a number of studies that not all current coatings and lubricants used in the automotive industry work well together in synergy [24]. Often a lubricant will not form an anti-wear and/or anti-frictional chemical-coating (a "tribofilm") on a component with an advanced coating, whereas it readily does so on uncoated steel. This can result in unexpected wear in the contact surfaces, most commonly the valvetrain and the ring/liner interface. Although few vehicles have been sold with these issues when used with the factory fill lubricant, some have failed in the field due to customers changing to a non-recommended lubricant when an oil change becomes due or deviating from the recommended fuel quality. There have also been significant material changes that have caused failures in the field. For example, some Nikasil liners introduced by BMW in the mid 1990s failed due to a reaction between the liner material and the sulfur when low quality high sulfur content fuel was used [25]. Considerable work needs to be undertaken in this area to build a knowledge base of fundamental understanding of which additive types, base lubricants and fuels work with different materials and coatings. If the industry requirement for lubricant backward compatibility is further relaxed, opportunities exist for new lubricants designed specifically to work with advanced coated engines rather than the current lubricants that must service both these and conventional uncoated engines. An applied research effort would need to include nanoscale research into the boundary contact, anti-wear molecule behavior, additive interactions and modified base stocks (e.g., esters) and their interactions with additives. Recently, novel approaches have been developed that permit previously unattainable insights into the formation process of protective tribofilms from anti-wear additives [26]. Exploiting such capabilities in tandem with developing novel additive functionalities has potential to enable a new generation of high performance lubricants.

In addition, new coating capabilities are coming to market that need to be explored. A patent was recently submitted on a novel ring coating recipe for use in gasoline and diesel engines [27]. This coating both reduces friction and increases durability. Piston ring coatings have been one of the fundamental attempts at reducing friction in the ring-liner interface. The evolution of piston ring surfaces for wear and scuff resistance is seen in Figure 5.

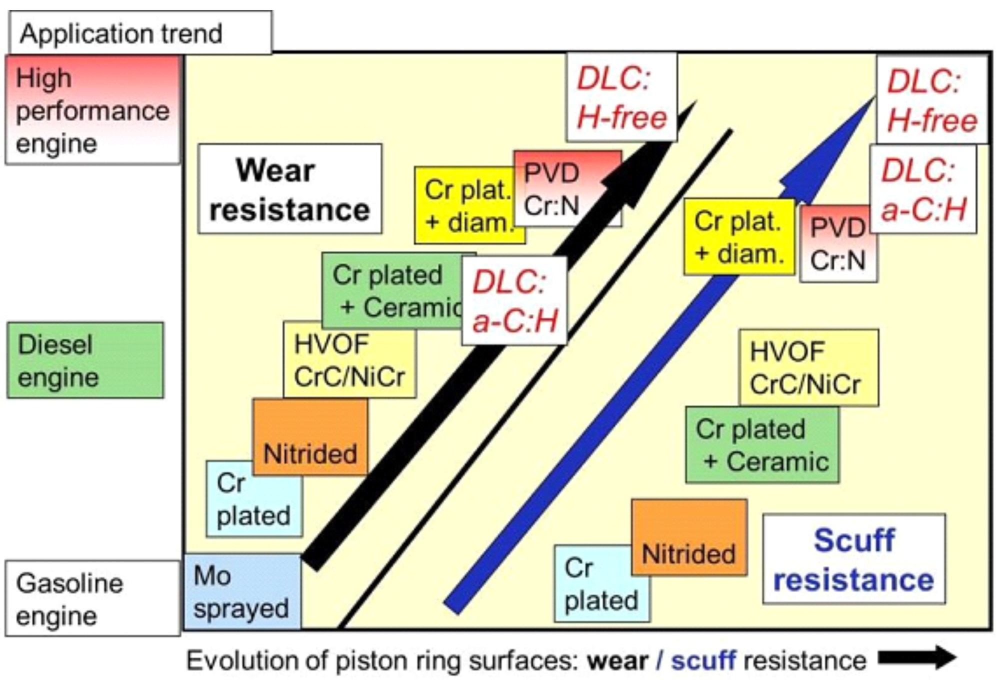

Figure 5. Evolution of piston ring surfaces: wear / scuff resistance [28].

Other examples of coatings and finishes include using the interaction of a lubricant base oil containing a nano-coating with transition metal catalyst that works under severe operating conditions [29] and shot peening cast iron blocks to produce new surfaces that result in significantly lower friction between them and a piston ring [30]. Self-lubricated components using novel coatings could also have similar results. There are currently no good low friction cylinder bore coatings. These would need to have high thermal conductivity for improved heat transfer while being durable, able to cope with thermal expansion of the bore and cost effective to apply during the production process. A change in lubricants was made in the 1950s when multi-grade oils were introduced. Another disruptive change is needed to introduce 'intelligent' oils. Examples include nanotechnology that releases supplemental additives into the oil as they become depleted, using microencapsulation technology, using nanoparticles that form superior protective tribofilms or novel ideas that improve the flat viscosity-temperature profile over a wide temperature range [31]. Ultra-low elasto-hydrodynamic shear strength base oil technologies would also be advantageous as would lower viscosity at cold start. Improved thermal conductivity of oils would remove the heat from combustion more quickly. Oils with greater resistance to forming deposits, particularly in turbochargers, and deposit-resistant coatings that can operate at high temperatures are required. Lubricants used in gasoline direct injection (GDI) engines also suffer from ~1% soot loading, thereby increasing the rate of timing chain wear. Novel methods of soot control are required. All of these are potentially fruitful research directions yielding fuel economy savings between 3 and 6% (0.372 and 0.744 quads).

Currently engine and driveline component surfaces are finished to the micrometer scale and run-in during the initial life of an engine. Developments could be made to improve these surface finishes such that they are specifically developed to the nanometer scale for running in. This would more closely control the quality and finish of the final run-in surfaces, having the potential to improve friction and wear response of the components and potentially extending their useful life.

Reduced losses in bearings and gears also hold promise for reducing vehicle energy consumption. For example, a recent report found that fuel economy savings of up to 2.5% (0.7 quads) in passenger vehicles and heavy trucks could be realized simply by using lower viscosity gear oils [32]. Overall we estimate savings of up to 15% (1.86 quads) could be achieved through the implementation of ideas in this section.

2.6 ADVANCED ENGINE SENSING AND ACTUATION

The traditional internal combustion engine is an assembly of multiple numbers of moving parts that exhibit sliding frictional losses. Throughout the operating range of the engine, the frictional losses span the range from boundary lubrication to fully hydrodynamic. Boundary lubrication is characterized by two sliding surfaces separated by a lubricating fluid that experience simultaneous partial mechanical contact, whereas fully hydrodynamic lubrication is characterized by two sliding surfaces separated by a lubricating fluid without mechanical contact between the surfaces. Machinery interfaces that exhibit boundary lubrication frictional losses are designed utilizing materials, lubricants and surface finishes that provide durability in combination with low friction coefficient. Engine components operating in the hydrodynamic lubrication regime rely much more on the characteristics of the lubricating fluid, in combination with the base design of the bearing surfaces themselves. The crux of the overall engine bearing design is that the modern vehicle engine is a transient machine, often changing speed/load conditions on a second-by-second basis, over a broad operating range. Further, the lubricant degrades as it is exposed to high shear stresses, combustion-created chemical species, engine wear metals, and high temperatures. To ensure a durable engine, the bearing surfaces and lubrication system within the machine are designed to withstand the most severe operating condition that may be encountered for normal engine use. For example, one might consider the conditions encountered when trucking goods from the U.S. East Coast to California, where a modern fully-loaded heavy-duty truck might be required to climb severe grades through the Rocky Mountains and almost immediately travel through desert conditions in Nevada at very high ambient temperatures before entering California. Further, the engine manufacturer must also protect against situations where the engine's lubricating oil has not been changed recently and significant lubricant degradation has occurred. To successfully design and produce an engine that can run at full load in conditions such as those described above, the engine manufacturer has traditionally "over-designed" the bearing systems of the engine. This provides the necessary safety factors for the design but also is designing-in inherent frictional losses for all engine operating conditions less severe than the worst-case scenario. One tribological solution to this design dilemma is the use of modern sensing and actuation. This could be applied to individual sliding components of the engine to allow an agile bearing system that can optimize its design characteristics throughout the operating range of the engine, the life of the engine lubricant, and as a compensatory strategy for mechanical wear of engine components [28,29,30].

The general concept is to utilize local sensing systems to monitor the operation of various bearing surfaces within the engine. For example, a typical journal bearing supporting the crankshaft of the engine might now utilize a local temperature and fluid-film-thickness sensor to monitor bearing performance and risk of bearing failure. In combination with various actuating elements, the lubricant delivery rate might be locally optimized, as could the mechanical bearing system itself. Several technologies have been developed that are representative of the concepts presented above and all are in in the concept stage. For example, Figure 6 [28] shows a method to modulate the lubrication paths to a journal bearing by selecting the number of lubricant supplies fed at any given time, thus controlling effective bearing area and associated maximum bearing load and friction loss.

Alternatively, Figures 7 and 8 [29,30] describe journal bearings that can be mechanically articulated to vary surface area on demand, providing controlled frictional loss characteristics. In Figure 7, the journal bearing is translatable with respect to the spinning shaft, resulting in a variable surface area bearing. In Figure 8, the bearing itself includes a varying area cutout feature (labeled 100 in the Figure), which, when rotated within the overall bearing assembly, can provide a controllable, varying bearing area to the highest loaded region of the journal bearing. This concept allows modulation of the bearing load capacity and its inherent friction loss. In more convenient terms, the mechanism can be adjusted to present itself as a small bearing for light loads and a large bearing for high loads.

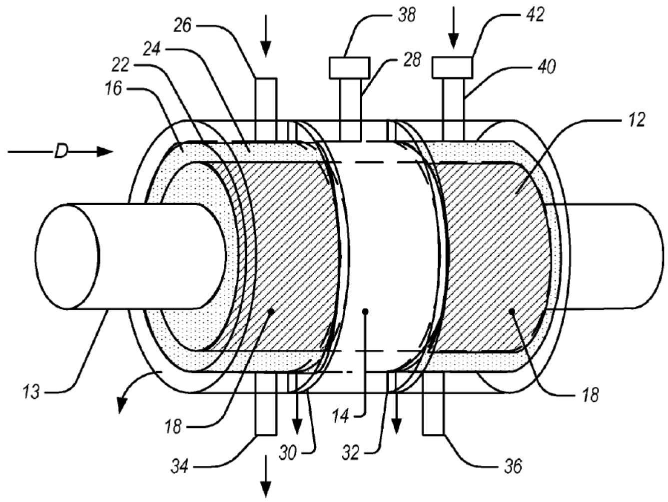

Figure 6. Method of modulating lubricant paths to a journal bearing [28].

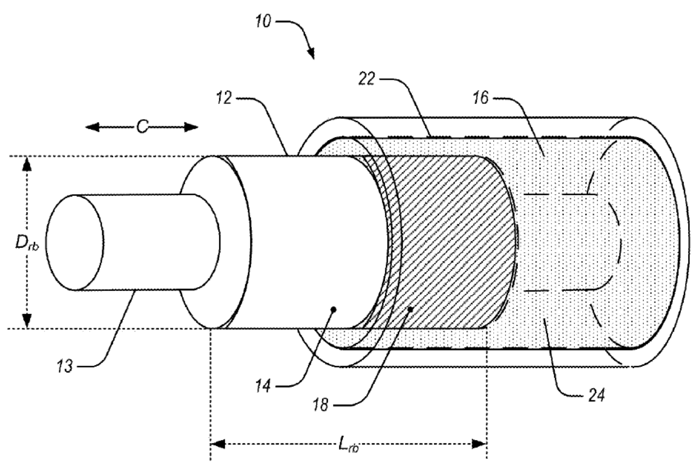

Figure 7. Method 1 to mechanically vary bearing surface area [29].

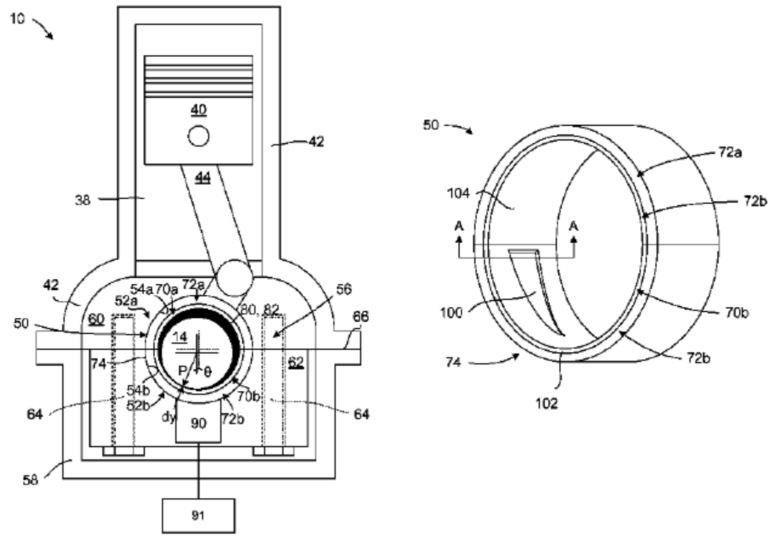

Figure 8. Method 2 to mechanically vary bearing surface area [30].

The frictional losses of modern engines vary over the speed/load range of the engine. Generally, the frictional loss as a percentage of delivered fuel reaches a minimum at high engine load and low speeds. The friction loss is typically about 5% at this condition. This operating point is generally associated with highest engine brake thermal efficiency, where modern engines can exceed 45%. As engine load decreases, or as engine speed increases, the friction loss as a percentage of delivered fuel increases. Frictional losses can increase to levels above 15% at some of these conditions, with engine brake thermal efficiency dropping below 20%. The frictional losses increase due to the mismatch of the bearing sliding surfaces relative to the off-peak engine operating conditions, as described in the earlier sections of this discussion. If application of the proposed sensing and actuation systems could be utilized, the percentage friction loss of the engine could be maintained at the more optimum values nearer 5% due to the on-the-fly matching of best bearing size for all operating conditions. The overall fuel savings available is considerable, in that the large percentage losses at lighter loads and higher speeds could be managed. This fuel savings would be largest for vehicles that spend considerable time at light load, such as modern passenger cars, where the fuel savings could approach 2% (0.25 quads).

2.7 COMPUTATIONALLY-AIDED DESIGN AND MODELING

With the increased use of component coatings in modern engines and drivetrains and the likely move to more advanced lubricants, computationally-guided interface designs are required. This could potentially lead to self-healing, ultra-thin fluid/solid tribofilms with desirable friction and wear properties that persist across the load, speed and temperature ranges of the engine and drivetrain. While high risk and requiring direct nanoscale research to enable this, academic and national laboratory research could be used to bring this to a point where industry could fund work for internal use. The process would need to be cost-competitive, environmentally friendly and eventually scaled up for testing.

The computational models would need to be energy-aware, related to modern science and be a design framework for guiding the R&D process of emergent tribofilms. The outcome would need to maintain or improve durability of components in increasingly magnified power density engines running at increased stresses and temperatures. This would require the development of new R&D processes for combining theoretical modeling and new test methodologies and experimental approaches. These models would need to include wear, friction, pressure, rheology, fluid dynamics, surface roughness profiles and molecular interactions.

To be able to work, development of in situ techniques for interrogating solid-solid interfaces need to be enhanced and developed so that the required input data for the models can be obtained experimentally [36,37]. An improved understanding of the elementary reaction steps would enable novel boundary films to be synthesized. It would allow the design of reactant/substrate combinations to tune film composition and properties in the model. It would be essential to include the compression shear effects on reaction pathways as well as the thermal effects. This requires modeling from a single contact and atomic scale up to predicted material performance and needs to include material properties, lubricant molecular behavior, oxidations, and stress and heat effects on tribo-film formation with the ability to include chemistry of the interacting surfaces into the design process. Development of analytical tribo- and mechanical- chemical rate theories, disentanglement of the thermo- and mechano-chemical effects and addressing non-thermal equilibrium effects is required. This modeling would require input from and will benefit OEMs, their suppliers, lubricant manufacturers, additive suppliers and coating technologists. One particular interface (e.g., ring liner or valvetrain) could be selected. Once benefits of this approach have been shown, it could then be taken by and worked on by industry through a consortium effort for other areas of the engine and drivetrain.

It is predicted that this type of approach could have significant impact on fuel economy as each interacting surface in the engine and drivetrain could be modeled and optimized. Potentially around 10% fuel efficiency improvements could be obtained, equivalent to 10.35 billion gallons of fuel or 1.24 quads of energy per year. In recent work where the focus was the friction reduction in the ring/liner interface, where only a coating on the running face of the piston ring was changed, a 7% saving at that interface was achieved with 50% less liner wear and 28% less ring wear shown through novel experimental methods [38].

2.8 FUEL CONSIDERATIONS

Lubricant interactions with alternative fuels can be an issue. Very little work has been done on how fuels and lubricants interact, particularly in the combustion chamber. There are some U.S. government funded programs looking at fuels, for example the Office of Energy Efficiency and Renewable Energy (EERE) Co-Optima program mentioned earlier [20], which is examining the co-optimization of fuels and engines. However, none of these programs take the further step to consider the role of lubricants. It is predicted that an increasingly diverse market will appear with natural gas, liquefied petroleum gas, dimethoxymethane, dimethyl ether, and naphtha all being considered along with varying levels of ethanol and biofuels [39]. These combust differently, and some percentage of the product creeps past the ring pack into the sump to mix with the lubricant. Both fuel type and engine architecture plays a role in the amount of fuel in the ring pack and the amount creeping past to the sump. Direct injection engines have a higher fuel quantity in the ring pack and hence the sumo, than port injected engines. In addition, lower volatility fuels have a greater tendency to creep past the ring pack into the sump oil. These interactions need to be understood to prevent loss of fuel economy control in vehicles not originally designed to operate with these fuels. This ability for fuels and combustion products to creep past the ring pack could also be used to advantage. Fresh antioxidants could be introduced through the fuel, or friction modifier additives could use the fuel as a direct delivery path to the ring pack to reduce friction in the ring pack [40]. This delivery method has been researched and shown to be promising. However, further research is needed to enhance its effect and make it commercially viable. Work to date suggests that 2–3% fuel economy gains could be achieved (0.37 quads).

2.9 ADDITIONAL CONSIDERATION FOR HEAVY DUTY VEHICLES

Heavy duty (HD) diesel engines operate under higher cylinder pressures than light duty gasoline engines. Engine life is also considerably longer than passenger vehicles, with a half million miles of useful life expected and over a million miles not unusual. Lubricant soot loading in HD engines is also considerably higher than passenger vehicles, typically up to 5%. Much of Sections 2.1–2.8 could be adopted first in light duty and then heavy duty vehicles. One example of design specific considerations for HD trucks is the valvetrain system. The valve springs are 30–40% stiffer than they need to be for normal driving engine speeds. This stiffness allows for potential engine over-speeding when the engine is used as an engine brake, but these stiffer valve springs also increase the frictional losses and energy usage in the truck during normal driving cycles, which is approximately 99.5% of the time. Recent developments have introduced engine architecture that allows the engine to act as a two stroke with no fueling during these braking events, thereby doubling the braking capability of the engine while using non-strengthened valve springs [41]. This is one example of novel technology concepts further improving fuel economy.

2.10 OTHER ENGINE TYPES AND DESIGNS

Almost all the above technologies, after development in the automotive sector, could be used for stationary natural gas engines, small engines for yard maintenance and watersport and generators. The energy saving impact would be considerably lower, but as the technology existed so would the financial investment required to translate it.

Development of completely new engine concepts could also be investigated. A number already exist, and tribological issues such as sealing against high oil consumption need to be investigated and implemented. For example, the Achates Power opposed piston engine has a claimed 30% gasoline and 50% diesel engine efficiency improvement with 10% lower production cost [42], like the rotary 'Extreme Power Internal Combustion' engine [43]. This type of engine will produce high power and torque in a compact, lightweight fuel efficient package. It is under development by the U.S. Navy and predicted to exceed diesel engine power-to-weight ratios by a factor of 10 and turbo-shaft engines by a factor of 2.

2.11 SEALS

Each rotating shaft that enters or leaves a major component in the engine or drivetrain has a seal, typically a lip seal with one or multiple lines of contact. These are designed to keep contaminants out and lubricants in. These seals are made from elastomers and have been in use in the automotive industry since the 1930s. Under normal conditions, the seals run-in and the asperity contacts on the shaft surfaces are smoothed to create a boundary contact regime with a very thin lubricant film.

Parasitic losses in the drivetrain come from four major areas: oil churning, gear contact, bearings and seals. It has been estimated that seals could contribute 5–15% of the total driveline losses. In testing by the Dana Corporation, power loss due to seals was as high as 13% of the total driveline friction under driving conditions [44]. This means for a heavy-duty truck travelling at 100 kph, the seals would contribute 0.7 kW of parasitic drag, which is 0.00002% of total vehicle friction. If this friction could be reduced by 50%, up to 14.9×10^{-6} quad could be saved for the heavy-duty truck industry, and up to 125×10^{-6} quad could be saved for the passenger car industry. Such savings could potentially be achieved through the use of new materials, combinations of materials and shaft coatings and use of these new coatings and materials to permit novel and new designs of seals with reduced contact areas and/or sealing forces.

2.12 TIRES

Tire rolling resistance relates linearly to wheel load. Most passenger car tires sold in the U.S. have a rolling resistance coefficient of 0.007 to 0.014. Therefore, a passenger car with four tires weighing 2,000 kg will have a total rolling resistance of between 30 and 60 Newtons. At 100 km/hr (approximately 60 mph) this equates to a loss of approximately 5 kW [45]. The rolling resistance is due to the hysteretic dissipation of energy in the materials composing the tire and is responsible for about 1/5 of fuel consumption in passenger cars and 1/3 of fuel consumption in heavy trucks. Combined, the tires' rolling resistance losses of ground vehicles consume approximately 2 quads of energy in the U.S. every year, and the tread rubber compound is responsible for about 1/2 of that (1 quad). Depending on the technology used, a reduction in fuel consumption by the tire could negatively impact the tribological functions of the tire such as traction (or friction) on the road, especially in inclement weather, and the wear life of the tire. A recent EERE-funded project completed in 2016 reported the development of tires with improved 5.5% fuel efficiency (0.68 quad) through the use of lighter materials and compounds that reduced hysteresis [46].

The pursuit of improved energy efficiency while retaining grip and wear life characteristics is crucial and requires further materials and design advances. For example, significant fuel economy savings can be made through changing the tire configurations of heavy duty trucks. Replacing the double steel wheel configuration with a single aluminum wheel reduces rolling resistance and un-sprung weight of the vehicle. This approach has been investigated and achieved an average fuel saving of 8.7% (1.08 quad) [47,48].

The key reason that low rolling resistance and high traction are at odds is that hysteresis of the tread material is responsible for both phenomena. However, an ideal tread material will have low hysteresis in the rolling resistance frequency domain (1–100 Hz strain rates) and yet have high energy dissipation in the high-frequency traction domain (10–1,000 kHz strain rates). In the 1990s, with the invention of highly-dispersible silica as a reinforcing nanofiller, there was a dramatic improvement in the compromise between rolling resistance and traction performances, attributable to a decoupling of hysteresis in the two frequency domains, as shown in Figure 9. Through materials, the tire industry is searching for the next breakthrough in tire performance. There are new nanomaterials, ranging in technology readiness levels (TRL) 2 to 5 (TRLs are covered in Chapter 6) that could potentially provide this paradigm shift in performance tradeoffs and expand the performance envelope of the tire. A 20% decrease in rolling resistance of each tire (while preserving the necessary tribological functions of tire tread) would save 0.2 quads of energy per year in the U.S. directly (rolling resistance accounts for approximately 12% of gasoline fuel consumption per vehicle). Furthermore, because the tire is the last part of the fuel-to-ground energy path, reduced rolling resistance drives a "virtuous cycle" in which less engine capacity is needed to deliver the same power to the ground, allowing lighter vehicles and drivetrain components to be used. This is an impact that can be undertaken across the entire vehicle fleet, as all cars require new tires periodically. Assuming a conservative tire replacement frequency of 10 yrs, this translates to 10% of the vehicle fleet replacing tires each year. In one year, 0.02 quads (10% of 0.2 quads) would be saved. In two years, vehicles would be saving 0.04 quads (20% of 0.2 quads) through tire replacement. In five years, 0.10 quads would be saved per year. After 10 years, the full 0.2 quads per year savings would be realized.

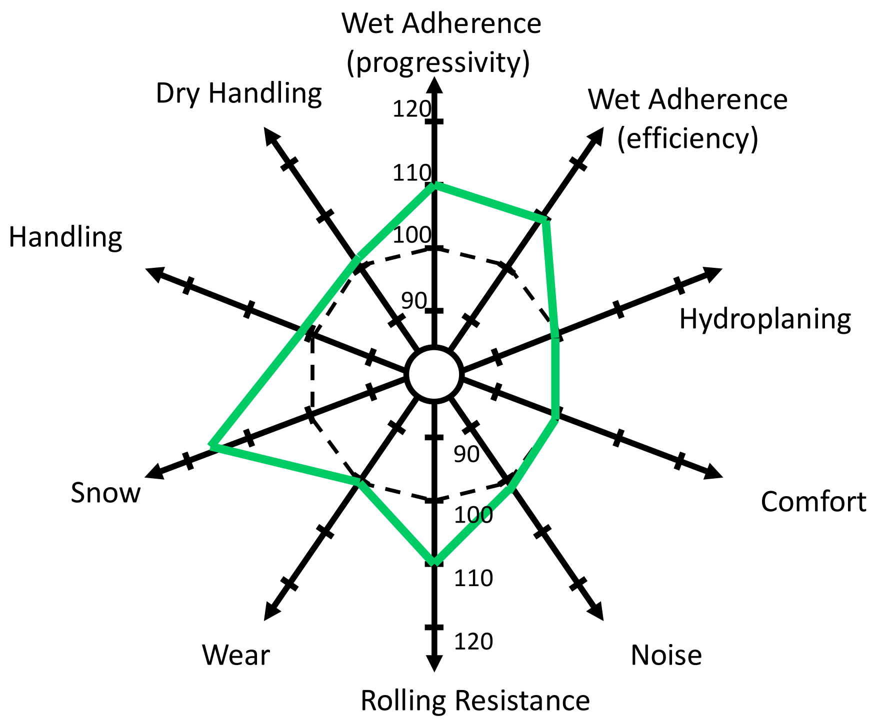

Figure 9. Performance chart (on a basis of 100 points, with higher numbers always better) of traditional carbon black fillers (black dashed line) compared to highly-dispersible silica (solid green line). Traction in wet and snowy conditions increases and rolling resistance in absolute decreases, with no compromise in other necessary tire performances. [49]

2.13 CONNECTED AND AUTONOMOUS VEHICLES

Autonomous driving vehicles are able to 'talk' with each other, allowing traffic flow to increase and become more orderly, reducing travel time and improving fuel economy. This is achieved using multi-objective optimization algorithms and has been shown to theoretically reduce fuel consumption at a 4-way intersection by 75% [50]. However, there are additional savings to be achieved through autonomous driving due to the optimizing of the vehicle speed and direction, which reduces the need for acceleration and braking. These would allow tribological savings to be made in lower power brakes and reduced wear of braking components as well as lower powered engines, stressing the lubricants much less and hence giving less engine wear and longer drain intervals through reduced lubricant degradation. An additional saving is the reduction in energy consumed in manufacturing vehicle components and repairing vehicles after accidents as autonomous vehicle are predicted to have lower accident rates. A number of recent studies have been examined future mobility requirements including connected, autonomous and smart vehicles [51].

2.14 AVIATION

Aviation accounts for 8% [52] (2.08 quads) of the U.S. energy consumption in the transportation sector, which is estimated to be 26 quads annually [53]. Most of the energy consumption in aviation which can be affected by tribology is associated with the performance and efficiency of the gas turbine engines that power aircraft. Tribology plays a major role in the shaft support bearings and lubrication systems which operate under extreme stresses, speeds and temperatures. Decades of development have resulted in high temperature bearing steels and synthetic ester-based aviation oils, which subsequently have provided highly beneficial spin-offs to other transportation and non-transportation sectors. Such spin-offs have, and should continue to be, a major benefit of actions taken in aviation.

Today, the cost of fuel and the impact of CO_2 emissions are major incentives for aggressive action to improve efficiency. New aircraft today are 70% more efficient than 40 years ago, and 20% more efficient than 10 years ago. Tribology technologies for engines have enabled these improvements through continued advances in bearing steels, high thermal stability oils, carbon shaft seals and abradable gas path tip seals. Now, after two decades of development, Pratt & Whitney is launching a new generation of geared turbofan engines which operate with 15% less fuel [54]. A planetary gear system separates the engine fan from the low pressure compressor and turbine. A slower and optimized fan speed significantly lowers fuel consumption, along with noise and emissions. Many enabling tribology challenges involving gear materials, bearings and thermal management had to be solved to achieve a reliable high power density fan drive gear system for the marketplace. The ultra-high speed planetary gear system used in these engines, which are lubricated with engine oil formulations, greatly intensifies the role of tribology for current and future generations of high efficiency propulsion systems.

In addition to the introduction of these new geared turbofans, the U.S. aircraft gas turbine industry is currently pursuing engine designs to reduce the total fuel consumption by 25% using variable cycle engines [55-57]. Even higher fuel saving using more revolutionary concepts are now on the drawing board. To achieve these fuel reduction levels requires turbine engines with improved thermodynamic efficiency. This means rotors that turn faster, higher pressure ratios, and higher engine cycle temperatures. In turn, this requires significant improvements in bearing steels, the development of novel high temperature lubricants, and better design tools for bearings, gears, and the lubrication system. As a result, the tribology of mechanical components that support the engine becomes a critical enabling technology. Without the development of the improvements in the tribological system, the projected fuel savings cannot be achieved.

For improved design, there is a great need to advance the elastohydrodynamic lubrication models used in bearing and gear analytical codes. Additionally, bearing and gear codes need to be seamlessly integrated into the overall engine design process. Improved tribology modeling is an aspect where universities can excel, but this aspect is currently not being tapped. Deeper integration and coordination between universities, government laboratories, small businesses, bearing steel suppliers, oil companies, and engine manufacturers is required for advancement in bearing and gear steels, development of novel high temperature lubricants, advanced seals (conventional and liftoff), and improved design methodology to meet the challenges. This action will enable the design of gas turbines that can meet the fuel savings projections and also maintain U.S. leadership in this key technical area. The high efficiency geared turbofans and the variable cycle engines on the horizon are bringing the aviation tribology journey to a critical and challenging stage.

The development and application of elastohydrodynamic theory, traction modeling and boundary lubrication during the two-decade period from 1960–1980 created the enabling tribology for aviation bearing and gear steels, high temperature synthetic oils, and first generation aviation design tools, some of which are still being used today. Many of these aviation propulsion successes were the result of leadership actions from NASA and the DOD. Pushing the state-of-the-art in the 1990s and 2000s started to produce some painful experiences and the realization that advancing technologies for performance and efficiency involving tribology were high risk ventures. There are few, though powerful, traditional lubrication mechanisms that must overcome a multitude of failure mechanisms that come into play at the extremes of operation. For aviation engine bearings, operating at high temperatures and speeds, the number of failure mechanisms actually grows when engines are required to operate on wing continually for many years. Extended operation results in issues like the thermodynamic decay of the martensite structure within the bearing steel. Also, one of the lessons learned is that the development of bearing and gear steels must be done *in conjunction with* the development of aviation oils. The formulators of aviation oils now have the dilemma of balancing the preferred anti-wear (AW) attributes for bearings with the needed extreme pressure (EP) attributes for gears. The mysteries and complexities of the lubrication and failure mechanisms embedded within the critical contacts of the components in service make it difficult to adequately represent tribology in design to the level expected for sophisticated aviation design practices.

So, out of necessity, the industry began to utilize the NASA Technology Readiness Level (TRL) stages of development and maturity measures to reduce risk (see Section 5.8). In recent years the TRL approach has been rigorously applied to the development of tribology for critical aviation components. New simulation testing and tribology modeling capabilities are starting to become available to substantially reduce risk and to accelerate tribology innovations that are urgently needed for energy efficient propulsion and drive systems. Advanced bearing and gear steels with innovative thermal-mechanical processing and surface technologies, along with unconventional base stock and additive technologies for lubricants, present new opportunities. Nanotechnology adds a new dimension to the mix for both designing and testing material structures, and understanding and characterizing lubrication mechanisms. Aviation material and oil suppliers believe the five-year to ten-year development cycle (from TRL 1 to TRL 6) can now be substantially reduced.

The aviation tribology journey, which brings us to the next generation fuel-efficient geared turbofans and future variable cycle engines, has an inherent problem that can be addressed by ARPA-E. Aviation tribology is not adequately integrated into aviation component and system design at present. Advances in bearing and gear materials, engineered surfaces, and advanced lubricants still come with high risk. The development of TRL 4 simulation testing and physics-based empirical modeling is needed to overcome "the valley of death" discussed in Section 5.8 for the transition of new tribology technologies into the marketplace. The aviation tribology community is also suffering from an aging workforce that has acquired a high level of multidisciplinary experience (this is discussed further in Chapter 7). Through several decades of major advances in aviation tribology, the center of gravity for expertise and active engagement has shifted among engine OEMs, NASA, DOD, suppliers, and academic institutions. Today, there is no clear central organizational driving force. There is also an inadequate critical mass of multi-disciplined tribologists devoted to aviation tribology. ARPA-E can play a role through a demonstration project that links simulation testing and tribology modeling with innovative materials and lubricants to achieve advanced component performance that actually becomes realized in the marketplace. The proposed approach has some similarity to the computationally-aided design and modeling discussed in Section 2.7. The major difference here is that for aviation the focus is on lubricated Hertzian contacts which are the heart and soul of highly stressed long-life aviation bearing and gear components. The significance of this action is that it is a paradigm shift in the process of tribology development which more effectively links the research and supplier communities with the OEMs. This is the key to solving "the valley of death" problem discussed above.

The needs and opportunities for aviation tribology for fuel efficiency are clear. Some actions, like special test methodologies and modeling, are already underway. Because of the reliability requirements and infrastructure associated with aviation propulsion systems, the introduction of new aviation tribology in service will be a staged process. Advanced oil formulations for bearings and gears are expected to be near-term, along with new high alloy steels formed using advanced thermal-mechanical processing. Next-generation oils with high temperature base stocks are far term, along with tribology-enabled new component designs. The recommended ARPA-E actions can greatly improve time-to-market and reduce development risk. These actions are required to achieve the anticipated 25% fuel efficiency improvement for the variable cycle engines on the horizon. They will also provide further improvements in fuel efficiency for next generation geared turbofan engines that follow the geared propulsion systems currently being launched. A reasonable estimate of the energy savings through tribology for aviation is 20% of the total consumption attributed to aviation in the transportation sector (20% of 2.08 quads), which is 0.42 quads.

2.15 MARINE

Much of the previous sections can be used for the maritime industry which, by volume of fuel consumed, operates large to very large diesel engines. According to the Bureau of Transportation Statistics, in 2010 more than 62,000 ocean-going transport vessels called at U.S. ports and carried $1.7 trillion worth of goods. Water transportation in 2010 directly contributed $36 billion and 64,000 jobs [58]. In 2012, the total amount of fuel energy consumed in the U.S.

Emissions Control Areas (generally extending 200 miles beyond the coastline) was estimated to be 0.15 quad [59]. A 2% fuel savings, along the lines of similar discussions in this chapter, would yield a reduction of 0.003 quad.

The marine pleasure craft engines typically fall into categories that would exist in the automotive world, but due to the volume present, they do not represent a significant fraction. The emphasis remains on the large ship industry, where per-cylinder displacements exceed 30 liters and can be as large as 1800 liters per cylinder. These large engines fall into the Category 3 emissions control under the 2010 EPA ruling. This ruling limits sulfur content in the fuel in the emission control areas (ECA) to 1000 ppm [60], but international maritime law allows 3,500 ppm in the open ocean. Sulfur is a natural lubricity enhancer and therefore its reduced levels can increase fuel pump and engine component wear. Some port cities, such as Los Angeles, further limit the fuel choice to ultra low sulfur diesel (ULSD) or liquefied natural gas (LNG) while the ships are within 25 miles of the port. These increase both the alternative fuel handling requirements of the ship and the necessary emissions control devices.

Currently CO_2 emissions from maritime shipping contribute 4–5% of the total worldwide. Design changes to engines to meet the demand for increased fuel economy and multi-fuel requirements may include longer stroke lengths, down-speeding, turbocharger cutout at part or low power demand and reduced crankcase lubricant consumption. All these may occur while still maintaining low cylinder bore wear rates of 0.03 mm per 1000 operational hours [61]. Lubricants for maritime shipping are not changed in the engines in the same way as for terrestrial vehicles; fresh oil is added to top up to the fill level on a periodic basis. This creates a completely different set of requirements for the lubricant formulator, and the above proposed design changes pose significant challenges for lubricant formulators, specifically with the reduced sulfur levels. Use of novel lubricants in conjunction with coatings on engine components are likely to be required to meet these demands for improved efficiency. This approach could yield a 2% fuel saving (0.003 quad).

2.16 RAILROADS

Along with DOE, the Department of Transportation's Volpe Center supports research and development in railway development and efficiency. Much of the previous sections of this chapter can also be used for the rail industry, which operates large heavy duty diesel engines and maintains track durability and tieing. The 25,000 rail freight locomotives used in 2012 consumed 3,600 million gallons of fuel with an average of 476 ton-miles per gallon of fuel consumed [62].

Besides the fuel saving strategies discussed in this chapter, which if 2% fuel saving was achieved would save 7.2 million gallons of fuel (0.001 quads[2]), there are indirect savings that could be achieved through reliability. Often a train will have three engines, one of which is solely used as a spare in case one of the other two fails. If reliability was improved, then one of the engines

[2] 2% of 3,600 million gallons equates to 7.2 million gallons. 1 Gallon gasoline = 120,000 BTU, $1x10^{15}$ BTU = 1 quad

would not be needed, thereby saving fuel. In addition, if the train length is 100 cars, stipulated by siding lengths, then that is one more car of freight that could be moved instead of a spare engine. This would equate to a further 1% (0.0005 quad equivalent) fuel saving.

Many studies have been undertaken into the unique wheel-track interface of railway systems notably by Sheffield University in the UK [63] and Argonne National Labs in the U.S. [64]. Unlike tires, the high strength steel wheels used on railroads do not deform and are therefore highly efficient when the cross-sectional (profile) shape of both are correct. However, wheelset misalignment and rubbing flanges increase fuel consumption significantly and poor rail and wheel profile matches often cause wear, fatigue and other defects requiring unscheduled maintenance and replacement. Quite aside from the increased fuel consumption, the replacement of wheel and track requires their manufacture, transport and installation all of which consumes additional energy. This has the potential to save more than 2% fuel (0.001 quads) of energy annually [63]. By combining increased reliability, fuel savings in the engines and fuel savings in the wheel-track alignment, a total of 0.0025 quads could be saved in the rail freight industry.

SUMMARY

- Continued efforts in improved engine technology that enable the use of reduced viscosity lubricants combined with novel additives have the potential to save 0.62 quads per year.
- 2.48 quads per year could be saved through component design and optimization of vehicle engines.
- Designing the engines and the lubricants in tandem is believed to have a potential 1.4 quads of energy saving per year.
- An annual saving of 0.744 quads is achievable through the use and development of advanced coating and finishes in engine and drivetrain components.
- The use of advanced sensors in engines and drivetrains for responses to specific engine parameters has the potential to save a further 0.25 quads of energy annually.
- Developments in modeling to include the friction, wear, pressure, rheology, fluid dynamics, surface roughness and hardness and molecular interaction of the lubricant is predicted to save 1.24 quads of energy annually once used for engine and drivetrain design and development.
- Development of lubricant/fuel interaction programs, similar to the co-optima program for fuel-engine interactions, would yield 0.37 quads of energy annually.
- Development of next generation tires with reduced rolling resistance without compromising ride and safety would yield 0.2 quads of energy saving per year, once all tires had been replaced.
- Advanced aviation engines on the horizon with variable flow configurations offer 25% improvement in fuel efficiency. These engines, along with next generation geared turbofan engines, require advances in bearing and gear tribology. The anticipated energy savings in aviation is 0.42 quads.
- Marine pleasure crafts and commercial shipping can save 0.003 quads of energy per year through the use of advanced coatings and lubricants, however, with the imminent reduction in fuel sulfur content, investment is required to prevent increased engine wear rates in the near future.
- Railroads require tribology research into improved engine reliability and rail-wheel interactions to save 0.0025 quads of energy per year.

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Chapter 3
Opportunities in the Power Generation Sector

3.1 INTRODUCTION

In 2015, the U.S. generated 4,078 TWh of electricity. The major energy sources and their percentage share of total U.S. electricity generation are show in Figure 10. Notably, due to the recent addition of gas-fired combined cycle generating plants, natural gas and coal now have similar shares of 33%. Of the renewable energy, wind was 4.7%, biomass and waste was 1.6%, solar was 1.0% and geothermal was 0.4% [1].

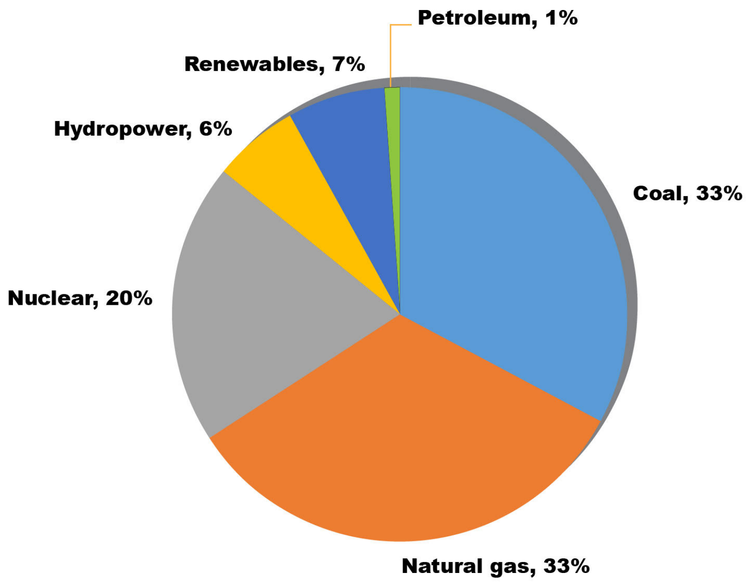
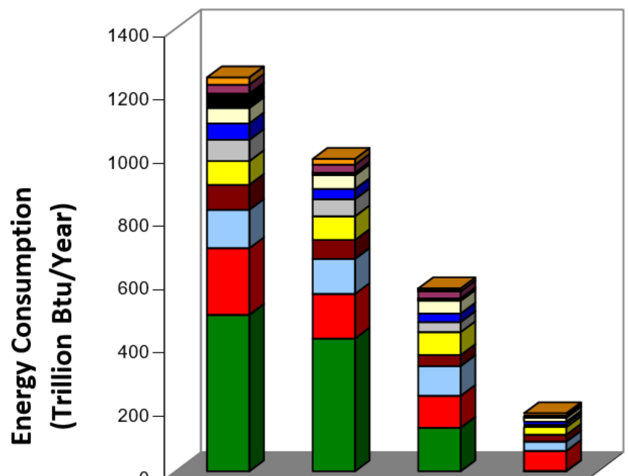


Figure 10. Major energy sources and percentage share of total U.S. electricity generation in 2015 [1].

There are key opportunities for reducing energy losses in the power sector throughout the supply chain, from primary energy resource production to electricity generation and distribution. Rotating and sliding components are found throughout the power generation sector, such as in steam and gas turbines, hydroturbines, generators, pumps, conveyors, coal mining machines, drilling and production equipment for liquid natural gas (LNG). Lower viscosity lubricants (oils and greases) tailored to the specific application combined with novel materials and coatings have the potential to have significant energy savings throughout the industry. In addition, improved sealing technologies, which provide adequate sealing while reducing frictional losses, will also help reduce energy loss. Coal gasification, oxygen plants and syngas processing for advanced integrated gasification combined cycle (IGCC) generation plants require pumps and material transport equipment, all of which will benefit from tribology research to improve efficiency and extend life. As outlined below, collectively we estimate roughly 4.02 quads of energy can be saved annually in the U.S. through the development of technologies supported by tribology research

3.2 MINING, PROCESSING AND TRANSPORTING COAL (AND URANIUM)

While the use of coal for power generation is declining in the U.S. due to cost pressure from natural gas in combined cycle gas turbine electricity generation and due to environmental concerns over coal combustion, it will remain a large part of U.S. electricity generation in the foreseeable future. Figure 11 shows that 485.2 TBtu/yr (1.66 quad) of electricity was used in the coal mining industry in 2006, and the potential improvements that could be made–in part through tribology–are shown by equipment category.



	Current	Best Practice	Practical Minimum	Theoretical Minimum
Blasting	24	18	10	5
Dewatering	28	25	23	7
Separations	46	8	7	2
Electric Equipment	48	43	40	13
Crushing	52	32	27	8
Drilling	67	54	32	9
Ancillary Operations	75	75	72	24
Digging	79	60	35	22
Ventilation	122	111	94	29
Materials Handling-Diesel	211	141	101	63
Grinding	494	420	138	2

Figure 11. Energy consumption by equipment category in coal mining industry in 2006 [3].

Tribology plays a significant role in the mining, processing and transportation of coal, and tribological improvements can lead to significant energy savings through efficiency improvement and improving the durability of equipment. The mining, processing and transportation of coal is included in Chapter 4 (4.4 Mining and Extraction) along with metals and industrial materials.

3.3 DRILLING FOR, PRODUCING AND TRANSPORTING NATURAL GAS.

The extraction of natural gas and oil from shale using directional drilling and hydraulic fracturing has dramatically increased the commercially available reserves of both gas and oil in the U.S. In 2015, 33% of the electricity generated in the U.S. was using natural gas [1], provided by 555,364 gas wells [4], and natural gas is predicted to produce more electricity than coal in 2017 [5]. This technology has reversed the climb in imports of crude oil to the extent that the U.S. could be a net exporter of oil or oil products in less than ten years [6]. At the same time, the increasing use of natural gas in the combined cycle gas turbine (CCGT) generation of electricity has dramatically reduced the cost of electricity and carbon emissions associated with electricity generation. Tribology plays a major role in both gas extraction and delivery by pipeline, and efficiency and durability will continue to improve through tribology research.

Drilling and production technology continues to develop rapidly, in terms of drilling speed, length of the horizontal sections and effectiveness of hydraulic fracturing and refracturing for gas and oil extraction. Drilling speed depends on an understanding of the tribology of the drill bits, either rotary or scraping, in terms of the rate of rock cutting and the number of trips required to replace worn or broken drill bits or to bypass stuck bits. The energy expended in this process is high and depends directly on the overall rate of progress of the drilling plan, which in turn is highly dependent on downhole tribology. In the horizontal section, which can extend several kilometers, the eventual length is limited by the friction of the drill pipe moving on the bottom of the horizontal hole. The size of cuttings needs to be small to allow extraction with the drilling mud (lubricant) without interfering with the drilling progress. Downhole motors driven by drilling mud pressure have universal joint systems and bearings that are very sensitive to the downhole environment of temperature, pressure and contamination. Tribology is a vital component of successful drilling for oil and gas through the use of coatings to reduce wear, efficient low friction coatings to allow material removal at lower energy loss and environmentally acceptable additives in the drilling muds to aid with reducing wear and friction at the drilling interface. Tribology of drilling muds can also be improved to help cool, lubricate and support the bit and drilling assembly [7].

Natural gas is mostly delivered to market via pipelines where the transportation energy is provided by large compressors powered either from the pipeline gas being used to power gas turbines or natural gas engines or by electricity from the grid. Pressures in pipelines are up to 10 MPa, and tribology plays a significant role in the efficiency and durability of the compressors and the turbines, engines and electric motors. Advanced tribological coatings can also be used on the pipeline walls to reduce the viscous drag between the gas and the walls. For long distance transmission of natural gas, and even for shorter distances when strong opposition to new pipelines is encountered, gas may be liquefied and transported in rail cars or tankers as LNG. Methane condenses at -162°C, and such cryogenic refrigeration requires turbocompressors and pumps that can operate effectively and efficiently under very low temperature conditions. There is a great opportunity for advanced tribology to improve the operation of such low-temperature devices. On site storage of gas as LNG is used in a growing number of CCGT facilities to ensure that gas is available to meet the electricity demand when other demands on pipeline gas, such as for domestic heating in winter, take preference and reduce supply for generation. The operation of LNG tankers for gas export also entails advance tribology in engines and other onboard equipment.

Using advanced tribology in the drilling equipment, pumps, engines and transportation of natural gas has the potential to save levels similar to those that predicted to be achieved in the transport sector. 28.3 quads of the U.S. energy was provided by natural gas in 2015 [8] and if we assume it takes 10% of this energy to extract and transport natural gas, a 5% saving, equivalent to 0.14 quad, is predicted.

3.4 STEAM AND GAS TURBINES FOR ELECTRICITY GENERATION

Steam turbines are widely used to convert heat energy to mechanical energy to drive electricity generators. They can be used as standalone units with steam from boilers heated by burning coal, natural gas or biomass, by nuclear reactors, by geothermal heat or by solar thermal energy. They can also be used in combined cycle units using the exhaust heat from gas turbines to generate additional electricity. Combined cycle units now have thermal efficiencies of greater than 60% [9], which is a big increase over the typical 30–40% of standalone units. Modern steam turbines now have output up to 2 GW and operate under extreme conditions, with supercritical steam to 620°C and pressures of 30 MPa (4350 psi) [9]. Tribology plays a role in all aspects of steam turbine operation from the lubrication and efficient operation of radial and thrust hydrodynamic bearings to the protection of blade tips operating at supersonic speeds and operating as steam seals against the housing to maximize turbine efficiency.

CCGTs are the fastest growing form of electricity generation in the U.S., with growth rates exceeding 4% per annum. This is especially the case where gas is plentiful and inexpensive from shale formations, if the gas is accessible by pipeline. In many U.S. locations, electricity generated by CCGT has undercut all other forms of energy on price, resulting in the closure of coal plants and even nuclear plants. CCGT combines a gas turbine (Brayton cycle) with a steam turbine (Rankine cycle) where the exhaust heat from the gas turbine is used to generate steam for the steam turbine. The combined thermal efficiency is greater than 55%, with about two thirds coming from the gas turbine and one third from the steam turbine. Siemens currently advertises its SCT5-8000H CCGT [10] system as the world's most efficient electricity generation unit with a 60.75% thermal efficiency. A further advantage of CCGT units operating on natural gas is that they produce less than 40% of the CO_2 of a coal fired plant for a given amount of electricity generated. This is due to a combination of high thermal efficiency and the roughly four times higher carbon to hydrogen ration of methane versus coal, which produces a higher steam to CO_2 ratio in the exhaust. CCGTs can use other fuels–e.g., hydrogen from syngas–possibly with much higher temperature and efficiency if fed with O_2 (no NO_x production). Turbines can also use hot, high pressure gas without combustion–e.g., helium from nuclear VHTR.

Tribology is an essential consideration in the design of higher power, higher efficiency turbines that can operate at the higher temperatures in supercritical plants. Tribology focus areas for steam turbines include design of hydrodynamic thrust and journal bearings with improved stability at high speeds, higher temperature capability and improved efficiency. New bearing materials for higher temperature operation are needed, as current Babbit alloy faced bearings are reaching their temperature limit. Savings could potentially be made if rolling or gas bearings were developed for these temperatures. New lubricants are needed to improve the efficiency of bearings through reduced viscosity change with temperature, and improved lubricant rheology data for input into computer bearing models will optimize efficiency and minimize wear over the range of operating conditions. The lubricants need to be stable at higher temperatures, protect against the formation of deposits, inhibit corrosion, have improved water and air separation, and have no tendency to cause foam. In addition, new materials and designs are needed to improve seal technology and to reduce erosive damage. Sealing applications range from unlubricated steam path seals to lubricant seals. Improved erosive wear resistance on rotor and stator blades and nozzles is needed to allow the higher operating temperatures and pressures for improved turbine thermodynamic efficiency.

3.5 VERY HIGH TEMPERATURE GAS NUCLEAR REACTORS (VHTR)

The Generation IV International Forum (GIIF) is developing six, generation IV nuclear reactors. One of these is the very high temperature gas reactor (VHTR), which will be helium cooled and operate at temperatures of 900–1000°C. This reactor will generate electricity and can be combined with processes such as the sulfur-iodine process to produce hydrogen [11]. VHTR projects are currently in progress in the U.S., France, South Africa, China and Japan.

This is such a new and novel area that we are unable to give a prediction of the energy saving potential using tribology as an enabling technology in the design of high temperature helium turbines and compressors. These technologies would be similar to those discussed for steam and gas turbines. However, this would be an additional benefit from this research.

3.6 CO_2 CAPTURE AND STORAGE (CCS)

Electricity generation contributes to about 40% of global anthropogenic CO_2 emissions. Rapid growth of coal-fired generation in India and China will significantly increase global CO_2 even though emissions are falling in developed countries. Inexpensive coal and gas plus high costs and little political will means that the move to non-CO_2 sources will be slow. The Intergovernmental Panel on Climate Change (IPCC) identified CO_2 carbon capture and storage (CCS) as a critical technology for greenhouse gas stabilization. The world currently produces about 35 GT per year, and the International Energy Agency (IEA) estimates viable global CO_2 storage of 16,800 GT in saline aquifers, depleted gas fields, shallow coal seams, and deep ocean for enhanced oil recovery [12]. Research is also being conducted into the conversion of CO_2 into commercial products. Besides power generation, other industries such as cement mills, refineries and chemical plants emit CO_2, and non-transportation sources produce about 20 GT per year. There are around 30 demonstration power generation CCS projects [13]. Disruptive tribology technologies include development of lubricants and coatings for inexpensive and reliable CO_2 compressors.

3.7 WIND TURBINES

The U.S. Energy Information Administration (EIA) determined wind energy production in the U.S. was 1.8 quads in 2015 [14], approximately 1.9% of total U.S. annual energy consumption and 21% of annual renewable energy production [15] (Figure 12), figures that are expected to continue to rise rapidly in the next few years. A recent comprehensive and highly cited peer-reviewed publication forecasts that an all-renewable U.S. energy portfolio in 2030 would consist of 50% wind energy production, corresponding to 42.3 quads of energy production per year [16] in the U.S.

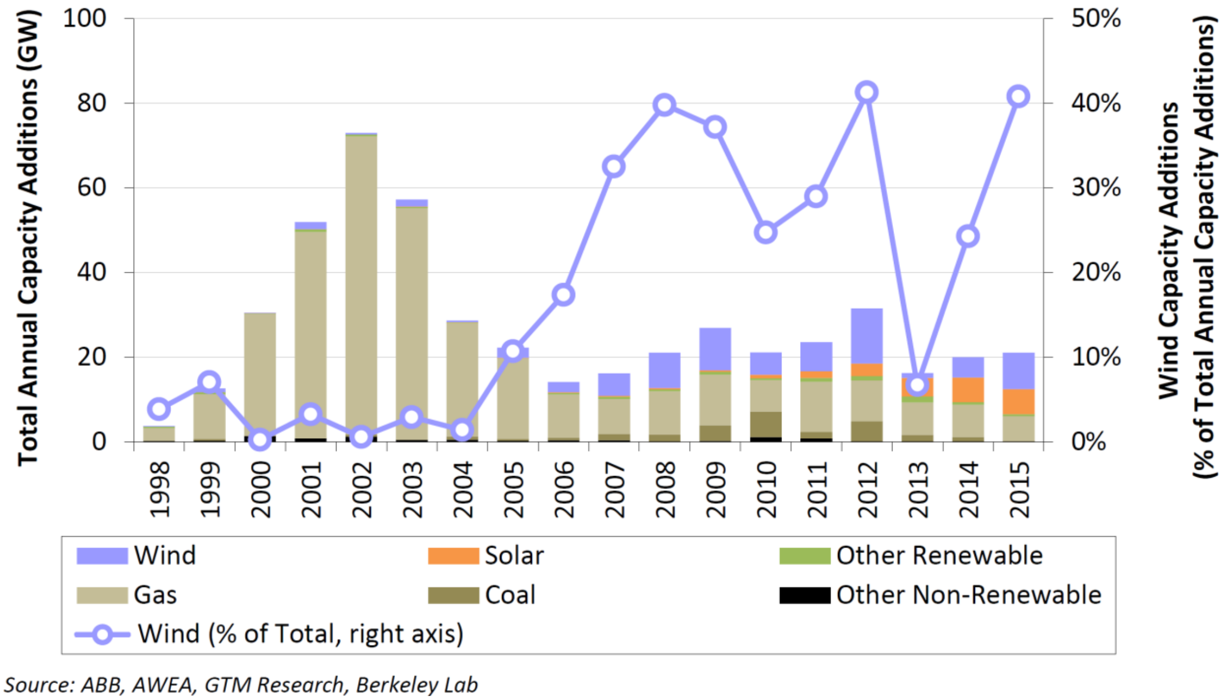


Figure 12. Plot of total annual capacity additions to U.S. electrical grids, 1998–2015.

Wind energy installation in the U.S. has significantly increased in the last decade (Figure 12), representing 31% of the total U.S. capacity additions. In some recent years, this outpaced all other additions to the electrical grid [14]. However, compared to other electrical generation sources, wind presents significant challenges when it comes to operations and maintenance (O&M) and the impact that O&M activities have on the levelized cost of energy (LCOE). While data about O&M costs are not consistent across the industry, some estimates report O&M costs for wind to be around 20% of total LCOE while LCOE for natural gas combustion is about 5% [17]. A significant portion of the O&M costs for wind is due to the maintenance and reliability challenges that are unique to wind compared to other electrical generation. This is mainly due to the simple fact that a wind farm/plant is composed of hundreds of individual turbines with an average nameplate capacity of a couple of megawatts, spread across rural areas or even possibly offshore. Furthermore, a conventional utility scale wind turbine is composed of thousands of moving parts, most of which are in the drivetrain and located in the nacelle on top of a tower that is 80–100 meters tall. A typical drivetrain consists of a main bearing, a three-stage gearbox (with a 1:100 speed increaser ratio), and the electrical generator (Figure 13). Additional major moving components are in the blade pitch mechanism and the nacelle yaw positioning system. All of these components involve contacting surfaces in relative motion and are often grease or oil lubricated.

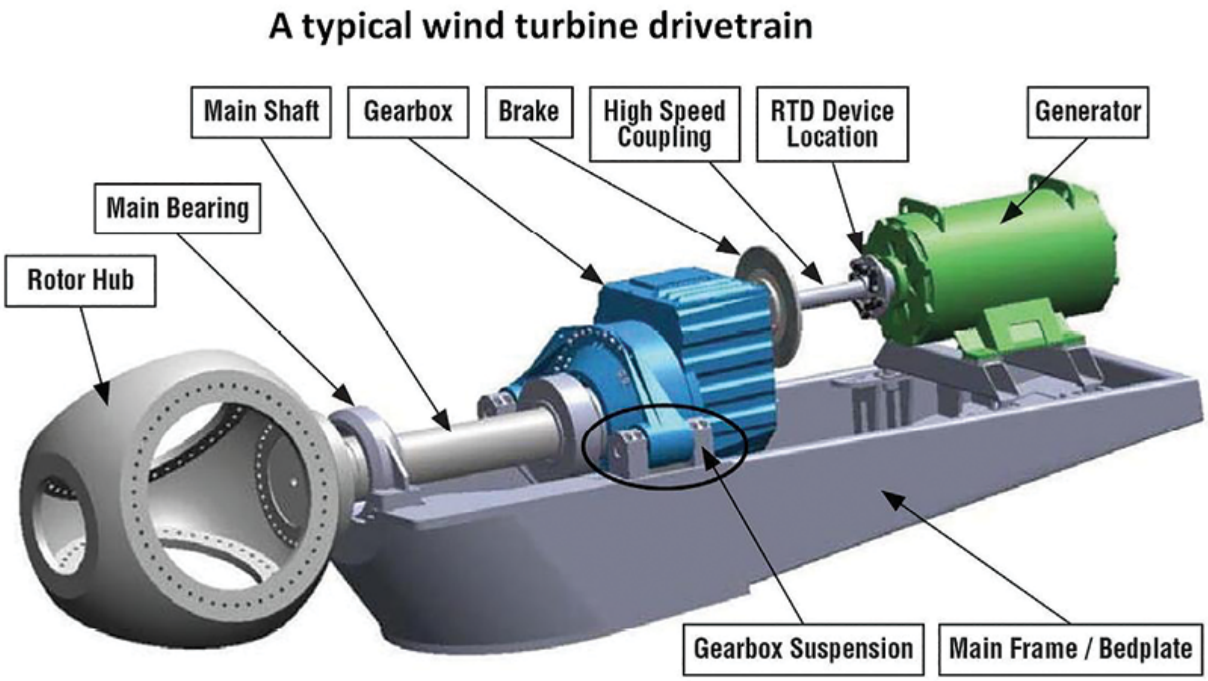


Figure 13. Schematic of a typical wind turbine drivetrain.

The unsteady operation of the turbine, due to wind fluctuations, grid faults, and emergency stops, present additional challenges in predicting the loads at the contact and designing the system for reliable operation. Figure 14 shows the resulting turbine downtime associated with specific subsystem failures, it also indicates that most of these subsystems are often related to tribological issues. In order for wind generation to cost effectively maximize energy production, the complex tribological system of wind turbines requires significant reliability and efficiency advancements. A literature study reveals that replacing an offshore gearbox might lead to months of downtime, and costs might sum up to one million euro for a 6 MW wind turbine. [18].

The potential to significantly improve wind energy production through tribology innovation is significant and may be divided into two general categories:

1. Increasing reliability and efficiency of existing machinery. For example, the development of novel coating materials and lubrication formulations that reduce maintenance intervals and costly downtime. Significant investments by lubricant companies have dramatically improved

this in recent years; however, further research into novel lubricants and coatings and their compatibility has the potential to make a significant impact in this area.

2. Developing novel technologies that enable more cost effective and efficient drivetrain design alternatives. For example, the development of electrical contact technology that obviates the need for rare earth metals in direct drive wind generators, a key strategic challenge identified by the U.S. DOE in a 2011 Critical Materials Strategies report [19]. Such contacts would require suitable tribological solutions to ensure reduced wear levels.

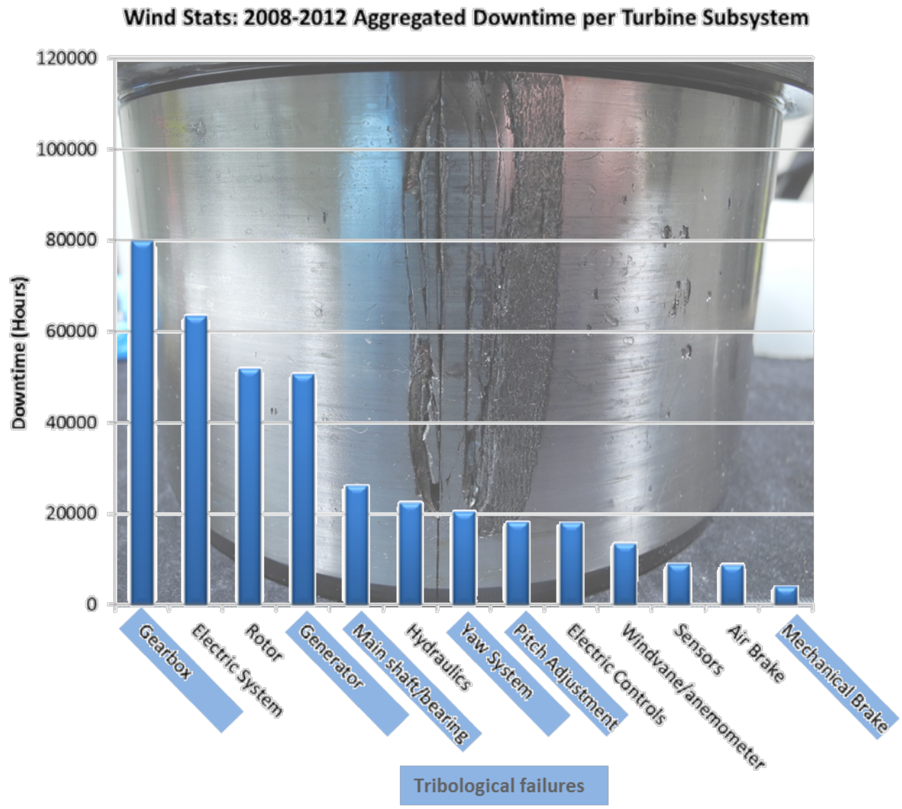


Figure 14. Plot of Aggregated downtime per turbine subsystem.

Mechanical losses in modern wind turbines are primarily confined to gearboxes through viscous drag of lubricated gears. Viscous losses were estimated to be about 3% of rated output for a 5 MW turbine [20]. The U.S. EIA reported annual wind energy production of 1.8 quads in 2015, and a 3% savings amounts to about 0.05 quad/year in potential savings by reducing viscous losses. By comparison, bearing losses in a similar system were estimated to be about 0.01% of rated output. A key value proposition for tribology research is in the improvement of reliability. While there are clear and substantial O&M cost reduction opportunities through increased reliability, we will focus our ensuing discussion on energy savings only. However, the effect of reducing maintenance costs on the proliferation of wind power is crucial to a more general discussion of value proposition for tribology research; in other words, energy savings measures omit the impact of reduced cost of energy generation.

The reliability of a wind turbine can be characterized using two parameters, the capacity and availability factors. The capacity factor is the percentage of time that a wind turbine can produce power–i.e., a measure of wind availability. The availability factor is a measure of reliability, the percentage of time that the wind turbine generates power when there is wind available for it to do so. The U.S. EIA estimated mean annual capacity factor for U.S. wind turbines in 2015 to be 32%. Availability factors differ significantly for onshore and offshore wind farms, with values as high as 98% for onshore and as low as 80% for offshore wind farms [21]. The lower figure for offshore farms is attributed to the added logistical complexities of servicing equipment in often remote and environmentally challenging locations.

A reduction in availability results from combined maintenance (planned) and system failure (forced) downtime. A 2013 analysis of wind turbine reliability found that most failures are associated with wear of tribological components and a progressive reduction in reliability with increasing turbine size [22]. As turbine sizes continue to rise [23] in response to demand for access to more abundant, higher efficiency offshore wind, developing higher reliability and efficiency tribology-related technologies will be critical to continued expansion of wind power.

The current opportunity for R&D, focused on improving tribological failures in wind turbine drivetrains, was recently outlined in a DOE workshop report [24]. The report highlights challenges related to identifying and characterizing contact failures and opportunities in lubrication, coatings and surface treatments. The predominant contact failure mode in wind turbine gearboxes is referred to as axial cracks or white-etching cracks (WECs). The WECs are the major cause–and fundamental root cause–of premature bearing failure in wind turbines, and methods for experimental testing are a matter of ongoing research. The report outlined that further research is needed to characterize the failure mode and to test material based mitigation technologies. The report also outlined the importance for further development and understanding of proper lubricant and surface treatments in all tribological systems of the wind turbine to optimize cost effective reliability improvements. For instance, diamond-like carbon (DLC) coatings can be used to treat bearings for improved pitting, scuffing, and wear.

Based on 2015 U.S. EIA reported annual production values [14] shown in Figure 15, we estimate that energy savings between 0.05 to 0.18 quads per year may be achieved through reductions in both maintenance downtime requirements (i.e., wear rates), and the frequency and probability of tribological system failure in wind turbines. Looking ahead and relying on estimates like those provided by Jacobson and Delucchi [16], the potential annual energy savings figures are forecast to grow rapidly into multiple quads per year over the next two decades, particularly if offshore outpaces onshore energy harvesting.

Potential avenues exist for substantial energy savings through the development of non-incremental technologies, enabling higher efficiency power generation. One aspect of this value proposition is in the improvement of wind turbine efficiencies at low wind speeds. Analyses [20,13] of the most widely used wind turbine generator topologies (i.e., squirrel-cage induction (SCIG), permanent magnet synchronous (PMSG) and doubly-fed induction generators (DIG)) show that there is a rapid drop-off in total generator efficiency to < 90% for wind speeds below about 10 m/s (approximately 22 mph) [20]; calculated efficiency curves as a function of wind speed and typical wind speed profiles are shown in Figure 16. PMSGs hold a clear advantage [19], however, there are economic challenges that stand in the way of widespread adoption, and these are discussed below.

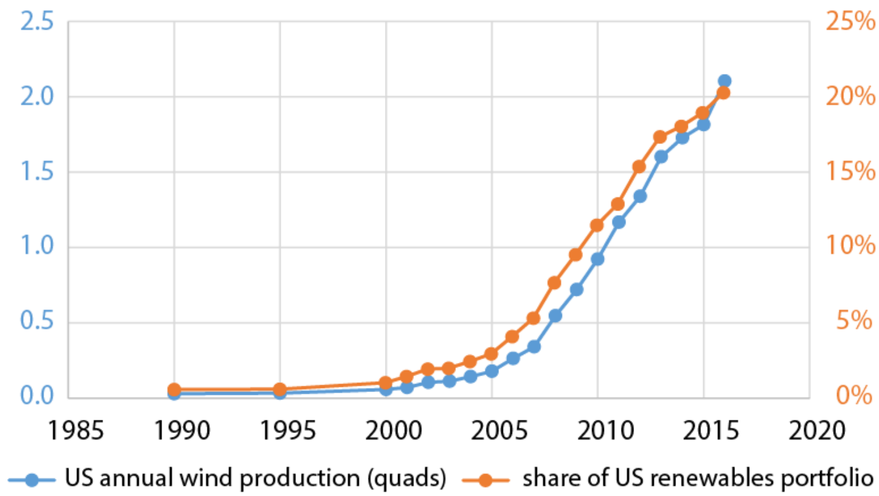


Figure 15. U.S. EIA annual wind energy production in quads and the corresponding percent of total annual renewable energy generation in the U.S. [14].

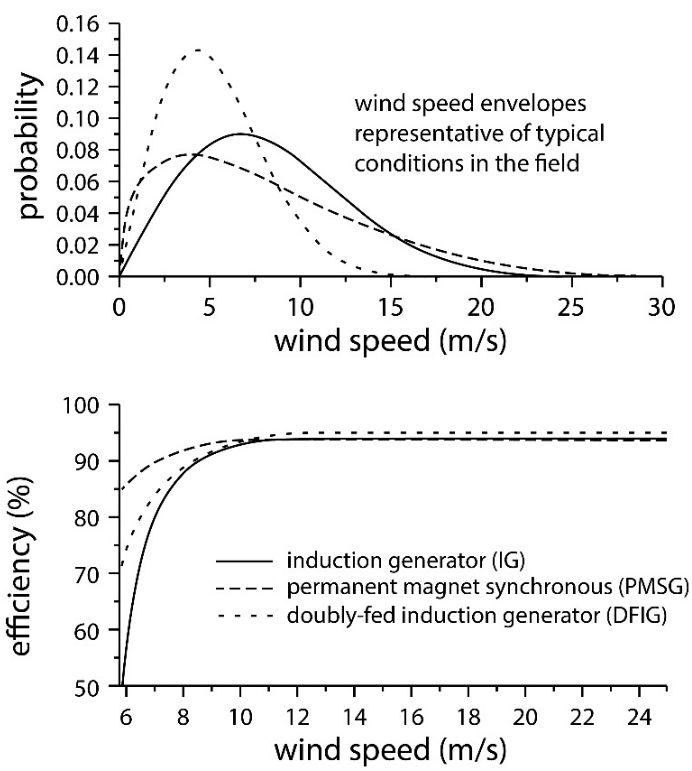


Figure 16. (Top) Three typical Weibull distributions of wind speeds and (bottom) calculated turbine efficiency as a function of wind speed [20].

In presently state-of-the-art 3 MW DFIG turbines, gearbox losses were found to be the primary source of unwanted energy loss, amounting to nearly 6.5% drop in generator efficiency, or 70% of total losses for these systems. These figures convey the clear advantage of direct-drive systems, even ignoring reliability challenges posed by gearboxes, addressed earlier [22,23]. However, the only viable direct-drive systems are PMSGs, which are built using an economically prohibitive amount of rare earth metals. The need to obviate rare earth metals in power generation technologies was identified by the U.S. DOE as a Critical Materials Strategy [24] in 2011, primarily due to an intractable dependence on foreign supply chains having a history of price and availability volatility.

The development of higher efficiency transmissions and alternative "power take-off" technologies for direct-drive synchronous generators has the potential to take advantage of otherwise wasted energy equivalent to approximately 5–10% of total annual renewable energy production. Based on 2015 production estimates of 1.8 quads/year [25], this amounts to 0.05–0.18 quad/year of potential energy savings through targeted innovation of tribological systems in wind turbine generators. This figure is similar in magnitude to previously estimated values achievable by improving reliability and availability.

The outcomes of innovation efforts aimed at improving the reliability and efficiency of wind turbine generators have direct and significant impact potential in other key industries. A prominent example of research synergy is the potential for guiding and informing the design of next-generation powertrains for electric vehicles, another rapidly growing market where innovation will significantly impact market growth, technology maturation and energy savings. Based on a 2015 U.S. EIA figure of 27.7 quads of energy expended on transportation (Figure 1, the LLNL energy flow chart), a cursory analysis suggests a growing opportunity for energy savings by improving the efficiency and reliability of vehicle electric motors. If we assume a modest improvement of 5% may be achieved through similar routes proposed for wind turbine generators, the potential for energy savings will be substantially greater than 1 quad in a fully-electric transportation sector. The value proposition of tribology research is clearly strong today, and will only continue to grow.

3.8 TRIBOLOGY NEEDS FOR OTHER RENEWABLE ENERGY

There are many other renewable energy technologies available where vast improvements in the unique tribological challenges could be achieved. This would both improve efficiency of current designs and also allow new technologies to become viable.

For example, solar thermal power with heat storage requires actuators for heliostats or parabolic mirrors to work reliably. Molten salt pumps are required for high temperature power towers, and materials and coating to resist the corrosion are required. These same coatings and materials would benefit hydroelectricity and wave, tide and ocean current power generation along with improved hydraulic fluids able to withstand wave stresses and corrosive environments. Geothermal power will also benefit from advanced tribology with advanced directional drilling and hydrofracturing for hot dry rocks.

Solar cells are often not operating at their rated production capacity due to the cell surface being partly obscured by dirt or a thin layer of material. Development of tribological films and coatings that repel dirt, both solids and liquids, from the surface of the solar cells will allow them to operate at full capacity. It is unknown exactly how many solar cells are installed in the U.S., but is estimated that 25 GW of installed photovoltaic capacity was present at the end of 2015 [26] producing 51.7 TWh of power [27]. Each 1% improvement in power generation would equate to a half TWh of power per year. This is equivalent to 3.41 btu/w-h (0.0017 quads per year).

3.9 EQUIPMENT FOR A MODERN ELECTRICITY GRID

Much of the current equipment used for electricity distribution will need to be replaced to create the smart grid envisaged by technology leaders in the field. Some of these will require advances in tribology, including reliable motor-operated switches and circuit-breakers, which require only occasional use but must reliably function when required to do so. Novel coatings and greases will be required. Cooling systems will also be required for the high power generators. Development of materials, coating and lubricants that will work at the cryogenic temperatures is required. Also, refrigeration systems and cryogenic pumps for liquid nitrogen-cooled superconducting transmission lines and superconducting magnetic energy storage rings will required advanced tribological engineering to optimize efficient energy output. In this case, advanced tribology will be used as a technology enabler, rather than directly as an energy saving technology.

SUMMARY

- Full credit for tribology improvements giving a 1% efficiency gain in power generation equals 0.38 quads of energy produced per year.
- Partial credit for enabling technology to increase average thermal conversion efficiency from 33% in 2015 to 55% in 2035, progressively reducing losses from 25.4 quads per year in 2015 to 10.3 quads per year in 2035, equals 0.76 quads of energy produced per year. Assuming a 5% credit for tribology advances leading to this enabling technology corresponds to 0.04 quads produced per year.
- It is difficult to put a value on tribology advances in renewable energy except perhaps in the area of wind energy where producing an additional 1 quad of energy annually is deemed realistic.
- Estimated total energy savings from tribology advances in power generation are estimated to enable 0.42 quads of additional energy produced per year.
- An additional credit for tribology advances leading to improved carbon capture storage cannot be characterized in terms of annual energy savings, but is important for national climate change goals. A 5% credit for tribology advances leading to enabling technology to capture, compress and store 100% of the 20 GT annual emissions of CO_2 from stationary sources around the world amounts to 1 GT of CO_2 per year.

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Chapter 4
Opportunities in the Industrial and Manufacturing Sector

4.1 INTRODUCTION

Energy prices impact the drive for efficiencies in the Industrial and Manufacturing Sector, with 'cheap' energy prices creating less of a drive than 'higher' energy prices. The environmental impact of energy production and the indirect costs to society are likely to make energy usage in the Industrial and Manufacturing sector a future critical issue [1]. Significant energy savings, in the region of 3.2 quads, are possible in these sectors with the use of the disruptive tribology solutions described in this chapter. Business response to energy prices must not be the sole driver behind investment if long term real solutions are to be explored that can benefit the industry and society as a whole and help make U.S. manufacturing competitive in the world market. This chapter will look at some of the key areas where savings can be made in the Industrial and Manufacturing sector.

4.2 MATERIAL PROCESSING

Pulp and paper making require large amounts of energy. The friction losses in an average paper machine equate to 44.8 TJ (42.5×10^{-6} quads) per year and are distributed as shown in Figure 17 [2].

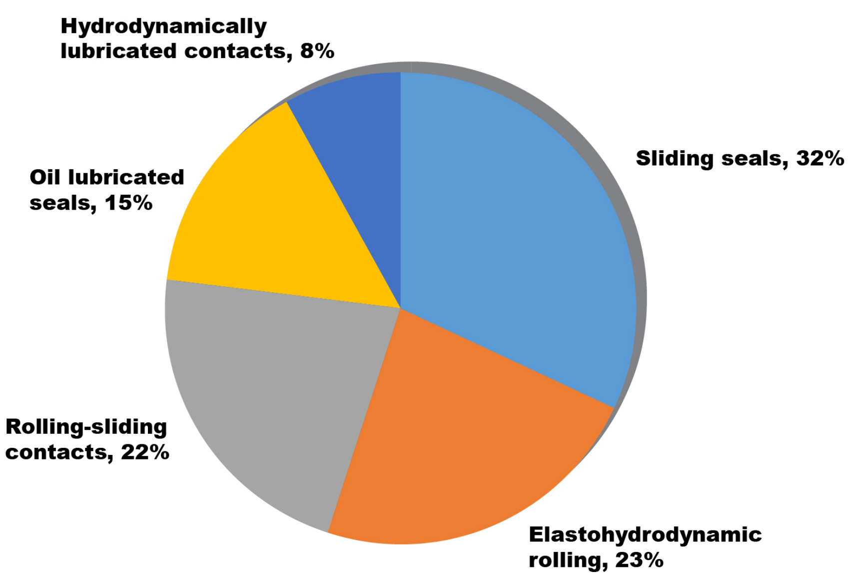


Figure 17. Distribution of frictional losses in a paper machine [2].

By taking advantage of new technologies for friction reduction in paper machines, friction losses could be reduced by 11% in the short term (10 years) and 23.6% in the long term (20–25 years) [2]. This equates to 0.00045 quads based on 450 machines in the U.S. [3]. Potential tribological solutions for reducing friction include highly durable, ultra-low friction coatings, low viscosity and low shear lubricants with novel additives and improved sealing materials.

Other areas of similar processing include tree harvesting, debarking, chipping and pulping. Similar savings through the same tribological solutions are also possible, giving 0.0018 quads (4 areas * 0.00045 quads).

Food processing is also a large energy consumer. Any size-reducing process involves erosion and abrasion, as does the simple process of moving things from one place to another. An estimated 520 billion Btu/yr is used by conveyors, which through careful choice of lubricant, roller materials and design could be reduced by 5%, equating to 88×10^{-6} quads per year (1 quad = 1×10^{15} BTU).

4.3 METAL WORKING

There are a number of areas in the metal working field where improvements could be made in energy conservation. There is a fine line between scheduled maintenance costs due to down time and down time due to unscheduled maintenance/ failures. Studies that could predict this would be highly beneficial. Many OEMs do not shut down plants for scheduled maintenance, thereby losing money when unscheduled shut downs occur and staff are on pay while waiting to return to full operation. Scheduled shut downs would permit parts to be available for a multitude of maintenance events and for staff to be at home instead of sitting idly at work, thereby improving morale and potentially productivity. As it wears, tooling affects the quality of the finished products and scheduled maintenance can be used to maintain quality.

Other areas that could see improvement are the machining lubricants, although current EPA legislation makes bringing new additives to market both expensive and time consuming. There are millions of operators across the U.S. using machine tools that all require lubricants and cutting tools. Closer collaboration between machine manufacturers, operators, tool manufacturers and lubricant suppliers would find many optimizations and energy saving opportunities. One possible approach to controlling friction in machining is to consider coatings and finishing of the tools and increased use of cryogenic machining. Research in this field is only just beginning so it is difficult to estimate quad savings.

Chatter is the self-excitement through frictional stick and slip events of the machine tool and workpiece. This is normally found in turning and milling operations, and the presence of chatter reduces both cutting speed and quality and also reduces tool life. Besides testing of new coatings, materials and finishes, advanced models could assist; however, they currently lack reliable friction data that accounts for the vibrations of the mating surfaces. Also of consideration would be the time-dependent variables that must be precisely measured and correlated with friction, including area of contact, speed, load, combined surface roughness, geometry and ambient temperatures and humidity [4].

Finishing processes have significant tribological losses. Hot rolling is the most tribologically inefficient and presents high potential for efficiency improvements through the practical use of tribological solutions. It is difficult to define potential energy gains due to lack of research in this area and an unknown number of machine tools and workshops. However, it is estimated that energy savings of 5% could be achieved (0.05 quads).

4.4 MINING AND EXTRACTION

Mining involves three basic sets of operation: extraction, material handling, and beneficiation (crushing, grinding and separation) and processing. In total 1,522.1 Trillion Btu (5.2 quads) of energy was used in 2006 [5]. In 2014, the U.S. had roughly 1,000 mines and 3,320 quarries [mining journal on-line, 2014] and the value of coal, metals and industrial materials mined in the U.S. in 2015 was $109.6 billion [6]. The U.S. produced 12% of the world's mineral raw materials in 2016, placing it as the world's second biggest producer [7].

Surface mining employs a variety of heavy equipment for removal and replacement of the overburden and extraction of coal, metals and industrial minerals. These include walking draglines, bucket wheel excavators, power shovels, bulldozers, conveyer belts and very heavy trucks. Each of these will benefit from advances in tribology in terms of both improved efficiency and extended equipment life in the particulate-laden environment. The life of the cutting, grinding and scraping surfaces in direct contact with rock depends on the wear of the contacting surfaces, and the energy involved in parts replacement can be greatly reduced through improved materials.

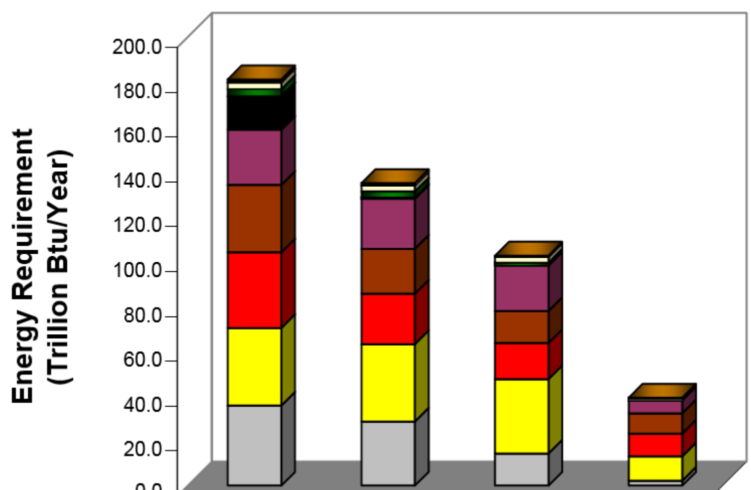
Modern longwall underground coal mining uses highly complex mining machines with either rotary cutting heads for thick coal seams or shearers for shallow seams. These are combined with movable hydraulic roof supports to protect man and machines and conveyer belts to remove the vast quantities of coal produced. Tribology plays a critical role through lubricants, wearing surfaces and seals in the dusty and dirty conditions of the mining process. For room and pillar mining, rock drills for blasting and equipment for moving extracted material to the surface all require effective tribological design for continued operation. Failure rates are high, resulting in lost production and energy wasted in manufacturing replacement parts.

Processing and transport of the extracted material requires conveyer belts, crushers, pulverizers and loading machines to fill trains, barges or ships. Again, these consume large amounts of energy, much of which is to overcome friction losses in the machines and contact with the mined material results in high levels of wear and parts replacement.

Figure 18 shows the energy required for mineral mining only and the savings obtainable in this area with standard practices and the dramatic savings that could be made through the use of advanced tribological and mechanical consideration [5]. Grinding is by far the most energy intensive process in all mining operations, comprising over 40% of all energy use in U.S. mining. More than 50% of potential energy savings identified through improvements would come from making grinding more efficient in both coal and metals mining. Thus, a significant fraction of energy could be realized through tribology research into grinding and related operations. The energy consumed by U.S. mining comes from diesel (34%), electricity (32%), natural gas (22%), coal (10%) and gasoline (2%) [8].

Trains and trucks were discussed in Chapter 2, and many of the same technologies could also be used in heavy mining equipment. In fact, material handling through diesel truck transportation represents the second largest category of energy consumption in U.S. mining after grinding [5]. Conveyors can be improved through the use of tribologically aware choices of coatings and lubricants, and jaw crushers and grinding mills can also benefit from careful materials and coatings choices and hydraulic lubricant development. Maintenance programs are often not well defined or followed in these fields, resulting in increased breakage of parts and, when lubricant change intervals are not observed, increased frictional losses and wear can occur due to lubricant oxidation and contamination. In addition to this, the Tribological mechanisms in the mining industry are usually more severe due to very high loading conditions, high levels of dust and often humid environments [9]. An excellent overview of global energy consumption due to friction and wear in the mining industry, along with potential world energy savings through the use of surface treatments, coating and lubricants for reduced wear and frictional losses is given by K. Homberg *et al* in [9].

If the savings shown in Figure 18 are valid across all mining activities, the potential savings in the U.S. would be on the order of 77%, equivalent to 3.1 quads ($3.1x10^{15}$ BTU) per year in saved energy. The theoretical minimum in Figure 18 includes use of best practices in maintenance, lubricant choices, material choices and use of latest modern equipment as well as use of improved coatings.



	Current	Basic Practice	Practical Minimum	Theoretical Minimum
Blasting	1.3	1.0	0.5	0.3
Electric Equipment	3.1	2.8	2.5	0.7
Grinding	3.2	2.7	0.9	0.0
Separations	14.9	0.6	0.5	0.1
Dewatering	24.6	22.2	20.2	5.8
Digging	30.1	20.1	14.3	9.0
Diesel Equipment	33.7	22.5	16.1	10.1
Ancillary Operations	34.5	34.5	33.3	10.9
Drilling	35.8	28.6	14.3	2.2

Figure 18. Energy requirements for the mineral mining industry in 2006 [5].

4.5 REDUCING WEAR OF MATERIALS

New experimental tools such as in situ tribology and simulation methods of large-scale molecular dynamics are converging. This allows tribologists to 'see' the sliding interface, which is leading to new breakthroughs in understanding wear, corrosion and mechano-chemistry. If this new understanding is used to design and develop systems with ultra-low wear, it will reduce the need to manufacture replacement parts, reduce down time and potentially decrease accidents due to breakages. The U.S. uses approximately 7 Billion tons (1.0 quad) of raw material in one year, much of which is imported [10]. If 5% of this was saved by reducing wear rates, 0.05 quads would be saved per annum (1.0 quad x 5%).

SUMMARY

- Machine losses in pulp and paper making through friction reduction in paper machines and additional strategies applied to tree harvesting could lead to a reduction of 0.0018 quads consumed annually.
- Energy consumed for metalworking operations could be reduced through improved metalworking lubricants, tool coatings, and improved finishing processes, by an amount roughly estimated to be 0.05 quads annually.
- Mining operations are energy intensive. Machinery used in mining for drilling rock and for extracting, handling, and processing materials is subject to large loads and often harsh conditions, with high associated failure rates. Grinding is a particularly energy-intensive process that has not been deeply studied for optimization. Improvements through tribological technology are estimated to be able to reduce energy use in mining by up to 3.1 quads annually.
- Fundamental understanding of wear has long been lacking, but new insights are emerging. Reduced wear would not only enhance safety and industrial efficiency, it would also reduce the need to process new materials to replace worn out parts. Much raw material is important to the U.S. so while the domestic savings through reduced energy consumption are modest (0.05 quads annually), globally the impact is much larger.

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Chapter 5
Other Opportunities: Nanotechnology, Materials and Novel Approaches

5.1 INTRODUCTION

Nanotechnology, innovative materials and other novel approaches to tribology for energy savings were discussed at the workshop and also considered in our online surveys. This chapter presents the results. In general, there is an abundance of highly innovative, disruptive, high-risk and potentially transformative ways that novel materials and nanotechnology can be brought to bear for tribological solutions to better energy security. Laboratory demonstrations and prototypes exist, but technology transfer to scalable, reliable and commercially viable products is a key challenge, fitting with ARPA-E's mission.

5.2 NEMS SWITCHES

Semiconductor transistors used in digital technology have influenced nearly every aspect of modern life. Their performance-to-cost ratio has improved by many orders of magnitude as they have been scaled down in size over the last 50 years. But these switches are now approaching their fundamental limits. As operating voltage is lowered, threshold voltage must also be lowered. Consequently, the devices tend to experience increased leakage due to a minimum subthreshold leakage swing, characteristic of 60 mV per decade, as shown on the left of Figure 23(a). This results in enormous inefficiency of metal-oxide semiconductor field-effect transistors (MOSFETs), which will annually consume many quads of energy in the coming decade unless solutions to this problem are found [1].

As also represented in Figure 19(a), the subthreshold characteristic can be reduced to 1 mV per decade or less by making a nanoelectromechanical systems (NEMS) switch. A typical MOSFET and a generic NEMS switch design are shown in Figure 19(b) and (c), respectively. NEMS switches are recognized as an important avenue for addressing the leakage problem in a 2015 report by industry experts [2].

However, operational reliability is seen as their Achilles heel [2]. This is because although they exhibit a tremendous improvement in leakage, the NEMS switch must reliably make and break mechanical and electrical contact for trillions of cycles. The interface at which this occurs is schematically represented in the Figure 19(c). Tribological issues during this process include the formation of an electrically resistive tribopolymer (TP), wear and adhesion, all of which are exacerbated as cycling continues. These can cause the device to fail, and thus cause calculation or sensing errors.

While the switch works up to millions to billions of cycles, there is a great need to conduct research to develop new materials, environments and processing methods that can meet the requirements of trillions of cycles and reduce wear, without failure. Extensive research is also needed to develop modeling methods that can successfully determine the underlying mechanisms of TP formation. We assess the current technology level at TRL 3.

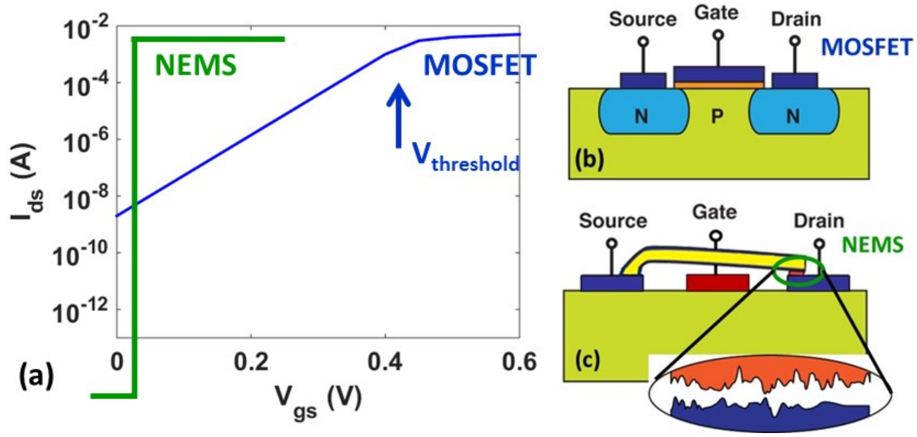

Figure 19. (a) Electrical characteristics of a MOSFET and a NEMS switch. (b) Typical MOSFET design. (c) Generic NEMS switch design. [2]

High performance computers are widely used today in diverse applications such as weather forecasting, aerodynamics calculations, probabilistic analysis, military assessments, forest fire management, nuclear stockpile stewardship, and to fundamental materials research. Areas of intense interest and research today are big data analytics and machine learning. Advances in these fields transform massive amounts of data into insights used to predict, anticipate, inform, and advise. Development of reliable NEMS through tribological research will aid all these areas and more, and permit energy savings in all computers. Figure 20 [1] shows that the total amount of energy consumed will be more than 100 quads by the year 2035, if growth in computation continues at the current rate. The current worldwide usage is already in the order of 1.0 quad.

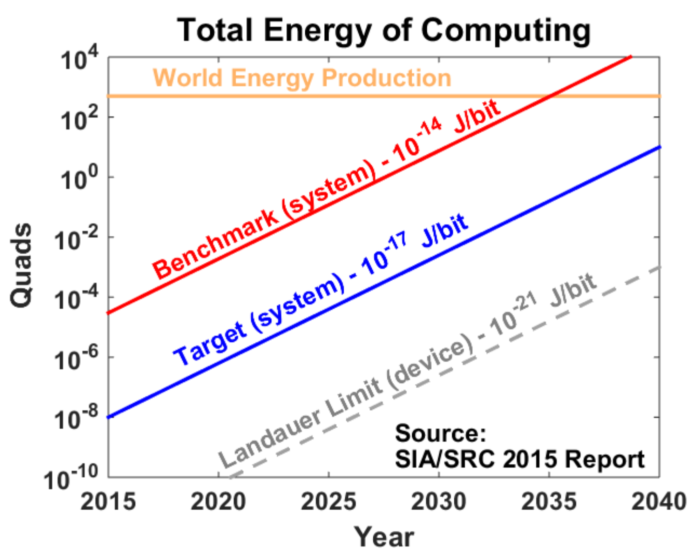

Figure 20. Total energy use of computing 2015–2040 [3].

Below we present two different assessments of annual U.S. computational energy consumption for the years 2016, 2025, and 2035.

Assessment 1: There is a strong trend towards Field Programmable Gate Arrays (FPGAs) over Application Specific Integrated Circuits (ASICs) for advanced computing. FPGAs are programmable *and re*-programmable *after* manufacture (no upfront design required). There are currently 200 million FPGAs in active use [3]. In 2025, we conservatively estimate there will be 1 billion high performance processors used in the U.S. A simple calculation of annual energy consumption (AEC) due to high performance computation is as follows:

$$(AEC) = (Number\ of\ Processors) \bullet (Watts\ per\ processor) \bullet Duty\ Cycle \bullet \frac{3.2\ 10^7\ s}{year} \bullet \frac{1\ Quad}{10^{18}\ Joule}$$

Therefore, the power consumed by each is 100 Watts, and each will be run at a duty cycle of 30%. Accordingly, AEC = $(10^9)\bullet(10^2)\bullet(0.3)\bullet(3.2\bullet10^7)/10^{18}$ = 0.95 quads in 2025.

Assessment 2: Koomey's work [4] provides another method to estimate the total power of computation based on a careful literature examination. Data centers (DCs) are widely used by industry and by internet service providers to enable communications and sharing of computational resources indicates data centers worldwide consumed 140 billion kWh/year in 2005, Figure 21. This equates with 0.5 quads of energy:

$$\frac{140 \bullet 10^9\ \text{kWh}}{\text{year}} \bullet \frac{3.6 \bullet 10^6\ \text{Joules}}{\text{kWh}} \bullet \frac{1\ \text{Quad}}{10^{18}\ \text{Joules}} = \frac{0.5\ \text{Quads}}{\text{year}}\ (\text{in year 2005})$$

Approximately 35% of DC installations are in the U.S. At a growth rate of 15% per year [4], predicted growth rate is shown in Figure 22. By the year 2025, this will consume 2.0 quads per year. Note that this represents the amount of computational power from data centers only.

The circuits in both the above assessments currently employ leaky MOSFETs. We estimate up to 90% energy savings could be achieved using NEMS switches.

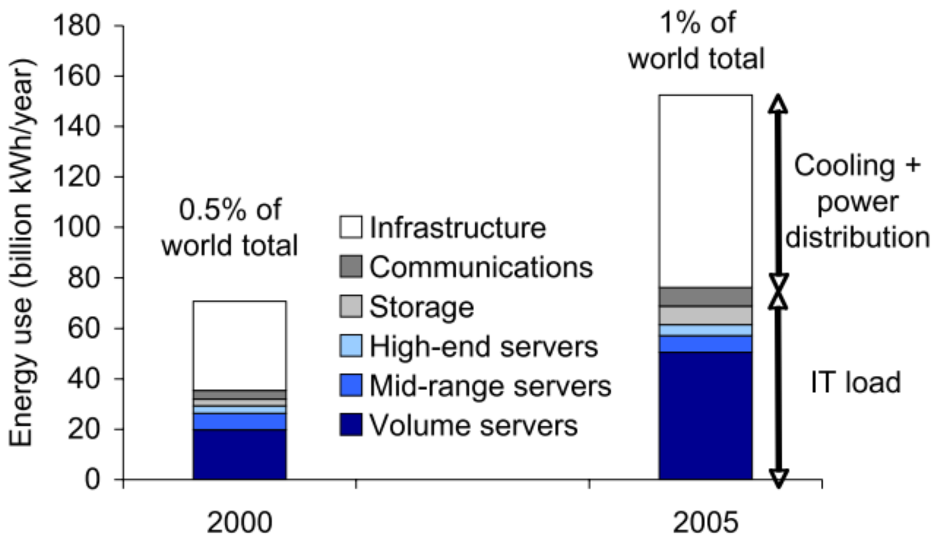

Figure 21. Estimate of worldwide total energy consumed by data centers. This continues to grow at a rate of 15% per year. U.S. consumption is 35% of world [4].

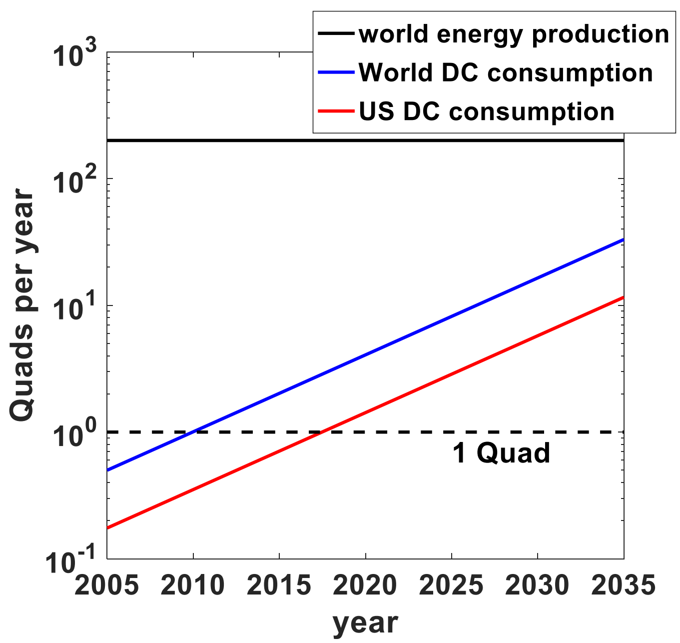

Figure 22. Estimate of data center (DC) power consumed per year [extrapolation from 4].

5.3 TRIBOELECTRIC POWER GENERATION

In the last two decades, the vast applications and distribution of mobile electronics have reached every corner of our life. A large number of sensors for health monitoring, medical care, environmental protection, infrastructure monitoring and security have been developed. The power for driving each unit is small and can be in the milli- to micro-watt range, but the number of units can be huge. As predicted by Cisco, by 2020 the world will have trillions of sensor units distributed on the earth [5]. The recent development of internet of things (IoT) and sensor networks dramatically change the traditional understanding of energy. The general characteristics of these types of power units are mobility, availability and sustainability. The conventional technology in use is batteries, which is not a viable solution for IoT. For trillions of batteries to be widely distributed, each having limited life, the monitoring, replacing, recycling and exchanging batteries will be a huge, if not impossible task. Most of the IoT would be impossible without making devices self-powered [6].

By using the electrostatic charges created on the surfaces of two dissimilar materials when they are brought into physical contact, contact-induced triboelectric charges can generate a potential drop when the two surfaces are then separated by mechanical force. This can drive electrons to flow between the two electrodes built on the top and bottom surfaces of the two materials. This is at the core of the recently-developed triboelectric nanogenerator (TENG) [7]. Since the first publication reporting the invention of the TENG device in January 2012, an instantaneous energy conversion efficiency of ~70% has been demonstrated, shown in Figure 23 [8,9]. TENG devices have been developed with four operations modes [9,10] as shown in Figure 24. These can be applied to harvest multiple sources of mechanical energy that are available, but currently wasted or not fully harnessed in daily life, such as human motion, walking, vibration, mechanical triggering, rotating tires, wind, flowing water and more. Prototype applications of TENG have been demonstrated in several cases, including as micro/nano power sources, self-powered sensors/systems, and large scale blue energy [9].

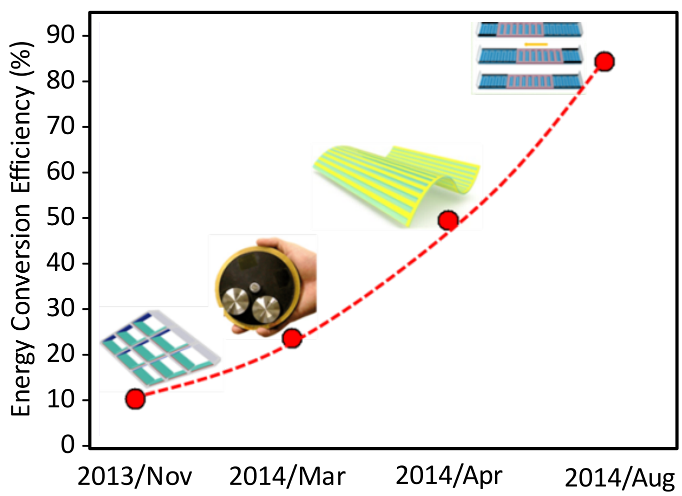

Figure 23. Rapid enhancement of the recorded energy conservation efficiency from triboelectric nanogenerator (TENG) devices.

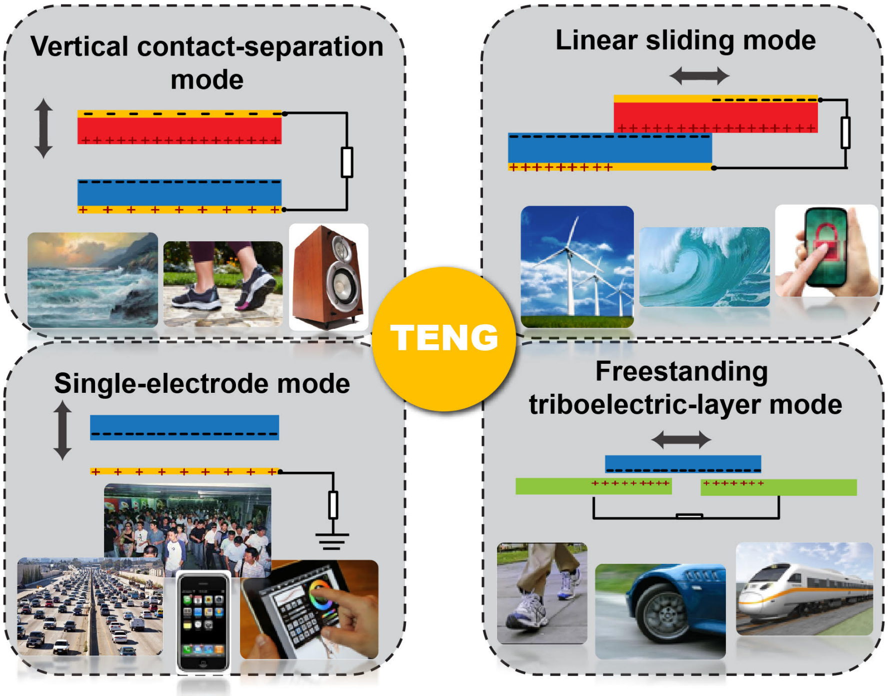

Figure 24. Four operation modes of TENG devices for broad applications.

However, operational reliability is the most crucial issue for TENG; this has been recognized and studied since its inception. Various strategies have been developed, such as contact/non-contact status transition [10] and rolling triboelectrification [11], with tremendous improvement in the number of reliable operation cycles. The contact/sliding interface at which triboelectrification occurs is still in need of systematic study. Figure 25 shows a schematic of such an interface. Tribological issues at this interface include the effect of contact between two triboelectric surfaces, wear and adhesion, all of which may change as cycling continues, thereby changing the charge transfer and power generated per cycle. These must be understood and controlled in order to make harvesting this mechanical energy reliable.

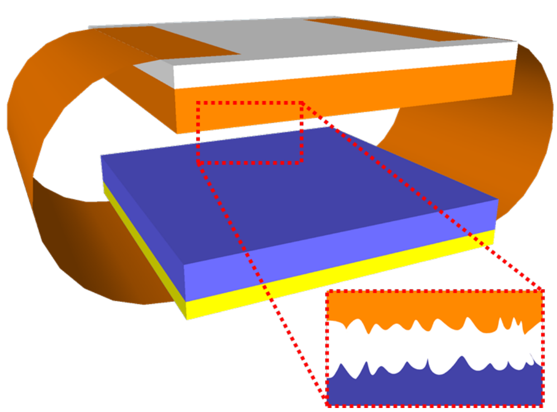

Figure 25. A schematic of a TENG, with the triboelectric surfaces shown as the inset.

As stated above, TENG devices can be used for various forms of mechanical energy harvesting, including that from body motions, ocean, and wind. High performance TENG devices can also be integrated with energy storage systems, like lithium ion batteries or supercapacitors, to enable self-powered operation of electronic devices and systems. Self-powered systems have several potential applications in portable electronics, sensor networks, the IoT, implanted devices, and in vivo biomedical monitoring [12]. TENG devices are particularly efficient while harvesting energy from low-frequency mechanical source, [13] such as ocean waves, which are not currently well utilized.

Below, one approximate assessment of annual mechanical energy harvesting from ocean (blue energy) through TENG devices is presented. Recently, a novel design was proposed to connect multiple TENG units into a network for large scale blue energy harvesting [14]. Such "TENG networks" (TENG-NW) that naturally float on a water surface convert the slow, random, and high-force oscillatory energy of water waves into electricity. An average power density of 1.15 MW/km2 was predicted based on experimental results [14]. By assuming 0.05% of the U.S. exclusive economic zone (the coastal zones where the U.S. has jurisdiction: 11,351,000 km^2 (4,383,000 $mile^2$)[15]) is used for energy harvesting through TENG devices (this is similar to the current fraction of California's land area that is covered by large solar farms, as a crude guide for this very novel idea), a simple calculation of the resulting annual energy harvesting in the U.S. is as follows:

Energy stored = (US exclusive economic zone)•0.05%•1.15 MW/km^2•(3.2×10^7 s)/year•
(1 quad)/(10^{18} Joule) = (1.1351×10^7 km^2)•($5\cdot10^{-4}$)•(1.15×10^6 MW/km^2)•
(3.2×10^7 s/year)/(10^{18} Joule/quad) = 0.021 quads

This is an aggressive target considering the large area involved (0.05% coverage corresponds to covering 56,750 km^2 of area covered by TENG devices. Importantly, TENGs are mostly made from polymeric materials without magnets, thus the weight of the total device is expected to be decreased greatly compared to current machines made from heavy materials (such as metals). Given their small size, the total weight reduction is estimated to be approximately 70% by simply comparing the densities of common polymers and metals. The low weight of TENGs reduces or eliminates the need for structural supports like building poles or towers for holding traditional electromagnetic generators.

The TENG technology, having been demonstrated in the laboratory, is at a TRL of 3, with some manifestations approaching TRL 4. Given the low cost and unique applicability resulting from a distinct mechanism and a simple structure, the TENG approach suggests an innovative and high risk but potentially sustainable alternative to traditional methods for large-scale blue energy harvesting.

5.4 VAPOR-PHASE LUBRICATION

Vapor-phase lubrication is a method of applying lubricant to a surface. It employs a stream of gas to transport vaporized lubricants to mechanical systems and/or expose the systems directly to lubricant vapors [16-22]. The lubrication mechanisms generally fall into one of three categories:

1. Condensation of a liquid film from the vapor phase, which provides liquid lubrication to the system with a continuous source of supply material.
2. Reaction of the vapor molecules with metals surfaces to yield a lubricating surface film comprised of constituents from both the substrate and adsorbing vapor.
3. Exposure of catalytic surfaces such as nickel at high temperature to light weight hydrocarbons, resulting in a lubricious carbon surface layer.

Vapor phase lubrication is a particularly attractive approach for systems where high operating temperatures are desirable and also in microelectomechanical systems (MEMS) technology, where systems are routinely rendered inoperative by the capillary effects of conventional liquids. The gas phase moreover allows access to interfacial contact regions that may not be effectively treated by liquids or greases. The tribological benefits can be summarized as follows:

- High temperature applications abound, for example in the power generating and aviation industries, where operating temperatures are limited by conventional synthetic lubricants to 500°C maximum. Tremendous energy efficiency gains could be achieved simply by increasing the operating systems. Vapor phase lubricants are demonstratively effective at high temperatures.
- Solid lubricants have been developed that can withstand high temperatures, but are not readily replenished: Vapor phase lubricants provide continuous replenishment.
- Some materials, such as molten glasses, have effectively lubricated at elevated temperatures, but solidify and do not lubricate at room temperature: Vapor phase systems provide lubrication over a wide range of operating temperature, and can also be tailored to low temperature applications, including ionic liquids.
- Traditional macroscopic approaches to lubrication are completely ineffective for micro and nano-scale applications. Vapor phase lubrication is a viable approach to lubricating such devices, which tend to be fabricated from materials that have highly unfavorable tribological properties. One of the most promising and compelling microscale applications, the on-chip MEMS microturbine for electrical power generation, remains stalled by air bearing failures associated with friction and wear.

Vapor phase lubrication is currently viable for expendable gas turbine engines, and has not been extended to MEMS or continuously operating heat engines. Research in the area of vapor phase lubrication is highly interdisciplinary: progress necessarily involves studies of the fundamental/molecular nature of lubricants, their mobility at short time scales, and their performance at a myriad of length scales. This area lies at TRL 2. Specific funding in this area would draw together the necessary experts to tackle the problem whereas such groups might not otherwise form. At the MEMS level, an interdisciplinary team is also required to push forward compelling applications such as on-board electrical power generation. While vapor phase lubrication has been demonstrated to be effective in selective materials cases for both high temperature systems and MEMS applications, a broad understanding of the mechanisms for fundamental design rules has yet to be established. In addition, vapor phase lubrication of a heat engine is likely to require a design that incorporates the lubricant method from the outset: Given the aging infrastructure of current power plants, and the need for future transportation methods, the time is now to develop such systems.

The systems clearly impacted by the potential for vapor phase lubrication are those where a higher operating temperature increases system energy efficiency. As a simple calculation, to demonstrate the impact of temperature on energy efficiency, consider the maximum energy efficiency theoretically possible for a conventional heat engine, $\eta = 1 - (Tc/Th)$, where Tc and Th are the cold and hot thermal reservoir temperatures. For a system that spans room temperature to 450°C, (300K to 723K) the efficiency is 58.5%. Raising the upper temperature to 650°C brings the efficiency up to 67%, a 14% increase in operating efficiency. Temperatures at this level are compatible with a wide range of materials employed in engines, including ceramics and steels. Stainless steels, for example, can be used at temperatures up to 925°C for 304 and 316 and up to 1100°C for the high temperature stainless grade 309(S). Such temperatures however far exceed the upper operational limit of conventional lubricants such as oils and greases. Heat engines are widespread in the transportation and power generation industries, which respectively yield 22 and 25 quads of rejected heat per year and operated respectively at only 21% and 33% efficiency in 2015, as displayed in Figure 1. A 14% reduction in the rejected heat in these two combined sectors annually corresponding to 0.14 x (22+25) quads = 6.6 quads annual reduction of consumed energy. While this is clearly a high estimate, it does not take into account the fact that replacement technologies would require less overall primary energy input, as the systems themselves would be more light weight.

The impact of MEMS technologies on energy use is difficult to estimate, as the technologies developed are likely very transformative, so it may be too early to predict. The contribution by de Boer and Piazza however in Section 5.2 on NEMS switches estimates 2–5 quad energy savings in the long term from the development of NEMS switch designs. The latter would be excellent candidates for vapor phase lubrication as a contact lubricant is clearly required to avoid switch seizure.

5.5 BUILDING HVAC SYSTEMS

Currently, the single largest use of energy outside of the transportation sector is the heating, cooling and ventilation of buildings. HVAC systems use approximately 13.4 quads per year in the U.S. in 2010, Figure 26 [23].

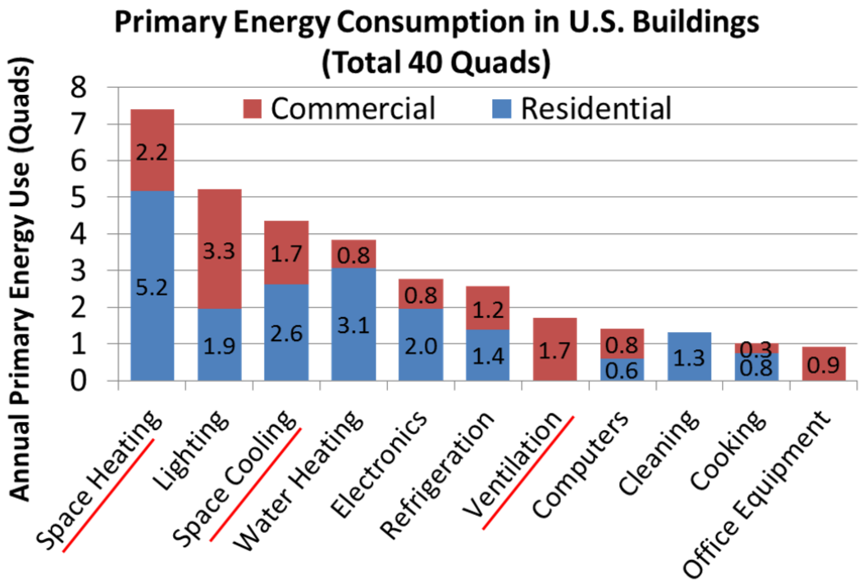

Figure 26. Building primary energy consumption by end-use [23].

It has been estimated that a holistic approach to innovative HVAC technologies could reduce energy consumption by 30 to 40% [24,25]. This would result in direct reduction of 4.2 to 5.6 quads consumed annually if all existing systems could be converted. Due to the complex nature of HVAC systems and building heat flows, much of the improvement would come from upgrading the physical structure, but tribological considerations of the refrigerant handling mechanisms could be in the order of 3–6% since the refrigerant pump is the main consumer of energy [26,27]. These considerations, like many others would focus on the piston or rotor sealing rings, bearings, bearing surfaces, or coating technologies. Practical savings of 6% from tribological sources could be up to 0.84 quads consumed annually.

5.6 GRANULAR MATERIALS PROCESSING

Recently, progress has been made in fundamental understanding of the impact of tribology on granular materials (construction materials, food products, pharmaceuticals, etc.) to increase efficiency in a sector that utilizes 10% of the energy produced on the planet. Given that very little effort has been expended to date in this area, the savings potential is massive. However, the TRL for such approaches is low (TRL 1 or 2). In addition, nanoparticles have significant potential as environmentally friendly alternatives to present day additives (i.e. green additives). Work is required to address how to keep them in suspension, functionalize their surfaces, examine how they perform in a fully formulated base fluid, and how well they behave with respect to time and temperature. Statistical methods may be necessary to optimize performance given the large number of parameters. This work would help close the gap between materials and lubrication engineering. There are numerous opportunities that have yet to be fully explored including ionic liquids. Due to the large range of industries that this technology spans and its infancy, we are unable to assess the level of quad savings that could be made. However, assessments during the workshop discussions ranged from 1.0 to 2.5 quads of energy consumed.

5.7 TRIBOLOGY 'AUDIT' OF EXISTING ARPA-E PROGRAMS

Many energy research programs that involve tribological interactions have been undertaken across different U.S. Government funding bodies. Some have been for CO_2 emission reductions; others have been for fundamental research, and many have been for the purposes of systems engineering efficiency gains. A great number of the latter have been, directly or indirectly, studies into efficiency gains that depend on the use of basic tribological principles. Moreover, there are many projects, including in ARPA-E, where tribology plays a role even though it is not the central focus (examples are given below). If an audit of all these projects was undertaken, and similar areas grouped together and studied, it is likely that two questions could be answered:

1. Are there existing tribological approaches, or new results obtained in some projects, that could be applied to solve tribology roadblocks or make tribology-enabled energy efficiency gains in other projects?
2. Are there similar tribology issues in multiple projects? If so, could there be combined investments to answer common tribology issues, thus enabling other projects to yield their full energy-saving potential?

To make an assessment of the level of quad savings of such a multi-agency, project optimization study, an initial 'audit' would need to be undertaken. By audit, we mean an independent assessment of the strengths, weaknesses, opportunities and threats of the existing programs, and evaluation of their overlapping interests related to tribological phenomena. Only considering existing programs at ARPA-E, we found examples of active programs and projects that might greatly benefit from a tribological 'audit' or assessment. A few examples where the audit would make significant impact include:

- Next-Generation Energy Technologies for Connected and Automated On-Road Vehicles (NEXTCAR). The projects in this program aim to reduce vehicle energy consumption via the use of automation and connectivity to co-optimize vehicle dynamic controls and powertrain operation. Existing engine and drivetrain design (including lubricant design) are optimized for typical driving patterns and start-stop cycles that may be very different in an automated network. This could affect vehicle efficiency as well as component wear. Tribologists could partner with the project PI's to identify opportunities up front to change engine and drivetrain designs for optimal efficiency and reliability.
- Hybrid Engine Generator for Residential Combined Heat Power (CHP). This project within the GENSETS program (Generators for Small Electrical and Thermal Systems) is being conducted by Sencera Energy, Inc., and Ohio University. The team is developing a novel kinematic Stirling-Brayton hybrid engine using flexure-based volume displacement instead of a conventional piston-cylinder Stirling engine for use in residential CHP systems. Eliminating

the piston-cylinder reduces friction losses, but other contacting, sliding components in the engine could be sources of parasitic losses that reduce the efficiency of this potentially transformative design. Tribologists could provide expertise in the design including loads, materials selection, and lubrication of this system.

- Advanced Lean Burn Micro-CHP. Also in the GENSETS program, this project being conducted by Mahle Powertrain (with partners with partners at Oak Ridge National Laboratory, Louthan Engineering, Kohler Company, and Intellichoice Energy) aims to develop a CHP generator that uses an internal combustion engine with a turbulent jet ignition combustion system that enables higher energy efficiency. The project explicitly aims to further increase efficiency by using low friction engine components. Tribologists could help the team meet this challenge by applying their expertise to the tribological engineering needed for this complex, high-temperature system.
- Solid State Processing of Fully Dense Anisotropic Nanocomposite Magnets. Awarded through the OPEN program and conducted by Electron Energy Corporation, Pacific Northwest National Laboratory and Ames Laboratory, the aim is to produce stronger magnets at lower cost and with fewer rare earth elements, thus enabling higher efficiency electric vehicle motors. The magnets are produced using a novel processing method, friction consolidation extrusion (FC&E). Compressive and shear forces are applied to a rotating plunger to tribo-mechanically form magnetic alloys from powders for which alternate processing schemes are prohibitively expensive, slow, or non-existent. This complex process could be optimized through tribological analysis and experiments, and tribological simulation methods could be deployed to rationally guide the optimization of the FC&E process, leading to economical and faster production of the magnetic materials.

5.8 AN ENERGY AWARE DESIGN FRAMEWORK FOR GUIDING R&D PROCESSES ACROSS TECHNOLOGY READINESS LEVELS

The success of energy savings through tribology greatly depends upon the implementation of innovative tribology sciences and technologies into marketable products. Like many other technologies, there is always a major challenge to transition excellent R&D results into innovative solutions for success in the marketplace. This challenging transition, sometimes referred to as “the valley of death”, is particularly arduous for tribology and its critical role as an enabler for energy saving mechanical systems. Tribology is not easily characterized with engineering design parameters for product development. The performance of a tribology interface is not an inherent property of the individual materials and their designs that make up the contact. Functional performance is the result of what is generated through dynamic mechanisms during operation and the environment that it creates and experiences. So, the reality is that tribology designs and the prediction of performance are specific to the small and remote contacting interfaces of specific components and the mechanical systems in which they are embedded. The application of tribology innovations into major mechanical systems for energy savings, where power density pushes the state-of-art, is high risk business where “the valley of death" can be enormous. An effective tool to guide R&D, develop and implement innovations, with reduced risk, is the application of the Technology Readiness Level (TRL) process that have been referenced earlier in this report.

The TRL system is a scale or grading system that judges the level of technology maturity along the path from a laboratory concept to full market implementation. It somewhat implies that the innovation and implementation process is linear where a laboratory concept progresses into a component that becomes part of an operating system. TRL is usually used to judge technical maturity and readiness for product development. It can also be used for judging the readiness of manufacturing or other critical development actions. The notion of TRL was introduced by a NASA engineer, Stan Sadin, in 1974 [28]. It grew into an effective tool within NASA for space systems; and it spread to other U.S. government agencies and the aerospace industry, particularly the Department of Defense (DOD). Today it is widely used in other agencies and industries in the U.S. and abroad. The adaptation of TRL in most industries results in the use of nine technical levels. The nine levels are frequently custom designed to suit a particular industry and its purpose. For ARPA-E the definition of the nine levels are summarized in Figure 27.

The use of TRLs has the potential to increase return on investment due to more careful choice of technologies, it also has the potential to allow research projects to be run in a more directed and efficient manner. As such the quad returns in using this method are unmeasurable, but will certainly result in returns higher than without its use.

TRL 9 : Actual technology system qualified through successful mission operations.

TRL 8 : Actual technology system completed and qualified through test and demonstration.

TRL 7 : Technology prototype demonstration in an operational environment.

TRL 6 : Technology demonstration in a relevant environment.

TRL 5 : Technology validation in relevant environment.

TRL 4 : Technology validation in laboratory.

TRL 3 : Analytical and experimental critical function and/or characteristic proof-of-concept.

TRL 2 : Technology concept and/or application formulated.

TRL 1 : Basic principles observed.

Figure 27. Summary of ARPA-E TRL levels [29].

SUMMARY

- Solid state transistors are increasingly energy inefficient. Coupled with the increase in computing, total energy consumption by computing is exploding and, extrapolating from current rates, will exceed world energy production by 2035. Solid state transistor inefficiency is also a limiting factor for portable devices and for Internet of Things. nanoelectromechanical systems (NEMS) switches provide opportunities to save large amounts of energy, estimated to be up to 2.0 to 5.0 quads of consumed energy annually by 2035. Existing NEMS switch technology lies at TRL 3. To enable commercialization, tribology research must be incorporated into the NEMS switch development, since failure at the mechanical contact interface is a primary factor limiting their commercialization.
- Triboelectric nanogenerator (TENG) technology utilizes charge transfer across contacting, sliding interfaces to store energy in compact geometries. Currently at TRL 3-4, such devices are estimated to be able to save 0.02 quads of energy produced annually in the US, although such estimates are very difficult to make as they depend on the specific device geometry to be deployed and the ability to scalably manufacture them.
- Vapor phase lubrication could be deployed in a number of high operating temperature applications including heat engines and gas turbines. Annual savings are estimated to be in the range of 6.6 quads based on a prototype heat engine calculation. The technology is at an early stage of TRL 2 since proof-of-concept use in a heat engine or turbine has not yet been demonstrated.
- Tribological improvements applied to technology in building HVAC systems, particularly refrigerant pump systems (piston or rotor sealing rings, bearings, bearing surfaces, or coating technologies), could reduce energy consumption by 0.84 quads annually.
- Improved methods for processing granular materials was estimated to have the potential to reduce annual energy consumption by 1.0-2.5 quads, although such technologies are at an early stage (TRL 1 or 2).
- Several existing programs in ARPA-E involve technologies where tribological interactions occur. An audit of tribology needs in existing programs is recommended. Technologies where the impact is highest could then benefit from tribology collaboration or consulting supported by ARPA-E.

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Chapter 6
Market and Policy Considerations in Applying Tribology to Energy Technologies

6.1 INTRODUCTION

There has been great progress in tribology in the last 50 years, including the deployment of micro- and nanotribology, the establishment of bio-tribology and the advancement of physically-based understanding of tribological phenomena. Despite this progress and the potential to improve energy efficiency and increase productivity, tribology is not broadly perceived as a "clean technology". Unlike renewable energy, energy storage, biofuels or carbon capture and sequestration technologies, tribology remains relatively unknown for the general public, and its potential benefits remain underestimated.

To understand the reasons why the full potential of tribology as a "clean technology" has been so untapped, this chapter explores the market and policy challenges of the discipline and the opportunities to overcome those challenges.

The speed and direction of research and innovation are determined by markets and by policy incentives. Challenges to the broad development of energy efficient tribological innovations are attributable to a combination of economic and market constraints as well as policy issues. Due to the nature of tribology applications, which enable and improve other technologies, we identify market failures that could prevent the development of tribological innovation. Policy incentives play an important role minimizing the effect of such failures by providing incentives for private investors through articulated policies or by allocating funds directly through government agencies to research and innovation.

To understand the effects of policy in tribology technology development, we provide an analysis of the drivers of energy policy in the last 50 years and show how the dependency on fluctuating oil prices may have produced periods of more and less support for energy efficiency technologies.

As great challenges go hand in hand with great opportunities, this chapter also analyses the opportunities to overcome the identified challenges. These opportunities arise from the existing market and regulatory conditions in various sectors, where cost reductions and energy efficiency are a priority. Taking advantage of these opportunities while developing the research agenda identified in this report will amplify the impact of tribology applications, create awareness of the discipline and will hopefully put it firmly in the ranks of clean technologies.

6.2 CHALLENGES

Tribology is an "enabling technology". An enabling technology, a term which has been coined mainly for IT technologies, is the equipment and/or methodology that, alone or in combination with associated technologies, provides the means to generate giant leaps in performance and capabilities of the user, product or process [1]. The growth and advancement of the automotive industry, the exponentially-increasing capacity of data storage and the success of modern hip prostheses are key examples of such "giant leaps in performance" enabled by tribology [2].

However, unlike the internet and other IT technologies, there is little public awareness of this discipline. After 50 years of progress, tribology is not yet recognized as a key enabling technology. Below are some reasons to explain why this has happened.

a) Economic and Market Constraints: Creative Destruction

As an enabling technology, tribology provides services and inputs to different industries to improve efficiency. This interaction with other industries has advantages and disadvantages. It creates gains, but it also creates losses.

On the positive side, tribology creates value to other industries. This means that the benefits from tribological applications translate to lower costs and fewer needed investments for adopting industries. These gains are essential to creating markets for tribology-enabled products. Figure 28 shows five key areas where tribology can create value. Jost [3] estimated that the most important area for this value creation is the potential savings in maintenance and replacement costs.

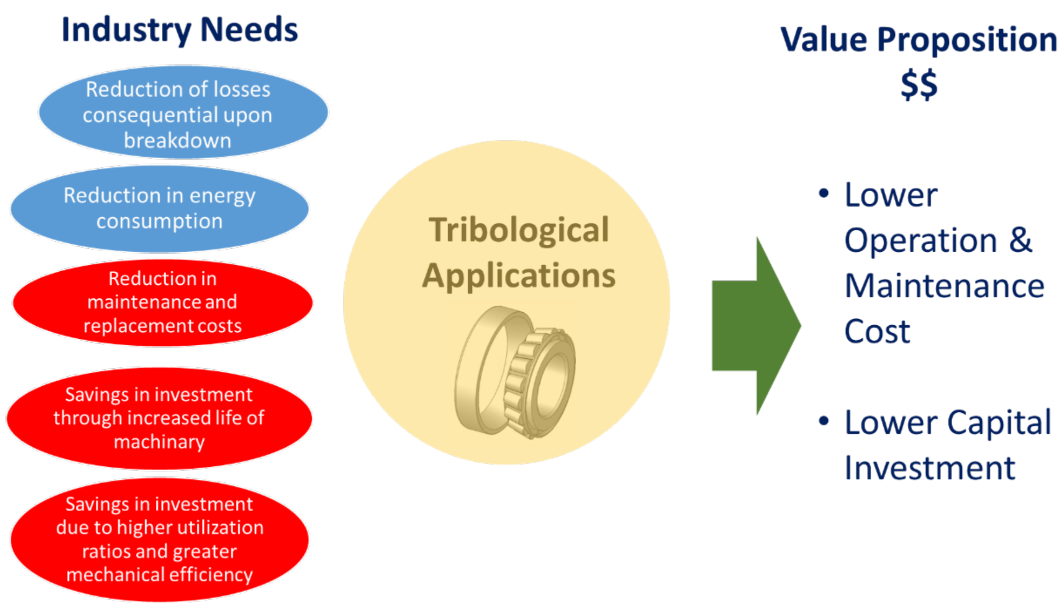

Figure 28. Value proposition of tribological applications.

On the negative side, the disruption of tribological innovation has adverse effects on the demand for existing tribological products. For example, when tribological progress makes possible a reduction of maintenance and replacement costs, thanks to better component designs and better lubricants, there will be a reduction in the demand for the components and the lubricants. Similarly, the longer the life of industrial machinery, the lower the demand for that machinery. This problem is what economists call "creative destruction" and is common to all quality improving innovations, not just tribology. The concept was first introduced by Austrian economist Schumpeter in 1942 and further developed by growth theorists in the 1980s and early 1990s analyzing the role of technology in economic growth [4]. For Aghion and Howitt [5], innovation renders current products obsolete and therefore destroys the value of previous research.

These negative and positive values that innovation brings are part of the business cycle that generates economic growth, as long as continuous new research keeps driving innovation.

Figure 29 illustrates the creative destruction faced by passenger car engine oil over the last 100 years. Every different service classification shows a new technology that became commercial. With new technologies, previous ones became obsolete, and the frequency of oil changes decreased, reducing demand for engine oils.

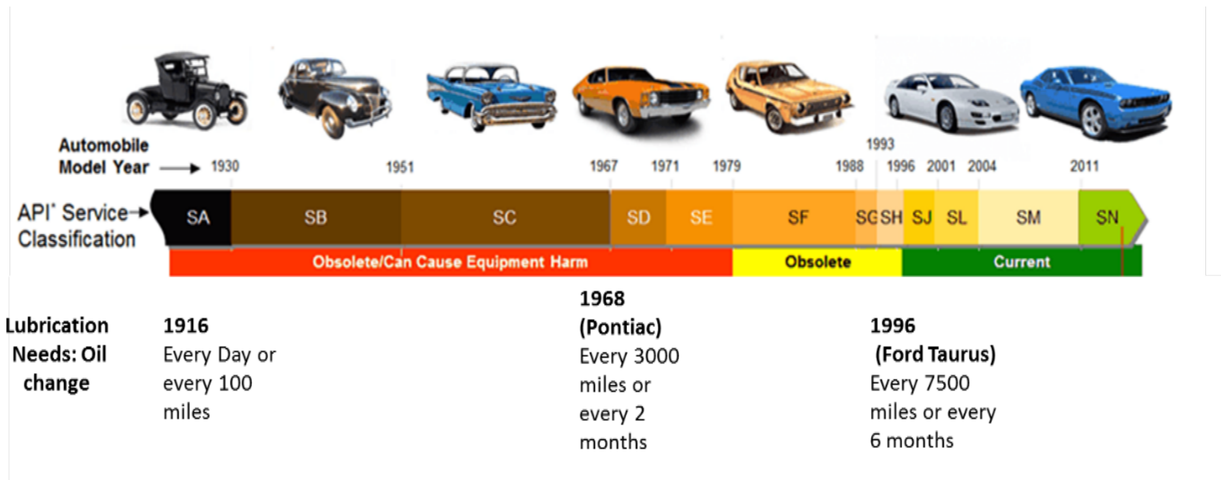

Figure 29. "Creative Destruction" example in passenger car engine oil [6].

Creative destruction becomes a problem when the prospects of future research totally discourage current research. In that case, a "non-growth trap" happens where innovation does not happen or its speed is greatly reduced.

b) Market Failures and the Role of Policy and Regulation

The speed and direction of research and innovation are determined by markets and by policy incentives. Policy incentives play an important role when the market fails to produce incentives and creates barriers that impede the development of research and innovation. Market failures happen in diverse ways. The "non-growth trap" described in the previous section is an example of market failure. Other examples of market failures include the uncertainty about the value of research in the future due to the high costs of research compared to future expected revenues, like the risk of the "valley of death" described in section 5.8.

Government intervention can address these market failures in two ways: (1) by establishing articulated policies and allocating resources for research and innovation in the areas of interest, and/or (2) by establishing regulations. There is no direct funding of research with regulations.

However, a regulatory framework provides incentives for industry and private investors to finance research and innovation.

Given the potential market failures faced by tribological applications, tribology research should benefit greatly from policies and regulations aiming to support energy conservation, energy efficiency, and environmental policies to reduce greenhouse gas emissions. It could also benefit from policies targeted to incentivize industries dependent on tribological products like the automotive sector.

However, in the last 45 years, energy conservation policies in the U.S. have been driven mostly by oil prices. Every time there has been a disruption in oil supply implying significant hikes in oil prices, the government has reacted by issuing legislation to address energy security (see Figure 30). Energy security legislation has favored energy conservation and energy efficiency as well as the development of alternative fuels and renewable energy. In the same way, when oil prices are low, priorities change, and from the policy side, energy security usually becomes less a priority. The fluctuation of oil prices and the lack of a permanent and articulated energy efficiency policy has been a problem for the development of energy efficiency fields like tribology. When oil prices are low, research programs are terminated, or remain poorly funded. Public funds are allocated to other priorities.

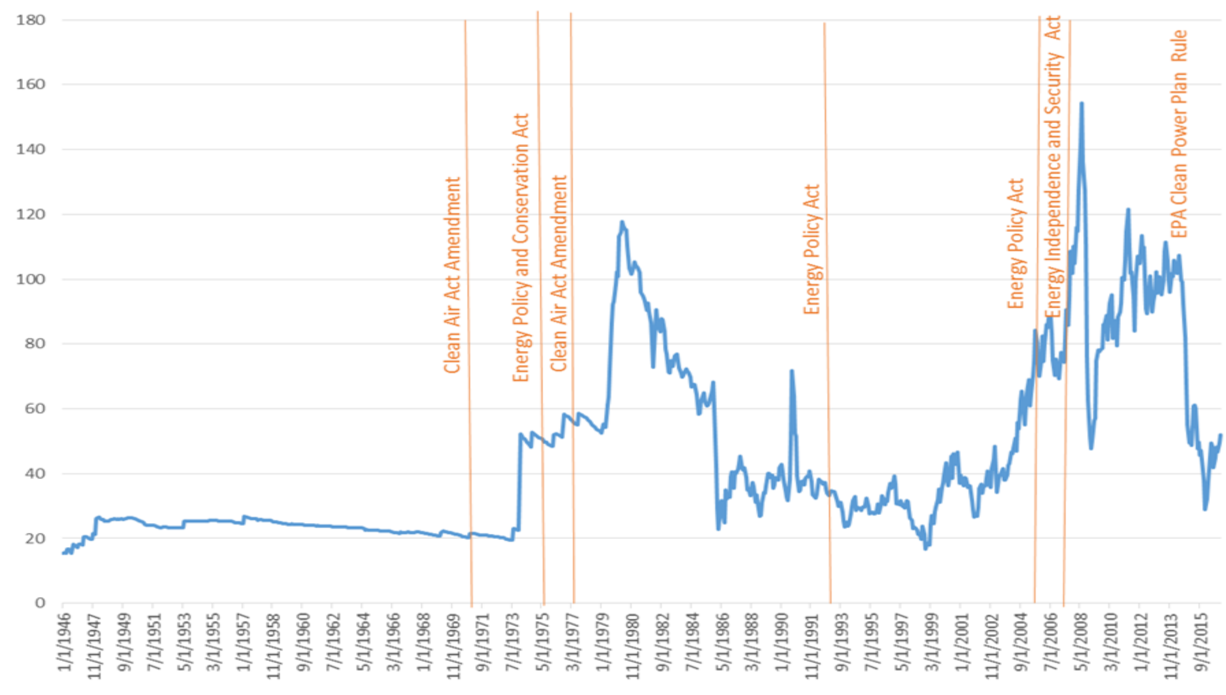

Figure 30. Crude oil Prices 1946–2016 WTI (NYMEX) adjusted for Inflation [7].

Environmental policy and regulations have also driven public and private funding for research on energy efficiency. These regulations require many industries to report greenhouse gas emissions, but only some specific sectors like the transportation and more recently the power generation sector are required to meet certain standards and reduce emissions.

c) Oil Shocks, Energy Policy and the Booming and Busting of Tribology

The 1970s boom

In the 1970s, following the oil embargo from Saudi Arabia and the oil supply shock of the Iranian Revolution, energy security became a top national priority. A number of regulations were enacted:

- In 1970 and 1977, Congress approved amendments to the Clean Air Act to authorize the development of comprehensive federal and state regulations to limit emissions from both stationary (industrial) sources and mobile sources. It also created the EPA.
- In 1975, the Energy Policy and Conservation Act was enacted to increase energy production and supply, reduce energy demand and increase energy efficiency. It also established the Strategic Petroleum Reserve, the Energy Conservation Program for Consumer Products, and CAFE standards for cars and light trucks.

These policies favored the funding of programs on alternative energies and energy efficiency at the Department of Defense, DARPA, the National Science Foundation, NASA and DOE.

The combination of funding and regulation had a tremendous impact in tribology research. In his essay about the history of tribology, the late tribologist Ken Ludema [8] described how the 1970s were a "heyday" for tribology research with many tribology groups doing research at Federal Agencies, in the private sector and in academia.

1980s and 1990s downsizing

Oil prices came down and even crashed in 1986 (Figure 30), leaving energy security outside the list of policy priorities. However, in 1990, the Iraqi invasion of Kuwait generated a "small and short-lived oil price spike" [9].

In response to this new shock, the government enacted the Energy Policy Act in 1992 to improve energy efficiency by mandating the establishment of energy efficiency programs for utilities, buildings, the residential sector and manufacturing equipment in the industrial sector. It also mandated programs to accelerate the development of technologies that could increase energy efficiency in order to improve productivity in the industrial sector [10].

For the automotive sector, the U.S. government not only halted the planned escalation but also mildly relaxed CAFE standards [10]. This shift was not good for tribology research, despite the opportunities provided by the Energy Act of 1992. A significant downsizing of tribology research groups took place in the 1980s and 1990s [8].

By 1985, a survey of the tribology industry (i.e., of those developing bearings, lubricants, coatings and power plants) found that only a tiny fraction of the large sums publicly reported as R&D expenditures were used to fund generic tribology research [12]. In some industries like the oil and gas industry, the budget cuts for tribology research were drastic [8] due to their lean profit margins.

There was also downsizing in public sector research groups (i.e., at national laboratories) and the reduction of tribology programs focused on energy efficiency. Tribology became a component within other programs. Despite this secondary role, tribology still became an enabler for other promising technologies. For example, by the early 2000s, tribology research played an important role in the development of microelectromechanical systems (MEMS); successes include the MEMS air bag accelerometer (now used universally in passenger vehicles) and the digital mirror display (used universally in light projection systems) [13].

The 2000 to 2014 era: a new but different oil shock

The American military intervention in Iraq in 2001 triggered a massive oil shock that lasted over the first decade of the 2000s and was exacerbated by Chinese economic growth. Oil prices hiked from less than $30/ barrel in November 2001 to an all-time peak of $155/ barrel in June 2008. After a brief fall in 2009, prices increased until 2014.

In comparison to the oil shock of the seventies and the one of 1990, this shock did not have negative effects on the U.S. economy [9]. A new Energy Policy Act was enacted in 2005 and then revised in 2007. Like the 1992 Act, it had provisions for energy efficiency, supporting and expanding the Energy Star program for energy efficient products, promoting voluntary commitments to reduce industrial energy intensity standards [14] and introducing standards for appliances [15]. The 2007 Act also established a program for energy-intensive industries to "support, research, develop, and promote the use of new materials processes, technologies, and techniques to optimize energy efficiency and the economic competitiveness of the U.S.'.

During this decade, research and development budgets in the oil and gas sector benefited from high oil prices and subsidies to the sector mandated by the Energy Policy Act of 2005. Progress in tribological research and more specifically in slurry (drilling fluids) tribology enabled the transformation of hydraulic fracturing with horizontal drilling. The extraction of shale oil and gas achieved unprecedented efficiency gains with such transformation.

2014 to present: the oil glut and climate policy

The progress in hydraulic fracturing was a game-changer in terms of oil and gas production in the U.S. (Figure 31). Given the increased production in the U.S. and the reluctance from OPEC to curtail production, oil prices collapsed in 2014.

For tribology research, the fall in prices could imply a downsizing similar to the one experienced in the 1980s. However, clean energy became a priority as part of the Obama Administration Plan to fight climate change. Although the Plan did not become law, some of its components like the Clean Power Plan became a rule and set standards in various sectors. These new opportunities for tribology research as well as other suggestions to overcome the above-mentioned barriers to unlock the full potential of tribology are described in the next section.

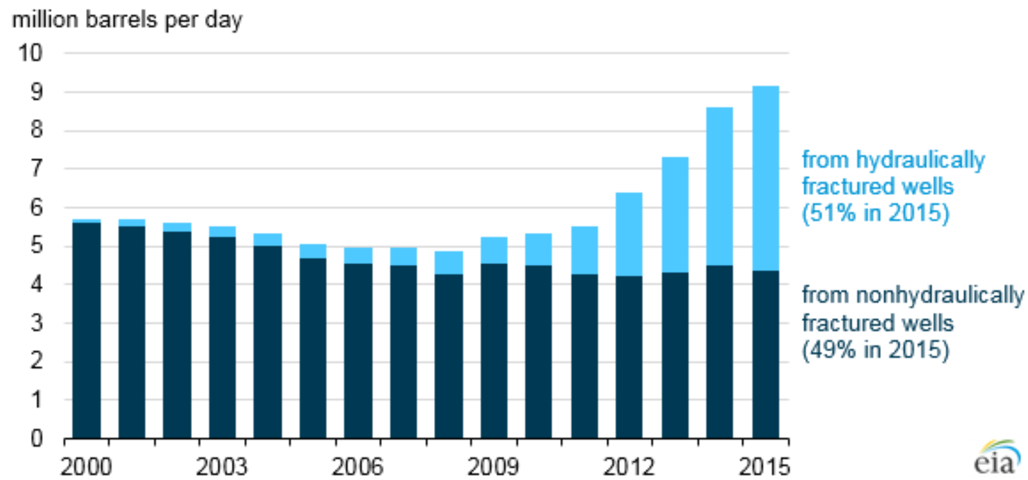

Figure 31. Oil production in the U.S. (2000–2015).

6.3 OPPORTUNITIES

Tribological applications (which include material selection, lubricant selection, and tribological practice and knowledge in design) add value to the recipient industries and processes. This value ensures demand for tribological applications, and provides incentives to private and public investors to fund tribology research. Creating and articulating this value is key for tribology research to overcome the challenges described above.

A review of the achievements of tribology applications in the last 50 years shows that tribology innovation has delivered such value. Yet, the full potential of tribology as a clean and energy-efficient technology, is untapped. In this section, we identify the opportunities and strategies that could play a role in overcoming the barriers for tribology research so that tribology can achieve its full potential as an energy-efficient technology.

a) Diversify Partnerships

Funds for tribology research are positively correlated with oil shocks. For policy makers, it makes sense to shift public research funds for energy efficiency technologies to other priorities when oil prices are low, when the main policy objective is energy security and not climate change. However, for private investors this is different. Traditionally, the main private investors in tribology research have been the automotive and the petrochemical sectors. For these industries, reducing research budgets when oil prices are low is counterintuitive. Both sectors benefit from low oil prices, as demand for cars increases when gas at the pump is cheaper. In the same way, the petrochemical sector benefits from cheaper inputs, when oil prices are low.

This could imply that R&D budget in the automotive sector depends significantly on fuel economy standards. It is likely that higher standards require higher expenditures in R&D to meet the standards. As a consequence, the relaxation of fuel economy standards in the 90's could have resulted in a reduction of R&D budgets.

For the petrochemical industry, the influence of oil price fluctuations in R&D budgets is explained by the fact that major oil and gas companies are the main players in the petrochemical and more specifically in the lubricant market [17]. Unfortunately, when oil and gas prices are low and their margins get reduced, these companies tend to cut R&D. Shell and ExxonMobil, the leaders in the lubricants markets, reduced their R&D expenditures by 17% [18] and 3% [19] respectively, from 2013 to 2015.

The partnership of tribology research with the lubricant and automotive sector has been fruitful. At the same time, it has generated a substantial dependency for tribology research on oil prices with the increased risk of research budget cuts from both federal agencies and private companies when oil prices are low.

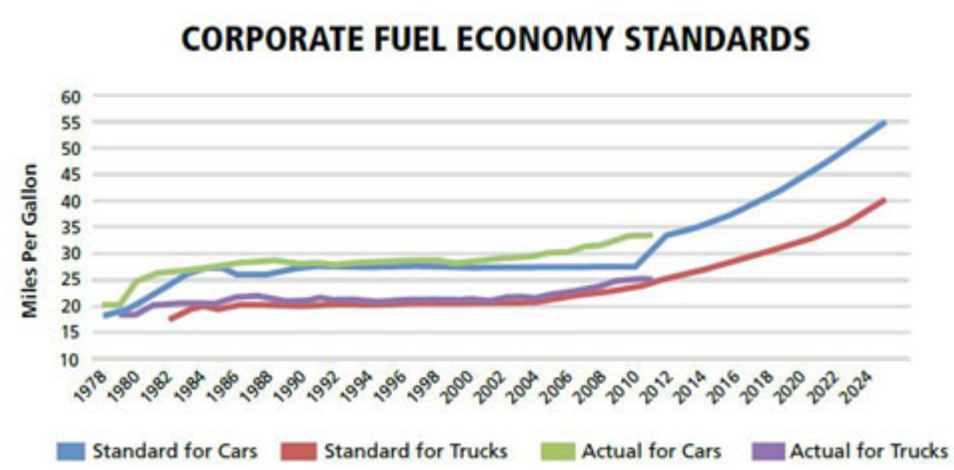

Figure 32. Mandated and achieved CAFE standards [20].

To decrease the risk of reduced research budgets in the private and public sector when oil prices are low, tribology researchers should aim to diversify their industrial partnerships involving other sectors, in addition to the automotive and oil and gas sectors.

Diversification, could also bring larger research funds, as the oil and gas and chemical sectors spend less in R&D than other sectors, like the computing and electronic sector or even the industrial/manufacturing sector (see Figure 32).

To enable this diversification, new research partnerships should be strategic: they should be established with industries having a great potential for energy efficiency gains through tribological solutions and benefitting from policy incentives to achieve those gains.

b) Strategic sectors for tribology applications

There are a number of industries seeking energy efficiency, or productivity gains, which could benefit from tribology. Three conditions can be considered when assessing strategic industrial partners for tribology research to be impactful: 1) industries with large energy losses due to friction and wear, 2) industries that are obliged to comply with standards and regulations, and/or 3) industries with tax incentives or that are subsidized by government programs.

This report has identified a number of sectors that meet condition 1. From the policy and regulatory side, we have identified opportunities in power generation, manufacturing, gas production and transportation.

c) Policy and regulatory opportunities

Power Generation Sector

Improving the efficiency of power stations to reduce carbon emissions is the main goal of the Clean Power Plan. The rule, issued in 2015, set standards for power plants, and customized goals for states to cut carbon pollution, considering each state's energy mix. As part of the Rule, the Environmental Protection Agency established three measures that could be used to achieve compliance: 1) improving heat rate at affected coal-fired steam power stations, 2) substituting increased generation from lower-emitting existing natural gas combined cycle units for reduced generation from higher-emitting affected steam generating units, and 3) substituting increased generation from new zero-emitting generating capacity for reduced generation from affected fossil fuel-fired generating units [21].

Ideally, opportunities for research to improve coal-fired stations performance could arise from the implementation of the rule, considering that the average global efficiency of coal power plants is only 27% [22]. In reality, compliance of the rule is likely to result in the future shut–down of coal-fired power stations given their high level of emissions, the cost to retrofitting existing plants and the persistent low prices and oversupply of natural gas in the U.S. which makes gas-fired stations very competitive.

Opportunities for tribology research from rule compliance lie therefore on developing cost-efficient applications to further improve the performance of natural gas-fired stations, like applications for steam turbines of combined cycle gas power stations.

The rule also provides incentives for net–zero generating capacity. Tribological applications in turbomachinery to improve performance and extend the life of hydro stations and wind turbines could have attractive market perspectives.

Among these two sectors, wind energy presents the biggest potential, due to several factors. First, this sector benefits from Production Tax Credits (PTCs) at the federal level that will be phased down in five years. Second, at the state level, this sector has benefitted from renewable portfolio standards (RPS) in 29 States and Washington, DC. Third, as explained in the 2015 Wind Technologies Market Report [23], "near-term wind power capacity additions will be driven by improvements in the cost and performance of wind power technologies, which continue to yield very low power sales prices…. As a result, various forecasts for the domestic market show expected capacity additions averaging more than 8,000 MW/year from 2016 to 2020".

Although the Report points out the negative effect of the phase-down of PTCs, this could be an opportunity for tribology research. In the absence of PTCs, technology will play an important role in reducing costs to maintain the competitiveness of the sector. Moreover, the operational and maintenance (O&M) costs of wind projects do not show the same downward trend that turbine and installation costs have experienced in the last ten years (see Figure 33). Reducing maintenance costs is an area where tribological applications could deliver great value as discussed in Chapter 4. Tribologists should work closely with the wind industry to achieve a downward trend.

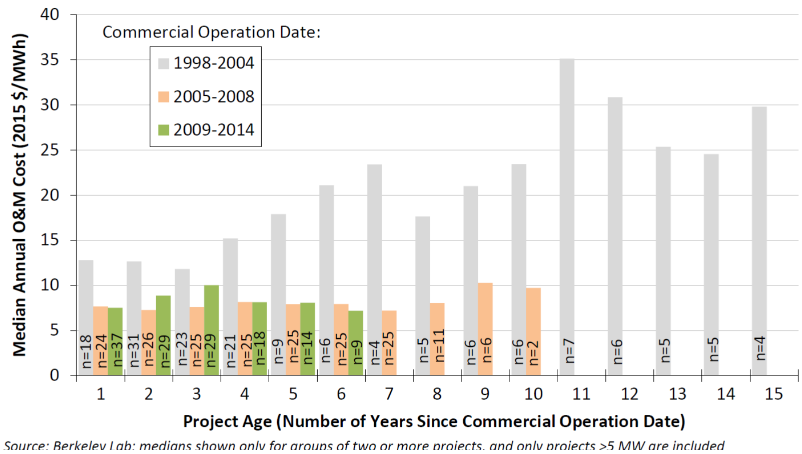

Figure 33. Median annual O&M costs of wind projects [23].

In the nuclear sector, there is also the potential to develop turbomachinery to reduce the maintenance costs of nuclear stations. However, under a low gas price scenario, the future of nuclear energy remains uncertain because nuclear stations cannot compete with gas-fired power stations.

On February 9, 2016, the Supreme Court stayed implementation of the Clean Power Plan pending judicial review. A negative outcome of the review may limit the opportunities for tribology to improve performance in the power generation sector. Only 19 States support the rule and will proceed with implementation regardless of the Supreme Court decision (see map in Figure 34).

Even with the prospect of the Supreme Court repealing the rule, the wind industry would continue to present important opportunities for tribology research. The schedule of PTCs and the situation in each individual state's RPS are not affected by the Supreme Court decision.

Industrial and Manufacturing Sector

The industrial and manufacturing sector covers a vast array of industries where tribology can create value, improving efficiency and reducing energy consumption. However, the fragmentation of the sector could be a barrier for tribology research to be impactful given the reduced size of some industries and their diverse technological needs. On the positive side, this sector has increased its spending in R&D in the last 10 years, spending above the chemicals and energy sectors combined, two sectors that traditionally drive spending in tribological research (Figure 35).

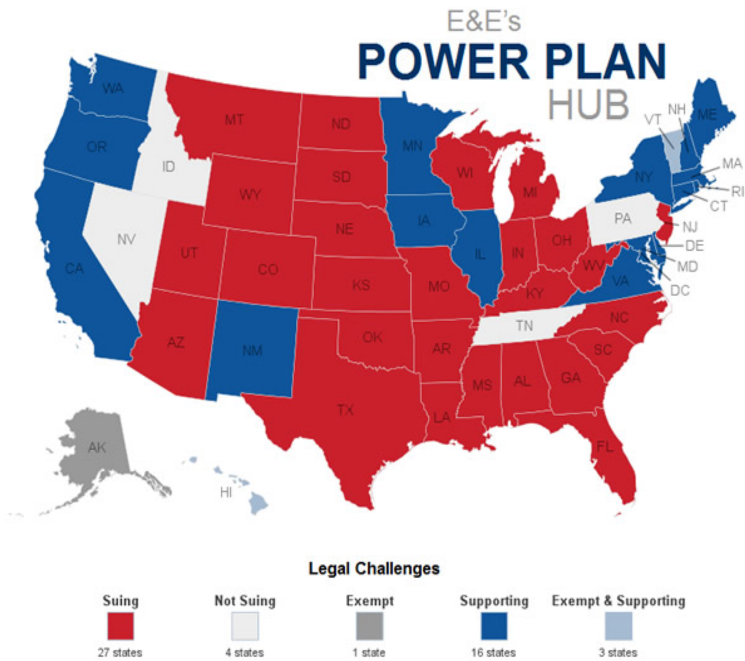

Figure 34. Legal challenges clean power plan [24].

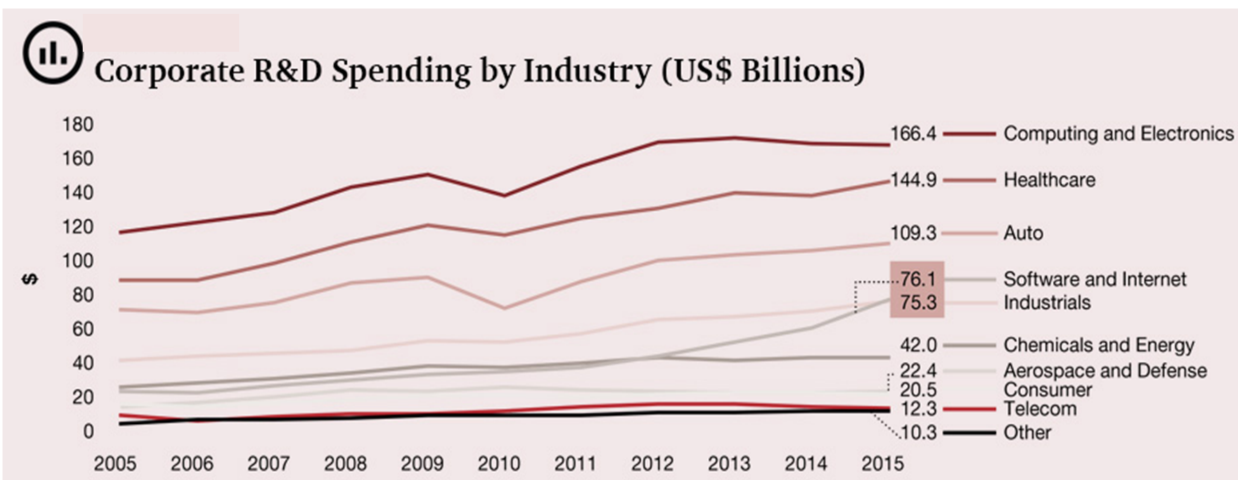

Figure 35. Energy efficiency standards [25].

From the policy and regulatory side, the Department of Energy has established energy efficiency standards for more than 60 different manufacturing products, including consumer products, commercial and industrial products, and lighting and plumbing products. Table 2 shows the list of consumer and industrial/commercial products subject to the standards.

As a policy tool, these standards have been very effective to reduce energy consumption and to foster technological change [26]. Assessing the tribological needs of the manufacturing processes of these products should help tribologists to identify areas of potential collaboration and future industrial partnerships.

Table 2. List of products subject to energy star standards

CONSUMER PRODUCTS		COMMERCIAL & INDUSTRIAL PRODUCTS	
Battery Chargers	External Power Supplies	Automatic Commercial Ice Makers	Packaged Terminal Air Conditioners & Heat Pumps
Boilers	Furnace Fans	Circulator Pumps	Pumps
Ceiling Fans	Furnaces	Clothes Washers	Refrigerated Beverage Vending Machines
Central Air Conditioners and Heat Pumps	Hearth Products	Commercial Package Air Conditioners & Heat Pumps	Refrigeration Equipment
Clothes Dryers	Manufactured Housing	Commercial Packaged Boilers	Single Package Vertical Air Conditioners & Heat Pumps
Clothes Washers	Microwave Ovens	Commercial & Industrial Air Compressors	Small Electric Motors
Computer and Battery Backup Systems	Miscellaneous Refrigeration	Computer Room Air Conditioners	Unit Heaters
Conventional Cooking Products	Pool Heaters	Dedicated-Purpose Pool Pumps	Walk-In Coolers & Walk-In Freezers
Dehumidifiers	Portable Air Conditioners	Distribution Transformers	Warm Air Furnaces
Direct Heating Equipment	Refrigerators & Freezers	Electric Motors	Water Heating Equipment
Dishwashers	Room Air Conditioners	Fans and Blowers	
	Set-Top Boxes		
	Televisions		
	Water Heaters		

Energy Star Compliant Certification. Through a less prescriptive regulatory approach, the EPA distinguishes the best performing plants within an industry with ENERGY STAR certification. Select manufacturing plants can earn ENERGY STAR certification if they achieve an ENERGY STAR score or Energy Performance Indicator (EPI). Table 3 shows the sectors eligible for the certification.

Table 3. Sectors eligible for Energy Star Plan Certification

ELIGIBLE INDUSTRIES FOR ENERGY STAR PLAN CERTIFICATION	
Auto assembly	Integrated paper mill
Cement	Integrated steel plant
Commercial bread & roll	Juice processing
Container glass	Petroleum refining (private system)
Cookie & cracker	Pharmaceutical
Flat glass	Pulp mill
Frozen fried potato processing	Wet corn milling

For each industry, there is a plant guide to identify energy efficiency improvements and cost saving opportunities. The guides list the most energy efficient technologies, and help plant managers to benchmark their performance compared to other plants within their industry. There is no mention in the guides about the benefits of a tribological evaluation of machinery or processes. Such an evaluation could be highly beneficial for industries like cement or paper. Its inclusion in the guide can create awareness about tribological solutions and it will allow tribologists to identify research needs.

Advanced Manufacturing Office Programs. The Advanced Manufacturing Office of DOE has a series of programs including research funding and support to help manufacturing partners to improve energy performance.

Through the Better Buildings, Better Plants Program, leading manufacturers and industrial-scale energy-using organizations sign a voluntary pledge to reduce their energy intensity by 25% over a ten year period. The Better Plants Partners (180 industrial companies, representing about 2,400 facilities and 11.4% of the total U.S. manufacturing energy footprint) benefit from DOE technical support to implement cost-effective energy efficiency improvements.

Facilities can pursue certification to Superior Energy Performance® (SEP™) and can have no-cost energy assessments from DOE's Industrial Assessment Centers (IAC). These Centers, funded entirely by DOE are located at 24 universities around the country. They conduct energy audits of the plants to identify opportunities, improve productivity, reduce waste, and save energy.

The assessments have a multidisciplinary approach, including engineering, economic and financial considerations. Unfortunately, there is no specific mention of tribology considerations in the training manual to perform such assessments [26]. Moreover, in the 429 related papers and publications based on and inspired by IAC activities, there are only 9 papers about lubrication and not a single one dedicated to tribology applications only.

There is an ideal opportunity for tribology applications to help DOE's partners achieve energy efficiency targets. As the pledges are voluntary and the plant audits are free, the number of companies that these programs could benefit is significant.

In addition to energy efficiency programs for the manufacturing sector, DOE is funding early-stage research to support innovative technologies in advanced manufacturing.

Gas Sectors

Under the current low price scenario in the gas and oil sector, opportunities for tribology research are limited. In the medium and long term, EIA estimates that "gas is nonetheless the fastest growing among the fossil fuels and increases its share in global primary energy demand from 21% today to 24% in 2040" [27]. The positive outlook for the gas sector, in combination with the regulatory framework of methane emissions, could foster opportunities for tribology research.

In May 2016, EPA issued three rules that will curb emissions of methane, smog-forming volatile organic compounds (VOCs), and toxic air pollutants from new, reconstructed and modified oil and gas sources. The rules set emissions limits for methane and cover additional sources to the ones previously included in a previous 2012 rule. For tribology, the most interesting aspect of the rules is the requirement to the owners and operators of new and modified well sites, gas processing plants and transmission and storage facilities to find and repair leaks. To comply with these regulations, the industry will need to invest in innovative and cost-effective technologies to improve pipeline surfaces while reducing corrosion.

Aviation

Last October, the International Civil Aviation Organization (ICAO) reached an agreement to introduce Carbon Offsetting and a Reduction Scheme for International Aviation (CORSIA). This agreement, which has the support of both industry and environmental organizations, aims to reduce emissions through a carbon market. Emitting airlines should have to offset emissions with credits. According to the Environmental Defense Fund [28] CORSIA affords airlines flexibility to choose how to cut CO from a set of options like:

- fly more efficient aircraft,
- use new technologies to set more efficient flightpaths and reduce delays,
- use sustainable lower-carbon alternative fuels, and
- invest in emissions offsets within or outside of the aviation sector (like programs for reducing emissions from deforestation and forest degradation in developing countries (REDD+))

The scheme will be voluntary from 2021 to 2026 and mandatory from 2027, with most small developing countries exempt. As of 12 October 2016, 66 States, representing more than 86.5% of international aviation activity, intend to voluntarily participate in the global MBM scheme from its outset, including the U.S., EU, China and other small nations [29].

Given the menu of options to reduce emissions, the airlines will implement the most cost-efficient alternative. Aircraft efficiency measures will be implemented only if their cost is lower than the emissions offsets or the implementation of efficient flightpaths.

If the industry decides to invest in more efficient technology for airplanes, there will be opportunities for tribology research to improve turbines and the fretting and wear of hinges, tracks, bearings, and gearboxes in airframes and engines. Section 2.14 identifies technological opportunities in this sector.

d) Non-regulatory opportunities

Electronics Sector

The strong growth of the electronics sector drives opportunities for the development of nano-tribology innovations that could expand nanotechnology applications. In comparison to other sectors where innovation is driven mostly by policy and regulation, in the electronics sector, innovation is key to remain competitive and support growth. As shown in Figure 35, R&D expenditures of this sector are the largest compared to all the other sectors of the economy. In the last ten years, those expenditures have doubled expenditures of the automotive sector, and almost tripled expenditures of the energy and chemical sectors combined. In particular, the nanoelectromechanical systems (NEMS) switch application described in Section 5.2 could save large amounts of energy by selectively replacing transistors, which are becoming increasing energy-inefficient.

Early Stage Interactions with the Industry

Tribology applications could be more impactful if tribology issues are considered in the design process of a given technology, and not at a later stage when the given technology requires tribological solutions to solve friction, wear and lubrication problems. Tribologists should aim to design, not just to improve. This idea is specifically proposed as part of the vehicle engine design cycle, discussed in Section 2.4.

Increase Tribological Awareness

Increasing awareness of the energy efficiency potential of tribology is necessary to attract private and public research funding on an ongoing basis, more diverse industrial partners and new talent to the discipline. Below are some suggestions of things that can be done to increase awareness:

- Education plays an important role to create and improve awareness. A comprehensive tribology course should be included in more engineering curricula, not only in the mechanical engineering curricula. Professional disciplinary organizations like the ASME, MRS, and AiCHE for example, could be approached by tribologists with materials and information to encourage such adoption in curricula. The Accreditation Board for Engineering and Technology (ABET), who accredits post-secondary engineering programs, could also be approached to ensure they recognize tribology as an important discipline whose inclusion in curricula is encouraged. Also, authors and publishers of educational textbooks could be encouraged to define modern tribology, for example, in introductory physics and mechanics textbooks (which always cover basic friction concepts) and fluid mechanics texts (where lubrication is a key application of fluid mechanics).
- Tribologists can write more for the general public about important tribological achievements and the game-changing technologies that tribology has enabled.
- Tribologists can work to build stronger relations with federal funding agencies like DOE, EPA, DARPA, ARPA-E by encouraging tribology student internships in those agencies, and by participating as a lobby group in the regulatory processes of EPA and DOE. STLE already devotes efforts in these directions, but additional participation by tribologists in academia and industry would help support this effort.
- Tribologists can further support entrepreneurship. As an enabling technology, tribologists can provide specialized services to medium and small industries which cannot afford research teams or highly specialized maintenance equipment.

6.4 CONCLUSION

Tribology has the potential to generate value and growth for recipient industries. At the same time, due to what economists call creative destruction, the prospects of future innovation can reduce the value of current research by making it obsolete. This is a market failure that reduces the incentives for private investors to fund research. To ensure a growth path driven by innovation, policy and regulation should address this market failure by providing adequate incentives to private investors, or by funding research in technology directly.

In the last 50 years, energy efficiency policy in the U.S. has been largely driven by the fluctuation of oil prices. Correspondingly, funds for tribology research are positively correlated with oil shocks. When oil prices are low, the government tends to change energy security priorities, shifting funds from energy efficiency technologies to other sectors. In the same way, the oil and gas industry, a major private investor in tribology research, tends to reduce their research budgets when oil prices low given its low margins. To minimize the risk of fluctuation in oil prices, tribologists should seek to diversify industrial partners beyond the oil and gas sector or the automotive sector.

Energy conservation and climate policy right now are the main drivers of opportunities to expand those partnerships and increase the impact of tribology as a clean technology. In regulatory and policy terms, the Clean Power plan in the electricity sector, DOE standards for energy efficiency of appliances and equipment, DOE programs for Advanced Manufacturing, EPA rules for the reduction of methane emissions, and international agreements for offsetting carbon emissions in the aviation could generate incentives for private and public investors to support tribology research.

Even if these policies drastically change in the next months as a consequence of a radical shift in climate policy, opportunities for tribology technology will remain and would perhaps expand since tribology innovation could help American industries to achieve cost reductions to become more competitive. Thus, tribology technology could benefit from industrial and manufacturing competitiveness policies.

To make the most of these opportunities, tribologists need to create awareness and make the world know about the full potential of their discipline, as Jost did 50 years ago. The time has come to do it again.

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Chapter 7
Workforce Development Needs

7.1 INTRODUCTION

There is, and has been for some time, a large and growing gap in the skilled workforce in tribology. One significant benefit arising from ARPA-E programs in tribology will be a substantive development of scientists and engineers who will help close this gap and form a workforce skilled in modern and innovative tribology technologies. This chapter briefly presents the workforce needs and benefits.

While graduate level programs in tribology once existed at several U.S. universities, there are currently no specific or well-established/developed graduate-level traineeship programs in place in the U.S. Substantive funding, infrastructure, industry engagement and human capital for tribology can be found in Europe, Asia and elsewhere.

The Society of Tribologists and Lubrication Engineers (with its local chapters and its 211 Industrial Members) is the only organization that offers specific educational and training courses at the graduate level in tribology; a few U.S. universities are also offering graduate level-courses in tribology as part of their materials, mechanical and chemical engineering curricula. For example, Noria, a private company, provides training courses in lubrication for industry [1]. Courses focus on basics and fundamentals (e.g., courses titled Industrial Lubrication Fundamentals, Oil Analysis and Machinery Lubrication). They reach a large number of people (over 5000 per year in 40 countries) but offer far more courses outside the U.S. than within. Much of this training is at a level appropriate for technicians. However, more advanced, hands-on training opportunities beyond these academic and industrial offerings are needed. In particular, the knowledge gap is rather wide in micro- and nano-scale mechanics, manipulation and mechanistic understanding of tribological phenomena, advanced modelling and simulation techniques, nanoscale coating design and synthesis, fundamentals of boundary lubrication, and novel additive-surface interactions, which have become essential in many types of manufacturing and energy conversion and utilization systems. Furthermore, many of the new and emerging opportunities described in this report represent forefront areas where few experienced practitioners exist. The report authors and workshop attendees concurred that industry is hungry to hire educated students at all levels in tribology, but they often turn to people trained overseas due to a lack of 'home grown' expertise. Alternately, they conduct training internally, which becomes increasingly challenging as greater numbers of the existing generation of trained tribologists are retiring.

Accordingly, developing a skilled workforce is of great importance if the energy efficiency benefits of tribology are to be realized. Such opportunities would empower future graduate students to acquire high-level skills and knowledge to pursue successful R&D in tribology and related fields in their future career.

Significant advances in tribology have occurred over the last few decades. With critical failures happening less often than in the past and with reasonable levels of efficiency achieved in some industries, a state of some complacency is apparent within funding agencies, academia and industry. However, the new urgency arising from climate change, environmental concerns, energy security concerns and economic competitiveness urgently motivates the training of a new generation of tribologists. This need for a trained research workforce is further underscored by the emergence of completely new micro, nano, and biotechnologies where tribological knowledge at the Ph.D. level is required to solve problems and to allow U.S. industry to compete.

In addition, new generations of novel tools provide opportunities to advance tribology research and innovation. These include: in situ electron microscopy imaging of contacts; atomic-scale probes of the topography, structure, and composition of materials and surfaces; and high performance computational models of sliding interfaces under realistic conditions that could never be simulated before.

7.2 POTENTIAL BENEFITS OF REINVIGORATED TRIBOLOGY WORKFORCE

The possible benefits of an improved tribological workforce for the areas covered in this report are listed below:

- Improved energy efficiency/reduced emissions of CO_2
- Reduced maintenance costs
- Reduced downtime of equipment
- Increased design ratings (e.g., higher loads and speeds; increased productivity)
- Enhanced environmental performance (e.g., exhaust system compatibility, bio-friendly fluids)
- Increased safety margins (e.g., lower toxicity or increased fire resistance of lubricants, cutting fluids, and other fluids in manufacturing systems)
- Successful implementation of disruptive new technologies whose tribological properties radically depart from the existing knowledge base

7.3 STRATEGIES FOR MAXIMIZING THE IMPACT OF ARPA-E FUNDING ON TRIBOLOGY WORKFORCE DEVELOPMENT

Although beyond the scope of ARPA-E's mission, the following strategies could be encouraged by the tribology community to support the training and education of students, trainees and junior industry researchers who will be part of any ARPA-E funded efforts. At the undergraduate level, experienced tribologists can be deployed broadly to provide guest lectures on tribology on campuses in various engineering courses. On-line lecture materials could be prepared that could enable far broader dissemination of tribological knowledge. The STLE has significant experience with training courses and an extensive network of motivated academics and industry practitioners with the expertise to deliver such material.

These strategies could also be effective for master's level students. Notably, there has been a significant increase in enrollment in engineering master's programs over the last decade, both via students starting master's programs fresh from other institutions (including a large overseas influx), but also via submatricalation programs where students in bachelor's programs stay an extra one or two semesters at their institution to earn a master's degree. These students tend to be very focused on pursuing industry careers and see the master's training as an important step toward better engineering jobs and more accelerated career progress. Accordingly, such students may be significantly motivated to further their knowledge of industrial topics including those related to tribology. Industry internships or hands-on research-oriented projects supported by faculty would be of interest to a significant fraction of these students.

At the Ph.D. level, several examples exist of programs where industry funding is provided to match government funding in tribology, including two recent programs in the UK that could be used as frameworks or sources of best practices for new doctoral programs in the U.S.:

1. The national Centre for Advanced Tribology at Southampton University (nCATS) [2] was initiated approximately 7 years ago. This center had five years of funding with the aim of being self-supporting after that.
2. A recent doctorate program jointly run by Leeds University and Sheffield University [3,4] was started and has approximately 12 PhDs funded every year for the next five years.

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Chapter 8
Conclusions

A total of 22.76 quads of potential annual energy savings in the U.S. were identified through the deployment of advanced tribology technology.

Table 4 lists in descending order the potential quad savings achievable by topic. There are common themes with advanced lubricants and coatings that appeared throughout the report, regardless of the application.

The research and development work required is intrinsically interdisciplinary and complex, and thus would benefit from structured programs that bring industry, government and academic researchers together. Excitingly, tribology technology has entered a new phase where disruptive approaches based on rational design of materials and systems are possible, thanks to recent progress in large-scale computational modeling of tribological systems, experimental methods with *in situ* capabilities and novel materials including nanomaterials. The potential impact of tribology technology is large, and the tribology community stands ready to take up the challenge of dramatically increasing energy efficiency in the U.S.

Table 4. List of potential quad savings, topics and report section in descending savings

POTENTIAL QUAD SAVING FROM TRIBOLOGY	TOPIC	REPORT SECTION
6.6	Vapor phase lubrication	5.4
3.1	Mining and extraction*	4.4
2.5	Granular material processing	5.6
2.48	Component and design optimization of engines	2.3
1.86	Advanced coatings in vehicle components*	2.5
1.3	Design engine/drivetrain and lubricant in tandem*±	2.4
1.24	Computationally-aided design and modelling of vehicle components	2.7
0.95	NEMS Switches	5.2
0.84	Residential HVAC	5.4
0.62	Engine and drivetrain lubricants±	2.2
0.42	Aviation	2.14
0.37	Fuel considerations	2.8
0.25	Advanced engine sensing and actuation	2.6
0.2	Tires	2.12
0.18	Wind turbine reliability and efficiency±	3.7
0.14	Drilling for, producing and transporting natural gas	3.3
0.05	Metal working*±	4.3
0.05	Wear reduction of materials*	4.5
0.021	Triboelectric power generation	5.3
0.003	Marine considerations*±	2.15
0.0025	Rail*±	2.16
0.0017	Tribology needs for other renewable energy	3.8
0.00014	Automotive seals	2.11

*Advanced coatings research would yield savings in all these areas, potentially to 4 quads or more per year.

±Advanced lubricant and additives would yield savings in all these areas, potentially to 2.2 quads or more per year.

ACKNOWLEDGMENTS

Report contribution from (in alphabetical order):

- Nicolas Argibay – Sandia National Laboratory
- Shashank Acharya – University of Pennsylvania (now at Northwestern University)
- Ewa Bardasz – Lubrizol Corporation (retired)
- Kristin Bennett – KB Science
- Maarten de Boer – Dept. of Mechanical Engineering, Carnegie Mellon University
- Angela Pachon Garcia – Kleinman Center for Energy Policy
- Aaron Greco – Argonne National Laboratory
- Robert Gresham – Society of Tribologists and Lubrication Engineers
- Greg Hansen – Southwest Research Institute
- Kevin Hoag – Southwest Research Institute
- Jacqueline Krim – North Carolina State University
- Dylan Morris – Michelin Americas Research Company
- Gianluca Piazza – Dept. of Electrical and Computing Engineering, Carnegie Mellon University
- Charlie Roberts – Southwest Research Institute
- Zhong Lin Wang – School of Materials Science and Engineering, Georgia Institute of Technology
- Dillon Weber – University of Pennsylvania
- Zijian Yang – University of Pennsylvania
- Yunlong Zi – School of Materials Science and Engineering, Georgia Institute of Technology

The executive committee would like to express their thanks to the Society of Tribologists and Lubrication Engineers (STLE) for supporting the workshop held in Las Vegas, May 2016, at the conclusion of the 71st STLE Annual Meeting and Exhibition, for publishing our article in the May 2016 issue of TLT Magazine promoting this study, and for providing web hosting sponsorship of the survey.

APPENDIX A – FULL BIBLIOGRAPHY OF COLLECTED LITERATURE

CHAPTER 1

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CHAPTER 8

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APPENDIX B – WORKSHOP ATTENDEES

NAME	AFFILIATION
Nick Argibay	Sandia National Laboratory
Pranesh Aswath	University of Texas at Arlington
Eva Bardasz	Lubrizol Corporation (retired)
James Batteas	Texas A&M University
David Burris	University of Delaware
Rob Carpick	University of Pennsylvania
Mark Devlin	Afton Chemical
Mike Dugger	Sandia National Laboratory
Ali Erdemir	Argonne National Laboratory
Oscar Fang	ExxonMobil
Arup Gangopadhyay	Ford Motor Company
Aaron Greco	Argonne National Laboratory
Bob Gresham	Society of Tribology and Lubrication Engineers
Timo Hakala	VTT Technical Research Centre of Finland
William Hannon	Timken Company
John Hermann	ExxonMobil
Fred Higgs	Rice University
Andrew Jackson	University of Pennsylvania
Harman Khare	University of Pennsylvania
Jackie Krim	North Carolina State University
Peter Lee	Southwest Research Institute
Pradeep Menezes	University of Nevada, Reno
Brendan Miller	Chevron
Dylan Morris	Michelin Americas Research Company
Angela Pachon Garcia	University of Pennsylvania
Jun Qu	Oak Ridge National Laboratory
Scott Rappaport	Shell Global Solutions
Carlton Reeves	ARPA-E
Eddy Tysoe	University of Wisconsin-Milwaukee
Jennifer Vail	DuPont
Martin Webster	ExxonMobil
Vern Wedeven	Wedeven Associates