A Report on Research Trends in Mechanics:
"U.S. ENERGY AND ENVIRONMENTAL CHALLENGES AND FUNDAMENTAL CONTRIBUTIONS FROM MECHANICS RESEARCH"

US National Committee on Theoretical and Applied Mechanics (USNC/TAM)

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OVERVIEW

Among the most pressing challenges facing our planet is the development of efficient, affordable, sustainable energy-generation technologies. Energy fundamentally underpins a society's capacity to provide food and water, clothing, shelter, treatment of disease, heating and cooling, and transportation for its members. The fact that an estimated 1.4 billion people worldwide do not have access to electricity, and that another billion only have unreliable access to electricity[1] suggests that more widespread, efficient, and sustainable energy generation systems could have a profound benefit for the quality of life on a global scale. Yet efficient energy generation technologies must also have minimal or at least a reduced environmental impact compared with present systems. Indeed, another major global scientific challenge is the environmental remediation required as a result of power and energy system-generated pollutants. As the backbone of engineering systems, the field of *mechanics* writ large (i.e., the fields of fluid mechanics, solid mechanics, mechanics of materials, computational mechanics, nano-mechanics, and so forth) continues to have a profound impact on the solution to global energy and environmental challenges. This report provides an overview of these challenges, and describes a number of promising technical directions in their solution for which the field of mechanics plays a key role. While this report is not intended to be a comprehensive evaluation of all possible energy and propulsion technologies of the future, it does identify the most promising technologies for which contributions from broad areas within mechanics will be crucial for success.

FUTURE ENERGY GENERATION AND STORAGE TECHNOLOGIES

Power and/or propulsion are the fundamental goals of most contemporary energy generation systems. While in recent years Americans have increased their use of electricity and transportation systems derived from renewable energy sources[2,3], technical advances in a range of fields can further

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accelerate this transition to renewables by improving their efficiency, cost, and sustainability. Electrical power production via wind energy, efficient solar cells via advanced materials, and efficient power plants fueled by biofuels or synthetic fuels all have as their core fundamental advances in fluid mechanics, materials science, and solid mechanics. Energy storage systems such as advanced batteries and fuel cells as well as electrochemical capacitors require contributions from electrochemistry as well as the mechanics of new materials and associated thermal transport phenomena. Transportation systems such as hybrid or fully electric ground vehicles could benefit enormously from advances in the energy storage arena in particular.

Wind Energy

The U.S. has experienced tremendous growth in the wind energy industry in recent years, doubling power generating capacity since 2011, reducing the cost of wind energy to near all-time lows, and supporting 75,000 jobs in the process. Last year alone, $25 billion was invested in new wind energy installations in the U.S., a figure that is projected to triple by 2030[4,5].

Basic research in fluid dynamics and solid mechanics will be essential to protect and further develop this key national investment. In particular, recent experience in Denmark and the United Kingdom has shown that wind farm underperformance and declining power production as wind farms age can result in higher costs for wind energy than initially anticipated, thereby affecting the long term viability and penetration of wind technology in a national energy portfolio[6]. Our ability to predict the initial and long-term performance of wind farms will require fundamental breakthroughs in our understanding of the aerodynamic interactions among groups of wind turbines, as well as new solid mechanics models to predict and circumvent structural failures.

As illustrated in **Figure 1**, aerodynamic interactions in a wind farm involve a complex interplay between each wind turbine and the disturbed wake of air created by the surrounding wind systems. The wake presents a two-fold challenge. First, the wake contains slower moving air and therefore carries less energy. As a result, the interior rows of some existing wind farms produce up to 40 percent less power than equivalent wind turbines operating in isolation[7]. To avoid this circumstance will require better tools to predict wind dynamics and to optimize the placement of turbines in wind farms. The scientific challenge is amplified by the fact that many new wind farms in the U.S. are sited in increasingly complex terrain to access favorable wind conditions. New experimental tools must be developed to enable detailed, three-dimensional measurement of the flow around individual wind turbines and around groups of wind turbines at full scale in the field. These efforts will complement traditional wind tunnel studies of scale model wind turbines, but will ensure that the full complexity of the real-world problem is captured. Field testing facilities for arrays of wind turbines have recently come online in California[8] and Texas[9], providing unprecedented opportunities to study wind farm physics prior to commercial implementation. These efforts should be replicated at other field sites with distinct wind conditions and terrain to provide a diverse range of test conditions to evaluate wind farms.

Experimental measurements must be married with development of advanced computational tools to simulate wind farm performance. Whereas experimental measurements are necessarily limited to a handful of wind turbines, numerical simulations could potentially recreate entire utility-scale wind farms, including the aerodynamics, structural mechanics, and grid behavior. Incorporation of solid mechanics and materials in these models highlights the second challenge posed by wake interactions in wind farms, namely, the unsteady loading of the structural components of downwind turbines. Failure of these components, especially the blades and gearbox, is directly linked to reduced availability of wind systems and, when underestimated, can lead to substantially higher life-cycle costs for the system and for the energy produced. Advances in materials science and manufacturing will only be properly leveraged if they are coupled with an improved understanding of the complex loads experienced by wind turbines and their associated structural responses. This knowledge will guide materials selection and influence manufacturing protocols. A multidisciplinary computational tool that integrates all of these facets is beyond the scope of existing technology. Therefore, a national commitment to development of the aforementioned tools is imperative to support U.S. leadership in wind energy and to ensure that the investments made today continue to produce benefits to society for decades to come.

Figure 1. Horns Rev Offshore Wind Farm, North Sea. Turbulent wakes visible in fog behind front row of turbines.

Geothermal Energy

Geothermal energy is derived from Earth's continually-replenished interior heat. While geothermal power plant systems extract energy from the subsurface more rapidly than the deep geothermal heat flux replenishes it, time scales of thermal recharge are decades, much shorter than those of fossil fuels, thereby rendering geothermal systems a renewable energy resource on human time scales. Geothermal reservoir life spans can be many decades, as exemplified by the first geothermal power plant in Larderello, Italy, which began operating in 1906. Geothermal energy is accessible in the shallow crust, from a few feet below the surface to depths of approximately 6 miles, depending on the technology employed and the intended application. Geothermal heat can be converted to 24/7-electricity production and/or used to offset 80% of space and water heating and cooling needs. While geothermal development has seen steady growth over the last half century, with recent and new research and technologies, many of which are based on foundational fields within mechanics, geothermal is poised for explosive growth in the next decade.

In contrast to wind and solar renewable energy resources, geothermal electricity can be generated continuously during the lifespan of a geothermal reservoir. As a result, geothermal power plants can be operated as baseload power sources without the need for power storage systems. Alternatively, geothermal power plants can be operated intermittently to fulfill peak power demand, directly replacing natural gas peaking power units. Thus, with large-scale implementation, geothermal energy can be the ideal clean energy companion of intermittent renewable energy sources. Moreover, geothermal energy supports far more jobs per Megawatt (MW) than fossil fuel power systems – eight times as many per MW as coal and 18 times as many as natural gas[10], accounting for all the jobs from resource harvest through power plant construction and operation, thus promoting job creation.

The U.S. currently supports the world's largest geothermal power generation capacity, with over 3 Gigawatt (GW) installed[11]. However, the geothermal power production potential of the U.S. is far from exhausted. Recent USGS[12] and DOE[13] estimates as well as a 2006 MIT report[14] on the future of geothermal energy estimate the country's geothermal electricity production potential at 100 to 500 GWe, or about 10 to 50% of the U.S. electricity requirements. However, these reports also point out that new research and technologies are required to realize this potential as some significant, but surmountable, obstacles still need to be resolved. Thus, research in, and rapid implementation of, all aspects of subsurface geothermal energy extraction and conversion is required to develop new, and improve existing geothermal energy systems. This includes advances in a number of areas for which fluid mechanics, solid/structural mechanics, and fundamental transport processes are foundational: (1) the use and optimization of various subsurface working fluids (water, CO_2, etc.) and power system working fluids (water, CO_2, refrigerants, etc.); (2) subsurface permeability enhancement to create enhanced geothermal systems (EGS); (3) the development of new drilling methods into deep, hot rock; (4) co-generation of electricity and heat; (5) translation of technologies and methods from other industries (e.g., oil and gas) to geothermal; (6) combining geologic carbon storage or enhanced oil recovery with geothermal energy use, both for use of carbon dioxide (CO_2) as the heat energy extraction fluid and for enhanced hot water production; and (7) optimizing ground-source heat pumps for space heating and cooling.

Depending on underground resource temperatures and heat extraction working fluid, geothermal power facilities can provide electricity, heat, or both. When underground water is used to extract heat, minimum reservoir temperatures of 40°C (100°F) or greater are typically needed for district heating. Where appropriate end-users and infrastructure exist, allowing geothermal to allocate energy for space/water and industrial process heating, geothermal can provide a clean source for this heating that accounts for 50% of U.S. energy requirements. In addition to sufficient reservoir temperatures, the underground reservoir must have sufficient permeability to allow for sufficient flow rates of the heat extraction fluid. Minimum permeabilities can be lower when CO_2 is used, rather than water. When natural permeabilities are too low for heat energy extraction, then artificial geothermal reservoirs may be generated by hydrofracturing low-permeability but hot rocks. This process – still much in its infancy – results in so-called Enhanced or Engineered Geothermal Systems (EGS) and builds upon techniques from the hydrocarbon industry. CO_2 based heat extraction systems can be installed in lower-permeability reservoirs without the need for hydrofracturing while significantly increasing power production and eliminating anthropogenic CO_2 emissions[k]. However, like EGS, CO_2-based geothermal systems are still in research and development.

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[k] **Disclaimer:** Drs. Saar and Randolph have a significant financial interest, and Dr. Saar has a business interest, in Heat Mining Company LLC, a company that may commercially benefit from the results of this research. The University of Minnesota has the right to receive royalty income under the terms of a license agreement with Heat Mining Company LLC. These relationships have been reviewed and managed by the University of Minnesota in accordance with its conflict of interest policies.

While geothermal power plants can supply heat and electricity at discrete locations, the shallow underground virtually anywhere can be used as a heat capacitor that is warmer than the atmosphere in the winter and colder than the atmosphere in the summer. These relatively small temperature differences can be increased with heat pump technologies in so-called ground-source or geothermal heat pumps (GHPs). GHPs are powered by a small amount of electricity, with which they extract three-to-five times as much renewable energy from the subsurface. Thus, GHPs can provide space heating and cooling anywhere, independent of deep geothermal temperatures, while reducing electricity or combustion requirements for heating by 80%. While geothermal energy has substantial potential to serve as a large-scale renewable resource, it has seen only modest investment and development, particularly in the U.S. With appropriate investment and associated research and commercialization, geothermal energy has the potential to supply a significant portion of the world's energy needs. This new, renewable, geothermal energy technology -- made in the U.S. -- could then set new technology standards, create new jobs in the U.S., and result in worldwide exports while producing electricity and providing district heating/cooling with virtually no greenhouse gas emissions.

Solar Energy

Sunlight is the most abundant energy source on the planet; the quantity of solar energy striking the Earth's surface averages about 1,000 watts per square meter under clear skies, depending upon weather conditions, location and orientation. Over the past few decades, a range of technologies have been developed to capture solar energy and use it in the generation of electricity or heat. Photovoltaic cells can convert light directly into electricity without substantial thermal or CO_2 emissions, hence this technology is considered to be among the most promising renewable energy solutions. Silicon based photovoltaic cells have dominated the solar industry for many years, although there are limitations to their widespread adoption due to high manufacturing costs and limited efficiencies[15]. Recent developments in thin film solar cells have allowed these devices to become more attractive due to their ease of manufacturing and compatibility with large-area, light-weight, flexible substrates, as shown, for example, in **Figure 2**. While several types of thin film solar cells have recently begun mass production, their widespread application is still inhibited by limited efficiency values.

Recently, advances in materials science have yielded materials with low crystallinity that demonstrate promising photovoltaic performance. The efficiency of these material systems increases dramatically with the addition of semiconducting organic oligomers and polymers[16]. Efficient light harvesting in these systems can be achieved by tuning the material absorption intensity and wavelength range. Optoelectronic properties of thin films also can be controlled through molecular design and processing parameters. The power conversion efficiency of these material systems has reached 10-15% via relatively inexpensive fabrication techniques, generally on the same cost order as those used for polycrystalline silicon.[17] In addition, thin film solar cells are becoming more attractive for integrated photovoltaic applications in building design. Solar panels with transparency in the visible range can harvest infrared light, serving multiple purposes, i.e., light transmission as with traditional glass windows, but with infrared light absorption as well, reducing heating effects and turning light into electricity during the daytime.[I] Further technical advances, including the development of higher performance electrode and interfacial materials, are needed to improve the performance of these promising technologies.

There is significant need, from the perspectives of both the photovoltaic industry and the scientific research community, for gaining a more fundamental understanding of the relationship between processing techniques and material properties. Photovoltaic cells should optimally operate under cyclical light exposure conditions in the ambient atmosphere, for lifetimes as long as 25 years. Robust, air-stable materials and devices need to be developed to meet these durability and operability requirements, which will eventually contribute to price reductions for practical applications.

Figure 2. Installation of flexible solar panels for rooftop solar power generation[18]

Solar thermal collectors comprise a range of technologies that were first developed in the 1950s[19]. Flat plate and tube solar collectors have been commercially available for several decades for residential heating of water or air, or, in conjunction with an absorption chiller, cooling. More recent applications have involved large solar power towers, with heliostats focusing sunlight on receivers which can heat water to drive turbines and generate electricity. An example of this is the solar thermal system currently being developed at the Ivanpah Solar Electric Generating System (ISEGS) in California's Mojave Desert[20]. Development of heat storage fluids for overnight and cloudy periods is a technical challenge for which advances in fluid mechanics have been particularly valuable. While molten salts have been used successfully for such storage, liquid metals as well as supercritical fluids[21] have been suggested to have improved transport properties and attendant benefits for solar thermal applications.

Electrochemical Energy Storage

Electrical energy storage (EES) technologies offer potential solutions to some of the most important issues we face in the 21st century: the reliability of the electrical grid, the electrification of the transportation sector to reduce dependence on the use of liquid fuels, and the projected doubling of worldwide demand for energy by 2050. One viable means of meeting the latter is based on electricity that can be generated from renewable sources, such as solar or wind, as noted above. However, the use of electricity from these intermittent sources requires efficient EES technologies in order to make the electricity available 24 hours a day[22]. Among the various EES approaches, electrochemical energy storage possesses a number of desirable features including pollution-free operation, high round-trip

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[I] **Disclaimer:** Solarmer Energy, Inc., a spin-off company from UCLA with leadership from Yang Yang, has developed a lightweight, flexible, polymer solar panel, produced using a novel, low-cost, high-throughput, roll-to-roll manufacturing process. These relationships have been reviewed and managed by the University of California in accordance with its conflict of interest policies.

efficiency, flexible power and energy characteristics and low maintenance. The ability to make power sources from electrochemical energy has led to the unprecedented growth of portable consumer electronics.

The two dominant types of electrochemical energy storage are batteries and capacitors. While both devices are comprised of electrodes (anode and cathode) separated by an electrolyte, the energy storage mechanisms are very different. In a battery, electrical energy is stored as chemical energy whereas in capacitors (often called 'supercapacitors') energy is stored as surface charge. Largely because of the success of lithium-ion battery technology in the portable electronics market, these systems are the batteries of choice for powering the next generation of hybrid electric vehicles (HEVs) as well as plug-in hybrids (PHEVs). It is evident however, that improvements are needed in such areas as performance and cost without compromising safety. In recent years, nanomaterials and other advanced synthesis methods have led to significant improvements in performance and within the next few years the expectation is to have battery system packs of 200 Watt-hour kg^{-1} which charge in 3 hours, and whose cost will drop to below \$150 kWh^{-1} by 2030[23].

The development of large-scale energy storage for electrical grid applications will not only improve grid reliability but also enable the widespread use of renewables. Grid energy storage will effectively decouple generation and load and simplify the need to balance electricity supply and demand.[24] The availability of energy storage would help to eliminate the distinction between peak and baseload generation (**Figure 3**). Batteries represent an excellent energy storage technology for the integration of renewable energy sources. They can provide frequency control to reduce variations in local output and to mitigate output fluctuations while their high energy density enables them to be used in a distributed manner. The modularity and scalability of various battery systems is another attractive feature. High cost, however, represents a limiting factor. Yet the development of battery systems for grid storage is still at its inception. The one commercially available system is the sodium/sulfur battery which has been installed in some 200 locations world-wide. This battery is largely used for utility-based load-leveling and peakshaving applications. The battery operates at elevated temperatures (350°C) and thus identifying new chemistries to lower the temperature represents an important future direction. Redox-flow batteries possess several promising attributes for energy storage, with low cost being one of its key advantages. A number of utility-based demonstration projects are underway which will provide important information concerning operational characteristics of these systems and maintenance requirements. Lithium-ion batteries are also being actively investigated for grid storage applications. From its applications in consumer electronics and electric vehicles, this technology has already addressed issues of reliability, cycle life, safety, and other factors that are important for stationary energy storage. An important future direction here is the need to develop low-cost materials for such storage devices, and hence research investment to advance manufacturing processes and materials synthesis will be a key to future success.

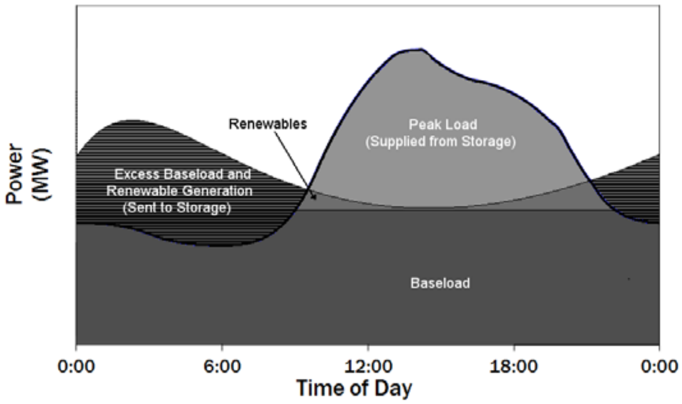

Figure 3. The electric power load on the grid changes over the course of the day. The changing load is met by several types of generation: baseload, intermediate load and peak load. If there is sufficient storage on the grid, it can be used to regulate the grid in place of intermediate and peak generation. At off-peak times, when the generation from baseload and renewables is greater than the load, the excess energy is stored. At peak times, when the total load exceeds the total generation from baseload and renewables, energy storage supplies the remaining load[23].

FUTURE TRANSPORTATION SYSTEMS

In addition to the generation of electricity and HVAC (heating, ventilation, air conditioning), efficient power generation for future transportation systems is of vital importance. While current land, sea, and air vehicles principally utilize the combustion of hydrocarbon fuel for propulsion, there are rapid technological changes occurring in all sectors, especially in ground vehicles. For ground transportation, hydrogen fuel cells have seen a recent infusion of emphasis by automobile manufacturers in meeting governmental zero-emissions standards, although the cost of fuel cells, as well as technological challenges in producing sufficient sources of hydrogen, create considerable challenges. Widespread usage could eventually result from development of low cost, high efficiency production of hydrogen fuel via steam reforming of hydrocarbon fuels, electrolysis of water, or other means. On the other hand, hybrid electric automobiles and buses, including plug-in hybrid vehicles, and all-electric vehicles utilizing state-of-the-art energy storage (battery) technology have become quite commonplace over the past decade. While the current sources of electricity for powering such vehicles typically consist of power plants based on coal or natural gas combustion, hydroelectric energy generation, or fission-based nuclear energy, it is expected that future sources of electricity for such transportation will include those associated with wind, solar, and geothermal technologies, as discussed above.

It is less likely, however, that future air and sea vehicles will substantially rely on electricity and electrical storage technologies, other than for auxiliary power sources, given the nature of the propulsion process required for each to operate. In the case of air vehicles, while there have been demonstrations of high-altitude, long-endurance (HALE) aircraft that are powered by solar cells[25] and/or solid oxide fuel cells, it is expected that such technologies could not be used to completely propel large scale commercial passenger or cargo aircraft, nor could they be used for military transport, fighter, or bomber vehicles, which will likely continue to rely on liquid fuels for combustion-based propulsion for at least the next decade or two. Energy density as well as fuel density considerations make hydrocarbon-based propulsion the likeliest source for airbreathing propulsion in the coming decade or more. Similarly, most seafaring vessels rely on fossil fuel-based propulsion, utilizing internal combustion engines, diesel engines, or gas turbine engines to drive the ship's propellers, although the military has made widespread use of marine nuclear power plants to propel submarines and aircraft carriers. And while superconducting motors, fuel cells, and high-speed generators will have a positive impact on the design of future naval vessels, it is likely that for at least the next decade or two, hydrocarbon combustion will be a primary means of seafaring propulsion.

Energy Efficient Air Vehicles

Current and future energy-efficient aircraft systems rely substantially on fundamental technical advances in the fields of fluid mechanics (including chemically reactive flows), solid mechanics, computational and experimental mechanics, and the mechanics of materials. Technical advances which can improve fuel efficiency and reduce emissions from aircraft engines, for example, could save hundreds of millions of dollars per year for airlines[26] and the military[27], while simultaneously reducing aviation's environmental footprint. Technological advances for improved aircraft fuel efficiency are often categorized according to their contributions to components within the Breguet Range Equation[28], representing the approximate distance an aircraft can travel at a given cruising speed with a given initial amount of fuel. The Range equation says that for a given amount of fuel, improvements in aircraft range can be attained via improved aerodynamic performance (lift-to-drag ratio), improved engine performance (or lowered thrust-specific fuel consumption), and lighter aircraft structural weight.

Over the past few decades, substantial improvements in aircraft fuel efficiency have been achieved via technologies for which the field of mechanics is foundational. Advances in aerodynamic design have arisen via long term contributions from both computational and experimental fluid mechanics, including winglets and other wing retrofits[29]. Winglets have been shown to improve fuel economy by 5-10%, depending on the aircraft and the winglet shape; they increase the effective aspect ratio of a wing without significantly increasing the wingspan, via alteration of the wingtip vortices thus reducing the lift-induced drag caused by such vortices. Decades-long improvements (reduction) in aircraft engine specific fuel consumption have arisen from a number of fundamental approaches, including increases in the engine bypass ratio (BPR) for turbofan engines, allowing proportionately more air to be utilized for thrust delivery; and increases in the turbine inlet temperature, allowing improved overall thrust generation. Many of these technologies were developed through basic and applied research sponsored jointly by the DOD, NASA, DARPA, and industry under the Integrated High Performance Turbine Engine Technology (IHPTET) program[30] (1987 – 2005). NASA's focus for many years has also been placed on reduced engine emissions, including nitrogen oxides[31] which for higher altitude aircraft can affect the ozone layer, and carbon monoxide. The widespread use of composite materials in aircraft has had a profound impact on aircraft structural weight as well as operability. These and other technical achievements for improved vehicle efficiency have been the result of decades of investment in basic and applied research in reactive and non-reactive fluid mechanics, solid mechanics, the mechanics of materials, and control systems.

State-of-the-art technical concepts based on advances in mechanics could lead to further improvements in aircraft efficiency and reduction of aviation's environmental footprint. Experimental measurements must be combined with the development of high fidelity computational tools for simulation of aircraft fluid-structure interactions as well as non-reactive and reactive flow processes. From the aerodynamic perspective, passive flow control devices can be used to enhance performance; these include strakes or vortex generators to control aft body separation as well as riblets for viscous drag reduction. Active aerodynamic flow control via distributed microsensors and synthetic jet actuators[32] or single dielectric barrier discharge (SDBD) plasma actuators[33] could have benefits for boundary layer separation delay as well as stall suppression. Entirely new aircraft configurations such as the Blended Wing Body could have a significant improvement in aerodynamic efficiency as well as the potential for considerable fuel savings[34]. Lightweight composite aircraft structures could similarly improve overall vehicle efficiency, as can "active" structures incorporating embedded sensors and actuators to allow integrated vehicle structural health monitoring[35] and optimized performance.

There are also considerable advances that could be achieved from evolutionary as well as revolutionary concepts for airbreathing engines. The follow-on program in the U.S. to IHPTET, called VAATE (Versatile Affordable Advanced Turbine Engines), has remarkably ambitious goals[36] with respect to performance, fuel efficiency, and cost reduction. Such improvements, in addition to reduced NOx, CO, and (inherently via fuel efficiency) CO_2 emissions, could be achieved via a number of promising technical advances. The emerging interdisciplinary field of closed loop combustion control[37] is one that holds a great deal of promise for optimized engine performance, including gas turbines. Closed loop control of complex reactive flowfields involves sensed information (e.g., in the hot section of the combustor or within the rotating machinery) being fed back to actuation systems (e.g., fuel or dilution air injectors) in near-real-time, allowing alteration in operation to recover from upset conditions or optimize performance. Such control can be made a reality in part through the development of high temperature, ceramic based microsensors, developed from specifically tailored materials.

As noted previously, the nature of aircraft lift and thrust generation is such that combustion of liquid fuels (likely hydrocarbons) will continue to be the primary means of propulsion for the foreseeable future. Although hydrogen has a heat of combustion per mass that is a factor of three higher than that of aviation fuel (e.g., Jet A or JP-8), its energy density by volume as a liquid is only one-fourth that of Jet A. The large volume needed by cryogenically cooled hydrogen storage tanks moreover would create challenges for airframe designers. Future hydrocarbon fuels for aviation as well as sea transportation could be derived from fossil fuel/petroleum, or from a range of alternative fuel options; these will be discussed in the following sections.

Hydrocarbon Extraction and Transportation

The use of petroleum-based fuels is dominant in transportation systems and stationary power plants in the U.S. Burning of hydrocarbons is acknowledged as a primary source of increased CO_2 levels in the atmosphere associated with global climate change[38]. Although alternative power and fuel sources are sought and under extensive development, as noted above, petroleum-based hydrocarbons are projected to remain one of the primary energy resources in the coming decades, particularly for certain segments of the transportation industry such as aviation. Many mechanics-related challenges are associated with accessing and harvesting oil and gas while minimizing adverse environmental impacts.

Advances in drilling and production technologies have led to extraction of petroleum from ever deeper off-shore wells thought previously to be inaccessible[39]. At the same time, the recent Deepwater Horizon (Macondo well) blow out and spill, with catastrophic environmental consequences and cleanup and liability costs in the tens of billions of dollars, has led to extraordinary scrutiny of advanced oil recovery practices and the need for improvements in safety and reliability. In deep-water offshore drilling, petroleum pumped upward may pass through very cold surrounding environments. If the petroleum includes significant viscous or waxy content, it may solidify and plug lines, especially if flow is interrupted. Even if the well is designed to accommodate variations in fluid content and surrounding environmental temperature, it may need temporary shut down due to extreme weather events or unpredicted mechanical failures. In this case, it is extremely challenging to restart the flow, especially since the blockage will likely be located more than a mile beneath the ocean surface. Also, as these wells are extremely expensive to drill and operate, they require higher upflow rates than in the past, raising new possibilities of flow instabilities at the downhole end of the well leading to potential production inefficiencies and failures, either of which brings huge costs. Many questions exist as to how to predict and control the complex and interacting fluid mechanics and chemistry in these systems to ensure both performance and reliability over the long term.

Advances in hydraulic fracturing technologies have led to significant increases in domestic and international production of oil and gas[40]. In areas where hydraulic fracturing is planned or in process, there are also environmental concerns, including the potential for ground or surface water contamination[41] and possible causation of seismic events[42]. In hydraulic fracturing (**Figure 4**), water containing chemicals and sand is driven into a well at high pressure so that the surrounding shale formation develops small fractures. The sand acts as a proppant to hold the fractures open when the pressure is subsequently reduced, and oil, gas, and accompanying water are pumped out of the well. This flowback water contains the original fracture fluid chemicals as well as chemicals or minerals originating in the shale formation. Although recycling of the flowback water during the fracturing and production process has increased significantly in the past several years, certain contaminants such as heavy metals accumulate in the fluid. At the end of production, this fluid either is injected into disposal wells deep underground or else must be treated to be reclaimed. Recent efforts in development and utilization of liquid gelled petroleum (also called liquefied propane gas or LPG) to replace water in the fracking process have demonstrated considerable success, albeit with financial challenges[43]. Such gels can vaporize underground, hence removing the need for flowback and treatment of the fluid. In considering how to maximize extraction capacity while minimizing adverse environmental impacts, many technical issues arise. The fracturing process combines complex structural mechanics, fluid mechanics, and chemistry, and any model must couple a huge range of length and time scales. Although fracturing occurs over microscopic length scales, the fractures themselves may eventually generate seismic motions on kilometer scales. Similarly, flows of a multiphase mixture move through microscopic pores or cracks, but the individual pores are part of a large overall matrix that is highly inhomogeneous and changing in time due to local dissolution and precipitation reactions with the rock structure, and plugging by fluid contents. Since the larger scale and longer term effects are driven by micro and even molecular scale effects, they are extremely challenging to predict or model.

These examples represent only a few of many requiring prediction of long-term environmental effects, or development of novel materials, designs, and processes for improved performance and reliability or mitigation of environmental impact. Multi-scale predictive models that can integrate fluid mechanics, solid and material mechanics, and chemistry would radically accelerate analysis, product development, and process design. Desirable capabilities include simulation of multiple fluid phases, interfacial tension and contact line effects, fluid/structure interactions, physical instabilities within complex fluids, chemical reactions within fluids and at solid surfaces, and surface shape evolution due to dissolution or precipitation, and deformation under pressure. To advance predictive modeling, carefully-designed experiments that push the state of the art in measurement techniques are needed. Such experiments, focused on both individual and coupled effects, are imperative to provide appropriate qualification data for improved models.

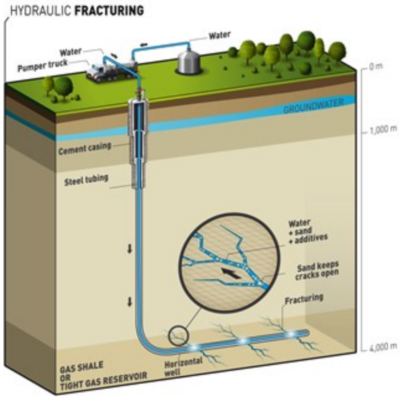

Figure 4. Hydraulic fracturing process [44]

Alternative Fuels for Air, Sea, and Ground Transportation Systems

Propulsion systems for which alternatives to hydrocarbon combustion are unlikely, e.g., aircraft, can benefit enormously from advances in alternative fuels as well as technologies to improve overall efficiency. Other transportation systems such as ground and sea vehicles may similarly benefit from the more widespread use of liquid fuels derived from sources other than crude oil, especially those that are close to being overall “carbon neutral” in the production and combustion cycle.

Bio-derived fuels have received significant attention in recent years. Microalgae biomass is a promising biomass feedstock for alternative jet fuels, offering minimal competition with food crops for land, fertilizer, and water[45]. However, at present, low algal biomass productivity and high-cost oil extraction and conversion processes are major technical barriers to affordable and sustainable algal jet fuels. Future advances in this arena, as well as conversion of alcohols and sugars to hydrocarbons, hydrotreatment of algal oils, production of Fischer-Tropsch liquid synthetic fuels from natural gas or synthetic gas, and conversion of biomass to bio-oil with hydro-processing, could allow vehicles to have a significantly reduced overall carbon footprint. The aviation industry as well as the U.S. Air Force have been aggressively moving in the direction of testing and certifying aircraft for operation with alternative fuels. For example, 50-50 blends of Fischer-Tropsch liquid synthetic fuels and conventional military aviation fuel (JP-8) have been certified for use by the entire Air Force fleet[46]. The airlines are similarly pursuing development, testing, and certification for a range of bio-derived fuels, and there are numerous promising alternatives.

ENVIRONMENTAL CHALLENGES

As noted earlier, future highly efficient and sustainable energy generation technologies should have a minimal environmental impact, and it is important to be able to accurately quantify this impact. Measurements and modeling for oceans and atmospheres are critical for environmental protection and remediation, and the broad field of mechanics similarly plays a foundational role in this arena. Spatially and temporally resolved measurements and simulation capabilities for determining pollutant concentrations in the atmosphere as well as the origins and transport of contaminants in waterways are necessary to understand the implications of future power and propulsion systems. The mechanics of fluids, species transport, and environmental chemistry all play a crucial role to such phenomena.

Atmospheric Pollutants

Air quality has improved dramatically in most locations in the United States over the past several decades. This is a result of numerous technological improvements and regulations, targeting mobile sources, industrial sources, consumer products, fuel distribution and so on. As air quality has generally improved in the developed world, in many parts of the developing world, air quality has been improving much more slowly, or in some cases, deteriorating. Despite the many improvements to air quality over recent decades, there are hundreds of thousands of Americans and millions of individuals around the world who suffer increased illness and in some cases, death as a result of exposure to air pollution[47]. Technical advances in modeling and measurements, aided by fundamental contributions from atmospheric fluid mechanics, are among the keys to ameliorating these environmental problems.

As the air quality has improved (in the US), understanding of the impacts of airborne pollutants on human health has also progressed. As a result of the new health data, National Ambient Air Quality Standards (NAAQS) have been revised downward several times, and on occasion new pollutants have been added to the list of specifically regulated pollutants. One such example is the addition of a standard for particulate matter smaller than 2.5 microns in diameter in 1997, with revisions 2006 and 2012. This new regulation recognizes that the existing particulate matter standard, did not sufficiently target small particles originating from processes involving a gas phase, generally either combustion or oxidation reactions in the atmosphere. At present there is strong interest in even smaller particles, those smaller than 0.1 microns in diameter, known as “ultrafines”[48].

Epidemiological studies of health outcomes necessary to develop regulations are hampered by reliance on very crude methods to estimate air pollution exposures. Ideally, the exposure history of an individual presenting with a health condition would be well understood; improvements in the quality of exposure estimates is expected to drastically reduce the uncertainties associated with epidemiological investigations. Currently exposures are estimated from combined atmospheric dispersion/pollutant emission models, from land use regression models, or in the case of a roadway source, simply the distance of the home address from a freeway[49]. Exposure estimates, as well as our understanding of spatial distribution of pollutants, would be greatly improved with development of more cost effective sensors, and with networking of those sensors. Needed are inexpensive, sensitive monitoring devices that could be deployed in multiple locations simultaneously. Ideally they would provide high time resolution, robust performance and low power consumption, and target pollutants of most interest for health, including greenhouse active species.

Many of the adverse health outcomes in the developing world could be reduced with inexpensive, cleaner alternatives especially for small engines and other small combustion devices such as cookstoves and heaters. Engines and burners need to have lower emissions, improved efficiency, optimization to different fuels, and critically, improved durability with respect to minimizing emissions over the useful life of the device. Current examples are the two stroke engines and small four-stroke compressed natural gas engines employed in scooters and auto-rickshaws in many locations in the developing world. These commonly have extremely high emissions, and are thus in urgent need of replacement and retrofit technology.

Further improvements in air quality are intimately related to future economic and technical development pathways, with some pathways tending to improve air quality and others tending to degrade it. Distributed generation offers potential to enhance flexibility and cogeneration options, but tends to shift combustion closer to population centers and to smaller engines, which can be both less efficient and more polluting. Climate change will also play a role in future air quality; in general the atmosphere is expected to become more effective at trapping pollutants near the surface, intensifying the types of meteorological events that lead to high pollutant concentrations. In addition, both incidence and size of wildfires are expected to increase as temperatures rise, further enhancing air pollution[50]. On the other hand, many alternative transportation technologies, such as electric vehicles and transit, as well as industrial energy efficiency technologies have potential for substantial co-benefits in the form of reductions of pollutant emissions. The final outcome for air pollution of the different factors needs to be investigated with atmospheric models. Improvements to these are needed. Several examples of areas in need of attention include improving their ability to deal with complex terrain in urban areas, under the stable atmospheric conditions that are common in urban areas, and in the development of detailed emissions models for ultrafine particle emissions and other non-criteria pollutants.

Water and Soil Pollution, Remediation Methods

Pollution of groundwater and soil is a widespread environmental problem caused by various industrial, agricultural, municipal, energy production, and military activities. Improper manufacturing, use, and disposal practices have resulted in uptake and accumulation of toxic chemicals in water resources, food chains, and have impacted human and ecological health. The extent of subsurface contamination by organic and inorganic compounds and radionuclides is significant, with an estimated 300,000 contaminated sites in the US alone[51]. Although substantial progress has been made in reducing and containing hazards over recent years, intentional and accidental releases still occur, a considerable magnitude of historical contamination is documented, and new sources as well as health end-points are continually being identified. Assessment, design, and optimization of new and existing technologies for reducing the mass, toxicity, mobility, volume, or concentration of the contaminants in soil and water resources relies on mechanics of fluids, transport phenomena, and biogeochemical processes. Some priority areas for mechanics-based research and technology transfer are summarized below.

1. **Bioremediation:** Under favorable conditions, bacteria and fungi transform contaminants completely into non-toxic products such as carbon dioxide, water, organic acids, or mineral salts. While bioremediation is generally less costly and less disruptive than physical-chemical treatment, complex interactions among pollutants and their remediation technologies

in mixed waste streams and sites are not yet fully understood[52,53]. The availability of broad-spectrum enrichments as well as non-pathogenic pure cultures and purified enzymes optimized for specific contaminants and environmental biogeochemical conditions will make bioremediation more acceptable to the public and regulatory agencies. Development of environmental molecular diagnostics, including "omics", fluorescent probes, and stable isotope-based methods[54], mechanical modeling, and systems biology approaches will be crucial in successfully implementing natural and engineered bioremediation.

2. **Phytoremediation:** The use of plants for soil and groundwater cleanup and in constructed wetlands is an attractive technology because of its cost-efficient and energy-efficient mechanics[55]. Typical organic contaminants, such as petroleum hydrocarbons, gas condensates, crude oil, chlorinated compounds, pesticides, and explosives, can be addressed using plant-based methods. Phytotechnologies also can be applied to typical inorganic contaminants, such as heavy metals, metalloids, radioactive materials, and salts in the subsurface[56]. Mechanistic modeling of phytohydraulics and phytoaccumulation is currently lacking. Collection and characterization of plants that are indigenous to a variety of climates and soil types as well as hybrid transgenic varieties with selected adaptation and remediation capabilities should also be a research priority.

3. **Physical-chemical Treatment:** Physical separations via sorption and air stripping, and chemical transformations via oxidative[57] or reductive[58] mechanisms are some of the most established technologies for contaminated site remediation. Research responding to the challenges of large dilute plumes, conceptual site models, site closure strategies, and long term monitoring is warranted. Efforts should be directed towards green remediation technologies with smaller energy and water footprints, integration with renewable energy production and ecosystem services, and minimal human and exposure to contaminated media during transport and offsite treatment. Application of technology combinations for multiphase extraction, advanced oxidation and membrane processes, permeable reactive barriers, and treatment trains involving physical-chemical-biological processes will also be valuable for source remediation as well as site remediation of persistent as well as emerging pathogens and chemical contaminants.

4. **Electrokinetic and Thermal Technologies:** Application of a low-intensity direct current through the soil between ceramic electrodes causes ions and water to migrate toward the electrodes. Metallic cations, ammonium ions, and positively charged organic compounds move toward the cathode. Anions such as chloride, cyanide, fluoride, nitrate, and organics with negatively charged functional groups move toward the anode. Subsequently, contaminant ions are removed at the electrode by electroplating, precipitation or co-precipitation, complexing with ion exchange resins, or pumping of water near the electrode[59]. Heating of the subsurface via injection of steam, radio frequencies, or vitrification, provides the most chemically stable sequestration of heavy metals and radionuclides or destruction of hazardous organic chemicals[60]. Thus, efforts should be focused on conserving costs and energy requirements of these technologies for on-site as well off-site remediation.

5. **Nanotechnologies:** Application of engineered nanomaterials for soil and water remediation has the potential to be more efficient and cost-effective than conventional methods due to the increased reactivity of nanoparticles and the possibility of minimally invasive in situ treatment. Early studies and demonstrations of nanoscale zero-valent iron for the degradation of halogenated organic compounds, nanoscale calcium peroxide for the destruction of petroleum hydrocarbons, nanoscale metal oxides for the adsorption of metals, and nanoscale silver in drinking water filters are promising[61]. However, these methods are very

new, and their mobility and stability in the subsurface and aquatic environments as well as their potential health impacts need to be comprehensively investigated[62].

CONCLUDING REMARKS

The alternatives for energy-generation technologies are quite extensive, with specific technical solutions being most appropriate for given geographical locations and specific applications. Yet the scientific and economic challenges in producing safe, reliable, affordable, sustainable, and especially environmentally sound energy options are considerable. It is only through a well-coordinated, strategic investment in the science and technology underlying these alternatives and their environmental impact, for which the broad field of mechanics is foundational, that the U.S. in particular and the planet in general will achieve a more robust and secure energy future.

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