Energy & National Security: An Exploration of Threats, Solutions, and Alternative Futures

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<u>Abstract</u>* – Findings of multiple Department of Defense (DoD) studies and other sources indicate that the United States faces a cluster of significant security threats caused by how the country obtains, distributes, and uses energy. This paper explores the nature and magnitude of the security threats as related to energy—some potential solutions, which include technical, political, and programmatic options; and some alternative futures the nation may face depending upon various choices of actions and assumptions. Specific emerging options addressed include Polywell fusion, renewable fuel from waste and algae cultivation, all-electric vehicle fleets, highly-efficient heat engines, and special military energy considerations.

FOREWORD

This paper presents the professional opinions of the author. While some may disagree over the implications of energy to national security, the fact remains that the Department of the Navy (DoN), the DoD, and the nation face what may be the most significant challenge of this time: how to ensure the security of our energy sources within the limits of technology, policy, budgets, and national will. This paper encompasses a review of the various energy issues and potential technological solutions. Inherent in this essay are policy implications. It is not the intention of the author, DoN, or DoD to propose these solutions as "the right" solution. Rather it is the intention to discuss them in light of the technological challenges facing their implementation.

The Naval Surface Warfare Center, Dahlgren Division is currently initiating the Asymmetric Energy Solutions (AES) project directly designed to assist the DoN and DoD in addressing these complex energy issues. The Asymmetric Defense Systems Department will be addressing these issues through AES by exploiting the current capabilities of that department, the Dahlgren laboratory complex, other Navy laboratories, and other public and private entities, including academia. AES will identify energy security technology options relevant to the DoN and DoD, including naval global platform support options and naval infrastructure support options.

The author intends to provide insight into the national and international energy challenges, and address them from a DoD perspective. In today's interconnected world, energy source, generation, and application technologies cannot be addressed in the single light of DoN and DoD requirements. However, by combining the international, national, and defense issues in this paper, the author hopes to highlight in the mind of the reader their interdependency, which must inform the holistic energy solution. Advances in DoN and DoD technologies and acquisition strategies can directly and indirectly affect the national and international markets. DoD fiscal investment in research and development, and technology purchasing is extensive and can be determinative in promoting timely deployment of technology. As in the past, DoD's technological advances will find their way into the commercial market in some fashion.

OVERVIEW

The Energy Security Challenges

The United States faces a cluster of significant security threats caused by how the country obtains, distributes and uses energy. The issues that directly confront DoD threaten the U.S. military strategically, fiscally, and operationally. However, in the larger context of national security, the United States faces potential economic hardship, with combined recession and inflation, and a growing drain of wealth needed to acquire imported petroleum, consequences of human-and/or-nature-made power disruptions to wide areas, and environmental consequences of energy production and use. The combined threat equals any the nation has ever faced. However, currently available solutions could within years, not decades, substantially mitigate the threat.

These solutions can improve military capability with reduced cost, thwart terrorism, contribute to world stability, mitigate climate change ramifications, and create a new economic prosperity both in this country and internationally. The future of the United States and the world depend on the nature and tempo of the solutions selected by the country—its institutions and its leadership, both public and private. The United States consumes a quarter of the world's oil produced daily. The U.S. actions related to energy dominate the course of the world. The military is the single biggest consumer and purchaser of energy in the United States and can have a significant impact on solutions picked and tempo of implementation.

This paper is intended to provide insight for both the military and national discussions on energy alternatives. To accomplish this objective, it explores the nature and magnitude of the security threats, as well as some potential solutions that are representative but cannot be exhaustive given the breadth of subject; and suggests a way ahead to a more secure future.

Surveying the Energy Security Landscape— An Executive Summary

Energy issues loom large in national and global discussions on economics and national security. Multiple Defense Science Board (DSB) studies report that U.S. military forces are inefficiently designed, cost more than necessary, and are constrained in operational capability because energy requirements are not accurately and integrally incorporated into overall requirements generation and materiel acquisition analysis. The cost of military operations balloons as the price of oil rises. The effective loss in spending power in a year from the doubling of oil prices from last year equals about $8 billion for DoD. This 1-year fuel expense could buy eight Arleigh Burke destroyers or more than 20 F-22 Raptors.

The military and the broader national security community confront the economic drain of importing oil. Since 2007, the price of oil has doubled to a historic high; food prices soar, and the growth of food crops for fuel is blamed; inflation is ignited attributed (to some extent) to the rising price of fuel, which touches everything; while reflection on the Katrina hurricane disaster and gas price spikes from hurricane Ike's influence shows how little oil production and refinery-capacity margin exists in the world. The effect of rising energy cost negatively impacts the entire economy and further drains the resources the United States needs to maintain military capability.

National security hinges not just on military power projection, but protection of energy infrastructure at home and outside of the United States as well. The DoD contends with this responsibility. Incidents such as terrorist attacks and weather-related disasters point to vulnerabilities of the energy infrastructure.

Today, use of petroleum determines a nation's standard of living and level of military power. Some potential bottlenecks threaten access to this energy source. The United States relied on petroleum for about 40% of its total energy requirement of roughly 101 quadrillion Btu (British thermal unit) in 2007. Petroleum imports accounted for about 70% of U.S. total petroleum consumed. China and other emerging industrial nations will inevitably demand more energy, and the total quantity for the United States to consume will be eroded. A significant engineering debate exists over whether the relatively inexpensive oil, which civilization has come to rely on, can still be produced. Some experts project that the world has already or will soon pass "peak oil" production, after which, oil will become more and more expensive to produce and a rarer and rarer commodity.

Exploration of new reserves around the United States is expected to provide additional years of crude production. However, the Department of Energy (DOE) projections indicate a 7- to10-year lead time from exploration of a new reserve until product flows to the consumer. This fact suggests that near-term petroleum access to meet a growing demand means buying more imports. Even if availability of crude oil were assured, availability of processed petroleum product may be constrained because of a dearth of refining capacity, which emerges from the growing world demand for products and the failure of industry to invest in this low-profit-margin side of the business.

Add to the above one more wrinkle—the environmental effects of fossil fuel use. In June 2008, the U.S. intelligence community reported to Congress "wide-ranging implications" to national security due to climate change across the planet. The testimony responded to the most recent report published in 2007 of the Intergovernmental Panel on Climate Change (IPCC), which asserts that fossil fuel use is the principal cause of global warming. Although neither endorsing nor negating that position on causation, the testimony to Congress accepted that global warming and climate change is happening and must be addressed. According to the testimony, the United States can expect to suffer tens of billions of dollars in damages from severe weather, and loss of productivity and heavy tolls for fixing and replacing infrastructure. Intensified storms will threaten many nuclear facilities, oil refineries, and other energy infrastructure, especially along the Gulf Coast. Exteriorly, the United States will face a rising need for humanitarian and stability operations. The worldwide ramifications could cost in the range of 3% of annual global GDP as climate change continues through the century. These anticipated events directly challenge DoD's ability to defend the nation and supply international help when tasked by the President.

Energy security challenges abound. However, significant emerging technological opportunities can address and perhaps eliminate most of these problems and substantially mitigate others.

1. The military can use its consolidated purchasing power to encourage rapid development and deployment of alternative energy, and implementation of efficiency measures. The DoD can save money, enhance mission assurance of military facilities, reduce or more effectively reorient force structure, and provide greater operational capability by adapting its requirements-setting and acquisition processes to specifically and fully address its energy consumption. The DoD can, in effect, increase its force acquisition budget by decreasing its fuel budget. The federal government, as a whole, can likewise use its research development investment, its purchasing power, and its policing authority to foster rapid deployment of technology and processes to alleviate the security risks from current energy-use strategies.

2. The military gains greatly from increasing vehicle efficiency by increasing the operational range of vehicles, reducing demand for logistics investment, and reducing the force structure and mission requirement to defend logistics forces. By DoD's investing to do so, the entire nation gains. The amount of U.S. petroleum imports roughly equals the total U.S. fleet consumption of petroleum by cars and trucks. The United States imports about 70% of its petroleum product consumption. Car and truck engine fuel efficiency for most operation sits around 25%.

Among the many options available to DoD and the country, here are some possibilities:

a. Outfitting the U.S. vehicle fleet with emerging-technology engines, which achieve over 50% efficiency, would cut petroleum use and import requirements in half. Example engines are discussed in this paper.

b. Using hybrid-electric vehicles could raise the fuel efficiency even higher and provide a deeper reduction in oil imports.

c. An all-electric vehicle fleet, which could be recharged from non-petroleum-based electricity sources would completely eliminate the need for imported oil. Electrical storage solutions such as that offered by the company EEStor's new ultracapacitor are discussed. Current electricity power production infrastructure could accommodate the switch to electric vehicles and hybrids.

d. The DoD has the purchasing clout to influence rapid development and deployment of high-efficiency vehicles. The DoD action would enhance national security in multiple ways, from enabling greater operational capability for the military, to mitigating some infrastructure vulnerability, to national economic advantage in using domestic energy and potentially creating new domestic business and jobs.

3. Assured access to fuel is a must for the military and the nation. Fossil fuels are finite commodities, which do not regenerate in a time period meaningful to consider them as renewable fuels. However, a host of renewable alternative fuels are being produced today.

a. Alcohols, such as ethanol and butanol, are generated by bacteria or catalysis.

b. Diesel, gasoline, and others, such as 2.5-dimethyl furan, are generated by chemical processes, such as Fischer-Tropsch (FT), or biological processes.

c. Various technologies can turn waste into fuel, thus addressing two problems.

d. Algae, the original source of petroleum, can be grown to produce specific types of fuels, including diesel and gasoline, and can be used as a feedstock for other processes to produce artificial petroleum products. Algae produce prolifically and in dense concentration so that enough fuel product from algae could be produced in open ponds in an area of 25,000 square miles (which is the approximate combined size of San Bernadino and Los Angeles counties in California) to replace all U.S. petroleum needs. Other techniques that require building some industrial infrastructure can reduce that land-size requirement by a factor 10 or greater. Algae grow virtually anywhere. The United States could replace the entire world need for petroleum with algae products from an area four times the size of that just described. Various renewable and synthetic fuel options are discussed herein.

4. The DoD, and especially the DoN, could benefit greatly from the potential of nuclear power. But nuclear fission power is expensive and presents ongoing safety concerns. A spinoff from a form of nuclear fusion developed in the 1960s by Farnsworth and Hirsch has achieved groundbreaking success recently. This Polywell fusion device was pioneered and scientifically demonstrated in 2005 by Robert W. Bussard. This type of fusion can use boron-11 and hydrogen as the fuel. Fusion of these elements produces no neutrons and no radioactive waste. Estimated cost to build a Polywell electric plant is less than that for a similar power-producing, combined-cycle gas plant or coal plant. A gigawatt-sized reactor would be a sphere about 15 meters in diameter. If all power for the United States were generated with boron-11 and hydrogen Polywell fusion, the total yearly requirement for boron would be less than 5% of current U.S. boron production and would cost less than two trainloads of coal at current prices for both commodities. A single coal plant requires a trainload every day for full-scale operation. The U.S. Navy could adapt such devices to ship propulsion and free ships from the tether of petroleum use and logistics. The Polywell device could enable very inexpensive and reliable access to space for DoD and the nation as a whole.

5. Solar and wind power offer potential relief for DoD's and the nation's infrastructure security vulnerability. Emerging technical capability, and dropping prices in solar photovoltaics and wind-power generation may enable distributed-power production and reduce security vulnerability from monolithic production and distribution methods currently in place. The U.S. wind and sun resource is vastly greater than the required energy for the United States. Cost and industrial-base production capability drive the speed of implementation. However, with sun- and solar-power proliferation comes the need for efficient, cost-effective electricity storage. Many storage options exist, but they confront cost, size, reliability, and safety factors.

a. In 2008, wind power is still about 60% more costly than electricity from coal plants. Solar power is over twice as expensive as wind power. But the technologies are improving, and the costs to produce power are plummeting. The potential from such sources for distributed power—which removes customers and facilities from dependence on the grid—is, in itself, a huge security boon that could help alleviate issues associated with infrastructure vulnerability, while also decreasing energy demand on limited-quantity fossil fuels.

b. Photovoltaic power could be particularly valuable to the military. Especially as conversion efficiencies increase, the military could use high-energy lasers to deliver power to unmanned vehicles and other remote locations. All-electric or rechargeable hybrid vehicles with high-density storage could stay deployed or engaged in mission indefinitely as long as they could replenish from time to time by laser via their photovoltaic arrays. Emerging approaches to photovoltaic technology suggest the possibility of 80% conversion efficiency per cell. An interesting synergy might derive from using a new Massachusetts Institute of Technology (MIT) window-light-gathering unit combined with these highly efficient converters to provide a compact power array capable of double duty. Most of the area the window occupies on the surface of a vehicle possibly could be used as an aperture for sensors and communications arrays.

In summary, the energy security threats are diverse and potentially severe; potential solutions are diverse and very powerful. Different scenarios for the future unfold depending on what options for energy technology the nation (and world) exploits and how aggressively the options are pursued. These scenarios vary widely: from extinction of mankind; to the end of industrial civilization; to creating extreme hardship across the globe with a severe population crash; to a very unstable international peace, with resource wars, famine, and severe weather change rocking humanity. A feasible future could also be a new global prosperity based on abundant clean energy, which enables abundance of other resources.

EXAMINING THE NATURE OF THE THREATS

Military Energy Issues

The DoD Office of Force Transformation and Resources commissioned a 2007 report on the DoD energy strategy, which identified the Department's issues in terms of "disconnects" between DoD goals and practices as follows:

"*Strategic: DoD seeks to shape the future security environment in favor of the United States. But our dependence on foreign supplies of fuel limits our flexibility in dealing with producer nations who oppose or hinder our goals for greater prosperity and liberty.*

Operational: DoD's operational concepts seek greater mobility, persistence, and agility for our forces. But the energy logistics requirements of these forces limit our ability to realize these concepts.

Fiscal: DoD seeks to reduce operating costs of the current force to procure new capabilities for the future. But with increased energy consumption and increased price pressure due to growing global demand for energy, energy-associated operating costs are growing…

Environmental: In parallel with the increase in the global demand for energy is an increase in concern about global climate change and other environmental considerations. Therefore, when identifying technical solutions to its energy challenges, DoD should also consider a fourth disconnect—environmental ." [1]

The DSB commissioned two Task Forces which developed separate reports: one in 2001 [2] and one in 2007 [3], to examine DoD's energy strategy. According to the DSB 2007 Task Force report issued Feb 2008, current U.S. military's energy strategy risks both operational capability and mission performance. Additionally, in the 2008 final report, the Task Force warned of military installation vulnerabilities from potential commercial power disruption and inadequate backup power.

The 2008 DSB report indicates that the military suffers from unnecessarily high fuel consumption, which compromises and constrains its operational ability, its tooth-to-tail force structure. How the military operates with regard to fuel use and delivery creates opportunities for a threat to degrade or blunt U.S. force operations, provides the threat a large target in the energy-delivery logistics force, and demands a high financial cost over the life cycle of DoD's materiel. The Task Force also concluded that military installations worldwide "are almost completely dependent on a fragile and vulnerable power grid, placing critical military and Homeland Defense missions at unacceptable risk of extended outage."

Further, the report indicates that DoD does not have the modeling tools, strategy, policies, metrics or governance structure to effectively manage its energy risks. It noted that DoD has not heeded the 2001 Task Force's findings, nor implemented the 2001 recommendations. Specifically, the 2001 Task Force reported that DoD's requirements and acquisition processes do not value or reward energy efficiency, nor reduce logistics. According to the study, DoD does not attempt to use efficiency in energy or other aspects of logistics to guide development of solutions to provide military capability. As a result, DoD sacrifices potential military capability, which the services could have bought had they not needed to invest in force structure and infrastructure to make up for the lack of energy efficiencies. Efficiency does not necessarily equate to less capability, but rather can equate to increased military power at reduced cost and risk. The 2001 Task Force recommended that ACAT I programs, the largest defense acquisitions, establish energy efficiency in the key performance parameters and that trade-off analysis use "Fully Burdened Cost of Fuel."

Currently, in DoD's systems acquisition trade-off studies, the acquisition community uses the current "cost at the pump" that the Defense Energy Support Center (DESC) would charge for on-site purchase for a gallon of fuel, rather than the Fully Burdened Cost of Fuel, which includes delivery of fuel to the operational platform or unit. This practice means that cost for fuel would be considered perhaps $4.00 per gallon of jet propulsion (JP) fuel rather than the delivered cost of perhaps 10–20 times that much, plus the force-structure cost for the logistics units, the security force to protect the logistics units, and the potential casualties to those forces that may occur as they bring fuel to the tactical units. Using the notional "price at the pump" produces vastly distorted acquisition decisions.

The Task Force found further systemic behaviors in DoD that stem from this energy indifference. DoD under-invests in

Science and Technology that could yield reduction in logistics and increased efficiency. DoD has not implemented procedures that reduce needless energy consumption and reward efficiency achieved by operators. The services could buy off-the-shelf technology that would reduce energy consumption. Both long-term and near-term options exist. However, no organizational accountability exists to ensure energy efficiency, nor optimized logistics. The Task Force considers DoD energy problem so significant that it merits an immediate $500 million/year program to address the issues and appointment of a DoD senior coordinating official for energy.

The 2007 DSB study included many expert briefings and site visits, with many insights revealed. Not all of the information presented in these briefings and discussions could be distilled in the final report, and some information presented below may fit that category. The following data points from the study suggest the dimensions of the problem, but also point to remedies.

1. Eighty percent of all U.S. materiel shipped in and to the Iraq forces was fuel. Ninety percent of the fuel trucked to remotely deployed forces in Iraq and Afghanistan was used to air-condition uninsulated tents. Long caravans of fuel trucks required to deliver the subsequent heavy fuel loads become vulnerable to an improvised explosive device or other guerilla attack. If the tents were insulated to cut down on fuel use, heavy-lift helicopter delivery or parafoil air-drop of the remaining small fraction of the current shipments could conceivably replace the truck caravans otherwise needed. Using less fuel could save lives.

2. Most of the fuel consumed by DoD is JP fuel. Close to 50% of that JP is consumed by fuel transport planes to move fuel where it is needed. The 2001 DSB study indicated that if tactical aircraft, such as the B52, could extend their range by 30%, they would reduce air refueling requirements, and thereby eliminate the demand for part of the air refueling fleet. In addition to the fuel, the logistics aircraft investment could also be saved. The 2007 Task Force discovered that high-performance aircraft engines are being developed that could provide that 30% efficiency. With fuel efficiency, a key performance parameter in future aircraft design, unrefueled aircraft range could extend beyond—perhaps well beyond—an extra 30%.

3. The M1A2 main battle tank gets about 4 mpg (miles per gallon) as its 1500 horsepower turbine moves the 80-ton vehicle. However, much of its fuel is used by its crew to keep the environmental and other systems running when the tank is not rolling (i.e., 0 mpg). Turbines can be extremely efficient at a specific design load, but tend to be extremely inefficient otherwise. The DoD could replace the large, thirsty turbine with high-efficiency, off-the-shelf diesel engines to increase gas mileage. Auxiliary generators could reduce the fuel drain by the crew when the tank is parked.

The Task Force's yearlong investigation uncovered these and other illustrations of DoD's current lack of fuel policy and identified means to address the problems. Key findings state that DoD has "no unifying vision, strategy, metrics, or governance structure" to deal with energy issues, and current information gathered about energy is insufficient to make good decisions. The DoD has no current simulation mechanisms to wargame fuel issues or strategically plan fuel requirements. Therefore, DoD has no structural mechanism to systemically or systematically address the problems. However, the study concludes that many options exist to solve energy issues, including more efficient platforms and engines, conservation processes, and alternative fuels for assured fuel access. DoD problems mirror broader U.S. issues, and DoD actions could enable or promote solutions to national energy challenges.

The DoD problem is large but has largely been ignored. In worst-case scenarios, DoD expects to get priority access to U.S. energy resources. The DoD—the biggest single user of energy in the country—uses about 300,000 barrels of oil per day compared to the 21–22 million barrels of oil per day used by the United States as a whole. The United States produces about 30% of the oil it consumes from domestic sources. The military, in case of sudden disruption of all imports, could obtain enough fuel to operate with only a small portion of domestic production.

Assured access (or not), DoD pays a heavy price for fuel. Every $10.00 increase in a barrel of oil costs DoD over a billion dollars per year. Manpower, operational tempo, reconstitution, and acquisition are threatened by dependence on volatile international fuel prices. The "energy tether" to tactical forces is a military Achilles' heel and, in its own right, must be addressed. However, the military energy problem faces an additional problem of the potential disruption of critical military infrastructure.

Infrastructure Vulnerability

Largely, DoD has assumed that local power grids will provide needed power to support national security missions. Backup power plans consider only limited-duration (a few days at most) interruptions in service from the grid. Examples of large-scale power outages caused by natural calamity or systems overload suggest that DoD must develop a new approach. Further, the threat of coordinated terrorist disruption of power through physical or cyber attack and the potential for disruption of the flow of energy producing resources mandates that DoD reevaluate and redesign power access to mission-critical facilities.

Although DoD has analyzed installation vulnerabilities, it has not been able to consistently fund and implement mitigations. The 2007 Task Force strongly recommended that DoD get a firm understanding of risk management and power outage consequences. The report suggested various mechanisms to better ensure power access, including conservation; on-base, power-generation options; and grid islanding. One particularly notable point from the report is the possibility of natural or human-induced widespread power outages, which could endure for months or even years, and which could be very difficult to recover from if mechanisms for recovery were not well developed and implemented in advance. A classified annex to the 2008 Task Force report discusses this vulnerability subject in greater detail. This is not just a DoD problem. National security demands intelligent planning and action by national leadership to address the threats, which include acts of war, terrorism, or natural catastrophe—all of which could prevent oil production, distribution across the oceans, and potential infrastructure destruction or disruption in the United States [4].

Even with a larger U.S. domestic crude oil supply, a refinery bottleneck could continue to drive prices higher and create shortages of refined products. A 2005 report by ICF Consulting [5] predicted that to keep pace with growing demand for refined products, the already strained world refining capacity needed to grow at least 8 Mbbl/day (million barrels per day) (about 9%) by 2020. Refining is a low-profit-margin part of the oil business. It entails significant operation expenses, maintenance, and environmental issues. The United States has not built a new refinery since the 1970s. The shutdown of refineries as a result of hurricane Katrina and the subsequent product shortages demonstrate that the "Refinery Capacity Crunch" is upon us.

Infrastructure vulnerabilities must also be examined in the light of global climate change warnings. Severe storms, especially around the Gulf Coast; new patterns of drought in the west; and heavy rains in the east could reduce crop production; cause mass migrations; or threaten or actually destroy infrastructure such as oil refineries, nuclear power plants, and transportation means. The Intelligence Community's 2008 testimony to Congress warns that the United States will need to plan for tens of billions of dollars of infrastructure repair, replacement, and upgrading. Tropical diseases previously not a threat to the homeland could invade and become pervasive as the climate warms. The financial cost would likely result in 3% annual decline in world GDP for years. A 10% total decline in GDP is defined as a depression [6].

However, both Task Forces indicate that DoD could substantially enhance its performance by acting with awareness of its reliance on energy. The 2008 Task Force made several specific technology recommendations in that regard—principally aimed at building aircraft that delivered longer range and better performance per fuel required. Overall, the studies concluded that DoD can improve its ability to provide national security and world stability at reduced cost by:

- Making energy performance part of the key performance parameters in acquisition programs,
- Using Fully Burdened Fuel Cost in analysis of alternatives,
- Incorporating full costs of logistics into military requirements development and acquisition processes,
- Incentivizing personnel to be energy efficient,
- Promoting immediate adoption of more energy-efficient processes and procedures in operations both at the tooth and the tail,
- Acquiring more fuel-efficient off-the-shelf systems,
- Investing in science and technology to provide better performance versus fuel use and logistics needs,
- Directly addressing grid-reliance vulnerabilities, and
- Requiring less fuel and logistics to achieve desired military performance

National Economics and Resource Availability

The United States' dominant military power flows directly from the ability of the U.S. economy to resource national defense and international military engagement. The national security of the United States is based on its national economic viability and its economic competitive prowess and success. National economics is a crucial DoD interest and a determinative limitation on DoD capability. Assurance of energy resource availability to sustain national economic prosperity is a crucial DoD responsibility. A multifront war—both on the battlefields of Southwest Asia and potentially importable within our own borders—warns us of potential catastrophic energy-distribution disruptions. The U.S. need for foreign oil grows, but the leadership and/or cultures of nations that sell the United States large quantities of oil often do not share American ideals of pluralistic democracy, personal freedom, and equality of opportunity.

As reported to the DSB Task Force, petroleum experts indicate that although the world's discovered oil reserves are enough only for the next 40 years, that situation has always been such for at least a century simply because it is not economic for the oil industry to find more than 40 years of oil. So the arguments are raised that the oil production-consumption imbalance is not a threat, but just an artifact of the free market and the flat world.

America has not produced enough oil for itself since the 1970s. Since that decline, members of OPEC discovered that they could manipulate international oil prices. A 25% reduction in Mideast oil production after the Yom Kippur War and an embargo against the United States caused prices at the pump in the United States to quadruple [7, 8]. In the late 1990s, the price of oil was under $20 per barrel. The price per barrel of oil in 2006 was around $65.00, in early 2007 in the low $70s. In 2008, oil passed $140 per barrel. At least one market analyst says that since oil is a commodity on which people speculate, double that price is totally conceivable. Another analyst, Henry Groppe, suggests that the current oil prices are just a bubble [9]. However, he believes that the new low for oil prices is going to be higher than $70 per barrel, and that natural gas prices will likely rise by a factor of two or three.

Some economists blame the current high oil prices on a monetary issue—the weak dollar. Whatever the impetus may be, rising oil prices are a direct threat to international economic stability. Further, as pointed out by Jason Henderson in *The Main Street Economist* [10] increased fuel price means increased food price, and growing fuel crops rather than growing food further creates food price inflation.

However, world oil production may have already peaked. Arguments and evidence in books—such as *The End of Oil* by Paul Roberts and *Twilight in the Desert* by Matt Simmons—strongly suggest that there are no new large oil reserves to be discovered and tapped [11]. The current mother lode of oil in the world is Saudi Arabia, and using the best technology available, the Saudi production has not increased much. Additional oil, such as Canadian tar sands and Venezuelan heavy crude, cannot be produced in quantity to make up for the decreasing production in other fields. Access to oil is not just a political or even technological issue, but a matter of the resource being a fundamentally limited commodity. The price of oil must therefore increase even if the United States could start producing all of its current oil needs. The Energy Information Agency (EIA) in a March 2004 report—*Analysis of Oil and Gas Production in the Arctic National Wildlife Refuge* [12], indicates that after exploratory drilling of a new reserve begins, significant oil production from that field does not come to market for 7–10 years. As an example, the expected oil reserve in the Arctic would provide approximately 1 year's worth of total U.S. consumption spread over a couple decades starting about 10 years after drilling begins. Of course, that amount of oil equates to over a trillion dollars in market value to the companies that get to sell the oil, but it really does not do much at all to sustain the U.S. economy or security. The Gulf of Mexico offers several times as much oil—again, not a long-term solution and too distant in time to help with the oil flow for over a decade. The world oil market will drive the price up and cause reduced use—eventually.

So, why not use our "vast" quantities of coal to provide both electrical power and via such technologies as FT convert coal to liquid fuel? More will be discussed later on FT, but problems hit from multiple directions—cost of FT facilities, cost to the environment or additional cost of fuel from sequestration, energy inefficiency of FT, and resource commodity constraints. There's only so much coal, and if you use it at a greater rate, it disappears rather quickly before the end of the century. With 263 billion short tons of reserves, the United States has about 225 years of domestic coal, but converting coal to fuel would more than double that consumption rate [13].

Given the over 13 Mbbl/day imported in 2007 by the United States [14], each $10.00 increase in price per barrel equates to about $50 billion from U.S. pockets given to other countries including Venezuela, Saudi Arabia, Russia, and Nigeria. And, of course, these funds can not be spent in this country for medical care, infrastructure improvement, education, or military reconstitution. As previously mentioned, the biggest single spender in the United States for energy is the Defense Department, which uses over 300,000 barrels a day. A $70-increase per barrel since last year, if sustained for 12 months, equals about $7 billion, which could buy two Sea Wolf submarines or half of an aircraft carrier.

The military challenge to assure national energy access must be met to ensure national economic security. The economic threat of potential oil-import interruption is so important that it must be reiterated and elaborated upon. Energy enables our cars to get us to work; our trucks and trains to transport goods; our farms and factories to produce our food and goods to live; our water systems to run; our home and industrial appliances to heat, to cool, to clean, to maintain, to build, and to light; our grocers to maintain food in refrigeration for distribution; our computers to provide information and automation; our air transports and air traffic control to function; modern universities to educate; industry, academia and government laboratories to create new knowledge and technological innovation; doctors and medical facilities to use modern medical procedures and equipment; the ability to develop and produce modern necessary materials, such as plastics, fertilizer, and pesticides; and our military to defend us and help secure world peace and economic opportunity for the world. Our society, our economy cannot function without a ready, affordable, and adequate supply of energy [15]. Oil use correlates directly with standard of living and military capability. Two nations with the largest economies in the world—China and the United States—already rationalize this into their international policies [16].

As of 2007, about 70% all petroleum products used in the United States went for transportation. The United States imported about 70% of its total petroleum consumption [14]. These numbers and their implications are discussed in detail in Appendix A. Diagrams 1 and 2 [14] in Appendix A illustrate this "big picture" on U.S. energy flow and petroleum consumption. The bottom line is that security and DoD mission are linked directly to this oil import reliance, and DoD can have a major impact on reducing or even eliminating this reliance.

As previously noted, the DoD Office of Force Transformation and Resources 2007 special report on energy strategy [1] specifically noted the environmental aspect of energy use as one of the four "disconnects" in current DoD energy use. The DSB 2008 report on energy strategy also mentions environmental implications in DoD's addressing its current energy challenges. Dr. Thomas Fingar, speaking for the U.S. intelligence community, reported to Congress in June 2008 the potential implications of climate change to national security [6]. The United Nations' IPCC 2007 report [17] documents scientific consensus, which accepts fossil-fuel-use-induced climate change. It is this climate change that the intelligence community's testimony to Congress addressed. Top military and intelligence advisors are announcing for the record that the consequences of climate change also threaten national security. Prudent planning suggests that DoD and, more broadly, the total U.S. command authority must consider as a key national security issue the effects of global climate change [18].

Many challenges could confront the United States in terms of stability operations and international humanitarian need, as well as potential internal homeland support in which DoD would likely have to engage [6, 17–19]. The United States could face multiple, simultaneous potential international crises around the world, which could range from rescuing natural disaster victims, to helping to keep peace within resource-challenged nations, to augmenting security in key resource nations, to peacekeeping among nations, and more. Even countries with nuclear weapons, such as India and China, could square off against each other in resource wars provoked by climate change. The shape and size of the U.S. military force structure could be profoundly affected by the size and quantity of direct military engagement needed and by the level of homeland defense requirements emerging from climate change.

Economic loss to the country directly impacts the nation's ability to provide self-defense, lead the international community, assist in stability operations, support human rights abroad, defend our allies, and provide international humanitarian assistance. The economic realities of energy access and consumption loom large over national security. For a comprehensive quantitative look at energy consumption and use challenges, see Appendix A, which contains statistics and implications of those statistics, as well as definitions for a number of energy-related unit measures.

Summary of Vulnerabilities and Threats

Responsible access to energy could be the single largest U.S. strategic security issue short of full-scale nuclear war. The threats of nuclear or biological weapons terrorism do not offer the same broad-scale impact to U.S. national security as the combined energy problems. The rise of a hostile military equal, if it should happen, is decades away. The energy-use challenges are pervasive and current.

The solutions to the total energy problem involve economics, technology, politics, industrial-base development, and, very likely, unintended consequences. Multiple solutions are being proposed and pursued. Some are perhaps ill-advised and even counterproductive. However, many good options exist to make the United States energy independent and more secure, as well as making DoD much less energy-tethered—and responsibly so within years, not decades. Changes in energy strategy for the nation and DoD can enhance military readiness and cost effectiveness, boost the national economy and general welfare, as well as drastically cut carbon emissions, which can help mitigate the impact of climate change [18].

EXAMINING POTENTIAL TECHNICAL SOLUTIONS

The Shell Oil Company recently published a "Dialogue with the Country" [20] in which it cites people's opinions about the energy crisis and gives a twelve-step program to address the problem. The publication says that as in any self-help program one must first admit that one has a problem. Given the current rise in fuel prices and concurrent political rhetoric, and actions of private citizens, perhaps the United States has accomplished step 1.

Alternatives to Foreign Oil & Methods to Mitigate Climate Change

What technological options then are available to relieve petroleum reliance? Some technologies are mature but need significant investment and nurturing to establish an industry. Some technology is at the level ready to prototype, but still needs substantial investment to prototype and then follow-on funds for years to develop the industrial base. Some technology is still in investigation but could be more rapidly developed with a focused financed effort. Some technical approaches are not ready or are simply the wrong path from a holistic perspective of providing national energy independence with financial and environmental responsibility. Some solutions are not so much technological as industrial, social, managerial, and political in nature. A broad front of solutions is definitely called for.

The advantages and disadvantages of several important solutions are examined below to demonstrate both readiness and appropriateness. This section addresses several major solution areas. Because of the breadth of these subjects the discussions are not exhaustive. Specific technologies—which can contribute to a given solution or perhaps broadly across solutions—are discussed in the "Technical Options" section.

More Efficient Fuel-Burning Engines for Vehicles

Less consumption is the best possible alternative if one can get equal performance. From looking at the fact that 80% of materiel supplied to Iraq and Afghanistan theaters was fuel, DoD can identify fuel savings as a focus for reducing logistics needs, the force that goes into providing those needs, and the forces required to protect the logistics forces. For the military, the true cost to provide a barrel of fuel to deployed forces, which includes the fuel required to deliver fuel, is as much as five times the "cost at the pump" [2]. If DoD can deploy vehicles that have much larger range for a given fuel requirement, it can achieve a new advantage in maneuver warfare. This can be accomplished by cutting recurring fuel expense and thus freeing assets to acquire additional advantage in operational performance. More efficient, tactical fuel use and, thus, significantly reducing fuel consumption, has a multiplicative positive effect.

A DoD investment in higher efficiency vehicles can have broad, positive effect in the homeland as well as on the battle field to reduce all aspects of the energy challenge. Virtually all U.S. vehicles run on petroleum products. The vast majority of this petroleum comes from outside the United States. Oil is rapidly and simultaneously becoming both a commodity in greater demand and greater scarcity [11]. Before the United States hit peak oil in 1970, a single barrel of oil from West Texas provided enough energy to produce 30 other barrels of oil, but oil used versus produced from the Gulf of Mexico is on a one-to-five ratio [21].

As previously noted, the U.S. transportation sector consumes roughly the equivalent of all imported petroleum products. Transportation is a great "target of opportunity" to introduce technology innovation; i.e., internal combustion engines (ICEs) and external combustion engines, including turbine-drive vehicles. But ICEs (mostly gasoline) drive most vehicles and they achieve only 20–25%, or less, energy efficiency [22]. As a thought experiment, imagine a row of ten 1-gallon cans of gasoline for your car, and then throw eight of those in the garbage. That's what our ICEs in effect do. We use 2 gallons out of 10 and throw the rest away. If current engines could be replaced with extremely high-efficiency engines, which are 2 or even 3 times higher in efficiency, the demand for imported oil could be cut at least by half. Vehicle engine inefficiency is determinative in petroleum demand.

Current ICEs, diesel or gasoline powered, are not even close to the theoretical maximum efficiency. Even current car fuel cells have only about 35% efficiency [23]. Immediate replacement of the U.S.-land-vehicle-fleet's ICEs with 50% efficient engines would cut petroleum consumption by over 6 Mbbl/day, eliminate the delivery costs and delivery security issues, mitigate/eliminate refinery processing shortfalls and bottlenecks, and save the U.S. economy over $260 billion a year in import costs (at $120 per barrel).

Because today's car engines run at about 20–25% engine efficiency, incrementally raising engine efficiency by 25 or 30% saves less than 10% of national petroleum use. The United States needs 200–300% efficiency improvements to make substantial progress toward energy independence and carbon emission reduction. Plug-in hybrids, fuel cells, radically improved-efficiency heat engines, and all-electric vehicles powered by batteries or ultracapacitors offer this level of magnum leap in conservation without having to sacrifice performance. Example heat engines, fuel cell, and electric vehicle technologies are discussed in under "Technology Options." The examples and options discussed are not intended to be exhaustive, but rather indicative that much can be done and done quickly.

The U.S. vehicle fleet is huge and replacement will not happen quickly. The United States has over 250 million vehicles on the road [24]. Yearly, the United States replaces around 8% of the fleet. Even if the country started a 2009 "crash" program allowing new purchases only of high-efficiency vehicles (if industry could affordably provide the product), fleet replacement takes until 2021. However, if complete replacement of vehicles—or at least their engines—with 50% efficiency engines were achieved, the United States could eliminate 6 Mbbl/day of oil from the current 20.7 Mbbl/day demand. The reduction could eliminate almost half of the U.S. daily petroleum imports. Apart from the other financial and potential climate benefits of this reduction, U.S. oil-refinery capacity would not have to increase. DoD could save force structure and fuel cost, and enable expanded operational performance if vehicle range could double with a doubling of energy efficiency and, consequently, halving the fuel-logistics requirement for such vehicles.

High-efficiency, affordable engine replacements can be achieved in the near future. Industrial base considerations could inhibit producing and fielding tens of millions of new, high-efficiency engines needed for the entire U.S. fleet, but DoD investment can drive expanded production and reduced cost. Raw material production and transport, production line development, safety qualification, public acceptance, and other factors play in determining how quickly the car and truck fleet could migrate to high-efficiency engines. Government support can boost their rapid production and deployment through mandatory fuel standards, carbon emission reduction mandates, and tax benefits to producers and consumers. DoD development and acquisition can accelerate how increasing oil prices will promote conservation-enabling technologies, such as the high-efficiency fuel burners.

All-Electric Vehicles—Beyond Burning Fuel in a Vehicle

DoD is already developing hybrid-electric vehicles, but also can promote and take advantage of all-electric vehicle technology, which could be an enabler in building unmanned vehicles that can stay on mission for greater duration. The all-electric tactical vehicle for DoD, with today's technology, may have limited application, but that may soon change [25–27]. However, in projecting possible future capability and in considering the broader security implications for the country, DoD could serve itself and the nation well by investing to promote such technology.

The best mechanism to reduce petroleum consumption in vehicles, and the cost and logistics that go with it, is to not use petroleum in vehicles. All-electric cars can run on stored electricity from any source, including hydroelectric, geothermal, nuclear, photovoltaic, wind, burning biomass, or whatever. Electric motors can typically achieve 90% efficiency [28]. Electric motors can drive cars, trucks and, potentially, even aircraft. An all-electric-motor fleet would use only about one quarter of the energy required by the current U.S. land vehicle fleet and would not need petroleum. Electric vehicles themselves do not emit greenhouse gases. Electric power plants needed to charge the vehicles could run on renewable or nuclear power from domestic and, perhaps, environmentally benign sources.

Even today, electricity storage technology for all-electric vehicles is sufficient to meet the commuter needs of most Americans. Cost of electricity storage today is comparatively high. However, considering only fuel use, using electricity to power vehicles costs less than burning petroleum-based fuels. Oil prices soared over $140 per barrel in 2008, and gas at the pump exceeded $4.00 per gallon. Electricity is still cheaper if oil were only $20 per barrel. Electric cars, which recharge overnight during off-peak hours, use what equates to less than 50 cents per gallon fuel.

Currently, the ICE Btu are import-petroleum based. Electric Btu can come from U.S. resources. According to the Economist magazine, wind power could provide 20% of grid power in 20 years (but that may be substantially accelerated), and the solar power industry grows by 50% per year [29]. Exciting breakthroughs in electrical generation technologies from fusion power have only recently been reported [30–32]. The electric-vehicle fleet melds well with the growing alternatives for grid power production.

Even with today's electrical infrastructure, the homeland could accommodate at least a 70% switch to all-electric, light-duty vehicles [33]. Currently, most U.S. electrical power production comes from over 500 coal-fired plants and from natural gas plants. Diagrams 3 through 5 [14] in Appendix A show the U.S. source-to-use flow of natural gas, coal, and electricity. In 2006, coal provided 50% of U.S. electric power production, natural gas about 17%, petroleum, nuclear about 20%, and renewables (including hydroelectric) about 10.4%. The United States holds about 260 billion tons of domestic coal reserves. With efficient coal-to-electricity conversion, these supplies could provide additional power for high-efficiency electric cars and not exhaust the domestic coal supply as quickly as conversion of coal to liquid fuel would.

Can the current electric power infrastructure meet the additional demand of an electric fleet? A 2006 DOE study [33] conservatively projected that over 70% of the light-duty vehicle fleet of cars, SUVs, and vans could be powered from the existing electrical power production and distribution infrastructure time, if the vehicles were plug-in hybrids charging on off-peak hours. Different regions of the country have different levels of margin, especially depending on how power is produced. The Pacific Northwest appears to be the least adaptable, and the Northeast and South are particularly adaptable to using an off-peak power margin to charge electric vehicles. The power system is designed for peak loads, which according to the report, only occur a few hundred hours every year. The nation averages about a 16% margin in electrical production capacity over peak loads. Because the electric vehicle fleet would not instantly spring into existence, the electricity infrastructure should have time to adapt.

Until electrical storage endurance improves or fuel-cell technology improves, the all-electric vehicle might meet limited DoD mission needs. However, electric vehicle technology is here and readily deployable. The companies FEV Global and Raser Symetron recently showed off their proposed electric hybrid drive train, which would provide 100-mpg capability to a full-sized SUV [27]. Additionally, others are already developing electric-hybrid efficiency for DoD. DoD can be a principal enabler in reducing the cost of electrical storage by using its huge development and acquisition investment resources.

In the broader U.S. economy, the all-electric vehicle today has sufficient capability for most family uses, with greatly reduced energy-consumption cost. Cost of in-vehicle electrical storage is still an issue, but is being worked along multiple technical paths. Electric hybrids are proliferating and improving in cost and performance. Research and development in batteries, capacitors, fuel cells, and superconducting-coil-storage systems offer multiple avenues for breakthroughs, as well as continued incremental progress.

Electrical storage performance will improve. Cost will drop. An all-electric-vehicle fleet offers the potential to eliminate U.S. foreign-oil dependence and mitigate geopolitical tensions, eliminate the need for extra petroleum refineries (~8 Mbbl/day deficit in the next decade), decrease operating costs for vehicles, improve vehicle reliability and lifetime, reduce military logistics burden and save lives, eliminate fossil-fuel based carbon emissions in the atmosphere, and increase domestic jobs and economic opportunity. Economics will produce an all electric fleet. A government-encouraged market would make it happen faster.

Synthetic and Renewable Fuels

The Air Force has programs to demonstrate that renewable and synthetic fuels can power jet airplanes [34–37]. The Naval Research Advisory Council in 2005 recommended synthetic fuels as the way ahead to assure military fuel needs. The military needs high-energy density in its platforms for performance and endurance. Renewable fuels can deliver those capabilities without using imported or domestic petroleum. According to Department of Transportation statistics [24], the government as a whole used about 6.3 billion gallons of vehicle fuel in 2006, of which about 3.89 billion gallons were DoD JP and aviation gas, and 1.7 billion gallons were DoD diesel use. With this level of demand, DoD can establish a market and, thus, the industry to produce fuels from domestic sources and, in the process, provide the pathway to imported petroleum independence for the whole country.

In the summer of 2008, the airline industry was particularly hard hit by the high price of fuel. JP fuel accounts for roughly 75% of DoD vehicle fuel consumption—though that JP comes in a couple of varieties and is used in more than just aircraft. DoD is a big consumer. Although one may argue that cars and even trucks can be made all electric, as of today, long-range aircraft used by airlines cannot be made all electric. A renewable fuel industry and the airline industry make a good match [38]. DoD and the airline industry can help each other with investments to help birth an assured source for domestic, high-quality jet fuel.

Although most auto and truck engines run on diesel or gasoline derived from petroleum, vehicles could burn a wide variety of fuels from nonpetroleum sources. Economics of rising petroleum prices should drive development of a U.S. synthetic/renewable fuel industry. However, past fluctuations in world oil prices have severely hampered development of such an industry. Illustrative of this effect is the 1999 report by the DOE National Renewable Energy Laboratory (NREL), which reported both the high potential for the use of algae as a renewable fuel source but also that the project was cancelled because oil prices had dropped below $20 per barrel and *were projected to stay low for the next 20 years* [39].

Synthetic fuel research and development projects proliferate. Each product-process pair has benefits for specific utility. Dozens of companies stand ready to produce and deliver synthetic/renewable alternatives to petroleum-based fuels. If DoD (and/or other federal agencies) by high-volume, long-term contracts provided a price floor for the product, the market could drive full development of the synthetic fuel industry. Ideally, the best of breed will flourish. See Appendix B for a discussion on business model and market influences in regards to development of a new fuel/energy industry.

The DOE lists about a dozen alternative fuel options, such as ethanol, butanol, green diesel (diesel from renewable sources), biodiesel, and hydrogen. Not all alternative fuel options are environmentally and economically benign. The United States must be careful not to induce negative, unintended consequences when producing petroleum alternatives, such as Michael Grunwald reported in his article, “The Clean Energy Scam” [40]. Using staple food crops, such as corn or soy bean, and using the high-quality farmland to the exclusion of growing food in order to produce renewable fuel, have significant negative consequences. Although ethanol from corn offers many farmers new financial gain, consequences threaten in higher food prices and potential food commodity shortages. Even if all the U.S. farmland were planted with corn for ethanol production, the United States would be hard-pressed to replace its current petroleum use with the resulting ethanol. However, ethanol from cellulosic plants grown in marginal soil might be a potential boost to the fuel supply but will still require huge areas of land.

Although replacing all food crop production in the United States with corn or soybean growth for ethanol would not provide sufficient synthetic fuel to replace the 21 Mbbl/day demand for oil, an area about 250x100 miles (equivalent to a 12.5 mile strip spanning the length of the U.S.-Mexican border) of algae production could provide synthetic fuel equivalent for the U.S. energy needs [39]. DoD action could guide the nation forward

Synthetic products (from crops that grow on marginal land, from algae, from waste, from sewage, from coal, and from natural gas) have the potential to completely replace U.S. petroleum consumption and end U.S. energy-import dependence, while enabling the United States to share excess energy with needy countries. Proper government incentives can prevent use of high-quality cropland (and crops) to produce fuel, ensure a price floor to synthetic fuel so that the synthetics will begin to predominate and eventually replace petroleum, and prevent expensive and environmentally damaging approaches to producing synthetic fuel.

The DoD, or the federal government in a wider action, could ensure a price floor for synthetic/renewable fuel that would give investors and entrepreneurs the needed safety net to invest and build the synthetic fuel industry. In addition to whatever energy consumption the United States can avoid through advanced efficiency measures or increased domestic petroleum production, synthetic fuels can remove the U.S. bondage to imported oil. Renewable synthetic fuels offer not only U.S. independence, but also a potential domestic fuel produced in enough quantity to export. The additional source of renewable energy offers a wider global security. Renewable fuels offer an environmental bonus since they can eliminate new atmospheric carbon emissions.

A special case of renewable and synthetic fuel options relates to the concept of creating a hydrogen economy. In this concept, hydrogen would become the fungible energy storage and exchange mechanism for potentially all or most sectors from military to industrial to commercial to residential to transportation. The hydrogen would be made by some high-efficiency means, stored, and distributed or perhaps produced in a distributed fashion so as to avoid the technical challenges of storage and distribution. Other such whole-economy solutions have been suggested. But there are problems.

Hydrogen is the most plentiful element in the universe and exists in vast quantities combined with oxygen as water in the world’s oceans. Hydrogen for energy storage or as an energy carrier interests because of its high energy-to-mass ratio as shown in Table 1. Also, when it is used in an engine or fuel cell it does not directly produce pollutants or problematic greenhouse gases. Hydrogen is at least notionally producible by all countries of the world. For DoD to make wide-scale use of hydrogen as fuel, it would have to find some processes currently unavailable to efficiently produce this fuel at the site of use and/or find a mechanism to make it volumetrically more energy dense and easily transportable, and less potentially dangerous as a target of attack, since hydrogen gas is explosively flammable. Also, in the broader context of U.S. national needs, these and other problems of hydrogen fuel present themselves.

Can the various problems for the hydrogen economy in production, distribution, storage, and final energy use be overcome? One kilogram of hydrogen can produce more than three times the amount of energy that a kilogram of gasoline or diesel will produce when they are burned. A hydrogen fuel cell has theoretically much higher efficiency than an ICE. Compactly stored hydrogen used in fuel cells operating at over 80% efficiency might provide a path to conserve energy, provide several factors increase in platform endurance for military vehicles, and potentially eliminate (certainly mitigate) carbon emissions to the atmosphere. Research may provide an enabling breakthrough

Table 1. Fuel Energy Comparisons

Fuel	Megajoules/kilogram	Megajoules/liter
Hydrogen	143	10.1-liquid hydrogen
	143	5.6 -700 bar compressed
	143	.01079 – room temp& bar
Liquid Natural Gas	55	25.3
Propane	49.6	~26.8
Butane	49.1	~26.8
Gasoline	46.9	34.8
Aviation Gas (not JP)	46.8	33.5
Diesel	45.8	38.6
Jet Fuel (JP)	43.8	35.1
Gasohol (Ethanol 10%)	43.54	28.06
Biodiesel	42.2	37.8
Coal	32.5	72.4
Butanol	36.6	29.2
Ethanol	31.1	23.5
Methanol	19.9	17.9

in mass production, storage, and distribution. However, at this time, technical readiness level appears to not support marshalling a national program to implement a hydrogen economy. The newly published MIT discovery in catalytic production of hydrogen from water turns into the best possible result: it would enable a solar/electric economy with residential hydrogen storage [41, 42]. However, even with this technology breakthrough, DoD and other users of hydrogen in vehicles and by industry would still be problematic.

Other metallic, molecular, or phase-change energy-carrier mechanisms (e.g., zinc, aluminum, compressed air, ammonia, hydrogen peroxide, and liquid nitrogen) have been proposed that would somewhat emulate the hydrogen economy concept. Each would be used by various mechanisms (e.g., batteries, fuel cells, and heat engines) to produce energy and be recycled or produced by some other prime power (e.g., nuclear, solar, hydroelectric, and geothermal). These other economy concepts in general are significantly less well thought out and less well financed in research than the hydrogen economy [43–45].

The United States need not wait for solutions to the hydrogen or similar "economies" problems. Other renewable fuel options appear achievable both in the near term and with bright promise for the long range. What specific government actions can help? From the DSB Task Forces' reports and related discussions, the energy strategy report for the DoD Transformation Office, and sources such as the National Resource Defense Council and others the following are synthesized [1–3, 46, 47].

DoD, as a normal course of business, strives—through various mechanisms, including contracting and acquisition—to maintain and/or develop the U.S. industrial base that supplies DoD and enables the country's military strength. DoD consumes more fuel than any other single user in the nation. Fuel industrial base is crucial to DoD. DoD accounts for over 90% of total federal government fuel use even thought the Postal Service uses almost as much gasoline as DoD. DESC, as fuel acquisition hub for the federal government, could be instrumental in developing a renewable fuel industry that provides the standard of fuel required by DoD at an ensured, consistent price, which is both favorable to the government and develops and maintains this new industry. The government could ensure a floor-price for all domestically produced renewable fuel. However, this action might require that the government be the purchaser of last resort and eventually mandate the use of government fuel stocks to distribute to gasoline stations. Since the Defense Logistics Agency's (DLA's) Defense DESC contracts for all fuel used by the government, DLA could contract for acquiring all government fuel with the following stipulations:

a. Define required fuels to encourage competition from synthetically produced diesel, jet fuel, aviation and motor gasoline, and fuel oil. Do not compromise on fuel performance standards or systems compatibility—the providers would have to deliver high-quality fuel, which the DESC would certify.

b. Purchase domestic nonpetroleum fuel production from domestic sources, which could be renewables, coal, or natural gas.

c. Encourage carbon neutrality in the production and use of the fuel, which will reinforce the industry to produce more renewable fuel and/or carbon reuse/sequestration when sources such as coal and natural gas are used. Discourage the use of food crops and food-crop farmland in production of the fuel. Encourage the use of marginal or usually nonarable land or even marine agriculture in renewable fuel production—such as growth of switch grass, seaweed, and algae for fuel production.

Broader government actions to encourage industrial base development might include mandating more stringent fleet fuel efficiency for automobiles and trucks sold by manufacturers in the United States. Mandates against carbon emissions with fines against vehicle owner-operators would hasten fleet renewal. Tax credit incentives for purchase of very high-efficiency ICE and electric vehicles and hybrids would push rapid fleet replacement.

As suggested by the DSB Task Force and mentioned previously, DoD could establish an Office of National Energy Security with the duty and resources to set energy use requirements on all future systems and facilities, as well as mandate retrofit and Planned Program Product Improvement for substantial energy conservation. The office could be supported by a laboratory or consortium of government labs and industry resourced through that office on a project-by-project basis to produce prototypes specifically designed to make DoD more energy efficient and petroleum independent. The $500 million/year recommended by the DSB would be sufficient to run this office and support labs. Establishing this office would not violate the law of bureaucracy that ensures that any bureaucracy established to end a problem will never achieve that goal so as to stay in existence. This office would serve more as a combination police department and venture capital office to ensure DoD adheres to energy goals and encourages efforts to achieve them.

Nuclear Power Options

Three technologies usefully exploit nuclear energy today. Radioisotope thermoelectric generation produces isotope-decay-generated heat and has been used in space probes, pacemakers, and lighthouses. Hirsch-Farnsworth nuclear fusion reactors fuse deuterium to generate neutrons, but they have not yet been demonstrated to produce net power. For more on half-life fusion, see the nuclear fusion section under "Technology Options." The third type, nuclear fission reactors, is based on a controlled chain reaction of neutron emissions from uranium, plutonium, or thorium. All nuclear power plants and naval vessel power are nuclear fission reactors [48, 49].

In a prime example of DoD leading the way in technology deployment, the U.S. Navy pioneered the use of nuclear fission power in the United States. The first U.S. naval vessel powered by nuclear fission, USS *Nautilus*, put to sea in 1954, 3 years prior to the first U.S. commercial fission-powered reactor went on the grid in Pennsylvania in 1957 [49]. In a 2008 action, Congress has mandated that the next-generation cruiser, the so-called CG-X, will be nuclear powered.

Enormous amounts of power can be generated by very small amounts of uranium, plutonium, or thorium or fusion materials, such as deuterium. Estimates indicate that enough of the heavy elements are mineable or can be produced in breeder reactors to power civilization for at least hundreds of years—tens of millions of years in the case of fusion materials. The United States has access to sufficient domestic supplies of uranium through the 21st century and perhaps as long as 1500 years. Nuclear power does not directly produce carbon emissions. Wide-scale replacement of current fossil-fuel driven power generation with nuclear power could mitigate carbon-emission-based climate change and perhaps help other nations with energy shortages.

However, wide-scale use of nuclear energy to replace fossil fuel presents complex problems. The 2003 MIT cross-disciplinary study, *The Future of Nuclear Power* [50] recommends maintaining the nuclear fission power industry as a viable option specifically to reduce the effects of carbon-emission-induced climate change. It cites three other potential mechanisms to mitigate carbon emissions: improved efficiency in use and production of electricity; renewable energy sources; and, carbon sequestration from fossil-fueled power plants. Not intending to exclude or rank any of these choices the report recommends nuclear fission power expansion only because it is an additional path to carbon- emission reduction. The report cites four major obstacles to expansion of nuclear fission power: cost, safety, proliferation, and waste.

Nuclear power by itself does not directly replace most U.S. use of petroleum. Nuclear power plants could eliminate the demand for the 30 quads of fossil fuel (mostly coal and natural gas) that the United States burned to produce electricity in 2007, but only 0.72 quads were petroleum [14]. Nuclear-generated electricity could power the electric-vehicle revolution which, as previously discussed, could eliminate foreign oil need. Also, nuclear power's ability to efficiently produce mass amounts of hydrogen gas could enable help to usher in a hydrogen economy, if hydrogen's other issues could be resolved. The extremely high-temperature (800–1000 °C) designed reactors can very efficiently produce hydrogen from water.

Nuclear fission plants are not the only option for nuclear power. Apart from the standard tokamak/ITER nuclear fusion research that DOE has pursued, a brand of nuclear fusion pioneered by Philo Farnsworth in the 1960s and augmented by Dr. Robert W. Bussard may provide a power-producing fusion plant by 2015.

Other than through nuclear weapons or solar radiation, mankind (to date) has been unable to obtain net energy from nuclear fusion. Potentially fusion can produce more energy than fission with none of fission's problems of fuel source, waste products, or weapons proliferation. Fusion of a mass of deuterium and tritium (the easiest fusion to accomplish) yields three times the energy produced by fission of an equivalent mass of U-235. Light-element fusion does not produce the extremely long-lived nuclear waste of heavy-element fission. High-energy neutrons, released by the tritium-deuterium fusion, impact the fusion-containment material and can make that material radioactive. With proper selection of materials, the timespan of radioactive danger from such irradiated material can be on the order of hundreds of years, rather than hundreds of thousands of years—fission's legacy. Fuel is abundant. Tritium can be bred in a fusion reactor. Enough deuterium exists to power worldwide energy consumption many times the current level for over a billion years [51].

The vast majority of research money in fusion has been spent on the tokamak-style magnetic containment technology [52]. Other technical approaches have been suggested such as the famous low-energy approach by Pons and Fleishman [53], and sonoluminescence [54]. Recent success in Polywell fusion promises a near-term path to the promise of nuclear power without the problems. Various technologies are discussed in "Technical Options." The information on fusion research and development herein is not intended to be exhaustive, but representative of the promise and status of human-harnessed fusion power.

Current nuclear power technology offers potential to replace all electrical-grid power production without need of any fuel source import and without carbon emission. However, fission systems pose various significant long-term safety and security hazards. Research offers significant potential improvements in fission reactor performance, safety, and potential to store waste. Assured mechanisms to prevent weapons proliferation and catastrophic accidents must emerge, or U.S. security could actually suffer from fission power production expansion.

The ITER nuclear fusion program is still about four decades away from projected net power production. The ITER-based systems, if successful, will be physically far too large for naval vessel use, but could serve as grid power should they eventually be developed.

The Bussard Polywell machine has shown remarkable recent success [55–57]. The Navy could use such systems on future naval vessels to eliminate the energy tether for ships—perhaps as early as the CG-X, which has been mandated by Congress to be nuclear powered. Large-scale expansion of this potentially affordable, safe nuclear power could enable all other approaches to alternative-fuel economies, energy independence and, ultimately, national security. While DoD uses of the Bussard systems could revolutionize military operational capability, in the world at large the ramifications of its adoption as the principal mechanism to produce power are perhaps too all encompassing to project—no less than emergence of a new civilization.

Virtually all U.S. Navy aircraft carriers and submarines are nuclear powered. New forms of nuclear fusion power may reduce the cost and size of nuclear power plants and increase safety to the point that they can be deployed quickly to the need of any DoD units, even forward-deployed in theater, to power aircraft and space vehicles as well as naval vessels—without danger of meltdown or generation of nuclear waste. Such nuclear plants use small amounts of fuel, a fuel that is abundant enough to last mankind for many millennia. Nuclear power can eliminate the need for fossil fuel use, which has limitations both in known quantity, distribution, access, processing, and global environmental impact. The United States, beyond independence, can be a net energy exporter with emerging nuclear power options.

A Brief Recount of Some DSB Task Force 2007 Recommendations

Getting more efficient DoD platforms and engines [1–3]. This paper is devoted not so much specifically to military energy issues as to relating the broad mix of national security issues and synergies for solutions and the potential for DoD to lead and enable the national response in this crucial security area. References 1–3 examine at length the subject of platform and engine efficiency and other core military energy problems and options. There's no intent to duplicate those extensive reports here, but a thrust of their findings is particularly worth noting—DoD can do much more with less by better energy efficiency.

The DSB 2007 Task Force reported on various technologies for more fuel efficient platforms (e.g., aircraft, ships, and land vehicles). Not just the engines but the platform as a complete system must be designed for fuel efficiency. Both DSB Task Forces (2001 and 2007) recommended that DoD incorporate fuel efficiency as a key performance parameter in specifying and buying new equipment—what DoD refers to as "acquisition."

The February 2008 report discussed various efficiency approaches. For example, an armored land vehicle can be made viable, robust, and more easily transportable with materials that weigh less. Aircraft design and materials can help provide extra range and operational performance. As previously noted, if some aircraft can extend their range by 30%—evidently quite achievable by DSB findings—the air refueling fleet can be significantly reduced. Huge savings would accrue in reduced fuel use and increased operational security by removing a vulnerable link in the combat chain.

The possibility of much more efficient aircraft—which the 787, as the first whole body composite commercial aircraft suggests—offers military and national payoff for security. Also, electric hybrid, or all electric commercial aircraft may one day be possible. Aircraft could benefit from the efficiency, reliability, cost, and size advantages of the electrical motor as prime power. Ninety percent of the thrust from a turbojet engine comes from the large bypass fan. Therefore, performance in some missions would not be sacrificed by using electric powered aircraft with an advanced, efficient electrical storage/generation technology.

The 2008 report shows many worthwhile technologies for fuel conservation that also improve operational performance. According to References 1–3, finding technologies are not the issue so much as DoD policy and acquisition processes. DoD can improve operational capability, increase operational security, and save fiscal resources by giving priority to and integrating fuel use issues into requirements setting and acquisition options analysis. The DoD is confronted with a broad and complex scope of challenges and alternatives, which include high-performance alternative fuels, more efficient fuel use, assured access to power for critical installations, and consideration of energy related issues in the national military strategy.

Addressing Infrastructure Vulnerabilities. The 2008 Task Force publication specifically addresses the sensitive issues of power-grid vulnerability and assured access to energy for critical civilian and military facilities. Some considerations are already being addressed. The report itself gives sufficient discussion concerning the unclassified areas.

Considerations ranged widely on solutions. As an example option, military installations might be able to produce fuel from waste (trash and sewage) and use high-efficiency engines, such as previously noted, to run electrical generators. This might not solve grid-dependence but could help in an emergency and also in terms of cutting overall fuel requirements. The report discusses these and other topics. A classified appendix is available.

Sensitive and classified issues are involved in energy infrastructure in the homeland and in military installations worldwide. No matter what else happens, DoD must deal with these and consider augmenting infrastructure robustness in the light of climate change. These issues are not detailed here.

TECHNICAL OPTIONS—A NONEXHAUSTIVE DISCUSSION OF 15 TECHNOLOGY AREAS

1. Heat Engines

Lift up the hood of almost any truck or car and you will find an ICE running on the Otto, Miller, Atkinson, or Diesel Cycle. Practical considerations of cost to produce, expansion fluid used, and engine endurance help determine the actual efficiency of these engines. However, fundamentally the ratio of heat source temperature and ambient temperature determine an ICE's maximum theoretical efficiency. Alternatives to current ICEs exist in fact and in design. Not to give an exhaustive options list (which might include the quasiturbine and Stirling designs), but to show the feasibility of rapidly fielding high-efficiency engines, two examples are discussed below.

The StarRotor engine is a Brayton cycle engine being developed by StarRotor Company, Texas A&M University Professor Mark Holtzapple's start-up company [58]. The engine consists of two cylinders containing rotors that compress air in one cylinder and expand air to extract energy in the other cylinder. The first cylinder compresses air and feeds it to an external combustor, which then passes the compressed-and-heated air into the expander which extracts the energy. The folks at StarRotor believe the engine will be at least 50% energy efficient. That performance compares very well to the typical 20–25% energy efficiency of automotive ICEs. Because the engine is an external combustion engine, it can run on virtually any fuel that burns.

Another example of a potential revolutionary engine improvement comes from the new company, Cermetica. It is commercializing breakthrough materials-processing technology developed by former Georgia Tech Professor, Katherine Logan (now at Virginia Tech). Robert Wisner's, one of Cermetica's founders, concept is similar to the Wankle engine but would use the proprietary materials-processing technology to make a titanium-diboride, high-temperature ICE with basically only one moving part and very low part count otherwise. Wisner believes that this engine will be able to achieve 50% efficiency and run on a variety of petroleum or synthetic fuels.

Either of these engines should be smaller and require much less maintenance than current production ICEs. Their flexible fuel capability synergistically enables proliferation of alternative fuel production. Cermetica and StarRotor exemplify the potential but are not the only new engine options. Totally new engines are not the only answer.

Diesel engines already offer higher efficiency than most gasoline engines. The DOE's Energy Efficiency and Renewable Energy office sponsors a Vehicle Technologies Program. As part of that effort, the Advanced Combustion Engine program has a goal to increase production diesel engine efficiency by fifteen percentage points (for light truck diesels, 30% to 45%, and for heavy truck diesels, 40 to 55%) by 2012 [59]. However, diesel engines have advantages even with today's capability. Diesel engines have a higher compression than spark-driven gasoline engines. Because the fuel in a diesel is ignited by the compression of fuel not by a spark plug, the fuel throughout the volume of the cylinder is more evenly exposed to the ignition condition. A gas engine's spark plug does not evenly expose the complete volume of the gasoline in a cylinder to the spark. A larger ratio of fuel in the diesel is detonated compared to that in the gasoline engine. Diesel engines typically can achieve greater than 40% efficiency at full load. Notionally, although with many assumptions and caveats, replacing gasoline engines with clean diesel engines could reduce consumption of petroleum for vehicles by 15% (about 1.35 Mbbl/day) and thus reduce oil imports by the same amount.

Turbine engines (or microturbine engines) can theoretically be made highly efficient -greater than 50% [60]**.** Turbines vary greatly in efficiency depending on the load/speed condition in which they operate. However, they can use multiple types of fuel. They can be made with only one moving part, to need little or no lubricant to rotate, and to need much less maintenance than piston engines. Turbines have operating lives as long as 20,000 hours, which would be about 30 years of service for a 20,000 mile-per-year vehicle averaging about 30 mph (miles per hour) over the course of all trips for a year. Currently turbines cost more than production vehicle ICEs. However, turbines need not cost any more than ICEs if they were produced in the same quantity yearly as ICEs are.

2. Hybrid Electric Vehicles

Hybrid electric vehicles can take advantage of the high efficiency of electrical motors and electrical storage devices and combine that with running high-efficiency engines at maximum efficiency, only to charge electrical storage when required. A hybrid electric vehicle could theoretically milk maximum efficiency from a microturbine. If a Tesla turbine for a vehicle could indeed achieve 80%+ efficiency [61] at optimum operation, a hybrid could enable that mode of operation. Replacing the entire vehicle fleet in the United States with such hybrids could cut petroleum imports to the level that no imports need come from outside North America.

Current hybrid vehicles achieve over 50–60 mpg with proper driving style by the operator. Hybrid vehicles can give a range today that current all-electric vehicles don't. Plug-in hybrids with a 60-mile range will, for most people on most days, run only on the plug-in charge. These plug-in cars will contribute advantages of the all-electric fleet until the all electric fleet comes. All-electric vehicle technology is discussed separately.

3. Fuel Cells [62]

Fuel cells produce electricity electrochemically not by combustion. They are not subject to the limitation in maximum efficiency of a heat engine. Fuel cells theoretically can achieve over 80% energy production efficiency. Conceptually, fuel cells could reduce demand for petroleum-based fuel by a factor of four. In practice, current automotive fuel cells average 25–35% efficiency. However, other applications of fuel cells typically achieve 50–60% efficiency. Systems in which the heat produced by the chemical reaction is also captured for energy production achieve as much as 90% efficiency.

Fuel cells have no moving parts and can be extremely reliable as well as quite. The Germans have a fuel-cell driven submarine. NASA uses fuel cells for space missions. Fuel cells can run on hydrogen and oxygen and have nothing but water as an exhaust. Other fuel and oxidizer options also are used.

Current fuel cells are not as energy dense as ICEs and are relatively costly. Most current fuel cells use the very expensive metal platinum as a catalyst. New much less expensive catalyst options are available. Nanotechnology offers help. A new membrane technology developed by an MIT chemical engineer, Paula Hammond, offers much better performance (50% power increase) for straight methanol fuel cells [63]. Currently, platinum costs alone can price fuel cells out of the market for replacing ICEs. However, potential use of nickel, iron, or other catalysts (usually nanotechnology assisted versions), can replace platinum and make fuel cells more affordable and perhaps more effective [64, 65].

Many fuel cell technology options are being pursued in commercial development and research. The cost versus performance will continue to improve. Fuel cells will compete with other technologies to deliver power to both the automobile and the home [66].

4. All-Electric Vehicle Technology

Let's look at the cost to provide power to a petroleum fueled vehicle. As an example, assume a 30 mile/gallon vehicle traveling at 60 mph and that requires 13 horsepower (10 kilowatts (kW)—typical for an automobile on a straightaway) to drive it at that speed. In one hour, the vehicle will travel 60 miles, expend 10 kilowatt-hours (kWh) of energy, and use 2 gallons of fuel. At $3.00 per gallon, the vehicle costs, in fuel use alone, $6.00 for 10 kWh, which equals 60 cents per kilowatt-hour. Consider that a kilowatt-hour of coal-supplied electricity averages 5 cents, even solar power price per kilowatt-hour is only 20 cents, and that the price of the petroleum-based fuel is probably significantly more than $3.00 per gallon.

Multiple car companies are producing or developing the electric hybrid and even the all-electric car such as the Tesla. These cars require hefty electrical storage and/or onboard electricity generation. Batteries for electricity storage, depending on how they are made, have their own problems—safety and environmental. However, much is being done to produce high-performance batteries and battery alternatives. For example, the Tesla entrepreneurs chose to use lithium-ion batteries such as computer manufacturers install, because they believe that the computer industry will drive better battery development [67]. Still other developers are exploring other nonlithium ion options that are potentially less expensive, longer lasting, energy dense batteries [68]. If electrical battery storage improved as the computer industry's famous Moore's Law predicts for computing technology, within 10 years the future electrical vehicle storage device would cost less than $300 and have similar to the same energy delivery capability per kilogram as the ICE. This slope of improvement may not be achievable, but electrical battery performance and cost will improve and will directly benefit the electric vehicle.

In a different approach, the company EEStor in Cedar Park, Texas, in partnership with Lockheed Martin, is developing an assembly line for a new kind of ultracapacitor (ultracap) based on the dielectric, barium titanate [69, 70]. This ultracap unlike the much smaller capacitors in commercial and military electronics will be able to store dozens of kilowatt-hours of electrical energy. Richard Weir, company cofounder, says that these ultracaps will have three-to-four times the energy density (energy per kilogram) as a lithium-ion battery (such as Tesla and General Motors are using for their electric cars) and ten times as much energy density as lead acid batteries (such as are currently under the hood of most cars). These ultracaps supposedly will be able to take full charge within minutes. The company is planning to ship its first commercial product within months. Zenn Motor Company, a Canadian electric-car company, plans to use them in their all-electric sedan to be sold in the Fall of 2009. Other ultracapacitor options are being pursued such as the carbon nanotube approach at MIT [71].

How does electric power compare to other alternatives? *Popular Mechanics* magazine in 2006 published a cost comparison for various fuels to drive similar cars from New York to California. Table 2 [72] shows the dollar-cost based on fuel prices in 2006 for that cross-country trip.

The list shows that even if the electric vehicle prices may not be lowest, running on electricity might be a bargain anyway. The Honda EV Plus's trip was not only lowest in cost, its distance was farther because of the electrical energy available from 1 ton of coal, which allows a 3311-mile trip versus a 2999-mile trip for the gasoline-powered Honda Civic. Thus, the electric-powered Honda got 55.19 miles per dollar versus 14.1 miles per dollar for the gas-powered Honda.

Not in this table is the Roadster all-electric from Tesla Motors. Tesla advertises a 220-mile range per charge and 50 miles per dollar cost to run the Roadster [73]. Considering that the cost of electricity production has not suffered the same price rise as gasoline since 2006, electricity as prime vehicle power looks very attractive but not just for cost of fuel.

Electric vehicles also recycle energy. EV Plus and the Roadster were designed to produce and capture electricity from braking. The kinetic energy in the moving vehicle is captured by a mechanism such as by making the motor serve as a generator or by running a generator from the rotating motion of the wheel-drive train. Because of this electricity regeneration, driving in stop-and-go city traffic gives the electric vehicle a longer run on a battery charge than highway driving allows. The opposite situation applies for the ICE-car. Most automobile travel is city driving.

Also, unlike the ICE, electric motors do not have to expend power unless they are actually providing motion to the vehicle. When sitting at traffic lights, while a combustion engine would be burning fuel, an electric-car motor need not drain electricity. Also, electric motors are vastly more efficient at using energy than combustion engines. Three-phase-electrical-motor operating efficiency is typically 90% compared to the typically 20–25% efficient ICE. The 500-horse power Raser Symetron motor installed in a Formula Lightning racing car for an appearance at Monaco is rated at 92% peak efficiency, produces more torque than the ICE it replaces in similar fuel-burning Formula vehicles, and is about half the weight of that ICE [74]. Similarly, Tesla Motors advertises 85–95% efficiency for its motor [75].

The industrial base for production of millions of electric motors already exists. Electric motors, using cheaper and more plentiful energy, operate as much as five times more efficiently than ICEs. New electric motor technology offers possibly even better efficiency and lower cost. For example, faculty members at Lund University in Sweden have developed a means to use iron powder and plastic to make the magnetic components in permanent magnetic motors [76]. The inventors believe the technology will double the energy density and cut the cost in half.

The major problem with electric vehicles is limited, expensive storage of electricity. A lead-acid battery pack, which might provide less than 100-mile range for a vehicle and which has a 3–4 year life, costs around $2000.00 [77]. The Tesla electric car company has chosen to use the type of battery used by laptop computers, lithium-ion batteries [78]. The lithium-ion batteries can last three (or more) times longer than the lead-acid batteries but cost 10–15 times more than lead-acid per watt-hour of energy stored. The Tesla entrepreneurs intentionally chose computer batteries to take advantage of the ongoing push by computer makers to produce better and less expensive

Table 2. Cross-Country Trip Fuel Cost Comparisons

Vehicle	Fuel	Trip Cost
1997 Honda EV Plus	Battery charge (1 ton coal)	$60.00
2005 Honda Civic GX	Compressed Natural Gas	$110.00
2006 Honda Civic	Gasoline ($2.34/gallon)	$212.7
2006 VW Golf	B100 Biodiesel	$231.00
2005 Taurus	E85/Ethanol	$425.00
1998 Taurus	M85/Methanol	$619.00
GM HY-Wire	Hydrogen	$804.00

batteries. The Tesla 220-mile range is more than adequate for most needs. However, the $100,000+ price tag is a stumbling block for many would-be electric car owners.

The DoD may be able to afford the price tag, but the performance substantially lags diesel or gasoline power. Energy density greatly favors carbon-based fuels. A lead-acid battery holds around 100 kilojoules/kilogram, lithium-ion batteries as much as 700 kilojoules/kilogram, but gasoline's energy density is 46,900 kilojoules/kilogram. However, as much as 85% of that gasoline energy is typically wasted in 15–25%-efficient combustion engines and gives delivered net energy of around 5,000 kilojoules for each kilogram of fuel. Even so, fuel burnt in combustion engines is about ten times better at storing and delivering energy than the lithium-ion battery.

To make a specific comparison, the 450-kilogram Tesla battery pack with 53-kWh capacity provides an energy density of 424 kilojoules per kilogram (1 kWh = 3600 kilojoules—see Appendix A). Assuming an average-energy-use efficiency of 90% for the Tesla system, the electric vehicle provides 171,720 kilojoules of useful energy per battery charge. Assuming a 20%-efficient-ICE vehicle burning gasoline with 46,900 kilojoules/kg, the gas vehicle needs only 18.3 kilograms of gasoline to equal the electric vehicle's energy delivery. One gallon of midgrade gasoline can provide about 132,000 kilojoules and at 20% efficiency delivers 26,400 kilojoules of useable energy. Therefore, 6.5 gallons of gasoline will deliver the same energy for the gas vehicle to use as one battery charge delivers to the electric vehicle. The 6.5 gallons of gasoline weigh about 43 lb, while the Tesla battery pack weighs about 900 lb. But that is not fair comparison for the electric vehicle, since the standard gasoline vehicle's engine, transmission, cooling system, and exhaust system will likely outweigh the electric-motor-battery-pack system. However, when compared only by system total energy delivered, a notional 15-gallon-gas-tank ICE vehicle gets about two-and-a-third times better range or endurance than the described electric power supply. This fact gives the battery (and other energy storage developers) a clear goal to surpass. A three-fold increase in electric energy density over the current lithium-ion battery pack will allow the electric vehicle not only to equal but to exceed the performance of the typical (15–25% efficiency) ICE gasoline burner.

Another potential electrical storage alternative are the various types of flow battery, which use liquid electrolytes stored in tanks to store charge, which is extracted in the battery's power cell [79, 80]. Such batteries can deliver power very quickly depending on the size of the power cell and the rate of flow of the electrolytes. In such systems the electrolyte can be recharged electrically, or the battery can be recharged by replacing the electrolyte. These batteries are not particularly compact nor energy dense and are currently employed by electrical power production load stabilization, where megawatts or many kilowatts of storage are needed, but volume is not a limiting factor. However, they have been demonstrated to be greater than 70% energy efficient [81] and can be charged and recharged many times.

5. Alternative Fuel Comparisons

Here are some basics about a few popular alternative fuels as compared to gas and diesel. Table 1 from Reference 82 shows the relative energy density for each of the most well-known fuel options. Note that the energy density for the second column in the table is in megajoules per mass, while the third-column energy density is given by volume.

The table reveals some interesting comparisons. The first four fuels are all gases at room temperature. They have high-energy content by mass, but are among the least energy-dense by volume (gallons or liters). Gasoline has higher energy per kilogram than diesel (a.k.a., #2 fuel oil). Because of diesel's higher mass-to-volume, diesel is the more energy-dense fuel per liter (or gallon) than either automotive gas or aviation gasoline.

Both gasoline and aviation gas are composed of short carbon-chain molecules with the relative quantity of eight-carbon-chain molecules determining the octane performance rating. Gasoline is more volatile and more easily sparked into flame and detonation than diesel. This makes them perform well in spark-driven engines and makes them more dangerous than diesel or jet fuel. Jet fuel is a kerosene-based fuel that shares characteristics with diesel in that they both have high concentration of molecules near or at 16-carbon-chain molecules. The quantity of cetane (16-carbon-chain hydrogen-saturated molecule) determines the performance rating of diesel. However, cetane above 60% does not appear to increase performance significantly [83].

The three alcohol fuels at the bottom of the table are noteworthy especially because of the rapid production rise of ethanol from corn and methanol from waste such as wood chips. Less well known by the general public, butanol, like the other two can be formed from bacterial fermentation. Butanol, however, has a significantly higher energy density, and does not have the corrosive effects on pumps, pipes, and engine seals that methanol and ethanol have. Butanol at 85% concentration can run in most any engine that currently uses gasoline and can be delivered by the same infrastructure without damage or special precautions. These butanol-deployment conveniences cannot be said of ethanol or methanol. Butanol is more toxic to the bacteria that produce it than ethanol and methanol are to their bacteria generators. This fact makes butanol somewhat more difficult to produce [84]. Because of the butanol advantages British Petroleum (BP) has begun a small-scale production project [85].

A potential biofuel of interest not mentioned in the table is 2,5-dimethylfuran. Researchers at the University of Wisconsin in Madison announced recently in *Nature* that they have developed a catalytic method to make this liquid from fructose, which is a sugar derivable from many plants [86]. The liquid has 40% greater energy density than ethanol, and it is not water soluble and does not absorb water as ethanol does.

6. Fischer-Tropsch Synthetic Fuel Generation

For many decades we have known how to produce synthetic versions of gasoline and diesel as well as alternative fuels, such as the alcohols and biodiesel. One mechanism previously mentioned, the FT process, is particularly worth examining for both positives and negatives [87–91]. FT was developed in the 1920s in Germany by the scientists for whom it was named and was used extensively by the Germans in World War II to produce diesel for the Wehrmacht since access to petroleum was largely denied them.

The FT process gasifies coal, biomass, and natural gas (methane) into a carbon-monoxide-and-hydrogen synthetic gas (syngas), which can then be recombined into a high-quality liquid fuel that can be engineered to desired specifications. A similar process exists called the Mobil process, which converts the feedstock into methanol as the intermediate building block before further engineering the desired fuel product. The Air Force has tested FT-natural-gas-derived JP fuel in multiple air platforms, including the B-1 and B-52. The fuel shows at least equivalent performance to standard JP, but the synthetic is mixed in 50% ratio with regular JP.

The FT process is energy intensive. FT can emit more carbon waste to produce the synthetic fuel than just burning petroleum-derived JP. The air force currently aims to meet half of its domestic-based fuel consumption needs by 2011 with FT-based JP. The result will probably be oil that's less expensive than JP derived from the $140-per-barrel oil. Desperate circumstances drove Nazi Germany in WWII and South Africa by SASOL under apartheid to develop substantial FT capacity to process coal to liquid fuel. Some significant improvements in FT processing have been made [92], but the environmental impact and limited ability to boost domestic production of natural gas suggest a better avenue through a complementary Defense Advanced Research Projects Agency (DARPA) program.

Using coal and FT poses several issues [2, 88]. The United States has perhaps 200 years of coal reserves at current consumption rates. However, switching to coal as a primary source of liquid fuel would cut that time to decades of reserves rather than centuries, while potentially causing tremendous pollution problems unless extensive and expensive carbon sequestration were employed. Also, FT plants are expensive, with entry level plant cost in the billions. China is pursuing a large effort on this path. China is spending $5 billion for a plant commissioned to produce 80,000 barrels of fuel a day (greater than $62,000/barrel/day). Typical oil refinery cost is about half that per barrel processed per day. To get toward 11 Mbbl/day (half our current use) would require on the order of $1 trillion. China is employing much of the workforce of the world competent to build such plants.

7. Renewable Fuels

Numerous alternative fuel options exist besides FT's coal-to-liquid synthetic fuel. Industry and government in the United States have a plethora of alternative fuel projects underway. Here are just a few to add to the Air Force projects already discussed.

Shell Oil has partnered with Virent Energy Systems to produce a synthetic gasoline from biomass [93]. BP, with partner DuPont, plans to produce butanol from bacterial-processing of biomass. BP and DuPont plan synthetic production of other fuels as well.

Still another company, Changing World Technologies (CWT), with an operating plant in Carthage, Missouri, uses the remains of turkeys from the nearby Butterball plant to produce #4 diesel [94]. CWT's plant powers itself from methane produced as part of the process. CWT uses a technology, called Thermal Conversion Process (TCP), to liquefy and depolymerize the feedstock by heat and pressure. The resulting product depends on the feedstock and processing parameters. Plastic, old tires, and pig manure are all particularly good feedstock. The diesel is being used at a local electrical power generation station. According to the joint DOE/USDA publication *Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* [95], even without counting conversion of food grain to fuel over a billion tons of waste biofeedstock is available in the United States yearly. One ton of high-quality waste can produce about 2 barrels of fuel. With a rough estimate of 1.5 billion tons of waste available annually from various sources including agriculture, sewage, and disposal of used plastic and other high-carbon trash, about 3 billion barrels of fuel could be generated yearly from TCP. The United States consumes about 8 billion barrels of petroleum per year. In addition, the high-carbon-content material already stored in landfills could be mined. Conversion of waste to fuel is particularly interesting because it addresses two important problems simultaneously-waste/sewage glut and energy shortages.

Other groups have competing technologies to turn waste into fuel and other useful petroleum products. Some examples include Global Resource Corporation (GRC), Texas A&M, and Green Power Inc [96–100]. The GRC technology uses a giant microwave to reduce material previously made from oil back into oil. Professors from Texas A&M developed a combined biological-chemical method to turn any biodegradable material into alcohols, which can be useful for a variety of purposes, including fuel. Their plant built at Bryan, Texas uses this process called MixAlco. Green Power Inc., uses a catalytic process at its plant in Washington State that can convert any high-carbon-content material into high-quality diesel fuel called nanodiesel. Green Power projected in 2006 that it could sell diesel profitably at under a dollar a gallon. Their technology as CWT's could be used to mine landfills and convert any high-carbon-content waste to high-quality diesel and with some upgrades could also produce gasoline.

Los Alamos has announced a concept called GreenFreedom which would use a newly-developed electrical-catalytic process to extract carbon dioxide from the atmosphere and convert it into designable fuels [101].

University of Maryland professors Steve Hutcheson and Ron Weiner have created a process to convert plant products from any cellulosic source into biofuels [102]. Called the Zymetis process, it is derived from a Chesapeake Bay marsh grass bacterium, which the scientists found has an enzyme that converts plant materials into sugar. Unable to isolate the bacterium in nature, they discovered how to produce the enzyme responsible for the conversion. This chemical they named Ethazyme in a one-step process dissolves cellulosic-material's (e.g., switch grass, algae, seaweed, wood chips) cell walls and converts the result into sugars. The sugars can then be used as feedstock for alcohol fuel generation.

Other biomass options also exist. Jatropha, a perennial bush, produces poisonous seeds rich with oil that can be extracted for fuel. The plant grows in marginal soil with low water need after the plant is established. However, some concern exists that jatropha will be cultivated by Indian and African farmers on prime farm land for profit of big companies at the cost of eliminating that land's use for desperately needed food crops.

8. Algae—A Notable Renewable Fuel Source

Algae, the original source of petroleum, can produce various renewable fuels. Algae grow very densely. Certain species of algae consist of as much as 50% oil. Enough algae feedstock to replace U.S. fuel needs could be grown in an area roughly 250 miles by 100 miles in open ponds on marginal land, such as in the U.S. desert southwest. But algae grow just about everywhere, and local varieties tend to displace the special high-oil-content algae, the best fuel feedstock. The less expensive means of growing algae in open-air tanks is problematic because of the threat of contamination. However, some are pursuing options to grow algae in enclosed silos or other such containers that expose algae to the required sunlight and perhaps enhance its growth by feeding it such as with carbon exhaust from coal-fired electric power plants.

A DARPA/Air Force joint effort is aimed at producing standard JP 8 fuel from biomass such as high-oil-content algae [36, 37]. The prime executors of the project are the DOE Sandia Laboratory and the Honeywell Company, UOP.

PetroSun Biofuels has started an algae farm in Harlingen, Texas, in a salt-water swamp and plans more farms in Alabama, Arizona, Louisiana, Mexico, Brazil, and Australia. PetroSun will ship the product to refineries to make biodiesel or biojet fuel [103–105].

Valcent Products Inc., and Global Green Solutions, in a joint venture, built a facility in Anthony, Texas, that is growing algae in an enclosed environment [106, 107]. Inside tall stacks of transparent, water-packed plastic bags that reside inside a greenhouse, the algae grow as the water is continuously circulated throughout the system of plastic bags. Algae are continuously extracted from the water. The system, because it is enclosed, can breed any particular type algae desired which fact allows for adjusting the algae crop to the desired fuel product. Thus algae production can be tuned to produce diesel, jet fuel or other petroleum products.

Algae are the premier renewable "crop" in growth density. Corn with the stover may be able to produce 1300 gallons of ethanol per acre per year. Soybeans and palm oil plants can yield respectively, about 48 gallons and 630 gallons of oil per acre per year, and pond-grown algae about 10,000 to over 15,000 gallons. The Valcent entrepreneurs project that they can produce 100,000 gallons of algae oil per year per acre. According to this projected production, about 13.6 million acres of algae would replace the entire world fossil-petroleum production of 88 Mbbl/day (about 32 billion barrels per year). To replace the U.S. military's 300,000 barrels per day using Valcent technology would require about 46,000 acres which is one-and-a-half times the size of Disney World.

A San Francisco company, Solazyme, approaches the use of algae for fuel production differently [108, 109]. They grow algae without sunlight in stainless-steel containers. The algae feed on sugar and produce a range of different types of oils which can be converted into different sorts of fuels. Because the algae grow in the dark and are fed sugar to grow rather than relying on sunlight and photosynthesis, the algae produce more oil and can be more densely grown than in ponds.

The use of densely and/or inexpensively grown algae to produce fuel could allow every nation to be a fuel producer and could eliminate the expense, risk, and ecological impact of drilling for oil or importing it. The technology to replace petroleum with algae-based products is neatly in hand. The question of whether an algae industry can deliver economically on a large scale remains to be demonstrated.

9. Hydrogen Fuel (or Zinc, or Aluminum, or Ethanol, or Compressed air, or Nitrogen, or…)

Some General Characteristics. Hydrogen concentration in the atmosphere is 500 parts per billion. Hydrogen readily and explosively combines with oxygen to release energy. There's no place on Earth to "mine" hydrogen in a form that is ready to use as an energy source [110]. Some energy-expending process must be used to get hydrogen into energy-currency form. Typically hydrogen is obtained from hydrocarbons by chemical or biological reactions, or from water by hydrolysis (high- and low-temperature techniques exist), or high-temperature steam forming [111].

However, using hydrogen as a fuel on an industrial scale has many fundamental issues that have not been resolved. Current industrial production capacity of hydrogen is not sufficient to meet the orders-of-magnitude increase necessary to supply the scale of demand required to replace current fuels. Hydrogen transportation is impeded by its being a gas at room temperature, and large volume must be sent to provide significant energy, by its embrittlement of metal pipes used to transport it, and by the high infrastructure and energy cost to convert it to liquid for storage and shipment [112].

Because hydrogen is a gas, its energy density by volume is very small. Even when hydrogen is converted to a liquid, it is only 25% as energy dense as gasoline. Liquid hydrogen has fewer hydrogen atoms per gallon than gasoline or diesel. For all these reasons, an automaker of a fuel-cell-powered car would tend to use standard petroleum fuel and extract the hydrogen from the hydrocarbon. Even though fuel-cells are perhaps 30% more efficient than ICEs, today they are technically, logistically, and economically challenged compared to the ICE or batteries. Hydrogen-fuel-cell cars currently are sold only by Honda and, in the United States, sold only in southern California where hydrogen filling stations exist.

Storage. The DOE funds research projects to improve hydrogen energy storage with a goal of 6% by weight hydrogen to storage system [113]. The DOE Hydrogen Program reports funding approximately 70 hydrogen storage research projects in 2007, some related to using metal hydrides as the storage mechanism about 80% of these at the DOE Metal Hydride Center of Excellence at Sandia National Lab and a similar number of projects in their Chemical Hydrogen Storage Independent Projects.

Through the DOE Hydrogen Sorption Center of Excellence at NREL, over a dozen projects examined such things as aerogels and nanotubes for hydrogen sorption storage. Another 20-odd projects explored various other storage concepts and issues including advanced compressed gas and cryogenic storage methods, storage using new materials such as glass microspheres, and storage safety issues.

Other storage examples not in the DOE list include using tiny quills from chicken feathers as suggested by Dr Wool at the University of Delaware [114], or using fullerenes. Rice University researchers showed how hydrogen could be compacted into 60-carbon fullerenes [115]. The researchers concluded that as many as 58 hydrogen atoms could be contained within the 60-carbon cage—a density that would exceed DOE's goal of at least 6% by weight hydrogen/absorber ratio. However, the H58C60 buckyball is also a hydrocarbon which if burned has energy comparable to other hydrocarbons and still produces greenhouse gas. Despite all of this research the current standard is to use compressed gas at about 750 bar which makes for a volumetrically challenged energy source.

Distribution. Hydrogen distribution is daunting. There is a single hydrogen-dispensing fuel station in Washington, DC, run by Shell. Southern California has a number of hydrogen stations. Honda plans to market (for lease) their FCX hydrogen fuel cell vehicle in southern California because this is the only place of significant public availability to hydrogen refueling. Hydrogen transports most inexpensively through gas pipelines. About 700 miles of hydrogen pipelines exist today compared to the million miles of natural gas pipelines. Using natural gas pipelines could immediately provide an infrastructure for distribution, but hydrogen embrittles the metal. Compressed hydrogen at 3000 psi (200 bar) travels in tube trailers via truck, rail and water vessels. Investigations to improve transport currently explore a safety sanction for 10,000 psi to improve efficiency and reduce cost. For long range transport hydrogen is liquefied and stored in cryogenic tank trucks. Liquification and cryogenic storage are expensive and energy intensive. The current lack of good options for transport drives the need for research into other storage and transport mechanisms [110–113, 116].

Production. Hydrogen is produced on an industrial scale to make ammonia for fertilizer, to hydrocrack petroleum, and as an essential ingredient in domestic steel production. But the scale of production required to replace petroleum is enormous in comparison [111]. The DOE's 2007 hydrogen program reports on about 70 projects investigating various mechanisms for hydrogen production in ten categories. These categories include hydrogen distributed production from natural gas and bioderived liquids, production from electrolysis, from biomass gasification, from solar high-temperature thermochemical water-splitting, by photoelectrical chemical (e.g., a material such as a semiconductor reacts with water in the presence of sunlight to separate the hydrogen from the water), from biological processes, from coal, by nuclear power, and by a category called "crosscutting," which included work in hydrogen fuel cells [113]. Simple electrolysis is the least efficient mechanism to produce hydrogen. High-temperature versions—such as might be enabled by high-temperature (800–1000°C) nuclear reactors—are much more efficient [111, 117–119].

Getting Hydrogen From Solar Power and Water? Distributed production would mitigate distribution and storage problems. A common question arises, "Could hydrogen production be dispersed such that people make hydrogen at home from water via electrolysis?" If this form of hydrogen production were viable, electricity with an already well-established distribution system would serve as a means for hydrogen distribution. Thus, hydrogen could be produced remotely on demand. The electricity could come from traditional power plants, such as coal and nuclear or from renewable and perhaps distributed electricity sources, such as solar and wind power.

As mentioned above, DOE funds many paths to hydrogen production, including using photovoltaic power from the sun. One DOE study from 2005 [120]—which specifically addressed solar- and wind-generated electricity as the means to produce hydrogen—was not very positive based on electrolytic capability of the day. However, a recent MIT announcement of a new kind of artifical photosynthesis, as explained in *Popular Mechanics*' August 2008 issue, might be the long-sought enabler for hydrogen production from solar power [41].

Solar power must have some concurrent mechanism to store energy because the sun does not always shine, nor always with the same level of ground-incident power. Hydrogen conceivably could fill that need. Solar-panel energy-conversion efficiency varies widely by price, but 20%+ efficiency is found in the highly expensive governmental-use-in-orbit sort, but less than 10% efficiency for the more mundane variety. To produce a kilogram of hydrogen requires about 50 kilowatt-hours of electrical energy. In good conditions, the sun provides about 1 kilowatt instantaneous power incident per square meter. A 10-meter by 5-meter array of solar panels producing electricity for 1 hour at 10% efficiency would provide 5 kilowatt-hours. With good weather conditions at optimum latitude at the right time of year, that size solar panel array may be able to generate 50 kWh per day. That much solar-provided electricity would supply, via electrolysis, 1 kilogram per day of hydrogen. The energy in one kilogram of hydrogen is about the same as the energy in one gallon of gasoline. Conceivably, in 15 days of ideal conditions, the solar array could make enough hydrogen to equal the energy contained in a car's full 15-gallon gasoline tank. For those who don't drive much, this might be sufficient, but probably not for most.

However, as previously noted, MIT researcher Daniel Nocera published results in *Science* magazine in August 2008 that seem to demonstrate a highly energy-efficient mechanism to use a cobalt/phosphate catalyst to electrolytically split water molecules at neutral ph and room temperature and pressure into constituent gaseous hydrogen and oxygen molecules [42]. This development, as announced by MIT News, could completely change the equation. However, the engineering tasks remain undone to apply this new scientific discovery [121].

If the Nocera discovery can be engineered to increase electrolysis efficiency sufficiently so that a household's photovoltaic array could produce enough electricity in the day to run the house and simultaneously extract enough hydrogen to generate the 6–10 kilowatts required by the household at night by use in a fuel cell or high-efficiency engine, then the world could conceivably convert largely to solar power. This prospect becomes especially attractive as the price for solar arrays drop to a dollar a watt (see note in Solution 6). However, as of today in 2008, engineering to produce hydrogen from solar-electric power is not viable.

Use in Fuel Cells. Fuel cells and the use of hydrogen, however derived, are worth special mention. ICEs generally have efficiency of 20–25% or less, even with a theoretical maximum efficiency of 60% for an Otto cycle. Fuel-cell maximum theoretical efficiency exceeds 80%, but in practice, current automobile fuel cells run at about 35%. Today's fuel-cell systems do not compare well to ICEs in energy per mass. Nor do they compare well to electric-motor/battery systems. The theoretical achievement of 80% efficient- hydrogen-fuel-cells, even with the factor-of-four disadvantage in energy volume-density compared to gasoline, would make a 15-gallon hydrogen-fuel-cell system comparable in endurance to a 15-gallon gasoline-burning-ICE.

10. Nuclear Fission Technology [122–127]

Thirty-one countries worldwide currently operate a total of 441 nuclear-fission-reactor electric power plants. Outside the United States, an additional 32 plants are under construction. The United States has 104 commercial nuclear-fission power plants. The U.S. plants provide about 20% of the nation's electric grid power. In addition, the U.S. Navy has built and run about 250 nuclear-fission power plants in deployed ships and submarines, and training and development sites.

Fission power plants run as heat engines, with fission-released radiation generating the heat. Generally, reactors use Uranium-235 or Plutonium-239 as fuel. Over 99% of Uranium is Uranium-238 (which is not in itself a fuel), less than 0.01% is U-234, and about 0.7% is U-235. However, when bombarded with neutrons, U-238 can be "bred" into Plutonium-239, which is a spontaneously fissile material and a good nuclear fuel. "Enriched Uranium" is made by increasing the U-235 content relative to the U-238 content. "Depleted uranium" has the U-235 isotope removed from the U-238 portion, which is the so-called depleted uranium. Other artificial isotopes exist and are important. Breeder reactors are designed to produce Plutonium-239 and can expand the fuel supply. Although natural quantities of U-235 for reactor fuel use are estimated to last about 1500 years, U-238 quantities, when used as a breeder fuel, have been projected to last beyond 10,000 years [122–126]. Thorium-232 has been proposed as a fuel. It absorbs a neutron under bombardment and beta decays ultimately to U-233, which is itself a nuclear fuel with a half-life over 100,000 years. Thorium-232, although 400 times more plentiful than U-235, is generally not used as a prime fuel in power plants [127]. Germany built a 300-MW Thorium pebble bed reactor but shut down the reactor for technical reasons after a year.

In general, reactors comprise seven major components. The nuclear fuel produces heat energy from fission, which converts water to steam. The steam drives a turbine that turns an electric generator. About 60% of the reactors today use U-235 as fuel. A metallic fuel cladding protects and contains the fuel. A moderator slows high-energy neutrons to levels under 1 electron-volt (eV) (used in "thermal" neutron reactors—see more below). The coolant material captures the heat and imparts it to the water for the steam turbine. Neutron-absorbing-material "control rods" modulate the rate of fission and, if fully engaged, shut the reactor down. A pressure vessel prevents radiation release from overpressure. Finally, a containment structure shields the external world from the radiation produced in the reactor.

Nuclear-fission power plants are designed and classified by neutron speed (energy): slow neutrons (less than 1 eV of energy), intermediate, and fast neutrons (millions of electron-volts). The intermediate speed appears suitable only for thorium reactors. The slow-neutron reactors use a moderator to slow down fission-produced neutrons so that they are more easily captured by U-235, which will then continue the fission cycle. The fast-neutron reactors require enriched uranium or plutonium and do not use a moderator. They are designed to have U-238 capture the high-speed neutrons, which starts the decay to produce plutonium and sustained reaction while "breeding" plutonium. In reactors, fissile uranium releases neutrons and radiation energy. The neutrons collide with other uranium atoms and cascade the fissions. The fission rate and quantity of material in fission determine the radiation energy level. A nuclear explosion requires a special set of circumstances and configuration that a power plant cannot achieve. Uncontrolled fission cascade in a power reactor can raise the temperature and possibly melt the core, but will not detonate.

Most reactors are thermal neutron reactors, which use some type of moderator to slow neutrons to "thermal" energy. Moderators include graphite, heavy water (deuterium water), light water (common distilled water), molten salt (a Gen IV concept—see Appendix C), liquid metal, and organic moderators (e.g., biphenyl). The liquid metal reactor allows higher energy density than other coolant/moderators and was first designed for submarine use. Metals used include sodium, sodium-potassium alloy, lead, lead-bismuth eutectic, and mercury.

Reactor coolant, depending on the design, can be the same or different from the moderator. In addition to the moderators mentioned, reactors can use gas (helium, nitrogen, and carbon dioxide) coolant. The water-cooled reactors come in three designs—pressurized water, boiling water, and open pool. Each has advantages and disadvantages.

Appendix C provides a summarized look at nuclear fission technologies and issues. For additional information, a 2003 MIT study entitled "The Future of Nuclear Power" [125] gives great insight into the technologies and issues of nuclear fission power. The MIT study noted that wide-scale use of nuclear energy to replace fossil fuel presents complex problems. Nuclear-power-plant initial cost compares poorly to any other conventional power plant type. Nuclear plant safety is inherently complex. The study states "the management and disposal of high-level radioactive spent fuel from the nuclear fuel cycle is one of the most intractable problems facing the nuclear power industry…" The MIT study suggests that nuclear power expansion should not proceed "unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small. Finally, the MIT study concluded that "nuclear power will succeed in the long run only if it has a lower cost than competing technologies."

11. Nuclear Fusion—Magnetic Confinement Fusion

References 50 and 51 provide an overview of the current state of mainstream fusion programs and technology. Most fusion research funds Maxwellian-distribution plasma confinement with magnetic devices (e.g., the tokamak project at Princeton and ITER) that use various configurations of electromagnets to contain tritium–deuterium plasma. The system pumps energy into the plasma until the nuclei can overcome the Coulomb barrier (electrostatic positive-charge repulsion of positive charge) and fuse . These "magnetic bottle" devices follow the concept of the Russian original tokamak (a Russian acronym for their fusion project).

When a tritium atom fuses with a deuterium, the result is a helium atom, a high-energy neutron, and 17.6 MeV. Other elemental atomic species can be used, but the energy required to produce fusion is higher for other species. Lithium Deuteride, He-3/He-3, Lithium-6/Lithium-6, and Hydrogen/Boron-11 pairs each have specific advantages as fuel. See more on H/B-11 below.

In 1997, the Joint European Torus (JET) produced 16.1 MW for less than a second and thus achieved an output of 65% of the total power put into the device. The JET did not reach break-even power output, even for this short span of time, but achieved the current record output for magnetic confinement fusion. The International Thermonuclear Experimental Reactor (ITER) is a planned magnetic plasma confinement experiment designed to achieve more energy out than input (ten times more peak power and five times more steady-state power) [128]. The ITER-expected costs range from $7.6 billion to $9.3 billion. The planned schedule shows 10 years of construction and 20 years of experiments. The ITER program plans no actual electric power generation—only thermal power for scientific and engineering research. The United States, Japan, China, European Union, Russia, Republic of Korea, and India have joined the ITER agreement, which went into force in 2007. Plans call for a follow-on device based on lessons learned from ITER. DEMO, as it is called, would be the first nuclear fusion electric power plant [129, 130]. DEMO would start operation in 2050.

Unlike nuclear fission—which has a multibillion dollar, power-producing industry; hundreds of working electric plants across the world; U.S. naval vessels safely powered for decades; and multiple, ever-improving designs for advanced reactors—net fusion power through the official DOE planned program is decades away.

12. Nuclear Fusion—Inertial Confinement Fusion [131, 132]

As part of its nuclear Stockpile Stewardship Program, DOE does research on producing fusion by concentrating extremely high-power laser or particle beams for nanoseconds onto a small pellet of fuseable material. This research also may provide useful insight into fusion power production and other high-energy particle physics. It is not principally a power-production research program but seems often to be confused as such in public discussion and reporting.

13. Nuclear Fusion—The Farnsworth-Hirsch Fusor [133]

The DOE and international groups have invested hundreds of millions of dollars and decades on the tokamak approach. If all works well for the ITER, a fusion power plant will come online in 2050. However, a device derived from the Hirsch-Farnsworth fusor may enable operation of a fusion power plant to begin by 2015—or earlier.

Philo T. Farnsworth invented the electron tube technology that enabled television. He also discovered a technique to produce fusion with a sort of electron tube. The basic concept of the machine is the confinement of energetically injected nuclei into a chamber containing a positive grid electrode and a concentrically interior negative grid electrode. The injected particles fly through a hole in the outer grid and accelerate toward the inner grid. Nuclei fuse when they collide with sufficient cross-sectional energy in the center of the machine. Particle-grid collisions limit obtainable output power. This fusion method is known as Inertial Electrostatic Confinement Fusion (IECF). Robert Hirsch joined Farnsworth in his lab and developed a more advanced version of IECF, which uses concentric spherical grids.

Tuck, Elmore, Watson, George Miley, D.C. Barnes, and Robert W. Bussard have extended the research. Many people have developed "fusors" (including a high-school student), which produce fusion from deuterium-deuterium reactions but do not produce net power. These devices have been used as compact neutron sources.

14. Nuclear Fusion—Bussard Polywell Fusion

Dr Robert W. Bussard published results in 2006 claiming that he had achieved 100,000 times better performance than had ever previously been achieved from an IECF device [134–136]. Bussard's machine replaces the physical grid electrodes with magnetic confinement of an electron gradient known as a "polywell" that accelerates the positive ion nuclei into the center of the negative gradient. His paper in the 2006 proceedings of the International Astronautical Congress states that he had developed a design based on his previous success that, if built, would produce net power from fusion. Bill Matthews's article in *Defense News* covered the story in March 2007 [137]. In November of 2005, the machine achieved 100,000 times greater performance than any previous fusor. Analysis of those experimental results led Bussard to conclude that his design will produce net power. Bussard's company, EMCC, continues his work since his death in October 2007. Alan Boyle at MSNBC.com covered recent developments at EMCC [138] in an online column in June 2008, and Tom Ligon, former Bussard employee, wrote a combination history and technical description published in 2008 [139].

Bussard referred to his confinement mechanism as "magnetic grid" confinement. The system has no actual, physical electrode grids, such as in the Farnsworth-Hirsch machines. In Bussard's concept of a net-power-producing machine, the high-energy fusion particles produced from fusion would directly convert their energy to electricity. The high-energy charged particles resulting from the fusion will fly toward an electrical-energy-capture grid (not used for particle confinement) and expend their energy by being decelerated by this grid, which will be tuned to the energy and charge of the fusion products. The high-energy particles need not actually impact the grid and heat it. Rather, they can decelerate as the electrical grid extracts energy from the charged particle's motion, thus "pushing" a voltage onto the grid and yielding direct electric power from the fusion. About 25–35% of the power in this type of device will be in bremsstrahlung power, which will have to be thermally converted. The total power efficiency will probably be in the 60–75% range.

One of the great advantages of IECF is the potential to use boron and hydrogen as the fusing elements. In a Bussard fusor, a sphere—with a strong magnetic field imposed on it and electrons injected into it—would develop a gradient of those electrons, such that the center of the sphere would appear to a positively charged particle as if it were a negatively charged electrode (somewhat like the electrode grid of the Hirsch-Farnsworth device). Positively charged nuclei of boron and hydrogen would be injected at appropriate angles into the sphere and would "fall" into the negative well of electrons toward this virtual anode at the center of the sphere. If the particles do not collide with each other, they will fly an oscillating path within the vessel by alternately traveling toward the center of the sphere and then out toward the sphere limits until the force of the "virtual" negative electrode at the center of the sphere again attracts the positively charged nuclei toward the center again. If the virtual electrode has sufficient power (about 156 kilovolts for boron/hydrogen fusion), when the hydrogen and boron nuclei collide, they will fuse. A high-energy carbon atom will be formed, which will instantly fission into a helium nucleus with 3.76 million eV of energy and a beryllium atom. The beryllium atom will instantly divide into two additional helium nuclei, each with 2.46 million eV of energy. Boron and hydrogen, when fused in this matter, produce 6.926 E13 joules/kilogram.

To place this ability in context, the United States consumed from all sources (e.g., nuclear, fossil fuel, and renewables) in 2007 approximately 107 exajoules (E18 joules). One hundred thousand kilograms of boron-11 with the proportional amount of hydrogen (which would be vastly smaller than the amount required for a "hydrogen economy") could produce about seven times more energy than the United States consumed from all sources by all modes of consumption in 2007. Therefore, (assuming 100% efficiency for simplicity's sake) about 120 metric tons (not 100 tonnes, because only boron-11, which is 80% of natural boron, gives the desired fusion with hydrogen) of amorphous boron would provide equivalent power for all U.S. energy needs for over 6 years. About 1.8 million metric tons of boric oxide (about 558,000 metric tons of boron) were consumed worldwide in 2005, and production and consumption continue to grow [140]. The United States produces the majority of boron yearly, although Turkey reportedly has the largest reserve [141]. At $2 per gram for 99% boron, the cost in raw boron to produce six times the United States 2007's energy supply (not just utilities but *all* energy) would be $240 million (120,000 kilograms × $2.00/gram)—6 years worth of U.S. power for a little more than the price of coal to run one coal-fired power plant for 1 year.

If a Bussard power plant consumed one gram of boron-11 per second, this fusion rate would produce approximately 69 gigawatts, roughly the simultaneous power output of 69 major electric power generating plants—more than one tenth of all coal-plant power generation in the United States. About 320 kilograms of boron-11 fuel ($640,000 worth of boron) at one of these fusion plants would provide 1 year's continuous power output at 700 megawatts. A typical coal-fired electric utility power plant nominally produces 500 megawatts of electricity, but it requires about 10,000 short tons of coal *per day* (a short ton is only about 91% the size of a metric ton). A short ton of coal for electric utilities cost around $56 in 2008. So, one day's worth of coal for a single coal-fired plant cost about $560,000, and a year's worth for a single plant cost over $204 million. The United States has approximately 600 coal-fired power plants, about 500 of which are run by utility companies for public power. A 500-gigawatt (or even larger) Polywell fusion plant (which could cost less than $500 million to build) built to replace a coal-fired plant will pay for itself by coal-cost savings in less than 3 years of operation if the charge per kilowatt-hour remains constant. Because the fusion plant has fewer moving parts and fewer parts in general, it should be less expensive to maintain and operate as well.

Over the past year, Bussard's Company, EMCC, has built a new device to verify and extend the 2006 results. Contingent on continued funding, a prototype power plant with 100 megawatts of net power production could be built at a cost less than $300 million, and producing power within 5 years—perhaps as early as 2015. Because of the nature of this device, the power output versus input is directly proportional to the seventh power of the radius of the containment sphere. A 100-megawatt power producer requires a sphere about 3 meters in diameter. A gigawatt power producer would require a sphere approximately 15–20 meters in diameter. EMCC's decade-ago designed machine size for a 100-megawatt generator to power a naval vessel is a cylinder about 20 feet in diameter and 30 feet in length.

With no way to convert a Bussard Polywell machine to a bomb, no radioactive waste produced, small relative size, ability to operate on abundant boron and hydrogen fuel, relatively inexpensive to build, and only moderate operational safety issues (high voltage and X-ray emission during operation), these machines offer a path to a magnum advance in civilization; elimination of the carbon emission aspect of climate change; a whole new realm of platform propulsion capability and deployed electricity abundance for the U.S. military; and abundant, inexpensive energy for all who adopt its use. These machines could be exported worldwide without concern that they would proliferate nuclear bomb technology.

15. Getting Off the Grid & Less-Tethered Logistics—Solar Power and Distributed Fuel Production

Some options on improving security robustness include finding ways to not be tied to a grid. Relieving the tether to a grid must address providing not only electricity to homes and facilities, but also vehicle fuel. Distributed solar power and alternative fuel production offer an opportunity to distribute power production and eliminate distribution bottlenecks.

As solar cells decrease in cost and increase in energy conversion efficiency, at some point they may be so economically attractive that many U.S. households will start installing them as their primary power. Coal-powered electricity currently costs 5 cents per kilowatt-hour. As reported in the June 21, 2008, *Economis*t magazine [29], the cost of a kilowatt of solar photovoltaic power went from 50 cents in 1995 to 20 cents in 2005 and continues the downward slope. In comparison, wind power costs about 8 cents per kilowatt-hour. Large-scale wind farms require a grid, but single-building windmill generators and building-mounted photovoltaic cells do not require the electric grid to power that building.

Various researchers have recently announced breakthroughs that should increase photovoltaic power-output efficiency, lower cost, and make production and deployment easier. Photo cells with greater than 40% conversion efficiency have been demonstrated [142], while less efficient cells are being produced in mass quantities that will potentially drive the cost of solar power below that of coal power production [143]. The renewable industries are making steady advance toward cheaper-than-coal electricity.

The solar industry is only a tiny fraction of the current national power production, but is growing by 50% per year. But just as the wind doesn't always blow, the sun doesn't always glow. To free facilities from the grid with solar and wind power, some commensurate improvement in electricity storage must emerge—also at affordable prices. However, even if only daytime solar power were available, cost of additional utility power backups could be reduced.

Let's examine the numbers for solar energy requirements for a simple example—a home. A forward-deployed, solar-powered military unit away from easy-access fuel logistics might be comparable to a home. Homes in an area where grid power had been shut down or otherwise not available would be the exemplar for not having to rely on the power grid. A large, all-electric house at maximum power consumption would need 12 kilowatt on-demand production. A 5-meter by 10-meter solar panel array, which could easily fit on most home roofs, could produce that much power if the array could achieve 24% conversion efficiency. Current technology for commercial photo cells is less than 10%. But let's assume the homeowner could deploy a 15-meter by 15-meter array that, even at 6% efficiency, would produce more than enough power when the sun is shining. Sun certainly does not always shine with 1.5 kW/m^2 ground incidence, as in ideal circumstances, but various options exist for electrical storage, and technology will improve. Assuming 12 hours of 1 kW/m^2 daylight, to enable the residents with 6-kW consumption through the night requires 12 hours × 6 kW = 72 kilowatt-hour storage.

Lithium batteries could certainly accommodate that requirement, but they are expensive. Flow batteries and fuel cells are options. Perhaps ultracapacitors, as previously mentioned in the electric-vehicle section, will soon be available at a price that would enable large-scale use. Storage mechanisms continue to improve in performance and price. The MIT-Nocera potential breakthrough in hydrogen production from water may be the needed enabler in energy storage to make solar power predominate [41, 42]. The research has suggested the promise, but an engineered prototype is an undetermined time away.

Another example of useful progress in photovoltaics comes from MIT researchers, who reported this year a mechanism to capture sunlight in a window-like solar concentrator that consists of a plastic or glass plate coated with a light-absorbing dye [144]. The light entering the window is absorbed by the dye and re-emitted toward the edges of the window, where it can be converted to electricity by photovoltaic cells. The window acts as a solar collector/concentrator that does not need to mechanically track the sun's motion. Others have proposed photo cells that could achieve 80% electrical conversion efficiency [145].

With the combination of extremely high-efficiency energy conversion and a mechanism to collect light from a large area created by the marriage of these two technologies, one could transport power over long distances via laser. Example military uses could include beaming power via high-efficiency laser on nuclear-powered naval vessels and charging, with the laser light, an unmanned vehicle's electrical storage unit. An unmanned vehicle could thus deploy indefinitely as long as the laser could periodically hit its recharging, light-collecting window with enough laser power. This concept gives another look at going around the typical power delivery infrastructure.

What about distributed fuel production? Algae grow everywhere. Everywhere people live, they make waste streams of sewage and garbage that can be turned into fuel. Technologies previously discussed (e.g., CWT and/or Green Power, Inc.) could generate diesel, and perhaps gasoline as well, from waste and from algae. The processing technology is not that of the typical refineries used for petroleum. Such fuel-production technologies could be built in many sites across the country to take advantage of the waste streams and distributed growth of algae. If fuel were produced from distributed inputs in towns and cities across the nation, production and distribution vulnerabilities from the infrastructure bottlenecks just about disappear.

ADOPTING SOLUTIONS—A TOTAL SYSTEM'S APPROACH

As previously discussed, the total scope of defense and energy security is broad and complex. The DoD faces internal strategic, operational, fiscal, and environmental challenges, such as the military implications of climate change in operational tempo and force structure, as well as mitigating energy infrastructure vulnerabilities both for its own assets and the nation's. Further, the nation and DoD, as a consequence, are impacted by the economic drain of high oil prices and the bondage to foreign oil, the possibility of denial of access to foreign oil, broader infrastructure vulnerability, and the homeland security implications of climate change. Energy security is complex and cross-disciplinary in nature, and requires the coordinated application of various solutions. Let's examine a set of options informed by the solution set just discussed that can address all of these requirements.

More Fossil Fuel

One approach to getting additional energy is to mine more fossil fuel by converting coal to fuel and by drilling for more oil and natural gas. This tactic will produce energy sources. Whether the cost of energy would be substantially reduced is not certain. The demand from China, India, and other emerging societies could swamp any such fossil-fuel, supply-side increases for a fundamentally nature-limited resource. Both oil and coal are finite commodities. The required time to develop a new oil field is not exact, but projections [12] suggest 5 to 10 years for significant new amounts of oil reaching the market as a new reserve is explored. The cost of converting coal to oil could wash out any financial benefit and more rapidly deplete the known coal reserve. The FT process would require carbon sequestration to prevent a huge increase in fossil-fuel-based carbon emissions and would raise the price for the fuel produced.

Efficiency

Less energy would be required by using it with greater efficiency. Current automobiles and trucks achieve about 20–25% efficiency of energy use. Converting fossil fuel to electricity consumes about 64% of the quads available in the fuel. Certainly, for vehicles, multiple options can improve fuel efficiency: to at least 50% with new heat engines, perhaps 60–80% with fuel cells using alcohols or even current fuels, and as much as 95% with all electric vehicles. Efficiency in airplane fuel consumption (airplane consumption is a tenth that of the car and truck fleet) can also improve by at least 30% and perhaps double in efficiency. The technologies are no longer research, but require significant investment to make them commercially abundant and affordable. The potential impact of a low-cost, high-energy-density electrical storage mechanism (such as the reported ultracapacitor from EEStor) cannot be over emphasized. All ground vehicles could quickly evolve to all-electric power, and some issues related to stationary power from renewable sources would resolve. Upgrading coal/gas power plants to combined-cycle power production can increase electrical-energy production efficiency.

The U.S. military could play the key role in making these investments for vehicles and become the first to derive the benefits in improved operational capability at lower cost and less logistics burden. This tactic will help alleviate infrastructure vulnerabilities and perhaps mitigate climate change effects the military would have to prepare to handle.

Renewable Fuels

Many renewable fuel options could service the task of developing renewable energy sources for fuel and electric grid power. Brazil has already shown that a large country can achieve oil independence with renewable fuel. However, governmental supervision must ensure that approaches to renewable fuel do not, in themselves, harm the environment and do not deplete or drive up the cost of other crucial commodities, such as food grains and, therefore, must not monopolize land needed for food crops. Various approaches to turning waste into fuel and to producing fuel from algae offer potential abundant, inexpensive petroleum substitutes. If the military and government help to develop this industry by providing an assured demand at an acceptable price to both fuel consumer and provider, the industry should be able to quickly (less than 15 years) fill the reduced demand achieved by increased efficiencies.

In 2008, wind power is still about 60% more costly than electricity from coal plants. Solar power is over twice as expensive as wind power. But the technologies are improving, and the costs to produce power are plummeting. The potential for distributed power—which removes customers and facilities from dependence on the grid—is, in itself, a huge security boon that could help alleviate infrastructure vulnerability problems.

Photovoltaic power could be particularly valuable to the military. Especially as conversion efficiencies increase, the military could use high-energy lasers to deliver power to unmanned vehicles and other remote locations. All-electric vehicles with high-density storage could stay deployed or engaged in mission indefinitely as long as they could replenish charge from time to time by laser via their photovoltaic arrays. Emerging approaches to photovoltaic technology suggest the possibility of 80% conversion efficiency per cell. An interesting synergy might derive from using the MIT window-light-gathering unit combined with the high-efficiency photovoltaic converters to provide a compact power array, while most of the area it occupies on the surface of the vehicle can also be used for radio frequency sensors or communications arrays.

A market with government incentives could quickly make wind and/or solar preferred electricity providers for various applications.

Nuclear Energy-Polywell Fusion

The use of nuclear energy can be expanded by developing and deploying the Polywell machine. Nuclear fission technology has unresolved challenges: potential for weapons proliferation and nuclear terrorism, continued international stress and military requirements from trying to prevent nuclear weapons proliferation, nuclear accidents at power plant and processing sites with potentially catastrophic results, long-term waste storage and environmental contamination, and the high cost for plants and slow return on investment. Polywell fusion avoids all these issues.

As far as can be determined without actually building a fully power-producing nuclear fusion plant of the Bussard Polywell kind, this technology has been demonstrated and is being developed. A Polywell power-producing plant that uses non-polluting boron-11/hydrogen fusion should be constructed and operating by 2015—according to current plans. Proliferation of this technology will not threaten the U.S. security from nuclear bomb proliferation and would remove an excuse for rogue countries to claim that they need to develop fission power for commercial uses.

Summary Solutions

In summary, the U.S. government could establish policies and programs to quickly build a Polywell fusion plant and enable a fusion industry based on this technology; replace the national vehicle fleet with one that uses high-efficiency engines and slashes energy demand with hybrids and/or all-electric drives; develop a renewable fuel industry with government emphasis and oversight so as to avoid unintended negative consequences; invest in photovoltaic cells for military use; use government demand for energy products to encourage industry growth and lower costs; and insist that DoD incorporate energy use as an essential, integral element in requirements setting and acquisition.

Military Prep for Some "Worst-Case Scenarios"

It has been said about the September 11, 2001, terrorist attacks on the United States that they were "unthinkable." How does a military or national security authority defend the United States if its support staff does not push itself to think the "unthinkable" and, thereby, identify needed remedies and precautionary measures? With this question in mind, let's take a quick look at some "unthinkables" regarding energy security for which the U.S. military and nation must be prepared. Let's ask some questions to promote *thinking responsibly*.

Robert Duncan, in his Olduvai theory [146], projects an end to industrial civilization should the world run out of petroleum.

There are certainly other ways than petroleum to power civilization. But the United States and its allies are not self-sustained in petroleum production and rely on parties whose interests often do not coincide with ours. The world can quite literally run out of producible petroleum, but even before that event, petroleum can serve as an economic weapon and can be cut off from delivery to the United States. Such a denial of access can come from a contrary political decision from abroad, by weather and other aspects of nature, and by terrorist attack (no matter what the national source or philosophical bent of the terrorists), by criminal action, by war waged upon our nation, or by acts of war between other nations. Disruption in shipping of oil could be devastating and is not "unthinkable." The DoD would play a key role in dealing with these potentialities. How should the DoD prepare?

Access-denial problems also pertain to the delivery of electricity and fuel within the homeland and to military facilities at home and abroad. The United States has never faced wide-scale power outages that last for months or even years. The results would be devastating. The DoD's mission of national defense suggests that the DoD must actively engage to provide energy access assurance by various means, including infrastructure protection, augmentation, and offloading. The national command authority's broader responsibility suggests that industry's engagement and partnership is essential and must be informed by national security needs and guidance, which the military is qualified to provide. What missions, structures, and agreements need to be defined that are not?

A 2003 Pentagon-commissioned report [147] on the security implications of climate change, the *National Intelligence Assessment on the National Security Implications of Global Climate Change to 2030* report to Congress [6], together with the IPCC 2007 [17] report, which tied together climate change and energy use, all suggest that DoD must again think the "unthinkable." What if the oceans rise, crops fail, large populations migrate, resource wars proliferate, nuclear powers confront one another over tightened resources springing from climate change, the economy tanks from rocketing energy prices, terrorism is intensified and expanded, and the military is tasked to stability operations in multiple places, including perhaps within the homeland? How can the DoD's strategy toward its own energy use help defuse the climate issue within its own lifelines and in the broader national community?

"What's the worst type of biological attack or limited terrorist nuclear attack against energy such as pipelines, oil fields, or shipping choke points? What part of the world or against what population, nation, or infrastructure would be attacked? What risk mitigation or repair needs to be in place? Is it ready? Or, what if the military had to deal with the most significant implications of climate change, as suggested by the Pentagon report? Or, what if there were no more oil to be had?" Asking such questions can only help DoD prepare and be ready for the "unthinkable."

One of the most dangerous events that can happen on a naval vessel is a fire. The U.S. Navy excels at damage control, such as the heroes of USS *Stark* showed in the 1980s. A fire usually starts small and can be put out by a single sailor with a bucket of water or fire extinguisher if detected early by the watchstander. If discovered after 15 minutes, the fire's firefighting requirement can include the entire crew. Who has the watch for energy security?

Military Prep for a "Best-Case" Scenario-Technology with Inspired Leadership

The DoD can lead the way in developing and implementing many changes in technology and energy resource use. The military can begin to incorporate logistics (and energy logistics in particular) integrally into total DoD capability requirements and acquisition processes. The DoD can invest development and acquisition dollars to enable rapid deployment of new forms of energy and energy conservation that do not decrease capability, but increase operational capability. The federal government, as a whole—with its buying power for energy-using equipment and energy sources and policing guidance—can prevent the vagaries and perhaps excesses of the free market from contributing to energy security problems.

The military has a historic opportunity to influence production of high-efficiency land vehicle engines. The wars in Iraq and Afghanistan are wearing out the land vehicle fleet. The Army and Marines will have to reconstitute, which means buying tens of thousands of new land vehicles. If DoD established a demand and industrial infrastructure for high-efficiency engines, electric hybrids, and perhaps even all electric vehicles, not only could DoD cut its future fuel consumption dramatically and logistics force, but would also spin-off the benefits to the entire country. Rapid development of an electrical storage device, such as promised by EEStor, would create several revolutions in alternative energy use and production.

The military is investing in high-efficiency aircraft engines, as the DSB 2007 report identified. With incorporation of fuel use as a key performance parameter in all acquisitions, rapid deployment of such technologies could become a priority. Again, the entire nation would benefit as airlines were able to use such assets.

In trying to relieve possible infrastructure vulnerabilities, the military can promote more rapid deployment of wind and solar power, which would not only contribute to a distributed military power system, but a distributed national power system. These power sources, if used to charge electric and plug-in hybrid vehicles, can produce quads of energy that would otherwise have to be imported as petroleum. Wind and solar have the additional benefit of not contributing to atmospheric carbon and that, in itself, can be both a security bonus, as well as a public relations bonus. Creating high-efficiency and inexpensive photovoltaic technology helps everyone, and the military may get a particularly useful benefit from it by allowing a tether-free approach to refueling forward-deployed vehicles and units, both manned and unmanned.

The Bussard Polywell fusion machines can be quickly prototyped, contingent on funding. The Navy could particularly benefit from a relatively inexpensive and compact power source for naval vessels that needs no refueling for years and does not share the issues that nuclear-fission power plants have. Polywell technology offers the opportunity for a new world civilization that does not have energy constraints suffered by the current fossil-fuel-based civilization.

The DoD is the largest single consumer of petroleum products in the nation. Its purchasing actions can be determinative in promoting development of an alternative fuel industry. According to a report from the Congressional Office of Technology Assessment [148], the U.S. government owned over a half million land vehicles in 1989. According to that report, the federal government keeps vehicles from 3–6 years and, consequently, buys about 100,000 vehicles per year. The DoD and Postal Service each owned about 30% of this fleet. According to Department of Transportation statistics [24], the government as a whole used about 6.3 billion gallons of vehicle fuel in 2006, of which about 3.89 billion gallons were DoD JP and aviation gas, and 1.7 billion gallons were DoD diesel use. The federal government and DoD especially are major vehicle and fuel customers, with the potential for great influence with purchasing power and development investment.

The military—together with the additional purchasing power of the entire federal government, which owns and operates these mass quantities of vehicles—can set a target of buying exclusively alternative fuel, set the standard for that fuel and police that standard, and develop an industry of suppliers by guaranteeing a certain level of purchase at a certain price. No one in the private sector has comparable resources or the flexibility to so act as a monolithic buyer. The best alternative fuel options and best alternative fuel production options can be guided largely by the military. The various and many alternative fuel technologies can compete in a guided competition orchestrated by DoD. The competition would result in an industry that can provide not only all DoD fuel needs, but is launched to provide national needs.

The DSB Task Force in its 2008 report specifically recommended that a single office be installed in DoD to orchestrate all such matters energy-related and be resourced with at least $500 million per year and be given technical laboratory support. When has there been a better time to "make it so"?

Just as recessions for the last 40 years have resulted from high oil prices, the economic booms of the 1960s and 1990s benefited greatly from cheap oil. But oil is a limited resource, a world commodity largely beyond U.S. control or control of its first-world allies. A best-case scenario for energy can be achieved with abundant availability of renewable fuels produced in the United States and all countries (such as from algae) from high-efficiency use of fuels, especially from high-efficiency vehicles; from rapid deployment; and from price reductions for abundant sustainable energy sources such as wind, solar, and Polywell fusion. A world of abundant energy would be a world of abundant water resources and food. Abundance could contribute substantially to world stability and greatly influence military force requirements.

GENERAL OBSERVATIONS: ENERGY, SECURITY, CHANGE, & COMPLEXITY

Diverse Challenges and Responses—A Clear and Present Danger

The current global status of energy cost, access, potential disruption of use, and climate change related to energy use constitute a clear and present danger to the United States and its allies. Because of the complexity and breadth of the energy security issues and problems, no single solution, no single technology delivers the robustness of responses required. However, many Knights on White Horses (KOWH) are racing to the rescue. Various targets of opportunity present themselves for resolution. Controversy and debate surround some approaches. Let's sum this up and call for action.

KOWH—Nuclear Fission. Some environmentalists (such as James Lovelock), nuclear engineers, and power companies tell us that non-carbon-producing nuclear fission power can replace our use of fossil fuel [149–153]. By building several thousand nuclear-fission power plants around the world (only about 400 exist today), the supremacy of petroleum and the power of petroleum-owning states can be lessened, the potential economic ups and downs of petroleum reliance alleviated, and the potential end-of-oil scenario avoided, while global warming may be slowed, and the worst effects of climate change may be averted. Opponents argue with challenges of nuclear waste disposal, environmental contamination from processing and perhaps reactor accidents, nuclear proliferation dangers, and the high cost of the facilities [125, 154, 155). An advocate such as James Lovelock tells us about the revival of Mother Nature around Chernobyl since humans have deserted the place. However, opponents also point out that full proliferation of nuclear fission as the way out of the current energy conundrum means a multimillennial commitment of trust in the goodwill, willpower, perseverance, consistent competence, and unyielding management of a nuclear fission industry for the good of man above other motives, such as profit. Such opponents suggest that a breach in this trust for hundreds of thousands of years into the future could cause the extinction of mankind. Proponents suggest that even with today's fission technology, the power plants in the United States are safe and reliable alternatives to imported energy, and research can resolve all other issues.

KOWH—More Petroleum. Oil companies tell us that they must explore and drill more, and that oil simply cannot be replaced in this half of the 21st century. The Saudis, with the largest proven oil reserves, tell us that they have plenty of oil to fuel civilization but refuse to release information to prove the assertion [11, 156]. Neither are they producing prolifically extra oil. Various experts, however, believe that "peak oil" has arrived. To the contrary, some traditional energy experts point to the vast quantities of shale oil and tar sands, which may have become economical to mine—though they may have to break some environmental eggs to make that omelet.

KOWH—Renewable Fuel. Many, many people are trying to cost effectively produce renewable and synthetic fuels to replace petroleum-based fuels. Algae, switch grass, sewage, agricultural waste, plastic garbage, food crops, wood chips, jatropha, and carbon plucked from the atmosphere all offer the potential to serve as replacements for fossil fuel. Advocates show, with convincing figures, that the entire national requirement for energy, and even excess for export, can be produced in this country from these sources, with the added benefit that they are "carbon neutral" because their use will release to the atmosphere only carbon, which is taken from the atmosphere to produce the feedstock.

KOWH—Fischer-Tropsch. Among other fuel ventures, the U.S. military is investing to produce synthetic fuels via the venerable, old FT process, which the regimes of Nazi Germany and apartheid South Africa used to produce fuel from their abundant supplies of coal. The Air Force feedstock would be natural gas. FT is energy intensive, approximately doubles carbon pollution versus simply burning petroleum, and the FT facilities are expensive to build. However, folks with lots of coal to burn tend to be strong advocates of FT deployment. China is moving quickly to build a host of FT plants—an 80,000 barrel per day plant prices at about $5 billion which is about twice the price of an oil refinery with the same throughput.

KOWH—Wind and Solar Power. "Alternative energies" do not own much of the market right now, but new developments are quite promising. Solar power has been held back because of poor efficiency in conversions and other technical and cost aspects, but recent new technical breakthroughs may change that situation rapidly. However, solar power is only a fraction of a percent of current electricity generation and costs at least double wind power per kilowatt-hour. Wind power costs about 8 cents per kilowatt-hour compared to coal's 5 cents per kilowatt-hour (the cheapest today). Wind power appears about to take off and power much of the electric grid. The recent push by T. Boone Pickens certainly does not endanger that prospect.

KOWH—Nuclear Fusion. Nuclear fusion power has seemed to be perennially 5 decades away from net power production, as it was in the middle of the last century, and still appears to be—even by the most recent international plans concerning the ITER and DEMO projects. However, a very significant piece of just-demonstrated technology, Polywell fusion, may quickly bring fusion power to reality by 2015.

KOWH—The Hydrogen Economy. Can technology overcome all the problems with producing, storing, and transporting hydrogen to enable the *hydrogen economy*? Versus all the other alternatives, is hydrogen fiscally, environmentally, and logistically worth the efforts?

Targets of Opportunity—DoD and Transportation. Transportation is U.S. oil's Achilles' heel. Oil does not contribute substantially to grid power. Rather, it drives cars and trucks, and flies airplanes. However, will the industries that produce cars, trucks, and airplanes (which account for about 70% of U.S. oil consumption and about 30% of carbon emissions) affordably utilize new technologies available to them to provide vehicles that do not waste 75–80% of the fuels poured into them? Vehicle energy consumption equals U.S. oil imports. Producers and proponents of extremely high-efficiency engines, hybrid plug-ins, and all-electric vehicles argue the advantages of conservation, which does not have to mean less capable or more costly vehicles. Vehicle heat engines with 50%+ efficiency would cut oil imports by about 50% even if they used standard petroleum-based fuel. Their use of renewable or synthetic fuel would eliminate imports while reducing the amount of renewables infrastructure needed. An all-electric fleet powered by electricity from windmills (or other sustainable/renewable domestic sources) would simultaneously eliminate oil imports and looming oil-refinery undercapacity, which may exceed 8 Mbbl/day worldwide by the end of the next decade.

The U.S. military uses less than 2% of the total U.S. oil consumption. But the military wants to ensure itself a source of fuel and is pursuing various technical alternatives to do so. DoD faces significant cost and operational capability problems today because of past practices of largely ignoring total fuel costs, ignoring fuel efficiency in platforms acquisitions, and in setting operational requirements and analyzing how to fill those requirements. As the Army and Marines have totally worn out their land vehicle fleets (purchased under Ronald Reagan as Cold-War deterrence) in the current two-front South Asia war, they and the nation are presented with a world-historic opportunity. Within 2 years from initiation, the military could prototype and validate a combination of extremely high-efficiency engines, electric hybrids and all-electric vehicles, as well as develop the organizational processes to include all of logistics and, especially, energy logistics integrally into future force design and acquisition. The development and validation could be done for much less than a billion dollars, which is less than the price of a single day's U.S. oil imports, or about 2 weeks of military fuel consumption costs at $4.00 per gallon of fuel.

If the military preferentially buys these fuel-efficient alternatives and develops a reliable market for them, a new industry—able to provide the American public cost-effective fuel efficiency—can prosper. Similarly, military and NASA demand helped jump-start the semiconductor industry over 40 years ago,as well as helping develop radar, communications, and computing technology. Today, an all-electric, high-performance military truck or HMMMV-like vehicle, with range exceeding 500 miles, and which could be recharged by solar panels, is technically achievable, even if expensive. Repeated experience seems to indicate that military investment can drive down the cost of new technology to the level of consumer affordability. In the process of saving the U.S. citizen's money and making the country more secure by reducing or eliminating oil imports, the military could provide itself with more flexible, logistics-reduced, operational capability.

The United States has the best potential to lead the world through these rough times in partnership with both long-time allies and emerging, responsible international partners, such as China and India. A coalition of North America, the rest of the former British Empire, other NATO nations, Israel, Japan, Korea, China, India, and Brazil could lead the world into a new civilization through the huge readjustments required, while avoiding large-scale, full-fire belligerence.

Energy and the Environment [6, 17–19, 157, 147]. Climate change is happening and has happened multiple times in human history. Global warming could produce widespread political instability and resource wars, the spread of tropical disease to northern latitudes, and famine from loss of crops in prime, arable land that would rock civilization. The United States would face reengineering its infrastructure and, to some extent, the economy, and switching away from carbon-emitting energy use, while being ready to act in many places in the world to foster/enforce stability and not allow a general international collapse. Prudence suggests that the potential catastrophes of climate change and its causes be considered and addressed as the United States and DoD approach energy security solutions.

Taking Action The various technical solutions already discussed in this paper should indicate that the United States faces no physical dearth of energy sources. And these KOWHs will eventually come home. The United States is confronted primarily with a leadership challenge. The challenge is as much economic, business model, and worldview, as technical.

Acting wisely could bring a new age of plenty, with energy enough to export, to create excellent jobs and new career fields, to provide more bang for the buck in the military, to establish national security, to promote international stability and prosperity, and to discourage the causes of extremism. The DoD could lead the way in prototyping new energy technologies and establishing market demand for them. With that potential transformation comes the removal of energy scarcity as a cause of inflation and economic woe, and mitigation of the impact of climate change. Such is the promise for prompt and wise action.

WHERE TO NOW?

"True wisdom is less presuming than folly. The wise man doubteth often, and changeth his mind; the fool is obstinate, and doubteth not; he knoweth all things but his own ignorance." Ahkenaton [158]

In a 2004 speech [156], Ali al-Naimi, the Saudi Arabian Minister of Petroleum and Natural Resources, suggested that the world was not even close to "peak oil," that the Saudi oil reserve projections were very conservative, that they could produce oil for another 100 years, that they could easily raise daily production by 10–15 Mbbl/day (more than their daily exports to the United States) to stabilize world supplies and prices, and that the Saudis were dedicated to keeping the $22–$28 price-per-barrel range for OPEC oil. What happened? The author of *Twilight in the Desert* suggests that the Saudis have passed peak oil production, and cheap oil from the Saudis just is not there to be had.

Many alternative fuel production options offer the ability today to provide nonfossil, renewable fuel but need help to establish national-level production capacity. Emerging and already available transportation vehicle-efficiency options could dramatically cut petroleum demand and within years (not decades) eliminate U.S. petroleum imports. Several extremely promising technologies will likely overtake fossil fuel in producing grid electric power and will produce it inexpensively and reliably, while eliminating problems of using fossil fuel and nuclear fission. But which voices will leadership heed, where will the choices lead, and will they act with sufficient speed?

In his book, *Collapse*, Jared Diamond [159] describes in detail how some rather famous lost societies chose not to husband their resources, chose not admit to their existential resource problems, and thus failed to make absolutely essential changes. Although some argue that the coming of "peak oil" entails the end of industrial civilization, such need not at all be the case. A society and, for that matter, our military that runs on energy and can be economically devastated by fluctuating energy prices, must guarantee itself responsible access to energy or the Olduvai consequences might arise.

Strong, united national leadership; rapid, concerted exploitation of new technologies; and truly admitting that "we must change" can bring the United States and the world to a safer, more prosperous civilization than ever before. Energy runs modern civilization, and defines standard of living and military power. Energy exploitation and climate change appear to be linked, and though climatic change is unavoidable, we can wisely consider it while addressing energy security. We can add robustness to our infrastructure, prudently maximize use of our resources, accelerate adoption of needed changes, guide the free market to help, rather than to exacerbate problems, and protect those least able to fend for themselves. Government must lead. The largest energy user in the government, DoD has many paths to better use fuel and realign force structure for better mission capability with less fuel.

The potential for catastrophe is real. The United States must not wait for desperate times and then take desperate measures. Winston Churchill said, "An optimist sees opportunity in every danger, a pessimist sees danger in every opportunity." Vast opportunities surround us.

APPENDIX A—ENERGY STATISTICS AND THEIR IMPLICATIONS

Some Useful Energy-Related Units and Measures [160, 161]

- An International Table British thermal unit (Btu) = 1055.06 joules.
- A million billion Btu (i.e., 10E15 Btu) is called a quadrillion Btu or simply a "quad." The United States uses about 100 quads a year.
- 1 quad = 1.05506 E18 joules; 10E18 joules is called an exajoule.
- Thus, 1 quad is approximately 1 exajoule (actually 1.05506)
- 1 barrel of oil equivalent equals 5.8 million Btu (MBtu).
- One barrel of oil is 42 gallons.
- A gallon is a measure of volume.
- A ton of coal is an English unit measure equal to 2000 pounds.
- A tonne (metric ton of coal) is 1000 kilograms (which is about 2200 pounds).
- One ton of coal equivalent equals 25.2 MBtu.
- One tonne (metric ton) equivalent equals 27.5 MBtu.
- A watt is a unit of power or expenditure of energy over time:
- 1 watt = 1 joule/second (i.e., it takes a joule of energy each second to deliver a continuous watt of power)

Power is often given in thousands of watts known as kilowatts, millions of watts known as megawatts, billions of watts known as gigawatts, or even a million times a million watts known as a terawatt. The U.S. electrical power system at peak power can produce about 1 terawatt.

When calculating how much power was delivered for how long, the units are frequently given in kilowatt-hours. The number of kilowatt-hours for a battery or other electrical storage system for an electrical vehicle is an indicator of the range of that vehicle. If a vehicle requires 15 kilowatts of power to drive a vehicle at 55 mph, and the vehicle travels for 4 hours at 55 mph and thus 220 miles, then the electrical storage system had to have a capacity of at least 15 kilowatts times 4 hours or 60 kilowatt-hours (60 kWh).

1 kilowatt-hour of electricity equals 3412 Btu

Running the Numbers on U.S. Energy Demand

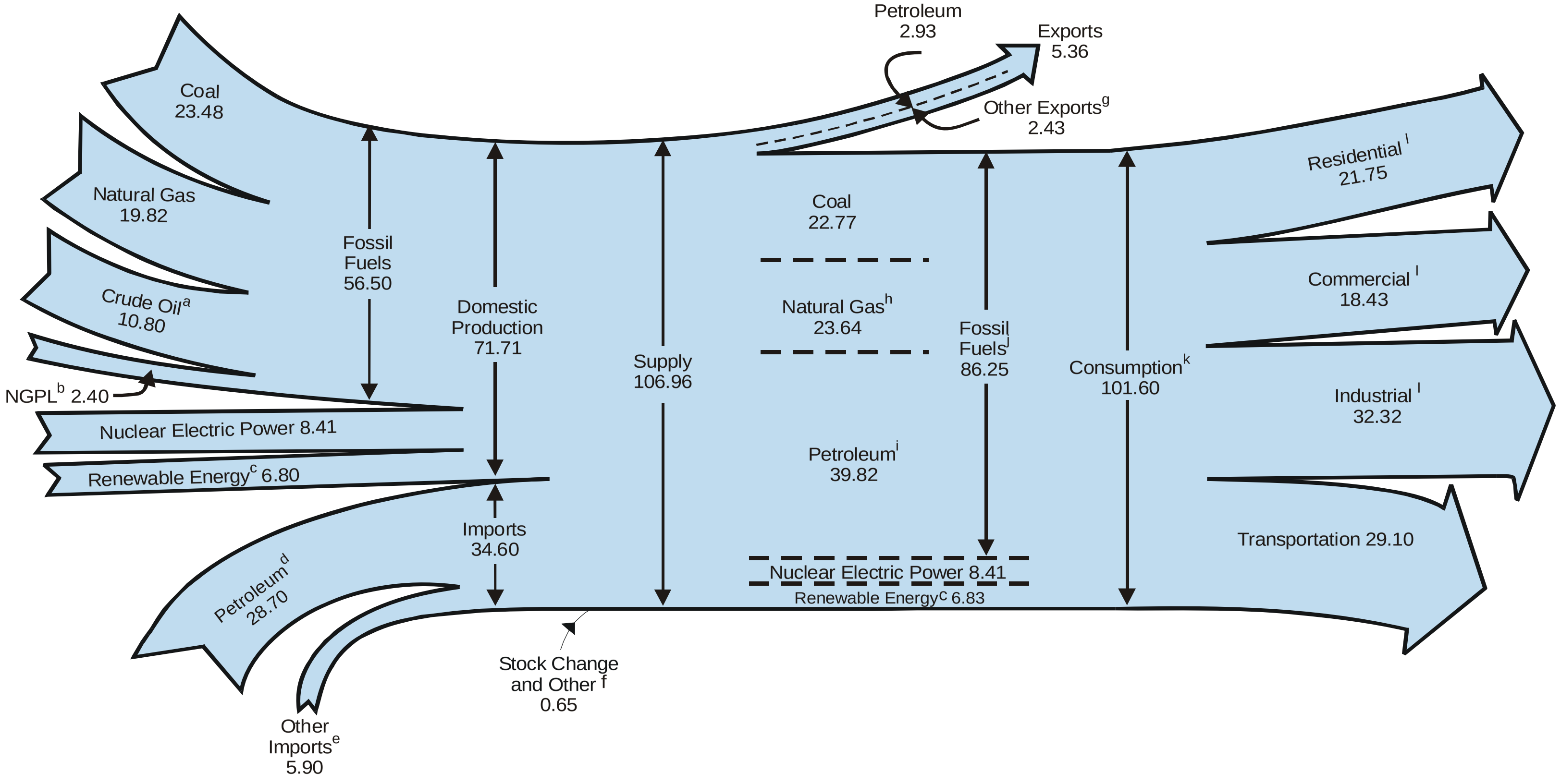
The following statistics reveal a crucial aspect of U.S. energy vulnerability. To grasp the magnitude and nature of the vulnerability, one must look closely at the numbers. The DOE's EIA produces a wealth of documents and statistics on energy, including sources and means of production and consumption of energy. The following information comes from EIA statistics.

How much energy does the United States use and where does it come from? According to the EIA's Annual Energy Review (AER) 2007 [14], in 2007 the United States consumed a total of 101.6 quadrillion Btu (quads) of energy from all sources. In total, the United States imported 34.6 quads of energy. About 83% of the imported energy was petroleum in the form of crude oil or refined petroleum products. Diagrams 1 through 5 are taken from the EIA 2007 AER. Diagrams 1 and 2 elegantly show, respectively, the total U.S. energy input and consumption flow, and the total petroleum flow. The statistics cited below are slightly different from those in the diagrams because of numerical rounding.

Looking at the total energy picture, not just petroleum, U.S. 2007 total domestic contribution to energy supply (101.6 quads minus imports) came from the following sources: *Coal 23.48 quads, Natural Gas 19.82 quads, Domestically Produced Crude Oil 10.80 quads, Natural Gas Plant Liquids 2.40 quads*, Nuclear Electric Power 8.41 quads, and Renewable Energy 6.80 quads. In addition to these domestic energy products, the country imported 34.6 quads, including 28.7 quads of petroleum and 5.46 quads total of natural gas, coal, coal coke, fuel ethanol, and electricity. The United States also exported 5.36 quads, of which 2.93 were petroleum. Therefore, the United States imported 28.7 quads of petroleum of the total 101.6 quads of energy consumed. Except for petroleum imports from outside of North America, continued U.S. access to energy seems well in hand. But how the U.S. accesses and uses petroleum is crucial to the energy security question.

The U.S. total daily petroleum consumption in 2007 was 20.698 Mbbl/day, while 2006 daily consumption equaled 20.697 Mbbl/day, and 2005 was 20.802 Mbbl/day. Imported petroleum for 2007 equaled 13.439 Mbbl/day and came predominantly from nine countries: Canada (2.426 Mbbl/day), Mexico (1.533 Mbbl/day), Saudi Arabia (1.489 Mbbl/day), Venezuela (1.362 Mbbl/day), Nigeria (1.132 Mbbl/day), Iraq (0.485 Mbbl/day), Russia (0.413 Mbbl/day), United Kingdom (0.278 Mbbl/day), and Brazil (0.202 Mbbl/day), over 50 other countries supplied the remaining 3.494 Mbbl/day. The United States supplied from domestic petroleum sources

Diagram 1. Energy Flow, 2007
(Quadrillion Btu)



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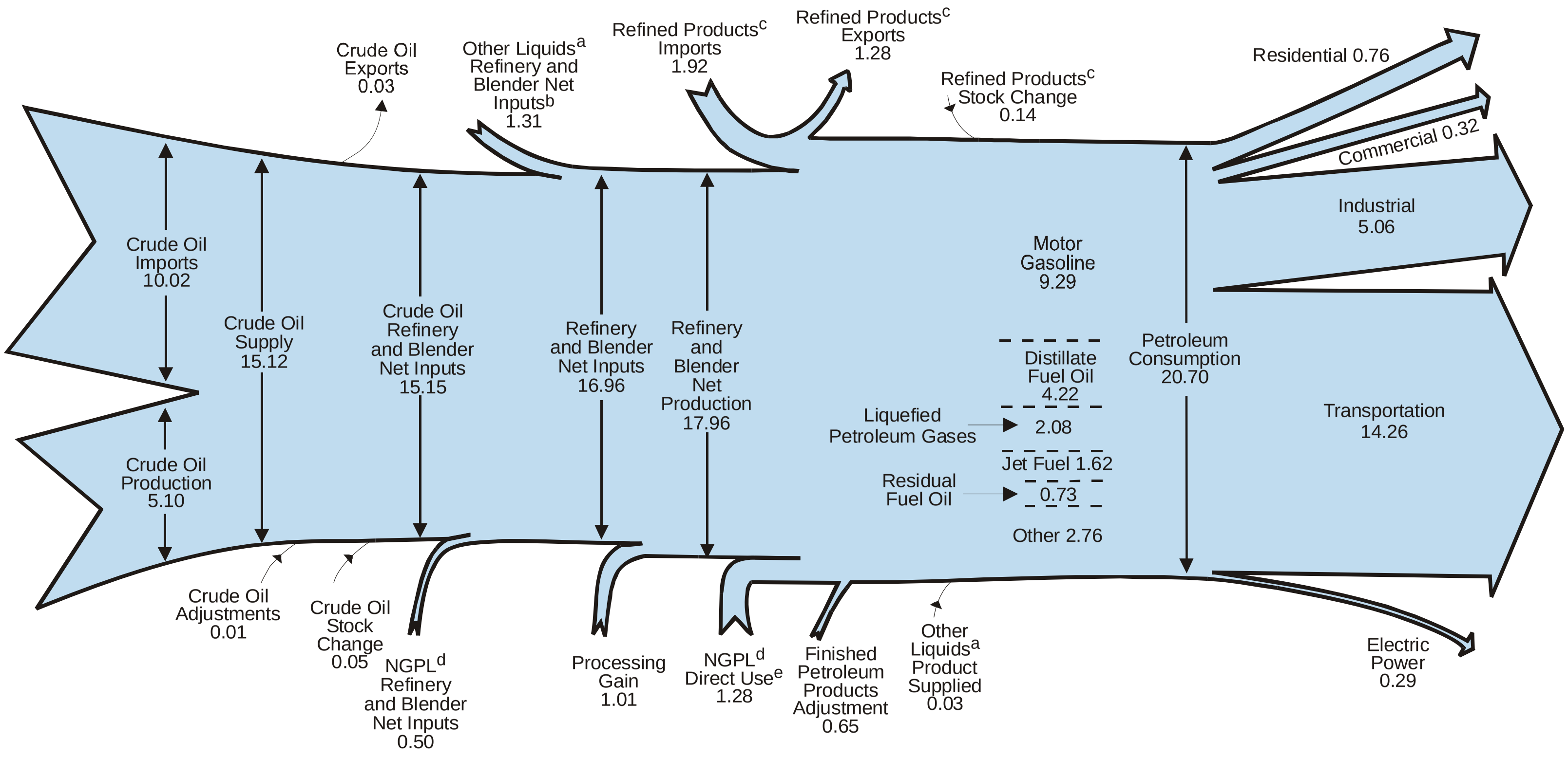
[a] Includes lease condensate.
[b] Natural gas plant liquids.
[c] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.
[d] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[e] Natural gas, coal, coal coke, fuel ethanol, and electricity.
[f] Adjustments, losses, and unaccounted for.
[g] Coal, natural gas, coal coke, and electricity.
[h] Natural gas only; excludes supplemental gaseous fuels.
[i] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.
[j] Includes 0.03 quadrillion Btu of coal coke net imports.
[k] Includes 0.11 quadrillion Btu of electricity net imports.
[l] Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

Diagram 2. Petroleum Flow, 2007
(Million Barrels per Day)



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[a] Unfinished oils, other hydrocarbons/hydrogen, and motor gasoline and aviation gasoline blending components.

[b] Net imports (1.41) and adjustments (-0.05) minus stock change (0.02) and product supplied (0.03).

[c] Finished petroleum products, liquefied petroleum gases, and pentanes plus.

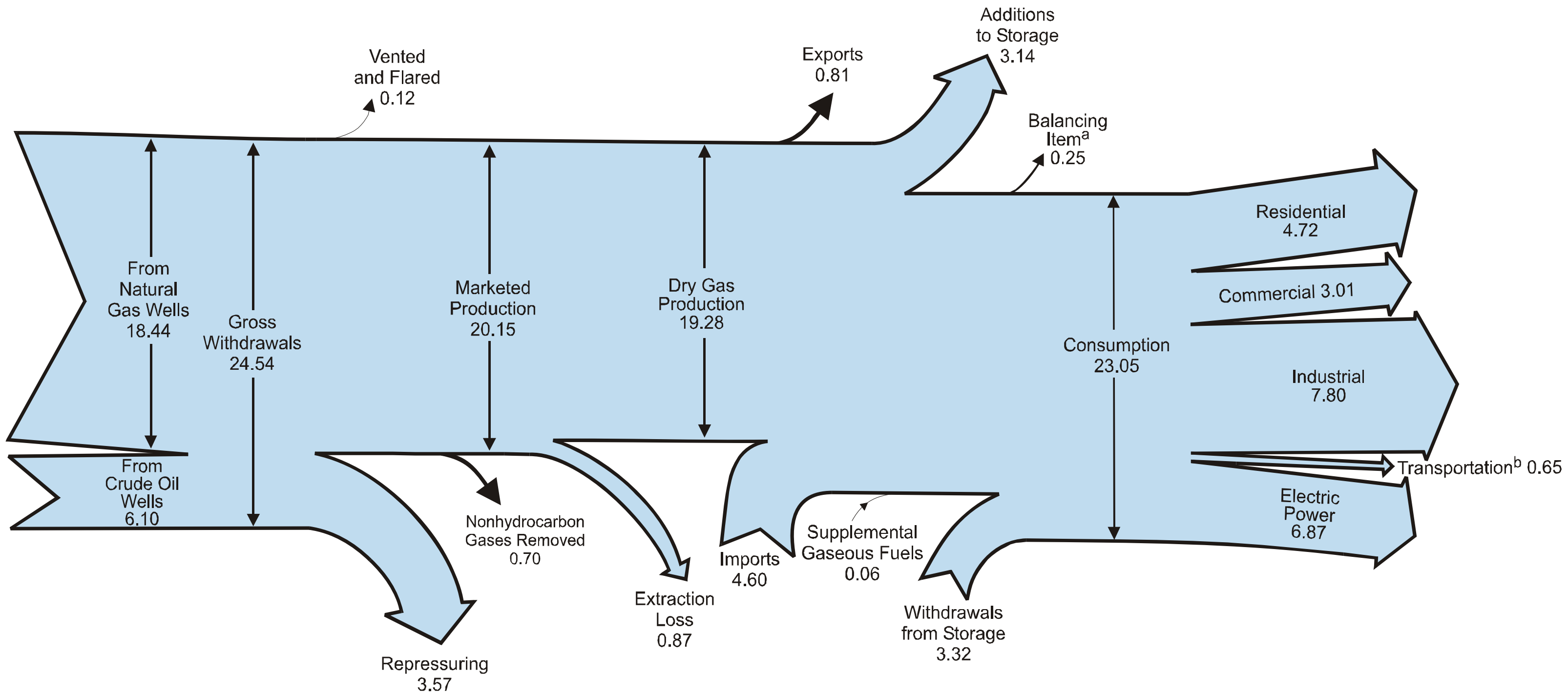
[d] Natural gas plant liquids.

[e] Production minus refinery input.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 5.1, 5.3, 5.5, 5.8, 5.11, 5.13a-5.13d, 5.16, and *Petroleum Supply Monthly*, February 2008, Table 4.

Diagram 3. Natural Gas Flow, 2007
(Trillion Cubic Feet)



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[a] Quantities lost and imbalances in data due to differences among data sources.

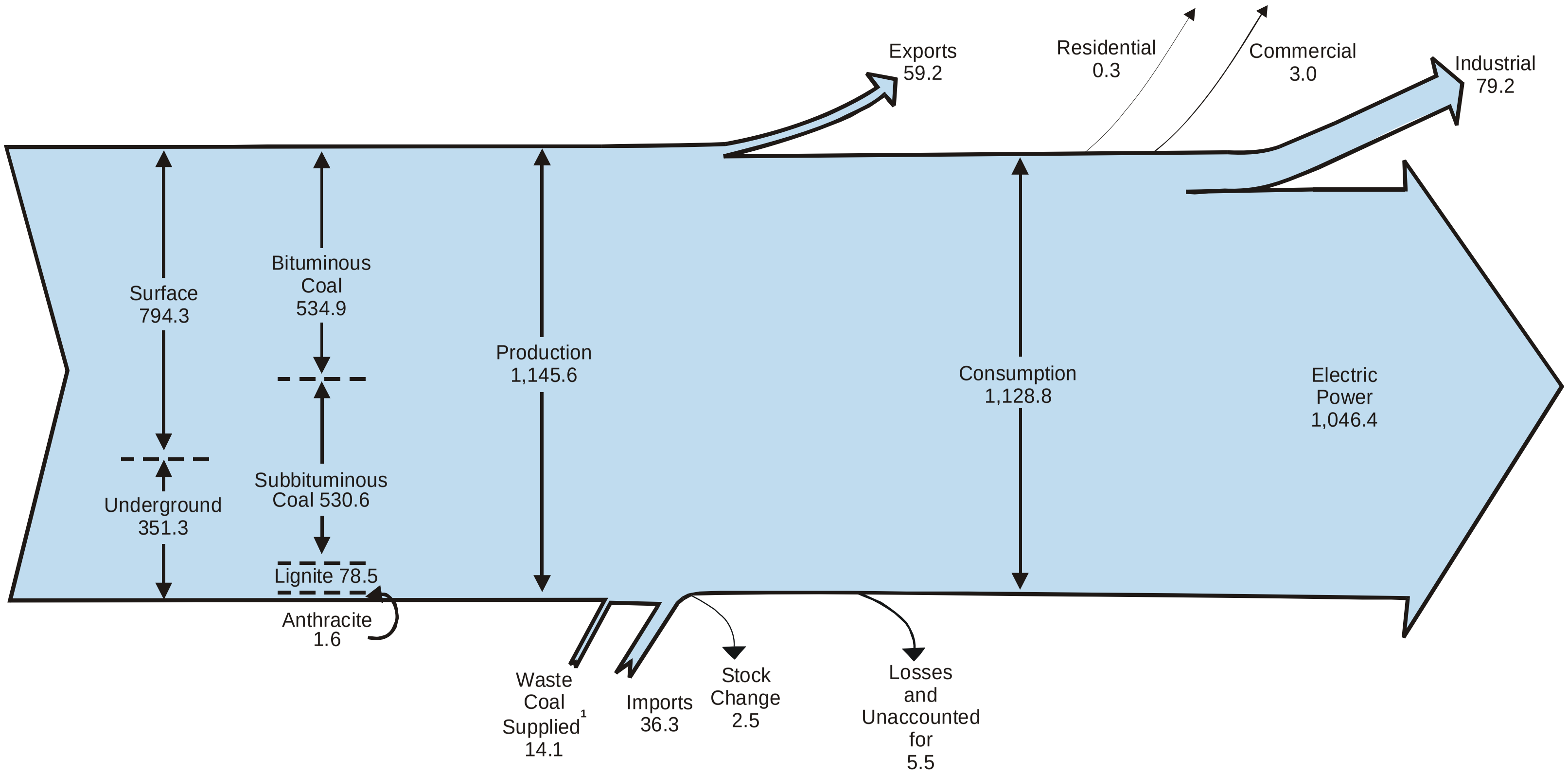
[b] Natural gas consumed in the operation of pipelines (primarily in compressors), and as fuel in the delivery of natural gas to consumers; plus a small quantity used as vehicle fuel.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 6.1, 6.2, and 6.5.

Diagram 4. Coal Flow, 2007

(Million Short Tons)



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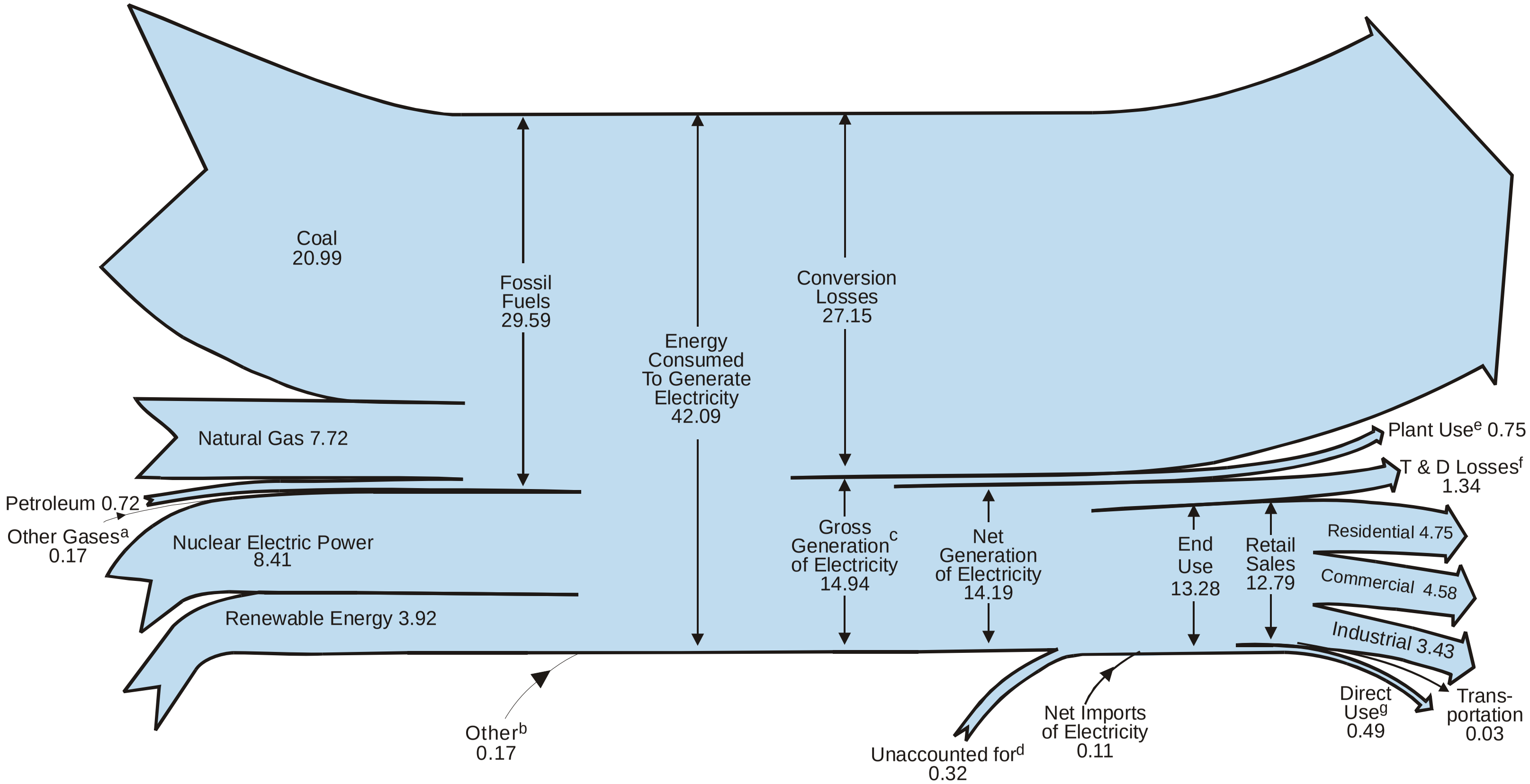
[1] Includes fine coal, coal obtained from a refuse bank or slurry dam, anthracite culm, bituminous gob, and lignite waste that are consumed by the electric power industrial sectors.

Notes: • Production categories are estimated; other data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 7.1, 7.2, and 7.3.

Diagram 5. Electricity Flow, 2007
(Quadrillion Btu)



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[a] Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

[b] Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).

[c] Estimated as net generation divided by 0.95.

[d] Data collection frame differences and nonsampling error. Derived for the diagram by subtracting the "T & D Losses" estimate from "T & D Losses and Unaccounted for" derived from Table 8.1.

[e] Electric energy used in the operation of power plants, estimated as 5 percent of gross generation.

[f] Transmission and distribution losses (electricity losses that occur between the point of generation and delivery to the customer) are estimated as 9 percent of gross generation.

[g] Use of electricity that is 1) self-generated, 2) produced by either the same entity that consumes the power or an affiliate, and 3) used in direct support of a service or industrial process located within the same facility or group of facilities that house the generating equipment. Direct use is exclusive of station use.

Notes: • Data are preliminary. • See Note, "Electrical System Energy Losses," at the end of Section 2. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 8.1, 8.4a, 8.9, and A6 (column 4).

7.884 Mbbl/day, and this includes a 1.005 Mbbl/day gain in volume expansion from refinery processing of petroleum into products, such as diesel and gasoline, which are not as dense as crude oil. A total of 58 non-OPEC states (including Mexico, Canada, and Russia) and 11 of the 12 OPEC states (we don’t get any Iranian oil) provided processed or unprocessed petroleum products to the United States. Fig. 1 visually displays these domestic and import figures for petroleum.

Not counting the refinery processing gain, the United States and its North American neighbors supplied 10.838 Mbbl/day –55% of U.S. petroleum needs, and the United States alone provided about 35% of its needs. Granted, the possibility of oil supply disruption between North American neighbors seems vanishingly small. But NAFTA partners provided only about 30% of our imported oil.

The way in which petroleum was used breaks out as follows by Consumption Sector: Transportation 14.265 Mbbl/day, Industrial 5.06 Mbbl/day, Commercial 0.32 Mbbl/day, Residential 0.76 Mbbl/day and Electric Power Generation 0.29 Mbbl/day. Transportation accounted for 68.9% of U.S. petroleum consumption, while electric power generation accounted for a little over 1%.

Transportation consumption in 2007, the vast majority of petroleum consumption, divided as follows (in Mbbl/day): Motor Gasoline 9.076, Distillate Fuel Oil (Diesel) 3.048, Jet Fuel 1.623, Residual Fuel Oil 0.414, Lubricants 0.066, Liquefied Petroleum Gases 0.021, and Aviation Gasoline 0.017. All told, the U.S. transportation sector used 14.265 Mbbl/day of petroleum, and U.S. petroleum imports (without deducting the U.S. petroleum exports) equaled 13.439 Mbbl/day. Fuel to power ground vehicles (e.g., cars and trucks) and jet airplanes equaled 13.747 Mbbl/day. An equivalent of the entire petroleum import went to powering those vehicles. *Any efficiency in vehicle fuel consumption buys virtually a one-for-one gain in eliminating petroleum imports*.

As of the last quarter of 2007, the world consumed petroleum at a rate of 86.65 Mbbl/day. The U.S. portion of total world consumption was about 24%, Europe’s 18%, China’s about 9.1%, Canada’s 2.7%, Japan’s 6%, and countries from the Former Soviet Union about 5% [162]. What happens when China and India exceed U.S. oil consumption?

Relating the Energy Numbers, Energy Dependence, and Security

Today’s world oil economy creates a potential demand on DoD to maintain the international order. U.S. foreign oil reliance sends hundreds of billions of dollars out of the country every year and puts the nation in potential jeopardy from cutoff of that resource. However, the United States must look beyond its own energy needs. High energy prices affect the world economy and can contribute to international instability and masses of desperate people—which can result in tasking to the U.S. military. India and China are blooming industrially and will quickly be able to consume all oil on the international market, which the United States foregoes with alternatives. China has already surpassed the United States in carbon emissions. Ultimately, U.S. energy security must come from a

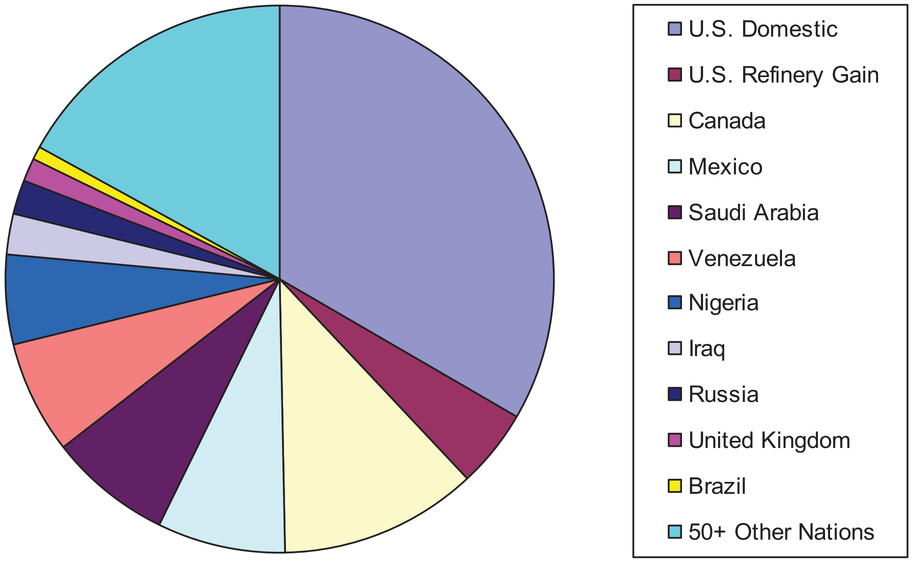


Fig. 1. U.S. Petroleum Sources

worldwide solution. The United States can lead the world, and DoD's ability to influence development of energy options can be a key enabler.

The energy production and consumption figures show that the United States can achieve energy independence if it eliminates transportation fuel imports. Addressing industrial, residential, or commercial energy consumption does not solve the import-dependence problem. According to 2007 data from EIA, and although the situation is not simplistic, if the United States replaced motor gasoline, diesel, and jet transportation fuels with domestically-produced energy, it would not need imported petroleum. U.S. domestic petroleum production has declined since the peak production in 1970 of 9.64 Mbbl/day to about 5.1 Mbbl/day in 2007. In 2007, total inputs to U.S. refineries were about 15.12 Mbbl/day. However, even if domestic crude oil production could be sufficiently increased (tripled), U.S. refinery capacity is barely sufficient to supply national fuel needs. Currently, the United States has enough refinery capacity to process about 17.5 million barrels of oil per day and imports about 2 Mbbl/day of refined product. As previously noted, refinery capacity would have to grow rapidly this next decade to keep up with world consumption. The United States will probably need a combination of solutions, which include improved transportation fuel efficiency, additions to improve efficiency of electric power production and distribution, and domestic production of non-petroleum-based renewable fuels [14].

Freeing the United States from imported petroleum would create domestic jobs, enable a more stable and secure economy, and help get a tighter handle on supply disruption. Developing alternative power sources for the national electric grid can help the United States to develop a more robust infrastructure, achieve economic gain, and decrease carbon emissions. As T. Boone Pickens has pointed out, eliminating the trillions of dollars the United States will pay in the coming years for petroleum imports will also contribute to national security. At \$120 per barrel for 13.5 Mbbl/day, the United States would pay \$1.62 billion daily—about \$3 trillion in 5 years if at that average price, which could very likely rise. That daily cost in fuel would cover the purchase of a *Nimitz*-class aircraft carrier every week or 100 F-22 aircraft every 3 weeks. The financial consequence is of direct concern to the U.S. government and directly impacts DoD resource constraints.

Crude oil import demand, processed petroleum demand, vulnerabilities in energy production and distribution infrastructure, economic impacts from world oil price fluctuations, potential disruption in all aspects of U.S. society, military energy requirements, and environmental impacts together highly suggest that assured, affordable, responsible energy access is the great national security challenge. The rest of the world also faces such challenges. Ultimately, the United States must achieve energy security for itself, and part of that will be achieved by promulgating its success around the world.

APPENDIX B—IMPLEMENTING A NEW ENERGY PARADIGM: A SPECULATION ON A TYPE OF ENERGY AND INERTIA, WHICH DEFINE COMPLEX SYSTEM STATES AND MODULATE SYSTEM CHANGE

The Clayton Christensen and Brian Arthur "effects" [163, 164] suggest that business models, first paths, and level of investment outweigh best technology. These theories indicate that the government should guide industry development and not leave this crucial national security asset totally to free market development.

Since this paper suggests that a new energy paradigm is required in order to assure U.S. energy security, it is only appropriate that it ask how much government leadership versus free market force will be required to establish this new complex state. Will the invisible hand of the free market solve the combined military security, fiscal, and environmental problems? Market mechanisms do not seem to apply to the organizational and fiscal disruption necessary to change DoD's way of setting requirements and acquisition as the DSB and others have recommended. Can market mechanisms provide real-time feedback that provides a guiding hand toward sustainable fuel sources that are initially more expensive than unsustainable sources, or values the slow motion of climate change or potential catastrophic disruptions of energy supply, which have never been experienced? Inertia in organizations, industries, and public opinion may tend to bog down attempts to replace petroleum, especially if the price swings low again. The huge capital investment in current energy solutions will, of course, slow movement away from fossil fuel. People who have power and wealth derived from the current energy paradigm may not willingly relinquish that position to the upstarts who try to bring alternatives.

Perhaps both Clayton Christensen and Brian Author address different facets of this same jewel. Christensen, in his theory of disruptive innovation, points out how difficult it is for the large company, with a solid customer base that asks for specific capability, to go against that tide and bring an innovation that the customers may not even realize they need or want, and which will very likely make obsolete the current products its customers are buying. Prime examples include IBM's failure to capitalize on the personal computer; the Swiss watch industry's failure to produce the digital watch, which they first developed; and the steamship's original use in the low-end inland-waterway transport business rather than the high-profit margin open-ocean transport.

W. Brian Arthur speaks of the economic "law of increasing returns," which hints at the idea that an object in motion tends to stay in motion. When related to a product or technology, this theory says that whatever gets ahead in a market tends to stay ahead, and whatever falls behind tends to stay behind. Arthur says that both laws of increasing returns and decreasing returns function simultaneously in industries. But increasing returns is particularly powerful in high-technology industries—aspects of the energy industry might fit this category.

What factors make this law apply? The need for huge upfront investment to start a project before return on investment gives advantage to the current provider (e.g., costs for new high-efficiency engine production lines, as well as the initial investment to fully test and validate them; costs for alternative energy power plants or other infrastructure; costs to produce and field electrical energy storage; any large-scale production with novel materials and construction needs; and switching to a farming mindset versus a mining mindset).

Arthur also points out that new technologies frequently must fit into an "ecology" or "network." Technologies may need multiple simultaneous innovations to make them work, including the knowledge base of users. Possible energy examples include the utility lines to distribute windmill-generated electricity, the storage capacity to hold electricity when the winds die down, a network of fuel stations to deliver new fuels, and labor skills to build and maintain cars that don't run on the ICE.

Oil companies know how to drill for oil and produce it. They know about expected returns on investment based on the size of an oil field. They can think easily in terms of a trillion dollars of oil waiting under an unexploited oil lease. This does not mean that the industry can relate well to the idea of putting an equivalent amount of funding and effort into producing renewable fuels, even if that project has, not the technical risk, but potentially better return on investment.

Large electric power companies know how to make money from coal, natural gas, and possibly nuclear plants. That does not necessarily translate into their willingness and skill to develop a solar-panel market or windmill farm, or invest in other alternative energy sources. Knowing how to conduct warfare with current sets of tools and being quite innovative in their use does not equate with the ability to design an entirely new military tool set that uses much less resource but delivers more capability. All major military technology innovations tend to be injected against the grain of the existing military power structure. Apparent behavior oddities from "the powers that be" in any domain all seem predictable from the Arthur and Christensen theories.

Arthur and Christensen document this industrial, organizational, and economic-market phenomenon, which the author would characterize as an inertia and energy combination that appears to be common to all complex systems. Every energy equation of physics and engineering has a similar form, with the amount of energy in a system defined by the multiplication of an "inertia-carrying" term, such as mass or spring constant, or dielectric permeability. And, that inertia term is multiplied by the square of a forcing function, such as voltage, pressure, or velocity. Further, the adaptation of that system seems to be broadly definable in time-related equations similar to fluid flow or electrical flow, or simply the equations of motion of an object. Degree of adaptation or ease of change relates directly to the inertia-inducing term, the initial value of the forcing function, and whether or not additional orders of change to the forcing function exist.

To relate this energy/inertia/adaptation concept to the U.S. energy security problem, consider that infrastructure, established market and customer supplier relationships, history of profit, corporate self-image, inability or unwillingness of leadership to see need for a change, uncertainty and fear of change amongst the public and their leaders, entrenched power and wealth, technological maturity, and other factors contribute to an inertia term that mitigates against change. Commodity shortage, rising prices, real and perceived environmental and economic dangers, operational and technological opportunity, and potential profit opportunity serve as forcing functions to change and adaptation. Also, as in the strong-man view of history, a single remarkable leader can be the final required catalyst, or forcing function, for change. Adaptation registers as "movement," such as toward new markets and new customer/supplier relationships, new infrastructure investment, and maturation and proliferation of emerging technology.

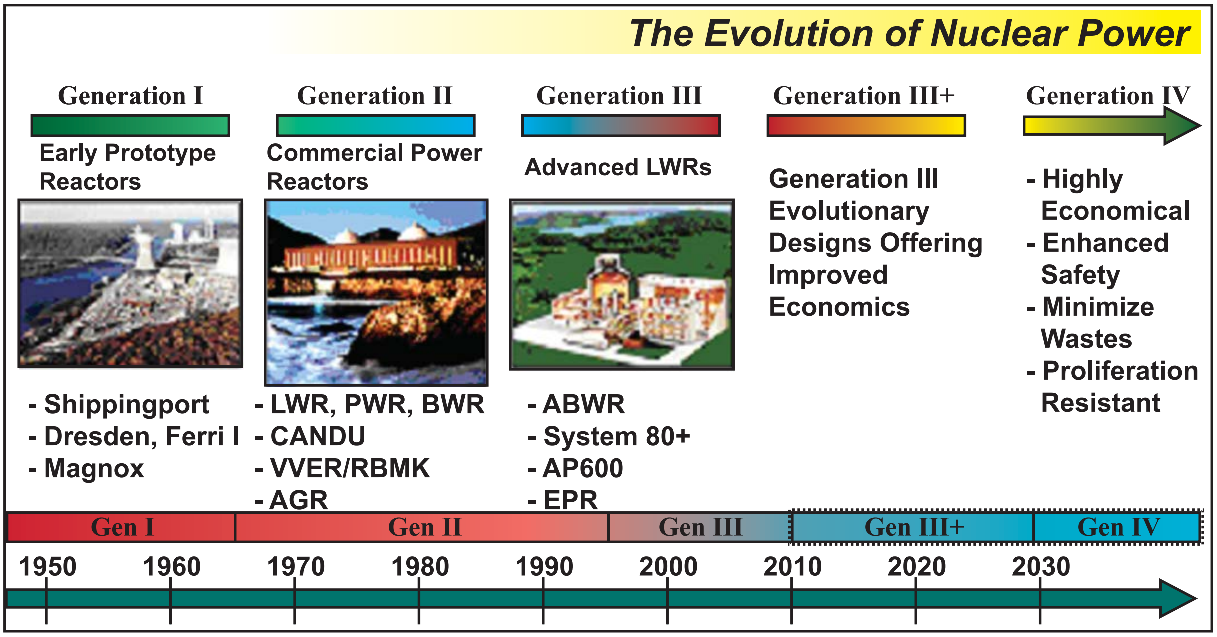
A bottom-line assessment emerging from these concepts is that the current energy paradigm is a fast-moving vessel that will take a very large amount of forcing function to change course. Forcing functions could come from commodity cost skyrocketing to economy-crippling levels; actual petroleum flow disruption; a wild-card psychological phenomenon, such as an announcement of imminent climate calamity from a very well-respected source (would have to be more influential than the IPCC and its report); a revolutionary technological breakthrough (perhaps pioneered by DoD); or an inspiring national leader who applies constant focus on the issue. The disruptive technology effect could eventually change energy source and use by its method of sneaking into nonmainstream markets and improving to the point that its capability to fulfill need is more favorable than the mainstream approach. The Bussard fusion device would definitely be a revolutionary technology. Solar photovoltaics, the wind-power industry, renewable fuels, and high-efficiency engines may be closer to the disruptive technology.

APPENDIX C—NUCLEAR FISSION TECHNOLOGY OPTIONS AND ISSUES

Table 3, taken from the World Nuclear Association [165], shows the type of nuclear fission reactors that are currently being marketed and by whom.

The DOE's insert on the *Evolution of Nuclear Power* from its Generation IV website [166] shows the current and projected "evolution" of nuclear fission power (see illustration and text on opposite page).

Generation IV reactors are either in design or prototype but not off-the-self models yet. Nine founding nations chartered the Generation IV International Forum (GIF) in 2001 to develop the next-generation nuclear reactors. By 2006, 13 members had joined. The GIF is developing six new reactor designs for deployment by 2030.



The Evolution of Nuclear Power

Concerns over energy resource availability, climate change, air quality, and energy security suggest an important role for nuclear power in future energy supplies. While the current Generation II and III nuclear power plant designs provide a secure and low-cost electricity supply in many markets, further advances in nuclear energy system design can broaden the opportunities for the use of nuclear energy. To explore these opportunities, the U.S. Department of Energy's Office of Nuclear Energy, Science, and Technology has engaged governments, industry, and the research community worldwide in a wide-ranging discussion on the development of next-generation nuclear energy systems known as **"Generation IV."**

Table 4 from the World Nuclear Association [167] summarizes the six Gen IV technologies.

No nuclear power plants have been built in the United States since the Three-Mile-Island power plant incident in 1979. Builders of new power plants claim that modern designs significantly improve safety. An Economic Simplified Boiling Water Reactor (ESBWR) uses passive safety techniques that do not require operator or automated intervention [168]. The Pebble Bed Reactor takes advantage of the Doppler broadening effect, which enables U-238 to absorb more neutrons as fuel gets hotter, rather than the U-235, and naturally slows the reaction rate [127].

Norman C. Rasmussen, Macfee Professor of Engineering at MIT, estimated that the likelihood of a serious nuclear accident in any of the current 104 U.S. reactors is approximately 1 in 3.3 million over the next 30 years, which is to the end of their design life [169]. A Nuclear Regulatory Commission (NRC) document, NUREG-1150 [170], shows that expected nuclear accidents are much less probable than the NRC's goals. The NRC Safety Goal is 5 x 10^{-7} for average probability of an individual early fatality per reactor per year: NUREG-1150's projection depends on reactor type PWR 2x10E-8 or BWR 5x10E-11. NRC's goal for average probability of an individual latent cancer death per reactor per year was 2x10E-6. NUREG-1150 predicted for PWR 2x10E-9 and BWR 4x10E-10. These statistics indicate a very low probability of danger and death from nuclear power plants.

To help revitalize the nuclear industry in the United States, DOE started the Global Nuclear Energy Partnership, in 2007. This controversial initiative is intended to encourage global use of nuclear power among the partner countries, to promote use of reprocessed waste as fuel, and internationally standardize business practices to eliminate proliferation danger. The DOE initiated the national Nuclear Power 2010 Program [171] in 2002 as a government/industry cost-sharing venture to facilitate U.S. production of new plants; development and deployment of better technology; and to examine policy, economic, and other issues related to revitalize a U.S. nuclear power industry. The Energy Policy Act of 2005 [172] promotes nuclear power development. Nine U.S. companies have plans to build 16 new plants. The fact that all the plants built in the United States with a 40-year design life come due for refueling and re-licensing by 2020 highlight the importance of a "reenergized" industry.

Table 4. Generation IV Fission Power Technologies

	neutron spectrum (fast/ thermal)	coolant	temperature (°C)	pressure*	fuel	fuel cycle	size(s) (MWe)	Uses
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	288	electricity & hydrogen
Lead-cooled fast reactors	fast	Pb-Bi	550-800	low	U-238 +	closed, regional	50-150** 300-400 1200	electricity & hydrogen
Molten salt reactors	epithermal	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Sodium-cooled fast reactors	fast	sodium	550	low	U-238 & MOX	closed	150-500 500-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-550	very high	UO_2	open (thermal) closed (fast)	1500	electricity
Very high temperature gas reactors	thermal	helium	1000	high	UO_2 prism or pebbles	open	250	hydrogen & electricity

However, wide-scale use of nuclear energy to replace fossil fuel presents complex problems. The 2003 MIT cross-disciplinary study, *The Future of Nuclear Power* [125], recommends maintaining the nuclear-fission power industry as a viable option specifically to reduce the effects of carbon-emission-induced climate change. It cites three other potential mechanisms to mitigate carbon emissions: improved efficiency in use and production of electricity; renewable energy sources; and, carbon sequestration from fossil-fueled power plants. Not intending to exclude or rank any of these choices, the report recommends nuclear power expansion only because it is an additional path to carbon-emission reduction. The report cites four major obstacles to expansion of nuclear fission power: cost, safety, proliferation, and waste.

Nuclear Fission Financial Aspects

Nuclear-power-plant initial cost compares poorly to any other conventional power plant type. Nuclear plants can now be built in 40–60 months rather than the 10 years of the earlier deployment era. But the upfront cost of investment while no income is generated, together with discount rates for capital at 10% or higher, launch the capital outlay estimates anywhere from $2000/kW to $6000/kW ($2 billion to $6 billion initial plant cost for 1 gigawatt) according to the Economics of New Nuclear Plants in Wikipedia [173]. The EIA 2006 report is cited in Wikipedia as showing the lifetime cost variance by fuel source as follows:

- Fission—$59.30 per megawatt hour
- Wind—$55.80 per megawatt hour
- Coal—$53.10 per megawatt hour
- Natural Gas—$52.50 per megawatt hour

These figures do not consider the cost for carbon taxes or backup power.

MIT's 2003 report concluded that the real, levelized power cost was $67/MWe-hour for fission, $42/MWe-hour for pulverized coal plants, and $38–$56/MWe-hour for natural gas-fired, combined-cycle plants. Natural gas plants are relatively cheap to build, but the fuel is expensive, and natural gas prices are now higher than MIT's projected "high." Fission fuel costs are comparatively low, but construction and operations are expensive.

A carbon "cap and trade" policy makes fission more competitive. MIT's analysis showed that a carbon emission tax of $100/ton of carbon emitted would raise the cost of coal to $66/MWe-hour, almost equal to fission's, and gas-fired electricity to equal fission's cost if gas prices were as "high" as $6.72/MBtu of gas. Electric power generation in 2005 pumped 2 billion tons of carbon into the atmosphere according to *Discover Magazine—Better Planet Special Issue 2008*. A $200 billion incentive could promote fission power development. MIT's study proposed a $200 thousand/MWe ($200 million for a 1-GW plant) tax credit for new nuclear construction to encourage the builders of the first 10 new plants.

As a separate aspect of cost, the MIT study noted a dramatic difference in life-cycle costs depending on the fuel-cycle chosen—either once-through fuel or reprocessed fuel. The study participants concluded that the reprocessed-fuel cycle, as recommended in the new DOE Global Partnership initiative, was 4.5 times more expensive than the once-through cycle.

Under current lack of governmental regulation of carbon emissions, fission power is the most expensive electrical power plant option to build. It requires the most upfront capital, does not start returning investment for up to 5 years (maybe more) and takes many years to recoup total investment. Under

Table 3. Current Fission Reactor Options

Country and Developer	Reactor	Size MWe	Design Progress	Main Features (improved safety in all)
US-Japan (GE-Hitachi, Toshiba)	ABWR	1300	Commercial operation in Japan since 1996-7. In US: NRC certified 1997, FOAKE.	• Evolutionary design. • More efficient, less waste. • Simplified construction (48 months) and operation.
USA (Westinghouse)	AP-600 AP-1000 (PWR)	600 1100	AP-600: NRC certified 1999, FOAKE. AP-1000 NRC certification 2005.	• Simplified construction and operation. • 3 years to build. • 60-year plant life.
France-Germany (Areva NP)	EPR US-EPR (PWR)	1600	Future French standard. French design approval. Being built in Finland. US version developed.	• Evolutionary design. • High fuel efficiency. • Low cost electricity.
USA (GE)	ESBWR	1550	Developed from ABWR, under certification in USA	• Evolutionary design. • Short construction time.
Japan (utilities, Mitsubishi)	APWR US-APWR EU-APWR	1530 1700 1700	Basic design in progress, planned for Tsuruga US design certification application 2008.	• Hybrid safety features. • Simplified Construction and operation.
South Korea (KHNP, derived from Westinghouse)	APR-1400 (PWR)	1450	Design certification 2003, First units expected to be operating c 2012.	• Evolutionary design. • Increased reliability. • Simplified construction and operation.
Germany (Areva NP)	SWR-1000 (BWR)	1200	Under development, pre-certification in USA	• Innovative design. • High fuel efficiency.
Russia (Gidropress)	VVER-1200 (PWR)	1200	Replacement for Leningrad and Novovoronezh plants	• High fuel efficiency.
Russia (Gidropress)	V-392 (PWR)	950-1000	Two being built in India, Bid for China in 2005.	• Evolutionary design. • 60-year plant life.
Canada (AECL)	CANDU-6 CANDU-9	750 925+	Enhanced model Licensing approval 1997	• Evolutionary design. • Flexible fuel requirements. • C-9: Single stand-alone unit.
Canada (AECL)	ACR	700 1080	undergoing certification in Canada	• Evolutionary design. • Light water cooling. • Low-enriched fuel.
South Africa (Eskom, Westinghouse)	PBMR	170 (module)	prototype due to start building (Chinese 200 MWe counterpart under const.)	• Modular plant, low cost. • High fuel efficiency. • Direct cycle gas turbine.
USA-Russia et al (General Atomics - OKBM)	GT-MHR	285 (module)	Under development in Russia by multinational joint venture	• Modular plant, low cost. • High fuel efficiency. • Direct cycle gas turbine.

PWR-Pressurized Water Reactor uses water under high pressure as coolant and moderator (about 60% of reactors –Three Mile Island is one)
BWR-Boiling Water Reactors use water as coolant and moderator under somewhat lower temperature than the PWRs
(Advanced Boiling Water Reactors and Economic Simplified Boiling Water Reactors are updated subtypes)
PHWR (CANDU) is a Canadian designed Pressure Heavy Water Reactor that uses heavy water as moderator and coolant
RBMK Russian designed reactor uses water as coolant, graphite as moderator and is a Plutonium breeder. Chernobyl had four RBMKs.
GCR/AGCR Gas Cooled Reactor or Advanced Gas Cooled Reactor use graphite moderator and gas (CO2) as coolant
LMFBR -Liquid Metal Fast Breeder Reactors use lead (lead-bismuth eutectic) or sodium as coolants without moderators and breed plutonium
AHR-Aqueous Homogeneous Reactors have uranium salt mixed with the moderator in heavy or light water and are the easiest to initiate with only a pound of P-239 or U-233 required to run, but they have corrosion problems

deregulation of the power industry, power producers compete in cost to provide electricity to distributors. Electricity providers (the business generating the electricity) can be replaced quickly whether or not their investments have been recouped. This market environment drives power production decisions away from investments that pay off only in the very long-term—such as fission power.

Finally, the MIT study concluded that, "Nuclear power will succeed in the long run only if it has a lower cost than competing technologies."

Nuclear Fission Safety

The MIT study noted that nuclear plant safety is inherently complex. Reactor design, workforce competence, management processes and commitment, and policing of standards all contribute to complexity. MIT concluded, "There is no plant design that is totally risk free." New reactor designs (as previously noted in this paper) can improve safety. However, "the record of reprocessing plants is not good" according to the MIT report. Current NRC safety standards are appropriate and must be extended globally. MIT recommended research focus on fuel-cycle safety analysis and reactor design for safety. The study suggests that nuclear safety requires continuous, sustained commitment to safety performance above all other operational issues.

Fission Waste Management

MIT's study states, "The management and disposal of high-level radioactive spent fuel from the nuclear fuel cycle is one of the most intractable problems facing the nuclear power industry…" The group agreed with other studies that stable geologic formations can contain the nuclear in a stable salt dome waste and prevent its impacting the "biosphere." However, significant issues regarding mechanisms of handling, storage, and transportation are unresolved. The DOE scheduled a 1998 opening of the Yucca Mountain repository that would be the master warehouse for nuclear waste storage in a geologically stable salt dome. However, legal battles have prevented its use for storing nuclear waste. Recently, Congress Daily [174] reported that the planned Yucca Mountain waste repository cost estimate has escalated to $90 billion, which will include 100 years of operation. The waste will remain radioactive for hundreds of thousands of years.

Spent fuel continues to stockpile at reactors and above ground facilities. With the projected expansion of the nuclear industry to an additional 1000 separate 1-gigawatt plants, an additional Yucca-Mountain-equivalent geologic storage site would be needed every 3–4 years.

The MIT nuclear fission study recommended investigation into deep bore-hole storage, alternatives and additions to Yucca Mountain, and investigation into multiple-decade centralized storage for fuel until it can be geologically deposited for the duration of the radioactive threat. Various fission waste-handling schemes have been suggested—from launching the material into outer space, to geologic storage, to recycling the waste to new fuel, to irradiating the waste to quickly reduce its half life. However, no fail-safe mechanism has emerged. Perhaps this area would be a good target for potential research to remove one impediment to nuclear fission industry expansion.

Nuclear Weapon Proliferation

The MIT study concludes that nuclear power expansion should not proceed "unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small." Nuclear industry expansion increases the risk of the irresponsible actor or the dedicated foe gaining access to technological information, facilities, and stocks of weapons-grade fuel. The MIT study recommends various approaches to mitigate the proliferation threat.

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Energy & National Security

An Exploration of Threats, Solutions and Alternative Futures

Larry C. Triola

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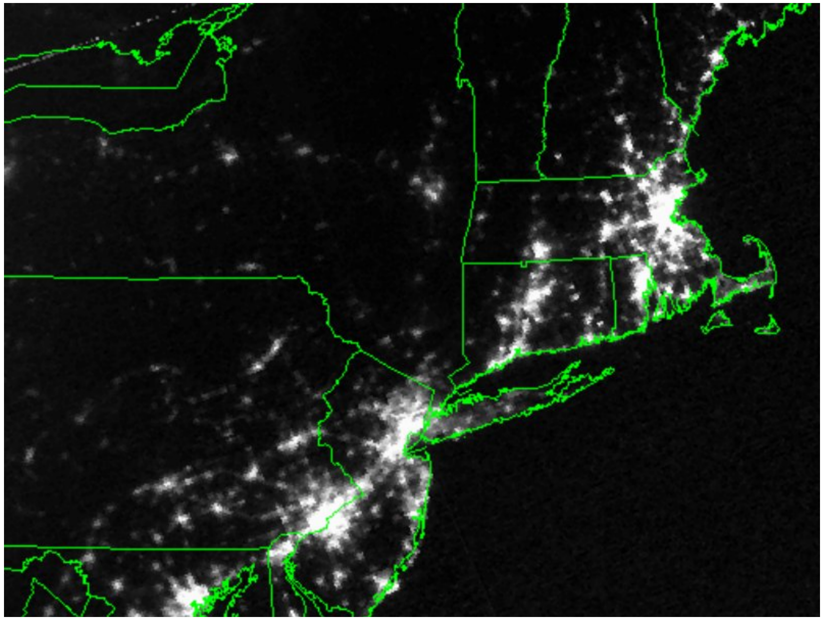
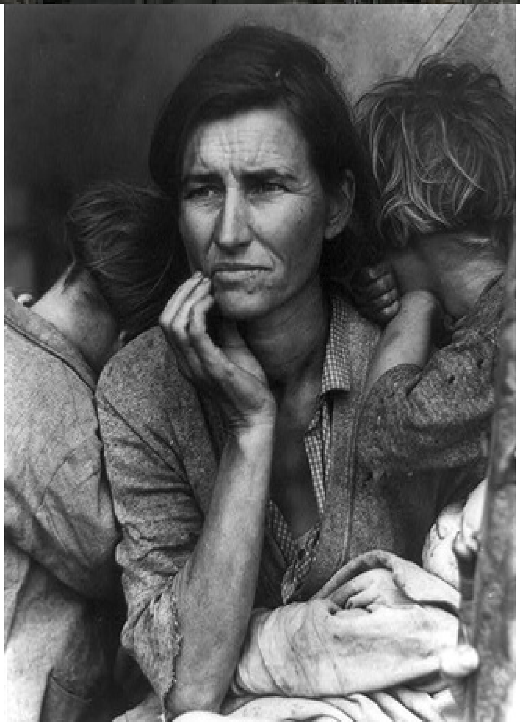
DoD Fuel Use Strategy

Infrastructure Vulnerability



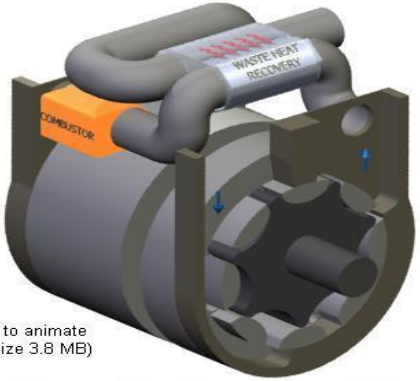
Economic Energy Security



Climate and Implications

Fuel Efficient Platform Design

Engine Efficiency



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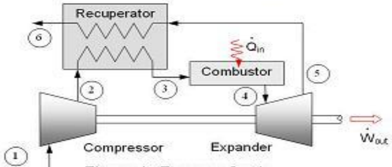
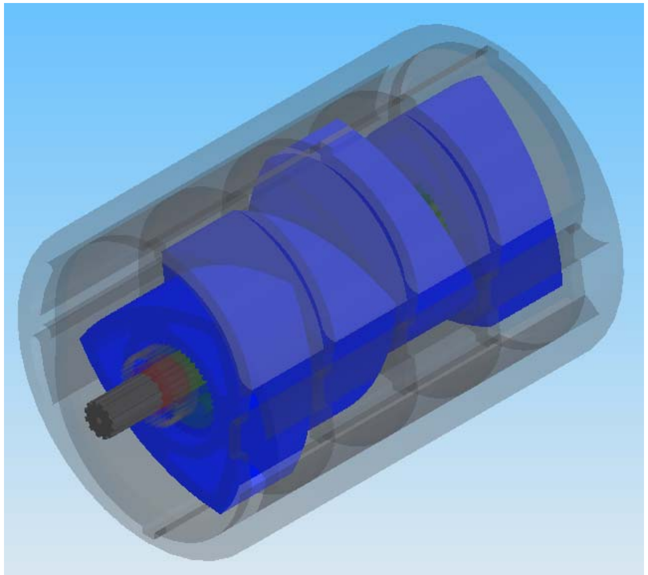
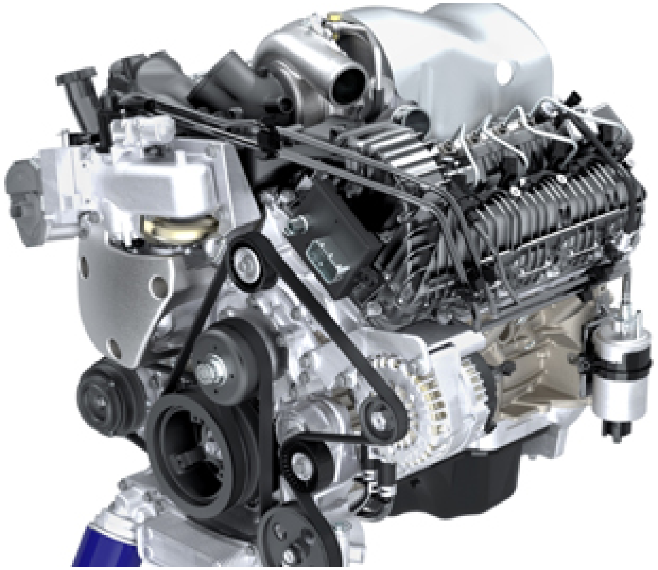
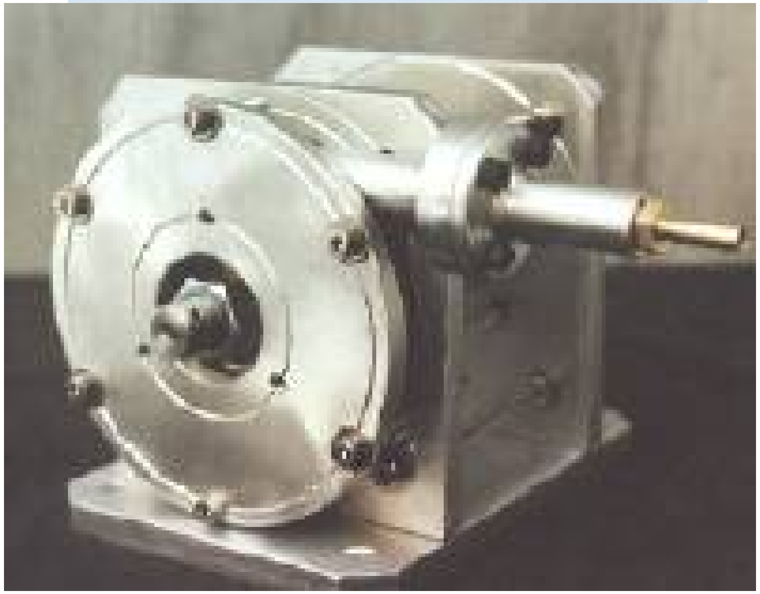


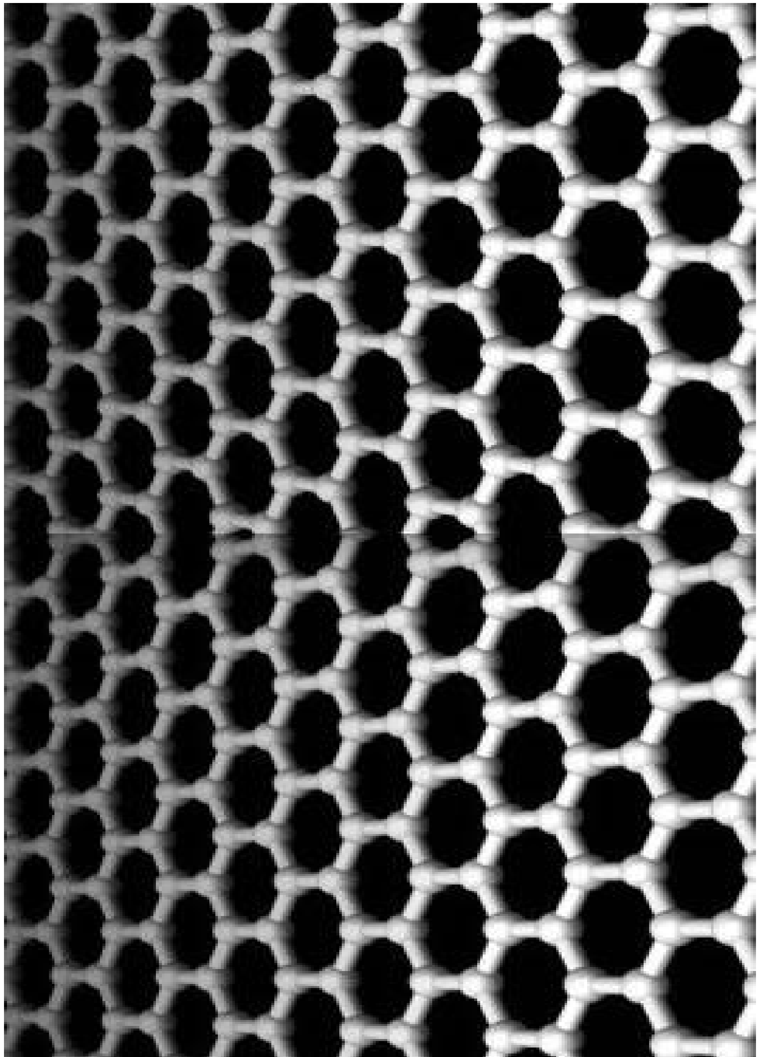
Figure 1: Brayton Cycle



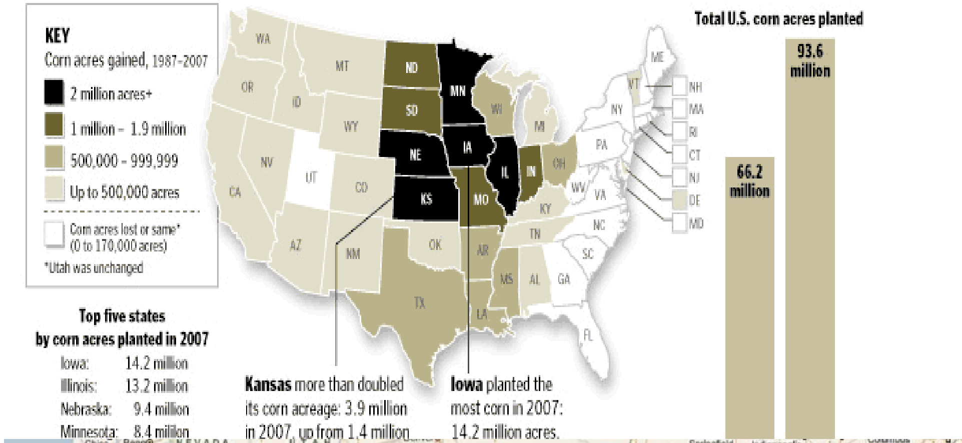




Electric Vehicle Technology



Renewable Synthetic Fuels



KEY
Corn acres gained, 1987-2007
■ 2 million acres+
▨ 1 million - 1.9 million
▨ 500,000 - 999,999
☐ Up to 500,000 acres
☐ Corn acres lost or same* (0 to 170,000 acres)
*Utah was unchanged

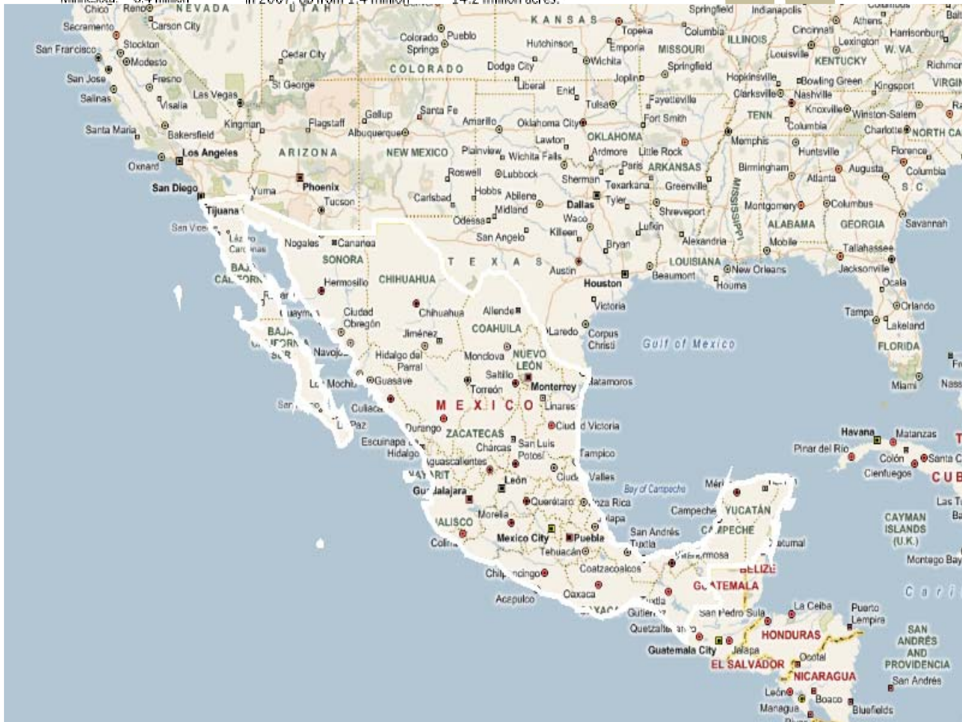
Top five states by corn acres planted in 2007

Iowa:	14.2 million
Illinois:	13.2 million
Nebraska:	9.4 million
Minnesota:	8.4 million

Kansas more than doubled its corn acreage: 3.9 million in 2007, up from 1.4 million

Iowa planted the most corn in 2007: 14.2 million acres.

Total U.S. corn acres planted



Alternative Power and Distribution

5 DefenseNews March 5, 2007

WORLD NEWS

Fighting for Fusion

Why the U.S. Isn't Funding A Promising Energy T

y WILLIAM MATTHEWS

On Nov. 11, 2005, the day his mall fusion reactor exploded in shower of sparks and metal ragments, even physicist Robert Bussard didn't know what he had chieved.

For 11 years, the U.S. Navy quitly funded Bussard's research. It vas a small project with a very arge goal: deriving usable energy rom controlled nuclear fusion.

Funding ran out at the end of 005 and Bussard was supposed o spend the tail end of the year hutting down his lab. He kept ostponing that in an effort to finsh a final set of experiments.

He completed low-power tests September and October and bean high-power testing of the reactor in November.

After four tests Nov. 9 and 10, n electromagnetic coil short-ciruited as electricity surged rough it, "vaporizing" part of his eactor, Bussard said, and bringg his tests to an end.

"The following Monday, we tarted to tear the lab down. Noody had time to reduce the data at was stored on the computer. wasn't until early December at we reduced the data and oked at it and realized what we ad done," he said.

Bussard said he and his small am of scientists had proven that uclear fusion can be harnessed s a usable source of cheap, clean nergy.

But for more than a year now, ussard has been unable to move the next step in his research. t 78, he is in ill health and his ientific allies fear that the longought breakthrough he appears have achieved may fade into bscurity before it can be fully eveloped.

No small part of the problem is at the U.S. Energy Department as a competing project, and has pent five decades and $18 billion n an as-yet-unsuccessful effort solve the fusion puzzle.

"Who would believe that a tiny ompany based on one person

BORON FUSION

U.S. physicist Robert Bussard believes that a novel form of atomic fusion based on boron could be harnessed to create electricity cheaply and cleanly, without hydrogen fusion's superhot temperatures, dangerous radiation, and enormous reactors.

Electromagnetic coils

Electron containment field

Insulating stands

Fuel
Boron and protons are injected

Yield
Helium and electricity are captured

Bussard says the boron fusion could be induced by creating an inertial electrostatic confinement machine that uses electromagnetic energy to force boron and protons together.

FUSION REACTIONS

HYDROGEN: Hot and dirty

- Powers the sun and thermonuclear bombs.
- Yields heat and neutron radiation.

● Proton ● Neutron

Deuterium
(heavy hydrogen 2)

Tritium
(heavy hydrogen 3)

Helium

Free neutron, heat and other radiation

BORON: Non-radioactive

- Could be tested in new kind of machine.
- Yields helium and electricity.

Hydrogen nucleus

Boron

Carbon

Beryllium

3 Helium atoms and electricity

SOURCE: *The Advent of Clean Nuclear Fusion*, Robert W. Bussard, Ph.D., Oct. 2006

DEFENSE NEWS GRAPHIC BY JOHN BRETSCHNEIDER

His idea was the basis for the

process does not produce ra-

"Who would believe that a tiny company based on one person could solve the riddle that has escaped literally thousands of researchers?"

Don Gay
Former U.S. Navy engineer

with deuterium, not boron — in November 2005 proved that the boron process will work.

The boron reactor would be similar to, but more powerful than, the reactor that blew up in 2005.

Bussard's reactor design is built upon six shiny metal rings joined to form a cube — one ring per side. Each ring, about a yard in diameter, contain copper wires wound into an electromagnet.

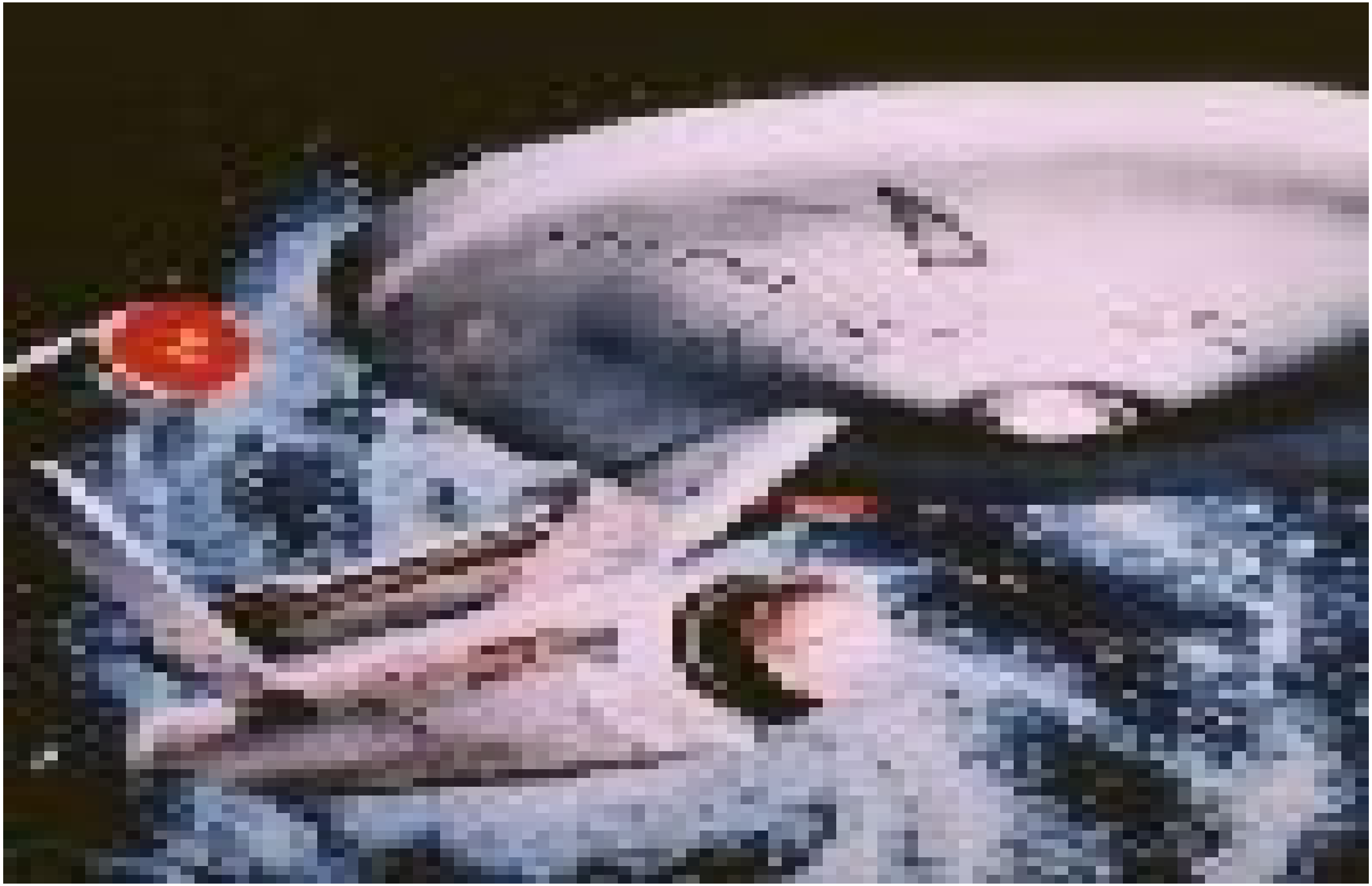
The reactor operates inside a vacuum chamber.

When energized, the cube of electromagnets creates a magnetic sphere into which electrons are injected. The magnetic field squeezes the electrons into a dense ball at the reactor's core, creating a highly negatively charged area.

To begin the reaction, boron-11 nuclei and protons are injected into the cube. Because of their positive charge, they accelerate to the center of the electron ball. Most of them sail through the center of the core and on toward the opposite side of the reactor. But the negative charge of the electron ball pulls them back to the center. The process repeats, perhaps thousands of times, until the boron nucleus and a proton collide with enough force to fuse.

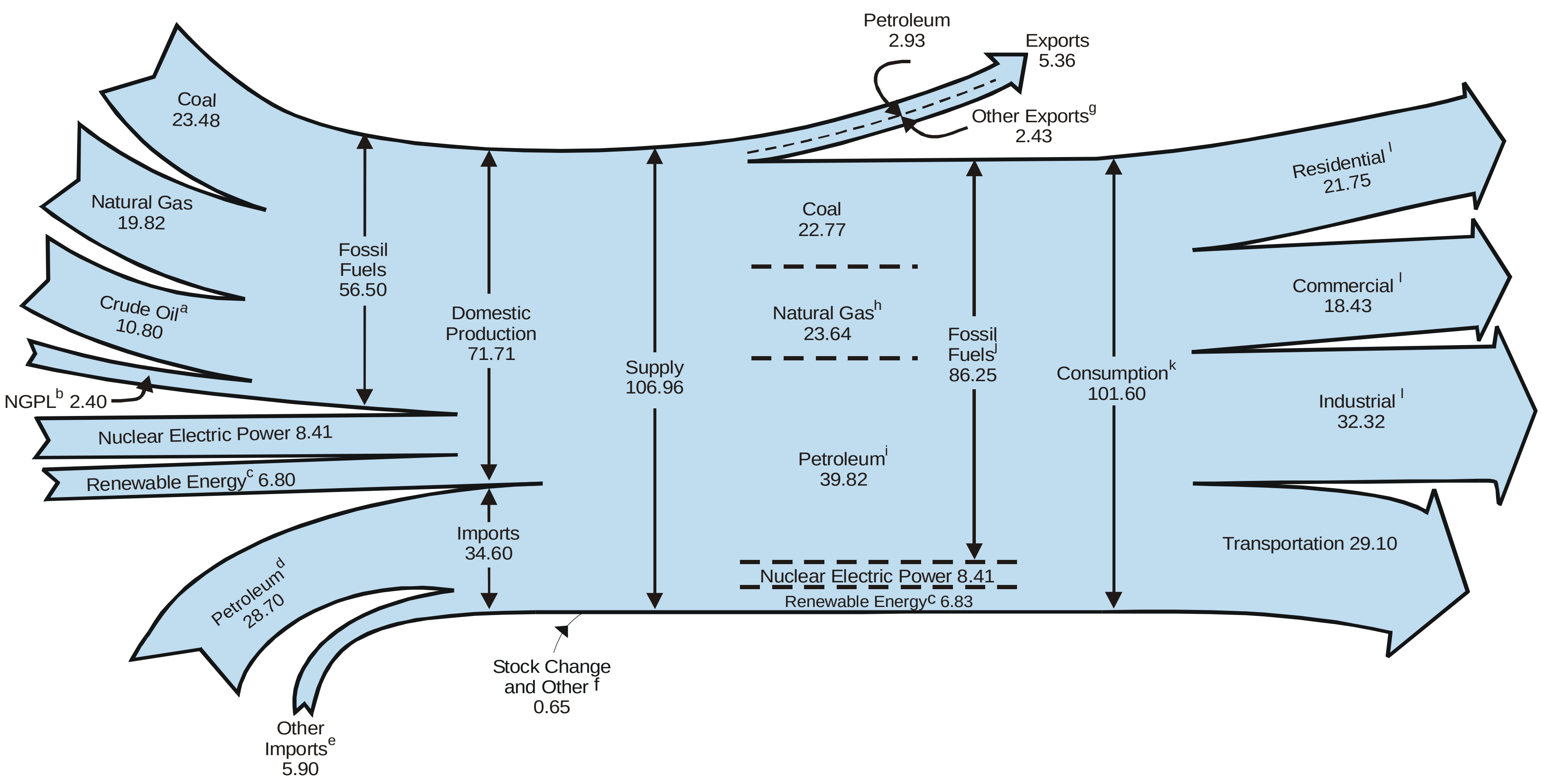
That fusion turns boron-11 into highly energetic carbon-12, which promptly splits into a helium nucleus and a beryllium nucleus.

Quo Vadimus?



BACKUP SLIDES

Diagram 1. Energy Flow, 2007
(Quadrillion Btu)



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[a] Includes lease condensate.

[b] Natural gas plant liquids.

[c] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.

[d] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.

[e] Natural gas, coal, coal coke, fuel ethanol, and electricity.

[f] Adjustments, losses, and unaccounted for.

[g] Coal, natural gas, coal coke, and electricity.

[h] Natural gas only; excludes supplemental gaseous fuels.

[i] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.

[j] Includes 0.03 quadrillion Btu of coal coke net imports.

[k] Includes 0.11 quadrillion Btu of electricity net imports.

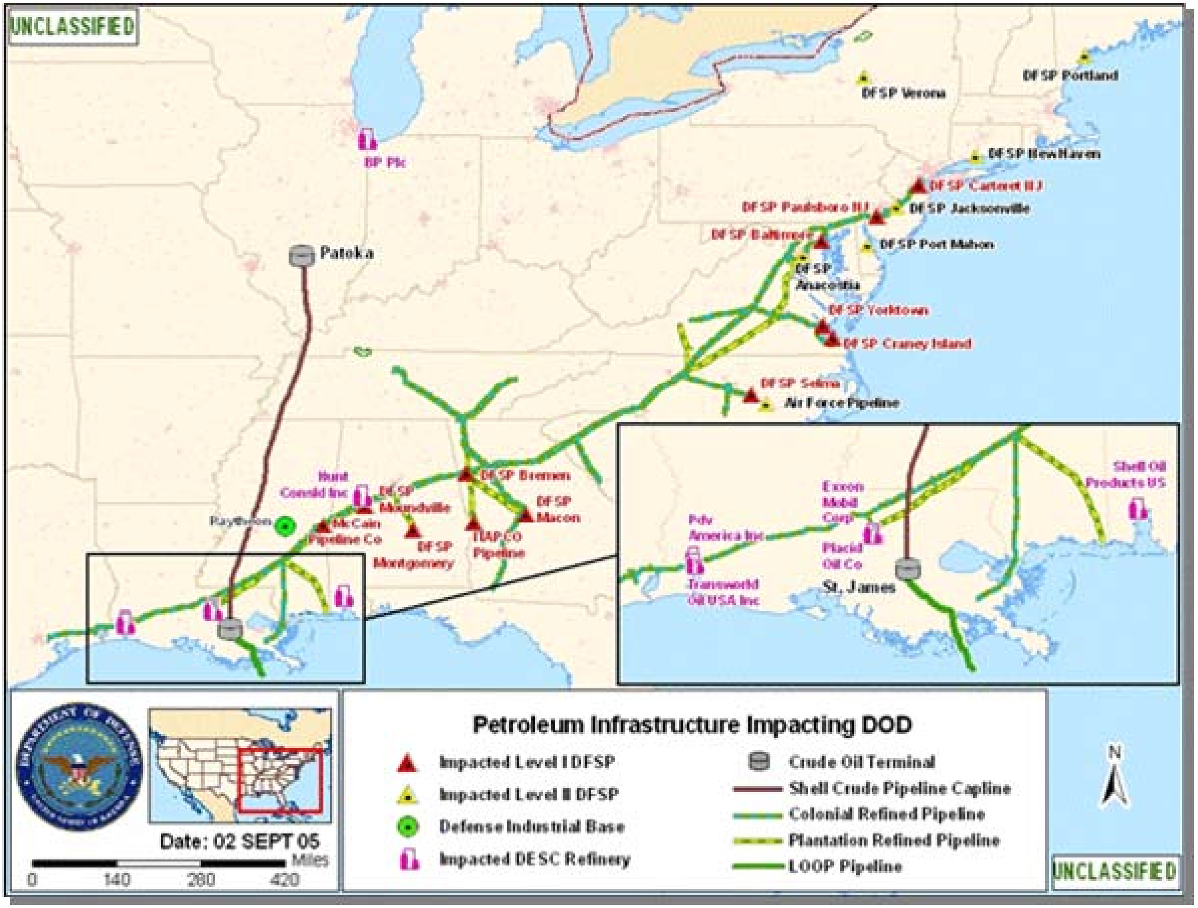
[l] Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

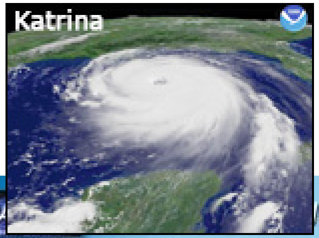
Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

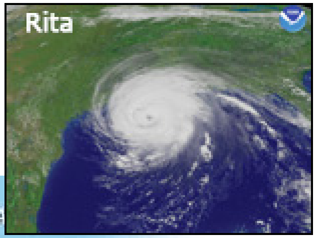
Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

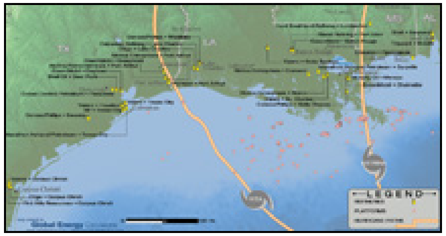
Fuel Convoy

Interdependency Analysis







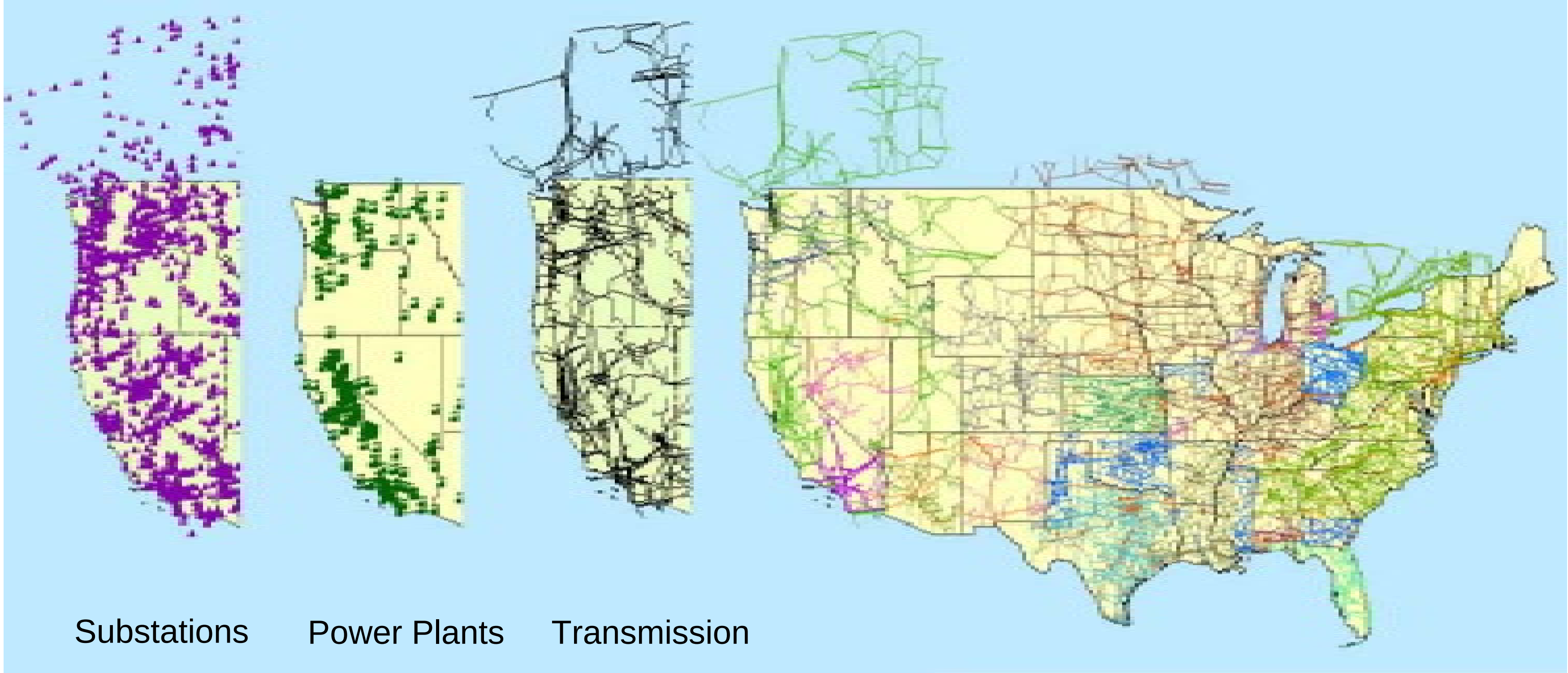


Analysis – Supply to End Users:

- Available networks
- Logistics
- Impact magnitude

Katrina/Rita Effect:

CONUS Electric Power Dataset



Data Build-out Example

CONUS Electric Power Infrastructure Dataset

ISSUE:

- **Insufficient accuracy in commercial datasets**
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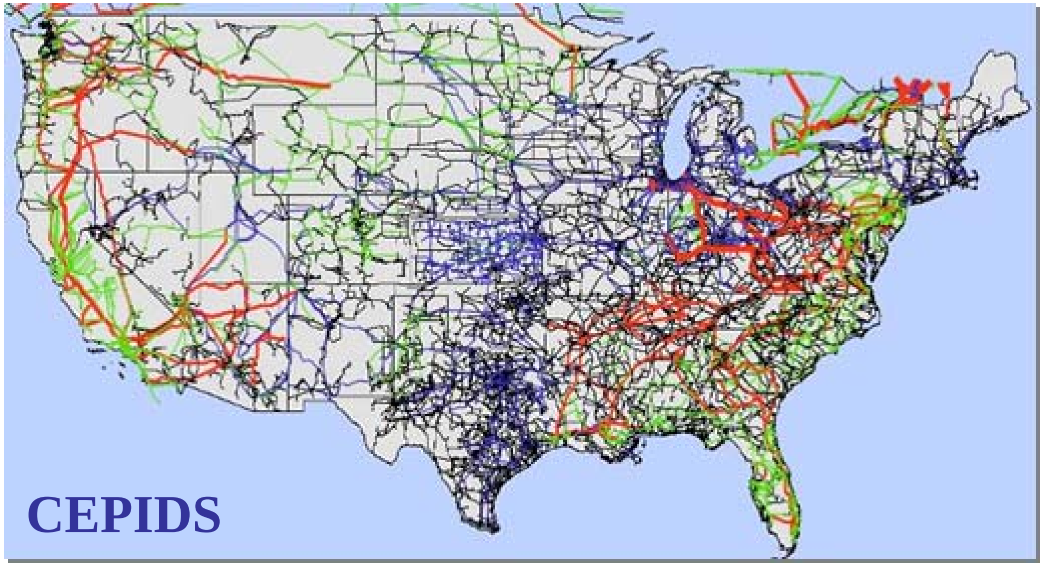

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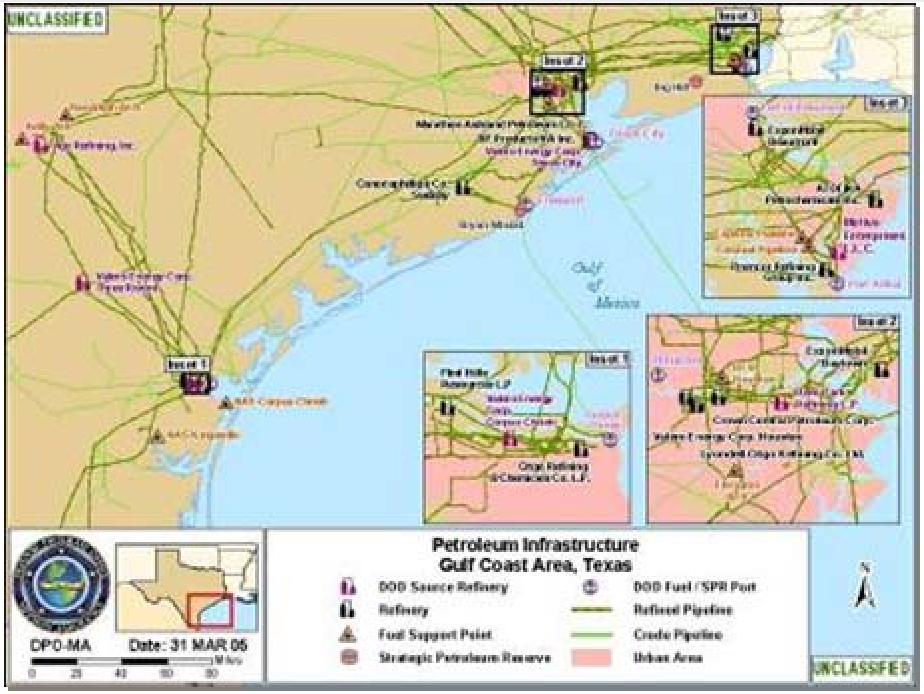

Petroleum

Leveraging existing data

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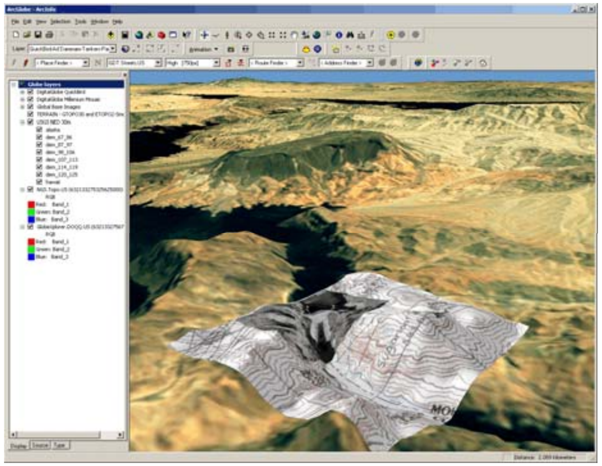
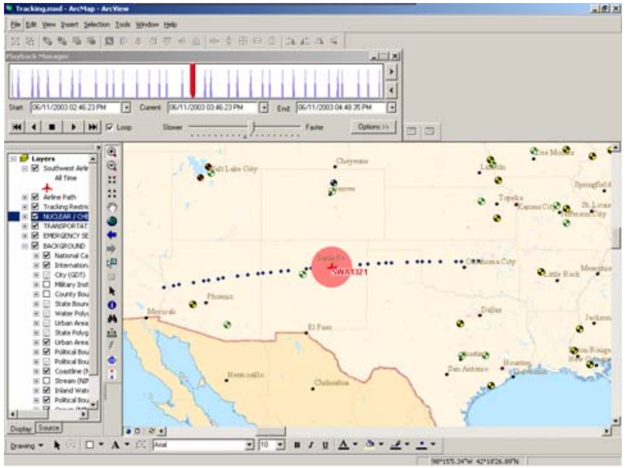
Geospatial Analysis Capabilities

View Shed/Line of Sight



Terrain Modeling/Mobility

3-D Fly Through



Sensor Integration

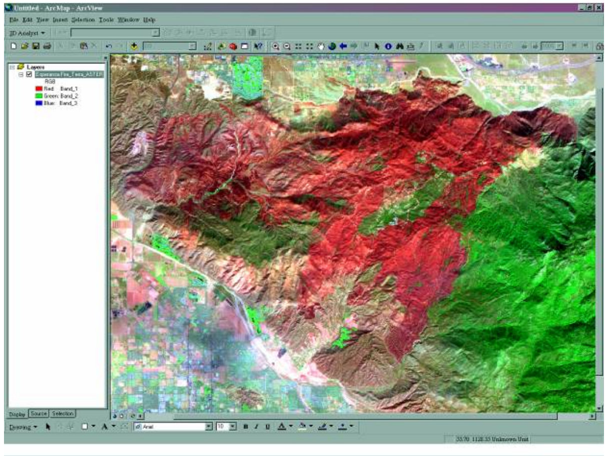
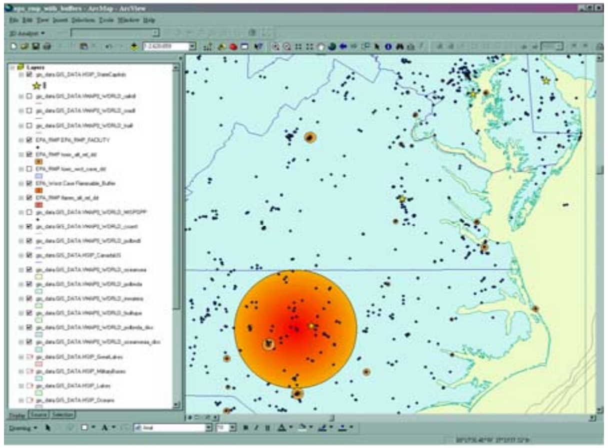
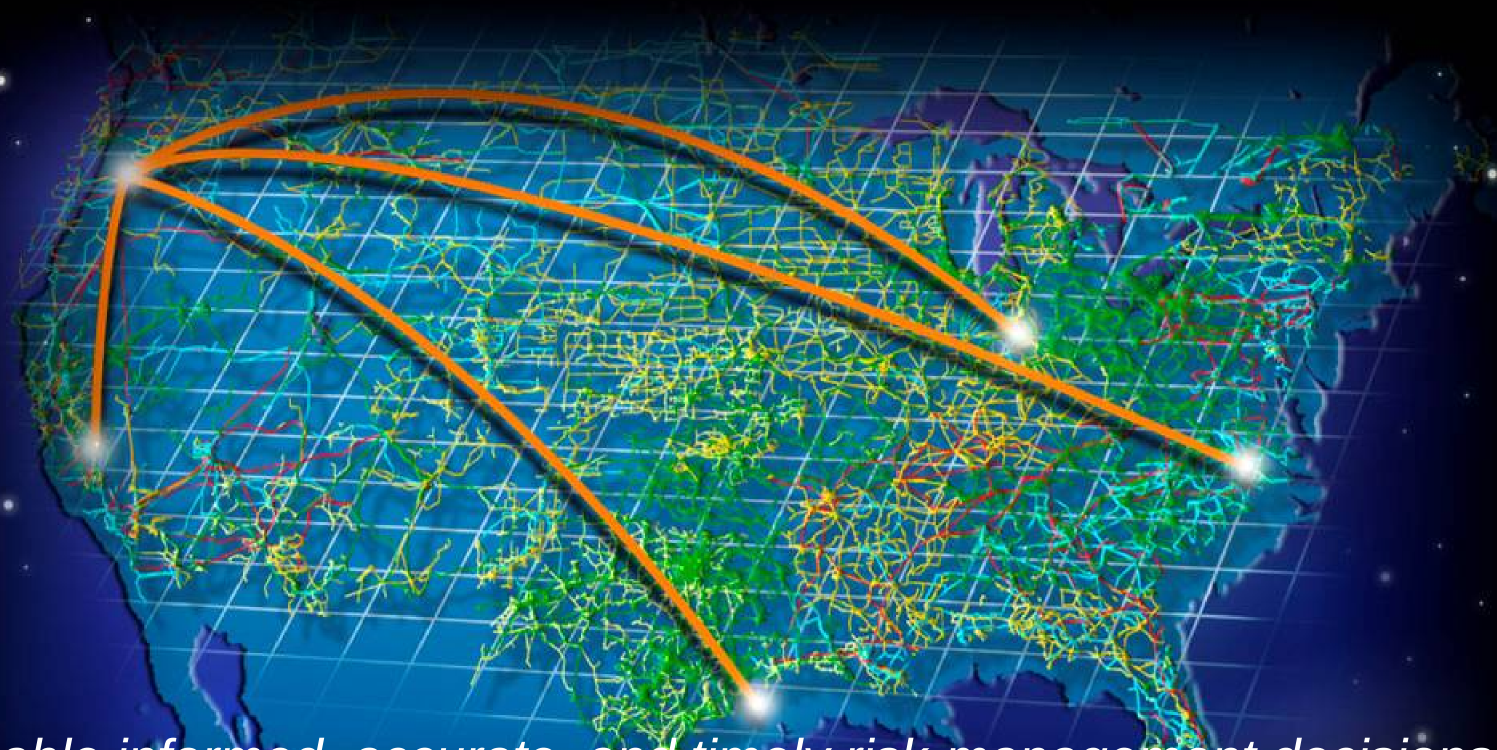


Image Exploitation



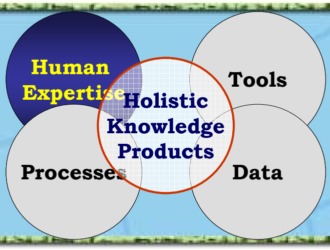
Site Selection

Mission



- *Enable informed, accurate, and timely risk-management decisions spanning the full spectrum of operations through technical analysis, assessment, integration, innovation, and decision support to assure the availability of physical and non-physical networks and infrastructure for DoD, federal, state, and local agency missions.*

Analyst Backgrounds



INDUSTRY EXPERIENCE

verizon

Dominion
It all starts here:

AT&T

TRW

KOCH INDUSTRIES INC

NORTEL NETWORKS

STATOIL

BASF

ALLTEL®

TENNECO

pepco

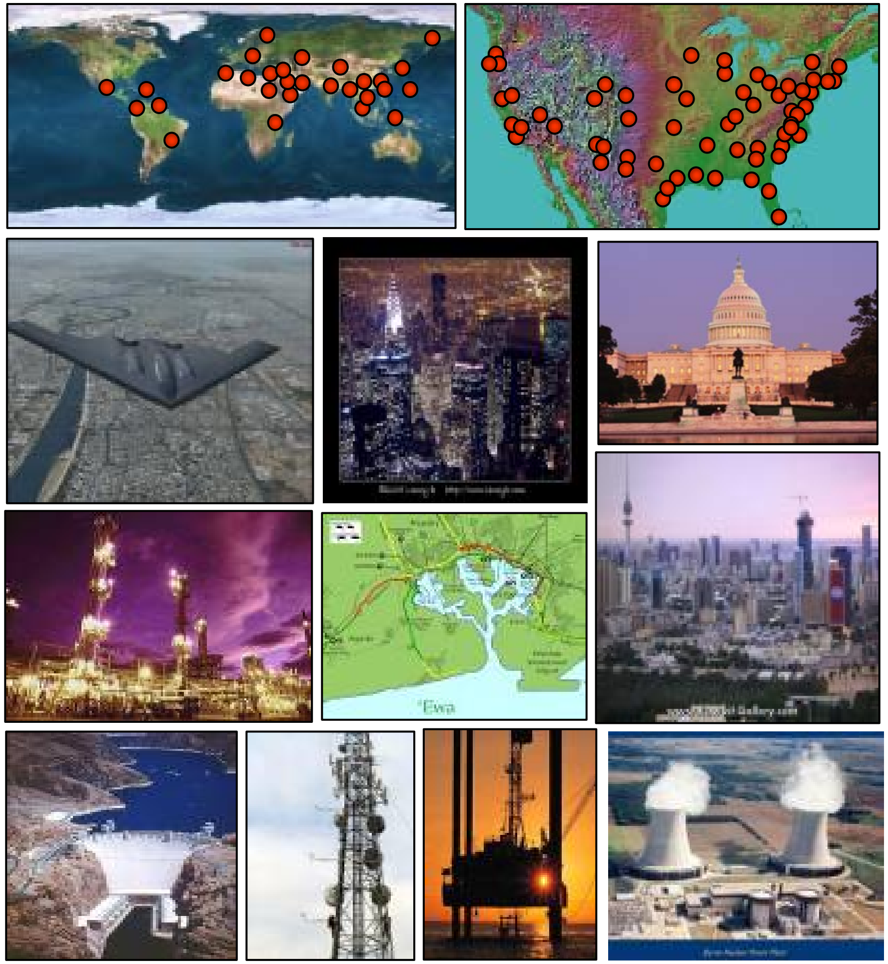
Constellation Energy

GTE

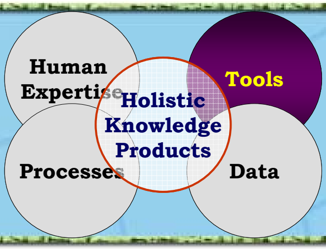
FMC

ARCO

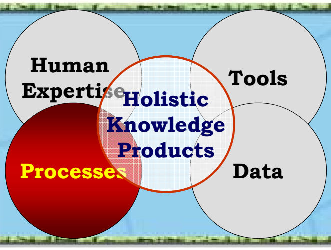
TARGETING & PROTECTING EXPERIENCE

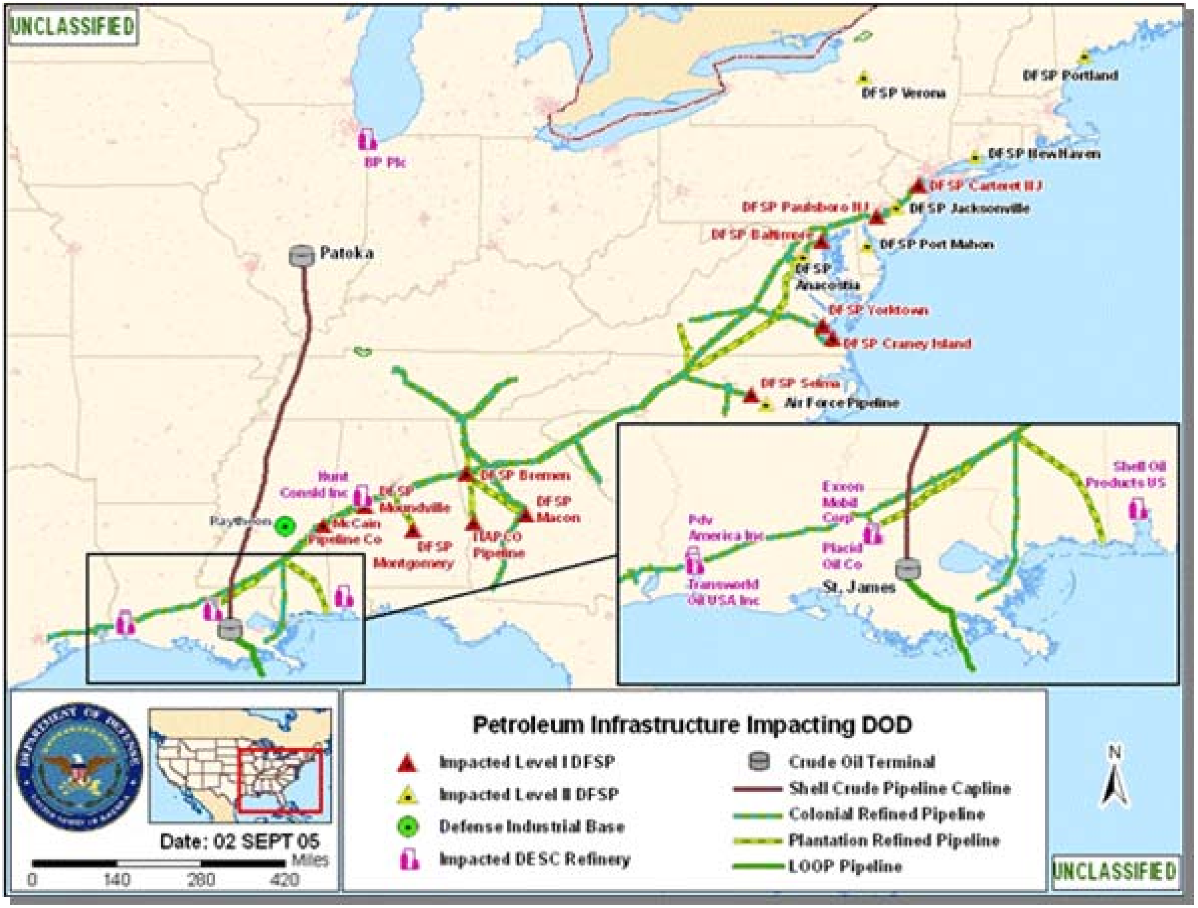


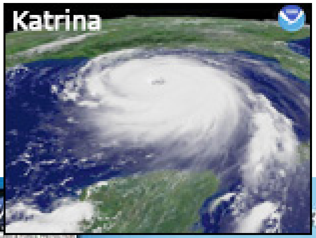
Tools for Analysts & Users

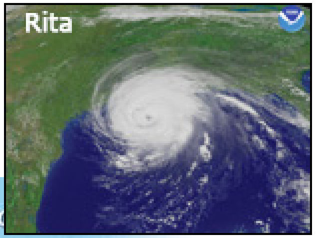


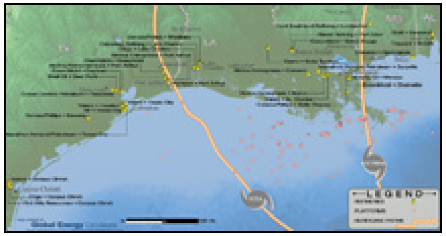
Interdependency Analysis











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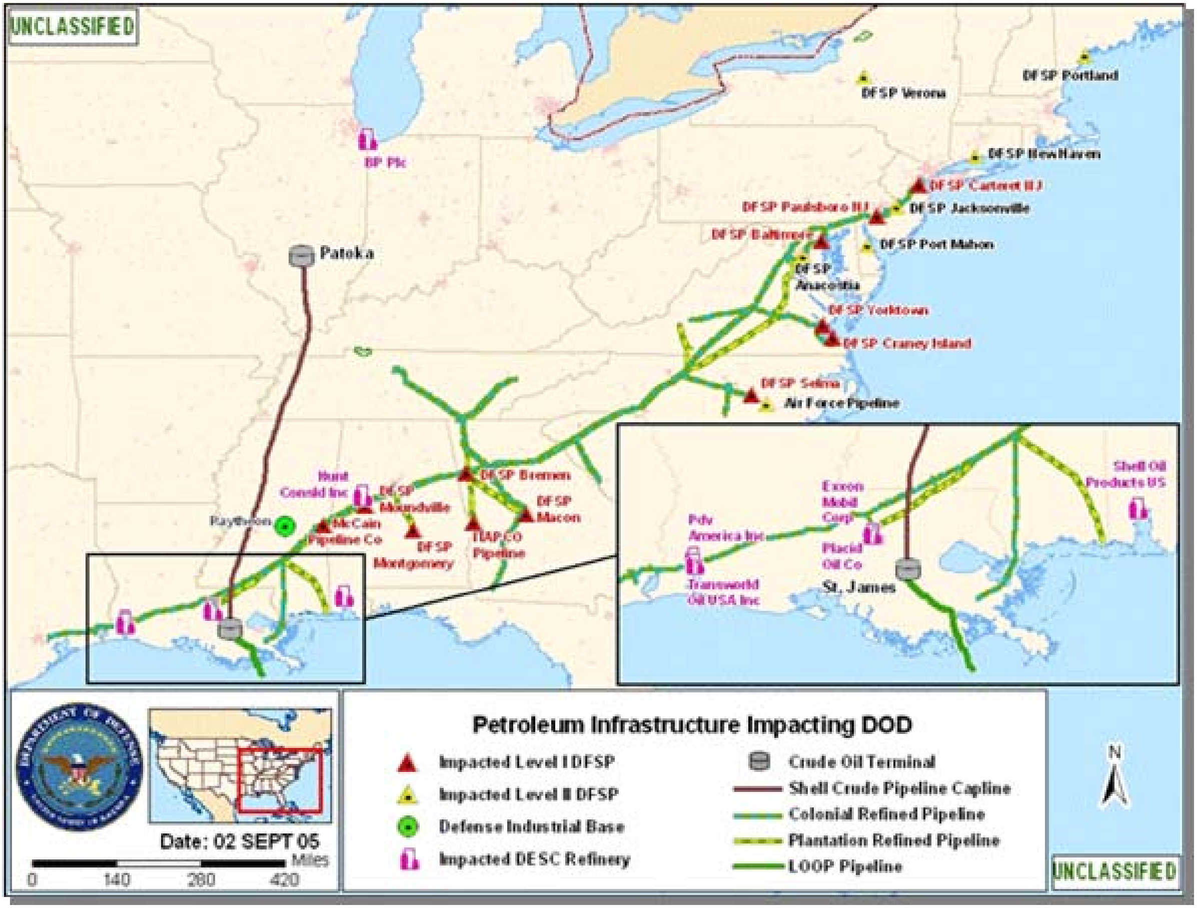

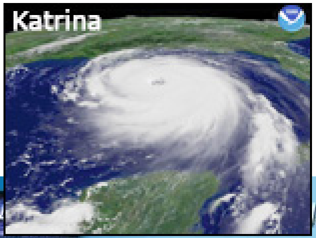

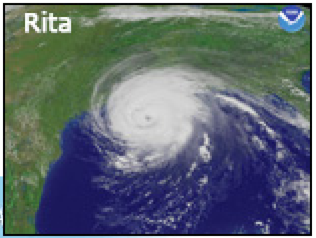

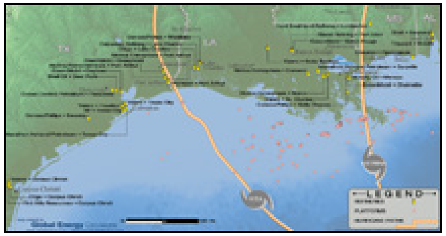

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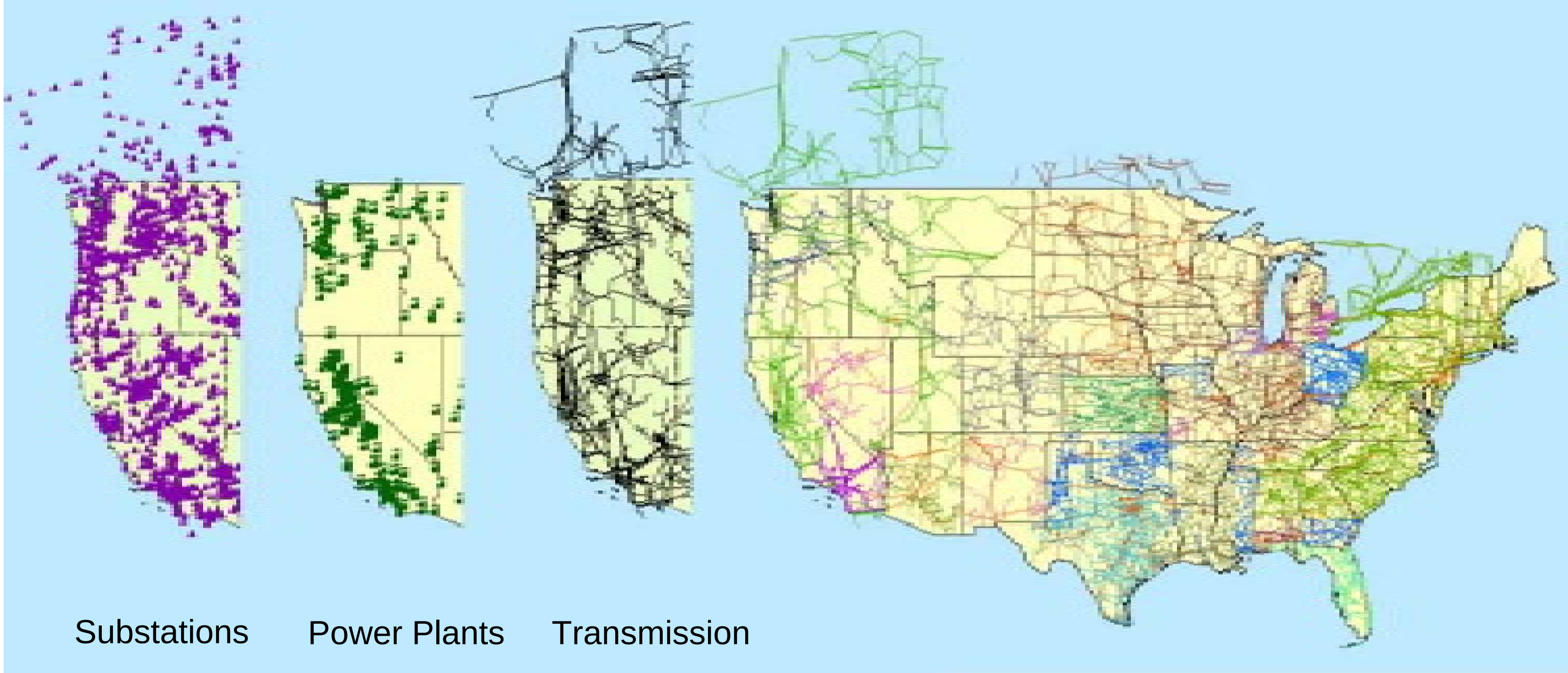

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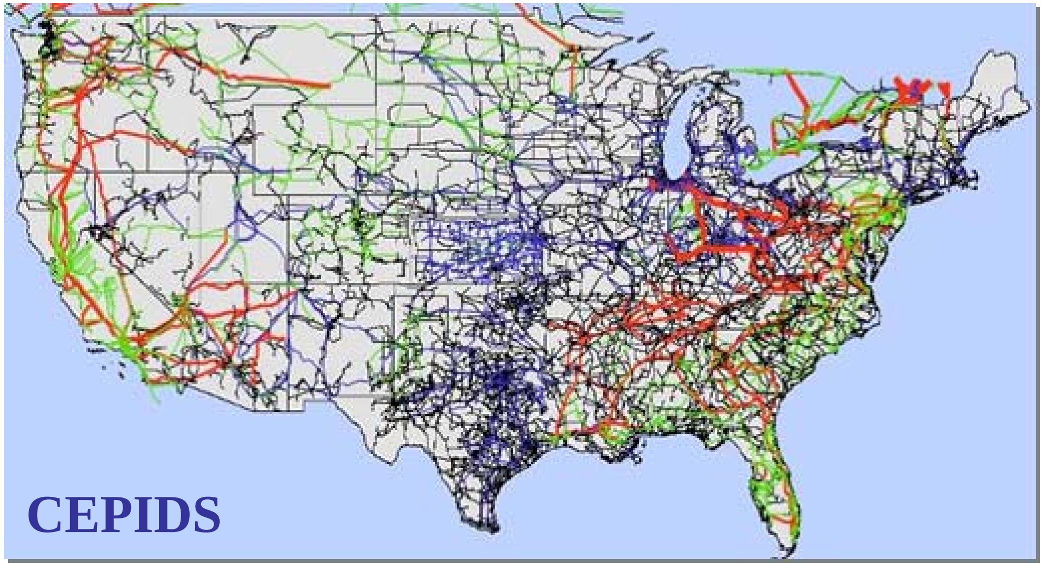

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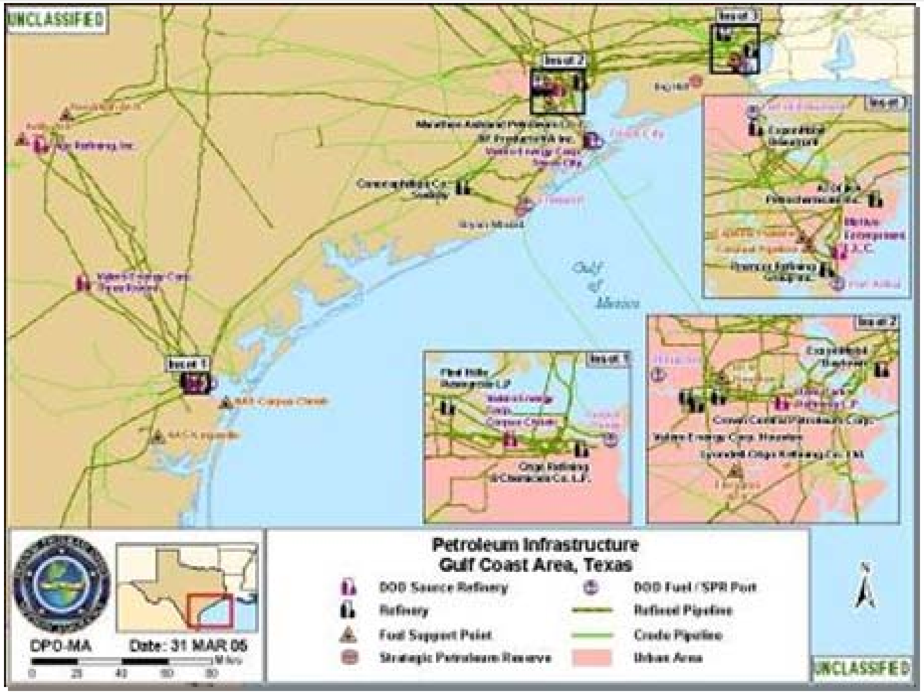

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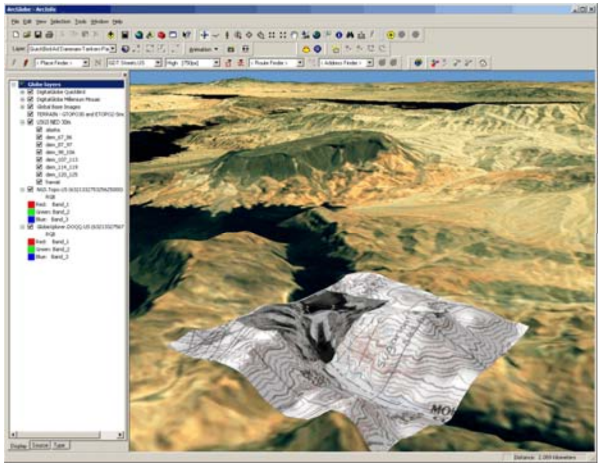

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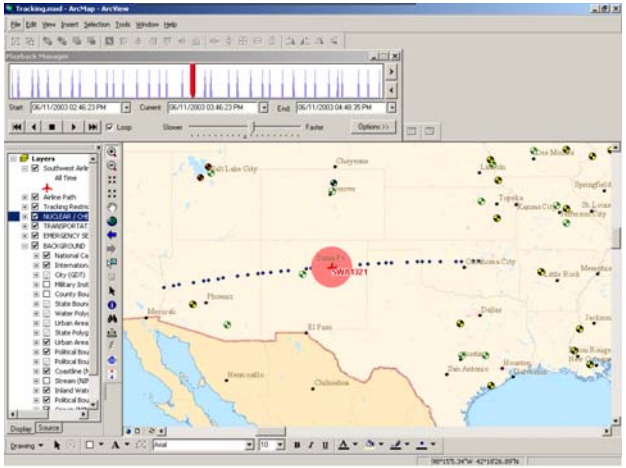
3-D Fly Through



Sensor Integration

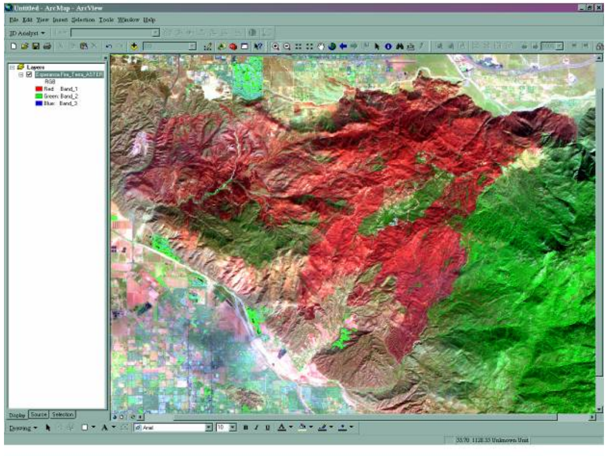
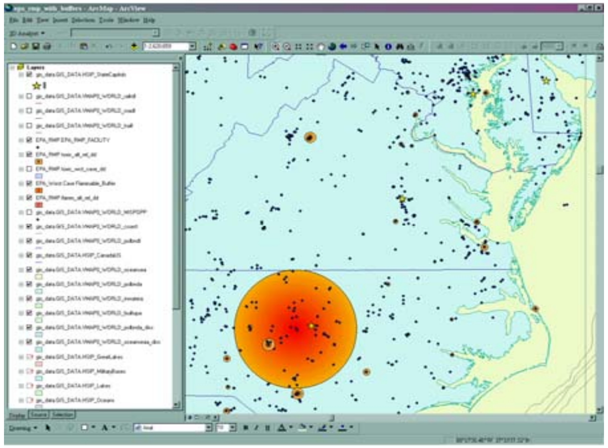
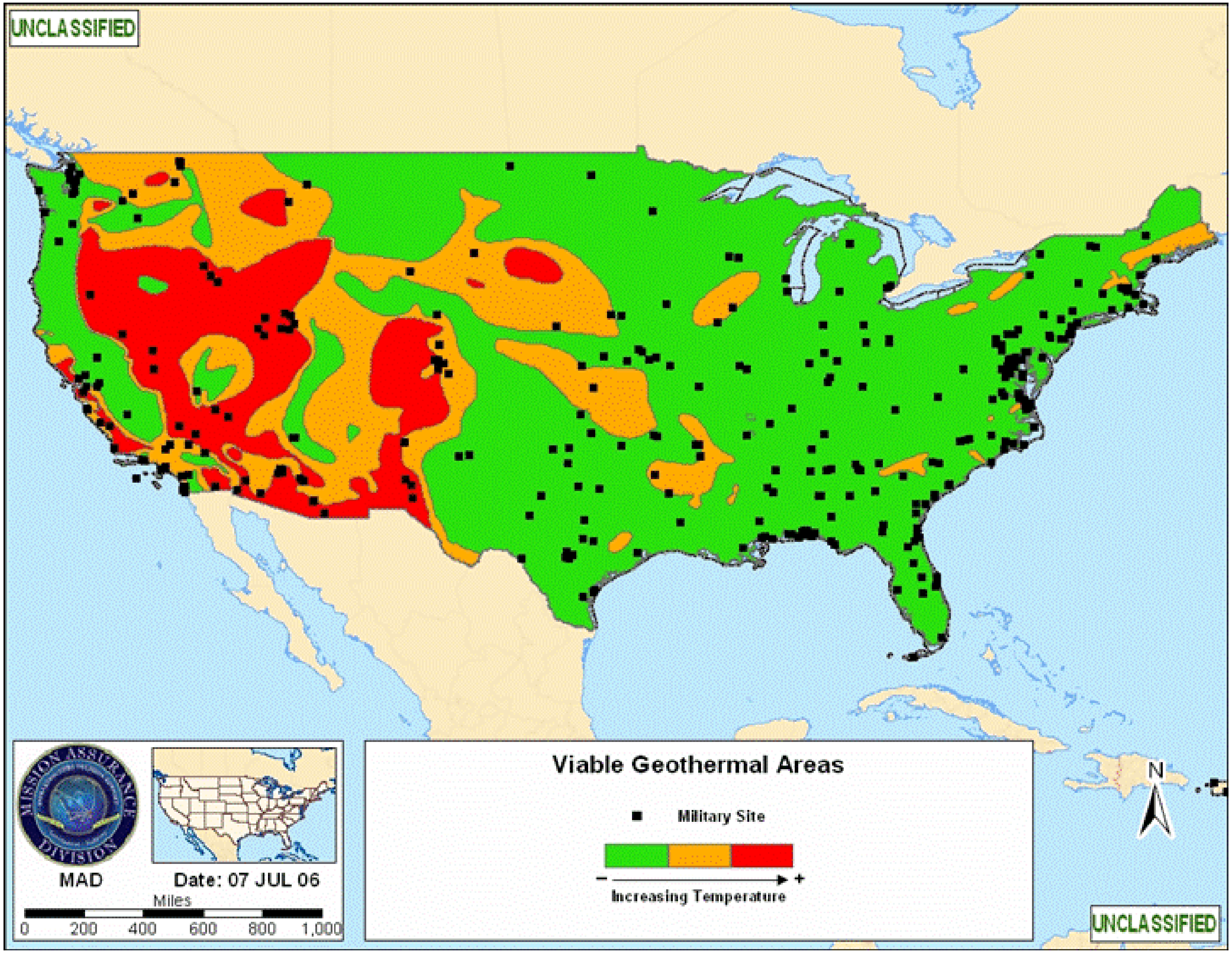


Image Exploitation

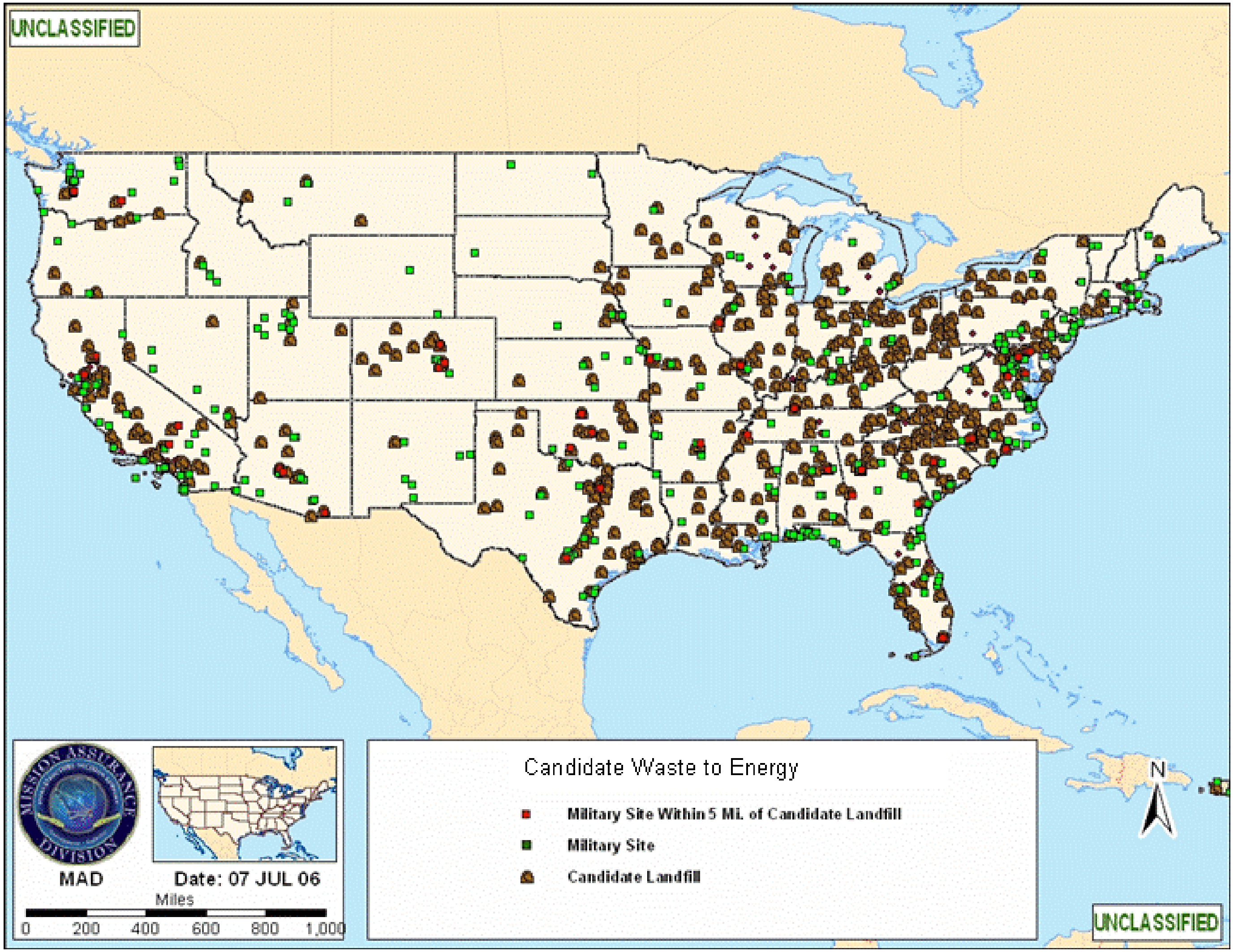


Site Selection

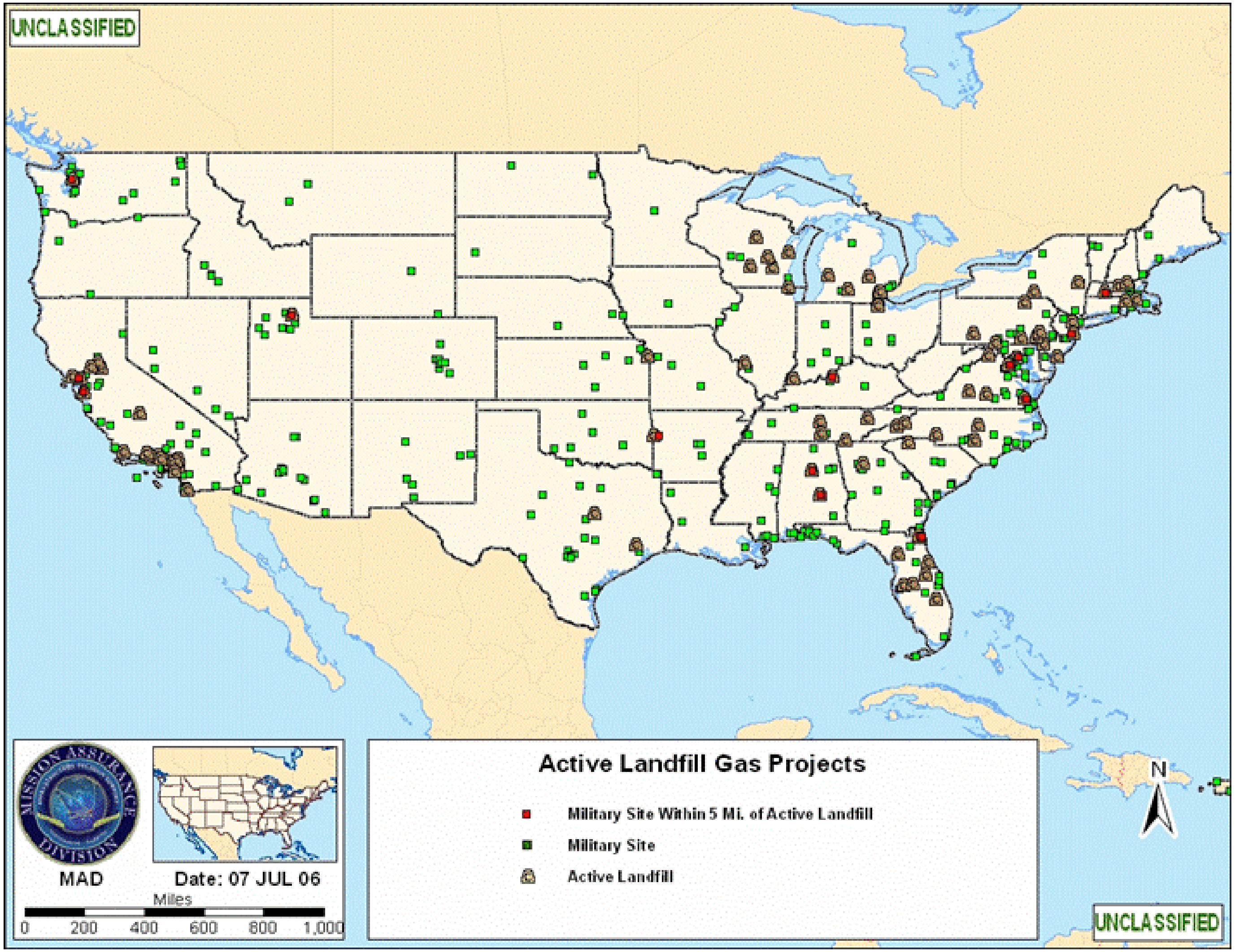
Geothermal – Optimal Locations



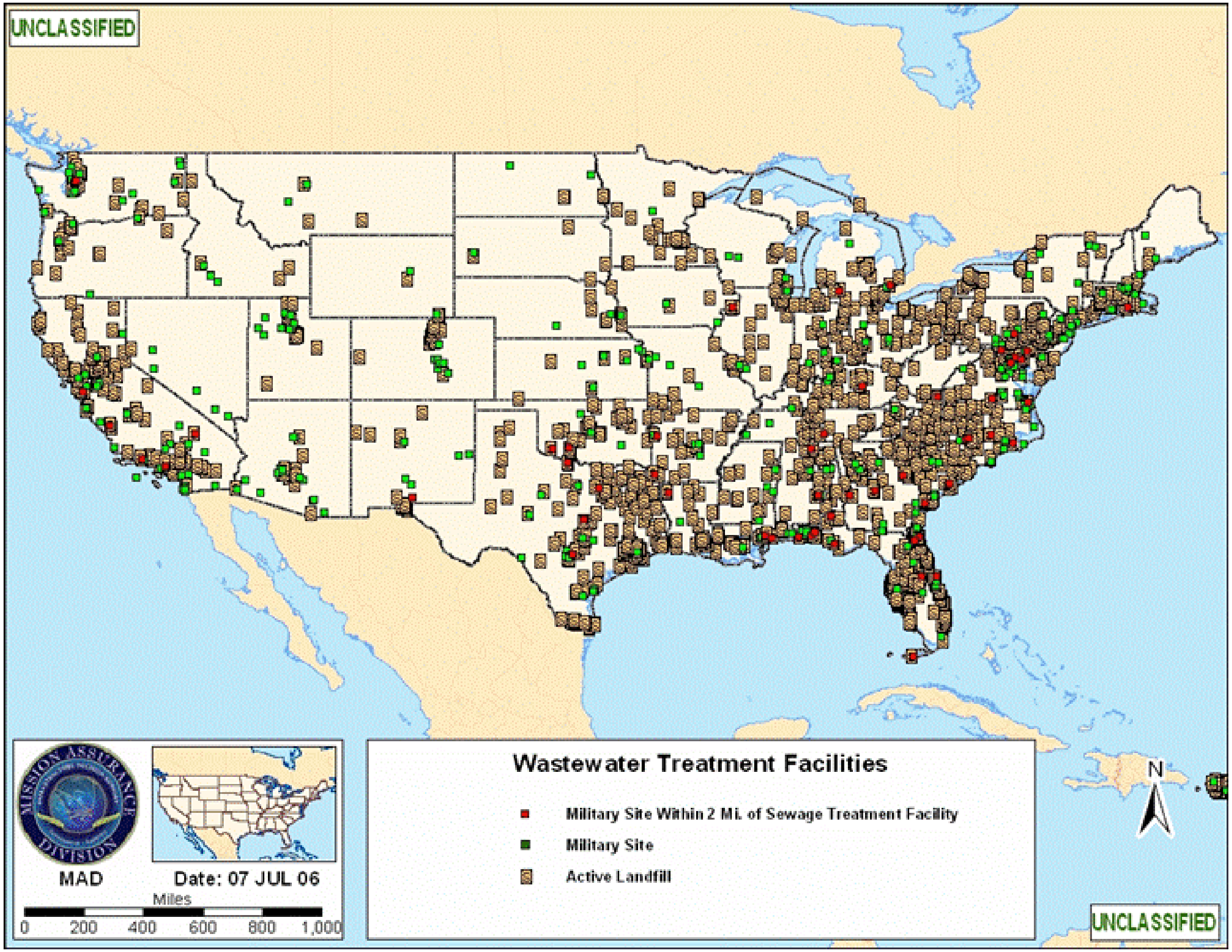
Municipal Waste – Optimal Locations



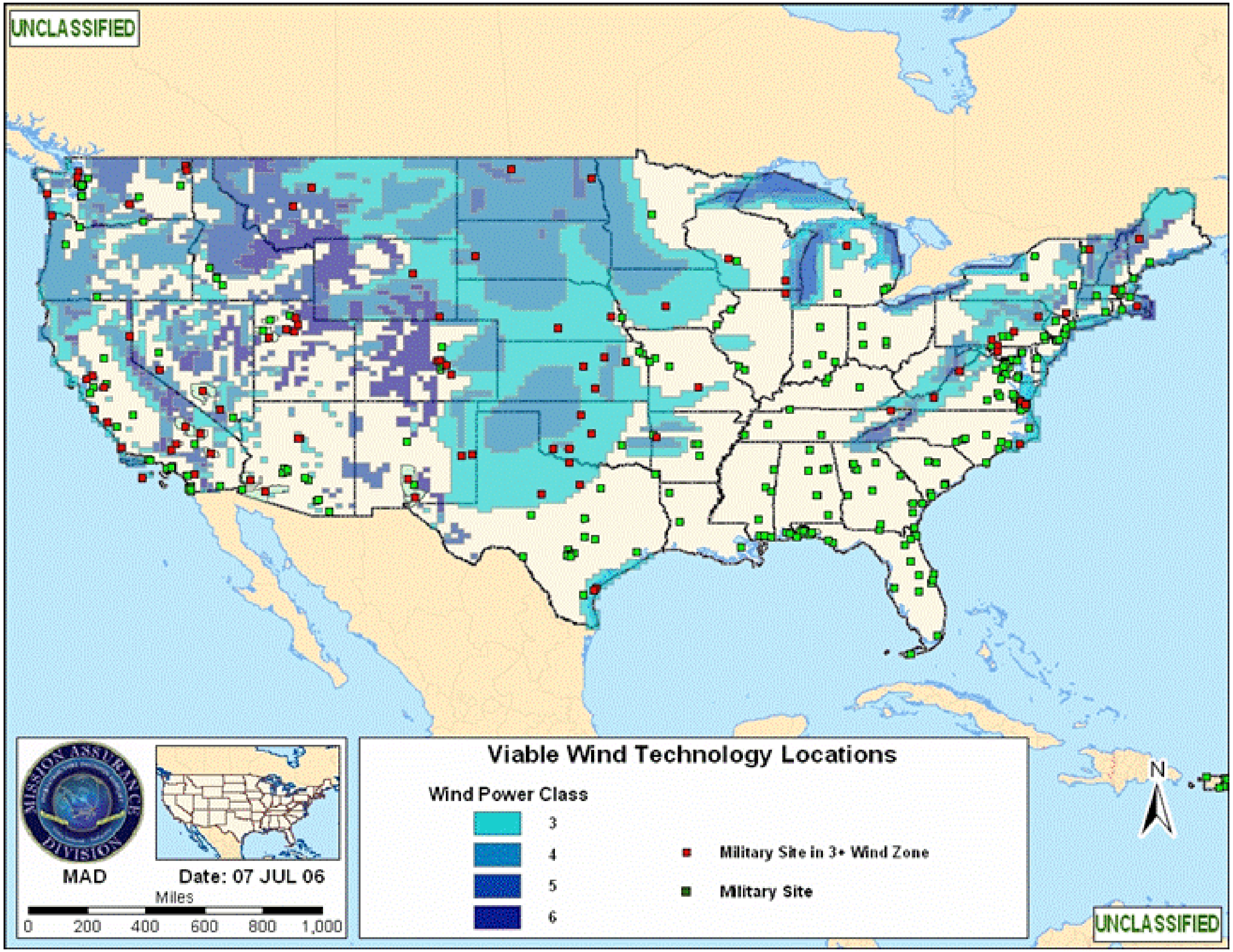
Landfill Gas – Excess Gas Projects



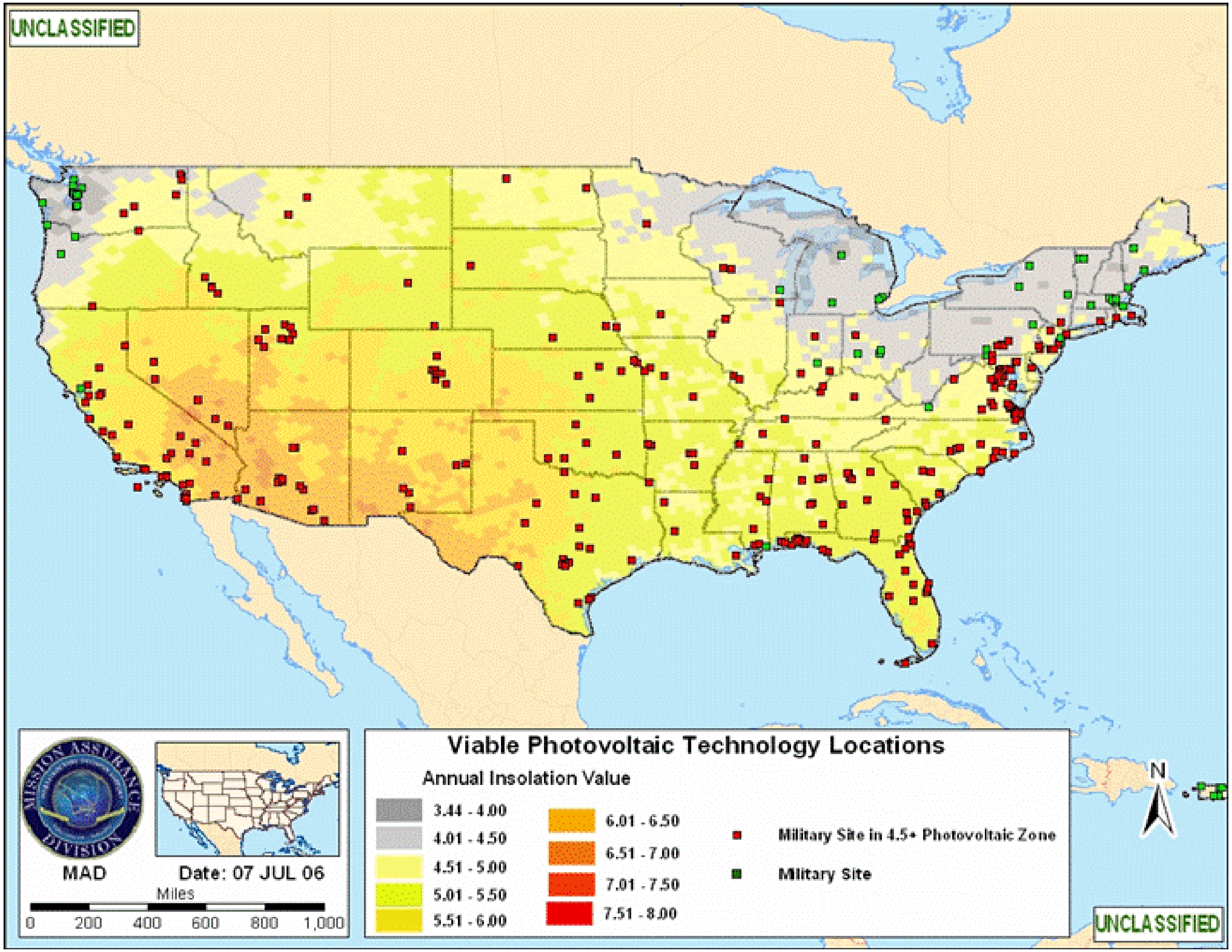
Wastewater Gas – Optimal Locations



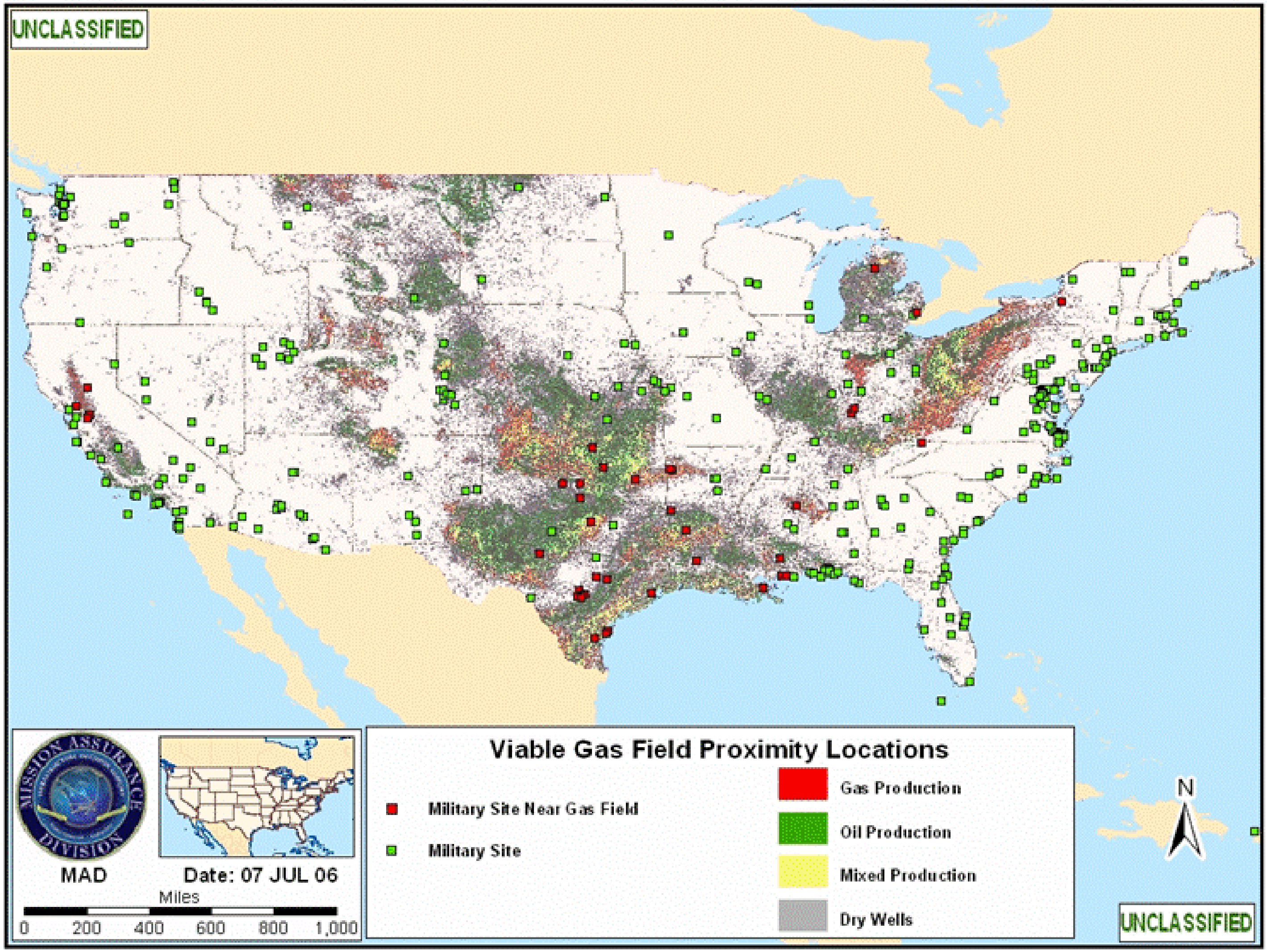
Wind – Optimal Locations



Photovoltaic – Optimal Locations



Natural Gas – Optimal Locations



Biodiesel - Optimal Locations