DOD's Energy Challenge as Strategic Opportunity

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Energy is the lifeblood of modern societies and a pillar of America's prowess and prosperity. Yet energy is also a major source of global instability, conflict, pollution, and risk. Many of the gravest threats to national security are intimately intertwined with energy, including oil-supply interruptions, oil-funded terrorism, oil-fed conflict and instability, nuclear proliferation, domestic critical infrastructure vulnerabilities, and climate change (which changes everything).[1] Every Combatant Command has significant and increasing energy-related missions. Energy has become such a "master key"—so pervasive in its tangled linkages to nearly every other security issue—that no national security strategy or doctrine can succeed without a broad and sharp focus on how the United States and the world get and use energy. For the first time, 37 years after the 1973 oil embargo, the 2010 Quadrennial Defense Review is expected to recognize energy's centrality to DOD's mission, and to suggest how DOD can turn energy from a major risk into a source of breakthrough advantage.[2]

The Department of Defense faces its own internal energy challenges. The heavy steel forces that defeated the Axis "floated to victory on a sea of oil," six-sevenths from Texas. Today, Texas is a net importer of oil, and warfighting is about 16 times more energy-intensive: its oil intensity per warfighter rose 2.6%/y for the past 40 years and is projected to rise another 1.5%/y through 2017, due to greater mechanization, remote expeditionary conflict, rugged terrain, and irregular operations.[3] Fuel-price volatility also buffets defense budgets: each $10/bbl rise in oil price costs DOD over $1.3 billion per year. But of immediate concern, DOD's mission is at risk (as recent wargaming confirms), and DOD is paying a huge cost in lives, dollars, and compromised warfighting capability, for two reasons:

- pervasively inefficient use of energy in the battlespace, and
- ~99% dependence of fixed-facility critical missions on the vulnerable electricity grid.

This discussion of both issues draws heavily on the Defense Science Board's 2008 report *More Fight—Less Fuel*.[4] That analysis, building on and reinforcing its largely overlooked 2001 predecessor,[5] found that solutions are available to turn these handicaps into revolutionary gains in warfighting capability, at comparable or lower capital cost and at far lower operating cost, without tradeoff or compromise. The prize is great: as the Logistics Management Institute said,[6]

> …aggressively developing and applying energy-saving technologies to military applications would potentially do more to solve the most pressing long-term challenges facing DOD and our national security than any other single investment area.

Fuel logistics: DOD's soft underbelly

Fuel has long been peripheral to DOD's focus ("We don't *do* fuel—we *buy* fuel"), but turbulent oil markets and geopolitics have lately led some to question DOD's long-term access to mobility fuel. Echoing the International Energy Agency's chief economist, Dr. Fatih Birol—"We must leave oil before it leaves us"—some analysts assert world oil output capability has peaked or soon will. They overlook recent evidence that "peak oil" is more clearly imminent in demand than in supply. U.S. gasoline use—an eighth of world oil—is probably in permanent decline.[7] So may be OECD oil use since early 2005.[8] Deutsche Bank projects world oil use to peak in 2016, then be cut by electric cars to ~40% below the consensus forecast or ~8% below current levels by 2030.[9] This assumes China's new cars will be 26% electrified by 2020 (China's target is 80%), and omits lightweight and low-drag cars, superefficient trucks and planes, and other important oil savings well underway.[10] Oil, as I've been predicting for two decades, is becoming uncompetitive even at low prices before it becomes unavailable even at high prices.

Nobody knows how much oil is in the ground: governments, which often don't know or won't transparently reveal what they have, hold about 94% of reserves. But DOD, like the U.S., has three compelling reasons to get off oil regardless: security, climate, and cost. Long-term oil availability concerns for DOD are misdirected; even more so, as we'll see, are proposals to create a defense synthetic-fuel industry. True, the Department is probably the world's largest institutional oil buyer, consuming in FY2008 (Fig. 1) 120 million barrels costing \$16 billion—93% of all U.S. Government oil use. But oil is a largely fungible commodity in a global market; the Department uses only 0.4% of the world's oil output (about what two good-sized Gulf of Mexico platforms produce); and in a crisis,[11] DOD has oil-buying priority. Rather, the issue is that *DOD's unnecessarily inefficient use of oil makes it move huge quantities of fuel from purchase to use, imposing high costs in blood, treasure, and weakened combat effectiveness*.

Logistics uses roughly half the Department's personnel and a third of its budget.[12] One-fifth of DOD's oil—at least 90 million gallons each month—supports Iraq and Afghanistan operations that have increased forward bases' oil use by tenfold.[13] Of the tonnage moved when the Army deploys, roughly 50% is fuel—perhaps more.[14] A typical Marine combat brigade needs more than a half-million gallons of fuel per day. *Desert Storm*'s flanking maneuver burned 70,000 tons of fuel in five days.[15] Delivering all that fuel is a huge job for brigades of logistics personnel and for the personnel and assets needed to maintain and protect the logistics chain.

Despite extensive land and air forces trying to guard them—a "huge burden on the combat forces"[16]—fuel convoys are attractive and vulnerable targets, making them one of the USMC Commandant's most pressing casualty risks in Afghanistan.[17] In FY07, attacks on fuel convoys cost the U.S. Army 132 casualties in Iraq (0.026/convoy) and 38 in Afghanistan (0.034/convoy).[18] About 12% of *total* FY07 U.S. casualties in Iraq and 35% in Afghanistan were U.S. Army losses—including contractors but not other Services nor Coalition partners—associated with convoys.[19] Their constrained routes expose them to IEDs, which probably caused the majority of 2009 U.S. fatalities in Afghanistan. Should that conflict follow an Iraq-like profile, its casualty rates could hypothetically rise 17.5%./y.[20] Just the dollar cost of protecting fuel convoys can be "upward of 15 times the actual purchase cost of fuel,…[increasing] exponentially as the delivery cost increases or when force protection is provided from air."[21] The ~8,000 gallons per troop-year consumed in Afghanistan at a typical delivered cost of \$25–45/gal, reportedly accounts for ~20–36% of the ~\$1 million/troop-year cost of deployment there.[22]

Thus attacks on fuel assets, and other serious hazards to fuel convoys, increase mission risk, while fuel logistics and protection divert combat effort and hammer oil-strained budgets. Yet *most of the fuel delivered at such high cost could have been avoided by far more efficient use.* Efficiency lags because when requiring, designing, and acquiring the fuel-using devices, *the Department has systematically assumed that fuel logistics is free and invulnerable*—so much so that wargames didn't and often couldn't model it. Instead of analyzing fuel logistics' burden on effectiveness and signaling it by price, DOD valued fuel at its wholesale price delivered in bulk to a secure major base (around \$1–3/gallon), rather than *at its fully burdened cost delivered to the platform* in theater in wartime (usually tens and sometimes hundreds of \$/gallon). Lacking requirements, instructions, shadow prices, rationales, or rewards for saving fuel, hardly anyone considered the military value of achieving, nor strove to achieve, high fuel efficiency.

As consequences became obvious in theater and began to emerge in wargames, the Department in 2007 started changing its policy[23] so as to value energy savings at the "Fully Burdened Cost of Fuel" (FBCF, in dollars per gallon), including force protection, *delivered* to its end-user in theater. The 2009 National Defense Authorization Act (NDAA) codified both FBCF and new energy Key Performance Parameters (KPPs, in gallons per day or mission). Those are to receive similar weight to traditional KPPs like lethality, protection, and reliability that encapsulate the Department's pursuit of capability. In principle, FBCF and energy KPPs will both guide requirements-writing, Analyses of Alternatives, choices in the acquisition tradespace, and the focus of DOD's science and technology (S&T) investments. In practice, energy KPPs have not yet been applied (their "selective use" is allowed but not yet launched), and much work must be organized and resourced to get the FBCF numbers right and apply them systematically.[24]

The FBCFs initially in use are incomplete. Current guidance[25] still appears to omit support pyramids, multipliers to rotational force strength, actual (not book) depreciation lives, full headcounts including borrowed and perhaps contractor personnel, theft and attrition adjustments,[26] and uncounted Air Force and Navy lift costs to and from theater. All should be included: FBCF should count all assets and activities—at their end-to-end, lifecycle, fully-burdened total cost of ownership—that will no longer be needed, or can be realigned, if a given gallon need no longer be delivered. Thus if fielded fuel-supply need shrinks, so do its garrison costs for related training, maintenance, etc. Conversely, garrison costs should be additive to FBCF, not dilutive: some analysts average peacetime with wartime costs to water down FBCF, or even assume a peacetime operating tempo, but as the 2008 task force said, "FBCF is a wartime capability planning factor, not a peacetime cost estimate."[27]

Even before these conservatisms are made realistic, initial FBCF estimates value saved fuel often *one to two orders of magnitude* higher than previously. If these new metrics gain momentum and top-level focus, they could drive strategic shifts and innovations that could revolutionize military capability and effectiveness.

Two new capabilities

More Fight—Less Fuel roadmapped a detailed military energy reform agenda, broadly backed by DOD's 2008 Energy Security Task Force.[28] DSB offered specific solutions for its key findings: that DOD lacks the strategy, policies, metrics, information, and governance structure to properly manage its energy risks; that technologies are available to make DOD systems more energy-efficient, but they are undervalued, slowing implementation and resulting in inadequate S&T investments; and that there are many opportunities to reduce energy demand by changing wasteful operational practices and procedures. (For example, in 2006 I noticed much superfluous weight inside a USAF heavy aircraft. My brief next morning launched that afternoon a treasure-hunt yielding nearly a ton of rapid weight reduction in that aircraft type. It was then extended to three other types, yielded billions of dollars' present-valued fuel savings, and entered 2008 Air Force operational policy. Such savings weren't previously captured because no one had been responsible or rewarded for them, although "every 100 pounds of excess weight removed from one of our strategic airlift aircraft results in an annual savings of 240,000 gallons of aviation fuel."[29])

The 2009 NDAA codified reforms on the lines recommended by DSB, to be led by a new DOD Director of Operational Energy, who was nominated on 10 December 2009. Meanwhile, some encouraging Service adoption had begun, such as the *Army Energy Security Implementation Strategy*[30] and Navy Secretary Mabus's invigorating energy goals.[31] But the DSB task force, not stopping with bureaucratic fixes, had added the even more incisive finding[32] that "DOD's energy problems [are] sufficiently critical to add two new strategic vectors"—an older term for "succinct descriptions of capabilities that would make a big difference in military operations"[33]—to complement the four historic ones: "speed, stealth, precision and networking."

In today's more familiar language, Endurance and Resilience are new capabilities that drive *and* apply new operational requirements. An Endurance capability will create transformational strategies and tactics that both tell the requirements-writer to make a new platform fuel-efficient *and* inspire the force planner to exploit its increased range and agility. Today's DOD habits would instead tend to make it heavier with the same range—much as Detroit's engine improvements since the 1970s, rather than saving one-third of civilian cars' fuel, only made them more muscular. The need to change entrenched habits in force planning and operational requirements makes big new capabilities both vital and hard. Driving them deeply into doctrine, strategy, organizational structures, cultures, training, reward systems, and behaviors needs strong, consistent, persistent senior leadership. But once so embedded, new capabilities disruptively and profoundly improve military effectiveness and cost-effectiveness.

The Endurance capability

Endurance traditionally means "ability to sustain operations for an extended time without support or replenishment."[34] The DSB task force elaborated:[35]

> Endurance exploits improved energy efficiency and autonomous energy supply to extend range and dwell—recognizing the need for affordable dominance, requiring little or no fuel logistics, in persistent, dispersed, and remote operations, while enhancing overmatch in more traditional operations.

A lean or zero fuel logistics tail also increases mobility, maneuver, tactical and operational flexibility, versatility, and reliability—all required to combat asymmetrical, adaptive, demassed, elusive, faraway adversaries. Endurance is needed in every "platform" using energy in the battlespace, from mobility platforms to expeditionary base power to battery-powered land-warrior electronics. Endurance is even more valuable in stability operations, which often need even more persistence, dispersion, and affordability than the combat operations with which they now enjoy comparable priority.[36]

The DSB report found "enormous technical potential to cost effectively become more fuel efficient and by so doing to significantly enhance operational effectiveness."[37] Current, near-term, and emerging efficiency technologies offer major fuel savings in land, sea, and air platforms,[38] with better warfighting capability (not one of 143 briefs disclosed a tradeoff), and with generally excellent economics and operational characteristics. Examples include (Fig. 2):[39]

- Quiet fixed-wing blended-wing-body heavy aircraft with doubled range and payload but 5–9 times lower fuel intensity.
- A C^4ISR aircraft with 50-hour loiter, 94% fewer sorties, 97% less fuel, and halved cost.
- A tripled-speed rotary-wing aircraft with 5–6 times greater range and fuel efficiency, permitting long-range vertical insertion for mounted maneuver.[40]
- A replacement tank engine with at least doubled range and 3–4 times less fuel intensity.
- The "blast-bucket light armored ground vehicle"—an experimental up-armored-HMMVV-replacement with significantly less weight, fuel usage, and cost, enhanced lethality and flexibility, protection comparable to a mine-resistant ambush-protected (MRAP) vehicle, and top-of-the-line pickup-truck agility and stability.

- Hotel-load retrofits that could save up to one-sixth of the Navy's non-aviation fuel.[41]
- Electric actuators with tenfold better performance, quadrupled fault tolerance, and 3–10 times lower mass and size.
- Aircraft structures with ~95% fewer parts, at least one-third lower weight, same or better strength and battle damage resistance, no corrosion, and lower cost.
- Zero-net-energy new buildings with similar or lower construction cost.

Early adoption has begun at a modest scale. For example, field commanders in Iraq noticed that[42]

> Fuel that is transported at great risk, great cost in lives and money, and substantial diversion of combat assets for convoy protection, is burned in generator sets to produce electricity that is, in turn, used to air condition un-insulated and even unoccupied tents….One recently analyzed FOB [Forward Operating Base] used about 95% of its genset electricity for this purpose, and about one-third of the Army's total wartime fuel use is for running gensets….

A single typical 60-kW genset burns 4–5 gallons an hour, or $0.7 million per year at a typical Afghanistan FBCF of $17.44/gal.[43] One FOB's gensets might cost $34 million per year—plus, at the FY07 casualty rate, nearly one casualty.[44] In the political theater of insurgency, such fuel logistics vulnerability also offers adversaries gratuitous opportunities for propaganda coups.

In response, DOD is spraying over 17 million square feet of insulating foam onto temporary structures in theater, saving over half their air-conditioning energy. This $146-million investment should repay its cost in 67–74 days at the estimated Iraq $13.80/gal FBCF—ten times faster than under the old assumption of undelivered and unprotected fuel. The first $22 million worth should save more than $65 million each year—and more than one convoy casualty.[45] Next steps include far more efficient gensets[46] and air conditioners, including emerging concepts for cooling without electricity.

LTG Mattis's 2003 challenge to "unleash us from the tether of fuel" and MG Zilmer's 2006 operational request from al-Anbar Province for a "self-sustainable energy solution" stimulated the Army's Rapid Equipping Force to develop a portable renewable/hybrid energy supply system, demonstrated at the National Training Center but not yet fielded. In theater, at the fully burdened cost of fuel, it would probably have paid back in months[47]—faster if credited for avoided casualties and enhanced combat capability. The Marines have pledged resources for such work.

Over several decades, concerted adoption of identified energy efficiency technologies hold the estimated potential to cut total DOD mobility-fuel requirements by about two-thirds, perhaps even three-fourths.[48] The fattest targets vary according to intent:[49]

- The most *gallons* can be saved in aircraft, which use 73% of DOD fuel. Saving 35% of aircraft fuel would free up as much fuel as all DOD land and maritime vehicles plus facilities use. New heavy fixed-wing platforms can save at least 50% and new rotary-wing platforms 80%, since those fleets use designs respectively 50–60 and 30–50 years old.
- The biggest gains in *combat effectiveness* will come from fuel-efficient ground forces (land and vertical-lift platforms, land warriors, FOBs). For example, Soldiers carry an average of 2 kg of batteries per mission-day,[50] reflecting an as-yet-uncomputed Fully Burdened Cost of Electricity.
- Savings *downstream* in a long logistics chain save more fuel: delivering 1 gallon to the Army speartip consumes about 1.4 *extra* gallons in logistics.[51]

- Savings in aerially refueled aircraft and forward-deployed ground forces save the most *delivery cost* and thus *realignable support assets*.

Reset, such as the tens of billions of dollars slated for *HMMVV* replacement, offers a ripe opportunity for leap-ahead performance if, for example, the sort of light-tactical-vehicle breakthrough mentioned above can get the "intensive development, design and competitive prototyping" recommended by the 2008 DSB task force.[52] A vehicle as protective and lethal as a 23- to 29-ton *MRAP*, but with acceleration, agility, and stability similar to a top-of-the-line pickup truck, and fuel economy, weight, and cost better than a 5–6-ton up-armored *HMMVV*, sounds more promising than a *HMMVV* or *MRAP*.[53] Yet the innovative competitor's prototyping remains stalled, and OSD policy bars using reset funds for innovative platforms.

Both DSB task forces recommended changes in DOD doctrine, structure, business processes, and other activities—emphasizing design and acquisition—to capture these opportunities aggressively and exploit five major benefits: military energy efficiency is simultaneously[54] a

- *Force protector*, with far fewer vulnerable fuel convoys.
- *Force multiplier*, freeing up convoy guards for combat tasks—turning fuel-guarders into trigger-pullers.
- *Force enabler*, equipping warfighters with the greatly enhanced dwell, reach, agility, and flexibility that can affordably dominate in both dispersed and focused combat.
- *Key to transformational realignment* from tail to tooth—shifts totaling multi-divisional size, worth many tens of billions of dollars per year.
- *Catalyst for leap-ahead fuel savings in the civilian sector*, which uses more than 50 times as much fuel as DOD. Valuing saved military fuel at FBCF will drive astonishing innovations that accelerate civilian vehicle efficiency, much as past military S&T investment yielded the Internet, Global Positioning System, and jet-engine and microchip industries. Such efficiency leapfrogs in cars, trucks, and planes could wean the United States, ultimately the world, from dependence on oil—the biggest security win of all.[55] If "our sons and daughters twice went to the Gulf in ~0.5-mile-per-gallon tanks and 17-feet-per-gallon-equivalent aircraft carriers *because* we didn't put them in 29-mile-per-gallon light vehicles, that's a military *and* a civilian problem—one that both communities must work together to solve."[56]

DSB's 2008 report summarized: "Unnecessarily high and growing battlespace fuel demand compromises operational capability and mission success; requires an excessive support force structure at the expense of operational forces; creates more risk for support operations than necessary; and increases life-cycle operations and support costs."[57] Yet radically boosting platforms' energy efficiency and combat effectiveness at reasonable or reduced up-front cost can turn each of these energy risks into major warfighting gains. Requiring and exploiting Endurance can give DOD more effective forces *and* a more stable world, at reduced cost and risk. This better-than-free opportunity must become a cornerstone of military doctrine.

This shift won't be easy. It requires fundamentally redesigning military energy flows to support fast-changing strategic, operational, and tactical requirements. It demands new DOD planning processes that recognize Endurance's operational value, so it gets required in platforms now in development, and appreciate that delivering an operational effect within a fixed energy budget is itself an important capability. A new system's energy budget is an important requirement—as important as any other—and should be analytically based on the size of the logistics tail the system demands and the burden that assuring successful delivery of that logistics tail imposes on the force. Severalfold-greater platform fuel efficiency comes from rapidly adopting and fielding advances in ultralight-and-strong materials, fluid dynamics, actuators, and propulsion, all synergistic with alternative fuel and power supplies. It also depends on transformational approaches, incentivized by FBCF and potentially required by energy KPPs but unfamiliar to most DOD contractors, that use integrative design to achieve expanding, not diminishing, returns to investments in energy efficiency[58]—yielding major energy savings at *lower* capital cost without trading off non-energy KPPs. Basic innovation in design and acquisition requires taking intelligent risks and rewarding those who do so. All this will require senior leadership to tackle head-on the issue that a previous DSB report described thus:[59]

> Often the very technology that can provide the United States with a disruptive advantage is itself disruptive to DOD's culture[,] and antibodies rapidly and reflexively form to reject it.

Yet such disruptive concepts can be so clearly beneficial that masterful and resolute leadership breaks through hesitancy and resistance. This is the Department's imperative today.

Fuel and power autonomy

Very efficient energy use stretches fuel and power made in theater from wastes, opportunistically acquired feedstocks, or renewable energy flows. Fedex and Virgin Airways plan to fuel 30% and 100% of their respective fleets with biofuels by 2020. Domestically produced biofuels from centralized, specialized plants do little for DOD's expeditionary needs, but much cutting-edge research emphasizes portable biofuel converters like an "opportunistic foraging herbivore."[60] The 2008 DSB task force favored promising expeditionary biofuel and synfuel technologies,[61] and the Services are examining some.[62]

In contrast, the DSB task force expressed "strong concerns" about the coal-to-liquids synfuels favored by the Air Force and Navy (but illegally carbon-intensive under a 2007 law), finding they do "not contribute to DOD's most critical fuel problem—delivering fuel to deployed forces," "do not appear to have a viable market future or contribute to reducing battlespace fuel demand," and don't appear to address a real problem. Fuel interdiction risk in theater is best countered by efficient use, diversified fuels and supply chains, and greater or more secure local stockpiling. If, the concern is long-term fuel availability, military and civilian end-use efficiency is by far the cheapest choice. In 2005, Wal-Mart's giant Class 8 truck fleet launched gallon/ton-mile savings that reached 38% in 2008 and target 50% in 2015.[63] General U.S. adoption of those doubled-efficiency civilian trucks will save 6% of U.S. oil—triple DOD's total use. SECDEF's JASON science advisors, whose energy report[64] also pointedly failed to endorse coal-to-liquids, suggested saving oil by redesigning the Postal Service's under-10-mpg delivery fleet.[65]

Nuclear power is sometimes suggested for land installations[66] or even expeditionary forces,[67] typically without discussing cost (grossly uncompetitive[68]), modern renewables (typically much cheaper), operational reliability[69] (usually needing 100% backup), or security. For these and other reasons, the 2008 DSB and JASON task forces didn't endorse this option. After vast investment in hardware and a unique technical culture, nuclear propulsion has proven its merit in submarines and aircraft carriers. In 2006–09, Congressional enthusiasts announced supposed Naval Sea Systems Command (NAVSEA) findings that nuclear propulsion in new medium surface combatants could beat $70/bbl oil. However, the 2008 DSB task force discovered that NAVSEA's actual finding ($75–225/bbl) had improperly assumed a zero real discount rate. A

3%/y real discount rate yielded a \$132–345/bbl breakeven oil price; NAVSEA didn't respond to requests to test the 7%/y real discount rate OMB probably mandates. Presumably the Secretary of Defense will reject this option and focus resources on making ships optimally efficient.

The 2008 DSB and JASON studies are redirecting the military energy conversation from exotic, speculative, and often inappropriate supplies to efficient use, which makes autonomous in-theater supply important and often cost-effective. But all such choices depend on a further fundamental reform in DOD's metrics and procedures.

Gross *vs*. net capability

A change that would boost operational capability by greatly increasing tooth-to-tail ratios was identified in a little-noticed but "important observation of the [2008 DSB] Task Force":[70]

> …[W]hat JCIDS[71] currently calls "capability" is actually the theoretical performance of a platform or system unconstrained by the logistics tail required for its operation. But tail takes money, people, and materiel that detract from tooth. True net capability, constrained by sustainment, is thus the gross capability (performance) of a platform or system times its "effectiveness factor"—its ratio of effect to effort:
>
> Effectiveness Factor = Tooth / (Tooth + Tail)
>
> Also, in an actual budget, Tooth = (Resources – Tail), so
>
> Effectiveness Factor = (Resources – Tail) / Resources
>
> Effectiveness factor ranges from zero (with infinite tail) to one (with zero tail). If tail > 0, true net capability is always less than theoretical (tail-less) performance, but DOD consistently confuses these two metrics, and so misallocates resources. Buying more tooth that comes with more (but invisible) tail may achieve little, no, or negative net gain in true capability. While the Department recognizes the need to reduce tail, the analytical tools needed to inform decisions on how to do so are not in place. Focusing on reducing tail can create revolutionary capability gains and free up support personnel, equipment, and budget for realignment. The Task Force recommendations are intended to build the analytical and policy foundation to begin introducing this way of thinking into the requirements, acquisition and budget forecasting processes.

In sum: current force planning does not and cannot predict or compare competing options' needed tail size nor their net capability, so after decades, "The tail is eating the tooth."[72] Reversing this impairment needs five missing steps: (1) an Endurance capability to drive and exploit operational requirements for radical efficiency, (2) enforced by energy KPPs, (3) valued at FBCF, (4) competed on *net* capability, and (5) tested with wargaming and campaign-modeling tools revised so they "play fuel" and reveal the full operational value of lean fuel logistics. All five together will help drive the Department toward ultimately breeding, where possible, a Manx force—no tail. Efficient and passively or renewably cooled tents in the desert can mean no gensets, no fuel convoys, no problem. Such a thrust toward efficiency in every use of fuel and electricity also strongly supports the second proposed new key capability—Resilience.

The Resilience capability

Resilience "combines efficient energy use with more diverse, dispersed, renewable supply—turning the loss of critical missions from energy supply failures (by accident or malice) from inevitable to near-impossible."[73] This capability is vital because the

> …[a]lmost complete dependence of military installations on a fragile and vulnerable commercial power grid and other critical national infrastructure places critical military and Homeland defense missions at an unacceptably high risk of extended disruption….[Backup generators and their fuel supplies at military installations are generally sized] for only short-term commercial outages and seldom properly prioritized to critical loads because those are often not wired separately from non-essential loads. DOD's approach to providing power to installations is based on assumptions that commercial power is highly reliable, subject to infrequent and short term outages, and backups can meet demands. [These assumptions are]…no longer valid and DOD must take a more rigorous risk-based approach to assuring adequate power to its critical missions.[74]

The 2008 DSB Task Force found that the confluence of many risks to electric supply—grid overloads, natural disasters, sabotage or terrorism via physical[75] or cyberattacks on the electric grid, and many kinds of interruptions to generating plants—hazards electricity-dependent hydrocarbon delivery, the national economy, social stability, and DOD's mission continuity.

The U.S. electric grid was named by the National Academy of Engineering as the top engineering achievement of the 20th Century. It is very capital-intensive, complex, technologically unforgiving, usually reliable, but inherently brittle—responsible for ~98–99% of U.S. power failures, and occasionally blacking out very large areas within seconds. That's because the grid requires exact synchrony across subcontinental areas, relies on components taking years to build in just a few factories or one (often abroad), yet can be interrupted by a lightning bolt, rifle bullet, malicious computer program, untrimmed branch, or errant squirrel. Grid vulnerabilities are serious, inherent, and not amenable to quick fixes; current federal investments in the "smart grid" don't require simple mitigations. Indeed, the policy reflex to add more and bigger power plants and power lines after each regional blackout may make the next blackout more likely and severe, much as suppressing forest fires can accumulate fuel loadings that turn the next unsuppressed fire into an uncontrollable conflagration.[76]

Power-system vulnerabilities are even worse in theater, where infrastructure and the capacity to repair it are often marginal: "attacks on the grid are one of the most common and effective tactics of insurgents in Iraq, and are increasingly seen in Afghanistan."[77] Thus *electric*, not oil, vulnerabilities now hazard national and theater energy security. Simple exploitation of domestic electric vulnerabilities could take down DOD's basic operating ability and the whole economy, while oil supply is only a gathering storm.

The DSB Task Force took electrical threats so seriously that it advised DOD—following prior but unimplemented DOD policy[78]—to replace grid reliance, for critical missions at Continental U.S. bases, with onsite (preferably renewable) power supplies in netted, islandable[79] microgrids. DOE's Pacific Northwest National Laboratory found ~90% of those bases could actually meet those critical power needs from onsite or nearby and mainly renewable sources, often cheaper.[80] This could achieve zero daily net energy need for facilities, operations, and ground vehicles; full independence in hunker-down mode (no grid); and increased ability to help serve surrounding communities and nucleate blackstart of the failed commercial grid.

Implementing these sensible policies merits high priority: probably only DOD can move as decisively as the threat to national security warrants. And as with the Endurance capability, exploiting Resilience—building on DOD's position as the world's #1 direct-or-indirect buyer of renewable energy—would provide leadership, market expansion, delivery refinement, and training that would accelerate civilian adoption. Already, the 2008 NDAA requires DOD to establish a goal to make or buy at least 25% of its electricity from renewables by 2020, and study solar and windpower feasibility for expeditionary forces. Under 2007 Executive Order 13423's Government-wide mandate, DOD must also reduce energy intensity by FY2015 to 30% below

FY2003. The Resilience capability would focus all these efforts on robust architectures and implementation paths, ensuring that bases' onsite renewables deliver reliable power to critical loads whether or not the commercial grid is working—a goal not achieved by today's focus on compliance with renewables quotas.

Resilience is even more vital and and valuable[81] abroad, in fixed installations and even more in FOBs (whose expeditionary character emphasizes the Endurance logic of Fully Burdened Cost of Electricity). Foreign grids are often less reliable and less secure than U.S. grids; protection and social stability may be worse; logistics are riskier and costlier in more remote and austere sites; and civilian populations may be more helped and influenced. Field commanders strongly correlate reliable electricity supplies with political stability. In Sadr City, MG Jeffrey Talley's (USAR) Task Force Gold proved in 2008–09 that *making* electricity reliable, underpinning systematic infrastructure-building, is an effective cornerstone of counterinsurgency.[82]

Reconstruction in Iraq and Afghanistan is starting to define and capture this opportunity to build civic cohesion and damp insurgency, while reducing attacks' disruption and attractiveness. A resilient, distributed electrical architecture can bring important economic[83] and social side-benefits, as with Afghan microhydropower programs for rural development. Cuba lately showed, too, that aggressively integrating end-use efficiency with micropower can cut national blackouts—caused by decrepit infrastructure, not attacks—by two orders of magnitude in a year.[84]

At home, DOD efficiency and micropower echo new domestic energy policy and startling developments in the marketplace. In 2006, micropower[85] delivered one-sixth of the world's electricity, one-third of its new electricity, and 16–52% of all electricity in a dozen industrialized countries (the U.S. lagged with 7%). In 2008, for the first time in about a century, the world invested more in renewable than in fossil-fueled power supplies; renewables (excluding big hydroelectric dams) added 40 billion watts of global capacity and got $100 billion of private investment. Their competitive and falling costs, short lead times, and low financial risks attract private capital. Shifting to these more resilient energy solutions goes with the market's flow.

Expanding DOD's energy voice

Endurance and Resilience offer synergistic national-security benefits far beyond those internal to the Department's mission effectiveness. As a dozen retired flag officers concluded,[86]

> We can say, with certainty, that we need not exchange benefits in one dimension for harm in another; in fact, we have found that the best approaches to energy, climate change, and national security may be one and the same.

Moreover, whether you care most about national security, climate change, or jobs and competitiveness, you should do exactly the same things about energy. Thus focusing on our energy actions' attributes and outcomes, not motives, could build broad consensus.

The resulting benefits could be enlarged by bringing DOD's perspective and expertise more vigorously into national energy policymaking. A common critique[87] holds that past federal energy policy has constituted the most comprehensive threat to national energy security, by

- perpetuating America's expanding oil dependence (via tardy or counterproductive policy choices, supporting foreign despots, funding both sides of the Iraq war, impugning U.S. moral standing, warping foreign policy/postures/attitudes, weakening national competitiveness, and enhancing U.S. economic vulnerability and fragility)

- strongly favoring overcentralized energy-system architectures that are inherently vulnerable to accidental or deliberate disruption
- creating attractive new terrorist targets (new LNG and nuclear facilities, and Iraq energy infrastructure rebuilt with overcentralized architecture at U.S. insistence)
- aiming to increase and prolong reliance on the most vulnerable domestic infrastructure
- promoting technologies (nuclear power, reprocessing, reactor types that would make uranium enrichment cheaper and more widespread) that encourage proliferation.[88]

Now that national energy policy is shifting—often for additional reasons like economic recovery, competitive advantage, and climate protection—DOD's knowledge of energy-related security risks needs to inform more systematically the councils of government. If national-security outcomes like these past ones are not what DOD wants, it is the duty of military professionals to say so. Their guidance, and increasingly their achievements, can help the Department of Defense build a stronger America and a richer, fairer, cooler, and safer world.

The United States can and must make oil no longer a strategic commodity—just as refrigeration did to salt (once so vital a preservative that countries fought over salt mines)—and electric power a boon unshadowed by threat.[89] DOD's leadership in adopting and exploiting the two new capabilities proposed here would dramatically speed that journey toward a world beyond oil—with "negamissions" in the Persian Gulf, Mission Unnecessary—and indeed beyond all energy vulnerabilities. Fighting for Endurance and Resilience in Pentagon decisions today can eliminate the need to fight for oil on the battlefield tomorrow.

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[1] Center for Naval Analyses, *National Security and the Threat of Climate Change*, 2007; Gwynne Dyer, *Climate Wars* (Canada: Random House, 2008); Thomas Fingar, unclassified summary of *National Intelligence Assessment on the National Security Implications of Global Climate Change to 2030*, 25 June 2008 testimony to USHR.

[2] Others can do so too. DOD cosponsored my team's detailed roadmap for eliminating U.S. oil use by the 2040s at an average cost of $15/bbl (Amory B. Lovins *et al.*, *Winning the Oil Endgame* (Snowmass, CO: Rocky Mountain Institute, 2004). Initial implementation progress is encouraging.

[3] Deloitte, "Energy Security: America's Best Defense," 9 November 2009. The historic rise partly due to more capable platforms and many non-shooter platforms. DSB (refs. 4 and 5) found only two of a typical armored unit's top ten battlefield fuel users (*Abrams M1A2*, #5, and *Apache AH-64D*, #10) are combatants: the water heater uses more fuel than the helicopter. Of I MEF's 2003 ground fuel in Iraq, only 10% went to "the heavy vehicles that delivered lethal force"; 90% fueled support vehicles (CNA, ref. 86, p. 9; "Breaking the Tether of Fuel," *Military Review* January–February 2007).

[4] Cochaired by former SECDEF James R. Schlesinger and GEN Michael P.C. Carns, USAF (Ret.), and posted 18 February 2008. I served on both DSB Task Forces (refs. 4 and 5). The views expressed here are solely my own.

[5] *More Capable Warfighting Through Reduced Fuel Burden*, chaired by VADM (Ret.) Richard Truly, was released just weeks before the 11 September 2001 attacks, muting its policy impact and requiring repetition by ref. 4.

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[6] D. Berkey *et al.*, "Energy Independence Assessment: Draft Final Briefing for Office of Force Transformation" (LMI, 12 January 2005), reviewing ref. 2.

[7] Russell Gold and Ana Campoy, "Oil Industry Braces for Drop in U.S. Thirst for Gasoline," *Wall Street Journal*, 13 April 2009.

[8] Cambridge Energy Research Associates, "Peak Oil Demand in the Developed World: It's Here," 29 September 2009.

[9] Paul Sankey *et al.*, "The Peak Oil Market," Deutsche Bank Global Markets Research, 4 October 2009.

[10] Ref. 2.

[11] For example, two-thirds of Saudi output—the sole source of liquidity in the world oil market—flows through one processing plant (already attacked once) and two terminals (the larger already attacked at least twice). Major disruption of foreign oil infrastructure or of a major U.S. chokepoint (such as the Trans-Alaska Pipeline System—as important to U.S. oil flows as the Strait of Hormuz, but far more vulnerable) would certainly make oil prices spike.

[12] As of FY97: Defense Science Board Summer 1998 Study Task Force, *DOD Logistics Transformation*, Annotated Briefing Slides, slide 7, which also shows that "Active duty combat forces [were then] half [the] size of active logistics forces." One estimate of DOD's FY09 logistics and sustainment cost is $270 billion—over half the base budget.

[13] Deloitte, ref. 3, p. 15. GEN Conway (USMC) noted that in 2001, a Marine infantry battalion had 32 canvas-topped *HMMVV*s and 175 radios, but in 2009 it had 55 armored *HMMVV*s and 1,220 radios.

[14] Army Environmental Policy Institute, "Sustain the Mission Project: Energy and Water Costing Methodology and Decision Support Tool," July 2008. Both DSB task forces were told that 70% of the tonnage needed to position the Army into battle was fuel; this might also be correct because of the fuel needed to deliver fuel in theater and because Navy and Air Force lift of Army assets is attributed to them, not to the Army. The actual percentage is unknown.

[15] Marvin S. Schaffer and Ike Chang, "Mobile Nuclear Power for Future Land Combat," *JFQ* **52**:49–55 (1st Quarter 2009) at 51.

[16] Dr. Ashton Carter (USECDEF/ATL&L), in 2009 Congressional testimony quoted by Deloitte (ref. 3), p. 15.

[17] *Id.*

[18] Army Environmental Policy Institute, "Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys," September 2009.

[19] Deloitte (ref. 3) and total U.S. casualty data from http://icasualties.org.

[20] Deloitte (ref. 3), p. 18.

[21] *Id.*, p. 19, assuming a 950-mile resupply round-trip using air cover that raises delivered cost to nearly $45/gal. Exponential cost increase with range is illustrated by a three-staged helicopter relay expediently delivering fuel in bladders slung beneath *CH-47D*s: the 2001 DSB panel (ref. 5, pp. 18–19, elaborating a 17 August 1999 brief by LTC Ronald F. Salyer (USARL)), found a corresponding delivered cost—probably nowhere near fully burdened— of $400/gal at a 400-km one-way supply range.

[22] Todd Harrison, "Estimating Funding for Afghanistan," 1 Dec 09 update, Center for Strategic and Budgetary Assessments. Data based on ref. 3.

[23] USECDEF(AT&L) Kenneth Krieg, 10 April 2007 memo "Fully Burdened Cost of Fuel Pilot Program."

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[24] Andrew Bochman, "Measure, Manage, Win: The Case for Operational Energy Metrics," *JFQ* **55**:113–119 (4th Quarter 2009). That article, to which I contributed, usefully summarizes mid-2009 implementation progress and gaps.

[25] A May 2009 draft methodology was developed for the Defense Acquisition Guide, and Defense Acquisition University has posted an FBCF Calculator. Another useful introduction is R. Cotman, "Computing the Fully Burdened Cost of Fuel," MORS, 30 Nov 2009.

[26] Deloitte (ref. 3) also notes at p. 15 that attacks are far from the only hazard: bad weather, traffic accidents, and pilferage lost DOD some 44 trucks and 220,000 gallons of fuel in June 2008 alone.

[27] Ref. 4, p. 31.

[28] A useful 2008 summary of activities has been posted by DDRE.

[29] Michael Aimone, 27 February 2007 testimony to Senate Finance Committee, p. 4.

[30] Posted 13 January 09.

[31] Hon. Ray Mabus, Naval Energy Forum, 14–15 October 2009. Ref. 24 notes uneven progress and emphasis among the Services. This will probably persist until the partial vacuum in formal OSD energy leadership is filled and procedural reforms are embedded into a coherent doctrinal and strategic context, such as that suggested here.

[32] Ref. 4, p. 35.

[33] 2006 DSB Summer Study reports on *21st Century Strategic Technology Vectors* (2007), Vol. 1, pp. x–xi.

[34] Ref. 4, p. 25.

[35] *Id.*, p. 35.

[36] DOD Instruction 3000.05, §4.1.

[37] Ref. 4, p. 37.

[38] Ref. 4. Innovation was encouraging on the supply side in the recent Wearable Power Prize (WPP) Competition, but seems to lag in efficient use.

[39] Amory B. Lovins, 2 December 2008 brief to DOD's Strategic Environmental Research and Development Program, based mainly on briefs to the 2008 DSB task force, and ref. 4, pp. 37–50.

[40] BG R.P. Swan (USA) and LTG S.R. McMichael (USA Ret.), "Mounted vertical maneuver," *Military Review*, January–February 2007.

[41] Amory B. Lovins *et al.*, "Energy Efficiency Survey Aboard *USS Princeton* CG-59," report to ONR, 30 June 2001.

[42] Ref. 4, pp. 29–30.

[43] *Vs.* $14.13/gal in Iraq (both from ref. 14), not counting the terms noted above as still omitted from FBCF, and omitting maintenance costs.

[44] Ref. 18 and, for genset and FOB data, COL G.D. Kuntz (USA), "Renewable Energy Systems: Viable Options for Contingency Operations," *Environmental Practice* **9** (2007):157–161.

[45] Troy Wilke & Bradley Frounfelker, "Tent Foam Insulation Cost Benefit Analysis," 48th Annual Army Operations Research Symposium (Fort Lee, VA), 14–15 October 2009; personal communications from Troy Wilke and John Spiller (29 November–1 December 2009).

[46] For example, the DARPA-sponsored OPOC (opposed-piston opposed-cylinder) genset has demonstrated 50% higher efficiency, 30% lower weight, and 75% smaller size, with more to come.

[47] Ref. 4, p. 45.

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[48] Lovins *et al.*, ref. 2, pp. 84–93, based on technology assumptions more conservative than many of the potentials briefed to the 2008 DSB task force.

[49] Ref. 39.

[50] Ref. 53, p. 24.

[51] *The Economist* (Monitor, "Greenery on the march," 10 Dec 09) reported this figure to be 7 in Afghanistan according to the British Army, but this appears to refer to unusually remote sites.

[52] Ref. 4, p. 41; see also pp. 31–32.

[53] Nominal weights from DUSECDEF A.E. Haggerty, "S&T and Maneuver Warfare," 29 July 2008, at p. 13. *MRAP* was quickly fielded after unconscionable delays in the requirements process: Christopher J. Lamb *et al.*, "MRAPs, Irregular Warfare, and Pentagon Reform," *JFQ* **55**:76–85 (4th Quarter 2009). The blast-bucket design was cheaply and rapidly developed without requirements via a bold initiative by the Chief of Naval Research, RADM (now Ret.) Jay Cohen.

[54] Ref. 39. My formulation of these benefits was kindly adopted by Haggerty at p. 16 (and 21–23, 34,…).

[55] Ref. 2 documents tripled-efficiency, uncompromised, but safer civilian cars, trucks, and planes using the best 2004 technology and with respective U.S. payback times of 1, 0.5, and 3 years. However, military platforms can also learn from civilian ones. The overweight Joint Strike Fighter has a lower advanced-composite mass fraction than Boeing's commercial *787 Dreamliner* (50% carbon-fiber composites by mass, 80% by volume—the largest single source of its 20% fuel saving at zero marginal cost). In 1992–94, the Lockheed-Martin Skunk Works even designed a *95%*-carbon-composites-by-weight tactical-fighter airframe, one-third lighter *but two-thirds cheaper* (at the 100th copy) than its 72%-metal predecessor; the project surpassed its goals but succumbed to the JSF community's immune system, and its advances seem to be getting adopted more in civilian than in military aircraft.

[56] Ref. 2, p. 93. See also pp. 261–265.

[57] Ref. 4, p. 3.

[58] Amory B. Lovins, *Advanced Energy Efficiency*, 2007 MAP/Ming Lectures, Stanford University School of Engineering, and "Energy End-Use Efficiency" (commissioned by Dr. Stephen Chu), 2005. For example, focusing first on platform physics (drag, rolling resistance, and especially mass) can often greatly downsize and simplify propulsion systems and transform manufacturing techniques, thus reducing marginal whole-system capital costs. These summaries of design experience, to be elaborated in an RMI casebook, show how optimizing whole systems (platforms or facilities) for multiple benefits, not isolated components for single benefits, often makes big energy savings cost *less* than small or no savings; optimizing systems against the value of saving watts, mass, volume, etc. from a fully compounded, whole-system, end-to-end, lifecycle perspective often yields major whole-system benefits; and radical end-use efficiency makes energy supplies smaller, simpler, cheaper, and more resilient.

[59] Ref. 33, p. xviii.

[60] Amory B. Lovins & James Newcomb, "Bioconversion: What's the Right Size?," 20 February 2008 brief to National Research Council Panel on Alternative Liquid Transportation Fuels.

[61] Ref. 4, pp. 50–51.

[62] Deloitte (ref. 3), p. 27.

[63] See the update to ref. 2 and RMI's 2009 Transformational Truck assessment.

[64] JASON, "Reducing DoD Fossil-Fuel Dependence," September 2006, JSR-06-135.

[65] JASON brief to DSB task force's Policy Panel, 6 September 2006.

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[66] *E.g.*, to Congress by GEN Carns (USAF Ret.), cochair of the 2008 DSB task force, which did not concur.

[67] Ref. 11.

[68] I've published basic comparisons and supporting details elsewhere.

[69] The 2008 DSB task force noted at p. 19 that the 14 August 2003 Northeast blackout shut down (for safety reasons) 22 nuclear units. The nine U.S. units, previously at 100% capacity factor, "took about two weeks to regain full capacity, and lost an average of more than half their capacity for 12 days." The Canadian units generally fared worse.

[70] Ref. 4, pp. 28–29.

[71] *Manual for the Operation of the Joint Capabilities Integration and Development System*, 31 July 2009.

[72] Ref. 12, slide 8.

[73] Ref. 4, p. 35.

[74] *Id.*, pp. 3 and 53.

[75] This risk and inherently resilient design alternatives were codified for DOD by Amory B. & L. Hunter Lovins, *Brittle Power: Energy Strategy for National Security* (Andover, MA: Brick House, 1981), summarized in a paper for USECNAV R. James Woolsey.

[76] University of Wisconsin researchers have studied this dynamic in power grids.

[77] Ref. 4, p. 55.

[78] Ref. 4, pp. 59–60: "DODI 1470.11 §5.2.3 states it is DOD policy to use onsite, self-contained power for critical functions, DOD-facilities-based microgrids, and netted area microgrids for extended strategic islanding, coupled with end-use energy efficiency measures. The Renewable Electricity Purchasing and On-Base Development Plan developed in 2004 by the Renewables Assessment Working Group was designed to quickly improve energy reliability and security at installations….Thus, policies and plans are in place to move towards islanding for critical mission purposes. However, the Task Force could find no evidence that DOD has taken tangible steps to implement this policy or plans beyond a very small number of high profile projects. This is so even though renewable energy sources…are often economically advantageous and resilient, reducing the risk of mission interruption." In 2008–09, however, efforts like the Army's Power Surety Task Force and the Navy's Dahlgren mission assurance staff began to build encouraging momentum.

[79] "Islandable" means onsite supplies can continuously serve the base and neighboring communities whether or not the commercial grid is operating. The electricity industry has developed, but rarely uses, consensus standards like IEEE 1547P for doing this safely and routinely. Islandable interconnection should become normal DOD practice to maximize resilience. DOD is also seeking legislative amendments to allow long-term DOD power purchase contracts from renewables and remove utilities' claimed veto right over non-geothermal on-base renewable projects.

[80] Mike Warwick, Mike.warwick@pnl.gov, 5 September 2006, 28–29 November 2006, and other briefs to DSB, ref. 4.

[81] Ref. 4, p. 61.

[82] Personal communication, 10 October 2009, and initial public reports.

[83] Amory B. Lovins *et al.*, *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size* (Snowmass, CO: Rocky Mountain Institute, 2002), an *Economist* book of the year.

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[84] M.A. Arrastía Ávila, "Distributed generation in Cuba," *Cogeneration and On-Site Power Production* **9**(6):61–65, Nov.-Dec. 2008, and Laurie Guevara-Stone, "La Revolución Energética: Cuba's Energy Revolution," *Renewable Energy World Magazine* **12**(2), March/April 2009.

[85] Defined here as cogeneration plus renewables minus big (>10 MWe) hydro. RMI maintains a global database.

[86] CNA Military Advisory Board, *Powering America's Defense: Energy and the Risks to National Security*, May 2009, cogently summarized by VADM Dennis McGinn (USN Ret.) in 30 July 2009 Senate testimony.

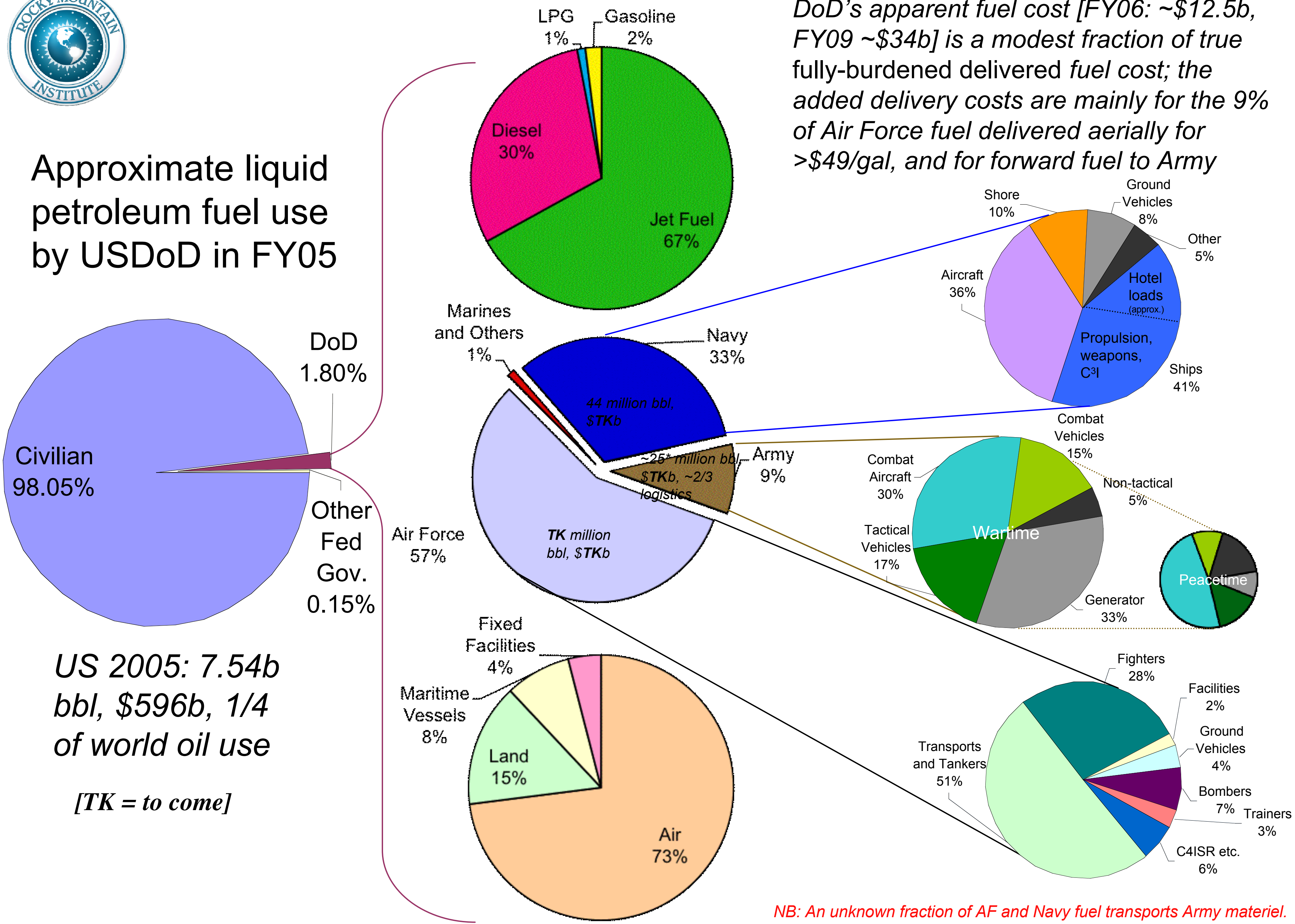
[87] Ref. 39 and other RMI publications, notably my 7 March 2006 testimony to the Senate Energy Committee.

[88] A.B. Lovins, L. Hunter Lovins, and Leonard Ross, "Nuclear power and nuclear bombs," *Foreign Affairs* **58**(5):1137–1177, Summer 1980; A.B. Lovins, "Proliferation, Oil, and Climate: Solving for Pattern," *Foreign Policy*, January 2010, in press.

[89] R. James Woolsey (DCI Ret.) and Anne Korin, "Turning Oil into Salt," *National Review*, 25 September 2007.

Approximate liquid petroleum fuel use by USDoD in FY05

DoD's apparent fuel cost [FY06: ~$12.5b, FY09 ~$34b] is a modest fraction of true fully-burdened delivered *fuel cost; the added delivery costs are mainly for the 9% of Air Force fuel delivered aerially for >$49/gal, and for forward fuel to Army*



US 2005: 7.54b bbl, $596b, 1/4 of world oil use

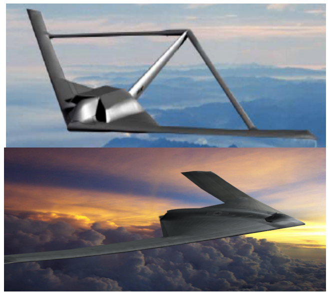
[TK = to come]

NB: An unknown fraction of AF and Navy fuel transports Army materiel. Oil used by contractors to which DoD has outsourced work is unknown.

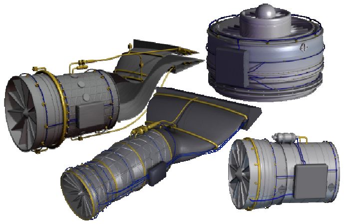
Some opportunities from DSB 08: dramatic gains in combat effectiveness *and* energy efficiency are widely available

(scaled-down wind-tunnel model)

BWB quiet aircraft: range & payload × ~2, sorties ÷ 5–10, fuel ÷ 5–9 (Σ 2–4)



SensorCraft (C⁴ISR): 50-h loiter, sorties ÷ 18, fuel ÷ >30, cost ÷ 2



VAATE engines: loiter × 2, fuel – 25–40%, far less maintenance, often lower capital cost

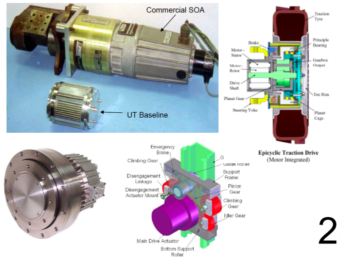
Optimum Speed Tilt Rotor (OSTR): range × 5–6, speed × 3, quiet, fuel ÷ 5–6

Re-engine *M1* with modern diesel, range × ≥2, fuel ÷ 3–4

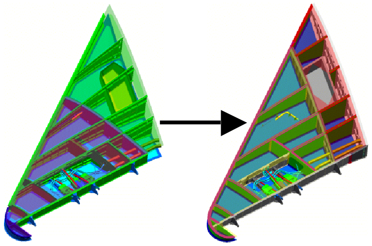
More lethal, highly IED-resistant, stable *HMMVV* replacement, weight ÷ 3, fuel ÷ >3 (up-armored *HMMVV* ~4 mpg)

Hotel-load retrofits could save ~40–50% of onboard electricity (thus saving ~1/6 of the Navy's non-aviation fuel)

FOB uses 95% of genset fuel to cool desert; could be ~0 with same or better comfort

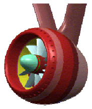


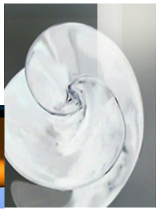
Actuators: performance × 10, fault tolerance × 4, size & mass ÷ 3–10



25% lighter, 30% cheaper advanced composite structures; aircraft can have ~95% fewer parts, weigh ≥1/3 less, cost less

Advanced propulsors can save much noise and fuel





Rugged, 2.5-W PC, $150, solar + back-up crank

A zero-net-energy building (it's been done in –44˚ to 46˚C at lower cost)

240-Gflops supercomputer, ultrareliable with no cooling at 31˚C, lifecycle cost ÷ 3–4