ENERGY INNOVATION *at the* DEPARTMENT *of* DEFENSE

ASSESSING THE OPPORTUNITIES

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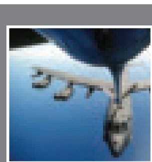
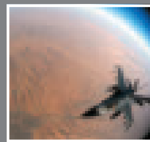


TABLE OF CONTENTS



INTRODUCTION

In recent years, driven by the demands of combat in Iraq and Afghanistan, as well as looming budgetary stress, the United States Department of Defense has increasingly focused on the ways in which energy affects its operations and the opportunities to improve its performance through the development and adoption of innovative energy technologies and practices.

Many observers see in this new focus exciting opportunities in the intersection of two powerful forces within one institution: the most potent engine of technological innovation in human history, and the unparalleled energy demands of national defense. DoD's historical record on energy innovation is extraordinary, and there is reason to hope that important advances might come from a renewed effort in this area. But there also appear at present to be significant limitations upon the scope and scale of DoD's likely influence on technological advance that can contribute to the nation's energy infrastructure as a whole, and particularly to the development and deployment of low-carbon energy systems that might affect the rate of climate change.

This report explores the landscape of these questions: What are the innovation models that have proven successful at DoD, and how might they be applied to develop and commercialize clean energy today, either within DoD itself or in other federal agencies?

To better understand this landscape, the report first provides an overall synthesis of key issues surrounding energy innovation at DoD, and then presents four papers that explore distinctive perspectives and elements of the DoD innovation process. As a whole, we hope the report adds up to a richly detailed analysis of specific institutional attributes of the DoD innovation system that seem relevant to the energy innovation challenge. Can policymakers successfully apply these lessons and capabilities to the context of the nation's civilian energy needs?

Key attributes of innovation at DoD identified in our report include:

- The strategic value of end-to-end research, development, demonstration, and deployment of technological systems; and specifically, DoD's focus on testing, evaluation, and continual systems improvement;

- The powerful effects of large and sustained procurement programs that are closely tied to the department's innovation capabilities;
- The proven effectiveness of two very different but highly effective innovation models: the widely extolled Defense Advanced Research Projects Agency, and the Strategic Environmental Research and Development/Environmental Security Technology Certification programs; and
- The importance of DoD's relations with commercial firms, and the related ability to guide and assess the effectiveness of its innovation activities in the context of its mission performance.

Limitations

Despite the apparent potential for progress in linking DoD to energy innovation in light of these attributes, there are also real reasons to question how much, or how easily, DoD's innovation capacity can or will be applied to the energy challenges that are most relevant to our national and global environmental goals. DoD offers important institutional lessons, and models for innovation driven by the defense mission—but lessons and models that may not always translate easily to the energy context.

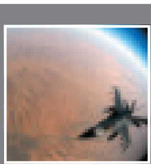
DoD's ability to house supply and demand under one roof, and to produce lasting improvements in complex systems over time, driven in part by large, sustained procurement programs, is nearly unique—and unlikely to be widely reproduced in the energy and climate context. There are significant constraints upon what DoD is likely to do directly in this area; the department is unlikely to become an all-purpose engine of energy innovation. Instead, it must be assumed that DoD innovation efforts will focus on technologies that are most likely to contribute to the military's mission. The extent to which these technologies have the potential to catalyze innovation relevant to large-scale reduction of global greenhouse gas emissions remains to be seen. An important open question in this regard is the degree to which DoD will see zero carbon baseload energy generation for its fixed installations as an area worthy of investments. For example, the development and deployment of advanced nuclear reactor designs such as small modular reactors is one potentially important opportunity to advance both military and civilian interests.

The Challenge

One challenge for policymakers concerned about energy and climate, then, is to maximize the ways in which DoD can contribute directly to progress on key energy-related technologies in ways that advance, or at least do not impede, the security mission. But policymakers must also think seriously about the ways in which the DoD innovation model can be applied beyond its institutional borders, and about what the DoD experience suggests with regards to the prospects for other proposals to enhance our national energy innovation systems.

Indeed, the principles that have animated successful innovation systems in the past appear increasingly clear—and are often absent from current discussions about energy innovation policy. The military-industrial complex that allowed America to win the Cold War was not built on a system of balkanized, technology-specific budgetary line-items and individual, disconnected institutional capabilities. Rather, it was a complex, highly integrated, multisectoral innovation ecosystem. Is it conceivable that we could move toward such a model for energy innovation?

DoD is doing a lot to advance energy innovation, and should continue to do so—but we must also be realistic in our expectations for the ultimate outcome of these efforts, unless greater attempts are made to consciously align DoD's efforts with larger national goals and resources, or unless institutions outside of DoD are able to re-create some of the key attributes of the defense innovation system.



DEFENSE DEPARTMENT ENERGY INNOVATION: NEEDS AND CAPABILITIES

In its reliance on energy, the U.S. military resembles other parts of society. At hundreds of bases in the United States and abroad, and in the communities surrounding them, military personnel and their families live and work in buildings heated by gas and lighted by electricity. Whether military or civilian, ships, planes, and vehicles run on petroleum. Commuters head to work with battery-powered mobile phones and digital tablets; soldiers head into combat carrying radios, GPS units, and night vision systems—and plenty of spare batteries.

This project explored three topics that link the innovation capabilities of the Department of Defense (DoD) with the military's current and future energy-related needs. Stated as questions, the three topics are these:

1) Just how does DoD innovate? What are the ingredients that have made for success in historical cases such as jet engine development? What factors distinguish DoD's capacity for innovation from that of other federal agencies?

2) What, more narrowly, can be said about needs and opportunities for future DoD contributions to particular energy technologies such as alternative (nonpetroleum) fuels?

3) More broadly, how might DoD's capabilities contribute to the larger set of national needs in energy technology—particularly the need for low- and zero-carbon energy technologies?

This report gives our answers. The basis includes the three case studies and three commissioned white papers that follow.[1] Drafts of the white papers and case studies served as the basis for a workshop that brought together two dozen experts on energy, innovation, and military affairs.[2] The analysis, findings, and conclusions that follow are, however, attributable only to the lead project organizers.[3]

Our work draws upon, and extends, an earlier analysis of energy-climate innovation, likewise grounded in case studies and expert workshops.[4] That study examined three technologies (solar photovoltaics, carbon capture and storage, and direct air capture of carbon dioxide), compared them to nonenergy innovations, and also compared the innovation-supporting activities of the Department of Energy (DOE) to other federal agencies, including DoD. Here, in recognition of DoD's unique institutional capacity for influencing technological change, we seek a deeper understanding of military innovation—how it works, and what defense agencies bring to the quest for low-carbon energy technologies.

Our earlier work led to four basic principles for invigorating energy-climate innovation:[5]

1) Intragovernmental *competition* should be encouraged.

2) Congress and the administration should treat decarbonization as a *public good*.

1 All are also available at www.cspo.org/projects/eisbu/.
2 A list of workshop participants can be found at the end of this report. The workshop was held in Washington, DC, on May 25, 2011.
3 Daniel Sarewitz, Samuel Thernstrom, John Alic, and Travis Doom.
4 *Innovation Policy for Climate Change* (Washington, DC: Consortium for Science, Policy & Outcomes; and Boston, MA: Clean Air Task Force, September 2009), www.cspo.org/projects/eisbu/.
5 *Innovation Policy for Climate Change*, pp. 2–3 and 37–38.

3) Weak forces of demand, characteristic of new energy technologies, make testing and *demonstration* especially important, and government must learn to manage this aspect of publicly supported R&D more effectively.

4) Feedback from customers and final users drives all innovation, making *procurement*, consistent with a public goods model, a powerful lever, underutilized in the case of energy technologies.

We now amplify these principles in the context of DoD and its national defense mission.

Competition. The military services, independent of one another until after World War II and retaining substantial autonomy, both cooperate and compete. Innovation has been a byproduct of rivalry between the Army, Navy, and Air Force for roles and missions, and for budget authority. When two or more of the services have common technical interests, as in gas turbines and jet engines, they often work together effectively, fostering innovation. Absence of internal competition, on the other hand, may mean some avenues for potential performance gains will be overlooked, as appears to be the case for low-power electronics as a means of reducing the number and weight of batteries carried by foot soldiers.

Public Goods. Defense is a classic public good, something that, like reduction of global greenhouse gases (GHG) emissions, individuals and communities cannot provide for themselves. DoD energy innovations can simultaneously contribute to the public goods of national security and advancing technologies that can help decarbonize the nation's energy system. However, because the national security mission will always have priority, DoD's contributions to GHG mitigation will depend on the extent to which the mission-driven needs of the services are aligned with needs for low-carbon energy and energy-related innovations in society at large.

Demonstration. DoD, far more than any other government agency, funds the development of technological systems through the full spectrum of innovation activities, from conceptual design to production, and does so as an integral part of an essential national mission. Demonstration, testing, and feedback from the field are intrinsic parts of the R&D spectrum, activities that link design and development with customers and final users and also link private firms, which bring innovations to fruition, with the public sector. DoD devotes a substantial share of its R&D spending to testing and demonstration. Other government agencies, lacking strong connection between their missions and their R&D activities, thus lack as well DoD's capacity to create the robust feedback linkages that are so important for the practical realization of new technologies.

Procurement. DoD, again on a unique scale in government, purchases technical systems in quantity. These systems must work, in the extreme during times of war. While engineers, scientists, and astronauts with extensive specialized training operate the systems of the National Aeronautics and Space Administration, for example, ordinary military personnel, many of them recent high school graduates, operate and maintain much of what DoD buys. For such reasons, the user community that DoD procurement supplies is more typical of consumers in the nation as a whole.

Because DoD pays for the development of a vast array of systems and equipment used on an everyday basis, the services and their contractors have strong incentives to manage innovation with practical ends in view, to demonstrate new technologies and test them extensively before placing them in the hands of ordinary military personnel, to extract "lessons learned" from operating experience, and to feed those lessons back into the ongoing process of innovation. DoD benefits from sources and scales of feedback into the process of innovation that other agencies generally do not have.

Military Innovation: How It Works

The Cold War shaped the U.S. military's approach to innovation. Pentagon managers and their counterparts in the defense industry know that lives and national security depend on how well they do their jobs. Fears of World War III may be gone, but technology retains its prominence in military policy as U.S. troops with their ceramic body armor, unmanned aerial vehicles (UAVs), and MRAPs (Mine Resistant Ambush Protected vehicles) fight on in Afghanistan.

DoD integrates into the pursuit of its mission the full panoply of R&D functions found in the private sector (box 1.1). Other agencies such as the Department of Energy aim to catalyze private sector innovation, but since the accomplishment of their mission does not usually require them to purchase the products of the research they support, they often must make decisions without benefit of the guidance that DoD managers take from planning and foresight exercises that go on constantly within the services. DoD is also unique among agencies in the degree to which its technology spending flows to private firms rather than to its own laboratories or to universities and other nonprofits. The sums are large—some $235 billion for R&D and procurement in fiscal 2011—and by other measures, too, DoD commands greater innovative capacity than the rest of government. The Army, Navy, and Air Force, for example, employ nearly 100,000 engineers and scientists between them. Most of the people, and most of the money, support acquisition of systems and equipment from firms in the extended defense industry (which is perhaps best thought of as a virtual industry). Eugene Gholz's white paper, "The Dynamics of Military Innovation and the Prospects for Defense-Led Energy Innovation," discusses the relationships between DoD and its contractors.

Box 1.1 Defense Acquisition and "Full Spectrum" R&D

Most of the dollars that support military technology development flow through DoD's acquisition budget. In Pentagon terminology, acquisition includes both R&D—or RDT&E, for research, development, test, and evaluation—and procurement. RDT&E claims over one-third of the acquisition budget.[a] The money supports DoD's many internal laboratories and technical agencies, including the Defense Advanced Research Projects Agency (DARPA). (The white paper by William B. Bonvillian and Richard Van Atta, "The Energy Technology Challenge—Comparing the DARPA and ARPA-E Models," provides an authoritative analysis of DARPA, a storied innovation seedbed.) The majority of RDT&E funds, however, pay for the design and development of particular weapons systems, work carried out primarily by private firms under contract.

Demonstration and testing account for a substantial share of the RDT&E budget. In fiscal 2011, funding categories labeled "system development and demonstration" and "operational systems development" claimed 60 percent of RDT&E dollars.[b] Much R&D by private firms serving civilian markets, whether automakers or computer software developers, explores how well prospective new products satisfy customer needs (actual needs, as opposed to expressed desires), seeks reductions in costs and gains in reliability, and otherwise meets marketplace demands. Likewise in defense, demonstration and testing are an inherent part of design and development. DoD's capabilities in testing and demonstration, as illustrated by the test beds for infrastructural energy technologies described in Jeffrey Marqusee's white paper, "Military Installations and Energy Technology Innovation," have few counterparts elsewhere in government.

Only about 15 percent of RDT&E falls under what DoD calls its Science and Technology (S&T) program. This includes basic research, applied research, and a third budget category labeled advanced technology development. The S&T program provides the closest parallels to the sort of work almost exclusively supported by other federal agencies. Within the Department of Energy, notably, the Office of Science gets the largest slice of R&D funding, in fiscal 2011 nearly $5 billion. As Bonvillian and Van Atta observe in their white paper, the Office of Science "views itself as a basic research agency, and rejects work on applied research, assuming it is the job of other parts of DOE to manage those efforts." The budget of the Office of Science is distributed by managers who "generally view themselves not as technology initiators but as supporters for the actual researchers located in [DOE's] national labs and in academia"; the office funds "a wide variety of basic physical science fields, aside from basic energy-related research." In some contrast, defense agencies charged with supporting relatively fundamental work, such as the Office of Naval Research, have remained consistently attentive to the long-term needs of the military; indeed, part of their job is to understand future needs and ensure an adequate knowledge base will exist when the time comes. Like their counterparts in DOE, on the other hand, managers in the National Institutes of Health (NIH) and the Agriculture Department, among other agencies, make their decisions without the sort of guidance DoD managers get from the mission needs of the services. NIH would look quite different and behave quite differently if it were charged with developing drugs and treatment regimens (e.g., for underserved Americans such as Medicaid enrollees) rather than simply supporting research in the biological sciences.

a Estimated fiscal 2011 RDT&E spending comes to some $81 billion. With procurement at $152 billion, acquisition is expected to be $233 billion. *Historical Tables: Budget of the U.S. Government, Fiscal Year 2012* (Washington, DC: Government Printing Office, 2011), table 3.2, p. 74.

b *RDT&E Programs (R-1), Department of Defense Budget, Fiscal Year 2012* (Washington, DC: Office of the Under Secretary of Defense (Comptroller), February 2011), p. III.

Innovations have many sources, not just R&D. Radical advances sometimes originate in centrally managed undertakings, appearing, like the atomic bomb in 1945, in the public eye full-blown. At least as commonly, they emerge over many years through repeated incremental innovation, a pattern illustrated by UAVs. The drones targeting insurgents in Afghanistan today descend from past generations of remotely controlled and robotic (autonomous) aircraft beginning nearly a century ago, at the time of World War I. Earlier drones also prefigure post–World War II cruise missiles and the precision-guided munitions that, after decades of work, proved their capabilities in the late stages of the war in Vietnam and then, during the 1991 Gulf War, delivered video images that illustrated U.S. military capabilities for a worldwide audience. A great many development programs and trials, conducted over many years with generally disappointing results, preceded and contributed to the first militarily effective UAVs, precision-guided bombs, and air-to-ground missiles.[6]

Broadly speaking, then, innovation, military as well as civilian, is best thought of as an ongoing, cumulative process fed by multiple inputs rather than as a series of episodic events stemming from invention, discovery, or research. Most advances in military technology stem from the acquisition process. But some originate in on-the-spot responses to enemy tactics: at least since World War II, the U.S. military has been known for this sort of "bottom-up" innovation.[7] The examples include such well-known weapons systems as fixed-wing gunships, which developed out of combat experience in Vietnam.[8] All four services, moreover, spend much money, time, and effort on the maintenance and repair of quite complex systems and equipment. Along with feedback from combat experience, which gave rise to the MRAP vehicle program, feedback from operations and maintenance has spurred many technical advances, contributing especially to greater reliability and reduced operating costs. These are, of course, primary concerns in energy innovation, since many energy systems are long-lived and, with traditional sources of energy still relatively inexpensive, alternatives face challenging cost targets.

Military Energy Innovation

Since the nineteenth century, energy-related innovations—railroads for rapid mobilization, steam power at sea in place of sail, mechanized land armies—have transformed military operations. Diesel-electric submarines terrorized shipping during two world wars despite their severe limitations as a weapons system. Nuclear propulsion removed those limitations at a stroke, opening a new era in undersea warfare. On its initial voyage in 1955, the U.S. Navy's first nuclear submarine, *Nautilus*, averaged more than 20 knots over 1,400 miles without surfacing, a speed diesel-electric submarines could barely reach, much less sustain for more than a few minutes. Commercial nuclear power followed in a few years, a spin-off from defense with mixed outcomes, for reasons explained in our previous study, *Innovation Policy for Climate Change*.[9] In a further example of spin-off, this one from aerospace, utilities began in the 1980s to purchase gas turbines based on military designs for generating electrical power.

Technology flows the other way too, from civilian applications to the military. If spin-off has flourished in the United States, DoD has sometimes been blind to spin-on potential. GPS receivers issued to troops in Afghanistan, for example, weigh 20 times more than units widely available at lower cost to hunters and hikers (or terrorists), 2 pounds compared with 5 ounces.[10]

Our case studies, summarized below, include further illustrations of energy-related military innovations, and provide analytical support for the findings and conclusions that follow.

Gas Turbines

Independent management of the technology base and of engine design/development by DoD and its contractors underlie 60 years of advances in the energy conversion efficiency of gas turbines and the propulsive efficiency of jet engines. Separation of the technology base from design and development became the norm in the 1950s (see box 1.2). It emerged because the earlier model—in which, to oversimplify only slightly, new technical knowledge emerged as a byproduct of design and development—became untenable as a result of rising complexity. Rather than addressing problems such as flutter of compressor or turbine blades (uncontrolled vibrations excited by fluid flow) in the course of engine programs, these became independent subjects of R&D, the objective being a body of knowledge that engineers and scientists could tap regardless of employer.

The general model that has been followed in recent years, including coordinated undertakings by the Air Force, Navy, and Army such as the Integrated High Performance Turbine Engine Technology (IHPTET) program and its successors, could be adopted for other energy-related technologies. The model is particularly appropriate for complex systems in which advances depend on several more-or-less independent fields of technical knowledge. For example, flow stability within a jet engine

6 Kenneth P. Werrell, *The Evolution of the Cruise Missile* (Maxwell Air Force Base, AL: Air University Press, September 1985): Paul G. Gillespie, *Weapons of Choice: The Development of Precision Guided Munitions* (Tuscaloosa: University of Alabama Press, 2006).

7 James Jay Carafano, *GI Ingenuity: Improvisation, Technology, and Winning World War II* (Westport, CT: Praeger, 2006).

8 Jack S. Ballard, *Development and Employment of Fixed-Wing Gunships, 1962–1972* (Washington, DC: Office of Air Force History, 1982).

9 See especially pp. 15–16.

10 *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan, April–May 2003* (n.p.: U.S. Army Center for Army Lessons Learned, n.d.), pp. 90, 108.

Box 1.2 Managing R&D

Until the 1950s, the U.S. military made no sharp separation between R&D and procurement. The services specified what they wanted, whether a new radio or a new fighter plane, passed the requirements along to their arsenals and supply bureaus or to external contractors, and—if acceptable prototypes eventually came back and the money was available—placed orders for production quantities. R&D was not unknown (civilians managed research on an ad hoc basis during World War II, for example), but neither was it routine. That changed quite suddenly as a result of the Korean War.

Defense spending had fallen precipitously after 1945. There was barely enough money to continue development of jet aircraft and nuclear weapons. During the early stages of the fighting in Korea, outnumbered U.S. troops equipped mostly with obsolete weapons were pushed back nearly into the sea. Policymakers concluded that the United States needed new generations of high-technology weapons, and DoD as an organization—or a congeries of organizations, since then as now each service did things its own way—had to find ways to acquire those weapons. Over the decade (1951–1960), RDT&E spending increased sixfold. DoD and the services had to learn to spend the money effectively. The learning came quickly, as the gas turbine case shows.

As an innovation in policy, or in government management and organization, the separation of generic technology development from system-specific RDT&E and procurement was not, strictly speaking, new or unique. From the 1920s, the National Advisory Committee for Aeronautics (NACA) conducted technology base work in support of both military and civil aviation, developing knowledge and methods that aircraft firms could apply in the design of airframes and powerplants. Yet NACA disappeared in the late 1950s, doomed by a less than exemplary track record. (Among other failings, NACA had, in a minor irony, neglected propulsion to such an extent that policymakers cut the agency out of jet engine work during World War II, unwilling to trust it with responsibility for a vitally important new technology.)[a] And in a contemporaneous parallel to the organization and management of gas turbine development, Hyman G. Rickover insisted that the navy's nuclear submarine program begin with extensive exploration of conceptual alternatives, followed by painstaking engineering studies and extensive testing of prototypes, before even beginning to design equipment for submarine installation.[b] This was a major reason for the triumphant and trouble-free debut of *Nautilus*, so different from recent cases such as the San Antonio class of diesel-powered amphibious transport dock ships, the first of which "has been beset by major defects since its builder, Northrop Grumman, delivered the ship to the Navy in 2005."[c] In his white paper, "The Dynamics of Military Innovation and the Prospects for Defense-Led Energy Innovation," Eugene Gholz traces the $18 billion program's difficulties to a misguided belief by Pentagon managers that the prime contractor, with experience in systems integration but not in the design and construction of naval vessels, could adapt its "core competencies" to shipbuilding.

a Virginia P. Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology*, NASA SP-4306 (Washington, DC: National Aeronautics and Space Administration, 1991).

b Richard G. Hewlett and Francis Duncan, *Nuclear Navy, 1946–1962* (Chicago: University of Chicago Press, 1974).

c Corinne Reilly, "Navy Says Trouble-Plagued San Antonio is Ready," [Norfolk] *Virginian-Pilot*, August 4, 2011. As this account relates, the San Antonio experienced a "disastrous maiden deployment in 2008," and in July 2011, after extensive repairs, it encountered its "latest troubles—leaks in all four engines…off the coast of Virginia." Another deployment has been scheduled for 2012. The very fact that the Navy delayed a second deployment by four years in the effort to rectify the San Antonio's shortcomings testifies both to the pathologies of acquisition, which are manifold, and the need to work through technical problems in military systems and equipment no matter how long it may take.

depends on the elastic response of vanes (some fixed and others moving) to dynamic pressures exerted by those same flows. Blade flutter results from similar interactions. The implication for policy is that disciplinary research, critical as it may be for energy-climate innovation, should be complemented, as in IHPTET, by multidisciplinary systems-oriented programs with engineering design/analysis components.

Effective management of gas turbine development reflects military demand for both performance and dependability. Critics sometimes suggested that IHPTET was overly coordinated to the point of rigidity, to the detriment of fresh thinking, and IHPTET follow-ons have been organized and managed in looser, less structured fashion.

Alternative Fuels

Liquid fuels are indispensable for the U.S. military. Nuclear reactors power submarines and aircraft carriers; otherwise the Navy's ships run on petroleum. So do all types of aircraft, trucks, and combat vehicles. Military installations buy electrical power, when they can, from local utilities, but diesel generators provide essential backup—and are the main power source at forward bases that lack grid connections. Direct consumption of petroleum accounted for more than three-quarters of DoD's energy use in fiscal 2010, costing $13.4 billion.[11]

Even so, given adequate forward planning, DoD has little reason to fear constraints on supply of petroleum-based fuels for several decades, perhaps many. A tightening international oil market, resulting in continuing price increases, would pose greater difficulties for other segments of the U.S. economy and society, and for other countries. DoD's expenditures on fuel may seem large, but should be viewed in the context of other routine expenditures. Even for the Air Force, the principal consumer with its fleet of nearly 6,000 planes, fuel accounts for only around one-fifth of operations and maintenance costs.[12] In Afghanistan and Iraq, fuel and water have made up 70 percent (by weight) of the supplies delivered to forward areas.[13] Transport convoys have drawn frequent and deadly attacks, but the only way to reduce risks, casualties, and delivery costs is to cut consumption (of water as well as fuel)—not something that alternative fuels can promise. Alternative fuels might have somewhat lower energy densities than petroleum (less energy content per gallon or per pound), meaning somewhat more fuel would have to be burned for the same power output, but not higher (by any significant amount). Indeed, alternative fuels cannot promise performance advantages of any sort.

If policymakers nonetheless decide to support production, the choice should be biofuels rather than coal-based synfuels. Whether burned directly or converted to gas or liquid, coal releases substantially more carbon dioxide (CO_2) to the atmosphere than other fossil fuels—unless it is captured and sequestered (e.g., in stable underground reservoirs). Only with a determined and complementary commitment to developing systems to capture and sequester the CO_2, would there be much point in planning for synfuels production, even though the technology is in hand. Biofuels pathways have only recently begun to be explored, except for alcohols and biodiesel, which are unsustainable in the United States in large production volumes, but have at least theoretical potential to replace petroleum without adding to the atmospheric GHG burden. Since climate change could bring new risks to international security, it would make little sense for DoD to begin purchasing synfuels.

The Air Force and Navy have nonetheless set ambitious goals for future purchases of alternative fuels, in the expectation that announcing such plans will induce innovation and private investment in production capacity. These hopes will probably be frustrated, unless DoD agrees to pay well in excess of prices set in the international petroleum market, a commitment that would almost certainly incite opposition from the oil industry and Congress and one that investors might not find credible. Such a policy could also lead to premature efforts to commercialize technologies that later prove unsustainable or simply uncompetitive.

Lighter Loads for Soldiers

Batteries make up a substantial portion of the 100 pounds or more carried by soldiers afoot. Commercial demand has driven battery innovation in recent decades, but consumer markets are much more price sensitive than DoD, and not many customers will pay for the absolute lightest weight. As a result, military and commercial markets have diverged, with DoD buying many types of specialized nonrechargeable batteries for soldier-portable equipment, since these weigh about half as much as the rechargeable batteries found in mobile telephones, laptop computers, and cordless drills. Even if substantially lighter rechargeable batteries become available, soldiers will often find themselves far from electrical outlets; while rechargers powered by solar cells, wind, and fuel cells have begun to reach the field, most electrical power at forward bases comes from diesel generators. Since the military market is small, and since weight will remain the priority—indeed, the Army and Marine Corps hope to reduce by half the loads carried by foot soldiers—

11 *Defense Logistics Agency Energy Fact Book Fiscal Year 2010* (Fort Belvoir, VA: Defense Logistics Agency Energy, 2011).

12 Eric J. Unger, *An Examination of the Relationship between Usage and Operating-and-Support Costs of U.S. Air Force Aircraft*, TR594 (Santa Monica, CA: RAND, 2009), table 1.2, p. 3.

13 *Defense Management: DOD Needs to Increase Attention on Fuel Demand Management at Forward-Deployed Locations*, GAO-09-300 (Washington, DC: Government Accountability Office, February 2009), p. 8.

continued innovation in batteries for consumer products may hold promise primarily for training applications and for powering vehicle-born equipment.

There is a second way the Army and Marine Corps can reduce the weight soldiers must carry: cut the amount of power consumed by equipment, such as radios, through application of well-known design practices pioneered in commercial markets. DoD contractors appear to make little use of such methods currently, probably because acquisition policies and practices do not create incentives to do so. Without higher priorities for low-power design, soldiers could end up carrying even more than they do today, if battery-powered systems and equipment (e.g., portable robots) proliferate faster than the energy density of batteries increases.

Generalizations from the Case Studies

The separation and largely independent management of research and system design set DoD apart from other federal R&D agencies. Many agencies provide broad funding for science and technology. DoD supports the design and development of systems that it expects to purchase and upon which it directly depends for fulfilling its mission. The national security mission acts as a source of managerial discipline somewhat analogous to profitability in corporate organizations, yet it is also something of a two-edged sword. "National security" has been used to justify technological overreach, including efforts to exploit new technologies before they have been demonstrated, and a preference for unworkable superweapons. The Army's recently aborted Future Combat System (FCS), "restructured" in 2009 and then canceled completely, is the latest example, one that absorbed $20 billion in RDT&E expenditures.

Incentives *do* exist for DoD to match technology development with actual military needs. They may not always be strong enough, as suggested by the Army's failure to pursue low-power electronics (and the lagging pace of diesel generator modernization, discussed in a later section). The same imperatives that underlay the ill-fated FCS program have led to simple yet revolutionary weapons such as laser-guided bombs.

Our case studies also suggest that advances in engineering knowledge tend to matter more than advances in scientific knowledge for system performance and for costs. Costs, in particular, fall under the purview of engineering, and while for DoD cost matters less relative to performance than it does for commercial customers, it usually has at least some bearing. Other research agencies for the most part do not directly confront such issues, because they are rarely involved in the demonstration, purchase, and mission-critical deployment of products derived from their research.

Energy and the Military Mission

When they could, militaries have treated fuel—aviation gasoline or jet fuel for planes, diesel fuel for armored vehicles, bunker fuel for ships—as an overhead item. Commanders expected to be supplied with whatever they needed and more; waste is part of war, and to want for fuel was to risk disaster almost as assuredly as to want for ammunition. The alternative might be destroyers forced to steam at half-speed or Patton's army stalled in France in 1944 after outrunning its fuel convoys. Military professionals also recognize that a desire for assured supplies of oil was among the reasons, or pretexts, for the wars started by Nazi Germany and Imperial Japan, and, further, that greenhouse gas–driven warming could, in some speculative scenarios, spark conflicts in which the United States might be called upon to intervene. (To be sure, serious analysis of possible linkages between climate change and national security has hardly begun.)

DoD Energy Consumption

To the extent that past policies gave priority to supplying war fighters with as much fuel as they could use—and some historians argue that logistics, even more than the production feats of American industry, won World War II—an explicit focus on reducing energy use would represent a genuine shift. Should efforts to save energy imply even a small sacrifice in performance on measures deemed critical for military effectiveness, the services may resist. On the other hand, there are good reasons, readily available means, and no apparent downside to reducing energy consumption on DoD's fixed bases.

Facilities and Infrastructure

The American military's 500-plus bases, depots, and other real estate holdings in the United States and abroad, mostly well removed from zones of conflict and some of them resembling small cities, get their energy—electricity, natural gas, gasoline for passenger vehicles—chiefly from commercial suppliers. Among energy sources, electrical power is critical. DoD depends on computer and communications networks numbering in the thousands. Most rely on civilian infrastructure for electrical power and voice/data links. So long as backup power is available (e.g., from diesel generators), essential communications and other C4ISR (Command, Control, Communication, Computers, Intelligence, Surveillance, and Reconnaissance), functions can be maintained. Smart-grid technologies that automatically isolate and reconfigure DoD's most critical networks during blackouts and other emergencies have been of particular interest to those who oversee the military's energy infrastructure.

Other fixed-base energy concerns emphasize costs and conservation. DoD's stock of buildings numbers over 300,000.

As discussed by Jeffrey Marqusee in his white paper, "Military Installations and Energy Technology Innovation," DoD expects to substantially reduce facilities, energy demand, in part by acting as an innovation test bed, identifying the best new technologies, and accelerating adoption. Important as these efforts may be, they affect only about one-quarter of DoD energy usage. The rest is consumed in operations, mostly by what DoD calls platforms—ships, aircraft, and ground vehicles.

DoD's Energy Dilemma: Fuel Consumption vs. Platform Performance

Military planners distinguish platforms from the weapons they carry. The Navy's new Littoral Combat Ship (LCS), for example, accommodates interchangeable weapon modules for mine, anti-submarine, and surface warfare. For systems including aircraft, armored vehicles, and the LCS, effectiveness in engaging or evading the enemy depends on platform performance—e.g., range, speed, maneuverability, and carrying capacity for troops and weapons. A fully loaded B-52 weighs nearly 500,000 pounds, about half of this the fuel, some 70,000 gallons, to transport the crew plus 10,000 pounds of bombs or other weapons on an 8,000-mile flight. Smaller attack planes can carry many of the same weapons and conduct generally similar missions, but have ranges of less than 1,000 miles; and although air-to-air refueling is routine, tankers are a limited resource. For ground vehicles, protective armor adds weight, requiring more powerful engines to maintain performance as measured by speed and acceleration. More weight and power mean greater fuel consumption.

System design is a matter of trade-offs, and DoD must compromise, as do airlines in buying planes, and consumers in deciding whether to buy a pickup truck from Chevrolet or a Volt, or a Corvette. In choosing a gas turbine engine for its M1 Abrams main battle tank, the Army opted for a power-to-weight ratio much superior to the traditional diesel engine, at the sacrifice of fuel efficiency. Indeed, the Abrams burns so much fuel—as much as two gallons per mile—that U.S. armored columns sometimes had to slow or even stop during the 1991 Gulf War to avoid outrunning the accompanying fuel trucks. (Pentagon planners, well aware of the fuel mileage figures, overestimated the capabilities of Iraqi forces and anticipated a slower pace of U.S. advance.) Ever since, the Army has discussed re-engining the Abrams with a more efficient powerplant. No action has followed, in part because of multibillion-dollar costs. But the case shows how mission-critical and energy-saving goals may be complementary.

While the 70-ton Abrams is essentially invulnerable to the improvised explosive devices (IEDs) and rocket-propelled grenades (RPGs) responsible for so many casualties in Iraq and Afghanistan, it is too big and cumbersome for conditions in most parts of these countries. Experience with the vehicles that have been used in these conflicts—Humvees, MRAPs, and Strykers—suggests that no matter the rhetorical emphasis DoD may put on energy saving, future generations of ground vehicles will probably weigh more, and thus burn more fuel, than current models. The original Humvee, unarmored and never intended for combat, weighed about two and a half tons; add-on armor kits bring that to as much as four and a half tons, depending on level of protection. (By themselves, the four-inch-thick bulletproof windows that replace a standard Humvee's vinyl side curtains weigh as much as two soldiers.[14]) Since a 10 percent rise in weight increases fuel consumption by about 7 percent (depending on operating cycle), up-armored Humvees burn more trucked-in fuel. With more weight than the chassis and running gear were designed for, they need more maintenance and wear out more quickly. Strykers, armored originally against heavy machine gun fire, weigh about 19 tons; add-on armor for protection against RPGs (but not IEDs, which produce an upward blast) raises that by two and a half tons (for slat armor) or four and a half tons (for reactive armor, which explodes outwards to destroy projectiles before they can penetrate the hull). When up-armored Humvees and Strykers fell prey to more powerful IEDs, DoD began an intensive program to acquire the MRAP, a family of vehicles with no standard design, and built by a number of vendors. The heaviest MRAPs weigh nearly 30 tons. Bigger, heavier vehicles consume more fuel directly and also indirectly, when transported to battle zones by truck, rail, ship, or air. A fully fueled C-130H cargo plane, for example, can haul 18 tons 1,000 miles; range drops in half with 20 tons on board, meaning that it takes two trips (or two C-130s) to move a single Stryker with armor kit a few hundred miles.[15]

Next-generation vehicles will probably weigh more and consume more fuel, despite advances in lightweight protective armor (ceramics, composites, and reactive systems). Armor must shield large areas; projectiles need only punch through in one spot. Large area protection inevitably adds considerable weight; vehicle size must increase to maintain interior volume; and maintaining performance as weight increases means extra horsepower. Fuel consumption rises, driven in this case by the IED threat that surfaced in Iraq and will not now be uninvented. Some observers have suggested that the Army's proposed new

14 *Opportunities in Protection Materials Science and Technology for Future Army Applications* (Washington, DC: National Academies Press, 2011), p. 80.

15 *Military Transportation: Fielding of Army's Stryker Vehicles Is Well Under Way, but Expectations for Their Transportability by C-130 Aircraft Need to Be Clarified*, GAO-04-925 (Washington, DC: Government Accountability Office, August 2004), p. 23.

troop carrier, currently designated the Ground Combat Vehicle, could end up weighing twice as much as the Bradley fighting vehicle it would replace, or almost as much as an Abrams tank.[16]

Powerplant innovations can slow the rate at which fuel consumption rises with weight, but cannot promise to reverse it. Military vehicles, with few exceptions (e.g., small wheeled robots) are too big and heavy to be candidates for battery-electric power. Hybrid powertrains may find application, and auxiliary power units (APUs) would provide near-term reductions in fuel consumption, since military vehicles spend a good deal of time moving slowly or idling (e.g., guarding intersections). Efficiency drops precipitously with output in any fuel-burning engine—to zero at idle, absent housekeeping loads for radios and heating or air conditioning. With an APU sized to operate efficiently at such loads, the main engine can shut down until needed. With a hybrid powertrain, the main engine can be downsized so that it operates, on average, at greater efficiency. For a military vehicle, unfortunately, that would mean sacrificing speed and acceleration needed in combat. (Passenger cars, unlike military vehicles, have substantial excess power and in most cases governed top speeds of something over 100 mph.) Navy ships with two or more engines, on the other hand, can size or supplement engines (including with batteries) to maximize efficiency.

Armored vehicles provide a telling illustration of DoD's energy dilemma. The general point holds for other platforms: greater performance—faster warships, helicopters that can get off the ground at high altitudes (as in the mountains of Afghanistan)—means greater energy consumption. Innovations that make possible greater efficiency can, alternatively, be turned to yield gains on other performance measures, which the armed forces may prefer, just as automakers have chosen to exploit new technological advances to raise horsepower levels rather than vehicle miles-per-gallon (which have not changed much since the early 1990s). Those trade-offs do not exist for diesel generators, but even then lengthy acquisition cycles postpone the gains for years. Thus, while the result may not be reduced energy consumption, there is nonetheless an operational rationale for improved efficiency of military powertrains, and this could provide spillover benefits in other sectors.

DoD's Modernization Dilemma: Moving Innovations through the Acquisition System

In the 2009 Defense Authorization Act, Congress instructed DoD to consider the fully burdened costs of energy in future acquisition decisions (i.e., life-cycle costs attributable to energy consumption). As yet, no information on fully burdened energy costs calculated under DoD's implementing regulations appears to be publicly available. More to the point, acquisition programs take years to complete, and systems then remain in service for decades. The major programs under way today will dominate DoD energy consumption for the next half century. These programs, such as the F-35 Joint Strike Fighter, reflect decisions made when DoD considered energy consumption primarily as it affected platform range (and carbon footprint was of no concern at all). The F-35 program began in the mid-1990s, when oil sold for around $20 per barrel; low-rate production began in 2005, testing and engineering development will continue until at least 2018, and current plans call for cumulative deliveries of 2,456 aircraft through 2035. Ongoing incremental changes to the F-35's engine, airframe, and flight controls will at best reduce fuel consumption a little.

Major systems invariably cost too much for frequent replacement, and consequently remain in service for lengthy periods. Acquisition costs for the F-35, DoD's most expensive program, are expected to exceed $385 billion.[17] Each Littoral Combat Ship, exclusive of weapons modules, will cost some $500 million (in 2011 dollars); the Navy hopes to buy 55.[18] DoD has purchased nearly 28,000 MRAPs for some $44 billion.[19] Modifications or retrofitting to reduce the energy consumption of existing systems, while frequently suggested, has almost always been rejected as too costly, as for the Abrams. For the B-52, designed in the early 1950s and still an Air Force mainstay, "numerous re-engining studies over the years (at least nine studies since 1984)" have reached the same conclusion: almost regardless of future oil prices, total costs will rise.

Although the F-35's 40-year acquisition cycle is extreme, even low-cost, straightforward programs take so long to complete that equipment may be obsolete by the time it reaches the field. More than four-fifths of the 125,000 diesel generators in DoD's inventory are decades old, based on designs laid down in the 1960s.[20] They burn more fuel than up-to-date equipment—in Iraq and Afghanistan consuming greater quantities than armored vehicles, helicopters, or trucks (including transport convoys that haul in the fuel)—and make more noise, which can alert the enemy.[21]

The Army began work on a family of five new generators (with capacities ranging from 5 to 60 kilowatts) in the late 1990s.

16 Sydney J. Freedberg, Jr., "Army Tries Again For A New Tank," *National Journal* (online), March 21, 2011.

17 *Joint Strike Fighter: Restructuring Places Program on Firmer Footing but Progress is Still Lagging*, GAO-11-677t (Washington, DC: Government Accountability Office, May 2011).

18 *An Analysis of the Navy's Fiscal Year 2012 Shipbuilding* (Washington, DC: Congressional Budget Office, June 2011), table 3, p. 15.

19 *Warfighter Support: Improved Cost Analysis and Better Oversight Needed over Army Nonstandard Equipment*, GAO-11-766 (Washington, DC: Government Accountability Office, September 2011).

20 Thomas D. Crowley, et al., *Transforming the Way DoD Looks at Energy*, Report FT602T1 (n.p.: LMI Government Consulting, April 2007), p. E-28.

21 *Report of the Defense Science Board Task Force on DOD Energy Strategy: "More Fight—Less Fuel"* (Washington, DC: Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, February 2008), p. 44.

Pilot production of the first of these Advanced Medium Mobile Power Sources (AMMPS) units began in 2011.[22] Once they are in full production, DoD plans to buy several thousand of the several AMMPS models each year, an annual total of around 10,000. AMMPS generators burn perhaps 20 percent less fuel, depending on the model, than units purchased under the preceding Tactical Quiet Generator (TQG) program, which themselves perform better than the 1960s-era generators that still account for most of DoD's inventory. Production of TQG generators began in the early 1990s, and procurement of some models will continue until 2015 or beyond. It may take almost as long, two or three decades, to turn over DoD's inventory of diesel-powered generators as it will to replace existing Air Force, Navy, and Marine Corps fighters with the futuristic F-35. The point is simple enough: shorter acquisition cycles may be highly desirable, but repeated efforts at reform since the 1960s have accomplished little; to cut energy consumption over the next two or three decades, the services have no real choice but to change their operating practices.

Reducing Operational Energy Consumption

There are straightforward ways to save fuel, and the services have begun to exploit them. Diesel generators networked via rudimentary "smart grids" reduce fuel consumption; some generators can be shut down, with those remaining online running more efficiently.[23] Much more can be accomplished. Private companies—airlines, ocean shippers, package delivery firms—routinely manage their fleets to minimize operating expenses, which for many are dominated by fuel costs. Dynamic scheduling keeps trucks as full as possible. Airlines cannot vary their schedules so easily; instead, they juggle fares constantly, offering tens of thousands of permutations via methods known as dynamic pricing to try to put a paying passenger in every seat. Operations centers oversee route adjustments based on weather and traffic to minimize fuel burn (in passenger and cargo planes, unfortunately, an obsolete air traffic control system limits flexibility).

DoD, with over 600 information systems just for logistics, employs similar planning, routing, and scheduling methods. Navy ships transit at relatively slow speeds to conserve fuel (reducing speed from 25 knots to 17–18 knots cuts fuel consumption roughly by half) and the Air Force ferries planes on fuel-saving routes. Even so, the private sector, motivated by profits, appears to save energy more consistently and aggressively. According to one recent account, for example, "While Mission Index Flying is new for [Air Mobility Command], it isn't a new concept. Cost Index Flying (the commercial equivalent of Mission Index Flying) has helped airlines manage bottom lines for over a quarter of a century."[24]

This could be taken as a case of spin-off followed by later spin-on, since the general family of methods in use for saving fuel, given the name operations research (OR) during World War II, and sometimes called operations analysis (a label that fits actual practices better), stems largely from military planning, with management antecedents in industrial management. As powerful computers became available for the extensive repetitive calculations on which the new methods depended, postwar applications exploded. Defense planners, for example, explored scenarios for deterring, or fighting, what many feared would be World War III. They asked questions such as where the Strategic Air Command's bombers should be based, how many targets in the Soviet Union they could reach, and how many tankers the Air Force would have to buy for air-to-air refueling. DoD and its contractors have a great deal of accumulated experience in methods that could now be turned to saving energy.

The Pentagon's new office for Operational Energy Plans and Programs, established under the 2009 National Defense Authorization Act to oversee energy savings on a department-wide basis, has called on the services to formulate "a clear understanding of how energy is being consumed at the point of use" as a basis for "well informed resourcing decisions."[24] Important as it will be to gather accurate and comprehensive baseline planning information, it should be plain that there is no need to wait for better data. Part of the purpose of OR and related methods is to improve decision making with data and information that may be incomplete, inaccurate, or otherwise unreliable. Where DoD has not already begun to do so, it should employ the available tools. There is no better way for the U.S. military to save energy and set an example for the rest of government.

Conclusion: Policy Principles

In our previous study, we laid out four principles for guiding federal energy innovation policies:[26]

1) Because innovation as a process is complex, as are energy markets and the energy system, policy should foster *diversity and competition in both technologies and institutional settings.*
2) Given the limitations imposed by basic physics on energy conversion, and the unpredictability of breakthroughs, policy should emphasize ongoing *incremental innovation, rapid diffusion, and continuous learning.*

22 See the Web site of the Mobile Electric Power program, www.pm-mep.army.mil.
23 Annie Snider, "Basic Minigrids Promise Major Fuel Savings in Afghanistan," *New York Times*, September 30, 2011.
24 Capt. Kathleen Ferrero, "C-17 Crews First to Use New In-Flight Program to Save Fuel," *Air Force Print News Today*, July 8, 2011.
25 *Fiscal Year 2012 Operational Energy Budget Certification Report* (Washington, DC: Assistant Secretary of Defense for Operational Energy Plans and Programs, January 2011), p. 6.
26 *Innovation Policy for Climate Change*, pp. 2–3 and 37–38.

3) Because a decarbonized energy system is a public good, like clean air or national defense, government should call on a *broad portfolio* of measures, not just research, seeking widespread applications and subsequent feedback-driven learning.

4) Because different technologies at different stages in development respond to different policies, the portfolio should put greater emphasis on *testing, demonstration, and procurement,* which have not been used very effectively to foster energy-climate innovation.

The current project's findings furthers these principles, and expands upon them:

1) Defense agencies and DOE (and its ancestor, the Atomic Energy Commission) have done a great deal already to advance energy technologies, pioneering nuclear reactors for submarine propulsion, with subsequent commercial spin-offs, and spurring increases in gas turbine efficiency. Continuing competition and cooperation between DoD and DOE should be encouraged.

2) DoD is unique among federal agencies in the degree to which it houses supply and demand for innovation under one institutional roof. Smart-grid technology and energy test beds, with the promise of substantial procurements to follow, show the promise and power of these features of the DoD innovation system.

3) DoD and its contractors have much experience in bringing together multiple innovations, major and minor, leading to system-level performance advances. Defense agencies understand, better than other parts of government, that technical advances in combination, rather than isolated breakthroughs, lead to big gains in realized performance. Defense agencies also understand that advances in engineering knowledge tend to matter more for system costs and performance than advances in scientific knowledge, and have learned to integrate these elements effectively into their innovation systems. And DoD also understands the necessity of combining disciplinary research efforts with multidisciplinary systems-oriented programs having engineering design/analysis components.

4) Because national security is subject to varying interpretations, shifting over time, it is not inconceivable that DoD could be given a somewhat broader role in energy innovation, viewed as a public good and consistent with its mission. But the more important and immediate point for our purposes is that when the energy innovation needs of the armed forces align with those in the civilian economy, as they often do, DoD and its contractors can bring to bear competencies in testing, demonstration, and procurement that are rare in other parts of government.

DoD contributions to energy innovation must reflect DoD's mission needs. Otherwise the incentives will be too weak. As Bonvillian and Van Atta note in their white paper, the Air Force, led by pilots, was slow to embrace pilotless UAVs—yet the operational logic of UAV's has proven too strong to resist. The lesson for energy-climate innovation is straightforward: mission-critical technologies will get commitment and support; others may not.

At the same time, DoD and the services arguably are still searching for a sense of the roles and missions they will be asked to undertake in the future. The challenges encountered in Iraq and Afghanistan—irregular warfare; long supply chains passing through mountainous terrain that hosts and hides hostile forces; few allies, some only feebly supportive—may or may not feature in future conflicts. Energy will always be vital for national security, and much of the innovation potential lies with low- and zero-carbon sources; that in itself should be reason enough to integrate DoD and the services more fully and effectively into the national energy-climate innovation effort.

1 DEFENSE DEPARTMENT ENERGY INNOVATION: THREE CASES

John Alic

The Department of Defense (DoD) accounts for four-fifths of federal government energy consumption (80.3 percent in 2010), followed at a great distance by the Postal Service (3.8 percent).[27] The case studies that follow deal with jet engines and gas turbines, alternatives to petroleum-based fuels, and soldier-portable power sources, chiefly batteries. The cases are brief, intended to illustrate patterns of defense-related innovation and government policies and practices. The heavily historical gas turbine case comes first to show how DoD adapted to growing technological complexity in the 1950s by splitting R&D (or RDT&E, for research, development, test, and evaluation) from procurement and, within the RDT&E portfolio, by splitting support for relatively generic knowledge development (e.g., compressible flow in rotating machinery, a core problem in design of gas turbines) from design and development of particular systems (e.g., the J-57 engine chosen to power the B-52 bomber).

Case 1: Gas Turbines and Jet Engines

Military Demand: Driving Force for Innovation

In 1948, six years after the first flight of an American-built jet plane, Secretary of Defense James V. Forrestal told Congress that "the fuel consumption of a jet Air Force was approximately forty-five times that of a traditional air force."[28] Forrestal's warning was prompted by the abysmal fuel efficiency of early gas turbines compared with the piston engines they had begun to replace. In the 1930s, manufacturers of aircraft piston engines devoted much effort to meeting the demands of the Army Air Corps and the Navy for range and endurance along with the demands of fledgling commercial airlines for reliability in passenger service. The Navy wanted patrol planes to scout for elusive enemies hiding in the trackless ocean. The Army, after suffering unsustainable losses of B-17s and B-24s over Europe in 1943, had to find some means to extend the range of escort fighters such as the P-51. By the end of the war, P-51s equipped with powerful yet efficient engines and disposable drop tanks could manage a round-trip of nearly 2,000 miles. Yet when the Korean War broke out in 1950, jet-propelled F-80s based in Japan, with a range of only about 200 miles, could barely make it to the Korean peninsula.[29]

These imperatives remain. Navy F/A-18s flying from carriers in the Red Sea and Persian Gulf, with less range than Air Force attack planes, could not accomplish much in the 1991 Persian Gulf War.[30] Unlike the F-80, with its first-generation jet engine, the F/A-18's range limitations were the result of deliberate choice to trade fuel load for payload. Indeed, the F/A-18's engines are far more efficient than anyone in the 1940s could have anticipated: by the 1980s, gas turbine fuel consumption had improved to the point that electrical utilities were buying them to meet peak power demand—an application that would have seemed irresponsibly wasteful when the jet engine was young and Secretary Forrestal delivered the remarks quoted above.

27 *Annual Energy Review 2010*, DOE/EIA-0384 (2010) (Washington, DC: Energy Information Administration, October 2011), table 1.11, p. 25.

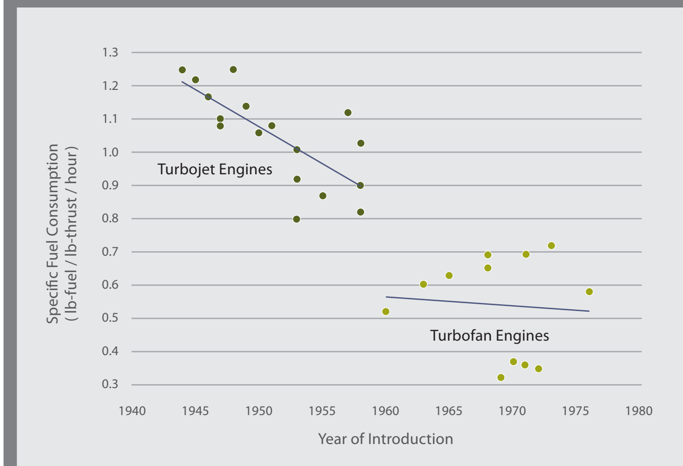
28 Quoted in Paolo E. Coletta, *The United States Navy and Defense Unification, 1947–1953* (Newark: University of Delaware Press, 1981), p. 69.

29 The F-80's range could also be extended with drop tanks (although that meant stripping bombs meant for ground attack, which World War II escort fighters had not needed) and in an example of the bottom-up innovation for which the U.S. military has been known, two Air Force lieutenants improvised a way to increase their volume. Marcelle Size Knaack, *Encyclopedia of U.S. Air Force Aircraft and Missile Systems, Volume 1: Post–World War II Fighters, 1945–1973* (Washington, DC: Office of Air Force History, 1978), p. 9. The Air Force gained its independence from the Army in 1947.

30 Thomas A. Keaney and Eliot A. Cohen, *Gulf War Air Power Survey: Summary Report* (Washington, DC: U.S. Government Printing Office, 1993), pp. 201–203 and 228.

Figure 2-1 shows the rate of advance over several decades. At first, engine manufacturers had trouble just designing and building a gas turbine that would start and run, much less produce useful power. (Without power in excess of that needed to drive the compressor, efficiency is identically zero.) Spurred by military demand and military funding, efficiency—useful output divided by energy input—increased and fuel consumption declined. By the 1960s, the dollars were coming from the Army, as well as the Air Force and Navy, for helicopters and the gas turbine–powered Abrams main battle tank.

FIGURE 2.1 Efficiency Gains in U.S. Military Gas Turbines



Notes. Thrust-specific fuel consumption (vertical axis) at rated military power (without afterburning). Turbofans, or fan jets, bypass some air around the core of the engine, increasing the efficiency with which thrust is generated, hence the thrust-specific fuel consumption (the quantity plotted); thermal efficiency (the parameter of interest for applications other than jet propulsion) does not change. Dates on the horizontal axis correspond to the end of development and testing and beginning of low-rate production. They are approximate to the nearest year. Over the first two decades especially, production commonly began well before the completion of development, with design modifications continuing to resolve stubborn technical difficulties.

Sources. J. L. Birkler, J. B. Garfinkle, and K. E. Marks, *Development and Production Cost Estimating Relationships for Aircraft Turbine Engines*, N-1882-AF (Santa Monica, CA: RAND, October 1982), table 1, p. 7; James St. Peter, *The History of Aircraft Gas Turbine Engine Development in the United States: A Tradition of Excellence* (Atlanta, GA: International Gas Turbine Institute of the American Society of Mechanical Engineers, 1999); Obaid Younossi, Mark. V. Arena, Richard M. Moore, Mark Lorell, Joanna Mason, and John C. Graser, *Military Jet Engine Acquisition: Technology Basics and Cost-Estimating Methodology*, MR-1596 (Santa Monica, CA: RAND, 2002), table 6.2, pp. 66–68.

Technological and Policy Evolution

The Air Force and Navy began many new engine programs during the 1950s, and many of these programs encountered serious technical difficulties.[31] "Before the 1960s, research into [jet] engine phenomena in the United States was generally carried out in the context of engine procurement programs. Requirements for the engine were established, and technology development was part of the process of designing a new engine."[32] Some prototype powerplants would not run at all. Others suffered from inexplicable combustion instabilities or mechanical vibrations. Compressors surged and stalled, creating chronic problems into the 1970s for fighter planes during violent maneuvers that distorted inlet air flows. These were no trivial issues. A test pilot writing in 1955 noted that "stalls may occur at any combination of altitude, power setting and flight condition… Once compressor stall commences, the pilot has little or no choice except to break off any attack and regain control of the engine by all means at his disposal."[33]

Pentagon managers realized that none of their contractors had the knowledge and skills necessary to move from design through development into testing and production in more-or-less smooth and predictable fashion. During World War II, policymakers had chosen General Electric (GE), a pioneer in industrial research with aircraft engine experience limited to componentry, chiefly turbochargers, to work on jet propulsion (based on British technology) in part because of the firm's broad-based R&D capability. Despite its technological prowess, GE struggled in the 1950s alongside Pratt & Whitney and other old-line engine manufacturers to master a series of technical puzzles new and different from any in their collective experience. This was the stimulus that led Pentagon managers to decouple technology-base R&D from powerplant design and development.

Analytical methods for designing compressors and turbines originated in the slide rule era and incorporated gross simplifying assumptions for tractability. Machinery when built did not behave as predicted. Nor could available analytical methods provide much guidance on what to change. The difficulties encountered with a particular engine design might be overcome, but all too often the engineering group, in the absence of insight based on physical understanding, had no choice but to proceed by trial and error. Research was the necessary route to findings that could be generalized. "Experience with an engine directed attention to earlier theoretical work and stimulated the revision in more modern terms."[34] DoD supplied much of

31 James St. Peter, *The History of Aircraft Gas Turbine Engine Development in the United States: A Tradition of Excellence* (Atlanta, GA: International Gas Turbine Institute of the American Society of Mechanical Engineers, 1999) summarizes the development histories of major engine designs by all active manufacturers.

32 William S. Hong and Paul D. Collopy, "Technology for Jet Engines: Case Study in Science and Technology Development," *Journal of Propulsion and Power* 21, no. 5 (September-October 2005): 769.

33 T. A. Marschak, *The Role of Project Histories in the Study of R&D*, P-2850 (Santa Monica, CA: RAND, January 1964), p. 60, excerpting from an Air Force flight test report on North American's F-100A, the first series-production supersonic fighter, fitted with a Pratt & Whitney J-57 engine.

34 William Rede Hawthorne, "Some Aerodynamic Problems of Aircraft Engines," *Journal of the Aeronautical Sciences* 24, no. 10 (1957): 717.

the funding that supported these "revisions" in theory and methods. The work went on primarily in industry. As for other systemically complex technologies, it was mostly firms with well-defined needs for technical knowledge—needs that reflected DoD requirements—that had the incentives and competencies essential for driving innovation on a broad front. Suppliers and the military's own laboratories worked with engine manufacturers. Then as now, only a handful of university research groups were in a position to participate.[35]

The military services let contracts for R&D on engine components, materials, and engineering design and analysis methods. Gas turbine performance, efficiency especially, depends on the maximum temperatures that components such as turbine blades will tolerate without early failure. Research groups studied basic material phenomena (thermally activated microstructural changes leading to degradation in properties) and life-prediction methods (blade elongation and failure as a function of time-temperature history). DoD also funded much work in computational fluid dynamics, computer-based procedures that could be applied to flow fields around gas turbine airfoils (and to aircraft wings and the hulls of warships). With digital computers to aid calculations, earlier simplifying assumptions could be relaxed and predictive accuracy improved, reducing the need for trial and error. Despite the success of theory-based methods, even today such areas as "operability and stall inception and combustor design…rely heavily on empirical information."[36]

Gas turbines cost a great deal to develop—today, well over a billion dollars. Much of the work may seem mundane, as suggested by several of the examples in box 2.1. Nearly invisible to those outside the gas turbine community, this sort of work has nonetheless made essential contributions to the performance increases plotted in figure 2.1 and to reliability, which has also increased greatly over the years.

Until the 1960s, "engine component research and development sponsored by the military had been somewhat random."[37] Over time, work sponsored by different branches, programs, and services coalesced in more structured programs focused on the components comprising the "core" (compressor, combustor, and turbine, through which incoming air passes sequentially). Early coordinated initiatives such as the Advanced Turbine Engine Gas Generator program led to the highly structured IHPTET (Integrated High Performance Turbine Engine Technology) program, for which the National Aeronautics and Space Administration and the Defense Advanced Research Projects Agency joined with all three military services. IHPTET ran from 1987 until 2005 and spent more than $2.2 billion, exclusive of industry funding.[38] DoD expects IHPTET's follow-on, the Versatile Affordable Advanced Turbine Engines (VAATE), to continue until 2017. VAATE's goals include fuel efficiency improvements of "up to" 25–35 percent, depending on engine type.[39] It includes two demonstration efforts with their own names, suggestive of goals: the Highly Efficient Embedded Turbine Engine (HEETE) program and the Advanced Versatile Engine Technology (ADVENT) program.[40]

Over the years, as jet engine performance improved, commercial demand complemented military demand. Powerplants for airliners and business jets incorporate innovations developed first for DoD; many engines have been produced in nearly identical versions for military and commercial sales. Even fighter engines, which must meet quite specialized requirements (box 2.2), yield spin-offs in the form of hardware and knowledge. Without the stimulus of military demand, some of the analytical techniques underlying the highly efficient turbines that electric utilities began to buy in the 1980s might never have attracted the necessary investment.

In many other weapons development programs, DoD and its contractors faced technical difficulties analogous to those sketched above for gas turbines—flutter in airframes, fracture in rocket motor casings, unreliable computer software. A look back at the work in the 1950s on the Army's tank-mounted Shillelagh missile found that

> *The problems encountered in the first 2 years of development were many and varied and not easily solved because of a lack of supporting basic research for Aeronutronic [the contractor] engineers to draw upon. Consequently, unanticipated increases in cost and manhours, not commensurate with technical progress, had to be borne while attempting to "advance the state of the art."* [41]

The government's response, again, was technology base funding to "advance the state of the art."

35 Gas turbine manufacturers "are eager to take advantage of the improved understanding and new techniques that academia can provide. The knowledge base for academic research is arcane, however, and the community of researchers is small. Presently, only about a half-dozen universities in the United States are making significant contributions." *The Impact of Academic Research on Industrial Performance* (Washington, DC: National Academies Press, 2003), p. 117.

36 Edward M. Greitzer, "Some Aerodynamic Problems of Aircraft Engines: Fifty Years After—The 2007 IGTI Scholar Lecture," *Journal of Turbomachinery* 131 (July 2009): 031101-1.

37 Richard A. Leyes II and William A. Fleming, *The History of North American Small Gas Turbine Aircraft Engines* (Reston, VA: American Institute of Aeronautics and Astronautics, 1999), p. 755.

38 *Materials Needs and Research and Development Strategy for Future Military Aerospace Propulsion Systems* (Washington, DC: National Academies Press, 2011), p. 41.

39 Steven H. Walker, "Fiscal Year 2012 Air Force Science and Technology," Statement to Armed Service Committee, Subcommittee on Emerging Threats and Opportunities, U.S. House of Representatives, March 1, 2011, pp. 12–13.

40 *Improving the Efficiency of Engines for Large Nonfighter Aircraft* (Washington, DC: National Academies Press, 2007), pp. 97–105, discusses IHPTET and VAATE. Also see *Air Force Acquisition & Technology Energy Plan 2010* (n.p.: U.S. Air Force, n.d.), pp. 20–21. HEETE aims at greater efficiency for installations requiring inlet and exhaust ducts designed to preserve stealth. ADVENT will demonstrate variable cycle technologies.

41 Elizabeth J. DeLong, James C. Barnhart, and Mary T. Cagle, *History of the Shillelagh Missile System, 1958–1982* (n.p.: U.S. Army Missile Command, August 17, 1984), p. 41.

Box 2.1. Gas Turbine Engine Development: An Example

General Electric began work on its T700 turboshaft in the late 1960s. Well before the engine passed its military qualification tests in 1973, the Army had selected the T700 to power the Apache helicopter, then in development, over a competing model proposed by Pratt & Whitney. The excerpts below from a retrospective study based on extensive interviewing highlight technical problems of the sort encountered in developing complex systems such as the T700—problems that differ considerably from those associated with the research part of R&D, at least as "research" is sometimes pictured.[a]

> GE engineers…simplified the combustor by going to a machined-ring configuration that was made in one piece. Earlier combustors were made of several pieces and tended to move and slowly deteriorate, limiting performance and life.[b]
>
> Engineers…encountered forced vibration of compressor blades when there was a resonant frequency common to both blades and housing. This problem required some redesign. Also, the unusually high rotational speed of the compressor shaft…called for improvements in the properties and design of the disks and blades. GE learned how to manufacture these assemblies in one piece that they termed "blisks," using powder metallurgy with a nickel-based alloy.[c]
>
> While most of the work on the engine was done on contract, the Army engineers co-located at NASA Glenn in Cleveland [the National Aeronautics and Space Administration's principal site for propulsion R&D] conducted 6.1 and 6.2 work [basic research and applied research, respectively] that supported the contractual effort….They worked on the shape of the air foils in the turbine, on the cooling system, on pitting in metals, and on lubrication. They ran in-house engine tests in which they mapped engine temperatures, measured heat distortions and overheating, and took heat transfer data. More recently, they have studied the possible extension of the operating life of the engine and the reuse of some components during major overhaul. They have devised inspection protocols, including methods and timing of crack detection in the metals. Army engineers made the fruits of all this labor, including data sets from tests and experiments, available to industry.
>
> One especially successful piece of Army 6.1 work at NASA Glenn was related to the process, now standard in the industry, for applying ceramic coatings to line the combustor and the blades in the hot section of the engine. Ceramic coating allows higher operating temperatures and hence greater efficiencies.
>
> The Army also funded 6.1 basic research at universities on rare-earth magnets that enabled significant weight and size reductions for starters and generators. The engineers at AATD [the Army's Aviation Applied Technology Directorate] realized the significance of university findings in this area and brought them to the attention of GE.

As these excerpts indicate, the contributions of Army personnel extended beyond program management. In programs involving multiple organizations with potentially conflicting objectives and incentives, DoD employees have often served as a communications hub linking rival firms.

a The excerpts are from Richard Chait, John Lyons, and Duncan Long, *Critical Technology Events in the Development of the Apache Helicopter: Project Hindsight Revisited* (Washington, DC: National Defense University, Center for Technology and National Security Policy, February 2006), pp. 11–12.

b Combustion is rapid and violent; it can do considerable damage in a short time unless combustor components are rigidly fixed.

c Blisks have come to be considered a major innovation.

Box 2.2. Gas Turbine Design Considerations

Military and commercial gas turbines are basically similar (with exceptions for "disposable" engines powering cruise missiles, which need run only a few hours), and powerplants fitted to bombers or military transports may be sold in nearly identical form to commercial customers. The core of the engines powering many Boeing 737s, for instance, was originally developed for a dramatically different sort of plane, the B-1, a long-range swing-wing strategic bomber capable of supersonic flight.

Airlines seek economy of operation above all. Their priorities begin with high fuel efficiency at cruise, the "design point," and low maintenance requirements during years of heavy use. Military planes fly few hours by contrast and jet fighters accelerate and decelerate, dive and climb, and transit between subsonic and supersonic flight. Fuel efficiency matters, and pilots cruise in fuel-conservation mode while ferrying or loitering in battle zones. Nonetheless, the success of combat missions hinges on performance under conditions far from the engine's optimal operating point. As a result, design considerations at both the front and back ends of the powerplant differ from those for commercial (and other military) aircraft, and can become quite complicated.[a] Whereas engines are normally hung on the outside of civil aircraft, they must be integrated with the airframe for supersonic flight or stealth, which means lengthy inlet and exhaust ducts within the fuselage. At the front, the ducts often incorporate variable geometry inlets for managing compromises between subsonic and supersonic regimes. At the rear, exhaust nozzles converge, then open out again, and afterburners boost thrust. Despite these differences, the core of the engine may be essentially the same as that of derivatives intended for commercial service.

a For a useful summary of operating regimes and efficiencies of engine types, see Philip P. Walsh and Paul Fletcher, *Gas Turbine Performance*, 2nd ed. (Oxford, UK: Blackwell Science, 2004), chap. 1. Bernard L. Koff, "Gas Turbine Technology Evolution: A Designer's Perspective," *Journal of Propulsion and Power* 20, no. 4 (July–August 2004): 577–95, provides an accessible component-level technical review of the sources of performance improvement over several decades.

Conclusion

Intense competition—involving the two largest American suppliers, GE and Pratt & Whitney, and Britain's Rolls-Royce—contributed to the fast pace of gas turbine technical advance. So did far-sighted management by DoD and the services, which by the end of the 1950s realized that traditional approaches to R&D and procurement were inadequate in view of new engineering complexities. Along with microelectronics and computing and earth-orbiting satellites, gas turbines are a preeminent example of dual-use innovation in the post–World War II period.

In the 1950s, the very idea of project or program management within DoD as an end-to-end activity, rather than a series of ad hoc decisions made as problems arose, was new. Today it is conventional wisdom that "developing new technology within an acquisition program is a recipe for disaster."[42] The lesson was not obvious at first; it had to be extracted from ongoing projects and programs, then absorbed and propagated. The lesson has also needed to be periodically rediscovered.

Case 2: Alternative Fuels for the U.S. Military

Liquid fuels account for over half of DoD energy use. Jet fuel powers diesel-driven electrical generators as well as aircraft, combat vehicles, and many naval vessels. The Navy and Air Force have publicized ambitious goals for replacing a portion of the petroleum-based fuels they use with alternatives.[43] These might be synfuels—liquids synthesized from coal or some other nonpetroleum hydrocarbon—or biofuels produced from plant matter. Army leaders, apparently seeing no good

42 *Evaluation of U.S. Air Force Preacquisition Technology Development* (Washington, DC: National Academies Press, 2011), p. 4. Acquisition, in DoD terminology, covers both procurement and RDT&E.

43 The Air Force, the largest consumer of fuel among the services, has set the following objective: "By 2016, be prepared to cost competitively acquire 50% of the Air Force's domestic aviation fuel requirement via an alternative fuel blend in which the alternative component is derived from domestic sources produced in a manner that is greener than fuels produced from conventional petroleum." *Air Force Energy Plan 2010* (n.p.: U.S. Air Force, n.d.), p. 8; further discussion appears on p. 25. The Navy's objective is as follows: "By 2020, half of the Navy's total energy consumption afloat will come from alternative sources." *A Navy Energy Vision for the 21st Century* (Washington, DC: Office of the Chief of Naval Operations, October 2010), p. 5. Both these statements should perhaps be regarded as "stretch goals." The Air Force and Navy also have set energy-related targets for infrastructure facilities on land.

reason to push for alternative fuels now, have stressed reductions in consumption.[44]

Making synthetic fuels from coal is not a technological challenge. Synfuels technology is mature, with production experience going back decades and hundreds of plants in operation worldwide. Uncertainty does attach to costs for large-scale synfuels plants incorporating the latest processes, but greenhouse gases (GHGs) are the major issue. Coal contains more carbon than oil, and without sequestration of the excess carbon dioxide (CO_2) released, net emissions increase. That increase would be contrary to the announced policies of the services.[45]

If DoD has no reason to push into coal-based synfuels, the military may have more to contribute to innovation in biofuels. Both sustainability and costs, which could prove uncompetitive even at oil prices well over $100 per barrel, pose obstacles to commercialization. There are many technological pathways to be explored in search of cost-effective technologies that could promise large-scale production without infringing on global food output and prices or adding to the atmospheric GHG burden. This is an agenda for the medium term and beyond. Both technical and economic uncertainties are large. With a decade or more of demonstration, scale-up, and learning ahead, biofuels—whether or not based on conservative technical choices—hold no immediate promise of replacing any substantial share of DoD's petroleum consumption. The longer-term R&D agenda for exploration of more speculative technologies, including algal feedstocks, might benefit from DoD's demonstrated ability to manage technology development with practical ends in view, rather than science.

Fuel Costs and Import Dependence

Over 80 percent of the petroleum purchased and consumed by the U.S. military consists of jet fuel designated JP-5 or JP-8; diesel fuel makes up nearly all the rest.[46] By volume, recent purchases peaked in fiscal 2003 with the invasion of Iraq, then declined even as rising oil prices pushed expenditures upward: fuel doubled as a share of DoD outlays, from 1.5 percent to 3 percent, between fiscal years 2004 and 2008. Consumption did not change much, but purchases rose from $7 billion (2004) to $18 billion (2008). Prices then fell back somewhat, but in 2011 DoD paid more for jet fuel just as motorists did for gasoline. Even so, the Energy Information Administration (EIA, part of the Energy Department) predicts relatively flat oil prices over the next quarter century, with inflation-adjusted prices in the range of $120 per barrel.[47]

Oil prices respond almost instantaneously to international political events (e.g., the threat of supply constrictions) and to economic fluctuations affecting demand. A small number of big suppliers—state-owned or state-controlled enterprises inside and outside the Organization of Petroleum Exporting Countries (OPEC), plus a handful of private multinationals—dominate production. In recent years, most have appeared to pump oil at or near capacity most of the time. By most indications, Saudi Arabia alone retains the ability to affect prices by raising or lowering output. Otherwise suppliers must act together to set prices, and in recent years that has come to seem mostly a theoretical possibility. Periodic fears of disruption linked with political unrest or war have had greater effects, and sharp swings in prices have been common, affected also by asynchronous demand variations in major markets. Price increases have been moderated by declining energy intensity (energy consumption relative to economic output) in most parts of the world. This is the principal reason EIA does not expect the long-term trend to be sharply upward.

Acknowledging the more dramatic scenarios some analysts put forward, there seems little in what is actually known about world oil reserves and the workings of the international market to suggest that the U.S. military faces either intolerably burdensome fuel costs or supply risks in the foreseeable future. DoD buys fuel alongside other purchasers. It is a big customer, but not big enough to affect prices. Long-distance transport of crude oil and refined products is routine and inexpensive. So long as the world market remains effectively integrated, it would take a massive injection of substitutable alternatives to affect prices. Private investors, absent proven capability to produce alternatives in substantial quantities at competitive costs—or a package of subsidies such as those for domestic ethanol, perhaps including binding price guarantees—will find little reason to increase production capacity rapidly. Fuel is fuel, and as output of substitutable alternatives builds it will simply flow into the international market at prices little different from those for other refined petroleum products.

Given U.S. dependence on imported oil, it is reliability of supply, rather than pricing, that might seem the larger issue.

44 *Army Energy Security Implementation Strategy* (Washington, DC: Army Senior Energy Council, January 13, 2009); *Power and Energy Strategy White Paper* (Fort Monroe, VA: Army Capabilities Integration Center, April 1, 2010).

45 *Air Force Energy Plan 2010* states, "Where possible, the Air Force will develop and utilize renewable and alternative energy to reduce greenhouse gas emissions" (p. 1). A *Navy Energy Vision for the 21st Century* commits the service to "lead federal efforts to reduce greenhouse gas emissions" (p. 4). Taken at face value, these statements would rule out liquid fuels made not only from coal but from oil shale or oil sands, which also push net GHG emissions upward.

46 *Defense Logistics Agency Energy Fact Book Fiscal Year 2010* (Fort Belvoir, VA: Defense Logistics Agency Energy, 2011). Military and commercial grades of jet fuel are similar to one another (suppliers charge slightly more for fuels meeting DoD specifications), and to diesel fuel; all are basically kerosene. The Navy specifies JP-5, which is less volatile than JP-8, for shipboard safety. Otherwise, DoD has been reducing purchases of fuels other than JP-8, intended to be the U.S. military's universally available "logistics fuel," and the Army now runs many of its diesel-powered vehicles and diesel-electric generators on JP-8. The services keep gasoline, which is much more flammable than kerosene, out of combat zones.

47 *Annual Energy Outlook 2011* (Washington, DC: Energy Information Administration, April 2011), table B1, p. 157.

But again, the market is international; indeed, DoD buys much of its fuel abroad—in recent years, something like half (box 2.3). Innovations—perhaps sustainable biofuels—would, once proven, migrate to the lowest-cost-production locations, many of them presumably overseas. (The United States has no monopoly on sunshine and arable land.) DoD and the government might support innovation and subsidize production, but it would be difficult to wall off domestic output without some compelling national security rationale. Wartime supply interruptions might be accepted as justifying government ownership and reservation of output for the military, but not indefinite fears of future interruptions. Private ownership coupled with domestic production and export restrictions would more than likely be seen as contravening bedrock principles of U.S. foreign economic policy, which since World War II has been based on borders nominally open to trade.

In any event, should serious bottlenecks in fuel supplies appear, the United States will be less vulnerable than many other countries, including major allies. The U.S. government can expect to outbid competing customers, beginning with poor countries totally dependent on imported oil and including wealthy economies such as Japan that benefit from the U.S. security umbrella. So long as there is fuel to buy (or commandeer, in war), DoD will be better able to afford it than almost any other customer. The armed forces have first claim on the Strategic Petroleum Reserve. Household consumers and airlines have more to fear from supply constrictions and price rises than DoD.

Logistics

Transport costs far exceed purchase prices when fuel must be delivered by tank trucks threading through hostile territory, as in Afghanistan, where casualty rates have been disturbingly high.[48] Along with trucks, helicopters, and armored vehicles, diesel generators, cook stoves, and water heaters for showers and dishwashing burn jet fuel at forward-operating bases. Transportation of fuel and water to combat areas accounts for around two-thirds of the fuel consumed in theater by ground forces.[49] As an expert group assembled by the Defense Science Board put it, "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 uninsulated and even unoccupied tents."[50]

Some of this consumption will be replaced by alternative low-temperature energy sources, regardless of whether the next U.S. war resembles those in Iraq and Afghanistan; but the costs of tanker aircraft will continue to pace the costs of air-to-air refueling, and costs for refueling naval vessels at sea will exceed those at dockside.[51] In any case, both costs and risks to personnel depend on the weight and volume of fuel to be transported. Provided the end product has the same energy content, it makes no difference whether it starts as crude oil or biomass. The only way to reduce costs and risks is to reduce consumption. To the extent this can be accomplished without sacrificing military effectiveness, supply concerns will be eased, freeing funds to be spent elsewhere and permitting soldiers and contract personnel to assume duties other than escorting convoys.

Design Constraints

Solar panels and wind turbines can replace some of DoD's generators. Fuel cells, which, as noted in the next section, convert the chemical energy in fuel directly into electricity, operate more efficiently than those generators. But there are no substitutes for liquid hydrocarbons in powering combat equipment. Second-best choices are greatly inferior; alternatives must closely mimic jet fuel. Motorists in Brazil may run their cars on ethanol, accepting fewer miles per tankful because a gallon of ethanol, like other alcohols, contains less energy than a gallon of gasoline or kerosene. Militaries will not similarly sacrifice range or payload in land vehicles, naval vessels, or aircraft. The weight and space taken up by fuel subtract directly from fighting power: range and endurance, weapons loads, electronic warfare pods, protective armor. Energy density—energy content per unit of mass or per unit of volume— is a critical variable, and petroleum has higher energy density than other widely available fuels.

U.S. military aircraft burn some 85 million barrels of jet fuel each year. No viable substitutes have been found (with exceptions for very small unmanned aerial vehicles, powered by electric motors for stealth). Jet engines and gas turbines, with modifications, will run as happily on alcohol as kerosene, but not as far; most alcohols have around two-thirds the energy content of JP-8, cutting range proportionately. The

48 Truck convoys drew 1,100 attacks in Afghanistan alone in 2010, according to General Duncan McNabb of the Air Force, as reported in "Threats to U.S. Supply Lines on the Rise, Says Transportation Command Chief," *National Defense* (blog), February 7, 2011, www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=303.

49 Herbert H. Dobbs, Jr., "U.S. Army TARDEC Military Dual-Use Needs with Commercial Idling Reduction," presentation at DOE National Idling Reduction Planning Conference, Albany, NY, May 17–19, 2004.

50 *Report of the Defense Science Board Task Force on DOD Energy Strategy: "More Fight—Less Fuel"* (Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, February 2008), p. 29. Fuel production at the point of consumption has sometimes been suggested—e.g., from garbage. This is technically possible, but holds little practical promise, except perhaps for applications such as space heating and hot water for dishwashing and showers. The reasons include scale (it takes a lot of trash to make significant volumes of fuel), reliability and maintainability, and quality control (off-specification fuel would risk damage to costly and militarily essential equipment).

51 Nathan J. Gammache, "Determining the Return to Energy Efficiency Investments in Domestic and Deployed Military Installations" (thesis, Naval Postgraduate School, December 2007), includes a chart (p. 50, based on unpublished DoD data) that indicates incremental costs of \$40–\$45 per gallon for aerial refueling and perhaps \$2–\$3 per gallon for supplying JP-5 to Navy carriers at sea.

Box 2.3. Oil Imports

The U.S. balance of trade has been consistently negative since the mid-1970s. At the time of the 1973–74 and 1979–80 oil shocks, petroleum imports made up 20–25 percent of the value of all imports. With falling prices, the value of oil imports declined, early in the last decade accounting for less than 10 percent of total imports. Over the past five years, oil imports declined somewhat by volume but, with rising prices, again rose as a share of imports, reaching about 19 percent in 2008 and then falling to 15 percent in 2010.[a]

Purchases by DoD do not contribute much to the import bill. The Defense Logistics Agency (DLA), which buys fuel for all the services, does so internationally. When possible, DLA takes delivery of refined products near the point of final consumption—e.g., jet fuel bought from suppliers in Russia and Kyrgyzstan for shipment to Afghanistan. Overseas purchases account for about half of the fuel bill.[b] DLA's domestic purchases include products refined from imported as well as domestic crude; assuming the import fraction to be one-half, close to the average for all U.S. petroleum consumption in recent years, DLA's fuel purchases represent no more than $3 billion to $4 billion in imported oil, about 1 percent of the value of U.S. oil imports in 2010 and less than 0.2 percent of the value of all imports.

The Energy Information Administration expects the 12 members of OPEC, which account for some 70 percent of estimated world reserves, to pump slightly more than 40 percent of world oil production over the next several decades.[c] U.S. oil imports will remain high. At the same time, supplies have become more diversified since the 1970s, and the OPEC cartel weaker. Canada now ships more oil to the United States than does any other nation (followed by Mexico, and only then Saudi Arabia). Domestic output has crept upward in recent years. All these factors tend to argue against a repetition of unexpectedly sudden supply constrictions. So does the dependence of many exporting states on oil revenues as a prop to internal security, by buying off political opponents or buying weapons to suppress them.

To some observers, common sense nevertheless seems to imply that dependence on imported oil weakens the U.S. economy, and by extension national security, given that military power depends, if indirectly, on the size and composition of a nation's economy. These extrapolations from dependence on imported oil to some sort of larger national vulnerability have little foundation in empirically grounded understanding of either economic affairs or military security. Within the analytical framework of economics, weakness and strength are problematic notions, lacking an accepted basis in quantitative measures; governments collect statistics on output, income, and productivity, not "strength." Trade deficits, furthermore, are usually taken to be derivative of savings and investment, viewed as the fundamental forces driving a nation's balance of payments. The implication of this more or less standard view is that a reduction in U.S. imports of oil (e.g., from greater domestic output), would simply lead to a rise in imports of other goods and services. Third, the relationships between economic performance and military strength are loose. The Soviet Union, after all, managed to remain a superpower for decades by steering a large share of economic output to its military.

The implications of oil imports for U.S. security interests, then, seem oblique. The administration's most recent National Security Strategy put it this way: "Dependence upon fossil fuels constrains our options and pollutes our environment." The document is a good deal blunter on climate change: "The danger from climate change is real, urgent, and severe. The change wrought by a warming planet will lead to new conflicts over refugees and resources; new suffering from drought and famine; catastrophic natural disasters; and the degradation of land across the globe."[d] No one can say whether one or more of the anticipated conflicts might culminate in war, or if U.S. forces might be called upon to intervene (or for that matter whether political turmoil or war might cut off oil supplies from fields in the Middle East). The causes of war are poorly understood, notwithstanding unending streams of studies examining past conflicts, and the contours of U.S. national security policy depend on domestic politics as much as, or more than, on international politics. The oil-exporting states of the Persian Gulf, for example, barely featured in U.S. foreign policy until Soviet troops entered Afghanistan at the end of 1979. Washington's earlier regional focus had been almost exclusively on Israel and Egypt. Yet the Soviet presence in Afghanistan, perhaps because the Kremlin's forces had occupied Iran during World War II and been reluctant to withdraw afterward, incited fears that America's principal enemy might gain a stranglehold over Middle Eastern oil. The Red Army later retreated and the Soviet Union itself dissolved, yet the United States went on to fight three wars in the region, with oil at the center of the first, in 1991, if not the other two.

a Trade figures from the Bureau of Economic Analysis, www.bea.gov. The United States also exports substantial quantities of refined petroleum products. In 2010, exports of petroleum (mostly refined products) amounted to nearly one-fifth (19 percent, by energy content) of imports (both crude oil and refined products).

b Anthony Andrews, *Department of Defense Fuel Spending, Supply, Acquisition, and Policy*, R40459 (Washington, DC: Congressional Research Service, September 22, 2009).

c *International Energy Outlook 2011*, DOE/EIA-0484 (2011) (Washington, DC: Energy Information Administration, September 2011), tables 3 and 5, pp. 26 and 38.

d *National Security Strategy* (Washington, DC: White House, May 2010), pp. 8 and 47.

energy density of kerosene-like liquids produced from coal or biomass, on the other hand, reaches 97–98 percent that of JP-8 (on either a mass or volume basis). The Air Force and Navy have been testing aircraft with 50:50 blends of petroleum-based and synthetic or biofuel—a straightforward technical task that, as expected, has not revealed any surprises. (Blends ensure sufficient aromatic content—a matter, basically, of ring-structured molecules—to protect seals and hoses in engines and fuel systems designed for ordinary jet fuel, which contains about 20 percent aromatics.) Hydrogen has a higher energy density than kerosene on a mass basis, but even compressed to 10,000 psi occupies five times the volume; a bigger plane to accommodate that volume would have more aerodynamic drag, driving up fuel consumption and requiring more powerful engines. Concepts for aircraft fueled by liquid hydrogen, which occupies less volume than compressed gas (but still about three times the volume of kerosene), have been proposed, always to be dismissed as technological overreach. (In the 1950s, the Air Force and the Atomic Energy Commission explored nuclear power for aircraft, aiming at a bomber that could cruise the skies indefinitely; this too proved overreach.) For aircraft, synfuels or biofuels remain the only alternatives.

Military ground vehicles never seem to have enough interior space; and weight, as for any vehicle, is the enemy of fuel economy.[52] Composites and ceramics help limit the weight of the armor on the Army's M1 tanks. Even so, the Abrams enters battle with only 40 rounds for its main gun because there is no room for more. Because they must be able to travel in deserts or forests, in mud or sand—and because combat vehicles depend on speed, acceleration, and agility to attack (or dodge) the enemy—militaries want powerful engines, all-wheel drive, and big, heavy, knobby tires or tracks—features that increase fuel consumption over and above that of road vehicles. The light and powerful gas-turbine engine in the Abrams gives it speed and acceleration that outclass the diesel-engined tanks of other armies, but performance, again as for all vehicles, comes at the cost of greater fuel burn, while fuel efficiency, as for all gas turbines, drops precipitously at low loads. "Current M1 engines at idle burn 12 gallons of fuel per hour to support a roughly five-kilowatt load [typically air conditioning and electronics], an efficiency on the order of one percent."[53]

The Navy cannot escape a similar logic, even though ships are space-constrained more than weight-constrained. Before World War I, navies refueled at far-flung coaling stations. Oil-fired boilers increased flexibility. Oil has about twice the energy density of coal (depending on the type of coal), but the big differences

52 W. Blair Haworth, Jr., *The Bradley and How It Got That Way: Technology, Institutions, and the Problem of Mechanized Infantry in the United States Army* (Westport, CT: Greenwood, 1999), includes extensive discussion of the compromises forced on the Army by engineering realities during design and development of the Bradley fighting vehicle.

53 *Report of the Defense Science Board on More Capable Warfighting through Reduced Fuel Burden* (Washington, DC: Office of the Under Secretary of Defense for Acquisition and Technology, May 2001), p. 45. Future combat or transport vehicles might be fitted with hybrid powertrains, most likely combining diesel engines and electric motors, to improve operating efficiency at light loads.

Box 2.4. Synthetic Fuels from Coal: Costs and Carbon Dioxide

Investor Uncertainty

The prospect of high rewards from innovation in low-cost conversion of coal to liquids, along with persistent concerns over supply in technically advanced countries without their own oil, notably Germany (a world leader in chemistry, chemical engineering, and the chemical industry since the 1880s), has led to decades of exploration and evaluation of plausible technical pathways. Only the Fischer-Tropsch (FT) process has been widely commercialized, and then mostly with governmental financing. Nazi Germany depended on FT synfuels during World War II; and South Africa, fearing an embargo of oil imports, embarked on production of FT synthetics during the years of apartheid. Production in South Africa continues, and commercial airliners serving Johannesburg routinely fill their tanks with 50:50 blends of petroleum-based and synthesized jet fuel.

FT and similar synfuels have attracted few private investors, who, given volatile oil prices, judge the risks excessive; in the absence of recent government investments, most existing plants are old or, if of more recent design, relatively small and intended in part for process development. Recent studies predict that coal-to-liquid conversion based on large new plants incorporating the latest technology could be economically competitive at crude oil prices in the range of perhaps $60 to $100 per barrel.[a] Since these estimates are preliminary, made without the benefit of detailed engineering studies, prospective investors view them, rightly, with skepticism. Cost overruns on past energy projects have been frequent and sometimes large (and underestimates almost unheard of). While successful experience with new plants would probably initiate a sequence of incremental innovations leading to cost declines, the starting point for such learning curves cannot be known until plants have been built and operating experience accumulated.[b]

As investors will continue to recall, Congress shut down the Synthetic Fuels Corporation, established in the wake of the 1970s energy shocks, after oil supplies loosened and prices plummeted. In the absence of credible government price guarantees, private financing will flow to massive new synfuels plants only if investors believe oil prices will remain high. So long as Saudi Arabia controls excess production capacity sufficient to drive down prices at will, investors may lack the necessary confidence.

The Burden of Added CO_2

When Congress approved the Synthetic Fuels Corporation in 1980, climate change had hardly any visibility. Today, the additional CO_2 released in making synfuels from coal would be widely seen as unacceptable. The dilemma could be resolved through capture and sequestration (long-term storage) of the excess, a subject we have reviewed previously.[c] Since the CO_2 from FT synthesis is relatively concentrated, unlike the dilute gases released by pulverized coal burned to generate electrical power, processes for capture promise to be simpler and less costly. Published estimates suggest it might add only a few cents per gallon to the costs of synfuels (including capture at the plant site, compression, transportation, and sequestration).[d] These processes, however, have not been demonstrated at scale, and even if separation turns out to be inexpensive, sequestration promises to be an obstacle. The first step should be demonstration of practices and policies for underground storage on a large scale acceptable to the public. If and when demonstrations begin, public opposition could well build with awareness.

a *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (Washington, DC: National Academies Press, 2009).

b Investors place greater confidence in results from actual demonstrations than projections based on R&D results and engineering studies. Mary Jean Bürer and Rolf Wüstenhagen, "Which Renewable Energy Policy Is a Venture Capitalist's Best Friend? Empirical Evidence from a Survey of International Cleantech Investors," *Energy Policy* 37 (2009): 4997–5006. Thomas J. Tarka, et al., *Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass*, DOE/NETL-2009/1349 (n.p.: Department of Energy, National Energy Technology Laboratory, January 14, 2009), bury the following caution near the end of their report (p. 61): "An overwhelming amount of risk will continue to exist until plants that integrate the technologies to produce liquid fuels from coal and coal/biomass mixtures are designed, built, and operated in the United States."

c *Innovation Policy for Climate Change* (Washington, DC: Consortium for Science, Policy & Outcomes; and Boston, MA: Clean Air Task Force, September 2009); also see the background paper for that project, "Energy Innovation Systems from the Bottom Up: Post-Combustion Capture," March 2009, www.cspo.org/projects/eisbu/.

d *Liquid Transportation Fuels from Coal and Biomass*, p. 191.

were reductions in manning, since stokers were no longer needed to feed boilers, and practical refueling at sea (coal could be transferred from one ship to another only in bags, baskets, or buckets, an emergency measure possible only in calm waters, while liquid fuel can be pumped aboard at sea from tankers). In the 1950s, nuclear reactors promised unlimited range, albeit at much higher first cost—an easy choice for submarines, for which nuclear power conferred great tactical and strategic advantages. That is not the case for surface ships, and after protracted conflict within the Navy and between the Navy's nuclear power faction and the Office of the Secretary of Defense, nuclear propulsion for surface ships is now confined to aircraft carriers.[54]

Synfuels and Biofuels

Sound policy would set two preconditions for large-scale production of alternative fuels: costs that promise to be competitive with petroleum-based fuels at likely future oil prices and GHG neutrality or reduction. At present, neither coal-based synfuels nor biofuels satisfy these preconditions. For synfuels, GHG sustainability is the principal obstacle. Because coal contains more carbon than oil (in the range of one-third more, depending on grade of coal), more net CO_2—the principal GHG—will be released on a mine or well to wings or wheels basis. For biofuels, both costs and sustainability pose questions that cannot at present be answered. Potentially sustainable pathways, such as aquatic biomass (algae), may or may not prove cost-effective, while established pathways, notably ethanol from corn, cannot promise sustainability either in terms of GHG release or effects on food supplies from agriculture.

With energy density similar to that of JP-8 as a first-order constraint, the ideal alternative would be a "drop-in" fuel that could be distributed via existing infrastructure (pipelines, tanker aircraft) and that required no changes to existing aircraft, ground vehicles, ships, and generator sets. That alternative would not be hard to achieve. Synthetic liquids have been made from coal since the 1930s by means of the Fischer-Tropsch process, other generally similar approaches are widely known, and biodiesel for road vehicles is available in the United States and elsewhere. The costs of pushing into synfuels might also be manageable. Yet for reasons summarized in Box 2.4 it would be foolish to contemplate large-scale production from coal without capturing and sequestering some or all of the CO_2 produced. This too seems possible technically. But neither extraction nor storage (e.g., in stable geological formations) has yet been demonstrated at scale; indeed, testing and demonstration have hardly started, despite years of discussion and planning by the Department of Energy (DOE).

Biofuels raise a different set of issues. When plant matter grows, it takes up CO_2 from the atmosphere. If cultivation, processing, and final consumption can be managed so as to balance additions and removals of atmospheric CO_2, carbon neutrality might be achieved without capture and storage. No one yet knows whether achieving neutrality in this way is possible. There are many possible starting points and reaction pathways, hence variables to be considered. Relatively few have been carefully explored.[55]

Ethanol from corn illustrates the questions that will have to be answered. U.S. production is viable only because of subsidies in the form of mandated blending with gasoline.[56] By most accounts, the consequences include increasing GHG emissions (because of added agricultural inputs, including fuels, agrochemicals, and land clearing), acknowledged when Congress in 2007 placed a ceiling on future consumption of corn ethanol and a floor under cellulosic ethanol.[57] In any case, alcohols hold little interest for DoD except perhaps in fuel cells (see the next section).

Nonalcohol biofuels might or might not combine military acceptability with sustainability. Diesel fuel and jet fuel can be made from biomass. Numerous small U.S. refiners produce biodiesel; capacity exceeds demand by several times.[58] Most U.S.-produced biodiesel comes from soybeans, a crop that, like

54 Aircraft carriers in fact gain little meaningful advantage from nuclear power, since they sail as part of a task force (necessary, in part, to protect the carrier from attack) that must be refueled periodically, and carriers too have to be resupplied periodically with jet fuel for their planes and, in times of war, munitions. On the conflict over nuclear power in surface ships, see Francis Duncan, *Rickover and the Nuclear Navy: The Discipline of Technology* (Annapolis, MD: Naval Institute Press, 1990).

55 To begin with, the carbon content of candidate types of biomass ranges from about 40 percent to 70 percent—a lot of variation, and a lot of carbon (although less than most coals). Stanislav V. Vassilev, David Baxter, Lars K. Andersen, and Christina G. Vassileva, "An Overview of the Chemical Composition of Biomass," *Fuel* 89 (2010): 913–33.

56 The Energy Policy Act of 2005, extended in 2007 by the Energy Independence and Security Act, sets minimum schedules through 2022 for biofuels consumption by fuel blenders. Randy Schnepf and Brent D. Yacobucci, *Renewable Fuel Standard (RFS): Overview and Issues*, R40155 (Washington, DC: Congressional Research Service, October 14, 2010). A number of states also subsidize biofuels.

57 Practical production of cellulosic ethanol from plant wastes and nonfood crops has not yet been demonstrated. Robert F. Service, "Is There a Road Ahead for Cellulosic Ethanol?" *Science* 329 (August 13, 2010): 784–85. *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (Washington, DC: National Academies Press, 2009) provides an extensive review.

58 *Monthly Biodiesel Production Report*, DOE/EIA0642 (2009/12) (Washington, DC: Energy Information Administration, October 2010), table 1, p. 3.

other common cultivars, converts no more than around 1 percent of sunlight into chemical energy. Although plant breeding and genetic engineering promise increased rates of crop growth, hence biofuel yields, algae appear to hold greater theoretical potential, converting up to 10 percent of sunlight into chemical energy.[59] Because algae grow in fresh, brackish, or salt water (e.g., as seaweed), they do not compete with food crops for land. Even so, much R&D appears necessary to identify the best strains and develop high-yield, low-cost production methods; candidate feedstocks number in the thousands or tens of thousands and few conversion processes have been explored in depth.[60]

Conclusion

As a technical matter, DoD could easily enough leave oil behind by supporting large-scale production of coal-based synfuels. There is no reason for DoD to do so, absent carbon capture and sequestration, a conclusion Congress reached in including language in the 2007 Energy Independence and Security Act that bars federal agencies from purchasing alternatives to petroleum-based fuels if this would lead to increased net GHG emissions.

Unlike synfuels, biofuels could prove to be GHG-neutral or GHG-negative without carbon capture and storage (a technology for which federal agencies charged with demonstration have accomplished little). Yet the knowledge base is skimpy for nonalcohol biofuels; little can be inferred about costs, and because the "fundamental chemistry of most [biomass conversion processes] is not well understood,"[61] it has been difficult even to establish R&D priorities. While algae boosters express optimism, one of the few carefully detailed analyses to appear concludes that "even with low capital charges, it is not possible to produce microalgae biofuels cost-competitively with fossil fuels, or even with other biofuels, without major advances in technology."[62] Major advances in technology usually require major R&D funding—and well-managed R&D.

Nearly alone among federal agencies, DoD knows how to manage science in support of technology. A multiservice undertaking of the sort that proved so effective in advancing gas turbines offers a possible model for aggressive pursuit of advanced, sustainable biofuels pathways (e.g., algae), a task that calls for R&D directed at eventual commercialization rather than the science-focused programs that DOE has preferred.

Case 3: Lighter Loads for Soldiers

Along with much other gear, foot soldiers carry electrical and electronic equipment, often including GPS receivers, electronic map displays, laser rangefinders, and night vision goggles. Power requirements for these systems range upwards from a watt or two. Radios are especially power hungry, the more so when transmitting. Ongoing technical advances—networked surveillance, data fusion, perhaps even sensors that see through walls—mean that troops will be asked to carry more, and will want to, because of the battlefield advantages.

The Pentagon's operational energy strategy states that troops in Afghanistan "may carry more than 33 batteries, weighing up to 10 pounds."[63] How much a particular soldier carries depends on specialty (loads for radio operators exceed those for riflemen) and mission length (longer missions mean more spare batteries). The average load runs around 100 pounds.[64] Loads have risen over the years, and the Army and Marine Corps would like to reverse that trend. While troops travel to forward areas aboard vehicles whenever possible, once on foot heavy packs reduce the speed, agility, and endurance of even the fittest soldiers. As part of the strategy for its Science and Technology (S&T) program, the Army hopes to "develop and mature technology" that would reduce loads on typical missions to something under 40 pounds.[65]

Reducing the weight attributable to electrical and electronic equipment calls for innovations in two main classes: lighter batteries (or other sources of electricity), more precisely batteries able to store more electrical energy per unit of weight; and equipment that reduces battery weight by drawing less power (without sacrifice in performance). Battery innovation is ongoing, driven in part by commercial demand. Well-known methods for the design of low-power components (e.g., integrated circuits, ICs) and systems can cut power consumption by two or more orders of magnitude in some cases, with concomitant reductions in battery weight. Nonetheless, the ongoing plans and programs

59 George W. Huber, Sara Iborra, and Avelino Corma, "Synthesis of Transportation Fuels from Biomass: Chemistry, Catalysts, and Engineering," *Chemical Reviews* 106, no. 9 (2006): 4044–98.

60 After supporting systematic study of algae-based biofuels for more than 15 years, DOE abandoned the effort in 1996. Last year, with interest rebuilding, DOE produced a new "national roadmap." See *A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae*, NREL/TP-580-24190 (Golden, CO: National Renewable Energy Laboratory, July 1998); and *National Algal Biofuels Technology Roadmap* (n.p.: Department of Energy, Office of Energy Efficiency and Renewable Energy, May 2010).

61 The quotation is from Huber, Iborra, and Corma, "Synthesis of Transportation Fuels from Biomass," p. 4093.

62 T. J. Lundquist, I. C. Woertz, N. W. T. Quinn, and J. R. Benneman, *A Realistic Technology and Engineering Assessment of Algae Biofuel Production* (Berkeley, CA: University of California, Energy Biosciences Institute, October 2010), pp. xi–xii.

63 *Energy for the Warfighter: Operational Energy Strategy* (Washington, DC: Assistant Secretary of Defense for Operational Energy, Plans & Programs, May 2011), p. 4.

64 For measured loads carried by soldiers in Afghanistan by specialty, see *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan, April–May 2003* (n.p.: U.S. Army Center for Army Lessons Learned, n.d.); averages appear on p. 113.

65 *Defense Research and Engineering Strategic Plan 2007* (Washington, DC: Director of Defense Research and Engineering, n.d.), p. 8. The document says little about how this seemingly improbable goal might be achieved.

of DoD have focused almost entirely on batteries and on possible replacements for batteries, such as fuel cells, to the neglect of redesigning systems and equipment to reduce power demands.

Batteries and Applications

DoD purchases and stocks hundreds of different battery types, many in small numbers for specialized applications. The guidance systems in Stinger missiles draw power from lithium batteries (earlier Stingers used chromate cells) that must function dependably for perhaps a dozen seconds after sitting in a warehouse for perhaps a dozen years.[66] The Navy has spent tens of millions of dollars on development of a custom-designed lithium-ion battery to power a submersible vehicle for its SEALs.[67] The Army has been working on thin rechargeable lithium-ion batteries contoured to ballistic vests.[68] In the longer term, power sources may be embedded into clothing—one goal of the Army's ambitious effort to develop "soldier systems" that would combine and integrate many of the functions now provided through separate pieces of equipment.

This is a vision for the future. With few exceptions today, each soldier-portable device has its own battery. Few of these interchange, few are rechargeable, and spares must usually be carried, since the imponderables of military operations mean that missions expected to be short sometimes last for days without resupply. Nonrechargeable batteries are widely specified for lightness: despite a doubling over the past 15 years in the energy density of rechargeable lithium-ion batteries popular in civilian applications, nonrechargeables store substantially more electrical energy per unit of weight (box 2.5).[69]

The services do not spend much on batteries, despite their many applications in military systems. Purchases amount to perhaps 1 percent of DoD's annual energy bill.[70] As for delivery of fuel, indirect costs can be much higher: expenditures for shipping batteries to the Middle East during the buildup to the 1991 Gulf War were put at more than $500 million (over and above the cost of the batteries).[71] RDT&E spending has also been comparatively small. Based on partial data, the Government Accountability Office (GAO) estimates recent Science and Technology program funding for batteries and fuel cells (i.e., technology base work, excluding RDT&E as part of weapons development programs) at about $170 million annually, a figure that is less than 1.5 percent of the S&T budget.[72]

GAO reports that only the Army, among the four services, has actively sought to standardize battery types. Sometimes there are good reasons for designing special-purpose batteries into equipment; in other cases, the services specify unique designs in search of illusory advantages, or contractors incorporate proprietary batteries to raise profit margins. Greater standardization would promote interchangeability and reduce the number of spare batteries soldiers must carry, increase economies of scale in production, and simplify logistics. A step as simple as including a state-of-charge indicator on all batteries would reduce the need for spares and resupply, since troops often discard batteries that retain half or more of their charge just to be safe. Given the proliferation of battery configurations, DoD ends up buying many different types in small numbers from a thin supply base, one that by most accounts is not very innovative. Some batteries are available from only a single manufacturer. During the invasion of Iraq in 2003, "demand for [BA-5390 and BA-5590 lithium] batteries surged from a peacetime average of below 20,000 per month . . . to a peak rate of over 330,000." Suppliers could not keep up, and "the Marines reported being down to only a 2-day supply."[73]

The Battery Innovation Landscape

Engineers, scientists, and inventors have worked for generations to improve batteries. Electric vehicles competed effectively for a time early in the last century with automobiles powered by gasoline (and steam) engines. Energy shocks in the 1970s led to renewed efforts to find substitutes for lead-acid batteries that might make hybrid and electric vehicles more viable. For the past several decades, metal-air cells—which employ a metal or a metallic compound as anode, with air circulating through

66 John Lyons, Duncan Long, and Richard Chait, *Critical Technology Events in the Development of the Stinger and Javelin Missile Systems: Project Hindsight Revisited* (Washington, DC: National Defense University, Center for Technology and National Security Policy, July 2006), pp. 11–12. Lithium-based batteries are attractive because the metal is so light, less than 1/20th the density of lead. They come in many varieties, including rechargeable lithium-metal hydride and lithium-polymer configurations, as well as familiar disposable dry cells.

67 *Defense Acquisitions: Success of Advanced SEAL Delivery System Hinges on Establishing a Sound Contracting Strategy and Performance Criteria*, GAO-07-745 (Washington, DC: Government Accountability Office, May 2007), p. 18.

68 *Soldiers*, January 2011, p. 41. For a useful guide to Army planning for portable power, see *Power and Energy Strategy White Paper* (Fort Monroe, VA: Army Capabilities Integration Center, April 1, 2010), pp. 20–24.

69 On advances in the lithium-ion system, see, e.g., Robert F. Service, "Getting There," *Science* 332 (June 22, 2011): 1494–96.

70 Troy O. Kiper, Anthony E. Hughley, and Mark R. McClellan, *Batteries on the Battlefield: Developing a Methodology to Estimate the Fully Burdened Cost of Batteries in the Department of Defense* (thesis, Naval Postgraduate School, June 2010), p. 9.

71 *Meeting the Energy Needs of Future Warriors* (Washington, DC: National Academies Press, 2004), p. 49.

72 *Defense Acquisitions: Opportunities Exist to Improve DOD's Oversight of Power Source Investments*, GAO-11-113 (Washington, DC: U.S. Government Accountability Office, December 2010). GAO was unable to collect full information, particularly on costs associated with integration of power sources into systems and equipment. Something over three-fifths of the S&T funds identified by GAO supported battery R&D, with most of the rest for fuel cells and small amounts for capacitive storage.

73 *Defense Logistics: Actions Needed to Improve the Availability of Critical Items During Current and Future Operations*, GAO-05-275 (Washington, DC: U.S. Government Accountability Office, April 2005), pp. 21 and 37.

Box 2.5. Battery Performance

Batteries convert potential energy stored in chemicals into electrical energy by causing those chemicals to react. In a primary or nonrechargeable battery, such as the dry cells used in flashlights, the chemical reaction proceeds in one direction only; once discharged, the battery must be discarded. In rechargeable or secondary cells, such as the lead acid batteries in cars, feeding electricity back in reverses the reaction.

Electrochemistry places theoretical upper limits on energy density—that is, how much energy a battery (or other energy storage device) can supply per unit of weight, normally given as watt-hours per pound, Wh/lb, or watt-hours per kilogram, Wh/kg. Technological advance for a given cell chemistry is in considerable part a matter of moving closer to the theoretical ceiling, which practical batteries seldom approach, through innovations in anode or cathode configuration, separators, electrolytes, and control systems. The military's lithium-manganese dioxide BA-5590 battery, for example, stores around 280 Wh/kg. This is nearly twice the energy density of available lithium-ion batteries, yet only 35–40 percent of the theoretical maximum for the lithium-manganese system.

Power density measures how fast energy can be withdrawn (as W/lb or W/kg). This is largely a function of reaction rates and heat buildup. Some batteries have good energy density but poor power density, making them unsuitable for applications requiring high output bursts, as might be needed for pulsing a laser.

In certain circumstances—where equipment designs accommodate rechargeable batteries, extra weight is tolerable, and recharging is practicable (which has meant mostly during training)—DoD has been moving away from its dependence on nonrechargeable batteries, which must be replaced when discharged. In the future, more equipment will no doubt be designed to accept either type, but so long as nonrechargeable batteries offer better energy density and power density, they will be the choice in the field.

a porous, nonreactive electrode acting as the cathode—have seemed to offer near-ideal combinations of lightness (they lack weighty chemicals on the cathode side of cell) and moderate cost. Rechargeable zinc-air cells, for instance, have long been a research target. (The zinc-air cells widely used in hearing aids are nonrechargeable.) Zinc is cheap, and the zinc-air systems promise energy densities 5 to 10 times better than today's lithium-ion cells. The obstacles begin with limited lifetime. Performance falls rapidly after a few to a few hundred charge-discharge cycles (typically because uncontrollable side-reactions at the electrodes lead to internal shorting), while targets for commercialization range from several thousand charge-discharge cycles to perhaps 10,000 for electric vehicles.

As the illustrations above suggest, even the best batteries, despite the advances of the past several decades, continue to seem costly, clumsy, and heavy. Because of performance ceilings imposed by electrochemical principles, they promise "limited specific energy with little room for improvement."[74] Since the determinants of battery weight are well understood and most of the obviously attractive chemistries have been the subject of at least some research, big jumps in energy density may not be achievable. Cost declines through development of cell types based on inexpensive starting materials hold greater promise.

Beyond Batteries

A few years ago the Air Force Scientific Advisory Board (SAB), stating that "combat controllers, pararescuemen, and combat weathermen often carry packs weighing several hundred pounds" and that "thirty percent of the weight is batteries," called for the elimination of batteries. According to the SAB, this would "change the game."[75] Their report does not say how batteries might be dispensed with, but the SAB most likely had fuel cells in mind (box 2.6).

Practical small fuel cells would provide a basis for lightweight power packs for soldiers. Larger units could replace towed diesel generators and serve as auxiliary power units to minimize inefficient low-load operation of the main engines in ground vehicles and naval vessels. Unlike solar and wind power, however, and despite massive investments in R&D over the past two decades motivated chiefly by prospective applications to electric vehicles, fuel cells have not been commercialized to any great extent. Costs remain prohibitive, for reasons alluded to in box 2.6, such as short-lived and expensive catalysts. For DoD, the attractions—quiet stationary power in remote areas, lighter loads for dismounted soldiers—justify much higher costs than civilian markets will accept. The Army has conducted a considerable number of fuel cell demonstrations in recent years, and in 2009 began shipping small numbers to Afghanistan.[76] Even if costs never decline sufficiently for high-volume commercial sales, advances in fuel cells for military applications will continue and applications spread.

Reduced Demand for Power

Electrical output, whether from batteries or some other source, is not an end in itself but an input to some other system. For minimum weight, soldier-portable systems should draw as little power as possible consistent with functional performance, so that battery weight can be minimized (the equipment itself should not be significantly heavier). Firms designing laptop computers, mobile telephones, and cordless power tools for commercial markets proceed in this way. DoD has not followed suit. A 2004 National Research Council study made the point forcefully: "Reducing power requirements for computation and communication by several orders of magnitude" can be achieved through "aggressive techniques tailored to each application and to the most likely soldier modes of interaction." Instead, the Army and its contractors continued to employ "outdated design techniques."[77] Little appears to have changed since the Army, which requested this report, received it more than half-a-dozen years ago.[78]

Opportunities for reducing power consumption include the following:

- Designing systems around low-voltage ICs (the lower the voltage, the lower the power drawn)
- Substituting custom-designed ICs for microprocessor- or microcomputer-based systems (executing functions in hardware consumes far less power)
- Incorporating state-of-the-art load management software (designed to meet the needs of dismounted soldiers and otherwise analogous to techniques used to conserve battery power in mobile computing and communications)

74 *Meeting the Energy Needs of Future Warriors*, p. 33.

75 *United States Air Force Scientific Advisory Board Report on System-Level Experimentation: Executive Summary and Annotated Brief*, SAB-TR-06-02 (n.p.: U.S. Air Force Scientific Advisory Board, July 2006), p. 33.

76 Thomas J. Gross, Albert J. Poche, Jr., and Kevin C. Ennis, *Beyond Demonstration: The Role of Fuel Cells in DoD's Energy Strategy* (McLean,VA: LMI, October 2011).

77 *Meeting the Energy Needs of Future Warriors*, pp. 7–8 and 69.

78 *Fiscal Year 2012 Operational Energy Budget Certification Report* (Washington, DC: Assistant Secretary of Defense for Operational Energy Plans and Programs, January 2011), which reviews the fiscal 2012 budgets of the services and their Future Years Defense Programs (looking five years ahead), does not mention any ongoing work aimed at reducing the power consumed by portable systems and equipment.

Box 2.6. Alternatives to Batteries

Fuel Cells

Like batteries, fuel cells convert chemical energy directly (i.e., in a single step) into electrical power. In fuel cells, as in primary batteries, the chemical reactions that produce electricity cannot be reversed; but unlike such batteries, a fuel cell can be refilled—e.g., with hydrogen—to provide a new "charge" of chemical energy.

In principle, fuel cells might run on hydrogen, alcohol, propane or butane, liquid hydrocarbons derived from petroleum, synfuels, or biofuels. Because all of these contain far more energy per unit of weight than the chemicals in even the best batteries, fuel cells promise advantages in energy density of 20 to 50 or even 100 times (depending on the system and on a net basis, including auxiliaries and packaging). Power density does not match that of batteries, but a hybrid system combining a fuel cell and battery could provide the best of both; drawn down to provide peak power, the battery would be recharged by the fuel cell during periods of reduced demand. (For short bursts of power, capacitors, which store energy as electrostatic charge, might replace batteries.)

In practice, as so often, costs and engineering realities pose obstacles. Hydrogen fuel cells offer simplicity and efficiency, but for reasonable volumetric energy density the hydrogen must be stored as either a very low-temperature liquid or a very high-pressure gas, as mentioned in the preceding section. This requires either a heavily insulated or a heavily strengthened storage vessel. Liquid fuels consumed directly in the cell or converted first to hydrogen via standard chemical processes known as reformation tend to foul or poison the catalysts on which fuel cells and reformers depend; good catalysts are expensive, and JP-8, which otherwise would be ideal for military applications, is one of the worst starting points because of relatively high sulfur content (sulfur is lethal to catalysts, and the sulfur content of jet fuel, unlike that of diesel fuel for road vehicles, remains essentially unregulated).

Comparisons

Fuel cells and batteries offer relatively high efficiency (the fraction of energy theoretically available that can be converted into useful work) compared to most other energy converters. The best diesel engines, for example, approach 40 percent efficiency under optimal conditions (i.e., the load-speed combination that gives the highest efficiency). While this is better than gasoline engines or gas turbines can achieve, some batteries approach 90 percent efficiency. For any fuel-burning engine, moreover, efficiency falls off at loads and speeds well away from the maximum point, so that average efficiencies do not approach the maximum under load-varying conditions, as for passenger vehicles. Cars and light trucks in typical urban driving, for example, may average 15 percent efficiency or less. For batteries and fuel cells, by contrast, efficiency does not change much with load (i.e., rate of discharge).

On the other hand, fuel-burning engines exhibit greater energy density and power density than batteries and have sometimes, for that reason, been considered for soldier-portable power. The technology for combustion engines is highly developed, manufacturing costs are modest, and small engines can be designed to operate much more quietly than leaf blowers or model airplanes. Miniature diesel engines could burn jet fuel. On the other hand, combustion engines would have to be integrated with a generator to produce electrical power, and all such engines scale down poorly, since heat and mechanical losses rise as a proportion of output. In most evaluations, the disadvantages have seemed to outweigh the advantages.[a]

a *Meeting the Energy Needs of Future Warriors* (Washington, DC: National Academies Press, 2004).

- Relying more heavily on remote processing (balanced against the relatively high power demands of robust communications links with troops in the field), with power-intensive computational functions shifted to systems at base camps, aboard vehicles, or perhaps carried by robotic platforms

Whenever a transistor or gate in an IC switches, it dissipates energy, consuming power. The amounts are tiny, but ICs pack millions of transistors tightly together, and the power inputs and heat outputs add up (the reason "server farms" run by companies such as Google display entire roofs covered by cooling equipment). Because heat dissipation has been a hurdle on the Moore's Law path to ever-increasing microcircuit density for several decades, much know-how concerning low-power IC design has accumulated. Low-power chip design practices can cut energy consumption by factors of 10 or even 100, more than enough to make a meaningful difference in power consumption, and the Defense Advanced Research Projects Agency funded a low-power IC program during the late 1990s, initiating a related effort in 2010. At the same time, "energy efficiency is a system-level problem," not just a component design problem. "Every aspect of the system has an impact on the energy efficiency, and the impact of a given subsystem is usually dependent on its interactions with other subsystems."[79] The more power drawn by existing equipment, such as radios, the greater the opportunities for weight saving.

Design of low-power systems calls for competence in technical areas that have advanced rapidly to serve commercial markets over the past two decades. Engineers must select appropriate chips (and peripherals) from perhaps thousands of alternatives, or else specify custom parts, choose appropriate clock and refresh speeds, and write software code for memory and display management to minimize energy consumption. Little of the applicable knowledge and experience base appears to be utilized in the design of equipment and systems for DoD, in part because the defense market is small and isolated from commercial markets and in part because the services continue to emphasize other performance measures.

Design choices in military equipment will differ from commercial practice. Trade-offs must be weighed in light of what matters for soldiers in combat. Reductions in power consumption, for example, might mean longer access times for painting screens or loading information, and someone will have to decide whether such compromises are acceptable. To this point, such questions seem rarely to be asked.

Conclusion

The power drawn by soldier-portable equipment will probably continue to rise, especially if innovations such as electromagnetic beam weapons and packable battlefield robots reach the field in quantity. Because soldiers already carry far more weight than desirable, DoD will continue to pay the necessary price for the lightest possible batteries (or other power sources, such as fuel cells). Regardless of future advances in batteries and other power sources, DoD should put greater emphasis on low-power design. This is not a research problem. There is an existing, available body of knowledge that DoD contractors could tap in designing the next generation of soldier-portable systems and equipment. The Army and Marine Corps should make sure they do so.

79 Thomas L. Martin, et al., "A Case Study of a System-Level Approach to Power-Aware Computing," *ACM Transactions on Embedded Computing Systems*, vol. 2, no. 3, August 2003, pp. 255-276; quotation from p. 256.

2 MILITARY INSTALLATIONS AND ENERGY TECHNOLOGY INNOVATION

Jeffrey Marqusee[80]

The Department of Defense (DoD) is the single largest energy consumer in the United States, although it accounts for less than 1 percent of total U.S. energy consumption. Three-quarters of DoD's $15 billion energy bill in fiscal year (FY) 2010 went for "operational" energy—largely fuel used by aircraft, ships, and tanks, as well as by the generators that produce electricity on forward-operating bases in Iraq and Afghanistan. The other one-quarter went for "facilities" (or "installation") energy—the traditional energy sources (largely electricity and natural gas) used to run the 500-plus permanent military installations in the United States and overseas.

Many see DoD as a key player in our nation's effort to start an energy technology revolution, both because of its heavy dependence on fossil fuels and because of its history of technological leadership. Understandably, most of the focus has been on operational energy. Fuel used in Afghanistan must be transported hundreds of miles by convoys vulnerable to ambush and improvised explosives. Thus, there is a direct link between energy innovation and mission effectiveness. Moreover, the operational energy challenge seems to call for a relatively straightforward application of DoD's traditional innovation model—namely, to inject energy concerns into the military requirements process, a process that places the highest priority on improved performance, with cost becoming a concern principally at the production and procurement stages.

Although they receive less attention, DoD's efforts in the area of facilities energy can also be a major driver of innovation. These efforts require a fundamentally different model of innovation—one in which cost considerations are central from the beginning. DoD has applied this model before with considerable success, however, to foster the development of innovative technologies to address environmental requirements. Moreover, despite the distinguishing preoccupation with costs, DoD's efforts to foster innovation in facilities energy (like those in the environmental area) draw on key elements of the traditional DoD innovation model—namely, the military's ability to serve as a sophisticated first adopter of new technologies, and to then buy sufficient quantities of those that prove effective to jump-start the commercial market.

Although DoD's principal goal for facility energy is to reduce costs, mission assurance is also a key consideration. Military installations rely almost exclusively for their power on a commercial grid that experts believe is vulnerable to disruption. This is a particular concern because permanent installations increasingly provide direct support to troops in theater, and also serve as staging platforms for disaster relief and homeland defense missions. Thus, DoD's efforts to make its installations more energy secure (including, but not limited to, support for smart-microgrid technologies) may be able to draw on the higher level of support and resources reserved for mission-related activities.

This paper explores how DoD can drive innovation in the area of facilities energy—a challenge that the department has set itself out of self-interest, but one whose efforts can benefit the country more broadly. First, it describes the energy challenges installations face and the barriers to innovative energy technologies entering that market. Second, it discusses DoD's successful efforts to foster innovative environmental technology, which faced very similar challenges. Third and finally, it describes DoD's efforts to date regarding installation energy.

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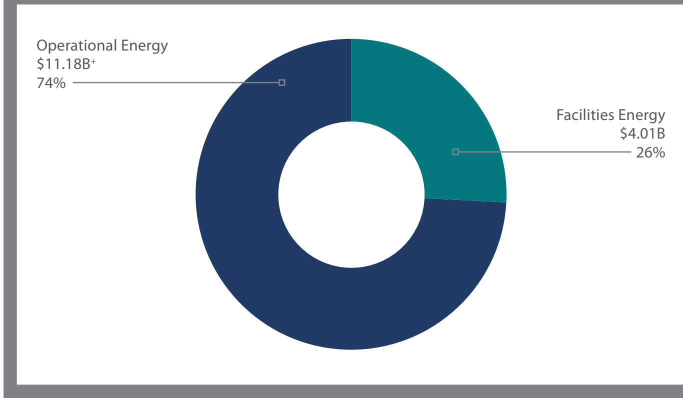
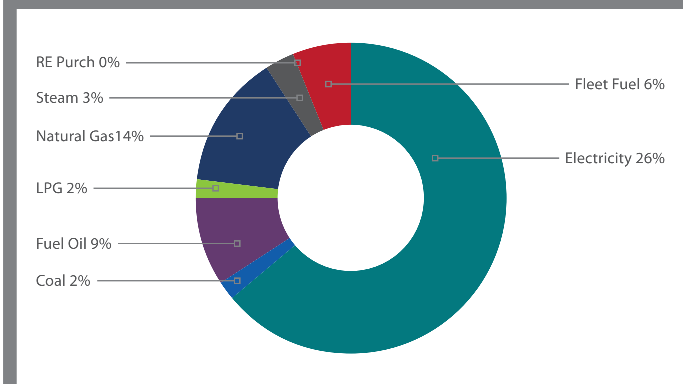
FIGURE 3.1 FY2010 DoD Energy Costs



+ FY09: $9.34B Fuel consumption was 9% less in FY10 than in FY09 but costs increased by 19.7%.

FIGURE 3.2 Makeup of Installation Energy



Installation Energy: The Challenge

DoD consumes over three-quarters of the energy used by the federal government; it is the largest local consumer of power in many areas of the country. Although installation energy represents only 26 percent of DoD's energy costs, it accounts for nearly 40 percent of DoD's greenhouse gases today; in the future, as drawdowns in the field take place, the relative importance of facilities energy in DoD's overall costs and greenhouse gas footprint is expected to grow. Currently, installation energy accounts for half of the Army's greenhouse gas emissions; in the future, it could rise to as much as 80 percent.

What drives this energy usage is the sheer size of DoD's built infrastructure: the department has more than 300,000 buildings and 2 billion square feet of building space—an order of magnitude more than the General Services Administration. The only organization with a built infrastructure of comparable size is Wal-Mart, which has 4,200 buildings and about 700 million square feet of space in the United States. But whereas Walmart's buildings are all big-box stores, DoD's inventory is highly diverse in terms of building type, size, and age. In fact, DoD's building stock is fairly representative of the larger U.S. commercial building stock.

Driven by economic and security concerns—and regulatory and statutory targets that reflect these concerns—DoD needs to significantly change how it uses and manages facilities energy. Toward this end, the department has set three interrelated goals:

1) Reduce energy usage and intensity.
2) Increase renewable and on-site energy generation (distributed generation).
3) Improve energy security.

FIGURE 3.3 DoD Building Stock

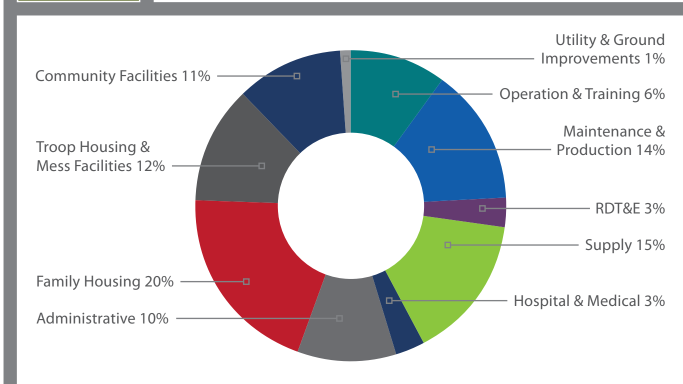
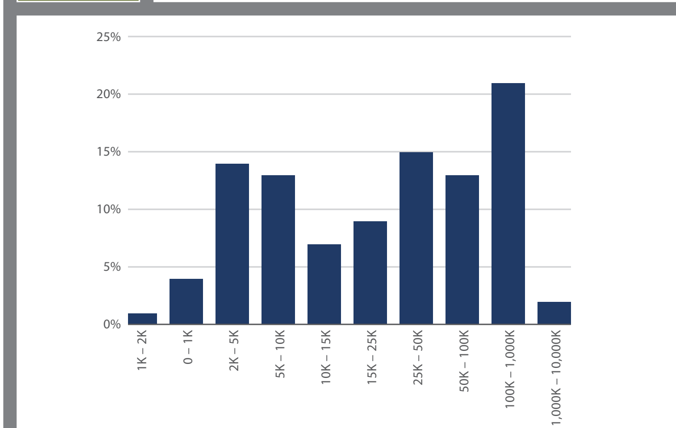


FIGURE 3.4 DoD U.S. Building Size Distribution (sq. ft.)



The Department is pursuing an aggressive plan to achieve these goals, using third-party financing as well as its own budget. However, existing technology and standard commercial practices will allow DoD to improve its energy performance by only a relatively modest amount, and the price will be steep: the Department's own estimate is that DoD will need to invest $1 billion to $1.5 billion a year to meet its 2020 statutory goal of a 37.5 percent reduction in energy intensity (2003 baseline).

By contrast, emerging technologies offer the opportunity to cost-effectively reduce DoD's facility energy demand by a dramatic amount (50 percent in existing buildings and 70 percent in new construction), and provide distributed generation and control technologies to improve energy security. Absent government involvement, however, these new and emerging technologies will not be widely deployed in time for DoD to meet its energy goals and obligations.

The key reason that DoD cannot passively rely on the private sector to provide a suite of new, cost-effective energy technologies is the difficulty of the transition from research and development to full deployment. Many have noted this challenge; it is often described as the "Valley of Death," a term widely used in the early and mid-1990s to describe the obstacles to commercialization and deployment of environmental technologies. DoD's environmental technology demonstration program, the Environmental Security Technology Certification Program (ESTCP), was created to overcome that hurdle.

Why can't DoD rely on the Department of Energy (DOE) to solve the commercialization and deployment problem? DOE has a mixed record in this area. Reasons for past failures at DOE are: 1) the lack of a market within DOE for the technologies; 2) overly optimistic engineering estimates; 3) lack of attention to potential economic or market failures; 4) a disconnect between business practices at DOE and commercial practices, which leads to demonstration results that are not credible in the private sector; and 5) programs completely driven by a technology "push," rather than a mix of technology push and market-driven pull.[81]

Many of these issues can be viewed as arising from the first: the lack of a market within DOE. Since DOE is neither the ultimate supplier nor buyer of these technologies at the deployment scale, it is not surprising that there are challenges in creating a system that can bring technologies across the Valley of Death. DoD's market size allows it to play a critical role in overcoming this challenge for the energy technologies the department's installations require, as it has for environmental technologies.

In addressing the barriers energy technologies face, and understanding the role DoD installations can play, it is important to understand the type and character of technologies that DoD installations need. Energy technologies span a wide spectrum in costs, complexities, size, and market forces. Installation energy technologies are just a subset of the field, but one that is critical in meeting the nation's and DoD's energy challenges. DOE, in its recent strategic plans and quadrennial technology review, has laid out the following taxonomy (figure 3.5):

FIGURE 3.5 Taxonomy of Energy Challenges

	SUPPLY		DEMAND
STATIONARY	Deploy Clean Electricity	Modernize the Grid	Increase Building and Industrial Efficiency
TRANSPORT	Deploy Clean Alternative Fuels	Progressively Electrify the Fleet	Increase Vehicle Efficiency

Source: DOE, Report on the First Quadrennial Technology Review, http://energy.gov/sites/prod/files/QTR_report.pdf.

It is useful to divide these energy technologies into two rough classes based on the nature of the market and the characteristics of deployment decisions. There are technologies whose capital costs at full scale are very high, for which a modest number of players will play a key role in implementation decisions. Examples include utility-scale energy generation, large-scale carbon sequestration, commercial production of alternative fuels, next-generation utility-grid-level technologies, and manufacturing of new transportation platforms. Some of these technologies produce products (e.g., fuel and power from the local utility) that DoD installations buy as commodities, but DoD does not expect to buy the underlying technology.

A second but no less important class of energy technologies are those that will be widely distributed upon implementation, and the decisions to deploy them at scale will be made by thousands, if not millions, of decision makers. These include:

1) Technologies to support improved energy efficiency and conservation in buildings;

2) Local renewable or distributed energy generation; and

3) Local energy control and management technologies.

Decisions on implementing these technologies will be made in a distributed sense and involve tens of thousands of individual decision makers if they are ever to reach large-scale deployment. These are the energy technologies that DoD installations will be buying, either directly through appropriated funds or in partnership with third-party financing through mechanisms such as Energy Saving Performance Contracts (ESPCs) or Power Purchase Agreements (PPAs). In the DOE taxonomy shown above, these distributed installation energy technologies cover the

81 P. Ogden, J. Podesta, and J. Deutch, *A New Strategy to Spur Energy Innovation* (Center for American Progress, January 2008).

demand space on building and industrial efficiency, portions of the supply space for clean electricity when restricted to distributed generation scale, and a critical portion in the middle where microgrids and their relationship to energy storage and electric vehicles reside.

There is an extensive literature on the impediments to commercialization of these emerging energy technologies for the building infrastructure market.[82] A key impediment (and one found not just in the building market) is that energy is a cost of doing business, and thus rarely the prime mission of the enterprise or a priority for decision makers. In contrast to sectors such as information technology and biotechnology, where advanced technologies often provide the end customer with a new capability or the ability to create a new business, improvements in energy technology typically just lower the cost of an already relatively low-cost commodity (electricity). As a result, the market for new technology is highly price sensitive, and life-cycle costs are sensitive to the operational efficiency of the technology, to issues of maintenance, and to the estimated lifetime of the component. Thus, a first user of a new energy technology bears significantly more risk while getting the same return as subsequent users.

A second impediment is the slow pace of technological change in the U.S. building sector: it takes years, if not decades, for new products to achieve widespread use. One reason for this is that many firms in the industry are small; they lack the manpower to do research on new products, and they have limited ability to absorb the financial risks that innovation entails.

A third impediment to the widespread deployment of new technologies arises from the fragmented or distributed nature of the market; decisions are usually made at the individual building level, based on the perceived return on investment for a specific project.

The structural nature of decision making and ownership can be a significant obstacle to technological innovation in the commercial market:

- The entity that bears the up-front capital costs is often not the same as the one that reaps the operation and management savings (this is known as the "split incentives" or "principal agent" problem).
- Key decision makers (e.g., architecture and engineering firms) face the liabilities associated with operational failure but do not share in the potential savings, creating an incentive to prefer reliability over innovation.
- Financing mechanisms for both energy efficiency (by energy service companies using an ESPC) and distributed and renewable energy generation (through PPA and the associated financing entities) require high confidence in the long-term (decade-plus) performance of the technology, and thus investors are unwilling to put capital at risk on new technologies.

Other significant barriers to innovation include a lack of information, which results in high transactional costs, and an inability to properly project future savings. As the National Academy of Sciences has pointed out, the lack of "evidence-based" data inhibits making an appropriate business case for deployment.[83] The return on the capital investment is often in terms of avoided future costs. Given the limited visibility of those costs when design decisions are being made, it is often hard to properly account for them or see the return. This is further exacerbated by real and perceived discount rates that can lead to suboptimal investment decisions.

Finally, the lack of significant operational testing until products are deployed severely limits the rapid and complete development of new energy technologies. The impact of real-world conditions such as building operations, variable loads, human interactions, and so forth makes it very difficult to optimize technologies, and specifically inhibits any radical departure from standard practice. These barriers are particularly problematic for new energy efficiency technologies in the building retrofit market, which is where DoD has the greatest interest. In addition to these barriers, which are common across DoD and the commercial market, DoD has some unique operational requirements (security and information assurance issues) that create other barriers.

DoD and Environmental Technology: A Successful Innovation Model

The impediments that new facilities energy technologies face today are very similar to those that confronted new environmental technologies in the mid-to-late 1990s—namely, a highly distributed and risk-averse market in which technologies were judged primarily on their perceived costs, often in the absence of reliable data on actual costs. To overcome those challenges, DoD created two programs: the Strategic Environmental R&D Program (SERDP), which supports the development of technology to meet DoD's high-priority environmental requirements; and the Environmental Security Technology Certification Program, which supports the demonstration and validation of environmental technologies—including, but not limited to, technologies developed with SERDP funding.

82 Examples of recent studies are "Energy Efficiency in Buildings: Transforming the Market," World Business Council for Sustainable Development, April 2009; and "Unlocking Energy Efficiency in the US Economy," McKinsey and Company, July 2009.
83 *Achieving Federal High Performance Facilities: Strategies and Approaches for Transformational Change*, (Washington, DC: National Academy of Sciences), 2011.

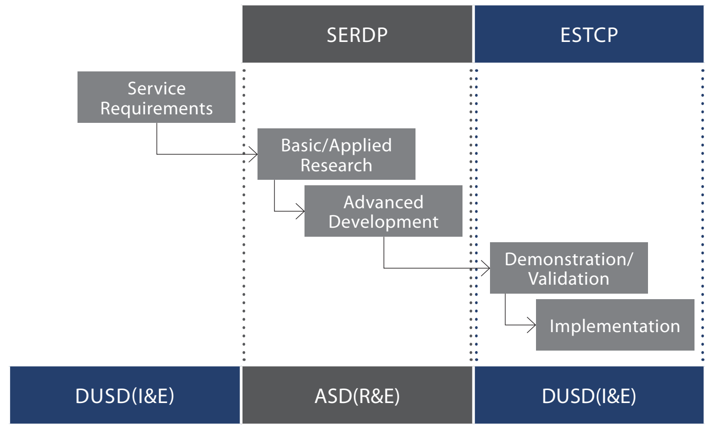
SERDP and ESTCP have amassed a very successful track record in the last fifteen years of advancing environmental science and engineering, and also transitioning technologies across DoD. For example, they have transformed how DoD remediates its contaminated groundwater sites. Technologies developed and demonstrated by SERDP and ESTCP are now used across DoD, and have become the standard of practice across the country for Superfund sites. As discussed below, DoD's efforts to foster innovation in facilities energy are limited to demonstration and validation because (in contrast to the environmental area) there is ample support for science and engineering in industry and the DOE. In other words, DoD's facilities energy effort replicates ESTCP but not SERDP. However, because the two programs are so closely intertwined, it is useful to look at them together.

Environmental technologies developed and demonstrated by SERDP and ESTCP are deployed on almost every DoD weapons system platform, are used in almost every DoD cleanup, and are part of the management of most installations across the services. These innovative technologies do not lead to new acquisition systems (although they are contained in many), nor are they adopted by initiating a new procurement program. They are typically transitioned through the commercial sector and bought back as services for environmental management; or they become part of new standards, specifications, or installation management procedures; or they are included through upgrades to existing systems during depot-level maintenance. As with energy, environmental issues are ubiquitous; it is assumed they can be managed (or worked around) rather than addressed through technological innovation; and decisions to deploy technologies are driven heavily by cost considerations and regulations. Yet improvements in environmental performance have significantly reduced DoD's costs and improved its mission performance, while allowing DoD to meet its environmental goals. Similar results are expected if DoD improves its energy performance.

SERDP's and ESTCP's effectiveness derives partly from structural factors (i.e., how the programs are organized), and partly from their approach to the problems and the linking of research and development investments to real world demonstrations. Officially, SERDP and ESTCP programs are structured as shown in figure 3.6.

This flow chart shows the classic one-way linear progression from basic research to implementation. Its roots date back to Vannevar Bush's classic paper, *Science, The Endless Frontier,* which influenced the structure and funding process for many federal R&D programs. Many have noted that this model neither fits the way research and development actually occurs, nor necessarily supports a robust innovation system.[84] Although the above is

FIGURE 3.6 Official Structure of SERDP and ESTCP



the official structure for the program, it does not reflect how innovation is supported and fostered within SERDP and ESTCP.

Structurally, SERDP and ESCTP have some unique elements, some of which were planned and some of which came about through circumstance rather than design. Having two programs—SERDP for the science and technology phase, and ESTCP for demonstration—under the same leadership has been important. The two programs are integrated in their goals and objectives but independent in their funding processes. Each program conducts independent reviews of proposals, but the reviews of active projects are conducted jointly, and findings are reported to a single director.

SERDP also has a unique authority in funding research and development. Although it is classified by DoD as a 6.3 program (which is typically associated with advanced development), it has statutory authority to address the full spectrum of science and technology development, from basic through applied and advanced development. This flexibility allows SERDP to avoid the artificial distinction between "basic" and "applied" research and development; SERDP does not subdivide the two activities. For the issues that SERDP and ESTCP address, fundamental science can and should be applied science. Even in the early stages of research, it is advantageous to be mindful of the likely "in-the-field" applications of the work and the technical and economic requirements, and structure a "basic" research project to address those "applied" concerns from the beginning. SERDP funds basic science, but in a way that ensures that key questions that relate to real DoD needs are addressed.

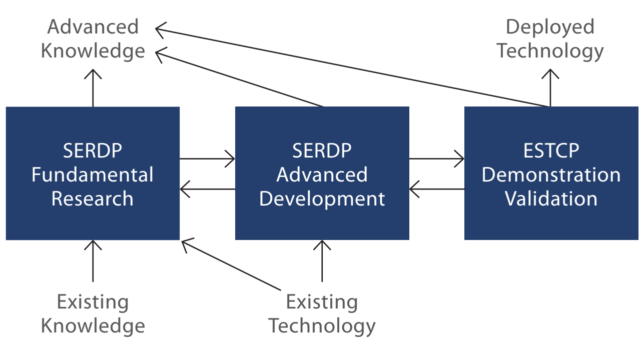
SERDP and ESTCP segregate funding decisions for each stage (science and technology vs. demonstration). This helps prevent the natural tendency to consider sunk costs in a project when evaluating its suitability for demonstration funding. The desire

84 See Donald Stokes, *Pasteur's Quadrant, Basic Science and Technology Innovation* (Washington, DC: Brookings Institution Press, 1997).

to make good on sunk costs has driven many poor investment decisions in the government; this structure serves as a check on that tendency. When ESTCP considers funding a demonstration project, no consideration is given to where its prior development took place. (In fact, as discussed below, for installation energy technologies, there is no plan for a SERDP investment, given the large development efforts funded by DOE and the private sector.) Finally, formally requiring a demonstration phase also forces rigorous assessment of the state of the technology, and brings into focus operational, technical, and regulatory issues that can be explored realistically only in the field; these are critical steps for environmental and energy technologies.

A more realistic flow diagram for SERDP and ESTCP investments is shown in figure 3.7. Science and technology investments are tightly linked between fundamental research and advanced development. Information is fed back from

FIGURE 3.7 Actual Structure of SERDP and ESTCP



demonstrations, both to contribute to innovations and to support advances in fundamental science and engineering.

The way SERDP and ESTCP are organized also fosters cross-pollination of perspectives and expertise, and works to create communities across DoD. When research proposals are evaluated, DoD not only considers their scientific merit (as determined by peer review); it also evaluates them with representatives from the services who have direct field experience. Having engineers and managers with this experience sit on research committees to review proposals is invaluable. It also creates a community within DoD, across different branches, for the issues being addressed, which helps support technology transfer. Technology transfer is not viewed as an activity to be done after a technology demonstration; it is integral to the research and demonstration process.

ESTCP demonstrations are conducted to answer the technical, economic, and operational issues of all the communities that have a role in future implementations. For a new weapons system, testing and evaluation is a standard and straightforward part of the acquisition process. In the environmental (and installation energy) area, implementation is highly distributed, technologies are procured through multiple mechanisms and pathways, and there is often no single acquisitions authority; demonstrations of these technologies are more complex, and are rarely done with this level of rigor outside of ESTCP. Its role is not to serve as a centralized mandatory gatekeeper that all innovative technologies must get past, but rather to be the instrument to accelerate innovation despite the barriers discussed above. Technologies are tested and evaluated to assess their current performance and costs, to meet the needs of all stakeholders involved in future implementations, and to feed information back to the R&D community either to facilitate more rapid development of the next iteration of a given technology or to stimulate future fundamental research.

The lessons learned by ESTCP in successfully fostering and transitioning innovative environmental technologies are being applied now to installation energy technologies. One key function of the program is that it centralizes the risk of innovative technologies so as to foster innovation across the DoD enterprise. It also works to leverage the existing engineering and support organizations of the services in the selection and execution of the demonstrations. Technology transfer is best done not by creating new organizational structures devoted to that mission, but rather by informing and relying upon the existing management structures of the services. This requires attention to development of the soft tools (guidance documents, training material, draft procurement documents, etc.) of DoD's management system that are essential to widespread deployment of technologies. It is also important to maintain transparency and openness throughout the testing process, including where demonstration results are concerned. In an arena in which decisions will be made by the thousands, DoD's traditional approach of limiting access to information will hinder the successful widespread adoption of new technologies.

DoD's Innovation Model for Facilities Energy

Broadly speaking, DoD's traditional innovation model is to make large investments to develop a new capability or weapons system that allows the U.S. military to dominate on the battlefield. In that context, costs are not a chief concern, given the dramatic benefits of the new technology; cost savings are more a part of production and procurement rather than the innovation process itself.

By contrast, with energy (and environmental) innovation, cost considerations must be integral from the beginning. Stated differently, DoD is highly sensitive to both performance and cost when it comes to energy technology. DoD's mission is national defense, not energy efficiency or environmental protection; as a general matter, DoD does not do something differently just because it's green—the technologies have to be cheaper and better than the technologies and methods that DoD is currently using.

Energy innovations must also integrate into existing infrastructure or processes. Innovation is therefore necessarily a mix of evolutionary improvements with less frequent radical innovations. Radical changes do occur, but DoD must be cognizant of how they can be transitioned given regulations and standards as well as large investments in legacy systems and processes.

Installation Energy Test Bed

The centerpiece of DoD's innovation model for facilities energy is its Installation Energy Test Bed. The test bed is designed to demonstrate emerging energy technologies in a real-world, integrated building environment in order to reduce risk, overcome barriers to deployment, and facilitate wide-scale commercialization. The test bed requires no new physical infrastructure; rather, it operates as a distributed activity whose key element is the systematic evaluation of new technologies, both to determine their performance, operational readiness, and life cycle costs, and to provide guidance and design information for future deployment across installations.

The rationale is straightforward. New technologies offer the opportunity to cost-effectively reduce DoD's facility energy demand by a dramatic amount and provide distributed generation to improve energy security. Absent outside validation, however, these new technologies will not be widely deployed in time for DoD to meet its energy goals and requirements, for the reasons discussed earlier.

Because it has such a large stock of buildings, it is in DoD's direct self-interest to help firms overcome the barriers to deployment and commercialization of their technologies. To overcome these barriers requires demonstrations that link emerging technology with real-world sites and end users in order to validate the technologies' cost and performance. Demonstrations can operate both as a technology pull and a technology push—to both accelerate the deployment of emerging technologies and foster the final development of the next generation of energy technologies. As mentioned previously, DOE has historically had limited success in playing this role, at least in part because DOE is not a market for these technologies. DoD, in contrast, is uniquely positioned to play this role for itself and the nation at large, due to the breadth of its infrastructure, the size of its market, and its long-established culture of test and evaluation and early technology adoption.

One indication of the value of this approach is that Wal-Mart, the largest private sector energy consumer in the United States, has its own test bed. Wal-Mart systematically tests innovative energy technologies at designated stores to assess their performance and cost-effectiveness. The technologies that prove to be cost-effective (not all of them do, which is itself a valuable finding) are deployed by Wal-Mart in all of its stores. This approach has helped Wal-Mart dramatically reduce its energy consumption. But whereas Wal-Mart's focus is narrow, because all of its stores are identical, the military needs solutions for a diverse mix of building types and sizes—everything from barracks and office buildings to aircraft repair depots and data centers.

DoD began the Installation Energy Test Bed as a pilot program in 2009 with $20 million in funds from the Stimulus Act. Seeing the value of these demonstrations, in 2010 the Department directed $30 million from the Energy Conservation Investment Program, a flexible military construction budget line, to ESTCP to continue the test bed. For FY2012, the President's budget proposes $30 million in RDT&E funds for the test bed.

ESTCP has successfully piloted the test bed over the last two years. Each year, ESTCP has invited private firms, universities, and government labs to identify emerging technologies that would meet DoD installation needs. The response from industry has been extremely strong: many of the ongoing demonstrations are viewed as critical elements in the business plans of both large and small companies seeking to bring their technologies to full commercialization and widespread deployment. In 2010, ESTCP received more than 300 proposals from leading corporations in the building energy sector, small start-ups with venture capital funding, and the major DOE labs. The proposals were reviewed by teams made up of technical experts from inside and outside of DoD, as well as service representatives familiar with the installations' needs. Winning proposals (about 15 percent of the total submitted) were then matched up with a service and an installation at which to demonstrate the technology. ESTCP expected some of the early projects to begin to show results in late 2011. The most recent solicitation closed in late March 2011; ESTCP received 600 preproposals whose combined requested funds were over a billion dollars.

The timing for an energy test bed is ideal, which is one reason the response from industry has been so strong. The federal government is investing significant resources in building energy R&D, largely through the Department of Energy, and the private sector is making even larger investments, as evidenced by the growth of venture capital backing for "clean tech." As a structured demonstration program linked to the large DoD market, the ESTCP test bed can leverage these resources for the military's benefit.

The test bed program carries out demonstrations in three broad technical areas: energy component technologies, both for efficiency and generation; system approaches to building energy control, management, and decision making; and installation-level smart-microgrid technologies.

Component Technologies

The test bed program demonstrates and evaluates advanced component technologies for both demand reduction and distributed generation—technologies that, due to real or perceived risks, are not being used across DoD. The value of these technologies is very cost sensitive: a new component must provide equal or better performance while reducing life-cycle costs. Life-cycle costs are highly sensitive to a number of factors, including the technology's operational efficiency, its maintenance costs, and the component's life expectancy. For technologies that appear particularly promising, ESTCP shoulders the cost of first implementation, feeds information back to the developers, and stimulates the adoption of technologies that have been shown to be cost-effective. This also saves DoD the expense of having costly mistakes repeated at individual installations.

One example of DoD's approach is the pilot program currently testing building integrated photo voltaic (BIPV) technologies. BIPV technologies are commercially available and could be deployed on thousands of DoD flat roofs; they could be installed during required roof replacements in place of a traditional roof, providing both a protective roof and a source of energy. Currently, however, neither the Army Corps of Engineers nor the Naval Facilities Engineering Command (NAVFAC) includes BIPV as a roofing option, because neither has data on the performance of the technology. The pilot program is collecting detailed data on the performance of BIPV along multiple criteria. NAVFAC leads this project in collaboration with Lawrence Berkeley National Laboratory.

Systems Approaches to Energy Control and Management

Although individual component technologies are important, the largest potential payoff lies in the opportunities to integrate technologies throughout a building and across an entire installation. Unlike other DoD platforms, such as aircraft and ships, buildings and installations have not been designed or maintained with a systems perspective. They are complex entities with many nonlinear interactions that affect energy flows and operations. A systems approach is needed to optimize performance for individual buildings and building clusters within an installation. Systems approaches will focus on new design tools and the exploitation of distributed sensors linked to innovative control strategies. In addition to the impediments to commercialization discussed above, systems approaches face another major obstacle: the lack of real-world testing, particularly in the retrofit market, where DoD has the greatest interest. DoD has a unique opportunity in this area due to the nature of its installations and the unique security concerns associated with information assurance that a demonstration must address.

For example, the pilot program is testing an innovative approach to "continuous building commissioning." Over time, the energy performance of buildings degrades; most buildings rarely meet their design intent, much less perform optimally. Advances in monitoring and modeling tools now make it possible to continuously optimize building performance. Two pilot projects demonstrating a whole-building monitoring system are assessing its ability to do the following:

1) Identify, classify, and quantify deviations from design intent or optimal performance regarding consumption of energy and water in the building;
2) Classify and identify the root causes of such deviation;
3) Identify corrective actions; and
4) Quantify the value of these actions in terms of energy and water savings and other economic benefits.

Project participants include United Technologies Research Center (lead), Lawrence Berkeley National Laboratory, the University of California at Berkeley, and Oak Ridge National Laboratory.

Smart-Microgrid Technologies

In addition to demand reduction and increased distributed energy generation, DoD's energy security goal requires the deployment of smart-microgrid technologies that allow DoD installations to "island" and provide operational capability in the event of grid failure. These same technologies offer DoD opportunities to reduce operational costs through demand response management. DoD's requirement for this class of technology puts it in a unique position: although DoD has security concerns not found in the private sector, it expects to use commercial smart-grid technologies in the future, rather than developing its own solutions. Standards and smart-grid technologies are expected to change significantly in the coming

FIGURE 3.8 Installation Energy Test Bed Projects, by Location, Start Date, and Service Type

Note: Eight demonstration projects occur at multiple locations.

years; DoD should not adopt an approach that is independent of, or inconsistent with, the changing commercial market. The test bed program will demonstrate emerging commercial technologies configured to meet DoD's unique security needs, and evaluate the critical operational and information security issues related to the use of these technologies.

For example, the pilot program is currently testing a General Electric smart-microgrid technology at the Marine Corps' Twentynine Palms installation in California. The technology is designed to manage and control the complicated interactions among heat and electrical power generation, power demand, energy storage, and power distribution and delivery. It can also optimize energy usage, and offers energy security by managing backup power operation for critical loads if the microgrid is disconnected from the bulk grid (or "islanded"). The technology is scalable and is applicable to multiple DoD installations that contain renewable resources. However, the economic value and security of such a system cannot be determined in the absence of real-world testing on a DoD installation. The system needs to be integrated with real-world generation and loads to assess its performance and finalize design details.

To date, nearly 50 demonstrations are under way across DoD as part of ESTCP's Installation Energy Test Bed (see figure 3.8).

DoD plans to continue this program in FY2012. A competitive process is under way to identify the next round of technology demonstrations in the following areas:

1) Smart microgrids and energy storage to increase energy security on DoD installations
2) Renewable energy generation on DoD installations
3) Advanced component technologies to improve building energy efficiency
4) Advanced building energy management and control
5) Tools and processes for design, assessment, and decision making associated with energy use and management

The interest from industry has been extremely high. Companies see the ongoing demonstrations as crucial means of bringing their technologies to full commercialization and widespread deployment. The current solicitation has attracted enormous interest, highlighting the pent-up need for efforts to move energy technologies beyond research and development and to overcome the Valley of Death.

Conclusion

DoD has been an enormous engine of innovation in America, driving the development of both defense technologies and, ultimately, very large sectors of commercial activity. In addition to its traditional focus on conventional military hardware, there is now great interest in applying those capabilities to energy innovation, an area of activity that can have enormous benefits both to the United States military and to the country as a whole. In thinking about this question, it is worth considering the two different (but complementary) models of innovation at DoD: the well-known Defense Advanced Research Projects Agency (DARPA) model, which has produced extraordinary technological breakthroughs (at great cost) that have allowed America to dominate the battlefield; and the more recent SERDP and ESTCP model, which focuses less on cost-insensitive breakthroughs and more on developing and demonstrating cost-effective technologies that can enhance the effectiveness of the overall fighting force. The SERDP and ESTCP's test bed cost-consciousness and ability to work across the spectrum from basic to applied research and demonstration makes it uniquely effective at assisting innovative technologies across the Valley of Death and into commercial viability. While the extraordinary "leap-ahead" innovations of DARPA more easily capture the imagination, the ability of the ESTCP's test bed program to improve the overall energy efficiency of the United States military—and the civilian economy—should not be overlooked. ESTCP offers both the military and the nation an effective approach that can leverage the large investments in energy technology developments at DOE and the private sector, and result in a real energy revolution.

3 THE DYNAMICS OF MILITARY INNOVATION AND THE PROSPECTS FOR DEFENSE-LED ENERGY INNOVATION

Eugene Gholz[85]

Many pundits and leaders in the U.S. government hope to use the model of successful military innovation to stimulate innovation for green technologies—notwithstanding criticisms that defense technologies are often expensive and esoteric and sometimes fail to meet optimistic performance projections. Advocates particularly hope that the Department of Defense (DoD) will use its substantial procurement budget to "pull" the development of new energy technologies; in their vision DoD will serve as an early adopter to help new energy technologies achieve economies of scale.[86]

This paper will build on the baseline of knowledge about military innovation—what we know about why some large-scale military innovation has worked while some has not—to explain which parts of the effort to encourage defense-led energy innovation are likely to be more successful than others. Innovation in major weapons systems has worked best when customers understand the technology trajectory that they are hoping to pull and when progress along that technology trajectory is important to the customer organization's mission; under those circumstances, the customer protects the research effort, provides useful feedback about the development effort, adequately (or generously) funds the effort, and happily buys the end product, often helping the developer appeal to elected leaders for funding. The alliance between the military customer and private firms selling the innovation can overcome the collective action problems that providing public goods like defense and energy security would otherwise face.

This model of military innovation is not the only way that the U.S. has developed and applied new technologies for defense, but it is the principal route to substantial change. At best, other innovation dynamics tend to yield relatively minor evolutionary improvements or small-scale innovations that can matter a great deal at the level of a local organization but do not attract sufficient resources and political attention to change overall national capabilities.

Applied to energy innovation, this understanding of innovation suggests that DoD will more effectively pull development efforts related to operational energy (e.g., fuel supplies to operating bases in Afghanistan) than efforts related to energy at military bases in the U.S., even if the efforts for home installations would cost less, would increase efficiency more, would better protect energy security (e.g., protecting against threats to homeland security), or would draw equal support from private-sector lobbying. The operational energy efforts better fit into the military's traditional concerns with innovation in the field that reduces casualties and eases logistical constraints (even at the cost of complexity in the logistics chain). Meanwhile, installation energy improvements try to gain political support by appealing to a more general conception of the national interest, recognizing that "security" claims are a useful political lever in the United States—a code word for "important"—but that promises to contribute to "energy independence" have failed to attract sustained support and real funding since President Nixon first used that phrase.

85 The author is currently on leave from the University of Texas at Austin and is working temporarily as senior advisor to the deputy assistant secretary of defense for manufacturing and industrial base policy. This paper was written in the author's private capacity, and it represents only his personal views, not those of the Department of Defense or any other part of the U.S. government.

86 The government has also launched a number of research initiatives such as ARPA-E (Advanced Research Projects Agency–Energy), modeled on DARPA (Defense Advanced Research Projects Agency), to push energy technology and to encourage invention and prototyping, but those efforts will not be the focus here.

However, the operational energy efforts may face other problems, as the demand for energy-efficient equipment to use in the field introduces new performance metrics into defense acquisition that are unfamiliar to the established defense industrial base, especially at the prime contractor level. The new performance metrics are likely to require some significant changes in industry structure, changes that draw on new technology companies. In past waves of military innovation, the defense prime contractors have successfully drawn in new technologies through mergers and acquisitions, joint ventures, and subcontracting relationships, building on the primes' core competency in understanding and responding to the desires of their military customers.

Sources of Innovation

The customer typically drives military innovation in the United States, and military customers obviously are used to making investment decisions based on interests other than the pure profit motive. Acquisition requirements derive from leaders' military judgment about the strategic situation, and the military works with political leaders rather than profit-hungry investors to fund the needed research, development, and procurement. This process, along with the military's relatively large purse compared to even the biggest commercial customers, is what attracts the interest of advocates of defense-led energy innovation: they hope to create an incentive to develop new energy technologies even if the technologies would not meet the normal rate-of-return criteria used by business. Instead, advocates hope to use the familiar mechanism that led defense companies to develop the high-tech weapons that won the Cold War and have performed so well in conflicts since.

Not surprisingly, the companies that have understood the sources of military innovation have performed the best over the years. When the Navy first started its Fleet Ballistic Missile program, the Special Projects Office wanted to give the Navy a role in the nuclear deterrence mission but did not initially provide much money to develop and build the Polaris missiles. Lockheed understood that responsiveness was a key trait in the defense industry, so the company used its own funds initially to support development to the customer's specifications.[87] As a result, Lockheed won a franchise for the Navy's strategic systems that continues in Sunnyvale, California, more than fifty years later.

By contrast, at roughly the same time as Lockheed's decision to emphasize responsiveness, the Curtiss-Wright Corporation, then a huge military aircraft company, attempted to use political channels and technological optimism to sell products of technology push, notably the company's preferred jet engine design. The Air Force preferred the products of companies that followed the customer's lead, and Curtiss-Wright fell from the ranks of leading contractors even in a time of robust defense spending.[88] Northrop later found itself in a similar position. The Air Force was not interested in buying the F-5 fighter, which the company had developed largely at its own expense. The company was confident that the Air Force would in the end accept the company's view of desirable technology, once they had seen the product, but the company was wrong. The Air Force wanted a fighter that tried to meet the performance requirements that the Air Force had specified. Northrop managed to sell F-5s in export markets and had enough other business to last as a U.S. prime contractor, but its experience shows the relative power of demand over supply in the U.S. defense market.

History shows that the U.S. military can be a difficult customer if the acquisition executives lose faith in a supplier's responsiveness, but the military can also be a forgiving customer if firms' good-faith efforts do not yield products that live up to all of the initial hype. Occasionally, a technology underperforms to such an extent that the program is canceled—for example, the ill-fated Sergeant York self-propelled anti-aircraft gun—but in many cases, the military accepts equipment that does not meet its contractual performance specifications and either nurtures the technology through years of improvements and upgrades or discovers that the system is actually terrific despite failing to meet the specs. The B-52 bomber is perhaps the paradigm case: it did not meet its key performance specifications for range, speed, or payload, but it turned out to be such a successful aircraft that it is still in use fifty years after its introduction and is expected to stay in the force for decades to come.[89] Trying hard and staying friendly with the customer is the way to succeed as a defense supplier, and because the military is committed to seeking technological solutions to strategic problems, the prime contractors have many opportunities to develop and sell innovation.

Of course, military desire for a new technology is not sufficient by itself to get a program funded in the United States. Strong political support from key legislators has also long been a prerequisite for technological innovation. While an excess of pork barrel politics might trap the American military with old equipment built in the "right" congressional districts, even though it doesn't meet soldiers' true needs, most of the time we don't get that excess. Instead, the military and the defense contractors learned to combine performance specifications with political logic: the best way to attract political support was to promise

87 Harvey M. Sapolsky, *The Polaris System Development: Bureaucratic and Programmatic Success in Government* (Cambridge, MA: Harvard University Press, 1972).

88 Eugene Gholz, "The Curtiss-Wright Corporation and Cold War-Era Defense Procurement: A Challenge to Military-Industrial Complex Theory," *Journal of Cold War Studies 2, no. 1* (Winter 2000): 35–75.

89 Michael E. Brown, *Flying Blind: Politics of the U.S. Strategic Bomber Program* (Ithaca: Cornell University Press, 1992).

heroic feats of technological progress, because the way to justify procurement of a new system (and the politically attractive jobs that came with production) was to promise that the new system would substantially outperform the equipment in the current American arsenal, even if that previous generation of equipment was only recently purchased at great expense. The political logic simply compounds the military's tendency for the technological optimism that creates such tremendous technology pull for military innovation.[90]

In fact, Congress wouldn't spend our tax dollars on the military without some political payoff, because national security offers a classic case of diffuse benefits (all citizens benefit whether they help pay the cost or not).[91] Military innovations' political appeal—whether supported by ideology (e.g., the "religion" that supports missile defense), an idiosyncratic vision (e.g., Senator John Warner's longtime interest in unmanned aerial vehicles, or UAVs), or the ability to feed defense dollars to companies in a legislator's district (e.g., California legislators, widely perceived as antimilitary, voted for the B-1 bomber and the MX missile)—prevents the United States from underinvesting in technological opportunities.

Because the military is blocked by the professionalism that defines American civil-military relations from overtly lobbying for its preferences, its trusted relationship with key defense contractors provides a key link in developing political support for military innovation. The prime contractors take charge of directly organizing district-level political support for the defense acquisition budget, and any major innovative project that the military hopes to invest in needs to fit into a contractor-led political strategy to be funded.[92] Other unusual features of the defense market reinforce the especially strong and insular relationship between military customers and established suppliers. Their relationship is freighted with strategic jargon, security classification, regulation of domestic content, socioeconomic set-asides, extremely costly audit procedures, and hypersensitivity to scandals driven by perceived or occasionally real malfeasance. The military has to work with suppliers who are comfortable with the terms and conditions of working for the government, who are able to translate the language in which the military describes its doctrinal vision into technical requirements for systems engineering, and who are trusted by the military to temper optimistic hopes with technological realism without undercutting the military's key objectives. The military feels relatively comfortable discussing its half-baked ideas about the future of warfare with established firms—ideas that can flower into viable innovations as the military officers go back and forth with company technologists and financial officers.

That iterative process has given the U.S. military the best equipment in the world in the past, but it tends to limit the pool of companies with which the military buyers directly contract to a particular set of firms: the usual prime contractors like Lockheed Martin, Boeing, Northrop Grumman, Raytheon, General Dynamics, and BAE Systems. The core competency of these companies is dealing with the unique features of the military customer.

In addition to that core competency (understanding the military customer), defense firms, like most other companies, have technological core competencies. In the 1990s and 2000s, it was fashionable in some circles to call the prime contractors' core competency "systems integration," as if that task could be performed entirely independently of a particular domain of technological expertise. In one of the more extreme examples, Raytheon won the contract as systems integrator for the LPD-17 class of amphibious ships, despite its complete lack of experience as a shipbuilder. Although Raytheon had for years led programs to develop highly sophisticated shipboard electronics systems, its efforts to lead the overall team building the entire ship produced an extremely troubled program. In this example, company and customer both got carried away with their technological optimism and their emphasis on contractor responsiveness (Raytheon was willing to promise to try to do just about anything). In reality, the customer-supplier relationship works best when it calls for the company to develop innovative products that follow an established trajectory of technological performance, where the company has experience and core technical capability. These are known in the business literature as "sustaining innovations." Trying to introduce an established supplier to new performance metrics —that is, trying to stimulate "disruptive innovation"—substantially raises the likelihood of problems on the contract.[93]

That is not to say that the military cannot introduce new technological trajectories into its acquisition plans. In fact, the military's emphasis on its technological edge has explicitly called for disruptive innovation from time to time, and the defense

90 Harvey M. Sapolsky, "Equipping the Armed Forces," in George Edwards and W. Earl Walker, eds., *National Security and the U.S. Constitution*, ed. George Edwards and W. Earl Walker (Baltimore: Johns Hopkins University Press, 1988).

91 Dwight R. Lee, "Public Goods, Politics, and Two Cheers for the Military-Industrial Complex," in Robert Higgs, ed., *Arms, Politics, and the Economy: Historical and Contemporary Perspectives* (New York: Holmes & Meier, 1990), pp. 22–36.

92 Peter J. Dombrowski and Eugene Gholz, *Buying Military Transformation: Technological Innovation and the Defense Industry* (New York: Columbia University Press, 2006).

93 This framework for understanding innovation, in which technological trajectories are linked to customer-supplier relationships, derives from Clayton M. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Boston: Harvard Business School Press, 1997). It is applied to defense in Peter Dombrowski and Eugene Gholz, "Identifying Disruptive Innovation: Innovation Theory and the Defense Industry," *Innovations 4*, no. 2 (Spring 2009): 101–17. For a related argument linking Christensen's framework to defense (that disagrees on one important aspect of the theory), see Gautam Mukunda, "We Cannot Go On: Disruptive Innovation and the First World War Royal Navy," *Security Studies* 19, no. 1 (Winter 2010): 124–59.

industry has responded. For example, the electronics revolution involved huge changes in technology, shifting from mechanical to electrical devices and from analog to digital logic—requiring support from companies with very different technical core competencies. Start-up companies defined by their intellectual property, though, had little insight into (or desire to figure out) the complex world of defense contracting—the military jargon, the trusted relationships, the bureaucratic red tape, or the political byways—so they partnered with established prime contractors as subcontractors, in joint ventures, and as acquisition targets. The trick is for established primes to serve as interfaces and brokers to link the military's demand pull with the entrepreneurial companies having the right skills and processes for the new performance metrics. Recently, some traditional aerospace prime contractors, led by Boeing and Northrop Grumman, have used this approach to compete in the market for unmanned aerial vehicles, although at this point, DoD still buys a plethora of different UAV designs from a wide range of suppliers, often through nontraditional "rapid" acquisition processes. Over time, as UAVs become a more standard item of military equipment and the wartime rapid acquisition processes revert to the normal procurement channels, the industry structure is likely to evolve further to cement the prime contractors' roles as information and systems integration brokers.

Given the pattern of customer-driven innovation in defense, the task confronting advocates of defense-driven energy innovation seems relatively simple: inject energy concerns into the military requirements process. The military innovation route might directly address key barriers that hamper the normal commercial process of developing energy technologies, finding markets that promise a high enough rate of return to justify the investment, and convincing financiers to stick with the projects through many lean years and false starts before they reach technological maturity, commercial acceptance, and sufficient scale to earn profits. But using the military innovation process presents three other challenges to energy innovation: fitting the role of energy technologies into the military leaders' strategic vision, finding political support to pay for implementing that energy-related vision in a time of relative budget austerity, and accessing technical skills to solve energy innovation challenges through DoD's customer-supplier channels that focus on companies selected in the past for a different set of technological competencies.

The Military (and Political) Customers

If the customer-supplier relationship is the key to demand pull for innovation, then the first step in understanding the potential for defense-related energy innovations is understanding the customers' priorities. The emphasis on customer organizations is especially important in this case because of the concentration on a relatively few customers in defense—various parts of the U.S. government—compared to the relative abundance of possible customer niches in the overall global economy. From the perspective of firms that actually develop and sell new technologies, the customers include the military services, whose various components each have somewhat different levels of interest in energy innovation, and also the political leadership, notably in Congress.

Military organizations decide the emphasis in the acquisition budget. They make the case, ideally based on military professional judgment, for the kinds of equipment the military needs most, and they also determine the systems' more detailed requirements, like the speed needed by a front-line fighter aircraft and the type(s) of fuel that aircraft should use. Relevance to the organizations' critical tasks ultimately determines the emphasis placed on different performance standards when the inevitable trade-offs come during the acquisition process.[94] For example, concerns for affordability and interoperability with allies' systems have traditionally received much more rhetorical emphasis, especially early in programs' lives, than they have received real emphasis in implementation, when the military actually procures and deploys equipment. When faced with the question of whether to put the marginal dollar into making the F-22 stealthy and fast or into giving the F-22 extensive capability to communicate, especially with allies, the program office not surprisingly emphasized the former key performance parameters rather than the latter nice feature. The challenge for advocates of military-led energy innovation is to link the performance metrics they would like to emphasize in defense systems to the military services' interests that are driven by links between strategic threats and organizational culture.

Energy innovation may add complexity to military logistics—it may involve, for instance, managing a mix of biofuels, or generating and storing distributed power rather than using standardized, large-capacity diesel generators—but that is not necessarily a high barrier to military adoption. The Army has always dealt with complex logistics, moving tons of consumables

94 Thomas L. McNaugher, *New Weapons, Old Politics: America's Military Procurement Muddle* (Washington, DC: Brookings Institution, 1989); Harvey M. Sapolsky, Benjamin H. Friedman, and Brendan Green, eds., *U.S. Military Innovation since the Cold War: Creation without Destruction* (London: Routledge, 2009).

and countless spare parts to the front to feed a vast organization of many different communities (infantry, armor, artillery, aviation, etc.), and the Navy's power projection capability is built on a combination of planning carefully what ships need to take with them, flexible purchasing overseas, and underway replenishment.[95] The old saw that the Army would rather plan than fight may be an exaggeration, but it holds more than a grain of truth. More than most organizations, the U.S. military is well prepared to deal with the complexity that energy innovation will inject into its routines, and even if the logistics system seems Byzantine and inefficient, the organizational culture does not have antibodies against this aspect of energy innovation.

On the other hand, investing in base infrastructure has tended to be a harder task for the military, because with a few exceptions the quality of facilities at bases is tangential to the organizations' critical tasks. People may rib the Air Force for the priority attached to making sure that bases have a decent golf course, but the bases do not really suffer (or benefit) from overinvestment in what is perceived as "nice to have" luxuries. It is local politics and their impact on congressional votes that maintains a robust number of military bases, and the politics feed on the money that soldiers and their families spend in the community, not on paying the additional up-front cost of installing efficient or experimental energy technologies.[96] The military installations that attract the most innovative spending are the installations where the spending contributes directly to American forces' combat edge—bases like the National Training Center that allow for highly realistic combat exercises. Advocates of energy innovation are unlikely to meld their pitch smoothly with that high-end organizational mission. If, instead, they pitch the energy innovations as "efficiency-enhancing," they will face the fate of every other efficiency-enhancing investment that military installations could make: energy innovation will be treated as a low priority somewhere in the mix of desiderata in the budget.

The Defense Industry and Energy Innovation

Operational energy seems especially important and exciting right now, because the United States is at war—and even more than that, because the current wars happen to involve a type of fighting with troops deployed to isolated outposts far from their home bases, in an extreme geography that stresses the logistics system. But as the U.S. effort in Afghanistan draws down, energy consumption in operations will account for less of total energy consumption, meaning that operational energy innovations will have less effect on energy security. More important, operational energy innovations will be of less interest to the military customers, who are unlikely to emphasize planning for a repeat of such an extreme situation as the war in Afghanistan.

Specific military organizations that have an interest in preparing to fight with a light footprint in austere conditions may well continue the operational energy emphasis of the past few years. The good news for advocates of military demand pull for energy innovation is that special operations forces are viewed as the heroes of the recent wars, making them politically popular. They also have their own budget lines that are less likely to be swallowed by more prosaic needs like paying for infrastructure at a time of declining defense budgets or by shifting strategic emphasis toward traditional high-intensity combat. While the conventional military's attention moves to preparation against a rising near-peer competitor in China—a possible future, if not the only one, for American strategic planning—special operations may still want lightweight, powerful batteries and solar panels.

Working with industry for defense-led energy innovation requires treading a fine line. Advocates need to understand the critical tasks facing specific military organizations, meaning that they have to live in the world of military jargon, strategic thinking, and budget politics. At the same time, the advocates need to be able to reach nontraditional suppliers who have no interest in military culture and are developing technologies that follow performance trajectories totally different from the established military systems. More likely, it will not be the advocates who develop the knowledge to bridge the two groups, their understandings of their critical tasks, and the ways they communicate and contract. It will be the prime contractors, if their military customers want them to respond to a demand for energy innovation.

95 Carl H. Builder, *The Masks of War: American Military Styles in Strategy and Analysis* (Baltimore: Johns Hopkins University Press, 1989).
96 Kenneth R. Mayer, "Closing Military Bases (Finally): Solving Collective Action Problems through Delegation," *Legislative Studies Quarterly* 20, 3 (August 1995): 393–413.

4 THE ENERGY TECHNOLOGY CHALLENGE: COMPARING THE DARPA AND ARPA-E MODELS

William B. Bonvillian and Richard Van Atta [97]

The United States faces powerful economic challenges in the complicated nexus of the economy, energy, and environmental issues. In this arena transformative innovation is understood to be a key public policy response. One element of the response has been the creation of an energy-DARPA—ARPA-E.

DARPA (Defense Advanced Research Projects Agency) was formed to address the problem of transformative innovation. Instigated by the Sputnik shock of 1958, the Advanced Research Projects Agency (subsequently renamed the Defense Advanced Research Projects Agency) was created with an explicit mission: to ensure that the United States never again faced a national security "technological surprise," like Sputnik, due to failure to pay adequate attention to and stay focused on breakthrough technological capabilities. DARPA itself can be categorized as a disruptive innovation, in that it creates an approach to fostering and implementing radically new technology concepts recognized as transformational.

ARPA-E (Advanced Research Projects Agency–Energy) was authorized in 2007 by Congress as part of the America COMPETES Act, was funded with an initial $400 million in the 2009 economic stimulus bill, and received $180 million for fiscal year (FY) 2011 in the April 2011 continuing resolution. It was designed to incorporate the DARPA model of accelerated innovation in the energy technology sector.

Short Summary of Paper Elements

ARPA-E offers a very interesting new institution to meet the profound energy technology challenge facing the United States. Because it is explicitly modeled on DARPA, this paper reviews the noted DARPA approach in detail. Briefly citing well-known features of DARPA, it explores in detail a number of important features that have not been well discussed in the policy literature on DARPA to date.

The paper then reviews the new ARPA-E model in detail. It first comments on how ARPA-E has adopted key elements of the DARPA approach. It then discusses new features the ARPA-E has been moving toward in a series of areas, largely driven by its need to confront the unique and difficult demands of the complex established energy sector where it operates. In addition, the further DARPA features enumerated provide potentially useful guideposts to ARPA-E as it continues to support innovation in the energy sector.

97 William B. Bonvillian is director of the MIT Washington Office and a former senior policy advisor in the U.S. Senate. He teaches innovation policy and energy technology courses on the adjunct faculties at Georgetown University and at Johns Hopkins-SAIS. Richard Van Atta, a former assistant deputy under secretary at the Department of Defense, is with the Institute for Defense Analyses and teaches security studies on the adjunct faculty at Georgetown University. An extended version of this paper appears in the October 2011 issue of *Journal of Technology Transfer*; readers who wish to see in-text documentation and a complete list of sources cited should consult that version.

Finally, the paper closes with a discussion of the profound technology implementation problems on the "back end" of the innovation system—demonstration, test beds, initial markets—that the authors believe both agencies must further confront, and it develops a working list of recommendations in this regard.

The DARPA Model

Well-Known Elements in the DARPA Culture

DARPA is widely understood to embody a series of unique organizing principles, not typical of other R&D agencies, including these:

- A flat, nonhierarchical organization, with empowered program managers
- A challenge-based "right-left" research model
- Emphasis on selecting highly talented, entrepreneurial program managers (PMs) who serve for limited duration (three to five years)
- Research performed entirely by outside performers, with no internal research laboratory
- Projects focused on "high risk/high payoff" motif, selected and evaluated on what impact they could make on achieving a demanding capability or challenge
- Short-term funding for seed efforts that scale to significant funding for promising concepts, but with clear willingness to terminate nonperforming projects

But the model goes beyond these well-understood features. Historically it has embodied a number of other deep features that should be accounted for.

Multigenerational Thrusts

DARPA does more than undertake individual projects. It has in many instances worked over an extended period to create enduring technology "motifs"—ongoing thrusts that have changed the technology landscape. Some notable examples are DARPA's work in information technology (IT), stealth, and stand-off precision strike. Some of these foci are what might be termed broad technology stewardship over a family of emergent technologies, including new sensing systems, such as infrared sensing, or new electronics devices. In these thrust areas DARPA has been able to undertake multigenerational technology thrusts and advances over extended periods, to foster multiple generations of technology.

Three technology areas stand out as having endured with significant contributions through many projects and phases during most of DARPA's history: sensing and surveillance; information processing; and directed energy weapon technology. DARPA made seminal contributions in several key aspects of these technologies. It is fair to say that in the information-processing area, DARPA-supported work was responsible for the foundations and initial stages of a revolution in information processing and transfer technology that has seen networked computers, desktop computing, and the Internet sweep the world, and is now having a similar impact on parallel processing.

While DARPA is an *advanced projects* agency, it is clear that it has always had more than a project-by-project perspective; and there have been broader, more general themes of the agency's programs. This became clear in the review comments on earlier DARPA studies conducted by the Institute for Defense Analyses, in which some former DARPA directors and high-ranking Department of Defense (DoD) R&D executives stated that the overall motivations and intent of the agency's research program were not adequately conveyed by project-specific write-ups.

Thus, it has often been the case that the projects pursued in specific DARPA program offices were part of a larger portfolio that itself derived from a more overarching view of possibilities or challenges in a specific technical or applications domain. These larger perspectives were usually organic—a DARPA office director or a DARPA director saw a broader theme that became the basis for formulating a set of projects. This was specifically the case in the information technology area that began with the now well-known vision of the first Information Processing Techniques Office (IPTO) director, J. C. R. Licklider, and steadily cohered under a set of subsequent directors who were essentially hand-picked by the prior director—with Licklider even returning after several years to manage the program for a second tour. Thus, the information technology evolution within DARPA was guided by a strong overarching perspective, but also by a very conscious effort to inculcate the IPTO programs with the vision and to grow the technical focus as an increasingly articulated and interrelated set of projects.

The Strategic Computing Program was begun in 1985 to consolidate the advances made in information-processing technologies and to stimulate their application into such areas as sensing and surveillance, autonomous vehicle operation, and command and control. Underlying this thrust was the view that significant advances had been made across several aspects of information-processing technology, ranging from massively parallel computer technologies to image-understanding algorithms, and that these different aspects should be combined and integrated into experimental applications. A key motivator behind this thrust was the desire by DARPA to take DARPA-stimulated advances in parallel processing computers beyond research and into development and applications, with specific focus on such artificial intelligence applications as autonomous vehicle guidance and C31 processing. The resources needed to realize these advances in an integrated manner were seen to exceed what could be accomplished from the comparatively small, disparate, but coordinated technology research budgets in the Defense Science and Information Science and Technology program offices.

Another element of the overall information technology thrust was DARPA's program in microelectronics, which was specifically aimed at developing "sub-micron electronic technology and electron devices" to "skip a generation in feature size on chips." [98] This program evolved into the VLSI (Very Large-Scale Integration) program, which led to a fundamental revolution in integrated circuit design and had major impact on computer technology. This thrust became the basis for DARPA's Microelectronics Technology Office.

To summarize, while DARPA is at base an "advanced projects" agency, it has also developed a capability to undertake multigenerational thrusts, in which a series of connected projects that nurture an overall technology domain are "stood up" over a series of technology generations. DARPA has undertaken this role largely through vision and leadership from particular DARPA directors and/or office directors.

Complementary Strategic Technologies

DARPA has repeatedly launched related technologies that complement each other and that help build support for the commercialization or implementation of one another. This concept of complementary technologies also ties to the notion of program thrusts. One way of thinking about this is that DARPA is not in the "thing" business—it is in the problem-solving business. While a specific innovation may have a major impact, it is unlikely that one such project by itself will adequately address a major challenge or problem. While DARPA may support an individual invention, it usually does so because that invention may be an element of an overall solution to a challenge.

Confluence with an Advocate Community

DARPA has spawned new economic sectors; these have in turns spawned new firms, which have garnered support from venture capital (VC). Accordingly, DARPA has been able to make its advances reinforce each other; it has been able to play an intermediary role with industry in part by building an advocate community across sectoral lines. A key element of DARPA's success in such areas as information technology, sensor systems, advanced materials, and directed energy systems is building the community of "change agents"—a broad community fostered over time from its program managers, from "graduates" of the DARPA program who go on to roles in academia and industry, and from contractors in universities and industry trained in the DARPA model and technology approaches.

Connection to Larger Innovation Elements

Going beyond the confluence with its support community, DARPA has been an actor within larger innovation efforts; it is often instrumental, but seldom a sole actor. This connection to larger innovation elements is important to DARPA's effectiveness because it does not have its own research facilities, and its program managers do not perform their own research. Thus, the DARPA PM's most important function is to identify and support those who have the potentially disruptive, change-state ideas and who will ably perform the necessary research. Thus, the PM is an opportunity creator and idea harvester within an emerging technology field. From this concept- or idea-scouting perspective DARPA has spawned a group of researchers, and from that, new firms that act to help effectuate the program's overall vision.

However, this downward and outward linking into the research community and commercial industry is only one aspect of DARPA's connectivity to larger innovation elements. DARPA, as an agency of the Department of Defense, is part of a broader innovation structure within and for DoD. Crucial here is that DARPA is an independent organization under the secretary of defense and is explicitly separate from the military service acquisition system. While the secretary of defense and the underlying Office of the Secretary of Defense (OSD) bureaucracy rarely directly involve themselves in DARPA's individual research programs, OSD leadership elements at various times have played a strong role in identifying the mission challenges they want DARPA to address. Thus, DARPA, working with OSD, has

98 The quotation is from testimony by Dr. Robert Fossum before Congress in 1979; cited in R. Van Atta, S. Deitchman, and S. Reed, *DARPA Technical Accomplishments*, vol. 3 (Alexandria, VA: Institute for Defense Analyses, 1991).

been able to tie its advances to the larger innovation elements in DoD, often implementing its technologies through service procurement programs.

Willingness to Take On Incumbents

DARPA at times has invaded the territory occupied by powerful companies or bureaucracies. It drove the desktop personal computing and the Internet model against the IBM mainframe model. On the military side of the ledger, cooperating with others in DoD, it drove stealth, unmanned systems, and precision strike and night vision capabilities—despite the lack of interest from and even express objections of the military services. At times these "invasions" have taken special mechanisms beyond or outside of (but in coordination with) DARPA to achieve.

On militarily specific technologies DARPA operates under a motif that is expressly separated and different from that of the military services; DARPA focuses more on breakthroughs and does not work on projects directly related to existing, expressly stated military requirements, which are inherently shorter term and engineering oriented. Thus, the concepts and technologies that DARPA explores provide capabilities that usually challenge and even disrupt the services' technology development and implementation interests. DARPA does try to involve the service R&D communities as prospective "customers" of its R&D as a means to foster transition. But for technology developments that are outside the usual systems that the services employ, transition often has been difficult and has required the involvement of executives from the highest levels of the OSD. This was the case for stealth aviation, unmanned aerial vehicles (UAVs), and standoff precision strike. The involvement of higher-level OSD officials has been required to overcome the services' uneasiness about bringing fundamentally new and different concepts into an existing operational environment, with the attendant risks and costs. One OSD effort to overcome these risk actors was the Advanced Concept Technology Demonstration program within OSD that explicitly began as a means to get advanced, prototype UAVs, such as Predator, into experimental use in actual military operations. Another example of high-level OSD involvement was then–under secretary for defense research and engineering William Perry managing the implementation of the F-117A stealth program directly out of his office.

On non-military-specific technologies DARPA has developed and implemented technologies that came to fruition despite the presence of existing firms with incumbent technologies. DARPA has not generally sought to take on existing firms directly; rather it has sought the development of new technologies and concepts, often seeding these in university research, and then seeking their transition into commercial implementation. At various times DARPA encouraged universities to transition DARPA-funded technologies (such as "inter-netted" computer workstations developed at Stanford) through demonstration activities with leading computer firms, such as IBM and DEC. However, the existing leading firms often have seen the incipient technology as being too narrow, too risky, or generally not germane to their current market plans, and have not taken on the new approach. These new technologies generally do not address the current or even projected markets that are the focus of the incumbent firms. DARPA has often had to push the potential application of these alternative technologies in areas where such current markets do not exist.

A critical feature in this DARPA effort has been to link to the VC community, which was looking for tech entries that offered prospects of rapidly creating new markets. DARPA became a key lead funder of advanced technologies that VC firms could then seek to bring into rapid commercialization; the VC sector emerged in parallel with DARPA's support of information technology. In addition, the DARPA imprimatur gave an indication to VC firms that the technology had some level of technical merit and had been vetted by very knowledgeable technologists. In addition, DARPA could foster the initial market by providing funds in related implementation-oriented DoD projects to acquire the newly developed technologies—that is, DARPA has at times filled the role of the lead customer willing to incur the higher costs and risks of the new technology in order to gain the value it afforded. This was, for example, the case with the acquisition of Sun Microsystems and Silicon Graphics workstations by DARPA VLSI projects to enable the design of more sophisticated integrated circuits. At other times DoD military users and contractors have wanted to acquire DARPA-supported technologies, such as early language translation systems, that provide security value ahead of commercial market acceptance. Thus, at times the power of DoD procurement can get around established technology markets and create initial markets for the alternative technologies. This ability to bring new technologies to initial markets is a capability that few agencies—for example, DOE—have.

Role as First Adopter/Initial-Market Creator

In addition to ties to demonstration capabilities, DARPA has undertaken a technology insertion or adoption role. In coordination with other parts of DoD, it has been able to create initial or first markets for its new technologies.

Ties to Leadership

DARPA has been particularly effective when it is tied to senior leaders who can effectuate its technologies through DoD or elsewhere. Because DARPA operates at the front end of the innovation process, it historically has required ties to senior DoD leaders to align with the follow-on back end of the innovation system.

Connected R&D

DARPA embodies what is termed "connected R&D"; it is not throwing its prototype technologies over the monastery wall, using a theory of "benign neglect" in the face of markets. It often uses DoD procurement to further its advances, and it funds, as discussed above, creative companies that can attempt to commercialize its products: it tries to guide its successful developments into commercialization, and builds portfolios of technologies to build depth for a technology thrust in emerging markets. *It is in the opportunity-creation business*, in some cases picking technology "winners." In DARPA's exploration of radical innovations it is generally recognized that its developments are ahead of the market; the research it is fostering does not meet an existing market need, but instead is creating a capability—a new functionality—that may (if successful) create a new market or application.

In conclusion, the above discussion of DARPA cited the well-known elements of its innovation culture, and focused on a number of less well-understood elements that have been important to its strength and capabilities. Both types of elements offer lessons in the energy technology sector to ARPA-E, which will be explored below. In addition, DARPA is not perfect, and a number of problems it has faced (not listed) also offer lessons.

ARPA-E: A New R&D Model for the Department of Energy

Replicating Basic DARPA Elements

ARPA-E was consciously designed by Congress to apply the DARPA model to the new energy technology sector. It is about the size of a DARPA program office. It has emphasized speed—rapidly moving research breakthroughs into technologies, through a process it labels "Envision-Engage-Evaluate-Establish-Execute." With funding received in the 2009 stimulus legislation cited above, it has awarded funding in six energy technology areas through spring 2011.

The discussion below lists well-known elements in the DARPA rule set and reviews how ARPA-E reflects and has adapted that model. ARPA-E is a *flat, nonhierarchical* organization, effectively with only two levels: eight program managers and a director. Like those in DARPA, the *program managers are "empowered,"* each with strong authority and discretion to administer a portfolio of projects in a related energy field, from storage to biofuels to carbon capture and sequestration. As in DARPA, the *project approval process is streamlined*—the PMs evaluate and conceive of the research directions for their portfolios. Essentially, there is only one approval box to check—the director—who retains approval authority before the contract is awarded, which generally goes very quickly. Although ARPA-E uses strong expert reviews to guide PM decisions, there is no peer review where outside researchers make the actual final decisions on what gets funded. As at DARPA, this PM selection process generally avoids the conservatism and caution that often afflicts peer review, which tends to reject higher-risk research awards if there are more than four applicants per grant award.

Like those in DARPA, the PMs use a *"right-left" research model*—they contemplate the technology breakthroughs they seek to have emerge from the right end of the pipeline, then go back to the left end of the pipeline to look for proposals for the breakthrough research that will get them there. In other words, like DARPA, ARPA-E uses a *challenge-based* research model—it seeks research advances that will meet significant technology challenges. Like DARPA, ARPA-E tends to look for *revolutionary breakthroughs* that could be transformative of a sector—thus far, it has had a penchant for high-risk but potentially high-reward projects. ARPA-E's design is metrics driven and "challenge based" for funding opportunities. Metrics are defined in terms of what will be required for cost-effective market adoption in the energy industry. PMs propose to the research community what will be required in terms of technology cost and performance for adoption, and then ask this community to pursue this goal with transformative new ideas.

Like DARPA, ARPA-E's PMs are a highly respected, technically talented group, carefully selected by a director who has asserted that there is no substitute for *world-class talent*. Typically, the PMs have *experience in both academic research and in industry*, usually in start-ups, so they generally know from personal experience the journey from research to commercialization. Recognizing that the ability to hire strong talent quickly was a key DARPA enabler, the House Science and Technology Committee, which initiated the ARPA-E authorization, gave ARPA-E, like DARPA, the ability to supersede the glacial civil service hiring process and rigid pay categories. In fact, ARPA-E's broad *waiver of civil service hiring authority* may be without precedent in the federal government.

Like DARPA's, ARPA-E's research program is organized around the three-to-five-year lifetime of its PMs. By statute ARPA-E's PMs are limited to three years of service (although this can be extended), so like DARPA's PMs, ARPA-E's PMs must work to get their projects into prototype and implementation stages in the three or so years they are at ARPA-E. Thus, *the project duration yardstick is the life of the PM*. This means that ARPA-E must forgo much long-term research; it must build its project portfolio by seeking breakthroughs that can move to prototype in—for science—a relatively short period. It will aim, therefore, like DARPA, at *innovation acceleration*—projects that can move from idea to prototype in the program life of its program managers. The House Science and Technology Committee, mirroring DARPA, also emphasized the availability to ARPA-E of highly flexible contracting authority, so-called *"other transactions authority,"* which enables ARPA-E to emulate DARPA's ability to quickly transact research contracts outside of the slow-moving federal procurement system. Although this authority has not yet been fully utilized, it remains promising as ARPA-E moves into new areas, such as prize authority, discussed below.

Like DARPA, ARPA-E is also instituting the *"hybrid" model*, providing funding support for both academic researchers and small companies and the "skunk works" operations of larger corporate R&D shops. DARPA has often tied these diverse entities into the same challenge portfolio and worked to convene them together periodically for ongoing exchanges. This has tended to improve the handoff from research to development by combining entities from each space, easing technology transition. Like DARPA, ARPA-E has worked from an *island/bridge model* for connecting to its federal agency bureaucracy. For innovation entities in the business of setting up new technologies, the best model historically has been to put them on a protected "island" free to experiment, and away from contending bureaucracies—away from "the suits." ARPA-E, as it was set up within DOE, has required both isolation and protection from rival R&D agencies and the notorious bureaucratic culture at DOE that may battle it for funding and the independence it requires. From the outset, therefore, it needed a bridge back to top DOE leadership to assure it a place in DOE's R&D sun. It received this from Energy Secretary Steven Chu, who was one of the original proponents of ARPA-E while serving on the committee that produced the National Academies' *Gathering Storm* report, and later testified in support of ARPA-E before the House Science and Technology Committee in 2006.

New Elements at ARPA-E

Thus far, we have described ARPA-E as though it were a clone of DARPA. However, ARPA-E faces a very different technology landscape than DARPA. DARPA has been able to launch its technologies into two territories that simplified its tasks. First, it has often been able to place its technologies into the procurement programs of the military services. In this approach, the military is able to serve as the test bed and initial "first" market for new technologies emerging from DARPA. Second, DARPA launches its technologies into civilian sectors; its keystone role in the IT sector is the most famous example. The IT revolution DARPA nurtured was a technology frontier, an example of "open space" technology launch.

In contrast, the energy sector that ARPA-E must launch into is occupied territory, not open space. Energy is already a complex established legacy sector (CELS). New energy technologies have to perform the technology equivalent of parachuting into the Normandy battlefield. Because it faces a very different launch landscape than DARPA, ARPA-E is learning to vary its organizational model. In addition, ARPA-E has assembled what is by all accounts a talented team; team members have put in place their own ideas on how to operate their new agency, as well. Thus, ARPA-E is not simply replicating DARPA; it is finding and adding its own elements appropriate to the complex energy sector where it concentrates and appropriate to its own staff.

Sharpening the Research Visioning, Selection, and Support Process

ARPA-E's director and PMs emphasize that they are working in what they call "the white space" of technology opportunities. Starting with their first research award offering, they assert they have consciously attempted to fund higher-risk projects that could be breakthroughs and transformational in energy areas where little work previously has been undertaken. This means that their research awards are purposely made seeking transformations, not incremental advance. Comparable to DARPA's model, this approach has placed technology visioning at the very front of the ARPA-E's research nurturing process.

ARPA-E has implemented an interesting two-stage selection process, in which applicants have a chance to offer feedback to the initial round of reviews. Because ARPA-E's director, like many researchers, had been personally frustrated by peer review processes in which the reviewers showed limited understanding of the science and technology advances behind his applications, he implemented a unique review process where his PMs allowed applicants to respond to their application reviews, followed by a further evaluation step. This "second shot" and "feedback loop" in the review process has improved evaluations because the PMs know their conclusions will be critiqued, has helped educate PMs in new technology developments, and has resulted in a number of reconsiderations of applications, improving the overall ARPA-E research portfolio.

The empowered program manager culture. There are eight PMs at ARPA-E as of this writing; there are no office directors, who in DARPA serve as an intermediate stage between PMs and the director. Because ARPA-E is roughly the size of a large DARPA office, it simply doesn't need them yet. Each PM picks his or her own inquiry areas; there is no overall technology plan. However, PMs do form macro challenges within the sectors they initiate with the director—for example, seeking a zero emission, long-range electric car. PMs therefore retain the flexibility of not being tied to a fixed ARPA-E-wide technology strategy. PMs also retain a great deal of control over their research portfolios, so are "empowered" like DARPA PMs, although they still have to persuade the director to support their program decisions. PMs have to have what they refer to as "religion"—they must have a vision of where they want to take their portfolios, performing as vision champions, in order to sell their projects both inside and outside ARPA-E. Part of "religion," then, is that they must work on being vision implementers. ARPA-E PMs expressed the view that this is the single most critical PM quality, aside from technical excellence. ARPA-E has purposely not created a formal personnel evaluation process for its PMs—like those in DARPA, PMs say they are expected to "manage to results," and they are judged by the director and their colleagues based on the outcomes, impact, and results of the portfolios they select.

Additional mechanisms for talent support. Under the ARPA-E fellows program, five outstanding recent PhDs help staff each PM and fill out the capability of each team. This institutional mechanism apparently may be responsible for a creative process of intergenerational contact and mentoring within ARPA-E, further ensuring that it becomes a continuous education environment, a key feature for creative R&D organizations. The new fellows also have been meeting as a group to attempt to come up with their own on new ideas. DARPA has no comparable group to help augment internal intellectual ferment. ARPA-E is also considering creating its own team of senior advisors—"technology wisemen," in short—who spend time at ARPA-E through frequent visits and so contribute to the PM teams.

All ARPA-E projects are selected, as discussed above, to be game changers—to initiate energy breakthroughs. However, within that broad requirement, as portfolios are assembled around a particular challenge area, PMs say they have found that they need a "risk mix." They generally include some "out there" projects that may or may not materialize, that are very high risk, but that are well worth pursuing because, even though they are far from implementation, the technology is potentially so important. But for most other portfolio technologies, the PMs want to see that they could be implementable in a reasonable period and that they could reach a cost range that would facilitate entry and commercialization. Some PMs find they need to emphasize more early-stage science in their portfolios than other PMs because their portfolio sectors require more frontier advances—so there is a mix, too, within portfolios, which balance between frontier and applied, science and technology emphasis. The grant approval rate varies between technology sectors, but (following the initial 2009 open-ended offering), PMs indicate the rate ranges from 5 to 10 percent.

Like those in DARPA, ARPA-E PMs have adopted a hands-on relationship with award recipients, talking and meeting at frequent intervals to support their progress and help them surmount barriers, and, when ready, to promote contacts with venture and commercial funding. In most research agencies, the job of the PM focuses on the award selection process; in ARPA-E, this is only the beginning. PMs view their jobs as technology enablers, helping their tech clients with implementation barriers.

Building a Community of Support

While Congress in designing new science and technologies agencies may get either the substantive design or the political design right, it does not often get both right. In other words, the creation of an agency that is sound and effective from a public policy and substantive perspective, as well as politically strong enough to survive, is a challenging policy design problem. ARPA-E was founded on a well-tested substantive model, the DARPA model, so as long as its leadership struggled to fulfill that complex design, there was some assurance of success from a policy perspective. Although the history of DARPA clones is not generally a positive one, ARPA-E's leadership has made the ARPA-E clone a widely acknowledged success. However, ARPA-E's political design has been a more complex problem; from the outset it has faced a political survival challenge. In part this is because it is a small, new agency fish in a cabinet agency filled with large agency sharks constantly on the prowl against funding competitors and turf incursions. These sharks include such long-standing major entities as the Office of Science, the applied agencies, including the Office of Energy Efficiency and Renewable Energy (EERE), and the seventeen national energy laboratories. To increase its chances of survival, ARPA-E needed not simply to avoid conflict with its large neighbors but to affirmatively turn them into bureaucratic allies and supporters. Moreover, it also needed to build support outside DOE, from the energy research community it serves and from industry. All this had to be translated into congressional support.

ARPA-E therefore has worked from the outset on building internal connections within DOE. The Department's R&D is organized into stovepipes. The Office of Science, a traditional fundamental science–only agency organized on Vannevar Bush–style basic research lines, funds its own nest of national labs as well as university research and reports to its own undersecretary. DOE's applied agencies, including EERE and fossil, electrical, and nuclear offices, fund development work primarily through companies and report to their own undersecretary. DOE's organization thus severs research from development stages, and historically very few technologies cross over the walls of the two sides of the DOE organizational equation, basic and applied. In theory, ARPA-E could serve both sides by drawing on basic ideas coming out of the Office of Science that could be accelerated, pushing them to prototypes, and then building ties with EERE and the applied agencies to undertake handoffs for late-stage development and demonstration. ARPA-E could thus serve both sides by working to be a technology connector within DOE.

There are potential downsides to playing the connector role—in some cases at DARPA it has been seen as inconsistent with performing the role of transformation instigator. However, ARPA-E has attempted this task, and met with success in forging a working alliance with EERE, a much larger agency with a budget of $2 billion a year. ARPA-E has EERE experts on its review teams and draws on their expertise; it has received strong support as well from EERE's leaders, who are working with ARPA-E on the handoff process described above (and discussed further below).

Integration with the Office of Science (SC) is still a work in progress. SC very much views itself as a basic research agency, and rejects work on applied research, assuming it is the job of other parts of DOE to manage those efforts. It funds a wide variety of basic physical science fields, aside from basic energy-related research. Managers at SC generally view themselves not as technology initiators but as supporters for the actual researchers located in SC's national labs and in academia. This represents a genuine culture clash with the energy breakthrough orientation of ARPA-E PMs. However, some attempts have been made to connect with the 46 new Energy Frontier Research Centers (EFRCs) formed by SC to focus on energy research in promising areas; two of ARPA-E's PMs report that they have selected one project each from EFRCs located at research universities.

Collaboration with the national energy labs has also proven a challenge. Because the labs are large employers, they have tended to become independent political power bases. However, ARPA-E has included labs in its research consortia, hoping the labs will view it as not simply a funding competitor but a funding supporter.

Summit. ARPA-E has worked at building relations with VC firms and large and small companies, and with awardees and nonawardees, through its annual Energy Innovation Summit. Begun in the spring of 2010, this widely attended summit has become a major technology showcase event in Washington, attracting large attendance and featuring prominent business, executive branch, and bipartisan congressional leaders in speaking roles. At these summits ARPA-E has featured its awardees as well as other strong applicants who did not receive awards but deserve attention. VC firms and companies swarmed around their technologies, building good will among attendees, whether they won awards or not. Importantly, by highlighting new energy technologies of interest to many sectors and firms, the summits have helped in building an advanced energy technology community around ARPA-E.

Support community. ARPA-E faced a major funding challenge in FY2011, when a change in political control of the House of Representatives and growing concerns over spiraling federal deficits led to cutbacks in federal agency funding. As noted, because ARPA-E received no funding in FY2010 (it received two years of initial funding in FY2009 through stimulus legislation), it needed affirmative legislation to survive. As a result of the good will that had been built in its first two years of operation, a community of support began to collect around ARPA-E to independently advocate for the agency's future with congressional committees, including VC firms, large and small firms that worked with ARPA-E, and universities, all enamored of its research model.

In summary, not only has ARPA-E proven a strong substantive success to date from a public policy perspective, but a political support base appears to be emerging that could help sustain it over time. ARPA-E could be in a position to achieve that rare combination, an integrated political design model, marrying political support with sound substance.

Technology Implementation

ARPA-E's director and PMs are acutely aware of their difficult task in launching technology into the complex established legacy sector of energy. ARPA-E has therefore taken a number of steps to assist in taking its technology to implementation, commercialization, and deployment. ARPA-E PMs consider the implementation process for technologies they are considering; before they fund a project they evaluate the technology stand-up process and how that might evolve. Their focus is not simply on new technology; they seek to fund projects where they can see a plausible pathway to implementation. This is aided by the fact that ARPA-E PMs generally have both academic and commercial sector experience.

"In-reach" within DOE. ARPA-E is working on building ties, as suggested above, with applied programs in DOE so these agencies can be ready to pick up ARPA-E projects and move them into the applied, later-stage implementation programs they run. ARPA-E's PMs have found that key to this DOE "in-reach" is building relationships between PMs and applied line scientists and technologists in the applied entities, particularly EERE, the Fossil Energy Office, and the Electricity Office. This is a bottom-up connection process. Meanwhile, in a top-down process, the ARPA-E director has worked in parallel at building ties between his office and the leadership of the applied agencies at DOE. But the PMs believe bottom-up connections are the key to "in-reach" success—without support deep in the applied bureaucracies, transfers simply won't happen, whatever the leadership levels agree to.

While DOE in-reach is part of the answer, another logical step for ARPA-E is to connect with DoD agencies potentially interested in ARPA-E technologies for DoD needs, given the latter's depth in test bed capabilities and first-market opportunities, which remain gaps in DOE's innovation system.

ARPA-E is in fact working on building ties to DoD for test beds and initial markets. DOE has executed a memorandum of understanding with DoD, but implementation is still largely at the discussion stage, and results are still "in progress." DoD and ARPA-E have recently partnered on two projects, however. DoD's own efforts on energy technology are just now coming into effect, but it is pursuing energy technology advances to meet its tactical and strategic needs, as well as to cut energy costs at its more than 500 installations and 300,000 buildings. As an indication of its serious intent, ARPA-E has on staff a technologist with significant defense contractor experience (he is on the Commercialization Team; see discussion below) working full time on collaboration with DoD. The potential role of DoD to test and validate and to offer an initial market for new energy technologies is well understood at ARPA-E, offsetting the fact that its home organization, DOE, generally does not engage in the innovation process beyond late-stage development and prototyping support.

Commercialization team. ARPA-E has assembled on staff a separate team working full time to promote implementation and commercial advances for ARPA-E technologies. These team members work with particular PMs on the most promising technologies emerging from their portfolios. The tactics this team develops in implementing technologies can include follow-on approaches for ARPA-E-funded technologies through in-reach with DOE applied programs, connections to DoD test beds and procurement, and connections to VC firms and interested company collaborators, or combinations of these. The team's work includes identifying first markets and market niches for ARPA-E technologies.

"Halo effect." ARPA-E is consciously taking advantage of the "halo effect" whereby VC firms and commercial firms pick up and move toward commercialization of the technologies that are selected by ARPA-E as promising. In other words, the private sector views the ARPA-E selection process as rigorous and sound enough that it is prepared to fund projects emerging from that process. ARPA-E recently announced, for example, that six of its early projects, which it funded at $23 million, subsequently received over $100 million in private sector financing. This effect has been seen at DARPA and at the Department of Commerce's Advanced Technology Program (renamed the Technology Investment Program). The VC or financing firm will perform its due diligence regardless, but ARPA-E's selection helps in identifying and, in effect, validating, a candidate pool.

Connecting to the industry "stage gate" process. The stage gate process is used by most major companies in some form in the management of their R&D and technology development. In this approach, candidate technology projects are reevaluated at each stage of development, weeded out, and only what appear to be the most promising from a commercial success perspective move to the next stage. This is not a process ARPA-E employs; like DARPA (as discussed above), it places technology visioning up front in its process and adopts a high risk/high rewards approach to meet the technology vision. Although ARPA-E's is a more fluid and less rigid, vision-based approach, it has recently started to work with its researchers to get their technologies into a format and condition to survive in the industry stage gate process. For academic researchers in particular, this is not a familiar process.

Consortia encouragement. Aside from stage gate connections to industry, in a different kind of outreach effort, ARPA-E is building an additional industry connection step between the firms and academics that it works with and the industries they must land in—consortia promotion. ARPA-E tries to pave the way for acceptance of its new technologies at firms by working to encourage companies that work in similar areas to talk to each other on common problems, including on technology solutions that APRA-E's current or prospective projects could present.

Prize authority. Following in DARPA's footsteps, ARPA-E has authority to offer cash prizes for meeting technology challenges and is considering how to use it. This could be an additional creative tool for technology acceleration and implementation but may require unique adaptations to fit the legacy energy sector.

To briefly summarize, then, ARPA-E has not only worked to replicate elements at DARPA, but it has attempted to build new elements in its innovation rule set as it confronts unique features of the energy sector where its technologies must land and of the DOE bureaucracy it must work with. These new elements can be grouped into three broad areas, as detailed above: sharpening the research visioning, selection, and support process; building a politically survivable support community; and implementing and deploying its technology advances. Organizational tools in these categories being developed at ARPA-E present lessons that could be relevant and useful to other innovation agencies.

Relevance of the Additional DARPA Features for Applicability to ARPA-E

A number of DARPA capabilities not generally noted in the literature to date have potential relevance to ARPA-E in strengthening its operations and enhancing its future capabilities. These are organizational options that are not necessarily relevant to ARPA-E's current start-up phase but that it could consider as it continues to evolve.

Multigenerational thrust. As noted, DARPA has been able not only to undertake individual technology projects, but to work over an extended period to create enduring "motifs"—generations of new applications within a technology thrust that have changed technology landscapes over an extended period. The approach ARPA-E is now implementing of projects with a three-to-five-year duration based on the expected "life" of its PMs will likely require supplementing with a multigenerational model, because many energy technologies will require ongoing advances before they reach maturity and optimal efficiency.

Strategic relations between technologies. DARPA has launched related technologies that complement each other and help build support for the commercialization or implementation of one another. Launching bundles of related technologies could similarly alter the energy landscape. As ARPA-E builds out its technology portfolios, it could work to envision linked and crossover technology advances, supporting complementary efforts.

Confluence with an advocate community. DARPA created a broad and sizable community over time from its PM "graduates" and numerous award recipients in both universities and industry. ARPA-E started out on a much smaller scale than DARPA, but needs to consciously work to build its community to make community members not only supporters for its continuation but an allied group of change agents. Its summit is a useful initial organizing mechanism in this regard, but ARPA-E will need additional mechanisms to achieve this.

Connection to larger innovation elements. DARPA has spawned new technologies that rose and converged with VC and entrepreneurial support and led to new economic sectors, particularly in IT fields. Thus, DARPA has been able to play an intermediary role with industry and to make its advances reinforce sectors that support them, creating a mutual synergy. ARPA-E will need to consider this approach with the firms and sectors it collaborates with, including those providing capital support, as its technologies advance. It is already moving in this direction, as the discussion of the new elements in its model suggests, becoming an actor connected with larger innovation efforts. It can play an instrumental role in these larger innovation systems, seldom as a sole actor, but instead as a team creator and player. The DARPA approach—in which its technologies spawned numerous IT firms that help effectuate its overall vision and are linked to other supporting elements in DoD—offers lessons for ARPA-E. As its technologies progress, it will need to consider the appropriate models for this kind of connection in the complex energy sector.

Willingness to take on incumbents. DARPA historically invaded territory occupied by companies or bureaucracies when it needed to foster technology advances. Perhaps the most famous example is how, in an effort to develop new command and control systems, it drove desktop personal computing and the Internet to displace the IBM mainframe model, in a classic example of disruptive technology launch. Because energy is a CELS, conflict with legacy firms with established technologies will be frequent and inevitable for ARPA-E. Accordingly, it will need to further build its support communities if it is to be successful in launching its technologies (see discussion on community building above). In addition, it will need to continue to enhance its technology implementation capabilities.

Role as first adopter/initial-market creator. DARPA has frequently undertaken a technology insertion role; in coordination with other parts of DoD it has been able to create initial markets for its new technologies, allowing the Department to serve as first technology adopter. DOE offers no comparable first market for ARPA-E technologies. Given DoD's interest in energy technology advances, it could serve as an initial market. ARPA-E will need to develop further strategies to find first adopters and initial markets, because the lack of track records of costs and efficiencies constitutes a serious barrier to commercializing and scaling new energy technologies.

Ties to technology leadership. DARPA has been particularly effective when it is tied to senior leaders who can effectuate its technologies through DoD or elsewhere. ARPA-E has been effective to date, as discussed above, in securing a network of leaders in the department, in the White House, and on Capitol Hill to support it, but it will need to continually work to bolster its ties to energy decision makers.

Connected innovation. DARPA has embedded itself in a connected innovation system, taking advantage of DoD's ability, as noted above, to operate at all stages of innovation, from research, to development, to prototype, to demonstration, to test bed, to initial-market creation. ARPA-E recognizes that because it will be launching its technologies into a CELS, it may be able to use DoD test bed and procurement roles, as discussed above, to further its advances. It can also fund creative companies that have the capability to commercialize its technologies into products, and that can otherwise guide its technologies into commercialization, building portfolios of technologies for depth in technology thrust into emerging markets. It can also leverage its technologies against regulatory mechanisms, such as fuel economy and appliance standards, or state renewable portfolio standards. These and additional tools will need to be sharpened.

The Remaining Technology Implementation Challenge for DARPA and ARPA-E

Both DARPA and ARPA-E face a profound challenge in technology implementation. For DARPA, the Cold War era of major defense acquisition budgets is long gone, and defense "recapitalization"—replacement of the existing generation of aircraft, ships, and land vehicles with new defense platforms—is evolving at a glacial pace. Finding homes for its evolving technologies, therefore, has increasingly become a difficult task for DARPA. Because technology transition was once a relatively straightforward task for DARPA, it has not yet fully faced up to the implications of how complex it has now become. ARPA-E faces a technology transfer problem of the first magnitude: the U.S. has a very limited history of moving technology advances into and transforming CELS, including in energy.

Although ARPA-E faces a long list of challenges, the problem of technology implementation is perhaps the most profound. This is because of the difficulty new energy technologies face, not only with the problem of the Valley of Death in moving from research to late-stage development, but the problem endemic to CELS of market launch—implementing technology at scale. ARPA-E has worked imaginatively to structure new elements into its model to address this problem. The models of the Strategic Environmental R&D Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) from DoD, where the R&D entity directly hands off to the test bed, provides an interesting new model in the energy area for ARPA-E to consider as it focuses on technology implementation. Collaboration with these programs, which ARPA-E is actively working on, may provide a crucial new tool set. ARPA-E is not alone in facing this implementation problem; the applied agencies at DOE, led by EERE, face a similar problem, and the SERDP/ESTCP combined model of R&D-test bed-deployment offers an interesting new approach. DARPA, too, despite remarkable past successes, is not immune, as suggested above, from the implementation problem, which appears to be growing. It, too, might learn lessons and make further uses of the SERDP/ESTCP approach.

In summary, implementation presents a major challenge for both agencies. DARPA needs to consider its existing portfolio of implementation support, and consider better connection to available tools (such as Mantech and the Defense Production Act, for example) for its manufacturing initiatives. ARPA-E has worked imaginatively on its implementation capabilities, but the complexity of its task requires it to consider additional mechanisms.

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While this report draws from the workshop held in Washington, DC on May 25, 2011, it does not represent the views, individual or collective, of the workshop participants or their organizations. We are grateful for their time and their insights.

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