The Clean Energy Dividend: Military Investment in Energy Technology and What It Means for Civilian Energy Innovation

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DOD played a major role in developing at least three of the most important energy innovations of the last 75 years: the nuclear reactor, the gas turbine/jet engine, and the solar photovoltaic cell.

This year, the Department of Defense (DOD) will invest $1.6 billion in research, development, testing, and evaluation (RDT&E) that is directly related to energy. The magnitude of DOD's investment in energy RDT&E reflects the importance of energy to the military mission. Everything the armed forces do requires energy, which is why DOD is the single largest energy consumer in the United States. For the same reason, energy is a source of vulnerability.

DOD's $1.6 billion-a-year investment in energy RDT&E also reflects the U.S. military's characteristic pursuit of advanced technology as a force multiplier. DOD played a major role in the development of at least three of the most important energy innovations of the last 75 years: the nuclear reactor, the gas turbine/jet engine, and the solar photovoltaic (PV) cell. DOD has been the driver for many major non-energy innovations as well, including radar, satellites, the Global Positioning System (GPS), lasers, computers and semiconductors, robotics, artificial intelligence, and the Internet.

Despite its scale, the military's investment in energy RDT&E is poorly understood outside of the defense community. In particular, few analysts have examined its relevance for advances in civilian clean energy innovation. The notable exception was a 2012 report which cautioned that DOD would not be an all-purpose engine of energy innovation, and concluded that "the extent to which the [energy technologies of most interest to DOD] will catalyze innovation relevant to large-scale reduction of global greenhouse gas emissions remains to be seen."[1]

This report seeks to enhance the understanding of DOD's investment in energy innovation, generally, and it revisits the specific question of how relevant this investment is for advances in civilian clean energy innovation. To be clear, this report is *not* a critique of DOD's energy RDT&E effort or its underlying energy policies, and none of our recommendations are directed at DOD or its congressional overseers. Rather, we take

DOD's energy investments as a given and try to explain and analyze them for a (largely) non-defense audience interested in clean energy innovation.

The report is organized as follows: First, we elaborate on the context for DOD's investment in energy RDT&E—namely, the importance of energy to the warfighter and innovation as a force multiplier. Second, we describe the challenges driving DOD's energy RDT&E spending and the technologies being advanced. Third, we assess how this mission-driven spending might contribute to civilian clean energy innovation. We do this by examining five pathways, or mechanisms, through which the military has influenced civilian uptake of technology in the past, and identifying specific clean energy technologies that will benefit from one or more of these uptake paths. Finally, we recommend ways the Department of Energy (DOE) and other civilian entities can better leverage—without compromising the military value of—DOD's RDT&E investments.

Key Findings

- The military relies on energy for everything it does, and consumes much of that energy in combat settings, where it is extremely costly—in human lives as well as dollars—to obtain. Realistically, future military platforms and capabilities will require more, not less, energy.
- DOD energy needs are changing as well as growing. Most significant, the dramatic increase in electrical systems onboard military platforms is driving electrification of the battlefield. That and the need to reduce the logistics footprint are creating requirements for distributed and portable power generation, smart energy networks, improved energy storage, and wireless power transmission.
- DOD's $1.6 billion-a-year energy RDT&E effort addresses challenges in the following areas:
    - *Dismounted soldiers and small troop units* carry ever more electronic gear that they must be able to power, without battery resupply, for longer-duration missions.
    - *Contingency bases* face a growing demand for electric power, and must automate the control and distribution of power to and from multiple sources and loads.
    - *Fixed installations (bases)*, which rely on a vulnerable commercial grid, must be able to maintain continuous power to critical loads during extended grid outages.
    - *Manned platforms* (aircraft, ships, ground vehicles) need to control and distribute power efficiently in support of increasing amounts of onboard electrical equipment.
    - *Autonomous systems* (e.g., drones) need the power to remain operative for long periods, travel for extended distances, and in some cases carry sizable payloads.

- *Directed energy weapons* need energy storage systems with extremely high power density, rapid recharge capability, and advanced thermal management.

- Although mission-driven, DOD energy RDT&E will contribute to civilian clean energy innovation because of the military's full-spectrum approach to innovation, which includes:
  - Investment in foundational science, technology, and engineering
  - Pursuit of technologies for military use before they are of commercial interest
  - Investment in R&D to leverage and advance commercial technology
  - Provision of infrastructure and platforms as test beds for demonstration and validation of commercial technology
  - Early adoption and large-scale procurement of new technologies that have not yet penetrated the commercial market
- Clean energy technologies likely to benefit most from DOD RDT&E and procurement are:
  - *Solar PV*: The military needs solar PV materials that are more lightweight, flexible, and efficient than the currently dominant silicon, for use in the field, on drones, and possibly on arrays in space. DOD is funding R&D on alternatives to silicon and seeking to slash their fabrication costs. As an early, cost-insensitive adopter, DOD can give new, higher-cost technologies the chance to gain a commercial foothold.
  - *Microgrids*: Stationary microgrids are a must-have for fixed bases. DOD's rigorous demonstration process is helping manufacturers overcome the impediments to commercialization, and with 500 active-duty bases and hundreds of smaller National Guard bases, DOD will be a major customer for microgrids. Mobile (tactical) microgrids are essential for contingency bases, and DOD's early-adopter role can help lower their cost and facilitate their deployment in the developing world.
  - *Energy Storage*: DOD needs better batteries for mobile missions and large-scale storage on its bases. It is funding R&D on commercial batteries to meet its stretch goals for battery performance, and as an early adopter can help finance their move down the cost and learning curves. It is supporting demonstrations of large-scale storage systems to facilitate commercialization; as an early adopter it can absorb non-recurring engineering costs, and as a customer (500 bases) significantly expand the market.
  - *Wide Bandgap Semiconductors*: Wide bandgap (WBG) devices have the potential to revolutionize power electronics, but only if their costs come down. DOD has supported advances in WBG technology for 50 years, and its next-generation hybrid vehicles require a level of performance in

power electronics that only WBG devices can provide. As an early adopter and major purchaser, DOD can help producers ramp up their production and reduce their costs based on economies of both scale and learning by doing.

- Other clean energy technologies likely to benefit from DOD RDT&E and procurement include:
  - Wireless power transmission: DOD wants to recharge drones remotely so they can remain aloft longer; and demonstrations using lasers are underway. Wireless recharging will facilitate the electrification of ground vehicles, among other clean energy uses.
  - Fuel cells: Fuel cells' endurance is valuable to DOD. The Navy and General Motors (GM) developed a fuel-cell-powered undersea drone that can operate without recharging for more than 60 days; and the Navy's fuel-cell-powered aerial drone flew for 48 hours.
  - Advanced composites: DOD is continuing its decades-long research on advanced composites, which are a major source of fuel savings for both modern commercial aircraft and the energy efficient surface transportation we will rely on in the future.
  - Fuel-efficient propulsion: DOD is funding extensive RDT&E to improve platform fuel efficiency, including improved aircraft engines and drag-reducing materials for ship hulls, some of which will have value in commercial markets.
  - Building energy technologies: DOD has funded more than 130 rigorous demonstrations of innovative, building energy technologies on its bases (e.g., electrochromic glass, waste-to-energy systems, and remote auditing tools) to facilitate their commercialization and deployment.
  - Very small modular nuclear reactors: Fixed installations in remote areas are an ideal early market for stationary very small modular reactors (vSMRs)—although DOD is unlikely to pay any of the non-recurring engineering costs.
- DOD's approach to innovation is well suited to energy innovation, including vendors' need to both demonstrate their complex technologies at scale, under realistic conditions (DOD bases and platforms, combined with the military's test-and-evaluation culture are a unique resource), and compete on price with low-cost incumbents (DOD values performance over price, and the military market is large enough to yield economies of scale and learning by doing).

Recommendations

1. DOE should factor DOD's needs and strengths as an innovator into the strategies of, and roadmaps for, both its fundamental and its applied research, development, and demonstration (RD&D) so as to capture DOE-DOD synergies.
2. DOE should partner with DOD on its stationary-storage programs.

3. DOE's battery technology programs should engage with DOD end users to identify their storage needs.
4. DOE's solar technology program should partner with DOD to speed the path to next-generation PV materials that can compete with silicon.
5. DOE's manufacturing initiatives should look to DOD to be an early adopter.
6. DOE should partner with DOD to advance the deployment of stationary (non-tactical) microgrids.
7. DOE's advanced small modular reactors (SMRs) program should look to DOD to be an early customer.
8. DOE, through its Building Technologies Office and Federal Energy Management Program, should lead a government-wide effort to demonstrate and validate energy technologies for the built environment in federal facilities.
9. Congress should direct the National Research Council to conduct a study to identify impediments to and opportunities for greater DOE-DOD collaboration on energy RD&D.
10. The U.S. Agency for International Development should explore opportunities to exploit DOD's work on tactical microgrids.

THE CONTEXT FOR DOD INVESTMENT IN ENERGY RDT&E

The magnitude of DOD's investment in energy RDT&E reflects the importance of energy to the military mission as both an essential enabler and a source of vulnerability. It also reflects the military's characteristic pursuit of technological innovation to enhance warfighter effectiveness.

Energy as Essential Enabler

DOD consumes energy for two broad purposes. The first is to support operations. *Operational energy* refers to the petroleum-based fuel used to power military platforms (aircraft, large drones, ships, tanks, etc.) and to run the diesel generators that produce electricity at contingency bases in places such as Iraq and Afghanistan. It also includes the batteries that power hand-held electronic devices and other portable equipment carried by troops.

The second use of energy is to support DOD's roughly 500 enduring military bases, or "fixed installations," in the United States and overseas. *Installation energy* (also known as *facility energy*) consists largely of the electricity and natural gas used to power the 300,000 buildings located on these installations, with their two billion square feet of building space. It also includes energy used by the 160,000 non-tactical vehicles housed on military bases.

The distinction between installation and operational energy has blurred in recent years as fixed installations—whose traditional role was to train and mobilize combat forces and maintain and deploy weapon systems—have taken on more direct support for combat operations. U.S. domestic bases analyze battlefield data in real time and manage flight control of foreign drone operations, among other things. Domestic bases also play a central role in staging homeland defense missions and providing support for civil authorities.

Because energy is essential to its combat mission, the military uses a lot of it. In FY17, DOD consumed 708,000 billion BTUs of operational and installation energy, which is more than 75 percent of the federal government's total energy consumption (and 16 times that of the next closest federal agency, the U.S. Postal Service) and about 1 percent of total U.S. energy consumption.[2] Focusing only on petroleum-based energy, DOD consumed 234,000 barrels of oil a day in FY17, down from 339,000 barrels a day in FY11.[3] This is 1.2 percent of the United States' total oil consumption and 0.25 percent of the world's total.[4] In FY17, DOD spent a total of $11.7 billion on energy, 70 percent ($8.2 billion) of which was on operational energy.[5]

Energy as Source of Vulnerability

As a combat enabler, energy is also a source of vulnerability for the military. This is nothing new. In the summer of 1944, lack of gasoline and other supplies brought General George Patton's hard-driving Third Army to a halt—a logistics failure some historians say delayed the end of World War II (fortunately, gasoline shortages did far more to cripple German forces).

Sixty years later, history repeated itself when U.S. ground troops participating in Operation Iraqi Freedom (OIF) were forced to halt their tank-led march on Baghdad in order to allow fuel trucks to catch up. (U.S. troops encountered less Iraqi resistance than anticipated, which meant their diesel-guzzling armored vehicles more quickly exhausted the fuel on hand.) General James Mattis, who commanded the 1st Marine Division in OIF, later famously challenged the Pentagon to "unleash us from the tether of fuel."

The tether of fuel proved extremely deadly during the conflicts in the Middle East, when resupply convoys carrying largely fuel and water to U.S. bases there became the most vulnerable target for insurgent attacks. One oft-cited report calculated that, in 2007 alone, 170 U.S. service members were killed or wounded in fuel-related missions in Iraq and Afghanistan.[6]

The threat to supply lines will only increase as DOD shifts its strategic focus from countering terrorism in the Middle East to the prospect of a conflict with near-peer rivals such as Russia and China.[7] A major concern is that such a rival could block or constrain the movement of opposing forces into a given theater of operations—what is known as anti-access/area denial (A2/AD)—including through disruption of fuel supplies (energy denial).

DOD's fixed installations face their own energy threat in the form of a commercial electric grid that is vulnerable to disruption from natural or manmade threats. And because DOD's fixed installations increasingly provide direct support for combat operations and logistics, a long-term grid outage on a military base at home could pose a threat to operations in the field.

Military's Longstanding Reliance on Technological Innovation

Technological innovation is key to how DOD tackles almost every military challenge it faces, and energy is no exception. Innovation figures prominently in the energy strategies issued by the Office of the Secretary of Defense (OSD) and the individual military services.[8] Roughly half of the services' spending on operational energy initiatives, as defined and tracked by OSD, is going to RDT&E.[9] Two energy RDT&E programs begun by the last Administration—the Operational Energy Capability Improvement Fund and the Installation Energy Test Bed—have been actively maintained by the current administration.

DOD has long been an engine of innovation in this country.[10] Military research, development, and procurement have been a major source of technology development across a broad spectrum of industries that account for an important share of U.S. industrial production.[11] Although the commercial sector is now the primary driver of technological advances in this country, DOD's approach to innovation remains a model of effectiveness.

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One reason for DOD's effectiveness is the sheer scale of its innovation effort. In FY19, the department will spend more than $92 billion on RDT&E and $144 billion on procurement.[12] The services employ some 100,000 scientists and engineers directly and support many more in industry and universities.[13]

Beyond scale, the single most important explanation for DOD's innovation record is the tight link between technology spending, including procurement, and the military's mission requirements. Unlike any other federal agency, DOD develops technology for its own use: Supply and demand are under one institutional roof, to use John Alic's apt phrase.[14]

This customer orientation has several implications. One is that DOD supports advances across the entire technology lifecycle, from basic science to commercialization. This contrasts with DOE, whose energy RD&D budget is devoted heavily to fundamental R&D. A related implication is the military undertakes extensive testing and evaluation of new technologies in settings that mimic the battlefield. The path from R&D to commercialization is not linear. DOD is a demanding, data-driven customer, and its rigorous test and evaluation (also known as demonstration and validation) process provides technology developers with valuable feedback.

Finally, DOD has been a successful innovator because it not only develops new technology, it procures it. DOD's role as an early adopter of, and a market-creating customer for, new innovations was critical to the development of integrated circuits, computers, and satellite imagery and communications, among other technologies.[15] Procurement is a policy lever most federal energy R&D programs lack.

DOD's use of this lever furthers innovation in two particularly important ways. First, because of its mission and deep pockets, DOD often chooses to pay a premium for higher-performing technologies. This is key because the earliest versions of major innovations are typically characterized by high capital and operating costs, and limited reliability.[16] As a technology matures and improves with use by, and feedback from, the military, it becomes cost competitive.[17] Second, the scale of DOD's buying power can attract new entrants to an embryonic industry, thereby stimulating competition. High-volume government procurement also can drive additional cost reductions and quality improvements, ultimately stimulating broader adoption of the innovation by commercial users.[18]

WHAT IS DRIVING DOD INVESTMENTS IN ENERGY RDT&E? FIVE "WARFIGHTER OPPORTUNITY AREAS"

In FY19, DOD will invest about $1.6 billion in RDT&E that is directly related to energy. Table 1 shows how the administration's proposed spending breaks down by program activity.[19] More than a third of the FY19 budget ($600 million) falls into the budget categories that correspond to basic research, applied research, and advanced technology development (6.1, 6.2, and 6.3). Collectively known as science and technology (S&T), investments in these three "upstream" R&D categories are likely to be the most relevant to the commercial sector. More than half of DOD's energy RDT&E ($824 million) is demonstration and validation (the 6.4 budget category); much of that budget line in FY19 is allocated to several large aircraft-engine projects that are well along in the R&D process. The two most "downstream" budget categories (6.5, or system development and demonstration, and 6.7, or operational system development) account for less than 10 percent of the total. (We omit budget category 6.6, which consists of spending on "RDT&E management," from table 1.)

Table 1: DOD FY19 Energy RDT&E Funding[20]

Budget Category	Funding
Basic Research (6.1)	$128 M
Applied Research (6.2)	$269 M
Advanced Technology Development (6.3)	$202 M
Science & Technology (S&T) Subtotal	**$600 M**
Demonstration and Validation (6.4)	$824 M
System Development and Demonstration (6.5)	$101 M
Operational System Development (6.7)	$43 M
RDT&E Total	**$1,568 M**

In addition to its direct spending on energy RDT&E, DOD funds R&D in many areas that are indirectly related to energy and thus not captured in table 1. For example, DOD has funded foundational research in materials science and engineering—fields that have been key to advances in everything from the composites used to increase aviation fuel efficiency to WBG semiconductors used for power electronics. DOD's deep support for advances in computational fluid dynamics have contributed even more directly to improved aircraft fuel efficiency, among countless other energy applications (e.g., the design of power plants).

The goal of DOD's energy RDT&E spending is to "enhance mission effectiveness and reduce operational risk through more effective and efficient use of … energy."[21] DOD's investments target five "warfighter opportunity areas": Soldier Power, Base Power, Platform Power, Autonomous System Power, and Weapon Power.

Soldier Power

Soldier Power focuses on the energy needs of soldiers and small troop units that operate on foot ("dismounted"), typically in remote areas and under harsh conditions. Dismounted soldiers are positioned at the leading edge of the battle and therefore sustain most of the combat casualties.[22] As the services have equipped warfighters with ever more sophisticated electronic devices and equipment, the requirements for portable power—and the sheer weight of the device-powering batteries soldiers must carry—have become a serious and growing challenge.

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This challenge is relatively new. In 2001, a typical 42-soldier platoon in Afghanistan required only about 2 kilowatt-hours (kWh) of electricity to power its devices for 72 hours.[23] Today's soldiers carry a host of energy-consuming devices, including night-vision goggles, emergency location beacons, laser telemetry devices, networked radios, and ruggedized smartphones. Comparable unit power consumption now exceeds 30 kWh, and the Army expects soldiers' power requirement to double by 2025 as they acquire augmented reality gear, next-generation squad weapons, and other new equipment.[24]

Current and Changing Practices

The military has traditionally relied largely on primary (non-rechargeable) batteries because of their lighter weight.[25] But as the price and performance of rechargeable batteries have steadily improved, DOD has begun substituting them; 2010 was the first year in which DOD bought more rechargeable than primary batteries. DOD suppliers use special designs and hardened cases to package commercial cells into finished batteries that meet DOD's needs for ruggedness, temperature range, shelf life, etc.

A decade ago, the Army introduced the conformal wearable battery (CWB) to reduce soldiers' battery burden—particularly the need to carry multiple types and sizes of batteries and match them to their corresponding devices. The tablet-size CWB provides a single rechargeable source of power for all soldier-worn devices, and is light (2.6 pounds) and flexible enough for soldiers to wear comfortably under their body armor. Based on lithium-ion (Li-ion) chemistries, the CWB provides power for 24 hours—longer than standard military batteries—and its multi-cell structure ensures the CWB will continue to function—even after one or more cells has been pierced by a bullet.

The Marines' power-generating solar "blanket," like the CWB, was an instant success when it was introduced in 2011. Flexible enough to be stuffed into a backpack, the smallest-size solar blanket can recharge a standard military Li-ion battery in about two hours.

Even with such innovations, batteries remain a burden. Army policy calls for infantry soldiers to carry enough portable energy for 72 hours of continuous operation without resupply. That translates to 15–25 pounds of batteries, on top of the 60–100 pounds of armor and other gear they routinely carry.[26] Although batteries have gotten lighter and more efficient, improvements in battery performance have been far outpaced by the computing capability of soldiers' gear and its associated power demand.

RDT&E Investment Drivers

Three challenges are driving DOD's RDT&E investments in Soldier Power:

- *Longer-duration missions without resupply*: The Army wants to extend its standard patrol from 72 to 144 hours, and the Marine Corps has a 2025 goal of its Marines being able to go ashore anywhere carrying only mobility fuel. Soldiers will need to be able to generate power and recharge, detach, and swap out power sources.
- *Lighter loads:* Dismounted soldiers currently carry loads that far exceed the recommended maximum—which is 30 percent of body weight.[27] Batteries account for only about 15 percent of the load—but are nonetheless a growing burden.[28]
- *Greater safety*: Li-ion batteries can catch fire or explode when penetrated by a bullet or other projectile.

Base Power

Base Power refers to the energy needs of military bases, which consist largely of building-related energy loads, including plug loads. DoD distinguishes between enduring bases, known as fixed installations, and non-enduring bases, known as contingency or forward operating bases. While energy is the lifeblood of both types of military base, they face different energy challenges, as contingency bases rarely have access to a commercial electric grid, while fixed installations rely on the commercial grid, but must keep the lights on during a blackout.

Contingency Bases

Contingency bases support tactical operations (contingencies) outside of the United States, ranging from disaster relief to counterterrorism to full-scale ground conflicts. A contingency base can include everything from a temporary expeditionary outpost set up to accommodate a small unit of soldiers to a semipermanent operating base, typically built around an existing airfield, which can grow to the size of a small town. Many contingency bases that were initially expected to be in place for only a few months have evolved into semipermanent posts.

Current and Changing Practices

Contingency bases comprise a mix of temporary shelters and semipermanent buildings. These structures and everything in them—from kitchen equipment to computers and communications networks—are powered by diesel generators (also called tactical generators) that convert liquid fuel (Jet Propellant 8, or JP-8) to electricity. These generators may also run equipment used to treat wastewater and solid waste that is not trucked off of the base. (The energy consumed by the vehicles and weapon systems located at a contingency base is not considered Base Power.)

Contingency bases have traditionally been characterized by very poor energy efficiency.[29] The generators are not networked and run at inefficiently low levels of capacity utilization (what one retired Army official referred to as "a poster child for waste"[30]). The utilization of electricity is also inefficient. The equipment used to cool poorly insulated shelters in U.S. bases in Iraq and Afghanistan accounted for a high fraction of base energy consumption during the summer months.

In response to the high costs incurred from protecting fuel convoys, DOD made it a priority to reduce the demand for fuel at bases in Iraq and Afghanistan. The Marine Corps put a charismatic F-18 pilot in charge of its Expeditionary Energy Office, and solicited hundreds of proposals to address tactical energy and water needs. Although many of the ideas were impractical,[31] the Marines deployed others, such as hybrid generators that supplement fuel with solar PV and a battery backup. Various types of insulation were shown to slash the cost of cooling temporary shelters.

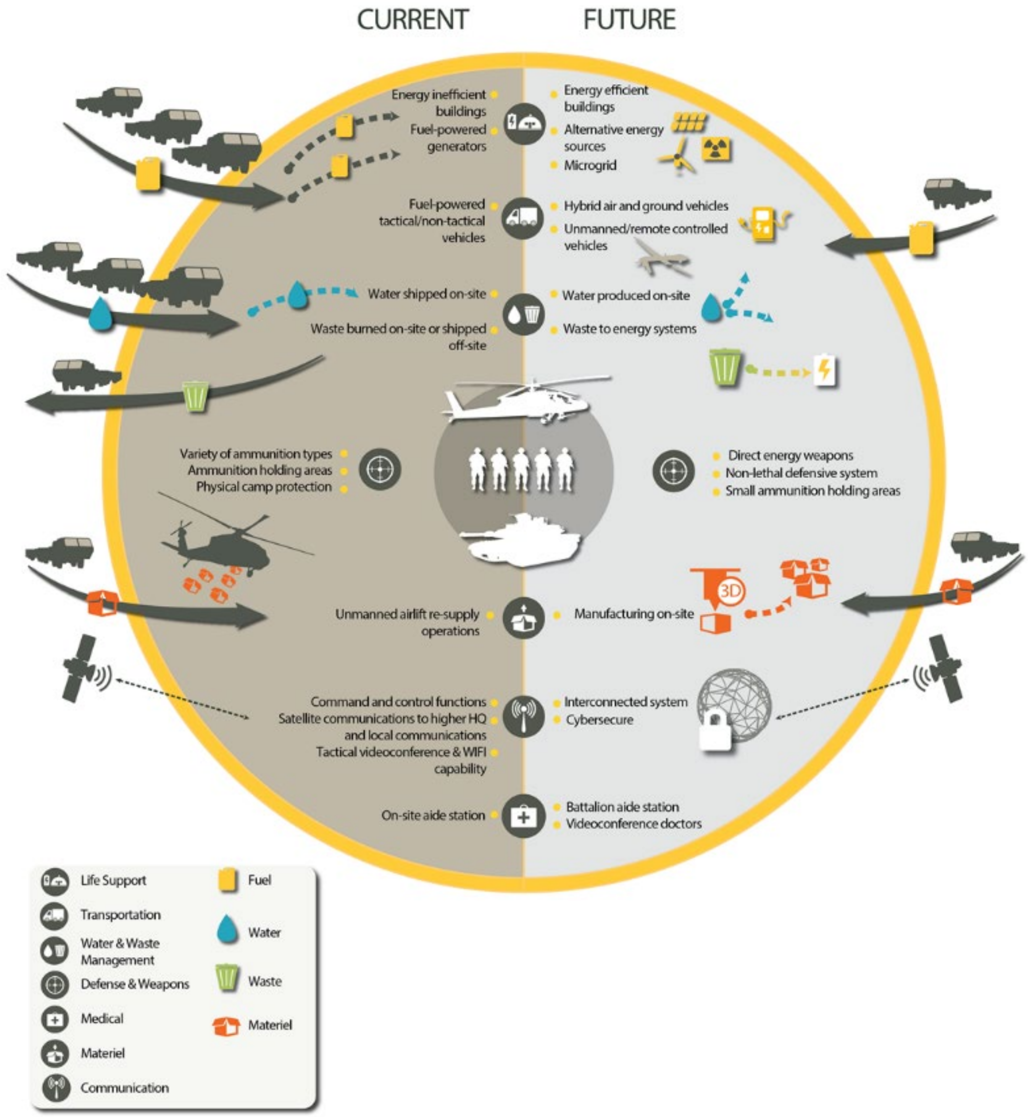
Despite some reduction in traditional building loads, the demand for electrical energy is expected to grow, particularly at the larger contingency bases, as a result of "future technologies load."[32] This load will likely include protective weaponry as well as activities designed to reduce the logistics burden imposed by the base—e.g., water desalination (replacing bottled water), 3D manufacturing (allowing for onsite vehicle maintenance), and conversion of waste to energy (reducing the need to truck waste products off of the base). See figure 1 for a comparison of energy needs on both a future and an existing contingency base.[33]

RDT&E Investment Drivers

Three challenges are driving RDT&E investments in Base Power for contingency bases:

- *More power, less fuel*: To ensure abundant power while reducing reliance on transported fuel, the services are investing in alternative energy sources, including wind and solar, fuel cells, waste-to-energy systems, and microhydropower and hydrokinetic systems. DOD is also exploring the use of vSMRs (see box I).
- *Adaptive power networks (tactical microgrids):* DOD needs mobile, cyber-secure, affordable microgrids for operational energy and disaster response. The microgrids need to allow for diverse, distributed generation resources, including renewables, and be able to handle large peak power demands for advanced weapons and sensors (see box G).
- *Enhanced energy efficiency*: RDT&E investments range from a more fuel-efficient tactical generator to technologies designed to reduce the building load (e.g., improved insulation for soft-wall shelters and membrane dehumidification for more efficient cooling).

Figure 1: A View of Future Contingency Bases[34]



Fixed Installations

Fixed installations rely almost entirely on the commercial grid. And with their 300,000 buildings and two billion square feet of building space, installations are major energy consumers. In FY17, they used 200,000 billion BTUs—more than half of it electricity—which represents 1 percent of the electrical energy consumed in the United States.

Fixed installations face two energy challenges. One is cost; even by DOD standards, the utility bill for fixed installation ($3.5 billion) is “real money.” The bigger challenge is energy security. Military bases must maintain power for critical functions (“critical loads”) during a grid outage, whatever its length. Major power outages are increasing in number and severity in the United States—due largely to severe weather—and military bases experience more and longer-duration outages than typical utility customers because many bases are located in outlying areas, where it takes longer to restore power.[35] As bases provide more direct support for combat operations, they also face growing risks from physical- and cyberattacks carried out via the commercial grid.

Current and Changing Practices

In anticipation of grid outages, military bases position a standalone diesel generator next to every building that must maintain continuous power in an emergency. A typical base has 100–200 such generators, each of which must have enough fuel to provide backup power for seven days.[36] Backup generators are affordable, and they afford a high degree of control to individual military operators, who typically purchase and maintain the backup generator for the building they occupy. However, backup generators have severe drawbacks as a strategy for ensuring energy security. Among other problems, lack of maintenance and testing reduces the reliability of individual generators in an emergency; and because the generators are not connected to one another, there is no backup for the backup power.[37]

Occupying 28 million acres of land, DOD's fixed installations are well situated to support renewable and distributed energy, which can enhance energy security when connected to an advanced microgrid. Although the services have been aggressive in working with the private sector to develop distributed generation assets (largely in the form of solar PV), energy security has not been a major consideration.[38]

In contrast to their success in siting renewable energy, the services have made only limited progress when it comes to energy efficiency, in large part because they have approached it as a way to comply with statutory goals and executive orders rather than as an essential element of energy security. From 2005 to 2015, DOD reduced its energy use intensity, or EUI (total BTU consumption divided by total square feet of space), by less than 1 percent per year on average—the worst record of the ten federal agencies that consume the largest amounts of facility energy.[39]

RDT&E Investment Drivers

Two challenges are driving DOD's RDT&E investments in Base Power for fixed installations:

- *Increased energy security and energy efficiency*: Fixed installations need a level of energy network reliability, resilience, and cybersecurity that exceeds that of many public-sector energy networks. Current investments focus on the demonstration and validation of advanced microgrid and energy storage technologies.
- *Reduced energy cost:* There are a range of technologies that can reduce the cost of facility energy, including components to improve building energy efficiency; building management and control systems; building-integrated and onsite generation; and microgrid and storage technologies. DOD supported demonstrations of the full range of technologies in the past, but current investments focus on microgrids and energy storage.

Platform Power

Platform Power refers to the energy needs of manned ships, aircraft, and ground (or "tactical") vehicles. Platforms consume energy both for propulsion and to power the weapon systems, sensors, communications technology, and other equipment carried onboard. They account for most of the operational energy DOD consumes, and each generation of platform tends to consume more energy than the last one because of new capabilities and improved performance.

Current and Changing Practices

DOD has a strong interest in reducing its reliance on liquid fuel because the military consumes fuel in combat settings, where it is extremely costly—in human lives as well as dollars—to obtain. Fuel efficiency is a particular priority for aircraft and helicopters, as liquid fuel is heavy, and aircraft are weight-constrained. An aircraft that uses less fuel can carry more payload or travel longer distances, and has less need for refueling.

Although liquid fuel will be key to mobility for many years to come, DOD is gradually electrifying its manned platforms.

Although liquid fuel will be key to mobility for many years to come, DOD is gradually electrifying its manned platforms. Onboard systems are already powered by electricity, and the military is preparing for a future in which most ships and ground vehicles will rely on hybrid-electric propulsion. (Military aircraft, particularly fighter jets, are unlikely to transition to electric propulsion in the foreseeable future because of the irreplaceably high energy density of fuel.) The hybrid drive allows a vehicle to propel itself using either electric motors tied to a diesel generator or battery, or a traditional combustion engine. This approach reduces fuel use. Even more important, the generator or battery that feeds the electric motors can more efficiently power the electrical systems onboard.

The growth in such systems has been dramatic. In 2001, the standard Army ground combat vehicle required a 150-ampere alternator to power its onboard systems; today, that same vehicle requires 10 times the amperage to run all of the weapon systems, computers, radios, monitors, and cameras carried onboard.[40] On ships, the proportion of energy consumed by onboard systems, including "energy-elastic" radars and weapon systems that have greater range when given more power, is approaching that used for propulsion.

Electric propulsion has other advantages as well. The powertrain for electric propulsion is typically smaller and lighter (along with fuel efficiency, the main reason automakers have embraced hybrid and electric vehicles). A second advantage is capacity: Replacing heavy mechanical systems with lighter electrical systems creates space that can be used to add onboard weapons or enlarge the living quarters on cramped ships. Third is survivability: The reduced acoustic footprint of electric power sources facilitates stealth; and elimination of the mechanical shaft that runs underneath today's ground vehicles and ships allows for platform designs that offer greater safety protection. A fourth advantage is the ability to generate exportable electric power. For example, the battery on a hybrid tactical vehicle could help power a contingency base or a refugee camp. Finally, because computers can interface better with electrical systems than mechanical systems, electric propulsion will facilitate the integration of smart-vehicle technologies, including the ability to operate ground combat vehicles in unmanned mode.[41]

RDT&E Investment Drivers

Four challenges are driving DOD's RDT&E investments in Platform Power:

- *Electrification*: The Navy is designing hybrid-electric ships (referred to as "electric ships"); and the Army wants to have most of its hybrid-electric infrastructure ready for testing by 2024, and a working, all-electric power train for its ground vehicles by 2027.[42] A key challenge is to increase the efficiency of the power distribution network, which—like a tactical microgrid—must be resilient to physical- and cyberattacks; able to provide levels of power that are highly dynamic (in time and magnitude); and able to interconnect with platform weapons and communications systems.[43]
- *Increased fuel efficiency for legacy platforms:* DOD's largest energy RDT&E programs are aimed at improving the propulsion of aviation platforms. For example, the Air Force has spent decades developing an "adaptive" engine for fighter jets that provides for greater fuel efficiency as well as higher thrust (see box D).[44] Reducing the penalty that platform weight and drag imposes is also key to fuel efficiency, as reflected in investments ranging from advanced composites for aircraft and tanks to sophisticated anti-fouling paints and coatings for ship hulls.
- *Greater safety:* A key concern is the fire risk associated with the recharging of Li-ion batteries.
- *Expanded options for liquid fuel*: While DOD platforms rely entirely on petroleum-based fuel (JP-8), the services routinely test commercially available ("drop-in") fuels produced from feedstocks other than petroleum for use should the need arise (see box J on why DOD is not likely to support the development of advanced biofuels in other ways).

Autonomous System Power

Autonomous System Power addresses the energy needs of unmanned military platforms, including unmanned aerial vehicles (UAVs), ground vehicles, and underwater or underground vehicles.[45] Autonomous vehicles are transforming the battlefield: They can be made smaller, lighter, and faster—and are more maneuverable—than manned vehicles. They can also remain in position beyond the limits of human endurance, and take more risk without jeopardizing human lives.[46] As it has with manned platforms, DOD is embracing electrification for many of its unmanned systems, although limits on existing energy technology hampers DOD's ability to deploy large numbers of these systems and take advantage of their full capabilities—particularly the potential for long-duration operation in unique and challenging environments.

Figure 2: UAV Groups

Group 1: Less Than 21 Pounds Operating Below 1,200 Feet	
Group 2: 21-55 Pounds Operating Below 3,500 Feet	
Group 3: 55-1,320 Pounds Operating Below 18,000 Feet	
Group 4: More than 1,320 Pounds Operating Below 18,000 Feet	
Group 5: More than 1,320 Pounds Operating Above 18,000 Feet	

Current and Changing Practices

DOD spends about $26 billion a year on unmanned vehicles. Most of that total ($20 billion) is for UAVs, which are used widely for both surveillance and strike missions. UAVs range from large, high-altitude systems, such as the Predator, Reaper, and Global Hawk, to small tactical systems like the Raven, Wasp, and Puma (see figure 2 for DOD's classification). The larger UAVs (groups 4 and 5) are powered by aircraft engines, and can remain aloft for up to 40 hours. The smaller and lighter UAVs (groups 1 and 2), most of which operate on battery power, typically have flight times of less than an hour.

U.S. military drones, which have operated with near impunity during the last 15 years of conflict, are facing an increasingly contested environment. In response, DOD is taking the sensors and other capabilities of UAVs in groups 4 and 5, and pushing them down to groups 1, 2, and 3, making it even more important to extend the flight duration of smaller, electric UAVs. Although DOD's unmanned ground and underwater systems are still in the R&D stage, they are expected to gain widespread use.

DOD is electrifying its unmanned vehicles for the same reasons automobile and aeronautics companies are electrifying cars and smaller aircraft. Most important, electric propulsion provides for longer-duration operations without recharging or refueling. In addition, electric power components are modular, which allows for interoperability across different vehicle designs. Finally, electricity is a "common currency," which facilitates energy processes (e.g., hybridization, harvesting, and storage) that reduce the need to refuel or recharge. For example, the Navy is developing a hybrid drone that is powered by solar PV during the day and a fuel cell at night—a process made possible by having electricity as the common denominator.

RDT&E Investment Drivers

Three challenges are driving DOD's RDT&E investments in Autonomous System Power:

- *Improved duration, range, and payload:* Unmanned systems need to remain operative for long periods of time, travel for extended distances, and, in some cases, carry sizable payloads. This will require some combination of the following: in situ energy generation (e.g., solar PV) or a fuel cell; batteries with improved energy and power density; the ability to transfer power at long distances (wireless recharging); and in-air (UAV-to-UAV) recharging.

- *High OPTEMPO:* Today, it takes one to two hours to charge a small UAV battery that will sustain a flight time of only 20–30 minutes. High operational tempo (referring to the pace of military activity) calls for batteries capable of rapid recharge, or fuel sources that can power a UAV in real time with no logistics burden (e.g., solar power).
- *Greater safety*: Li-ion batteries in particular pose safety risks (as previously noted).

Weapon Power

Weapon Power refers to the energy needed to operate directed energy weapons (DEWs), which emit beams of light or microwaves powerful enough to degrade or destroy a target. Once seen as futuristic "death rays" with the potential to transform warfare, DEWs are now viewed as a tactical system that can perform a broad range of missions—from zapping a swarm of drones to incinerating an enemy rocket—at a fraction of the cost of kinetic weapons. Faced with the prospect of threats from China and Russia, DOD has made DEWs one of its highest S&T priorities, and spending on directed energy RDT&E has doubled.[47]

The advantages of high energy lasers (HELs), the most mature DEW, are illustrative and include their high speed, precision, and low cost.[48] Power is the rub: DEWs need far more energy than is available on most military platforms, and must be able to manage extremely high power levels. The power requirements are daunting. As a senior Navy scientist summed up the challenge, "If the U.S. military is going to use energy as a weapon, it better have plenty of it."[49]

Current and Changing Practices

DOD's interest in lethal lasers goes back to 1959, when the newly created Advanced Research Projects Agency (ARPA, now known as the Defense Advanced Research Projects Agency, or DARPA) funded an outside proposal to build one.[50] DOD spent decades and billions of dollars trying to develop a laser powerful enough to defeat hard targets, including the space-based lasers that figured in President Reagan's Strategic Defense Initiative (SDI) and later a chemically fueled laser the Air Force tried to squeeze onto a Boeing 747.

The problems with chemical lasers—together with advances in laser diodes used in fiber-optic telecommunications—led DOD to shift its focus to electrical lasers. But whereas chemical lasers promised megawatts of output, electrical lasers generated mere kilowatts. In 2009, researchers at a Northrop Grumman lab ran the first bulk solid-state electrical laser able to emit 100 kW of power for a full five minutes. Five years later, the Navy incorporated the latest advances in fiber-optic lasers used for industrial cutting and welding to field a makeshift 30-kW laser weapon, the LaWS, on a docked ship in the Persian Gulf.

Advances in commercial battery technology have also been key to DOD's progress in HELs. As batteries have gotten smaller, cheaper, and more energy-dense, the specialized power systems of HELs have improved. One prototype system, developed for shipboard use, consists of three modular steel cabinets the size of large deep-freezer chests. Each cabinet contains 18 drawers with 480 Li-ion phosphate cells in each drawer, and can provide 465 kW of power for about 3 full minutes—enough power to fire more than 100 shots—before being recharged.[51] The services are now pursuing ever more powerful HELs at a rapid clip. And in contrast to the LaWS, these prototypes will be fully integrated into their platforms.

DOD is pursuing other types of DEWs as well, including high-powered microwave and neutral particle-beam systems, whose roots are also in SDI. The Navy has devoted significant R&D resources to its railgun, which uses electrical currents to sling projectiles over long distances at Mach 7. However, the pulsed-power requirement remains a major challenge, and the Navy has signaled that it will continue to support R&D, but likely not pursue a shipboard demonstration.[52]

RDT&E Investment Drivers

Two challenges are driving DOD's RDT&E investments in Weapon Power:

- *Sufficient power levels:* Some military missions will require weapons that can generate an order of magnitude more power than the 100–150-kW HELs currently under development.[53] And because DEWs are inefficient at power conversion, a MW-size laser may need tens of megawatts of input power—and in short bursts.[54] Thus, DEWs will require exceedingly high-density power sources and massive energy storage for high-rate pulsed power.
- *Thermal management:* The solid-state laser diodes used in military DEW systems are designed for industrial applications. Because the efficiency with which they convert electricity to light is only low to moderate, the power requirements are high, resulting in the generation of large amounts of waste heat that must be dissipated quickly. DOD is pursuing both ways to improve laser diode efficiencies and novel techniques for managing the thermal loads.

HOW (AND HOW MUCH) WILL DOD'S INVESTMENTS CATALYZE CIVILIAN CLEAN ENERGY INNOVATION?

DOD has been a successful innovator because its RDT&E and procurement are closely tied to the military mission. This bodes well for DOD's energy innovation effort, which—as the last section made clear—is focused squarely on technologies that will enhance warfighter effectiveness. Less clear is "the extent to which these technologies [will] catalyze innovation relevant to large-scale reduction of global greenhouse gas emissions."[55]

In this section, we examine how (and how much) DOD's mission-driven investments might contribute to civilian clean energy innovation. We look at the five key ways in which military R&D and procurement historically have influenced the uptake of technology outside of DOD—which we call "pathways of influence"—and identify about a dozen clean energy technologies that have intersected or will intersect with one or more pathways.[56] We take a closer look, in the form of "cases," at four technologies we believe will benefit significantly from DOD RDT&E and procurement (solar PV, batteries and energy storage, microgrids, and WBG semiconductors for power electronics). Finally, we look at advanced biofuels as a counter example—a technology that, despite the hopes of many in the clean energy community, probably will not see significant DOD investment because of its limited military utility.

Pathways of Influence

MIT President Emerita Susan Hockfield recently wrote, "The Defense Department has funded an astonishing amount of today's most remarkable technology going back decades."[57] "Defense spin-off" is the catchall term often used to describe the way military research, development, and procurement contributes to commercial innovation. In reality, the relationship between defense and civilian innovation is much more complex and bidirectional.[58]

Pathway #1: Investments in Foundational Science, Technology, and Engineering

One important pathway through which DOD influences commercial innovation is the military's investment in basic and advanced science, technology, and engineering methods. In FY19, DOD will invest $13.7 billion in "science and technology" (budget categories 6.1, 6.2, and 6.3). This includes $2.5 billion in basic and applied engineering R&D—double the amount provided by the National Science Foundation (NSF).[59] Because of its foundational nature, such R&D has commercial as well as military (i.e., dual-use) value. The list of dual-use innovations that originated with, or benefited significantly from, DOD-supported foundational R&D is long—and includes such game-changing technologies as digital computing, artificial intelligence, advanced materials, computational fluid dynamics, lasers, and advanced control theory.

Of direct relevance to energy innovation is DOD's deep support of research in advanced materials and composites. The academic field of materials science grew out of investments by DARPA and other parts of DOD, beginning in the late 1950s. The modern composites industry likewise can be traced to military RDT&E investments. As a result of this decades-long research effort, Boeing's 787, like the military's F-35, has about half of its structural weight in composites. Composites are far lighter than metals, and are therefore a major source of fuel savings for modern commercial aircraft and the energy efficient surface transportation we will rely on in the future. See box A for more detail on DOD's role in supporting advances in composites.

BOX A: ADVANCED COMPOSITES

The first generation of advanced composites, made of glass-fiber-reinforced polymers, was developed in the 1940s in response to DOD's need for high-strength, lightweight materials for military aircraft. DOD carried out the initial R&D at what is now known as Wright-Patterson Air Force Base in Ohio, and in 1944 flew the first plane with an advanced composite fuselage. Two decades later, the demands of military space programs spawned a second generation of advanced composites made of carbon-fiber-reinforced polymers. For many years, DOD and the National Aeronautics and Space Administration (NASA) were the primary customers for these high-performance, high-cost materials, and the aerospace industry, which makes commercial as well as military aircraft, still accounts for most of the demand. Also, beginning in the 1970s, as the technology matured and costs decreased, carbon fibers transitioned to high-end sports equipment such as tennis rackets, golf clubs, and fishing rods. Today, carbon-fiber composites are a key enabling technology for energy-related applications and the focus of DOE's Institute for Advanced Composites Manufacturing Innovation. DOD is continuing to support R&D aimed at developing the next generation of advanced composites. Among other things, DOD is pursuing advances in precursors, an improved understanding of the functional properties of advanced composites, and advanced manufacturing approaches.

Not all of the fundamental R&D that is key to deep decarbonization has "energy" in its name. Advances in information technology and computer-driven design tools—fields wherein DOD's large investments have been foundational—are critical to ongoing improvements in every aspect of clean energy, from battery design to energy generation, distribution, and management. And as a reminder of the importance of serendipity in science, Army researchers investigating advanced materials, for reasons unrelated to energy, recently discovered an aluminum nanopowder that generates hydrogen on-demand when mixed with water or any liquid containing water. The versatile hydrogen source, which can be manufactured in tablet form with a 3D printer, could be employed to power vehicles through internal combustion or in fuel cells used to power drones or electric vehicles. The Army's "just add water" discovery could make fuel cells a much more attractive option for civilian as well as military applications.[60]

Pathway #2: Pursuit of Advanced Technologies of Early Interest to the Military

A second pathway is DOD pursuing technologies that have military value well before the commercial sector sees their potential. DOD's requirements-driven approach to innovation favors big-leap advances and systems that offer high performance at a higher cost than other customers are willing to pay. While some defense technologies never penetrate the commercial market, wherein cost is a constraint on performance and technical improvement is incremental, other defense technologies do eventually find civilian customers once costs come down.

A classic example of this type of defense spin-off is GPS, the earliest version of which the Navy developed in the late 1950s as a way to better track its submarines.[61] Likewise, the first all-purpose electronic digital computer was built to meet the Army's need to calculate artillery-firing tables, and DARPA developed ARPANet (the precursor to today's Internet) as a way for scientists to communicate.[62] Although the transformative civilian impact of satellite mapping, computers, and the Internet seems obvious now, these innovations might only have occurred years later had there been an absence of military need.

Defense spin-off was also key to the development of today's civilian energy sector, as the commercial nuclear reactor and gas turbine exemplify. Although defense spin-off is no longer the dominant paradigm for U.S. civilian innovation, it remains an important source of innovation in the energy sphere (see box B).

BOX B: DEFENSE SPIN-OFF AND ENERGY INNOVATION

Much has been written about the decline of the defense spin-off process as a source of civilian innovation in this country. One explanation for the decline is military systems have become increasingly specialized and esoteric. Other oft-cited contributors are the rapid growth of the commercial market relative to the defense market, and the corresponding shift in technological leadership in many areas.[63]

The receding importance of defense spin-off has led some analysts to cast doubt on DOD's ability to contribute significantly to civilian clean energy innovation. However, that skepticism reflects an overly narrow view of the spin-off model. First, even though military systems have become more specialized, much of what goes into them—technical knowledge, production processes, hardware—remains dual use (or "multiuse") in nature.[64] Because energy technology is largely an input to military systems and processes, as opposed to an end product, DOD RDT&E may have more relevance for civilian innovation. Second, many of the energy technologies important to deep decarbonization are in their infancy. This is precisely the phase of the R&D/innovation cycle wherein military requirements diverge less sharply from those of civilian users, and where DOD as a customer is most likely to dominate the market. Although we discuss some of these mechanisms (e.g., DOD buying power) in the context of other pathways, they are also elements of the traditional spin-off model.

One example is wireless transmission of electric power over long distances. DOD wants the ability to recharge UAVs remotely so they can stay aloft longer, and several demonstration projects are underway using light beamed from lasers (see box C). The Navy is investing in technology that would perform the same function for underwater drones.

The commercial applications of wireless power transmission are easy to imagine. For example, with in-flight recharging, commercial UAVs could perform many functions now carried out by satellites—and at a fraction of the cost. In terms of clean energy innovation, wireless power transmission facilitates electrification. For example, with the ability to recharge batteries at a distance, it would be easier to replace combustion engines in ground vehicles with electric drives.

BOX C: LASER-POWERED UAVS FOR THE MILITARY

UAVs are a game changer for warfighters, and finding ways to keep them aloft for longer durations is a priority for the military R&D community. One promising approach involves the wireless transfer of power from lasers. The concept is straightforward: Take a battery-powered UAV with a solar PV cell on the wing. As the batteries drain, the UAV operator fires a high-powered laser (actually, multiple lasers shot through a series of mirrors to create a single, larger laser beam) at the PV cell. The PV cell converts the light from the laser into power the UAV can use (electricity), just as it does with sunlight.[65] The laser can be powered with energy from any number of sources, including a battery, generator, or hybrid vehicle. Although laser-beaming technology requires a direct line of site and clear weather conditions, military researchers believe they can recharge a UAV at a distance of up to 6.8 miles.[66] DARPA and the Army both have demonstration projects underway, and DARPA's project lead recently said the capability "can be delivered to the war fighter in the near future."[67]

Even more ambitious, DOD is exploring the idea of transmitting solar energy wirelessly from space to contingency bases and large manned and unmanned platforms.[68] DOE and NASA looked into the feasibility of using space-based solar to power the grid in the 1970s, but dropped the idea when the oil crisis ended. DOD revived it a decade ago as a way to get power directly to warfighters. Costs aside, significant barriers to space-based solar power remain. However, other major countries are investigating the idea in earnest. If DOD moves ahead, space-based solar power could eventually transform the energy sector.

A less certain candidate for spin-off is the Air Force's path-breaking "adaptive" engine, which will provide 10 percent greater thrust while consuming 25 percent less fuel (see box D). Historically, aviation has been a poster child for defense spin-off. DOD was instrumental in the development of the gas turbine/jet engine, and many military aircraft engines were produced for the commercial market with little modification (the same was true for airframes).[69] Although commercial and military designs have since diverged, even fighter engines yield spin-offs in the form of hardware and knowledge. Currently, engine manufacturers do not envision commercial demand for the adaptive engine because of its specialized requirements and associated costs. However, manufacturers may find ways to exploit the engine's new capabilities once it begins operation, particularly if commercial airlines reintroduce supersonic transport.

BOX D: THE AIR FORCE'S ADAPTIVE ENGINE

The key difference between today's commercial and military aircraft engines is the bypass ratio, which refers to the amount of air the fan moves around the engine core, rather than through it. Commercial engines—picture the big-fan engines that hang under the wings of commercial airliners and military transport planes—have a high bypass ratio, which conserves fuel and extends flight range. By contrast, the engines on needle-nose fighter jets have a low bypass ratio, which allows for greater thrust, but at the expense of fuel efficiency and range.[70]

In 2007, the Air Force, working with the Navy, began a formal program to create an engine whose performance could be optimized across the flight envelope, employing higher and lower bypass as needed. The Air Force has now demonstrated a three-stream engine, in which the two existing air streams—the core stream and the bypass stream—are joined by a third stream that can be directed around the engine case to reduce fuel burn, or through the engine core for higher thrust. This third airstream also dissipates aircraft heat load, thereby improving thermal management. In addition, the adaptive engine incorporates a higher fraction of heat-resistant materials and advanced components, which allows it to run hotter and therefore more efficiently, and reduces the amount of air required to cool it.[71]

Tests of the adaptive engine point to impressive gains: The Air Force estimates that it will provide 10 percent greater thrust and 30 to 35 percent more range while consuming 25 percent less fuel (or even more thrust and range gain with fuel consumption held constant). The need for aerial tanker support would drop proportionately. The engine is being designed for the space available on the F-22 and F-35, but may also be scaled down to fit into the F-15 and F-16.

Pathway #3: Military R&D That Leverages and Advances Commercial Technology

DOD increasingly seeks to leverage commercial technology both to avoid the cost of developing defense-unique solutions and to take advantage of the size and technological prowess of the commercial sector. DOD typically performs its own R&D to further develop the commercial technology or adapt it for military use, and the commercial technology developers in turn often incorporate DOD's enhancements. In this way, the leading edge of a given technology may move back and forth between the military and commercial sectors. This process of "spin-in"—or "spin-back-and-forth"—represents a third important way in which the military contributes to commercial innovation.

Consider lasers. Although the laser was a commercial invention, DOD dominated the follow-on research for many years. As the technology advanced, lasers found widespread commercial application—and market-driven improvements in the technology in turn made high-energy lasers more feasible for military use. DOD is now funding additional technical advances, some of which will likely get incorporated into commercial lasers.

In the energy sphere, solar PV technology illustrates this potential synergy between commercial and defense R&D (see box E). DOD is conducting extensive R&D to develop solar PV technology that is more lightweight, flexible, and efficient than the dominant commercial technology (silicon). Beyond investing in R&D, as an early adopter of a superior PV technology, DOD is willing to pay a premium for high performance (we discuss early adoption more under pathway #5). That combination of factors could push the frontier for solar PV in some positive new directions, possibly contributing to healthy market disruption.

BOX E: CASE #1—DOD, SOLAR PV, AND THE POTENTIAL FOR MARKET DISRUPTION

Improved solar PV technology is a must-have for DOD, to enable longer missions for foot soldiers, increase flight duration for UAVs, and reduce the logistics footprint of contingency bases. These and other military applications (e.g., space-based solar) call for solar PV materials that are lightweight and flexible, as well as highly efficient at converting sunlight to electricity. By contrast, the dominant solar PV technology, silicon, is heavy and inflexible, albeit moderately efficient.[72] Given the exciting promise of some niche and emerging technologies—and the barrier to entry they face from low-cost silicon—DOD's requirements could be instrumental in prying open the market for solar PV and preventing a technology many experts regard as suboptimal (silicon) from choking off the development of other, more promising technologies.

Shortly after Bell Laboratories invented the silicon PV cell in 1954, the Army's Signal Corps Laboratories began developing silicon cells that could power Earth orbital satellites (e.g., the Vanguard I, the world's first solar-powered satellite, was launched in 1958). Satellite power was the principal market for solar PV until the 1970s, when improvements in silicon PV technology drove its cost down dramatically. Then, beginning in the mid-1990s, government-subsidized investment in China and elsewhere led to another sharp drop in the cost of silicon PV cells—this one tied to production costs. Many U.S. start-ups pursuing next-generation solar PV materials and designs went bankrupt.

The commercial market for solar PV is dominated by grid-related applications (e.g., utility-scale PV) that value low cost over other attributes. Many experts are concerned that silicon's cost advantage is serving as a barrier to the adoption of superior technologies. For example, Varun Sivaram, the author of *Taming the Sun: Innovations to Harness Solar Energy and Power the Planet*, has argued that "ever more finely tuned processes to manufacture silicon cells and panels are not transferrable to the radically different (and, theoretically, much simpler) processes to print next-generation solar coatings."[73]

Despite silicon's dominance, some promising technologies have survived in less cost-sensitive market niches.[74] One is multijunction III-V solar cells, which DOD began using in space in the mid-1960s. Although III-V cells are significantly more expensive, their greater efficiency (roughly double that of silicon) more than offsets the higher cost when the surface area to be covered (e.g., a satellite) is small. Emerging technologies such as perovskites, organics, and quantum dots also hold significant promise. Perovskites—materials that in effect can be painted on a surface to create electricity—have increased their conversion efficiency from 4 percent to 23 percent in less than a decade.

DOD has long funded RDT&E to advance III-V materials, and it is likewise supporting research on perovskites and other emerging solar PV technologies. In addition, as with III-V cells, DOD can be a valuable early adopter, giving higher-cost solar PV technologies an opportunity to grow and gain a commercial foothold, beginning with less price-sensitive applications such as device charging and building- and vehicle-integrated solar PV.

DOD's interest in beaming solar energy to distant bases and platforms adds to the potential for market disruption. The system envisioned would use satellites to deploy orbiting solar arrays the size of football fields that would capture the sun's radiation, convert it to electricity, and transmit it to Earth in the form of microwaves or laser radiation. To that end, DOD is supporting RDT&E aimed at advancing perovskite technology, and reducing by an order of magnitude the cost to fabricate III-V materials. Drawing on its decades of experience using III-V cells in space, the Air Force is tackling the three most costly steps in their fabrication, and funding a pilot manufacturing line devoted to one of those steps (epitaxial growth).[75]

Major barriers to space-based solar remain. In addition to the difficulty deploying giant solar arrays from moving satellites, DOD faces challenges in how the solar energy would be transmitted to and received on Earth. Even if DOD abandons the effort, the RDT&E will not have been in vain, as it is directly applicable to the work on solar PV for terrestrial use. And if the effort continues, DOD would be an early demonstrator of a system that could, at sufficient scale, provide this country and others with an unlimited supply of renewable electricity.[76]

Energy storage represents another case in which DOD seeks to leverage commercial technology and markets to meet its needs—for both mobile missions (portable batteries) and military bases (large-scale stationary storage). For the former, DOD is supporting R&D in battery chemistries to develop (commercial) batteries that meet the military's "stretch goals" for performance and safety. For the latter, DOD is funding the demonstration and validation of large-scale storage solutions to facilitate their commercialization (we further discuss demonstration and validation under pathway #4). DOD's role as a relatively price-insensitive early adopter and customer (pathway #5) will also be important. By contrast, DOD's directed energy weapons will require storage solutions that, by and large, are not yet commercially available (see box F).

BOX F: CASE #2—BETTER ENERGY STORAGE FOR SOLDIERS, BASES, AND WEAPONS

DOD's urgent need for improved energy storage—a running theme in the last section—is really three overlapping needs, corresponding to three types of mission. The potential for DOD to advance commercial innovation varies by mission.

Portable Batteries

For mobile missions (soldiers, manned platforms, and autonomous systems), wherein the goal is to extend duration and reduce weight, DOD needs portable batteries with a very high energy density and rapid recharge rate. Safety is also critical. DOD wants to leverage the commercial market for portable batteries: Batteries are an important but minor component of many military systems, and commercial provision equates to lower prices and well-functioning supply chains. (The role of foreign manufacturers in those chains is a concern for DOD, however.[77])

DOD's wish list for portable batteries (higher energy density, faster recharge, and greater safety) is one commercial battery users would endorse, but are not yet willing to pay for. To bridge that gap, DOD funds considerable technical activity, often in partnership with industry, aimed at developing higher-performing (commercial) batteries.[78] In addition to basic and applied research, this activity includes the development of prototypes and improved manufacturing processes. From 2009 to 2012, DOD spent about $430 million on battery RDT&E—fully half the amount spent by DOE ($852 million)—with most of it focused on mobile missions.[79]

The military's desire to buy commercial batteries, together with its willingness to pay more for higher performance, is a potentially powerful combination. DOD's large RDT&E investment—with both its reliance on industrial partnerships and its broad, research-to-manufacturing scope—could contribute to the development of a new generation of batteries. And if the first products are priced for higher-end commercial markets, DOD could become a valuable early customer, helping to finance their rapid movement down the learning and cost curves.

Stationary Storage

For military bases, DOD needs large-scale, long-duration storage solutions (advanced and flow batteries, fly wheels, pumped hydro, and compressed air). Fixed installations need such solutions to operate during extended blackouts, while contingency bases need them to minimize logistics support. DOD's needs (scale, duration) are closely aligned with those of the commercial market, which is dominated by grid-related applications such as demand response, peak shaving, and ancillary services. Moreover, as with portable batteries, DOD is willing to pay more than commercial customers to meet those needs, albeit for a different reason: Fixed installations are more vulnerable to grid outages than other utility customers, and place a higher priority on the ability to operate during weeks-long blackouts.[80]

Because of the value they place on energy security, military bases are carrying out systematic demonstration and validation of new storage technologies (typically in conjunction with a microgrid), through DOD's Environmental Security Technology Certification Program (ESTCP) and its Installation Energy Test Bed. Large-scale storage faces major impediments to broad adoption: The technology is new and costly, electricity markets are volatile, and there is no independent data on the technical and economic performance of the technology. The ESTCP demonstrations allow vendors and base personnel to gain hands-on experience one installation at a time. And the performance data being collected—information ESTCP makes public as a matter of policy—will allow other would-be buyers to assess the risks and value to them. Because of the scale of DOD's installation footprint, this database will cover every energy market in the country.[81]

Beyond demonstration and validation, DOD's eagerness to be an early customer for promising stationary storage technologies means the military will bear many of the initial, nonrecurring engineering design costs. Vendors can leverage this investment to lower the cost to commercial customers.

Finally, DOD will be a significant customer for large-scale storage. The current U.S. market for large-scale storage is small: In 2017, new large-scale storage installations totaled only 107 MW.[82] DOD's fixed bases, of which there are about 500, will need at least 1 MW of storage, with the bigger bases potentially needing as much as 10 MW.

Storage for Directed Energy Weapons

Energy is the long pole in the tent for deployment of directed energy weapons, because current power levels constrain the range of DEWs, and heat generation limits the frequency with which they can be fired. DOD needs storage solutions with exceedingly high power levels and ramp rates (the rates at which power sources can increase or decrease output), rapid recharge rates, and advanced thermal management. Compared with those for mobile missions and military bases, the storage requirements for DEWs are far less aligned with commercial needs.

To minimize the investment in defense-unique technology, DOD is looking to exploit niche commercial solutions that offer exceedingly high power levels and ramp rates. For example, the Navy is evaluating shipboard use of flywheels developed to allow Formula One race cars to accelerate more quickly. However, these solutions may not exist at a sufficient scale to meet DOD's needs.

To meet its truly defense-unique needs, DOD will pursue R&D on high-voltage battery cells that are not a commercial priority, as well as supercapacitors with power levels far greater than those required to meet any foreseeable commercial need. In addition, DOD will pursue RDT&E on laser diodes and thermal management (more efficient diodes would generate less waste heat).

While the development of storage technology for DEWs appears to be largely a defense-unique undertaking, there may be some commercial synergy. For example, DOD's buying power could expand the market for niche technologies such as flywheels, and DOD's R&D on technologies with high power levels and ramp rates may have some relevance for frequency stabilization—the ability of the grid to stabilize when a large load or generation source drops off.

Pathway #4: Shared Infrastructure and Platforms as Test Beds for Demonstration and Validation of Commercial Technology

As the discussion of stationary storage made clear (see box F), an important way DOD contributes to commercial innovation is by providing shared infrastructure that can be used as a test bed to demonstrate and validate commercial technologies. Demonstration and validation is, of course, key to DOD's development of its military platforms and weapons. But the focus here is on the value of DOD assets for demonstration of commercial technology for which DOD is a potential customer.

DOD has unparalleled resources, including military bases with hundreds of structures and vast open areas used for testing and training. For example, DOD's Defense Innovation Unit, whose main office is in Silicon Valley, has encouraged "flying car" start-ups to test their prototypes on military bases.[83] DOD's vehicle platforms can also serve as test beds. For example, the Navy's Electric Ship R&D Center allows commercial firms and DOE laboratories to test electric power systems in a hardware-in-the-loop environment. In addition to its physical assets, DOD has a deep culture of test and evaluation that makes it an ideal host for commercial demonstration and validation.

Advanced (stationary) microgrids are a must-have for fixed installations, and DOD's rigorous demonstration and validation process is playing a critical role in helping microgrid technologies overcome impediments to commercialization.

For example, in 1995, DOD began funding the demonstration of innovative environmental cleanup technologies on its fixed installations. DOD was a potential customer for such technologies, as the groundwater on many bases had been contaminated with chemicals from on-base industrial activities. Armed with hard data from the demonstrations, the technology developers were able to transition their technologies to the commercial market, where DOD could purchase them as a customer (one of many). Nearly all the groundwater cleanup technologies now in commercial use received funding from DOD's environmental technology demonstration and validation program, ESTCP.

In 2009, ESTCP created an Installation Energy Test Bed program to perform a comparable function for energy technologies for the built environment.[84] The logic was similar: Given the military's vast installation footprint, it is in DOD's own interest to help firms overcome the barriers to commercialization of innovative energy technologies—technologies that are "out of the garage but not yet on the shelf." The test bed is "distributed"—i.e., the demonstrations take place on individual bases—which allows the testing to occur under real-world conditions with involvement by staff whose buy-in is critical.

ESTCP has funded 134 energy technology demonstrations in five areas: components to improve building energy efficiency; building energy management and control systems; tools for decision-making on energy use and management; onsite generation (including waste-to-energy and building-integrated systems); and microgrid and storage technologies. Although new funding is largely going to the last area (microgrids and storage), previously funded projects, some of them ongoing, are playing an important role in the commercialization of technologies across all five areas. (See the appendix for more detail on ESTCP's Installation Energy Test Bed.)

Box G looks at microgrids in greater detail. Advanced (stationary) microgrids are a must-have for fixed installations, and DOD's rigorous demonstration and validation process is playing a critical role in helping microgrid technologies overcome impediments to commercialization. In addition to serving as a critical test bed, DOD will be an early and large customer for advanced microgrids (pathway #5). Mobile, or tactical, microgrids are equally essential for contingency bases, which lack access to commercial grids. DOD's early adoption and procurement of mobile microgrids will help refine the technology and bring the cost down on a clean energy system that has enormous potential to lower carbon emissions in developing and remote parts of the world.

BOX G: CASE #3—MICROGRIDS: A MUST-HAVE FOR MILITARY BASES

No one is more excited about the developments in microgrid technology than warfighters in the Department of Defense.[85] Smart microgrids and large-scale energy storage offer a more resilient and cost-effective approach to ensuring energy security at DOD's fixed installations than the current one—namely, back-up generators and (limited) supplies of onsite fuel.[86] At contingency bases, tactical microgrids can significantly reduce the need for transported fuel to power diesel generators.

Fixed Installations

Advanced microgrids are a potential "triple play" for fixed installations. First, they facilitate the incorporation of renewable and other onsite energy generation, including combined heat and power (CHP) plants, waste-to-energy facilities (e.g., gasified landfills), batteries, and other forms of stored energy, as well as fossil-fuel generators. Second, when operating in parallel to the grid (i.e., grid-tied), they reduce installation energy costs on a daily basis by allowing a base to curtail its load or provide ancillary services in response to a request from the grid operator. Most important, the combination of onsite energy and storage, together with the microgrid's ability to manage local energy supply and demand, allow an installation to shed nonessential loads and maintain mission-critical loads when the grid goes down ("island" mode).[87]

Recognizing microgrids' value to fixed installations, DOD has sought to further their development by serving as a test bed for the demonstration and validation of pre-commercial systems. Advanced microgrids consist of innovative components and engineering designs whose performance is affected by site-specific factors such as the predictability of the load and the variability of intermittent renewable energy. Onsite demonstrations both give vendors the real-world experience they need to validate their engineering designs and allow potential buyers to analyze how the systems perform from an economic as well as a technical perspective.[88]

Since 2009, ESTCP's Installation Energy Test Bed has funded 32 demonstrations of advanced microgrid technologies, many of which incorporate innovative storage solutions, on military bases. The earliest demonstrations were designed to test the feasibility and cost-effectiveness of relatively simple advanced microgrid systems. Subsequent projects looked at more complex systems, with multiple baseload generators and high penetrations of intermittent renewable energy. Today's microgrid demonstrations focus heavily on cybersecurity and the integration of long-duration energy storage. Although most of the microgrids on military bases still consist of small demonstration projects, a few bases (typically ones that have hosted ESTCP demonstrations) are now deploying them using appropriated (military construction) funds or third-party financing.

- The largest microgrid is at Marine Corps Air Ground Combat Center Twentynine Palms, a base in California's Mojave Desert that covers an area the size of Rhode Island. The microgrid controls generation assets that can provide for a significant portion of the installation's electricity requirements, which range from 10 MW in off-peak winter hours to 26 MW on summer days. It uses an 8-MW CHP plant that can produce more or less power as needed, including ramping up quickly during a heat spike or power outage.
- Marine Corps Air Station Miramar in San Diego is building a large-scale microgrid at a cost of nearly $20 million. The microgrid, which will integrate renewable energy and conventional generation from diesel and natural-gas generators, will be able to power mission-critical and support facilities during a utility grid outage, as well as provide peak-shaving and demand-response capabilities when connected to the utility grid.
- Portsmouth Naval Shipyard in Kittery, Maine, is procuring an advanced microgrid coupled with a large-scale battery. When the microgrid is in grid-tied mode, the shipyard will be able to generate revenue by providing ancillary services to the local independent system operator. During a blackout, the microgrid-battery combination will allow the shipyard to maintain essential industrial processes.

As these vignettes suggest, vendors are successfully transitioning their systems to market. For example, General Electric's microgrid controller went directly from a three-year demonstration at Twentynine Palms to the commercial market.[89] The existence of multiple vendors in part reflects ESTCP's approach, which (historically like that of DARPA) is designed to ensure DOD can capture the benefits of competition.[90] With 500 active-duty installations and hundreds of smaller National Guard bases, DOD is on track to be, in addition to one of the first, one of the largest customers for advanced microgrids.[91]

Contingency Bases

Microgrids are no less important to the future of DOD's contingency bases. By exploiting onsite energy sources such as solar PV and battery storage, and by allowing diesel generators to operate at peak efficiency, tactical microgrids can greatly reduce the need for generator fuel and its logistics tail. The microgrids being developed for use on contingency bases are very different from those destined for DOD's fixed installations. Most significant, tactical microgrids are designed to operate in isolation from a large-scale grid. In addition, they must be portable for easy shipment to war zones; able to adapt to power needs that change quickly and frequently; and simple enough to be operated by field soldiers who lack technical expertise.

As with stationary microgrids, DOD could play an important role in the commercialization and widespread deployment of tactical microgrids. The potential market for microgrids in developing countries and remote parts of the developed world is vast, and the type of microgrid such areas need (one that is portable, adaptable, easy to operate, and able to run in isolation from a large-scale grid) is the definition of a tactical microgrid. While the technology is not yet sufficiently refined or affordable to penetrate this vast potential market, DOD—as an early adopter and large customer—could help change that.[92]

One key to wider deployment is the development of technical standards for tactical microgrids, which would allow developers to seamlessly integrate components produced by different manufacturers, thereby expanding competition and driving down costs. As a large customer for tactical microgrids, DOD is in a position to develop and disseminate such standards.

Pathway #5: Early Adoption and Procurement of Commercial Technologies

A final way in which DOD contributes to commercial innovation is through early adoption and large-scale procurement of new technologies or products that have little or no commercial penetration. (In contrast to earlier pathways, all of which center on DOD's role as an RDT&E performer, DOD's role here is as a customer; and the technologies are closer to market.) Because of its large budget and mission focus, the military is less sensitive to high costs and early failures than commercial customers and private investors—and it can provide feedback on a larger scale than commercial users. A partnership with DOD also sends a valuable signal to commercial investors.[93] Although a new technology or product may need to be modified for military use, it is in DOD's interest to see it gain a commercial market because of the advantages it brings in the form of declining costs and continued technical innovation.

DOD's role as a sophisticated first user and early, market-creating customer for new technology has been extremely important historically. Alic et al. describe its centrality to the development of integrated circuits:

> Government purchases of integrated-circuit chips in the 1960s fostered advances in microelectronics at least as much as did government-funded R&D. In anticipation of government purchases (but without R&D contracts from the government), Texas Instruments and Fairchild Semiconductor fabricated the first integrated circuits in 1959–60 and went on to sell chips in large numbers to the DoD and NASA. As costs came down and technical performance improved, commercial markets opened and accounted for four-fifths of sales by 1970.[94]

Turning to energy, DOD's role as an early adopter and potentially large-scale customer figures prominently in the three "cases" we have already examined: solar PV, batteries and stationary storage, and microgrids. Solar PV and batteries, in particular, could benefit from DOD's willingness to pay a premium for higher performance, as new-entrant technologies try to compete with the dominant, low-cost incumbents (silicon and Li-ion, respectively). (Stationary storage systems also could benefit from DOD's willingness to pay, albeit in a different competitive context.) For microgrid systems, the sheer scale of DOD demand could be an important factor.

Another technology DOD can help advance as an early adopter and customer is WBG semiconductors, which, if their costs come down, have the potential to revolutionize power electronics. DOD has supported advances in WBG technology for nearly 50 years—initially because of WBG's application to military radars—and its support has run the gamut from research to manufacturing to procurement. As box H describes, the military's next-generation vehicles require a level of performance in power electronics that only WBG devices can provide. The military will therefore pay a premium for performance as an early adopter, and go on to purchase commercial WBG devices on a vast scale.

BOX H: CASE #4—DOD AND WIDE BANDGAP SEMICONDUCTORS: FROM RADAR TO POWER ELECTRONICS

Wide bandgap (WBG) semiconductors have the potential to revolutionize power electronics—the process of converting electrical energy from one form to another (e.g., AC to DC), or changing its voltage or frequency using semiconductors, inductors, and capacitors. Power electronics is ubiquitous—in the functioning of products ranging from laptops to hybrid vehicles, the production of renewable energy, and the operation of industrial processes. However, it results in significant energy losses. Because semiconductor devices made of WBG materials such as silicon carbide and gallium nitride are more efficient than the silicon devices currently used, their substitution could reduce these losses.[95] WBG devices also allow for significant increases in power density and conversion speeds. And because converters can operate at higher efficiencies, power electronics components can be smaller and lighter.

DOE is devoting significant resources to advancing WBG technology, because of its implications for worldwide energy consumption. In 2014, DOE established its Next Generation Power Electronics Manufacturing Innovation Institute, known as PowerAmerica, at North Carolina State University, with the goal of making WBG devices cost-competitive within five years. Complementing PowerAmerica's focus on the fabrication of WBG materials, DOE's Advanced Research Projects Agency-Energy (ARPA-E) has funded several initiatives to advance the devices themselves, as well as their production.

These recent DOE initiatives build on military RDT&E in WBG technology that goes back nearly 50 years. Throughout the 1970s, the Office of Naval Research (ONR) funded fundamental university research on WBG physics, materials science, and engineering. Support for WBG technology expanded throughout the 1980s as DOD saw WBG's potential to revolutionize radio frequency (RF) applications such as military radars. In the early 2000s, DARPA undertook a major program to accelerate improvements in WBG materials. ONR and DARPA support led to the development—and the technology for the manufacture—of the WBG solid-state electronics systems used today. In 2013, DOD used its authority under the Defense Production Act (DPA) to ensure the United States had the industrial capacity to manufacture WBG devices for RF applications. A major beneficiary of DPA support was Cree Inc., which is now a leader in commercial power electronics.

WBG devices are currently being used in the radar systems of major military platforms such as the F-35. But power electronics applications will be an even bigger driver of DOD demand for WBG chips. DOD's next-generation platforms, including the Navy's electric ship and the Army's hybrid-electric combat vehicle, all require a level of performance in power electronics only WBG semiconductors can provide. Components being smaller and lighter is as important to the military as the higher efficiency of WBG chips.[96]

As an early adopter of WBG semiconductors, DOD is poised to play a role similar to the one it played in the commercialization of integrated circuits. First, although WBG devices will be more costly than silicon devices for some time, DOD is willing to pay a premium for performance. Second, the military market is large enough for commercial producers to be able to ramp up production and reduce their costs, based on economies from both scale and learning by doing. Third, DOD wants to see WBG devices become available in the commercial market so that it can buy them as a commodity. Thus, DOD is likely to steer its own R&D effort in a direction that aligns with commercial demand.

Fuel cells are another clean energy technology benefiting from DOD actions as an early adopter and customer. Fuel cells' endurance makes them an attractive energy source for multiple military missions. The Navy partnered with GM to develop a hydrogen fuel-cell-powered underwater drone that can operate for more than 60 days without recharging. In addition to enabling long-duration missions, fuel cells operate without generating carbon-dioxide emissions—a plus in terms of stealth (lower thermal signature), as well as the environment.[97] The Army also is teaming with GM to develop a fuel-cell-powered light-duty utility truck for tactical use.[98] And the Navy set a record with a UAV powered by a commercial fuel cell modified to use a cryogenic storage tank and delivery system for the liquid hydrogen fuel. The Ion Tiger flew for 48 hours—12 times longer than would have been possible using the equivalent amount of lithium batteries.[99] The Navy is also commercializing its cryogenic fuel storage/delivery system for use by commercial drones.

A final, more speculative example of a technology that could benefit from DOD's role as an early adopter and customer is vSMRs. SMRs are a subset of advanced reactors that have an output of less than 300 megawatts electric (MWe), and vSMRs have an output of less than 10 MWe. As box I describes, DOD is exploring the potential for vSMRs to address two different sets of power production needs.

BOX I: DOD AND VERY SMALL MODULAR REACTORS

The nuclear reactor, like the gas turbine/jet engine, was originally developed for military propulsion and adopted by electric utilities for commercial power production. DOD created its own nuclear power production capability in the 1950s, run by the Army Corps of Engineers, and built eight plants, six of which produced power for extended periods (all eight ceased operation by the 1980s). A 2-MW plant at Fort Belvoir, outside Washington, D.C., which was used primarily for training and testing, was reportedly the world's first nuclear power plant to be connected to the electric grid.[100]

The ongoing development of vSMRs has led to renewed interest in the use of nuclear power on military bases. DOD is proceeding on two tracks to examine the utility of stationary and mobile vSMRs, respectively.

Stationary vSMRs

DOD is exploring the possibility of putting a stationary vSMR on a fixed installation as part of a demonstration. In keeping with the FY19 National Defense Authorization Act, the demonstration would probably take place on a geographically remote base burdened with high utility rates. Although no vSMR is yet operational, several companies are working to bring their systems to market—and one or more of them could receive a license from the Nuclear Regulatory Commission (NRC) in the coming years (such a license would be a prerequisite for deployment of a nuclear reactor on a fixed installation).

Remote military installations are an ideal early market should vSMRs be shown to be affordable. DOD installations in remote locations often pay high rates for unreliable power, and they are already paying for energy security in the form of backup generators. A vSMR would generate baseload power for the installation on a day-to-day basis and, if appropriately configured, provide reliable power at a stable cost during extended blackouts.

That said, the military is not likely to pay any nonrecurring engineering costs for the vSMR, and it would probably take advantage of third-party financing to deploy it, paying commercial rates for vSMR-generated energy the base consumes. This approach is consistent with informal policy DOD adopted nearly a decade ago as part of its discussions of possible SMR deployment.[101] It reflects the view that, for a fixed installation, a vSMR is a "nice-to-have," like a solar array, as opposed to a "must-have," like a microgrid.

Mobile vSMRs

A 2016 report issued by the prestigious Defense Science Board (DSB) looked at the energy challenges facing contingency bases and concluded that mobile vSMRs could potentially be a tool for meeting the growing demand for large quantities of electrical energy.[102] DSB recommended the secretary of the Army investigate and invest in the maturation of vSMR technology and demonstrate its utility for contingency bases and remote fixed installations. In response to the DSB report, the Army recently issued a detailed analysis of the benefits and challenges of mobile vSMRs.[103] Currently, OSD's Strategic Capabilities Office is seeking information leading to the possible demonstration of a prototype mobile vSMR designed for rapid deployment and sustained, safe operation in austere conditions.[104]

The commercial vSMR designs under development would require extensive refinement to meet military requirements for mobility and forward deployment. Manufacturers would have to overcome regulatory and geopolitical challenges as well. DOD could play a valuable role in meeting these technical and nontechnical challenges; but that would probably do little to advance the deployment of vSMRs for civilian use because of the divergence in requirements.

Moreover, vSMRs' suitability for forward use is controversial, even within DOD. One concern is that nuclear reactors—even one that is relatively small and mobile—reduce the high degree of agility that contingency operations must maintain. Another concern is the potential for an adversary to weaponize a vSMR: Although the fuel used to power a vSMR could not be used to make a nuclear bomb, it could be mixed with conventional explosives to create a dirty bomb. One likely skeptic of vSMRs is the Nuclear Navy, which has a perfect safety record and whose leaders may fear an accident could make it harder for them to dock their floating reactors in foreign ports.

Conclusion

Overall, DOD's fixed installations, whose needs for (stationary) vSMR-type systems are aligned with those of civilian users, could contribute to their commercial deployment as an early, plug-and-play customer. This is a narrower role than DOD often plays with new technologies, but one that has the potential to be helpful (depending on the size of its demand). By contrast, DOD's contingency bases—for whom (mobile) vSMRs offer greater benefits but also pose more risk—have requirements that are not aligned with the commercial market. Thus, even if DOD does deploy mobile vSMRs, it may do little to advance clean energy innovation.

An Energy Technology that Will Probably *Not* See Significant DOD Investment

To round out our analysis of DOD's potential influence on clean energy innovation, we examine the limits of that influence. Specifically, we look at advanced biofuels—a technology many people in the clean energy community have proposed for military support in the form of R&D and targeted procurement. We conclude that the lack of direct military utility likely will limit such support (see box J).

BOX J: DOD AND TARGETED SUPPORT FOR ADVANCED BIOFUELS: BEYOND MISSION

Because liquid fuel is indispensable to the military, DOD has periodically supported the development of alternatives to petroleum-based fuels. In the 1970s, the Air Force conducted and funded R&D on coal-based synthetic fuel, and from 2007 to 2011, DARPA's BioFuels program spent $100 million to develop cost-competitive technologies for making jet fuel from biomass. Beginning around the same time, the Navy and Air Force set ambitious targets for replacing petroleum with drop-in alternative fuels, and in 2012, using authority provided by Title III of the DPA, the Navy partnered with DOE and the Department of Agriculture on a $500 million project to incentivize the construction of advanced biofuel biorefineries.

The DPA's advanced biofuels project has been extremely controversial. The Navy initially justified it on energy-security grounds, arguing that having biofuel production facilities in strategic global locations would reduce the risk of rivals disrupting its fuel supply lines. Critics argue that subsidies to production are a flawed policy, and that, in any event, biofuel supply lines would face the same threat of disruption. Two biorefinery projects broke ground in 2018 and are in the midst of construction—but additional funding is unlikely.

DOD support for RDT&E on alternative fuels is somewhat less controversial, and the military services will probably continue to test and certify promising drop-in biofuels. However, one should not expect to see DOD undertake a serious R&D effort in advanced biofuels.

Advocates of a more active DOD role in biofuels point to three vulnerabilities created by the military's reliance on petroleum: the budgetary cost, potential limits on access to global supply, and the logistics cost of getting fuel to the battlefield. Although the first two concerns may have been valid at one time, they no longer are. While nontrivial, fuel costs are a relatively small fraction of the services' operation and maintenance budgets, and the prospect of a price spike is low in today's more competitive international oil market. Moreover, because fuel is a globally traded commodity, biofuels will not affect its price for the foreseeable future. As for access to global fuel supplies, the United States' new status as a net energy exporter has substantially reduced whatever risk may have existed. The third problem—getting fuel to the front—remains serious; but the risks are the same whether the convoy is transporting biofuels or JP-8.[105]

Another line of argument is that DOD should conduct—or even lead—a major federal R&D initiative in biofuels because of the implications of carbon emissions and climate change for national security.[106] This, too, is likely to be a nonstarter. DoD is an effective innovator precisely because its RDT&E is so closely tied to the military mission. DOD sometimes undertakes RDT&E in response to congressional direction or other outside pressures. Historically, however, it has not sustained its support for technologies that do not offer improved mission performance.[107]

In short, fuel is a commodity DOD purchases in global markets and accesses through commercial supply chains—processes the development of biofuels would do little to change. DOD will purchase bioalternatives to JP-8 as they become cost-competitive (which it is already doing on a limited basis). However, it is unlikely to invest significant RDT&E resources to develop them.

RECOMMENDATIONS

In this section, we recommend ways civilian entities might leverage DOD's investments in energy innovation without compromising the military value of those investments. (Recommendations on the content of DOD's energy innovation effort are outside the scope of this report.) We focus largely on DOE and its explicit mission to address energy challenges through transformative science and technology solutions. In FY18, DOE spent $7.1 billion on energy RD&D (the equivalent of DOD's RDT&E) to advance that mission.[108]

As context for our recommendations, we begin with three broad observations. One, DOD's and DOE's approaches to innovation are quite different from—yet complementary to—one another. Two, DOD and DOE interact remarkably little when it comes to energy innovation. Three, stronger collaboration with DOD would strengthen DOE as an innovator, in part because certain elements of DOD's innovation system are particularly well suited to energy technology.

DOD's approach to innovation is driven by "demand-pull" in the form of requirements from the military customer. DOE's approach, dominated by the Office of Science, has been characterized as "technology push."

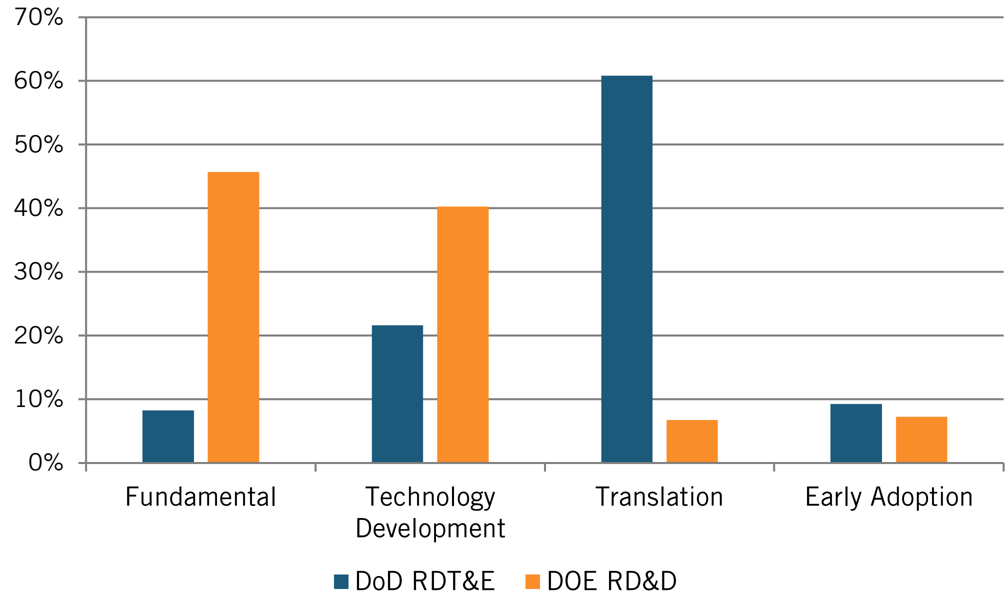
DOD and DOE Approaches to Innovation Are Complementary

Figure 3 compares DOD and DOE in terms of the fraction of their energy RDT&E budgets that goes into each of four categories of innovation activity: fundamental research, technology development, translation, and early adoption.[109] The major difference is DOE's energy RDT&E (RD&D) budget is devoted heavily to fundamental research, while DOD's skews heavily to technology development and translation.[110] Although ARPA-E and some of the programs in DOE's Energy Efficiency and Renewable Energy organization support R&D that is more applied, their individual budgets are dominated by that of the Office of Science.

Figure 3 reflects qualitative differences in the two innovation systems. Most significant, DOD's approach to innovation, including energy innovation, is driven by "demand-pull" in the form of requirements from the military customer. DOE's approach, dominated by the Office of Science, which funds exclusively fundamental research, has been characterized as "technology push."

A related difference between the two departments has to do with who performs the R&D. Fully 70 percent of DOE RD&D is performed in-house, by the national laboratories, compared with 36 percent of DOD RDT&E performed by defense laboratories (both figures refer to total R&D, not just energy R&D).[111] Stated differently, DOD directs more than twice as much of its RDT&E budget to universities and industry as does DOE.

Figure 3: Distribution of Energy RDT&E Investments for DOD (FY19) and DOE (FY17)



DOE and DOD Have Limited Interaction on Energy Innovation

DOD and DOE have remarkably little interaction when it comes to energy innovation.[112] Despite their shared interests, the two departments engage in little joint R&D planning, even on fundamental research and technology development (6.1 and 6.2). DOE develops its applied energy RD&D strategies and roadmaps with an eye to civilian energy needs and a major focus on price because of the nature of the commercial market. DOD's RDT&E effort is likewise focused on its needs.

Collaboration is not unheard of. In July 2010, the deputy secretaries of DOE and DOD signed a memorandum of understanding to enhance cooperation on energy security and clean energy innovation. The informal agreement was just that—there was no formal program or budget. However, senior officials did meet regularly, and a number of successful joint efforts resulted, including:

- ARPA-E and the military services collaborated to develop and build a hybrid energy storage module (HESM)—a long-duration energy storage system suitable for grid applications as well as military applications, such as directed energy weapons. ARPA-E and DOD each put $25 to $30 million into the multiyear project, and the services are transitioning the technology into specific systems (e.g., the Navy plans to use HESM for shipboard DEWs).
- In 2012, DOD's ESTCP partnered with DOE's SunShot Initiative to demonstrate a DOE-funded solar technology. The arrangement proved extremely beneficial to both programs, with DOD getting a cutting-edge solar array at a discount on one of its military bases, and DOE having its chosen technology tested at scale in a real-world setting, with the prospect of the military as a major customer.[113]

ARPA-E is currently working with the Navy on the use of WBG semiconductors in shipboard power conversion. ARPA-E is also nurturing several other small projects that have military customers.

However, these examples are the exception, not the rule. While individual DOE agencies and laboratories pay lip service to working with DOD, collaboration rarely happens in practice. The DOE labs, which are contractor operated, tend to look at DOD as a potential checkbook rather than a valuable test bed or a useful source of demand-pull. And the military services are themselves standoffish, wary that "collaboration" is a euphemism for DOD footing the bill.

Collaboration with DOD Would Make DOE a Stronger Innovator

Collaboration with DOD would make DOE a stronger innovator. (It would also help DOD, but the emphasis here is on the benefits to DOE.) DOE, by its nature, lacks the internal market that makes DOD such a powerful engine of innovation. Working with DOD would be a seemingly obvious way for DOE to introduce much-needed demand-pull into its R&D process.

DOD's approach to innovation is particularly well suited to energy innovation. First, as the energy storage and microgrid cases (boxes F and G) illustrate, energy technologies do not move from fundamental research and small-scale development directly into the commercial market. To mature their technologies, vendors need to experiment and demonstrate them at scale, under realistic conditions.[114] Opportunities for such "learning by using" in the energy area are rare, however. DOD represents a unique resource in this challenging environment. Its energy needs and long history of experimentation through demonstrations make it a motivated partner, and its vehicle platforms and infrastructure (military bases) offer an ideal innovation test bed.

Second, the energy market has large, well-established incumbents, and new entrants often have to compete solely on price because of the commodity nature of energy. Here again, DOD can play a much-needed role as an early adopter that values performance over price. DOD's use of, and feedback on, a new technology facilitates "learning by doing," and the defense market gives vendors the scale needed to reduce their manufacturing costs and become cost competitive.

In addition to the specific, program-level recommendations for DOD-DOE collaboration proposed below, we offer three high-level suggestions:

- The push for collaboration needs to come from DOE headquarters or from civil servants, not the DOE labs.
- DOE needs to recognize and emphasize the mutual interests of the two departments and the potential synergies from collaboration.
- DOE (and DOD) must bring real money to a project; when only one partners pays, it is not a real collaboration.

Recommendations for DOE

DOE should factor DOD's needs and strengths as an innovator into both its fundamental and its applied RD&D strategies and roadmaps so as to capture DOE-DOD synergies. DOE's fundamental research understandably focuses on supporting the DOE mission, and its applied RD&D appropriately targets the energy needs of the commercial sector, with a heavy emphasis on price. However, DOE should expand its focus to include DOD needs that are congruent with the civilian market, so that DOE's investments in fundamental and early-stage R&D can transition through DOD's late-stage R&D to defense products. Allowing the military to serve as a relatively price-insensitive early adopter can help vendors reduce their costs and become commercially competitive.

DOE should partner with DOD on its stationary storage programs. DOE has supported grid storage demonstration projects since the George W. Bush administration.[115] And ARPA-E recently announced $28 million in R&D funding for ten recipients as part of its new project to enable long-duration energy storage on the power grid at costs well below those of current technology.[116] Lower-cost technologies would allow grid storage to provide longer-lasting backup power and increased integration of intermittent renewable energy resources.

DOD is a natural partner for ARPA-E and the other DOE programs that support innovation in stationary storage. As box F describes, DOD's ESTCP is currently funding technology developers to model full-scale prototypes of new stationary storage technologies and gather data on their technical and economic performance under operational conditions. (At least two of the recipients of ARPA-E's recently announced funding for long-duration storage have participated in an ESTCP-supported demonstration project.) Additional value comes from DOD's interest in being an early adopter of stationary storage solutions—one that is willing to pay a premium for performance as vendors work to lower their costs—and a potentially large customer for such solutions.

DOE's battery technology programs should engage with DOD end users to identify their storage needs. DOE invests several hundred million dollars a year in battery RD&D through its Vehicle Technology Office (VTO), ARPA-E, and Joint Center for Energy Storage Research (JCESR) at Argonne National Laboratory. The technical work ranges from very basic science (JCESR is creating battery materials at the atomic level) to the development of long-range, high-risk technologies (e.g., ARPA-E's ongoing Integration and Optimization of Novel Ion-Conducting Solids (IONICS) project).

DOE (including ARPA-E, JCESR, and VTO) should identify opportunities to collaborate with DOD, which is spending as much as half of what DOE does on battery RDT&E. As box F describes, DOD's requirements for portable batteries (high energy density, rapid recharge, and improved safety) represent stretch goals: They are consistent with commercial demand but go beyond what commercial customers are willing to pay for currently. Collaboration on fundamental R&D could be fruitful, combining DOD's demanding requirements with DOE's highly specialized research capabilities such as exascale computing and genome modeling of battery materials. Collaboration on late-stage R&D

should target DOD end users as an early adoption market, providing valuable demand-pull for DOE's battery RD&D effort. As with stationary storage, DOD will pay a premium to achieve higher performance, giving commercial developers the necessary experience and scale to bring down their costs.

DOE's solar technology program should partner with DOD to speed the path to next-generation solar PV materials that can compete with silicon. DOE's Solar Energy Technologies Office (SETO) funds early-stage research that advances both solar PV and concentrating solar power (CSP) technologies. While SETO is supporting new PV materials such as perovskites, SETO's driving policy goal of reducing the levelized cost of solar electricity strongly favors low-cost silicon. Silicon's low price, which reflects years of manufacturing experience and large-scale demand, is a barrier to the entry of other, potentially superior new materials.

As box E describes, the military needs advanced solar PV for soldiers, UAVs, and space arrays—and its demanding requirements (materials that are lightweight and flexible, as well as highly efficient) can provide a pathway to new PV materials that can compete with silicon. DOD's own R&D on such materials is one step along that pathway, and its desire to be a pay-for-performance early adopter is another. And although—or perhaps because—DOD's ambitious pursuit of space-based solar must overcome huge technical challenges, DOE should be eager to partner on an endeavor that could transform the energy sector.

DOE's manufacturing initiatives should look to DOD as an early adopter. DOE manufacturing centers such as PowerAmerica and the Institute for Advanced Composites Manufacturing Innovation are tasked with reducing the cost and accelerating the commercialization of game-changing energy technologies. That process is neither fast nor straightforward; progress tends to be incremental and involve continuous learning. Early, niche markets and advances in manufacturing are key to challenging lower-cost legacy technologies.

DOD is an ideal early market for technologies that are the focus of DOE's manufacturing initiatives. For example, as box H describes, next-generation hybrid tanks and electric ships require a level of performance in power electronics only WBG semiconductors can provide. DOD wants to buy WBG devices commercially, but that market will not develop until costs come down. As an early adopter, the military is willing to pay a premium for performance, and it is a large enough market to allow WBG device manufacturers to ramp up production and reduce their costs. The same logic applies to advanced composites, a technology that traces its roots to military requirements.

DOE should partner with DOD to advance the deployment of stationary (non-tactical) microgrids. DOE and DOD have long recognized their common interest in microgrids—and the DOE laboratories were active in the DOD-led SPIDERS program, with its emphasis on cyber-secure microgrids for military bases (see endnote to box G). However, SPIDERS encouraged defense-unique solutions (the DOE labs figured prominently in some of them), and thus did little to advance commercial *or* military deployment of microgrids. Current DOE-DOD collaboration is limited to one-on-one projects, with individual DOE laboratories supporting microgrid deployment at specific fixed installations.

As box G describes, DOD's efforts regarding microgrids are proceeding on two tracks: DOD's ESTCP is continuing to fund the demonstration and validation of new commercial microgrid technologies on military bases, and the services are deploying microgrids using appropriated funds and third-party financing. While it continues to provide support for applied R&D on microgrid technology, DOE should recognize the opportunity DOD represents to accelerate actual deployment—including civilian deployment-- of microgrids.

A DOE-DOD partnership would speed military and civilian deployment of microgrids in key ways. First, DOE's understanding of and ability to model grid services would help DOD better determine the economic value microgrids offer when operating in grid-tied mode. Second, DOE has unique hardware-in-the-loop facilities that would allow DOD and others to test microgrid controllers and optimize their design in a fraction of the time it now takes. Third, DOD's microgrids offer an ideal test bed for experimentation with robust cybersecurity systems, which should be of interest to DOE's new Office of Cybersecurity, Energy Security, and Emergency Response, as it tries to accelerate the development of such systems.

DOE's advanced small modular reactors (SMRs) program should look to DOD as an early customer. DoE's Office of Nuclear Energy has long provided support for R&D, testing, and permitting of small modular nuclear reactors, which can enhance energy security for communities and federal facilities by ensuring they have power during an extended blackout. No SMR or vSMR has yet received an NRC license—although that could change—and the economic prospects for SMRs and vSMRs remain highly uncertain.

As box I discusses, DOD's fixed installations, whose needs for vSMR-type systems are aligned with those of civilian users, could contribute to their commercial deployment. DOD is not expected to invest RDT&E resources in stationary vSMR technology, and it is unlikely to pay a premium for the energy generated by a vSMR. However, DOD installations in remote locations, which often pay high rates for unreliable power, would be an ideal early market, assuming vSMRs can be shown to be affordable. The nuclear industry is eager to exploit that opportunity, and DOE can support it by providing testing for vSMRs, assisting in permitting, and facilitating third-party financing.

DOE, through its Building Technologies Office and Federal Energy Management Program, should lead a government-wide effort to demonstrate and validate energy technologies for the built environment in federal facilities. DOE supports energy technologies for the built environment at either end of the technology maturation continuum (research and diffusion), but not the intermediate stages. However, such technologies face a number of impediments to commercialization and widespread adoption, and many of them will need to undergo extensive demonstration and validation in real buildings if they are to transition successfully to the marketplace (see appendix). The federal government is the world's largest property owner—and its portfolio of buildings is ideally suited for this activity.

DOD's Installation Energy Test Bed has narrowed its focus to microgrids and storage, and DOE's own Energy Efficient Buildings Hub, which carried out demonstration and validation at a single, nonoperational location (a flawed approach in our view), was cancelled in 2016.

DOE should lead a government-wide effort to demonstrate building energy technologies in federal facilities. For starters, the Building Technologies Office (BTO) should couple the funding it provides for emerging technologies with a requirement that technology developers test their technologies in federal buildings. Such a partnership would allow DOD and other federal agencies to take more direct advantage of the advanced technologies BTO is funding—and BTO would capture the lessons learned from real-world testing of its technologies. Beyond that, BTO and the Federal Energy Management Program (FEMP) should foster demonstration and validation activities across the federal government through high-level leadership, coordination, and shared funding. While DOD and the General Services Administration (and possibly other entities such as the U.S. Postal Service) are uniquely positioned to carry out this demonstration and validation role, they are reluctant to fund it on their own.

Recommendations for Organizations Other Than DOE

Congress should direct the National Research Council to conduct a study to identify impediments to and opportunities for greater DOE-DOD collaboration on energy technology RD&D. The National Research Council (NRC) has deep expertise in military requirements and technology, including its Air Force Studies Board, Naval Studies Board, and Board on Army Research and Development. These boards are made up of outside experts who participate in NRC studies pro bono, with support from NRC staff. NRC also has deep expertise in energy technology and policy.[117] Congress should task NRC with conducting a study that would identify impediments to greater DOE-DOD collaboration on energy technology RD&D, and recommend specific opportunities for and ways to reduce the impediments to such collaboration.

The U.S. Agency for International Development should explore opportunities to exploit DOD's work on tactical microgrids. The U.S. Agency for International Development (U.S. AID) is responsible for coordinating Power Africa, a U.S. government-led partnership whose mission is to double access to electricity across the continent by 2030. To meet its goal of 60 million new connections, Power Africa is helping to expand grid rollout efforts and scale off-grid energy through microgrids and solar home systems.

U.S. AID should examine DOD's tactical microgrid initiative, including DOD's RDT&E investments and the military's role as an early market, to determine whether it can support U.S. AID's needs. The robust, automated, low-cost, and field-repairable systems DOD is developing for its contingency bases could provide a solution for small and remote communities in Africa. In addition, DOD's ability to set technical standards for tactical microgrids could support Power Africa's mission; by allowing a developer to seamlessly integrate microgrid components from different manufacturers, technical standards would promote competition, thereby driving down costs.

APPENDIX: ESTCP'S INSTALLATION ENERGY TEST BED

Emerging technologies hold great promise for improving energy performance in the built environment, but they face major impediments to commercialization and adoption.[118] Because such technologies largely serve to lower the cost of already low-cost commodities (electricity and heat), few building owners are willing to pay a premium to be an early adopter, instead preferring to wait and purchase a proven technology later on. The fragmented structure of the building sector compounds the problem, as the savings to any individual building owner are small.

A key problem is the lack of evidence-based data on the performance of the technologies under real-world conditions. For example, component technologies are highly cost sensitive: To be of value, a light-emitting diode light fixture or a condensing boiler must provide the same or better service at reduced life-cycle costs than more traditional technologies. Life-cycle costs, in turn, depend on factors such as the level of skill required to operate the technology, maintenance requirements, and tenant acceptance. Absent real-world performance data that addresses these and other factors, a potential user cannot evaluate true life-cycle costs.

The same is true for new systems approaches to energy control and management, which integrate component technologies across an entire building or campus of buildings. Although these approaches promise dramatic gains in energy performance, their effectiveness depends on a host of conditions, such as the nature of building operations (e.g., working hours of 9–5 versus 24/7), the variability of loads, and human interactions, to name a few.

As the largest U.S. consumer of facility energy, the Department of Defense has a direct self-interest in seeing this major barrier to technology commercialization and adoption reduced. And as the owner of 300,000 buildings, DOD is uniquely positioned to help address the need for data on the performance of these technologies under real-world conditions.

DOD does this by using its installations as a distributed test bed to demonstrate and validate the technologies in a real-world, integrated building environment. In 2009, DOD's ESTCP created the Installation Energy Test Bed. ESTCP uses a competitive process to select the technologies to be tested, and it funds the technology developer to conduct rigorous testing and assessment of the performance and life-cycle costs of the technology while addressing DOD-unique security issues. The technology developer (which must be a commercial firm, rather than a lab or university) also provides guidance and design information for future deployment of the technology across installations. By centralizing the risk and distributing the benefits of new technology to all military installations, ESTCP can provide a return on DOD's investment in the test bed.[119]

ESTCP has funded 134 energy technology demonstrations, of which 70 have been fully completed, in 5 areas:

- Advanced components to improve building energy efficiency, such as advanced lighting controls, high-performance cooling systems, and technologies for waste-heat recovery
- Advanced building energy management and control technologies
- Tools and processes for design, assessment, and decision-making on energy use and management
- Onsite energy generation, including waste-to-energy and building-integrated systems
- Advanced microgrid and storage technologies

Although new funding is going largely to microgrid and storage technologies, projects in the other areas are still underway.

Illustrative Projects

- 3M's daylight redirecting films can redirect up to 80 percent of the natural light from a window to interior space as far as 40 feet away. 3M installed the films in six DOD buildings, scattered across three climate zones, which were selected in part based on the availability of "control" space that would allow for a side-by-side comparison. The demonstration showed it was necessary to position a "diffusion film" in front of the redirecting film in order to reduce glare. After spending many months making that change, 3M released its daylight redirecting films commercially.
- Simuwatt Energy Audit is a cloud-based software that lowers the time and cost to perform walk-through building energy audits while preserving the data to facilitate portfolio-wide tracking, reporting, and decision-making. In this case, ESTCP supported both the development and demonstration of the technology—by Concept3D, in partnership with DOE's National Renewable Energy Laboratory. The demonstrations at six DOD facilities allowed Concept3D to refine the software solution, which it subsequently made available commercially.
- In addition to Simuwatt, ESTCP has supported the demonstration of a number of innovative auditing and diagnostic technologies, including FirstFuel Software, which audits the performance of buildings remotely using only utility-provided interval meter data supplemented by publicly available data. DOD (along with the General Services Administration) went on to be an early customer of FirstFuel's now-highly successful remote auditing services.
- General Electric's (GE) microgrid control system uses dynamic real-time algorithms and an energy management dashboard to control the complex interactions among electrical demand, heat and power generation, energy storage, and power distribution. GE perfected its microgrid control system during a three-

year demonstration at a Marine Corps base in California, and immediately released the technology commercially.

- United Technologies Corporation's (UTC) continuous commissioning technology uses automatic sensors and advanced modeling to adjust building controls in real time to maintain optimal performance. Although the technology has been used in a few high-profile buildings to cut energy use by half, UTC's goal is to make it cost-effective for deployment at scale. UTC demonstrated the technology at two DOD sites in Illinois. Using the results of these tests, UTC undertook larger demonstrations that, while still pre-commercial, were carried out for commercial customers in Asia. Having worked out major kinks and automated some of the more labor-intensive steps, UTC has been making the technology available in other parts of the world, with plans to enter the U.S. market after it gains additional experience.
- Soladigm demonstrated its electrochromic windows at Marine Corps Air Station Miramar in San Diego, CA. Electrochromic windows tint electronically to reduce solar-heat gain, thus allowing a building to get by with a smaller cooling system and eliminating the need for window shades.[120] The windows were installed on three sides of a building to validate the technology at scale and determine whether the building occupants liked it. Although the demonstration was considered a success, electrochromic windows remain a niche product.

ENDNOTES

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6. Army Environmental Policy Institute, "Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys," September 2009, https://www.aepi.army.mil/docs/whatsnew/SMP_Casualty_Cost_Factors_Final1-09.pdf.
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8. See for example, "2016 Operational Energy Strategy," 2016, https://www.acq.osd.mil/eie/Downloads/OE/2016%20DoD%20Operational%20Energy%20Strategy%20WEBc.pdf. See also the FY17 Annual Energy Management and Resilience Report, op. cit.
9. See endnote 20. OSD tracks spending on initiatives designed to increase warfighter capabilities, reduce logistics risks, and enhance mission effectiveness.
10. This role goes back at least to 1798 when the Army, fearing a war with France, contracted with Eli Whitney to produce 10,000 muskets within two years. Although it took him more than a decade to fulfill, the contract allowed Whitney to refine and apply his system of interchangeable parts, which gave rise to modern manufacturing and the assembly line. See, for example: https://en.wikipedia.org/wiki/Eli_Whitney
11. See, for example, Vernon W. Ruttan, *Is War Necessary for Economic Growth? Military Procurement and Technology Development,* Oxford University Press, 2006.
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13. Consortium for Science, Policy and Outcomes, op. cit., p. 5.
14. Consortium for Science, Policy and Outcomes, op. cit., p. 3.
15. David C. Mowery and Nathan Rosenberg, *Paths of Innovation: Technological Change in 20th-Century America,* Cambridge University Press, 1999.
16. David C. Mowery, Richard R. Nelson, and Ben R. Martin, "Technology Policy and Global Warming: Why New Policy Models Are Needed (or Why Putting New Wine in Old Bottles Won't Work)," *Research Policy*, Vol. 39, Issue 8, October 2010.
17. John A. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World*, Harvard Business School Press, 1992.
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19. The figures in table 1 reflect what the administration requested for FY19 as opposed to what Congress appropriated. Congress increased the administration's FY19 request for DOD energy RDT&E by about

$25 million (part of a $2 billion plus-up for DOD RDT&E overall); however, the final appropriations bill does not indicate how the plus-up is allocated across budget categories.

20. Table 1 is based on appendix E of DOD's "Fiscal Year 2019 Operational Energy Budget Certification Report," July 2018, available at: https://www.acq.osd.mil/eie/Downloads/OE/FY19%20Budget%20Certification%20Report.pdf. Appendix E lists about 250 operational energy initiatives, including but not limited to RDT&E. Individual RDT&E initiatives are identifiable by their program element number, which begins with "06," followed by two digits that refer to the specific RDT&E budget category into which they fall. For example, "0602" refers to 6.2 activity (applied research).

21. "Overview of DoD Energy & Power S&T," Energy & Power Community of Interest, Power Point Presentation, December 2017, https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2018/04/EPCOI_FY17_DistroA_SnT_Roadmap_20180227.pdf. The Energy & Power Community of Interest (E&P COI) includes the senior technical experts from the services and OSD who coordinate DOD's RDT&E activities in energy and power. Although the COI focuses on operational energy, the stated goal applies to facility energy as well.

22. Although we use the generic term "soldier" here, dismounted warfighters come from the ranks of all the military services, not just the Army, and include special forces units such as Navy SEALS and Air Force Combat Controllers. Members of the special forces carry some of the most sophisticated and power-intensive equipment used by ground troops.

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25. For a discussion of soldier-carried batteries, see John A. Alic, "Defense Department Energy Innovation: Three Cases," in Consortium for Science, Policy and Outcomes, op. cit., pp. 15–30.

26. U.S. Army, "U.S. Army Researchers Hope to Lighten the Battery Load for Soldiers," op. cit.

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31. Remarks by former Marine Corps Commandant Gen. James Conway, Atlantic Council, "Innovation at the Nexus of Advanced Energy and National Security," April 13, 2017.

32. Pacific Northwest National Laboratory, "Concept of Operations (CONOPS) for Powering Future Contingency Bases, Version 1.0," April 2017. See also DOD, Defense Science Board, op. cit.

33. Although figure 1 shows directed energy weapons (DEWs) as being part of the energy load at a future contingency base, DEWs will have dedicated power sources to meet their unique power requirements. See the "Weapon Power" section.

34. "Concept of Operations (CONOPS) for Powering Future Contingency Bases," op. cit.

35. Jeffrey Marqusee, Craig Schultz, and Dorothy Robyn, "Power Begins at Home: Assured Energy for U.S. Military Bases," Noblis, commissioned by the Pew Charitable Trusts, January 2017, https://www.pewtrusts.org/~/media/assets/2017/01/ce_power_begins_at_home_assured_energy_for_us_military_bases.pdf.

36. The Army recently increased the requirement to 14 days. However, bases cannot meet that requirement simply by adding fuel storage capacity: An additional week of operation would accentuate the existing reliability problems with backup generators, causing more of them to fail.

37. Marqusee, Schultz, and Robyn, op. cit.

38. Marqusee, Schultz, and Robyn, op. cit., pp. 25–27.

39. Marqusee, Schultz, and Robyn, op. cit., pp. 28–34.

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42. Todd South, op. cit.

43. Aric Haynes et al., op cit.; "'Pay Attention to the Power': An Interview with Dr. Rich Carlin," op. cit.

44. Another major RDT&E initiative is the Army's Improved Turbine Engine Program, which will allow helicopters to fly "higher and hotter" while carrying twice the number of troops and burning 20 percent less fuel.

45. Some sources distinguish between remotely piloted vehicles and truly autonomous vehicles. We use "autonomous" to refer to both.

46. Paul Scharre, *Army of None: Autonomous Weapons and the Future of War*, W. W. Norton & Co., 2018.

47. DOD is proposing to spend $1.1 billion on directed energy RDT&E in FY19, double the FY17 figure.

48. To elaborate, HELs' advantages include speed: Lasers engage targets at the speed of light. Another advantage is control: HELs can be dialed up or down with precision, which both allows for nonlethal as well as lethal applications and limits collateral damage. A third advantage is the energy to operate HELs comes from the electricity supplied by the platform: Simply stated, HELs will never run out of ammo (in DOD terminology, they have a "deep magazine") as long as power is available. Moreover, their direct cost—the fuel needed to produce the electricity—is only about a dollar a shot, which means higher-cost missiles and interceptors can be reserved for the most demanding threats.

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52. Jared Keller, "The Navy's Super Railgun is Dead (and Alive)," *The National Interest* (November 17, 2018), https://nationalinterest.org/blog/buzz/navys-super-railgun-dead-and-alive-36407.

53. Mary Miller, acting assistant secretary of Defense for Research and Engineering, quoted in Jon Harper, "Directed Energy Weapons: Can the Pentagon and Industry Deliver?" *National Defense* (October 26, 2018), http://www.nationaldefensemagazine.org/articles/2018/10/26/directed-energy-weapons-can-the-pentagon-and-industry-deliver.

54. Sarwat Chappell, op. cit.

55. Consortium for Science, Policy and Outcomes, op. cit.

56. These pathways can be thought of as mechanisms. Most of the technologies we identify, and our four "cases" in particular, are influenced by DOD investment in multiple ways—i.e., through multiple mechanisms. Since this section of the report is structured around pathways, for organizational purposes, we discuss specific technologies in the context of that pathway (mechanism) which in our view has had or will have the greatest influence on their development; but those discussions recognize the broader (multi-pathway) impact of DOD investment.

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58. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World*, op. cit.

59. National Science Foundation, *Science & Engineering Indicators*, https://www.nsf.gov/statistics/seind/. NSF typically invests around $1 billion per year in engineering R&D. Only DOE invests more than DOD in engineering R&D.

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63. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World*, op. cit.

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65. According to Will Rowley, an engineer with the Army's Communications-Electronics Research, Development and Engineering Center (CERDEC), the conversion process is more efficient when the light comes from a laser as opposed to the sun. "A solar panel has low efficiency just because it has to pick up many different wavelengths or colors. With a laser, however, you have one single wavelength or color of light. It can be much more efficiently absorbed, and that [PV cell] can be specifically engineered to get the maximum power conversion out of that [laser] light." Matt Leonard, "How it Works: The Army's Laser-Powered Drone Project," *GCN* (September 13, 2018), https://gcn.com/articles/2018/09/13/army-lasers-drone.aspx.
66. Kyle Mizokami, "Drones Recharged by a Laser Could Fly Forever," *Popular Mechanics* (August 8, 2018), https://www.popularmechanics.com/military/research/a22677285/darpa-drones-recharged-laser-silent-falcon/.
67. Nancy Owano, "Laser-Powered-Drones May Beat Endurance Hurdles," *Tech Xplore* (September 6, 2018), https://techxplore.com/news/2018-09-laser-powered-drones-hurdles.html.
68. Daniel Parry, "NRL Space-Based Solar Power Concept Wins Secretary of Defense Innovative Challenge," U.S. Naval Research Laboratory News Release (March 11, 2016), https://www.nrl.navy.mil/news/releases/nrl-space-based-solar-power-concept-wins-secretary-defense-innovative-challenge; Bryan Bender, "Harnessing the Power of the Sun from Space," *Politico* (August 10, 2018), https://www.politico.com/story/2018/08/10/solar-satellite-sun-probe-naval-research-laboratory-771264.
69. For a discussion of DOD's role in the development of the gas turbine/jet engine, which utilities began to buy in the 1980s, see Alic, "Defense Department Energy Innovation: Three Cases," op. cit., pp. 15–19.
70. Jim Mathews, "Engines of Innovation," *Air Force Magazine* (August 2017), http://www.airforcemag.com/MagazineArchive/Pages/2017/August%202017/Engines-of-Innovation.aspx. In addition to the bypass ratio, Mathews emphasizes the importance of the fan pressure ratio of the air that the fan takes in and the air that it discharges. Commercial aircraft engines have a low fan pressure ratio; fighter jet engines have a high fan pressure ratio. See also, Gareth Evans, op. cit.
71. Mathews, op. cit.
72. We use the term "silicon" to refer to crystalline silicon. Although there is another type of silicon—amorphous silicon—it represents a small and shrinking market, so we ignore it here.
73. "Unlocking Clean Energy," *Issues in Science and Technology,* Winter 2017, https://issues.org/unlocking-clean-energy/. There are parallels between silicon PV and Li-ion, the dominant battery technology some analysts worry could drive out technologies better suited to providing grid-level storage. See David M. Hart, William Bonvillian, and Nathaniel Austin, "Energy Storage for the Grid: Policy Options for Sustaining Innovation," MIT Energy Initiative, April 2018, http://energy.mit.edu/publication/energy-storage-for-the-grid/.
74. Thin-film technologies, including cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS), have a small share of the solar PV market. We do not discuss them here because their efficiency levels (12–16 percent) are too low for DOD to be a significant customer.
75. The Air Force's planned manufacturing pilot will focus on the use of hydride vapor-phase epitaxy (HVPE) for low-cost epitaxial growth. The other two cost drivers in the fabrication of III-V materials are substrate reuse and back-end processing.
76. Bruce Dorminey, "Trump Should Make Space-Based Solar Power a National Priority," *Forbes* (March 18, 2017), https://www.forbes.com/sites/brucedorminey/2017/03/18/trump-should-make-space-based-solar-power-a-national-priority/#42f1e553e691.
77. Richard Silberglitt, James T. Bartis, and Kyle Brady, "Soldier-Portable Battery Supply: Foreign Dependence and Policy Options," RAND Corporation, 2014, https://www.rand.org/pubs/research_reports/RR500.html.

78. For example, the Army has patented a Li-ion battery that is more energy dense and safe than commercial Li-ion batteries. The key is a high-voltage cell that provides large amounts of both stored energy and power. (In a high-voltage cell, the amount of stored energy is proportional to the voltage, and the power is proportional to the square of the voltage.) This particular cell uses a lithium cobalt phosphate and a high-voltage stable electrolyte. Another battery the Army has developed uses a highly concentrated aqueous (water-based) chemistry to eliminate the risk of fire.

79. Government Accountability Office, “Batteries and Energy Storage: Federal Initiatives Supported Similar Technologies and Goals but Had Key Differences,” GAO-12-842, August 2012, https://www.gao.gov/assets/650/647742.pdf.

80. Like grid-related commercial customers, DOD values stationary storage because it enables demand response, peak shaving, and other grid-related applications. The higher value DOD places on long-duration storage reflects its greater vulnerability to grid outages and its security-driven need to maintain operations, even during extended blackouts. This additional “value stream” is significant. For example, if a storage system eliminates the need for a backup generator, a military base could justify buying the system sooner rather than waiting until its price drops.

81. ESTCP has awarded six contracts to technology developers to model and potentially build and demonstrate full-scale prototypes of new stationary storage technologies, and gather data on their technical and economic performance under operational conditions. The results will be made publicly available. See the solicitation at https://www.serdp-estcp.org/Funding-Opportunities/ESTCP-Solicitations/Past-solicitation-pages/Installation-Energy-and-Environment-FY19/Outside-DoD-Federal-Proposal-Instructions2/FY19-ESTCP-Federal-Outside-DoD-EW-Topic-B9-Energy-Storage.

82. DOE, *2017 Renewable Energy Data Book*.

83. DIU is itself located on a former Navy base, Moffett Field, which NASA now controls. Moffett Field is the site of three historic airship hangars the Navy built in the 1930s and 1940s to house dirigibles and other aircraft. In 2014, NASA leased the hangars and the surrounding 1,000-acre site to Google, which is using the hangars as laboratories for developing drones, Internet-carrying balloons, and other technology. See, for example, Mike Wall, “Google Leases NASA’s Historic Moffett Field, Historic Hangar for $1.2 Billion,” *Space.com* (November 11, 2014), https://www.space.com/27741-google-leases-nasa-moffett-field.html.

84. Both authors were directly involved with ESTCP and the Installation Energy Test Bed. Marqusee was the director of ESTCP from 1995 to 2013, and Robyn, whose responsibilities at DOD from 2009 to 2012 included oversight of ESTCP, made the Installation Energy Test Bed one of her priorities.

85. Scott Van Broekhoven et al., “Leading the Charge,” *IEEE Power & Energy*, August 2013.

86. Although microgrid systems have been in use for years, they have been relatively unsophisticated, with a limited ability to integrate renewable and other distributed energy sources, little or no energy storage capability, uncontrolled load demands, and “dumb” distribution that is subject to excessive losses. Smart microgrids will serve as local power networks that can utilize distributed energy, manage local energy supply and demand, and operate seamlessly both in parallel to the grid and in “island” mode.

87. Dorothy Robyn, deputy under secretary of Defense for Installations & Environment, testimony before the House Armed Services Committee, Subcommittee on Readiness (March 29, 2012), https://www.acq.osd.mil/eie/Downloads/Testimony/robyn_testimony_hasc%20mar292012.pdf. See also, Marqusee, Schultz, and Robyn, op. cit.

88. “Microgrid vendors” is a catch-all term that includes firms that build the components used in microgrids (controllers, switches, batteries, communication devices, etc.); firms that design and build the microgrid system but do not manufacture components; and firms that do both.

89. See appendix.

90. Another important DOD investment in microgrid RDT&E was the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) program, which ran from 2011 to 2015. Led by DOD in collaboration with DOE and the Department of Homeland Security, SPIDERS

demonstrated ever more complex microgrids at three military bases in Colorado and Hawaii. The program focused heavily on cybersecurity (an emphasis ESTCP has since adopted) and encouraged defense-unique solutions, much like a traditional DOD acquisition program. By contrast, ESTCP consciously facilitates the development of commercial technology DOD can access as a (commercial) customer. Separate from ESTCP and SPIDERS, a number of military bases have carried out their own microgrid demonstrations.

91. National Guard bases often play a key role in disaster response and other events that coincide with large-scale blackouts. Although a typical National Guard base consumes only a few megawatts of electricity, and all such bases have backup generators, a microgrid is a more effective source of energy security.

92. The diffusion of cell phones may be a useful analogy. Just as cellular technology has allowed users in underdeveloped and remote parts of the world to get telecommunications service despite the absence of a wireline network, tactical microgrids will provide electricity in the absence of an electric grid. Only after cell phone manufacturers' and service providers' focus shifted from high-end customers to the mainstream market in developed countries did they begin targeting less-developed areas with lower-cost models.

93. Jeff Decker, "Reviewing Defense Innovation: Five Incentives for Forming Pentagon-Startup Partnerships," *War on the Rocks* (May 3, 2018), https://warontherocks.com/2018/05/renewing-defense-innovation-five-incentives-for-forming-pentagon-startup-partnerships/.

94. John Alic et al., "A New Strategy for Energy Innovation," *Nature* (July 15, 2010), https://cspo.org/library/opinion-a-new-strategy-for-energy-innovation/. See also David C. Mowery, "Federal Policy and the Development of Semiconductors, Computer Hardware, and Computer Software: A Policy Model for Climate Change R&D?" in *Accelerating Energy Innovation: Insights from Multiple Sectors*, Rebecca M. Henderson and Richard G. Newell (editors), University of Chicago Press, 2011, https://www.nber.org/chapters/c11753.

95. A bandgap refers to the amount of energy needed to release electrons in semiconductor materials so they can move freely, thus enabling the flow of electricity. Because WBG chips have larger bandgaps than silicon chips, electrical current applied to the device excites fewer electrons across the gap, which enables superior current control and reduces energy losses. Compared with their silicon counterparts, WBG devices can operate at higher voltages and power densities, which allows the same amount of power to be delivered with fewer chips and smaller components. They can also operate at higher frequencies, which helps simplify system circuitry and reduce system costs. In addition, their greater heat tolerance allows WBG devices to operate in harsher conditions and reduces the need for bulky insulation and additional cooling equipment. DOE, "Power America," https://www.energy.gov/eere/amo/power-america.

96. Consider an electric warship or a hybrid-electric armored tank with their many electric loads—propulsion, electric weapons, high-powered sensors, and multiple mission-specific electric modules. Since it is not practical for every load to have its own power source, the vehicle's power control system must ensure that all loads receive the power they need, when they need it. That is a major challenge, requiring many power converters. WBG devices allow for smaller converters, which means that more of them can fit into the vehicle. They also provide for higher power density, which will help a tank accelerate faster and a shipborne directed energy weapon get the pulse power it needs.

97. Kirsten Korosec, "GM is Working with the U.S. Navy to Bring Hydrogen Power to Underwater Drones," *Fortune* (June 23, 2016), http://fortune.com/2016/06/23/gm-navy-hydrogen-fuel/. According to the Naval Research Laboratory's head of alternative energy, Karen Swider Lyons, "[The Navy] is looking for weeks if not months of endurance….Highly reliable systems can take decades to develop and billions of dollars and we think we've found that with our partnership with General Motors."

98. The Army has spent the last two years testing GM's new "ZH2," based on the Chevy Colorado, which comes equipped with a 50-kW battery—charged by the fuel cell—that can be removed to power other applications. Daniel Wasserbly, "AUSA 2018: GM Develops Next-Generation ZH2 Hydrogen Fuel Cell-Powered Truck," *Jane's 360* (October 10, 2018), https://www.janes.com/article/83683/ausa-2018-gm-develops-next-generation-zh2-hydrogen-fuel-cell-powered-truck. DOE Office of Energy Efficiency &

Renewable Energy, "4 Ways that Fuel Cells Power Up the U.S. Military," September 13, 2017, https://www.energy.gov/eere/articles/4-ways-fuel-cells-power-us-military. On the strength of its fuel-cell work with the Navy and Army, GM has recreated a space and defense division (GM sold off its defense division in 2003 to General Dynamics), https://www.thetruthaboutcars.com/2018/10/general-motors-defense-division-up-and-running-hires-army-veteran-as-president/.

99. Naval Research Laboratory, "Ion Tiger Fuel Cell Powered UAV," https://www.nrl.navy.mil/lasr/content/ion-tiger-fuel-cell-powered-uav.

100. Michael E. Ruane, "How Do You Dismantle a Nuclear Power Plant? Very, Very Carefully," *Washington Post* (February 1, 2019), https://www.washingtonpost.com/history/2019/02/01/how-do-you-dismantle-nuclear-power-plant-very-very-carefully/?utm_term=.2304b378b75a. The other, largely remote, sites included Sundance Air Force Station, WY; Fort Greely, AK; Camp Century, Greenland; and McMurdo Station, Antarctica. Juan A. Vitali, U.S. Army deputy chief of staff (G-4) et al., "Study on the Use of Mobile Nuclear Power Plants for Ground Operations," October 26, 2018, https://apps.dtic.mil/dtic/tr/fulltext/u2/1064604.pdf; and "Army Nuclear Power Program," Wikipedia, https://en.wikipedia.org/wiki/Army_Nuclear_Power_Program.

101. For one source of analysis that helped inform this position, see Marcus King, LaVar Huntzinger, and Thoi Nguyen, "Feasibility of Nuclear Power on U.S. Military Installations," CNA, March 2011, https://www.cna.org/CNA_files/PDF/D0023932.A5.pdf.

102. "vSMRs may create an opportunity to invert the expeditionary energy supply paradigm from energy scarcity to abundant energy….. Not only could a reactor reduce the need for logistics related to power, but now-abundant power could essentially substitute or reduce the need for other infrastructure and logistics needs such as water, munitions, and potentially even fuel or spare parts. Defense Science Board, op. cit., p. 31.

103. Vitali et al., op. cit.

104. Specifically, the vSMR needs to be deployable by truck, ship, or cargo aircraft; designed for quick setup and teardown; capable of semiautonomous operation; and able to run for more than three years without refueling and with zero risk of a core meltdown should power and cooling be lost. See Request for Information, https://www.fbo.gov/index?s=opportunity&mode=form&id=da9031a5e3f2247392fc0559bd6a9e2f&tab=core&_cview=1.

105. This paragraph is a distillation of the more detailed case laid out in Alic, "Biofuel Battles: Politics, Policy, and the Pentagon," op. cit.

106. Alic, "Biofuel Battles: Politics, Policy, and the Pentagon," op. cit.

107. Even if it were willing to do so, DOD is not the right agency to lead a federal R&D initiative in biofuels. Such an initiative should focus on developing a fuel for cars and trucks because ground vehicles represent the biggest potential market for biofuels, and they are forgiving in terms of the types of fuel they will run on, which reduces the R&D challenge. By contrast, a DOD-led initiative would invariably focus on jet fuel, as aviation accounts for most of the military's operational energy consumption. The development of an alternative to jet fuel is far more challenging from an R&D perspective—and the potential market is far smaller.

108. This figure includes $4.5 billion in applied energy R&D and $2.6 billion in basic energy R&D (the basic energy sciences and fusion energy sciences lines in the Office of Science budget). John F. Sargent, Jr., "Federal Research and Development (R&D) Funding: FY2019," Congressional Research Service, October 4, 2018, Table 10, https://fas.org/sgp/crs/misc/R44888.pdf.

109. Because DOD and DOE use different taxonomies to describe their RDT&E, we cannot compare budget categories directly. The "Fundamental Research" category shown in figure 3 corresponds to what DOD calls basic research (6.1). "Technology Development" includes all of what DOD considers applied research (6.2) and early-stage advanced technology development (6.3). "Translation" includes later-stage advanced technology development (6.3) and all of what DOD calls demonstration and validation (6.4).

"Early Adoption" includes what DOD refers to as system development and demonstration (6.5) and operational system development (6.7).

110. Note that while neither department spends more than 10 percent of its RDT&E budget on early adoption, in DOD's case, that statistic is misleading because the vast majority of the military's early-adoption spending is supported by the Defense Department's procurement and military construction budgets.

111. National Science Foundation, *Science and Engineering Indicators*, https://www.nsf.gov/statistics/seind/.

112. The exception is naval nuclear reactors. DOE's National Nuclear Security Administration (NNSA) is responsible for producing the Navy's nuclear propulsion reactors, and the director of Naval Reactors in DOD (the position originally held by Admiral Hyman Rickover, the "father of the Nuclear Navy") also serves as a deputy administrator of NNSA.

113. In 2012, SunShot awarded $25 million to Soitec, a French semiconductor manufacturer, to operate a large factory in southern California as part of SunShot's effort to foster a competitive U.S. solar manufacturing base. ESTCP agreed to demonstrate the technology at the 1-MW scale on two separate bases (ultimately, the demonstration went forward at only one base, Fort Irwin, in California's Mojave Desert). Under the arrangement between DOD and DOE, SunShot provided the PV modules to the military at no cost, and ESTCP paid for the balance of the system and its installation. Although Soitec subsequently exited the solar business, it continued to support the demonstration at Fort Irwin.

114. Although the process is not linear, successful new technologies, including energy technologies, advance through four stages: fundamental research and technology development; technology translation, wherein pre-commercial prototypes and manufacturing processes are developed and demonstrated; early technology deployment, in which customers begin to adopt the new technology; and technology diffusion, with deployment expanding until it is widespread. The critical process of "learning by using" takes place during the translation stage. Learning by using allows developers to understand the relationships between design choices and performance, and to quantify the value propositions a new technology offers; it is essential to product development. "Learning by doing," which begins during the early adoption stage, includes the critical process of improving manufacturing efficiency, which leads to reductions in cost.

115. David M. Hart, "Making 'Beyond Lithium' a Reality: Fostering Innovation in Long-Duration Grid Storage," ITIF, November 2018, https://itif.org/publications/2018/11/28/making-beyond-lithium-reality-fostering-innovation-long-duration-grid.

116. DOE, "Department of Energy Announces Funding to Support Long-Duration Energy Storage," May 1, 2018, https://arpa-e.energy.gov/?q=news-item/department-energy-announces-new-projects-extend-grid-energy-storage

117. One of the authors of this report (Robyn) is a member of the NRC's Board on Energy and Environmental Systems (BEES).

118. The appendix draws on Section 9 ("Federal Technology Test Beds") of the "Report of the Secretary of Energy Advisory Board Task Force on Federal Energy Management," September 2016, https://www.energy.gov/sites/prod/files/2016/11/f34/9-2216_Report_of_SEAB_Federal_Energy_Management_TF_w_transmittal.pdf. Dorothy Robyn was a member of the task force and drafted Section 9 of its report. See also Robyn, Testimony before the House Armed Services Committee, op. cit.

119. The key is scale. If DOD demonstrates ten new technologies and three of them do not work out, it can deploy the other seven and still get a return on its investment because of the size of DOD's inventory. Thus, DOD accepts risk on individual projects in order to achieve a return across the program as a whole. For the same reason, Walmart, one of the largest private-sector energy consumers in the United States, operates its own test bed, systematically testing innovative energy technologies at designated stores to assess their performance and cost, and deploying the ones found to be cost-effective.

120. Electrochromic windows illustrate the impediments to commercialization of technologies for building energy efficiency. The major benefit of these windows will be the capital equipment savings from using a smaller heating, ventilation, and air conditioning (HVAC) system. Architecture and engineering (A&E) firms typically are responsible for sizing the HVAC system for a new building. No A&E firm will take the risk of installing a smaller chiller, however, without compelling evidence the windows will work as promised. Although DOE has helped fund the development of the technology, and venture capitalists have invested in it, the cost of electrochromic windows remains high and the demand limited. DOD's large-scale demonstration can help reduce the impediments to widespread commercialization by providing rigorous data on technical and economic performance as well as qualitative information on occupant comfort and productivity. DOD in turn becoming an early customer would further help jump-start the market.

ACKNOWLEDGMENTS

The authors are grateful to John Alic, Richard Carlin, David Hart, John Jennings, Henry Kelly, and David Mowery for their input to and comments on a draft of the report. They also want to thank the following individuals for their valuable input: Robert Atkinson, Valerie Browning, Lee Buchanan, Robert Charette, John Conger, George Crabtree, Jeff Decker, Ben Drake, Lisa Jung, Chris Kirchhoff, Mark Lewis, Arun Majumdar, Dennis McGinn, Dan Misch, Mike Mitchell, Richard Schilke, Amanda Simpson, Ben Steinberg, Edward Strohbehn, and Mike Telson.

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