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The Role of Energy Storage in Meeting 21st Century Department of Defense Energy Demands

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Executive Summary

Power and energy are critical to all Department of Defense (DOD) missions. As the capabilities of the force have increased through the years, so have the power and energy demands, and this situation has led DOD to begin factoring energy into key decisions. Despite an escalating number of energy goals and initiatives, the role of energy storage is not well established across the varied DOD use environments.

This paper focuses primarily on power and energy use in operational energy environments: expeditionary base camps, aviation systems, surface systems, and soldier power. Results from a literature review and interviews with subject matter experts (SMEs) were used to explore the role of energy storage in each of these environments. In addition, some of the most important parameters that should be considered when implementing energy storage technologies are described.

A brief overview of energy storage options for DOD is included along with some DOD-specific challenges, such as balancing investments in commercial and military-specific technology. The most prominent technical metrics for comparing energy storage technology are reviewed along with recently proposed operational energy metrics that could aid implementation. Additional pathways to implementation including demonstration and modeling are also discussed.

Key findings from this work include the following:

- Power and energy systems have traditionally been designed to meet a specific soldier-, platform-, or infrastructure-required capability. Integration and consideration of the range of these use cases have only recently been recognized as necessary to reduce energy use, and achieve efficiencies that simultaneously balance their competing demands.
- DOD faces constant pressure to increase force capabilities, which are often tied to higher power and energy demands. In operational scenarios, a choice must be made between decreased soldier loads and extended duration or increased capabilities. Improvements in energy storage technology can either reduce battery weight for a given amount of energy or pack more energy into the same size of battery. Decision makers must strategically consider what is most important (lighter weight or more energy) for a given situation.

- DOD environments pose some unique challenges to energy storage (e.g., weight concerns and extreme operating temperatures) that do not always allow for direct insertion of commercially available products. To leverage commercial technologies best while still developing modified or military-specific technologies, open architectures should be used to ensure that future systems can be integrated as needed.
- Technical metrics for energy storage technologies are well developed, but they are insufficient for aiding effective and efficient implementation in DOD environments. Operational metrics are critically needed to enable decision makers to implement energy storage solutions.
- Demonstration mechanisms for experimenting with and evaluating energy storage devices and integrating these devices into overall DOD energy systems are needed. This approach includes coupling energy production alternatives with management systems and storage approaches. The Experimental Forward Operating Base (ExFOB) is a good start, but more experimentation and demonstration are required at all levels to encourage innovation and, perhaps most importantly, to identify risks and overcome barriers to implementation.
- Organizational approaches for managing energy assets and focusing attention on energy systems for operational energy should be explicitly examined. The vastly increased demand and importance of operational energy has not been accompanied by the needed organizational capabilities and focus. These capabilities include technical expertise and training throughout the operational structure, managerial and organizational focus, analyses and assessments on alternatives that can provide needed energy most affordably and effectively, and demonstration and experimentation to facilitate development and transition of new capabilities.

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1. Introduction

A safe and reliable supply of power and energy is critical to all Department of Defense (DOD) missions. Every warfighter, weapons system, and platform, as well as base and operational infrastructure, depend on a form of stored energy or power delivery for successful operation. Moreover, operation on the modern battlefield demands increased amounts of power and energy due to advances in everything from battlefield intelligence to protection and detection, which increasingly rely on sophisticated electronics. As military systems become more complex so too will the power and energy demands, which are projected to grow more rapidly than current power generation and energy storage technologies can support. Simultaneously, competition for the world's oil supply, concern about climate change, and threats to logistics supply chains complicate access to power and energy. Appropriate power and energy solutions are therefore essential to meeting mission requirements without compromising task performance.

Assured access to power and energy has been a long-standing concern for DOD. The effects of shortages were visible during World War II when it became a controlling factor in critical times (Macksey 1986). Yet, only recently have energy considerations begun to factor into DOD decision making. This change was highlighted by the Defense Science Board (DSB) Task Force (2008) report that recommended that DOD "make energy a factor in the key Departmental decisions that establish requirements, shape acquisition programs and set funding priorities" (p. 3). Furthermore, it called on the department to reduce battlefield fuel demand and ensure uninterrupted power supply at critical military installations. Modest progress has been made since that time, including the release of the inaugural Operational Energy Strategy in 2011 and an Implementation Plan in 2012. Despite actions that coordinate operational energy responsibilities through the Assistant Secretary of Defense for Operational Energy Plans and Programs (ASD(OEPP)), each of the Armed Services maintains different energy goals and energy initiatives (Schwartz, Blakeley, and O'Rourke 2012).

Among the various goals and initiatives of the Armed Services, energy storage is a consistent interest since it provides many potential benefits in operational and installation environments. However, consideration of energy storage options has been fragmented across different DOD components, and the role it can play in various DOD environments is not well documented. Thus, this study addresses the following questions:

- What are DOD power and energy use environments?
- What is the role of energy storage in these environments?
- What are some suitable energy storage options?
- What are the problems of energy storage in these environments?
- What are some appropriate operational metrics that could help in implementing energy storage across each DOD environment?
- How can storage technologies and solutions be implemented across DOD?

A. Terminology

While power and energy are commonly used interchangeably, it is important to note the distinct technical differences between them. Specifically, *power* refers to a rate of energy delivered over time, often expressed in terms of watts (W). In contrast, *energy* is a measure of the amount of work performed by a physical system and is often quantified by joules (J), watt-hours (Wh), or British Thermal Units (BTUs). Energy can exist in several forms, including thermal, mechanical, or electrical. Within the military context, energy sources include petroleum (naturally occurring oil and gas), coal, renewables, and nuclear energy.

Because power and energy are nearly inextricable concepts, they are typically discussed together within the DOD context. Moreover, technologies such as fuel cells, which are energy conversion devices that produce power by drawing upon external energy sources (e.g., hydrocarbon fuel), are often examined as replacements for energy storage devices, including batteries. Thus, in alignment with DOD discussions on the topic, this paper will focus on power and energy storage that includes energy storage technologies (e.g., batteries) and energy conversion technologies (e.g., fuel cells) and hybrid systems that may also use power generation devices. Combined, these technologies provide the ability to deliver power and energy at the time and location desired.

B. Study Approach

The study began with a review of internal and external literature, including authoritative reports from organizations such as the National Research Council (NRC) and the Congressional Research Service (CRS) and a combination of programming documents, DOD reports and briefings, and other technical documents. Results were augmented through discussions with subject matter experts (SMEs) from organizations that include the CRS, the Defense Advanced Research Projects Agency (DARPA), and members of DOD's Power Sources and Technology Working Group.

2. DOD Power and Energy Use Environments

DOD power and energy use can be divided into two broad categories: installation energy and operational energy. Installation energy, sometimes referred to as facilities energy, is the energy that does not qualify as operational energy, including non-tactical vehicle use. Operational energy is defined in law[1] as the energy required for training, moving, and sustaining military forces and weapons platforms for military operations.

Drawing upon multiple sources (U.S. Army 2010; Shaffer 2012; Kidd 2011), DOD power and energy use environments can be subdivided further as shown in Figure 1. These environments will be described more fully in the following sections.

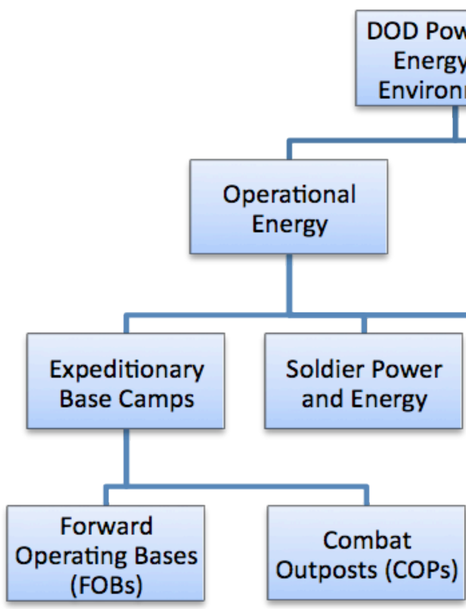
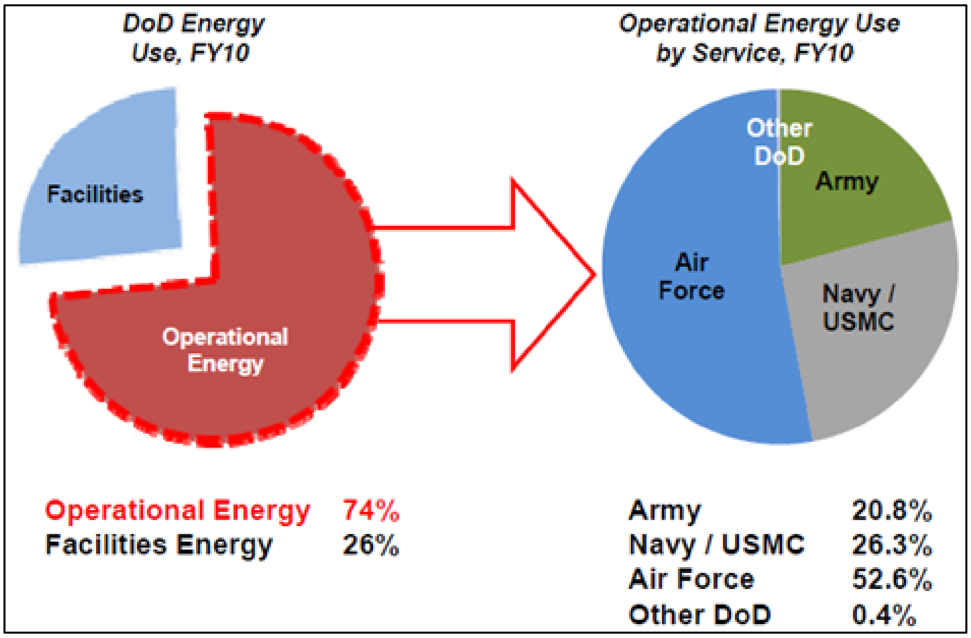


Figure 1. DOD Power and Energy Use Environments

In fiscal year (FY) 2010, the breakdown of operational vs. installation energy use was 74 percent and 26 percent , respectively, as shown in Figure 2. When breaking out the energy use into the separate Services, their varying missions and operations clearly result in some notable differences in demand. Despite these differences, each of the Services stands to benefit from the implementation of appropriate energy storage technologies.

[1] Section 2821(a) of the FY 2012 National Defense Authorization Act (H.R. 1540/P.L. 112-81 of December 31, 2011); 10 U.S.C. 2924.



Source: Fritz 2012, 4.

Figure 2. Comparison of Installation and Operational Energy Use, FY10

As evidenced in the following sections, power and energy systems have traditionally been designed to meet a specific soldier-, platform-, or infrastructure-required capabilities. Integration and consideration of the range of these use cases have only recently been recognized as necessary to reduce wasted energy and achieve efficiencies that simultaneously balance their competing demands.

A. Installation Energy

Although installation energy represented just one-fourth of DOD's total energy use in FY 2010, it remains a significant portion of DOD's energy-use portfolio. This level of use reflects current operations in Afghanistan and Iraq, but the split between installation and operational energy will likely be much different during peacetime (Schwartz, Blakeley, and O'Rourke 2012). DOD is now using demonstration projects at installations to test, evaluate, and scale-up innovative, emerging energy technologies, including energy storage.

At permanent installations, energy storage promises energy security and resiliency since it reduces dependence on the local grid. Furthermore, it can also provide the following:

- **Power quality.** Stored energy is used on the order of seconds or less to ensure continuity of quality power.

- **Uninterruptable power supply (UPS) bridging.** Energy storage enables continuous service when switching from one power source to another.
- **Energy management.** Energy storage can accommodate periodic variation in power-generating capacity, help to avoid peak demand issues, and maintain optimal loading of generators.
- **Energy security assurance.** Energy storage is critical for the ability to maintain power to facilities during grid outages. Typically, energy storage takes the form of liquid fuel for basic backup operations and battery storage to supplement generators with variable renewable power sources (Van Broekhoven et al. 2012). Further, the capability to operate independent of grid power provides capabilities that allow bases to be removed intentionally from the grid—"islanded"—in situations where security issues may warrant such action.

B. Operational Energy

Operational energy encompasses operations and facilities that range from semi-permanent installations in a conflict area, to Spartan combat outposts with only a small number of soldiers, to deployed squads either in vehicles or on foot. This section provides an overview of the role of energy storage and its requirements in the full range of operational energy environments:

- **Expeditionary base camps.** Vary greatly in size, purpose, and period of operation but include a variety of critical systems and other functions.
- **Surface systems.** Ground and maritime systems with maximum mobility and deployability.
- **Aviation systems.** Include manned and unmanned systems.
- **Soldier.** Longer times, greater distances, and at a sustained operational tempo.

1. Expeditionary Base Camps

In this paper, expeditionary base camps fall into one of two types:

- **Forward operating bases (FOBs)**. FOBs are semi-permanent bases located in a forward military position. They are typically sized to support a brigade or larger population, and energy demands tend to expand over time as the power needs of the base also grow. Some FOBs are used for extensive periods of time, but they usually consist of temporary or semi-permanent structures, electrical power grids, water and sewage systems, and force protection systems.
- **Combat outposts (COPs).** COPs include everything from patrol bases to anything smaller than an FOB. They are intended to sustain small units for extended

periods within their operational space. While no two COPs are exactly the same, most employ tents for shelter and use generators for power. The infrastructure includes temporary wiring, water storage, and austere shower facilities, which tend to be inefficient and therefore represent significant demand-reduction opportunities.

Although similarities are found in nearly all base camps (e.g., life support), unique tactical and geographic situations prevent a uniform approach to expeditionary power. These widely dispersed and highly variable operations are usually located away from sustained and dependable power sources. Generally, this situation has necessitated that U.S. or Allied forces provide expeditionary power, and, to date, this power has been provided primarily by diesel-fueled electricity generators supporting ad hoc electricity networks.

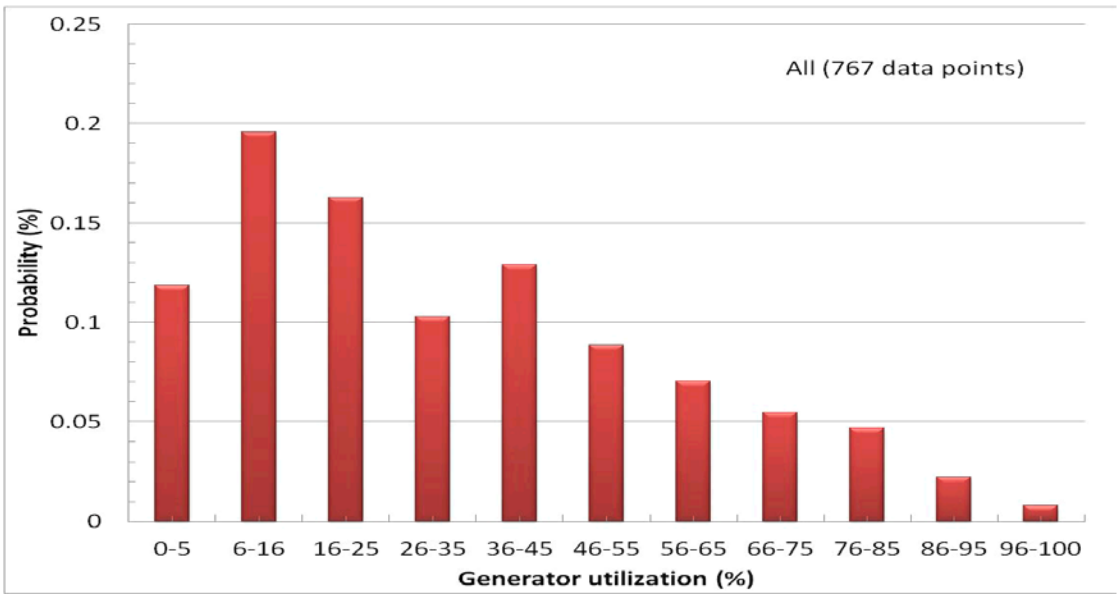
a. Role of energy storage

Energy storage solutions for FOBs and COPs should provide capabilities to use existing generators and the potential to integrate new generating technologies into the existing portfolio. Due to the logistical challenges of delivering fuel to expeditionary camps, the most direct application of energy storage is to support the existing infrastructure in ways that reduce overall fuel use. More permanent FOBs would be able to use larger scale storage solutions for applications such as grid-scale load balancing, permanent solar integration, and peak shaving to minimize generator use while maximizing efficiency.

Several primary motivating factors and applications underline the major roles that storage could increase capabilities at bases:

- **Power backup.** During events when load shedding is required, power backup capabilities would allow for mission-critical systems to remain powered for longer durations or for additional numbers of systems to remain operational until generating capabilities can be brought back online. As shown by hybridization efforts, existing lead-acid battery technologies have already been used for short-term energy storage and power backup (Newell and Shields 2012).
- **Load balancing for more efficient generator use.** Tactical generators generally on the scale of 15 to 500 kW are the primary "work-horse" generator sets used for contingency basing. Anecdotal and measured data on generator use shows that a mismatch often exists between the demands on tactical generators and generator fuel-use efficiency. The tactical generators operate most efficiently at 80 percent to 100 percent loads but face a 40 percent to 50 percent drop in generating efficiency at the 25 percent loads typical during deployed operational use (Bowes and Pifer 2010). Despite the potential to optimize generator loads, this "capacity

factor" is often very low in practice. Through spot measurements of 767 generators, the U.S. Marine Corps (USMC) Expeditionary Energy Office (E2O) demonstrated that the median capacity factor is a 32 percent load and that only 10 percent of the generators in operation have capacity factors of 80 percent plus, as demonstrated in Figure 3. This finding indicates the potential to substantially improve energy efficiency by coupling energy storage with generator use.



Source: Newell and Shields 2012.

Figure 3. E2O Spot Measurements of Generator Efficiency

- **Supporting the integration of renewable power technologies.** Micro-wind turbines and photovoltaic (PV) systems are intermittent and only produce power when natural resources (wind or sun) are available. Wind resources are highly location dependent and also have their own radiation or radar hazards. PV technologies generally require good power management systems to integrate with existing resources successfully and efficiently (Shaffer 2012). Storage levels required for renewable power technologies vary depending on the scale of the renewable system at the installation; however, systems are generally no larger than several 100 kW of peak generation (Newell and Shields 2012). USMC E2O efforts have attempted to integrate hybrid generating systems where tactical quiet generators (TQGs) are paired with PV panels. This system demonstrated several benefits of this hybrid approach: the system realized a 56 percent fuel-use reduction over traditional TQG-only operation, and generator run time was reduced by 78 percent (Newell and Shields 2012).

- **Enabling power management capabilities through microgrids.** This category refers to the use of specific energy-generating, energy-storage, and controls technologies to optimize generating capacity and provide scaling potential as loads increase and bases increase (or decrease) in size. Microgrid technology incorporates automated control technologies and aggregates load demand from multiple sources to meet the current and expected demands of the system most efficiently. Currently, microgrid design concepts are being developed by several organizations within DOD (e.g., Environmental Security Technology Certification Program (ESTCP)) and are being tested at Continental United States (CONUS) bases and at FOBs in Afghanistan (Shaffer 2012). This technology integration effort is being targeted to support load profiles on the order of 1 MW and is being deployed as a package solution where conservation efforts such as tent insulation, liners and shades, and lighting efficiency efforts (e.g., light-emitting diodes (LEDs)) are integrated into the "off-the-shelf" technology solution (Shaffer 2012).

b. Important parameters

Tactical applications of energy storage at FOBs and COPs vary widely depending on the overall scale and requirements of individual bases and the underlying generating equipment that is maintained on-site. The following parameters have been identified as important considerations for base camp power storage:

- **Power output.** Command Operations Center (COC) storage must be able to meet peak loads in the range of 4 to 5 kW per COC, with potential long-term requirements in the range of 150 kW to 10+ MW (DARPA BAA 2011).
- **Energy densities.** Energy densities are less critical in FOBs and COPs than other requirements, although DARPA has set long-term goals at 1,000 Wh/kg.
- **Cycle life.** Long cycle-life is desired for tactical microgrid applications or small-scale renewables integration due to constant cycling.
- **Integration with legacy equipment.** Storage must use existing diesel generator sets, TQGs, and new Advanced Medium-sized Mobile Power Sources (AMMPSs) at scales from 5 kW to 60 kW (Newell and Shields 2012).
- **Integration with international standards.** This integration is necessary to ensure interoperability with equipment as needed.
- **Gross weight, modularity.** Storage must meet basic logistical constraints of maximum dimensions and weight for transport (DARPA BAA 2011).

2. Surface Systems

Ground vehicles consume a significant portion of the operational energy budget. Combat and tactical vehicles use fuel while providing their basic services, including hauling troops and cargo, protecting warfighters, attacking enemy combatants, and supporting facility operations and logistics on bases (U.S. Army 2010). Further, these vehicles must also provide mobility and power for a vast and increasing set of combat and tactical systems including sensors, communications, computers, weapons, and environmental controls (U.S. Army 2010). Within the Army, 58 percent of energy is used by vehicles and equipment, and 42 percent is used for stationary facilities (Kidd 2011).

a. Role of energy storage

The three large-use cases for energy storage in ground vehicles are (1) hybrid boost and regenerative braking for propulsion, (2) starting, lighting, and ignition (SLI), and (3) "silent watch," the ability to idle engines while maintaining power for communications and surveillance equipment (Zanardelli 2009). Other needs include onboard weapons systems and smaller robotics, although unmanned ground vehicles (UGVs) can also be considered part of soldier power. Overall, these use cases can be divided into areas in which energy storage provides power to run a mobile device (robotics, UGVs) directly, to propel a vehicle, or to power onboard equipment (e.g., communications and sensing equipment) other than propulsion.

1) Energy storage for propulsion

Traditionally, ground transportation vehicles are propelled by an internal combustion engine, which is coupled to an alternator that provides electric power to a battery for uses other than propulsion, such as SLI. So-called hybrid electric vehicles (HEVs) conserve fuel by using electrical energy (typically stored in a battery) to assist propulsion during times of low-efficiency engine use and to recapture energy that would be lost to heat during braking through a process called regenerative braking.

The Army has been interested in hybridizing propulsion systems for tactical vehicles for many years and has spent at least $100 million in tactical HEV research and development (R&D) since the mid-1990s (Raney 2007). The first tactical HEV, the hybrid electric High Mobility Multipurpose Wheeled Vehicle (HMMWV) (aka, the Humvee) was tested in 1999, and R&D has been ongoing on high-power pulse technology and alternative architectures to house HEV drivetrains throughout the 2000s (David and Bochenek 2011). While much of the original purpose was to save fuel, the ability to perform silent watch, provide additional onboard vehicle power (OBVP) for electric equipment, and provide backup power for tactical outposts also provided significant benefits. However, the broader use of tactical HEVs has been held back, in part, by the need to find energy storage options that can meet rigorous military needs.

This need to match energy storage and rigorous military needs has not dampened the desire for increasing alternative fuel vehicles (AFVs) and full electric vehicles (EVs) among non-tactical fleets. For instance, 40 percent of Army's current non-tactical fleet of 80,000 vehicles are either AFVs or hybrid vehicles, and 1,000 of these vehicles are low-speed EVs (Kidd 2011). Current R&D focus areas include combining hybrid propulsion and onboard power; increasing the energy density of existing HEV batteries through alternative chemistries, safety and reliability testing, thermal management, manufacturing process control; and coupling capacitors and batteries to take advantage of high-power burst energy and bulk energy storage (David and Bochenek 2011).

2) SLI/silent watch

The other two large-use cases—SLI and "silent watch" capabilities for powering advanced equipment specific to military uses (e.g., weapon systems, communications, sensors, and so forth)—are grouped together because they usually rely on similar electrical systems that produce power by the vehicle alternator (typical for conventional and hybrid non-tactical vehicles) or, in some cases, by regenerative braking. OBVP demand for tactical vehicles has increased substantially and continues to increase. Further, shifting from the tactical vehicle's main engine to an energy storage device or a smaller auxiliary power unit (APU) can decrease the acoustic signature of the vehicle substantially, providing "silent watch" capability with attendant tactical advantages. By providing either an exportable APU or OBVP, a vehicle can also power a tactical outpost in place of a portable generator—a further advantage.

OBVP demand and the ability to provide silent watch capability have become more difficult while increasing in necessity due to rapidly rising vehicle power demands. New systems, including autonomous navigation systems, hit-avoidance systems, imaging and targeting systems, and many others, have increased tactical power demands from around 2 kW on past and current Abrams and Bradley models to an estimated 45 kW on the Ground Combat Vehicle (GCV) (Zanardelli 2009). If this full 45-kW power draw is used over typical time spans of 6 to 72 hr, the total energy need for silent watch ranges from 270 to 3,240 kWh for the GCV. This amount of storage is large compared with the current generation of hybrid electric, plug-in hybrid electric, and full EV batteries, which range from 5 kWh to 40 kWh (Zanardelli 2009). Even with advanced lithium-ion (Li) batteries that deliver 60 Wh/kg energy density, providing this storage would add 4 to 50 tons of mass and an impractical volume to the GCV.

Because of these large and growing power demands, significant work has been done to develop APUs that will provide some of the benefits of true silent watch along with the ability to store significantly more energy than possible with the current generation of energy storage devices. The Army Research Laboratory (ARL) continues to work to enhance OBVP and produce under-armor APUs such as one demonstrated for the M1

Abrams, which could save 4,300 gal/day/brigade, increasing range by 18 mi or saving $86,000/day at $20/gal (Shaffer 2009). A more exotic solution for current-generation silent watch vehicles (on the order of 10 kW) is in development—using a JP-8 reforming fuel cell, again coupled with advanced batteries. For future power demands such as the GCV, the Army's goal is to achieve this 45 kW at a fuel consumption rate of 2.5 gal/hr while remaining undetectable at 50 m at a failure rate of less than 1,140 hr (Zanardelli 2009).

The Army has also conducted R&D to develop a new 6T Li-ion battery for SLI and silent watch. Given the standard form factor, a wide range of customers would exist for such a battery, and the Army is collaborating with other agencies and commercial and military original equipment manufacturers (OEMs) (Dobbs 2011). The generation-1 battery has an energy density that is twice the density of the standard lead-acid 6T battery, allowing either extended silent watch or an increase in productive space onboard the vehicle (Ding 2012). The Army has also signed an agreement with the Department of Energy (DOE), called the Advanced Vehicle Power Technology Alliance (AVPTA), that includes the demonstration and evaluation of the 6T Li-ion battery for non-military uses.

b. Important parameters

Many energy storage parameters are important for military ground systems. While some of these parameters are similar to important parameters for commercial vehicles, others differ from their commercial counterparts. For instance, energy density is critical for all mobile systems (commercial and military) because the added mass of onboard energy storage decreases fuel efficiency. However, military mobile applications also differ in several ways from commercial energy storage solutions for vehicles. Important military system parameters include the following:

- **Energy density.** Less mass can be traded off with increased fuel economy or increased functionality (e.g., silent watch length). Further, military systems are often considerably heavier than commercial ground systems due to greater equipment, armor, and so forth.
- **Temperature range.** Military systems often require broader operating ranges than comparable commercial systems.
- **Safety.** Several issues associated with increased shocks, vibrations, and temperatures are important.
- **Thermal management.** While always important for batteries, thermal management can be more difficult in the broad operating environments of military systems (Raney 2007).

3. Aviation Systems

Manned and unmanned aviation systems are a critical component of operations. As was the case with Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF), future operations will probably continue to rely on aircraft and aerial delivery to support situational awareness and sustainment (U.S. Army 2010).

a. Role of energy storage

While energy storage typically takes a back seat to issues of light weight or fuel economy, it remains a critical component of aviation systems and can provide a variety of potential benefits that include the following:

- **APUs.** Efficiency drops precipitously as a fuel-burning engine decreases its output. Thus, shutting the main engine down and using an auxiliary power unit makes sense when possible to provide for low loads, such as radios and heating or cooling.
- **Unmanned aerial system mission endurance.** Compared to conventional, fossil-fueled systems, energy storage offers the promise of increased endurance for unmanned aerial systems, without increasing the logistics tail.
- **Hybrid-electric propulsion.** In this system, propulsion would be provided efficiently by two or more power sources, including an internal combustion engine and an electric motor. Many variants exist, just as for surface systems. For aviation systems, current options are too heavy and bulky to compete with the internal combustion engine. Ultimately, using a hybrid-electric propulsion engine would be a transformational development. It is a potential option that could be especially beneficial for unmanned aerial systems.
- **More-electric architecture.** This architecture is a concept in which components of an aircraft are built in a way that maximizes efficiency. Energy storage can help in balancing and synchronizing energy use and production within aircraft.

b. Important parameters

Many of the parameters important to energy storage for surface systems also apply to aviation systems; however, several parameters, such as sustained and reliable operation at high altitudes, are unique to this environment. Key parameters for energy storage in aviation systems include the following:

- Lightweight design and materials, which equate to increased fuel economy or the ability to add other systems for improved capabilities;
- High power density, which is needed for directed energy weapons and will place extreme demands on the aircraft electrical system to provide sufficient power;

- Consistent operation over a wide temperature range (from –40°C to +71°C) with exposure of up to +85°C, to an altitude of up to 65,000 ft (U.S. Navy 2010);
- Long lifetime, which reduces costly maintenance time; and
- Safety (though not as important in the case of unmanned aerial systems (outside of launch and recovery)), which remains a critically important consideration for suitable energy storage options.

4. Soldier

Soldier power includes lightweight energy sources that are either carried directly by a soldier or are highly portable. Examples range from commercial off-the-shelf (COTS) "AA" batteries to rucksack portable PV arrays, which support a wide variety of critical systems including communications and battlefield awareness equipment.

a. Role of energy storage

Energy storage has been an integral component of soldier power for a long time, but significant room for improvement remains and can provide the following:

- **Extended mission duration.** One objective is to find or develop storage technologies or alternative practices that can extend deployed dismounted unit operations beyond 72 hr for the given power demands. Moreover, it must provide power to the dismounted soldier who does not have access to a vehicle that can be used to recharge batteries or provide reliable access to a power supply.
- **Reduced logistical burden.** Modern technology devices increase the combat power of combat units and provide a technological advantage. This increased use of technology on the battlefield has caused a significant increase in mobile power requirements that is being met currently by batteries or rechargeable batteries. As noted by the NRC study (2004), providing power for forces in the field has become a major logistical problem. While several efforts have been made to improve power sources, these attempts are limited by the laws of physics, issues of safety (especially for fuel cells), and the inefficiencies of energy transfer and use. Technological solutions for supplying energy to the dismounted soldier are elusive. As for demand, while conservation is advisable, limiting the use of modern devices that provide our troops an edge would be self-defeating.
- **Lighter loads.** A major constraint is the warfighter combat load while he/she conducts dismounted combat patrols. A dismounted soldier or marine may carry from 35 to 100 lbs of gear that includes body armor, a protective helmet, weapons, ammunition, food, water, mission-essential tactical gear, and batteries. The weight of batteries carried on patrol is estimated to be up to 10 lbs, depending on the duty position and duration of the patrol. Even if the battery weight were to be

reduced, the consensus is that something else (e.g., another magazine of ammunition) would be added. Soldier energy demand is increasing as more individual and unit capabilities that require electricity are added. Figure 4 shows the types of individual equipment that dismounted soldiers currently carry. Added to this load would be any unit-level equipment, such as counter-improvised explosive device (IED) detectors, robots, or tactical unmanned aerial vehicles (UAVs).

Source: Mapes 2012, 9.

Figure 4. Typical Load for a Soldier on a 72-hr Mission in Afghanistan

b. Important parameters

In general, the current requirements of energy storage for soldier power include the following:

- Providing specific power and energy for soldier-carried storage devices;
- Extending soldier power requirements, which will increase today's 4 W continuous requirement to an approximately 200 W continuous requirement for future systems;
- Reducing energy consumption via power management algorithms;

- Integrating standard form factors in an attempt to reduce the quantity and variety of batteries (from typical 7 to 8) carried by the soldier and also maintain inter-operability with North Atlantic Treaty Organization (NATO) equipment;
- Identifying locally available energy sources and soldier power technologies;
- Providing interoperable interfaces between soldier systems and infrastructure and vehicle-mounted energy systems; and
- Developing rugged systems that are easy to operate and safe under the extreme battlefield operating conditions.

3. Energy Storage Options

The list of energy storage technologies with capabilities that are swiftly improving is growing. Yet, no one-size-fits-all option is available, so it is important to understand the demands and requirements of a use environment when attempting to implement energy storage solutions. Moreover, achieving one desired performance parameter may have a negative effect on another, thus requiring careful consideration and prioritization of needs from an operational standpoint.

This section will provide an overview of technologies from highly portable to stationary and then discuss possible metrics that would help program managers (PMs) and other decision makers in choosing the appropriate options.

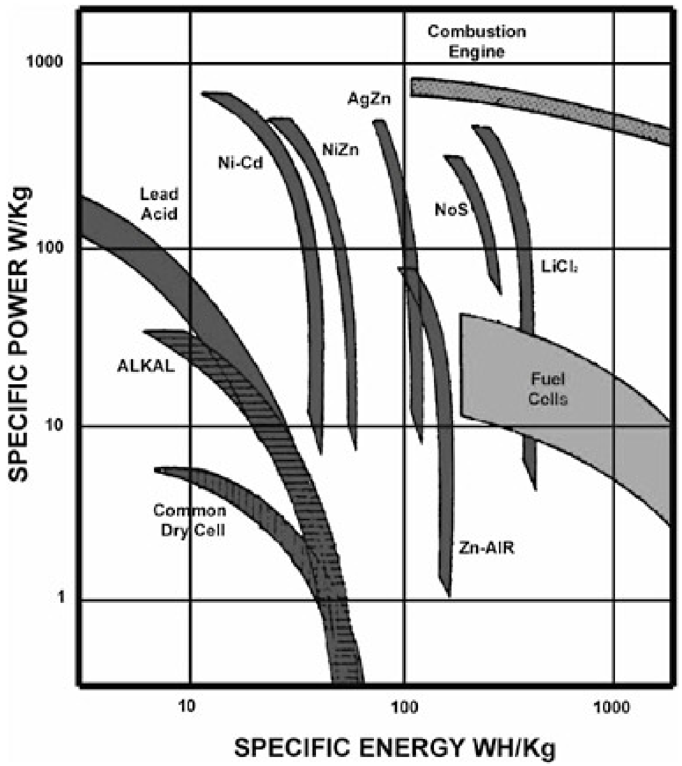
A. Technology Options

Energy storage can serve as the power source for a wide range of products ranging from hand-held radios for communication to vehicle propulsion and grid scale load-leveling. Each of these scenarios presents a different set of challenges, thus necessitating a variety of energy storage technology options. Many types of energy storage are available, and each falls into one of the following categories:

- Mechanical (pumped storage hydropower, compressed air energy storage, springs, flywheels),
- Thermal (thermal storage),
- Chemical (batteries, fuel cells), and
- Electromagnetic (super capacitors, superconducting magnetic energy storage).

Individual technologies in these categories face many tradeoffs. One of the most well-known tradeoffs is that of power density and energy, which is commonly presented in the form of a Ragone plot that charts specific power (W/kg) against specific energy (Wh/kg) (see Figure 5). As seen in the plot, most technologies provide either high specific power or high specific energy but not both. The combustion engine is the best example of high specific power and energy, but this feature comes at the cost of low efficiencies when compared with the other technologies on the chart.

Hybrid systems allow for accessing the advantages of multiple technologies. These systems combine multiple energy-storage technologies from the aforementioned categories, sometimes with generators or other secondary power sources such as PV solar

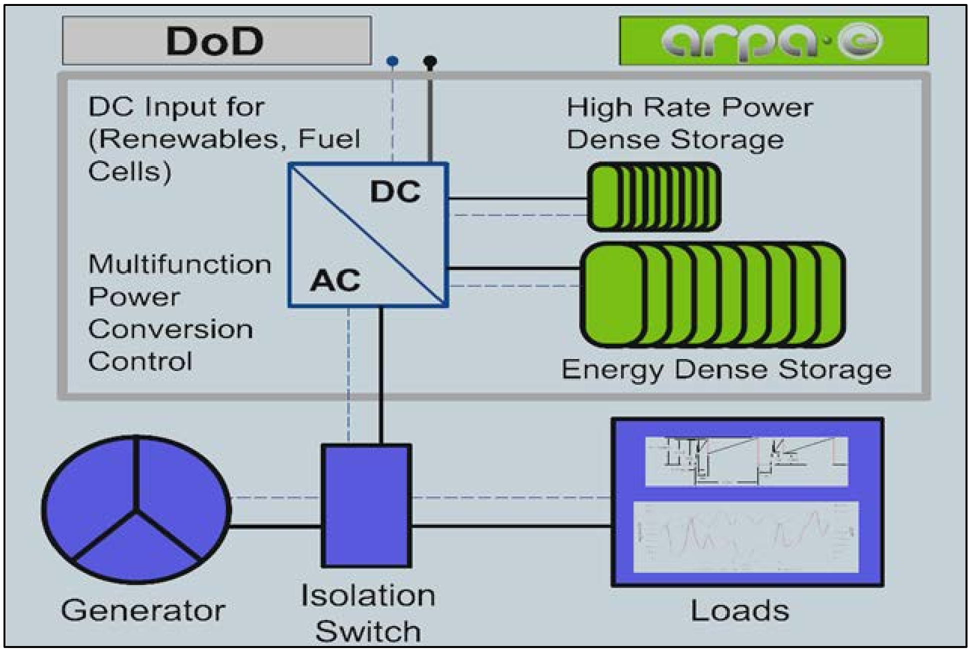


Source: National Research Council 2004, 40.

Figure 5. Ragone Plot of Various Energy Storage Systems

panels, all with controls designed to automate the performance of the system. Since each individual storage technology has tradeoffs (e.g., high power density but low energy density), creating a hybrid system allows a solution that could provide the advantages of each component technology. This type of solution is true in the case of the Hybrid Energy Storage Module (HESM), which is being developed in a program that is a joint effort by the Advanced Research Projects Agency-Energy (ARPA-E) and the Assistant Secretary of Defense for Research and Engineering (ASD(R&E)). The system, shown in Figure 6, uses multiple storage devices to provide high power density and high energy density that could be used on a tactical (1 to 10 kW) or distributed scale (100 kW to 1 MW). At present, a second-iteration Experimental Forward Operating Base (ExFOB) extended user evaluation is focused on hybrid power, and the system was recently deployed to Afghanistan (Newell and Shields 2012).

While the possibilities for further improvement across energy storage technologies are good and need to be pursued aggressively, the pace of improvement in areas such as portable batteries is likely to continue to be slow compared with other areas of technology development. Discussions with the current DARPA PM for soldier power show that the prospects of major advances in battery technology for portable use are regarded as highly unlikely; therefore, DARPA is focused almost exclusively on fuel-cell approaches.



Source: Hoffman and Johnson 2011.

Figure 6. Diagram of Hybrid Energy Storage Module with High Power and Energy Density

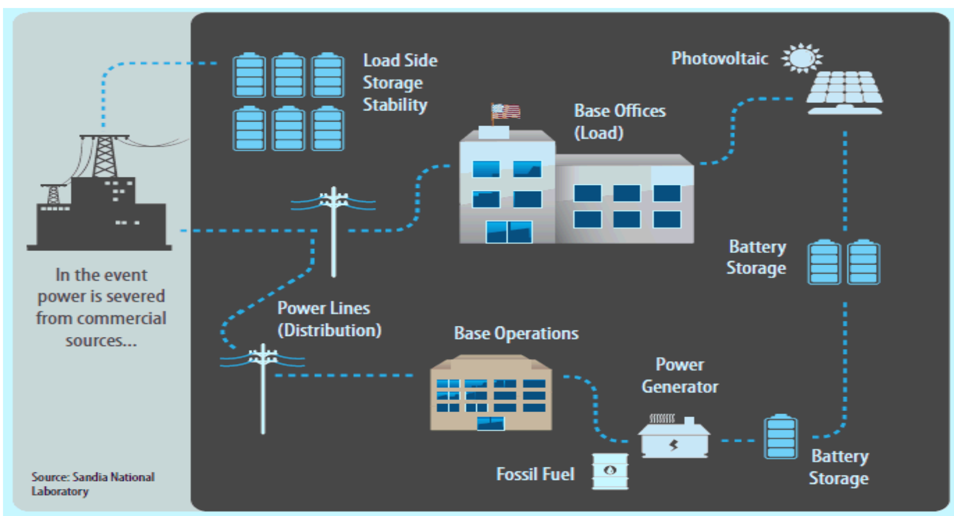
To continue to meet the demands of extended mission durations up to 72 hr, DOD must consider investing in long-term, relatively high-risk programs (e.g., Li-air batteries) and short-term hybrid and non-battery systems (National Research Council 2004).

B. Recent Trends in DOD Energy Storage

The differences in needs between facilities energy and operational energy are distinct. Furthermore, each can be split further into additional use environments with concomitant power and energy requirements that demand different energy storage solutions. For permanent installations, interest in energy storage has been recent, but a portfolio of storage technologies is being examined. Demonstrations are beginning to show the potential with selected energy storage options such as microgrids. In operational energy scenarios, batteries are the dominant energy storage technology, but additional technologies continue to be viewed as potential ways to augment capabilities. Batteries have consistently shown evolutionary improvements whereas alternatives, such as fuel cells and Stirling engines, could provide revolutionary improvements (NDIA 2011; National Research Council 2004). Despite continued R&D on promising energy storage technologies, their implementation in DOD environments is not straightforward. It requires a significant amount of additional effort to choose the right solutions for the specific application.

1. Energy Security Via the Microgrid

Microgrids are the combination and integration of several small- to medium-scale electricity generation, electricity storage, and controls technologies that can operate independently from a larger electrical grid. Often, microgrids incorporate distributed generation technologies and resources (e.g., solar PVs, microturbines), conventional small-scale generation technology (e.g., internal combustion generators), and energy storage (e.g., batteries, mechanical storage such as fly wheels), as depicted in Figure 7. The integration of these technologies with smart controls provides capabilities that allow facilities to operate in an "islanded" mode, where commercial grid electricity is not required to maintain capabilities. Microgrids have significant national defense applications for both CONUS and Outside the Continental United States (OCONUS) situations, where high-reliability facilities are faced with mitigating risks (e.g., aging electrical transmission and distribution infrastructure) or in expeditionary applications (e.g., tactical microgrids at FOBs or COPs).



Source: Pew Charitable Trusts 2011, 48.

Figure 7. Diagram of Potential Microgrid at DOD Installation

2. Recharging Systems for Extending Battery Use in Mobile Operations–Soldier Worn Integrated Power Equipment System (SWIPES)

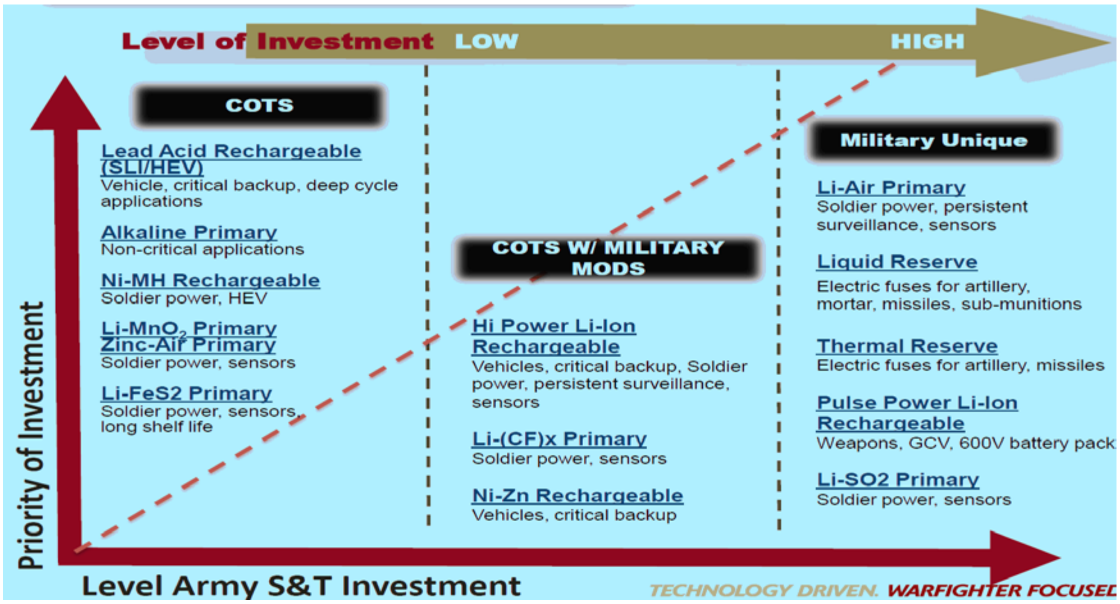
For soldier-carried electronics, one approach is to outfit the soldier with a central battery that can power multiple electronic devices. SWIPES contains a main conformal battery situated in a central location on a soldier's vest or rucksack. It employs chargers in the vest with power cables that extend to batteries, Global Positioning System (GPS) units, shot-detection systems, and handheld communications (up to four items). It reduces the weight of batteries up to 30 percent and allows for extended mission times without the need to of swap batteries or power sources by keeping devices charged at all times. This battery powers multiple end-item electronics, as shown in Figure 8.

Source: Mapes 2012, 15.

Figure 8. Diagram and Photo of SWIPES and the Accompanying Conformal Battery

C. DOD-Specific Challenges

Although many energy storage technologies are commercially available, DOD environments pose challenges that do not allow for direct insertion of commercially available products. When possible, DOD uses available commercial technologies and configurations, but some applications require operating characteristics that exceed those that are capable from these technologies. For instance, the military may require more extreme operating temperatures or resistance to salt, sand, dust, and altitude (Ding 2012). The energy and power densities required for tactical vehicle use may also be considerably higher than equivalents in the commercial sector due to the much heavier DOD vehicles. In such cases, military-specific versions must be either designed, or commercial technologies must be adapted for use. Thus, balancing the economical reliance on commercially available technologies is important while also investing in military-specific technologies, as shown in Figure 9 for Army batteries. It will also be important to use open architectures to ensure interoperability between government and commercial technologies that use energy storage technologies.



Source: Justice 2011, 32.

Figure 9. Priority and Level of Army Investments from COTS to Military-Unique Batteries

DOD faces constant pressure to increase force capabilities, which are often tied to higher power and energy demands. In operational scenarios, a choice must be made between decreased soldier loads and extended duration or increased capabilities. Improvements in energy storage technology can either reduce battery weight for a given amount of energy or pack more energy into the same size of battery. Decision makers must strategically consider what is most important (lighter weight or more energy) for a given situation.

Another important consideration for DOD is the logistics tail associated with energy storage options. The dominant soldier power source is the battery, which can pose a logistical challenge during deployment. As learned from OIF, just-in-time-logistics resupply cannot keep up with the rapid pace of military operations, leaving some of the force vulnerable when reliable delivery is not possible. The future force will require energy storage solutions that reduce the logistics burden and are adaptable to a variety of combat operations (National Research Council 2004).

In recent years, a rise in soldier-worn capability has dramatically increased the number and variety of batteries that have to be carried. This trend is unsustainable from a load and logistical perspective (Mapes 2012). Work is ongoing toward standardization of form factors and connectors and this work is necessary to ensure a tractable portfolio of soldier power systems. The military also needs convenient recharging methods that do not interfere with operations. The SWIPES (see Figure 8) is one approach to address this issue.

D. Metrics

When attempting to choose the appropriate technologies for a given environment, metrics can be a useful decision-making tool. For energy storage technologies, technical metrics are well known across the board. Examples of such technical metrics are well documented (Ashby and Polyblank 2012; NDIA 2011; Zanardelli 2010), and prominent examples include the following:

- **Energy density:** energy per unit volume;
- **Power density:** power per unit volume
- **Specific energy:** gravimetric energy (per weight);
- **Specific power:** gravimetric power (per weight);
- **Efficiency:** typically expressed as a percentage;
- **Cycle life:** how many times a device can be used before it stops performing satisfactorily;
- **Operating costs:** usually in terms of dollars/unit energy and will often include transmission and distribution costs;
- **Calendar life:** includes potential shelf life and use under specified conditions;
- **Operating temperature:** the full range of temperatures in which the system can function satisfactorily;
- **Ruggedization:** in the DOD context, can be specified by military standards;
- **Manufacturability:** ease and cost of producing the system; and
- **Safety:** ability to meet Occupational Health and Safety Administration (OSHA) standards and potential DOD standards.

Although technical metrics are mature, significant progress must still be made on developing operational metrics to assist energy storage implementation. Using appropriate metrics will help to assess tradeoffs better and ensure effectiveness and efficiency. Traditionally, DOD has focused almost exclusively on effectiveness, but that focus has created a large logistics tail and a less agile force (Bochman 2009). As DOD begins to consider the importance of efficiency, corresponding operational energy metrics that can assist in implementing technologies such as energy storage have to be developed.

The fully burdened cost of fuel (FBCF) is one example of a metric that has gained traction, particularly after the DSB study (2008) criticized DOD for systematically undervaluing the cost of fuel supply in operational energy scenarios. However, FBCF is still not well quantified or understood. It was codified in the 2009 National Defense Authorization Act as "the commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use." Despite significant analysis, widely different estimates of recent FBCF in Iraq and Afghanistan have ranged from as low as $3 to as high as $45, depending on the method of delivery (air or land), distance, and type of force protection used (Schwartz, Blakeley, and O'Rourke 2012).

A second operational energy metric that has been discussed is an energy efficiency key performance parameter (KPP). This KPP allows for the generation of requirements that fit the most important characteristics of a system based on the likely situations in which it was designed to operate (Bochman 2009). However, no program has implemented this metric.

Despite interest and progress in developing decision tools such as FBCF and the energy efficiency KPP, PMs are still left juggling schedule, performance, and non-energy costs. This approach leaves out consideration of energy and the potential efficiencies and capabilities that it could afford if it were properly included in program management and decision making.

No significant attention has yet been focused on other operational metrics, but many more could be developed to design systems for effectiveness and efficiency. Questions that could be useful in driving the development of operational energy metrics related to energy storage include the following:

- What is the potential for technology to reduce threats (e.g., through reduced noise and thermal signatures)?
- How will the technology reduce logistical burden?
- What is the potential for reducing the footprint of FOBs, COPs, and other encampments?
- What is the ability of the technology to free up other assets that can be otherwise employed in critical activities?

E. Pathways to Implementation

While developing operational energy metrics will help PMs in assessing the appropriateness of energy storage solutions for varying scenarios, many other actions are needed to implement energy storage technologies properly.

One area that is receiving more interest is the potential for modeling to aid in technology development. Hybrid systems that couple power generation with energy storage in commercial applications (i.e., power generation equipment including generator sets and PVs) often require detailed modeling for system design. However, for many of the use cases discussed here, such modeling—especially FOBs/COPs and soldier power—has been hindered by a lack of information on actual energy and power requirements in operation. Thus, activities that determine baseline energy and power requirements in operational settings continue to be crucial for developing accurate models that could incorporate advanced energy storage and its attendant mission benefits.

Another important activity is using demonstration projects to show the ability of energy storage technologies to work in actual operational scenarios. An example of this activity at the expeditionary base camp level is the second-iteration ExFob recently deployed to Afghanistan (Newell and Shields 2012), which is examining the efficiencies being afforded by hybrid systems that include energy storage technology. For other environments, such as surface systems or soldier power, sufficient testing and evaluation of advanced energy storage technologies will be critical for ensuring future implementation of newer technologies such as fuel cells.

4. Summary of Findings

From supporting radio communications on the battlefield to helping sustain operations at permanent installations, DOD relies on power and energy for all of its missions. Within the varied DOD power and use environments, a clear role for energy storage exists. However, challenges to implementation remain and include the following:

- Power and energy systems have traditionally been designed to meet a specific soldier-, platform-, or infrastructure-required capability. Integration and consideration of the range of these use cases have only recently been recognized as necessary to reduce wasted energy and achieve efficiencies that simultaneously balance their competing demands.
- DOD faces constant pressure to increase force capabilities, which are often tied to higher power and energy demands. In operational scenarios, a choice must be made between decreased soldier loads and extended duration or increased capabilities. Improvements in energy storage technology can either reduce battery weight for a given amount of energy or pack more energy into the same size of battery. Decision makers must strategically consider what is most important (lighter weight or more energy) for a given situation.
- DOD environments pose some unique challenges to energy storage (e.g., substantial vehicle weight and extreme operating temperatures) that do not always allow for direct insertion of commercially available products. To leverage commercial technologies best while still developing modified or military-specific technologies, open architectures should be used to ensure that future systems can be integrated as needed.

During this study, a few potential areas for further research were also identified:

- While the potential for modeling is significant to enable higher efficiency of installation and operational energy, the field has room for progress. However, for many of the use cases discussed here, such modeling, especially FOBs/COPs and soldier power, has been hindered by a lack of information. A strategy for recording baseline use and activities in various DOD environments could be outlined. This strategy will include an approach to measurements and, ultimately, an analysis of results.

- Technical metrics for energy storage technologies are well developed, but they are insufficient for aiding effective and efficient implementation in DOD environments. Operational metrics are critically needed to enable decision makers to implement energy storage solutions.
- Demonstration mechanisms for experimenting with and evaluating energy storage devices and integrating these devices into overall DOD energy systems are needed. This approach includes coupling energy production alternatives with management systems and storage approaches. The ExFOB is a good start, but more experimentation and demonstration are required at all levels to encourage innovation and, perhaps most importantly, to identify risks and overcome barriers to implementation.
- Organizational approaches for managing energy assets and focusing attention on energy systems for operational energy should be explicitly examined. The vastly increased demand and importance of operational energy has not been accompanied by the needed organizational capabilities and focus. These capabilities include technical expertise and training throughout the operational structure, managerial and organizational focus, analyses and assessments of alternatives that can provide needed energy most affordably and effectively, and demonstration and experimentation to facilitate development and transition of new capabilities.

Appendix A
Illustrations

Figures

Appendix B
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Appendix C
Abbreviations

AFV	alternative fuel vehicle
AMMPS	Advanced Medium-sized Mobile Power Source
AMTEC	Alkali Metal Thermal Electric Converter
APU	auxiliary power unit
ARL	Army Research Laboratory
ARPA-E	Advanced Research Projects Agency-Energy
ASD(OEPP)	Assistant Secretary of Defense, Operational Energy Plans and Programs
ASD(R&E)	Assistant Secretary of Defense for Research and Engineering
AUSA ILW	Association of the United States Army's Institute of Land Warfare
AVPTA	Advanced Vehicle Power Technology Alliance
BAA	Broad Area Announcement
BTU	British Thermal Unit
CNA	Center for Naval Analyses
COC	Command Operations Center
CONUS	Continental United States
COP	combat outpost
COTS	commercial off-the-shelf
CRRI	Center for Research in Regulated Industries
CRS	Congressional Research Service
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOE	Department of Energy
DSB	Defense Science Board
E2O	Expeditionary Energy Office
ESTCP	Environmental Security Technology Certification Program
EV	electric vehicle
ExFOB	Experimental Forward Operating Base
FCBF	fully burdened cost of fuel
FOB	forward operating base
FY	fiscal year
GCV	Ground Combat Vehicle
GPS	Global Positioning System
H.R.	House of Representatives
HESM	Hybrid Energy Storage Module

HEV	hybrid electric vehicle
HMMWV	High Mobility Multipurpose Wheeled Vehicle
IDA	Institute for Defense Analyses
IED	improvised explosive device
J	joules
Kg	kilogram
KPP	key performance parameter
kW	kilowatt
LED	light-emitting diode
Li	lithium-ion
MIT	Massachusetts Institute of Technology
MW	megawatt
NATO	North Atlantic Treaty Organization
NDIA	National Defense Industrial Association
NRC	National Research Council
OBVP	onboard vehicle power
OCONUS	Outside the Continental United States
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
OEM	original equipment manufacturer
OSHA	Occupational Health and Safety Administration
P.L.	Public Law
PM	program manager
PV	photovoltaic
R&D	research and development
RDECOM	U.S. Army Research, Development and Engineering Command
SBIR	Small Business Innovation Research
SLI	starting, lighting, and ignition
SME	subject matter expert
SWIPES	Soldier Worn Integrated Power Equipment System
TARDEC	Tank Automotive Research, Development, and Engineering Center
TQG	tactical quiet generator
U.S.C.	United States Code
UAV	unmanned aerial vehicle
UGVs	unmanned ground vehicle
UPS	uninterruptable power supply
USMC	U.S. Marine Corps
W	watts
Wh	watt-hours

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14. ABSTRACT
This paper has been developed for the Annual Eastern Conference of the Rutgers University Center for Research in Regulated Industries (CRRI) Advanced Workshop in Regulation and Competition. A major focus area of CRRI is energy regulation, competition, and market offerings. Power and energy are critical to all Department of Defense (DOD) missions. As the capabilities of the force have increased through the years, so have the power and energy demands, leading the DOD to now factor energy into key decisions. Despite an escalating number of energy goals and initiatives, the role of energy storage is not well established across the varied DOD use environments. This paper focuses primarily on power and energy use in operational energy environments: expeditionary base camps, aviation systems, surface systems, and soldier power. Results from a literature review and interviews with subject matter experts were used to explore the role of energy storage in each of these environments. Additionally, some of the most important parameters that should be considered when implementing energy storage technologies are described.

15. SUBJECT TERMS
energy, power, energy storage, installation energy, operational energy, energy storage technology

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