Reducing Energy Footprint on the Battlefield

Michael Bowes • Barry Pifer

CRM D0022638.A2/Final
June 2010

Approved for distribution: June 2010

Ronald Filadelfo
Environment and Energy Team
Resource Analysis Division

This document represents the best opinion of CNA at the time of issue.
It does not necessarily represent the opinion of the Department of the Navy.

Distribution limited to DOD agencies. Specific authority: N00014-05-D-0500.
Copies of this document can be obtained through the Defense Technical Information Center at www.dtic.mil
or contact CNA Document Control and Distribution Section at 703-824-2123.

Contents

Summary

CNA was asked to assess battlefield energy use and evaluate capabilities that might help the Marine Corps reduce fossil fuel use in an expeditionary environment.

Below we provide a summary of our findings. We list factors that drive energy concerns, point to promising solutions for reducing fossil fuel use, and offer recommendations on how to address primary capability gaps. Our focus is on energy use at distributed operating bases. We do not address aviation at this time.

Energy issues

Why is energy a concern?

The global energy situation. As a result of increased global competition for supplies, petroleum prices are expected to increase over the next 25 years. Rising prices, coupled with price volatility, will place an increasing burden on defense budgets unless the growing dependence on fossil fuels is restrained.

The operational situation. With the ongoing war on terrorism and potential future stability operations, Marine Forces are likely to continue to find themselves sustaining distributed operations in areas of limited infrastructure. In these situations, unnecessary fuel demand exposes operations to higher risk than is necessary and increases support costs.

Issues related to energy use in Afghanistan

Power generation. Electrical generators have been the largest fuel consumer for the ground forces at distributed operating bases.

- Inefficient use of generators has resulted in unnecessarily high fuel use. In part because of poor grid design, capacity is often more than twice the level needed to meet demand.

- The efficiency of the generators themselves is considerably less than can be attained with the current technologies.

Efficiency in electric power use. Conservation and improved efficiency in power-using equipment has the potential to reduce generator capacity requirements and fuel use.

- Air conditioning accounts for as much as 75 percent of the generator capacity at larger bases. Poor insulation of tents and structures adds greatly to the resulting fuel demand.
- Pumps (handling water and fuel) and electronic equipment (computers, radars, and communications) are other primary users of electricity. Electric motor start-up surges add to capacity requirements and heat issues related to electronics help drive air conditioning needs.

Other areas of concerns—motor vehicles. Tactical vehicles are the second largest user of fuel for ground forces, with logistics driving much of this use.

Where is the energy used?

Larger bases—high quantities of fuels used. Most fuel is used at the large support bases. This is where the potential to reduce quantity of fuel is greatest. The level of services is high and inefficiency is prevalent. Even at battalion-size bases, inefficient use of generators can be significant.

Small tactical bases—high fully burdened cost of fuel. The small bases are austere facilities, with limited fuel demand. Water requirements may far exceed fuel needs. While the quantity of fuel at the tactical edge may be small, the cost of providing fuel can be high. Further implicit costs are associated with the security risks to forces involved. The high costs and risks may justify enhancing self-sufficiency of smaller bases.

Potential energy solutions

Efforts are underway across the Department of Defense (DOD) to identify practices and technologies for reducing expeditionary use of fossil fuel. Primary areas of focus can be categorized as follows: (a) improving efficiency in power production and (b) conservation in energy use.

Efficiency in electrical power production. Primary technologies under consideration include the following:

- *Improved combustion engine generators.* The next line of tactical generators already promises 20-percent efficiency gains. Further advances are possible.
- *Improved power management.* Inefficient use of generator capacity can be a major factor in high fuel use. There is interest in developing small-scale systems to simplify power grid management. There is also interest in planning tools to assist with tailoring facility layout and the power grid in order to efficiently meet power demands.
- *Fuels cells.* These devices convert the chemical energy of fuels directly to electricity, avoiding inefficiencies associated with combustion engines. While systems fully suitable for military use (i.e., JP-8 using) are a few years away, they may eventually replace small diesel generators.
- *Solar cells.* Solar cells convert the energy from sunlight directly into electricity. While solar cells are readily available and steadily improving in efficiency, there are issues that make them impractical for large-scale use in an expeditionary setting (e.g., fragile, large footprint, and intermittent power). They may be of value in smaller, niche applications.
- *Other innovative power sources.*
    - — Various engine designs (e.g., Stirling engines, microturbines) are being evaluated as efficient alternatives to small diesels.
    - — Thermoelectric devices, converting exhaust heat directly to electric power, may improve combustion engine efficiency.
    - — Radioisotope generators can serve as very long-lived power sources, albeit with some risk of radioactive material leaks.

Conservation in energy use. Primary areas of interest include the following:

- *Insulation.* Insulation of tents with spray foam has been shown to reduce energy use by up to 50 percent. The challenge is to find a more suitable insulation for mobile forces.

- *Improved environmental control units (ECUs).* Air conditioning is the primary use of electric power at many bases. A new line of ECUs promises efficiency gains. Further advances are possible.
- *Other areas of concern.* Although not a focus of our report, efforts to improve fuel efficiency in aircraft and vehicles will be of key importance to reducing overall fuel use.

Conclusions and recommendations

We offer the following conclusions and recommendations as to how to achieve significant savings in fuel consumption at forward bases. While there is no magic bullet that will eliminate dependence on fuels and the logistics support associated with those fuels, considerable gains can be achieved by simply improving the efficiency of current systems. We recommend aggressive fielding of more efficient generators and environmental control units, rapid fielding of insulation for tents, and greater emphasis in training on responsibility for energy management. Efforts to address many of the capability gaps are already underway.

Power generation

For the foreseeable future, forward bases will rely on traditional generators to produce electrical power. Improvements in generator efficiency offer the potential for substantial fuel savings.

The next line of tactical generators (Advanced Medium Mobile Power Sources) promises efficiency gains of about 20 percent over current systems. Our analysis suggests that rapid deployment of these models will pay for itself in fuel savings within a year, reducing overall USMC fuel use in Afghanistan by over 6 percent (overall fuel use including aviation). Further advances are possible—such as improved electronic fuel injection and the incorporation of energy storage devices—and should lead to additional reductions in fuel use.

Recommendations:

- Prompt fielding of the new generators as soon as they become available—especially at the tactical edge where fuel cost is high. Any delay in replacing current systems would be uneconomical.

- Continued attention to improvements in the efficiency, weight, and noise levels of combustion engine generators.
- Continued attention to the development of fuel cells and alternative engine designs as potentially higher efficiency replacements for the small diesel generators.

Conservation—insulation and air conditioning

Currently, more attention goes to ensuring adequate power delivery at forward bases than to reducing energy demand. As much as 75 percent of the fuel used to generate electricity at large forward bases goes to air condition poorly insulated tents. Insulation can reduce this energy use by up to 50 percent. Spray foaming tents in Iraq achieved such gains, but these tents cannot be reused. Therefore, this particular foam is not the ideal solution for Marines, who require mobility. There is a critical need for effective, lightweight, easy-to-install, robust, and portable tent insulation. Our analysis suggests that insulation could reduce overall fuel use by more than 11 percent, the highest payoff of any single alternative. More efficient air conditioning and more attention to conservation would also be of high value.

Recommendations:

- Continued attention to finding an effective and portable insulation for tents, with rapid fielding of a suitable product.
- Continued improvements in the efficiency of environmental control units (ECU), with prompt fielding of systems that show good efficiency gains.
- Greater emphasis in training on responsibility for energy efficiency and conservation.
- Training for camp commandants to better manage energy resources.
- Ensure that future base support and acquisitions contracts require and reward energy efficiency.

Power management

Camps are set up quickly, with more attention to establishing the foothold, than to planning for efficiency. Each group is provided its own generator, often oversized for the load. As a result, generators are observed running at less than 50-percent load. This is wasteful and leads to maintenance problems. Furthermore, the problem can be exacerbated by a shortage in distribution equipment and trained manpower.

Our analysis suggests that a more tailored layout of the power grid, one that would eliminate excess capacity, might reduce generator fuel use by 25 percent. That corresponds to an 8-percent reduction in overall fuel use. There have been attempts to develop systems to simplify grid management. For now, though, the devices are too complex and expensive for widespread use in an expeditionary setting.

Recommendations:

- Continued attention to development of a small-scale, low-cost architecture capable of simplifying power management. Such a system should allow for easy integration of small clusters of generators, with automatic startup and shutdown of power sources, and managed energy storage to efficiently address peak loads.
- Integrate energy storage capability into stand-alone generators so that they more efficiently handle peak loads. This will allow for the use of smaller generators, each running more efficiently.
- Greater emphasis on efficient base layout and grid design when camps are first established, with better use of planning software or standard templates for base design.
- Greater attention in deployment planning to ensure that the switching equipment and wiring harnesses needed to link power sources and combine loads are available. (Fewer generators would be required if loads are combined.)
- Increase the number of individuals trained to setup, manage, and maintain generators at the tactical bases.

Renewable energy systems

Solar energy systems for generating electric power offer the promise of self-sufficiency. However, there are issues that limit the extensive use of solar in an expeditionary setting—large footprint, intermittent power, vulnerability, weight, and cost. To illustrate, we looked at using an available military system to meet 400kw of power demand, representative of a battalion-size base. System cost would be over $50 million, panels would cover three football fields, and the weight would be 575 tons (with 94 tons of batteries). In all likelihood, generators would also have to be in place to ensure power on cloudy days. Solar energy at this scale is probably not feasible.

Despite this, solar is suited to some small-scale applications. It can be useful for powering stand-alone systems not conveniently served by the power grid (e.g., security lights). It can also add security for smaller bases, meeting minimal critical needs as a buffer against fuel shortages. We see promise in flexible solar panels that can be applied directly to fabrics. A solar shade over a tent could help reduce heating load and provide a small amount of power, with no increase in base footprint.

Of potential concern are piecemeal efforts currently being used to develop and acquire solar systems. Such approaches can lead to difficulties with interoperability, maintenance, training, and logistics support.

Recommendations:

- Advocate for a more centralized approach within DOD to the evaluation and acquisition of solar power and other renewable energy systems.
- Continue looking for efficient, robust, small renewable energy systems to improve self-sufficiency at forward bases.

General recommendations

We also offer the following more general recommendations:

- Establish a permanent experimental forward operating base at 29 Palms (or similar location) where Marines can gain training in energy, water, and waste management.
- Establish a comprehensive requirements document that will spur commercial development of relevant energy solutions.

This page left intentionally blank.

Introduction

As oil prices reached their peak in 2008, energy costs became a primary concern for the nation. For the Department of Defense (DOD), outlays increased dramatically, with the cost of petroleum products rising from $6.8 billion in 2004 to $17.9 billion in 2008 [1, 2]. At the same time, other issues surrounding energy had started to gain the attention of DOD leadership: the impact of energy choices on climate, the potential for disruption to energy supplies, and an increasing concern over operational threats associated with providing energy to our military on the battlefields of Iraq and Afghanistan.

In February 2008, the Defense Science Board (DSB) released its report on DOD's energy strategy [3]. The report states that the key energy challenge is the risk to operational capability that results from high battlefield fuel use and from potential disruptions to fuel supply lines. We quote from that report:

> ...operations suffer from unnecessarily high, and growing, battlespace fuel demand, which degrades capability, increases force balance problems, exposes support operations to greater risk than necessary, and increases life-cycle operations and support costs. [3]

The findings echoed the concerns raised in 2006 by USMC Maj. Gen. Zilmer,[1] who, as a senior U.S. commander in Iraq, submitted an urgent request for renewable energy systems that would reduce the military's dependence on fossil fuel for power generation at forward bases and, thereby, lessen the number of supply convoys put in harm's way [4].

Tasking and study approach

In response to such concerns, the Assistant Commandant of the Marine Corps (ACMC) requested that CNA, in cooperation with the newly created USMC Expeditionary Energy Office, assess battlefield

1. Now Lt. Gen. Zilmer

energy use and evaluate capabilities that might help the Marine Corps enhance self-sufficiency in expeditionary environments.

This report addresses energy use by ground forces in distributed operations. We summarize data on fuel and power use, look at factors that contribute to unnecessary fuel use, review technologies and practices that may help reduce use of fossil fuel, and analyze the potential for fuel savings.

The study draws on information gathered from interviews and literature reviews. A CNA representative with the Marines in Afghanistan provided considerable assistance in gathering information on fuel use and logistics operations. We rely also on generator data provided to the Expeditionary Energy Office and data reported in an earlier USMC assessment of energy use in Afghanistan. We do not address aviation or vehicles; nor do we fully address the somewhat distinct issues related to providing power to the individual Marine on patrol.

Background

Senior USMC leadership understands that it must transform the way that energy is used in order to field a more robust and mobile fighting force. They are committed to this effort.

On 13 August 2009, the Commandant of the Marine Corp (CMC) hosted the first "USMC Energy Summit" [5]. In his keynote address, he set clear goals to reduce energy risk. He stated the following:

> We want to reduce energy consumption by 30 percent and [energy spent on transporting] water by 60 percent by 2015. We would also like to increase by 25 percent the reusable energy sources we use.

The CMC also said, "I'm particularly worried about battlefield energy efficiency" and announced that a task force would be "on the ground in Afghanistan within a month to study ways to improve energy efficiency in a deployed area." Within the month, the Marine Energy Assessment Team (MEAT) was in Afghanistan conducting an assessment of energy use by deployed Marine Forces [6]. They found efficiency problems at larger bases. At the more austere tactical bases, the problem was water—more specifically water delivery. As many as six trucks carried water (bottled water) to the tactical bases for every one carrying fuel.

During the summit, the Commandant also announced that a Marine Corps Expeditionary Energy Office would be established to develop and direct energy strategy with regard to expeditionary capabilities. The Expeditionary Energy Office was established in November 2009 and reports directly to the ACMC. The new office acted quickly to address water issues identified by the MEAT team. They visited Afghanistan to supplement the information collected by the MEAT team. They also moved to establish an experimental forward operating base (FOB) at Quantico, with the goal of demonstrating and evaluating commercially available technologies in the areas of efficient shelter, renewable energy, and potable water. The hope is that some of these technologies will be rapidly implemented in Afghanistan.

DOD energy initiatives

Others across DOD are also engaged in research and actions to improve energy efficiency and self-sufficiency at forward locations. Notably, the Power Surety Task Force was established in 2006. Originally part of the Army's Rapid Equipping Force, this task force took on the role of assessing Maj. Gen. Zilmer's request for renewable energy systems. They established technology demonstrations at an experimental FOB at Fort Irwin, California, exploring energy efficiency technologies (e.g., solar panels, insulation, LED lighting, and power grid management tools) that could be used in theater. It was their demonstration that led to the spray foam insulation of several million square feet of tents and temporary structures in Iraq [7].

The effort at Fort Irwin became the forerunner of the Net Zero Plus Joint Concept Technology Demonstration (JCTD). The purpose of the Net Zero Plus JCTD is to identify energy-related operational needs and demonstrate technologies that can be rapidly deployed to address those needs.

The Air Force Research Laboratory is also exploring energy technologies of value to deployed forces. Deployable solar power systems, efficient shelters, transportable waste-to-energy systems, and algae-to-fuel reactors are being evaluated at the Renewable Energy Tent City located at Tyndall Air Force Base, Florida.

Others in the DOD research community, including the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR), are seeking advances in energy technologies that might better support deployed forces. Within the systems commands, there are efforts that promise to improve the efficiency of the generators, environmental control units (ECUs), and tactical vehicles that account for much of the fuel use at forward bases.

Current energy situation and future outlook

The attention to battlefield energy occurs against a backdrop of volatile energy prices, concerns over dependence on imports, increasing global competition for fuels, and questions as to the long-term availability of traditional petroleum products.

DOD is the single largest user of energy in the nation, using twice as much fuel as the biggest U.S. air carrier [8]. This dependence on energy exposes DOD to price volatility, hindering their ability to budget accurately and leading to scrambles to make up budget shortfalls. In 2008, DOD spent $17.9 billion on petroleum products, purchasing about 15 million gallons a day [1]. The cost of this fuel has increased dramatically, up from $11.5 billion in 2006 and $6.8 billion in 2004 [2].

Although energy prices have moderated with the recent economic slowdown, the longer-term outlook is for increased competition for global oil supplies and rising fuel prices. The U.S. Energy Information Administration (EIA) evaluates a wide range of trends and issues that could have implication for U.S. energy markets. Recent EIA energy reports offer the following projections [9][10]:

- World oil prices are expected to rise gradually as global demand grows more rapidly than supplies from outside OPEC. By 2035, the price of crude is expected to reach $133 per barrel (in 2008 dollars), up 33 percent from 2008 prices.
- U.S. dependence on imported liquid fuel is expected to decline (from a high of 60 percent in 2006, to 45 percent by

2035). Reliance on imports is moderated by increased use of biofuels and increased U.S. oil production.

- U.S. consumption of liquid fuels (both fossil fuels and biofuels) will grow by 9 percent over the projection period, with biofuels accounting for most of the growth.
- Consumption of liquid fuels in non-OECD Asia is expected to double over the projection period, to exceed consumption in North America.
- Worldwide production of conventional liquid fuels is expected to increase by about 14 percent over the projection period.
- U.S. production of conventional liquid fuels, which had been in decline, is expected to grow as a result of offshore projects and enhanced recovery techniques.[2]
- High prices are expected to spur significant increases in conventional liquid fuel production from several other non-OPEC nations (including Russia, Brazil, and Kazakhstan).
- Production of unconventional liquid fuels (oil sands, biofuels, coal-to-liquids, and shale oil) is expected to increase and account for more than 12 percent of world liquid fuel production. Canadian oil sands and biofuels are the major contributors to this increase.

There are, of course, inherent uncertainties in energy market projections, particularly during periods of price volatility and transformation to new sources of supply. Nonetheless, the general picture is not one of a rapidly approaching end to petroleum supplies, nor of increasing dependence on imported energy supplies. On the other hand, an inevitable transition to greater use of unconventional liquid fuels, including biofuels, is becoming apparent. A strategy to prepare for the transition to biofuels would help mitigate its effects.

2. The extent to which the recent Deepwater Horizon oil spill in the Gulf of Mexico may affect these projections has not yet been determined.

Organization of this report

In the following section, we discuss battlefield energy use in Afghanistan. Next, we describe and analyze some of the primary options for reducing fuel use. Finally, we summarize capability gaps that the USMC must address in order to reduce expeditionary fuel use. In an appendix, we describe energy technologies under development. A second appendix provides fuel consumption rates for tactical generators.

Battlefield energy use

In this section, we examine how fuel and energy are used in Afghanistan and we consider the fully burdened costs of transporting fuel. We also look at organizational responsibilities that influence fuel use. Finally, we summarize the key issues.

DOD fuel use in Afghanistan and Iraq

DOD depends on petroleum-based fuel to sustain its forward-deployed forces. This fuel typically represents over half of the logistics tonnage for deployed U.S. ground forces. Transporting such large quantities of fuel to forward-deployed locations can present an enormous logistics burden and potential risk.

Overall, in 2008, the Defense Energy Support Center (DESC) supplied almost 2.7 million gallons of fuel a day to U.S. forces in Iraq and Afghanistan [1]. This is the equivalent of more than 500 daily truck loads of fuel or about 17 gallons per person per day (based on military personnel present).

Ground forces in sustained distributed operations typically use lower amounts of fuel. Statistics from 2007 show the Army using 9.5 gallons of fuel per soldier per day in Iraq and Afghanistan [11]. Data available on Marine Corps fuel use in Afghanistan [6] show them using similar amounts, about 8 gallon per capita each day.

Table 1, adapted from the DSB report [3], shows the recent wartime fuel consumption pattern for U.S. ground forces. In Iraq, generators, used overwhelmingly for air conditioning, were the largest single fuel consumer in the battlefield. Tactical vehicles, a category which includes vehicles used in supply operations, are another large fuel consumer. Fuel use by aircraft is also significant, but beyond the scope of this study.

Table 1. Distribution of wartime fuel consumption by U.S. ground forces

Category	Wartime consumption
Generators	34%
Aircraft	29%
Tactical vehicles	16%
Combat vehicles	15%
Non-tactical vehicles	5%

Source: Army data, adapted from the DSB report [3]

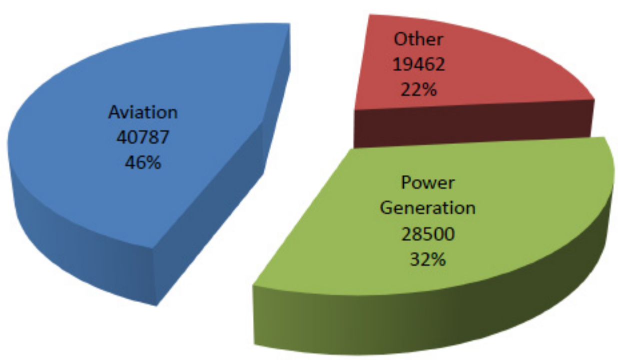
USMC fuel use in Afghanistan

We draw here on various data provided to the MEAT assessment team, the USMC Expeditionary Energy Office, and CNA analysts working with the Marines in Afghanistan.

How is fuel used?

Figure 1, adapted from the MEAT report [6], shows the distribution of fuel use by the Marine Expeditionary Brigade deployed in southern Afghanistan. In August 2009, average daily fuel use was 88,750 gallons a day for a force of 11,200. Aviation accounted for 46 percent of fuel use, power generation for 32 percent, and other uses (e.g., vehicles) 22 percent. Although aviation is the largest consumer of fuel for the Marines in Afghanistan, generators account for a substantial proportion of total fuel use. Overall fuel use was 8 gallons per day per Marine, with 4.3 gallons going to non-aviation uses and 2.5 gallons to generators.

Figure 1. Distribution of USMC daily fuel use in Afghanistan

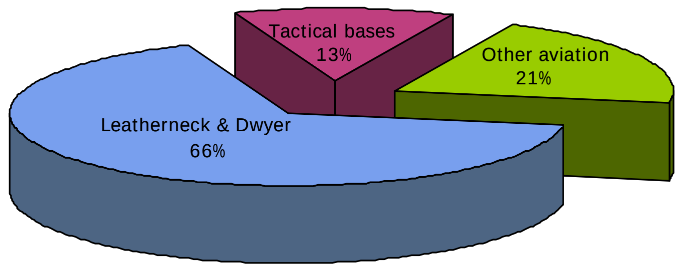


Source: MEB-A Bulk Fuels Officer, as presented in the MEAT report [6]. The data show average daily fuel use for August 2009.

Where is fuel used?

The majority of fuel is used at the largest bases. Fuel reports for August 2009 show that less than 15 percent of fuel goes to tactical bases, battalion-size or smaller. Most of the fuel is used at the major support camps (e.g., Camp Leatherneck and Camp Dwyer) or other air bases. Camp Leatherneck serves as the primary command and logistics center. Camp Dwyer is a rapidly expanding base and airfield built to support areas further to the south in the USMC area of responsibility.

Figure 2. Where is fuel used in Afghanistan?



Source: Combines information from Task Force Leatherneck fuel reports for August 2009 and MEAT data [6] on overall aviation fuel use.

Large support bases. Fuel use at Camp Leatherneck was 36,700 gallons a day in August 2009, with 15,400 gallons (42 percent) used for electrical generators [6]. A force of about 5,000 Marines was present at that time. There were 196 generators, with 19mw of capacity and 5mw of load [6].[3] The generators, when observed, were operating at less than 30 percent load. Air conditioners accounted for 75 percent of the generator capacity [6]. From the Camp Leatherneck data (and fuel data for Camp Dwyer), we estimate that per capita electricity demand at large support bases is about 1kw (average hourly rate of use), while per capita fuel use is about 8 gallons per day. Actual fuel use will depend on the intensity of aviation and vehicle activity.

Army Logistics Civil Augmentation Program (LOGCAP) contractors manage these large facilities. At Camp Leatherneck, the contractor is centralizing the provision of power, replacing the many independent

3. We calculate that the 15,400 gallons of fuel used for generators at Camp Leatherneck is consistent with average power demand of about 5.5mw.

generators that were observed by the assessment team. Generator capacity is expected to be reduced to just over 14mw.

Battalion-size bases. We have data, which were initially provided to the Expeditionary Energy Office, on generators for two battalion-size bases (Fiddler's Green and Payne). The bases differ substantially in power capacity and load, with electricity demand rates ranging between .5kw and 1.2kw per capita. There were 7 generators at one base and 55 at the other. We also have data on fuel deliveries to all battalion-size bases. Per capita fuel supplies ranged from 2.5 to 4.5 gallons per day.[4]

Based on the generator data, we estimate that 60 percent of the fuel used at these bases goes to generators. Actual use is highly variable, depending on mission. Power load is about 45 percent of generator capacity and the primary use of electrical power is air conditioning (over 50 percent). Pumps for handling water (water purification, laundry, and showers) are another primary consumer of electricity, as are electronics of various types (e.g., radars, computers, and communications). We note that the LOGCAP contractor takes over base support responsibilities at facilities once population reaches 400, but the generators and tents at these bases are for now still USMC owned.

Smaller bases. The smallest bases, company-size and below, tend to be austere. They use few vehicles and rely on foot patrols. Some may have air conditioning for a command operation center. Additional small generators may be used to power a refrigeration unit, lights, and pumps. The limited data we have on fuel supplies to two company-size bases show per capita fuel use of 1 to 2.5 gallons a day. Fuel use is almost certainly lower at more austere bases. At small bases, potable water requirements (perhaps 5 to 8 gallons a day per capita) may far exceed fuel needs.

In table 2, which draws on the data described above, we provide estimates of per capita electricity and fuel use by base size for the sustained distributed operations in Afghanistan. Per capita use calculations reflect U.S. military personnel numbers. The data represent a limited snapshot of fuel use. Information on fuel and power for

4. Some fuel may be further transported to nearby outposts.

smaller outposts is lacking, and the numbers here represent a best guess based on fuel data for two sites and information from interviews.

Table 2. Estimates of per capita electrical capacity, demand, and daily fuel use

Operating base size	Electricity capacity (kw)	Electricity demand (kw)	Total fuel use (gpd)	Generator fuel use (gpd)
Large support camps	4	1–1.2	7–9	3
Battalion-size bases	1–3	0.5–1.2	2.5–4.5	1.5–2.5
Company-size or smaller	<2	<1	.25–2.5	?

Source: Estimates are based on data from fuel reports for August 2009 and information provided to the MEAT team [6] and USMC Expeditionary Office on fuel and generator use.

Fuel delivery in Afghanistan

There have been few problems getting supplies to the big bases in Afghanistan. Private contractors deliver fuel to Camp Leatherneck and other major support bases via Pakistan for around $6 per gallon. The contractor owns this fuel until it is successfully delivered. Thus, most fuel arrives at modest expense and little direct risk to the Marines. There is, however, concern that the Taliban may be benefiting by collecting protection money from the contractors involved [12].

The problem is greater for the smaller bases. Fuel moves out from the logistic centers to the tactical bases. British estimates are that their tactical bases in Afghanistan account for just 3 percent of the related fuel use, but 25 percent of costs [13]. Force protection is by far the largest element of this cost. The Marines use escorted ground convoys to deliver supplies to the tactical bases when risks are acceptable. Air drops are more likely when risk levels are high. Constant efforts are required to ensure that routes are clear of explosive devices.

Fully burdened cost of fuel

The full cost of providing fuel to a forward base includes the purchase price of the fuel itself plus expenses related to storage, handling, protection, and delivery.

In table 3, we present recent estimates of the *fully burdened cost of fuel* (FBCF) calculated by USMC and CNA analysts [14]. The estimates are for delivery to a FOB 35 miles from Camp Leatherneck. The purchase price of fuel was $6.39 at Camp Leatherneck. To this they add operating costs—for force protection, fuel handling, and fuel delivery—and asset depreciation costs for the convoy vehicles. The FBCF for ground delivery was estimated to be $11.81 per gallon. Force protection costs ($3.95 per gallon) account for most of the additional cost above purchase price. When air support is required to further protect a ground convoy, the FBCF increases to $18.59 per gallon. For air delivery, the FBCF is estimated at $30.78 per gallon.

Table 3. Fully burdened cost of delivering fuel to the tactical edge

Delivery method (to FOB 35 miles away)	FBCF ($/gallon)
Ground convoy	$11.81
Ground convoy & air security	$18.59
Air delivery & air security	$30.78

Source: USMC PA&E and CNA estimates [14].

If anything, these estimates may be a little low, since they do not account for ongoing costs of ensuring that roads are clear, beyond the efforts of those travelling with the convoy.

Understanding the FBCF is important because it allows for informed cost-benefit analyses of investments in energy savings technologies.

Casualty factors

The calls to reduce fuel use have not been so much directed at saving money as at reducing the number of convoys in harm's way. In table 4, we present data on casualties (wounded or killed in action) related to resupply convoys in Iraq and Afghanistan. These data are from the Center for Army Lessons Learned (as cited in an AEPI report [11]).

The data include military and civilian casualties during resupply operations. The data show 75 casualties associated with Afghanistan resupply convoys in 2007. In Iraq, with a larger military population, there were 263 resupply casualties that year.

Table 4. Resupply casualties by theater and year

Theater	2003	2004	2005	2006	2007
Afghanistan	5	11	33	64	75
Iraq	531	994	618	452	263

Source: Data from Center for Army Lessons Learned, as presented by AEPI [11].

The Army data suggest that between .5 and .85 casualties per year can be expected for each million gallons of fuel delivered. For the Marines in Afghanistan, that would mean close to 30 casualties a year based on a usage of 90,000 gallons a day. In actuality, while there have been hostile actions each week against USMC vehicles in Afghanistan, there have been few attacks on fuel trucks. This is no doubt because the bulk of the fuel moves in private vehicles, presenting no military target. Further, there have been conscious efforts to avoid ground convoys where risk levels are high.

Water issues

The primary supply issue for many smaller bases has been water, rather than fuel. Any reduction in the quantity of water carried to forward locations reduces fuel use by logistics vehicles and reduces convoy exposure to threats.

In the past, water was delivered because of a lack of suitable water purifiers. There were no purification systems small enough for use at company-size bases. The new lightweight water purification (LWP) system can now fill that gap. Small Unit Water Purifiers (SUWP) will eventually address the needs of smaller platoon-size bases.

The remaining problem had been getting water certified as safe to drink. While water sources are generally available, with wells present or easily developed, there had been confusion as to what was required to certify water sources and the purifiers. The Expeditionary Energy Office has now taken steps to see that field kits are available for on-site testing and that appropriate training in their use is provided. These steps have begun to reduce the dependence on bottled water supplies.

Energy responsibilities

In joint operations, as in Afghanistan, responsibility for base layout and services is not always controlled by USMC. Planning for the large FOBs is a joint command responsibility, with initial construction often in the hands of Army engineers or contractors. At the larger bases, LOGCAP contractors eventually manage the facilities and support services. It is in planning, and as the foothold is first established, that the USMC may have the most influence on facilities layout and power generation. Of course, the fundamental issue of needing to reduce fuel use really remains the same, whoever is responsible.

Camps are built up quickly, with more attention to establishing a secure foothold than to energy efficiency. Marine Forces Central Command (MARCENT) operating as the service component for U.S. Central Command, provides the power capabilities to Marines. Their focus is on ensuring adequate power delivery to meet the critical needs of each group. Those decisions can lead to excess generator capacity.

The Marine forces themselves will arrive to find the equipment present and have little opportunity to plan for an efficient layout. Limited availability of wiring harness and power distribution boxes has made efficient grid layout difficult in Afghanistan. Electricians (MOS 1141) serving with the battalions are trained to install electrical power generation and distribution systems. There are insufficient numbers of electricians or technicians available, under distributed operations, to address the needs at every base. It is said that smaller bases may be visited just once a month to handle generator repair needs.

The Camp Commandant oversees base resources and services of the operating bases. The commandant is ultimately responsible for energy efficiency. Finding money to improve energy efficiency is made difficult by rules that limit spending on temporary facilities. A LOGCAP contractor handles day-to-day responsibilities for facilities management and support services at the larger bases. Their contract requirements will determine how actively they seek to improve efficiency in power production and use.

Data on energy use are important to situational awareness and for making informed decisions on investments in energy savings technologies. While such data are collected, the effort is mostly directed at ensuring logistics needs are met. Bulk fuel deliveries are tracked in daily and weekly fuel reports and anticipated demand is reported daily to U.S. Central Command. A Force Transportation Board tracks and approves each individual ground convoy. The Marine Air-Ground Task Force (MAGTF) Deployment Distribution Operations Center, Strategic Mobility Office tracks all air container deliveries. A Base Camp Management Report is due annually, reporting on whether available capacity is adequate to meet the demands for power, water, and facilities.

Findings in brief

Here we summarize the key points on battlefield energy use.

Electric power. Generators have been the largest fuel consumer for deployed ground forces [6]. Poor insulation adds greatly to electricity demand, with air conditioning accounting for much of the electricity used at larger bases. Excess generator capacity is frequently observed; the resulting inefficient use of generators adds to unnecessarily high fuel demand.

Motor vehicles. Motor vehicles are the second largest user of fuel for the ground forces, with logistics traffic driving much of this use. Any reduction in the quantity of fuel or water carried to forward locations will help reduce logistics fuel use.

Fuel use at the large bases. Most fuel is used at the large support bases. Inefficiencies in power production and use are prevalent at these bases. This is where the potential to reduce fuel use is greatest. Even at the battalion-size bases, inefficient use of generators can be a significant issue.

Fuel use at the small bases. The smaller tactical bases are usually barebones facilities with little energy use. There is little air conditioning and also very little vehicle activity.

Fuel delivery costs. While the quantity of fuel going to the tactical edge is small, the cost of providing fuel can be relatively high. Fuel is delivered to the large bases by private contractors for about $6 per gallon. Although there is the potential for disruption of this supply line, it has not been seriously threatened so far. At smaller outposts, because of threats to supply lines, fuel and water must be delivered by military convoy or air drop. The full cost of delivering this fuel, including force protection, is estimated to be between $12 and $31 per gallon. The high cost and risks may justify investment in renewable energy technology for the forward bases.

Water. The primary supply issue for many smaller bases has been water, rather than fuel. Steps have been taken to begin reducing this dependence on delivered water supplies. The new LWP system is being made available and field kits are now provided for on-site testing of water supplies.

Energy responsibilities. In joint operations, as in Afghanistan, responsibility for base services is not always fully controlled by USMC. It is as the foothold is being established and at the smaller bases that the USMC can help shape facilities and power generation efficiency.

Assessment of energy technologies

In this section, we identify some of the technologies available or under development that may improve energy self-sufficiency at forward deployed bases. We then assess potential fuel savings and other significant attributes for some of the primary options for reducing fuel use. Further details on technologies can be found in appendix A.

Potential energy solutions

Efforts are underway across DOD to identify practices and technologies for reducing expeditionary use of fossil fuels. Primary areas of focus can be categorized as follows: (a) improving efficiency in power production and (b) conservation in energy use.

Efficiency in electrical power production. Primary technologies under consideration include the following:

- *Improved combustion engine generators.* The next line of tactical generators (Advanced Medium Mobile Power Sources—AMMPS) promises 15- to 25-percent efficiency gains over current models. Advances, such as permanent magnets, allow significant weight savings and increased efficiency. Variable speed operation allows for improved efficiency when operating at less than full load. Further advances—such as advanced fuel injection and the incorporation of ultracapacitors as energy storage devices—will lead to additional reductions in fuel use.
- *Fuels cells.* These devices convert the chemical energy of fuels directly to electricity, avoiding the inefficiencies, noise, and pollutants associated with combustion engines. They could eventually serve as a lightweight, longer-lasting alternative to batteries, providing more power in a smaller space. They also have the potential to replace small generators, with both higher efficiencies and quieter operation. While many fuel cells are now commercially available, systems fully suitable for military

use are still a few years away. One critical challenge is the development of fuel cells that can run reliably on standard military fuels (JP-8).

- *Photovoltaic solar systems.* A solar cell is a device that converts the energy from sunlight directly into electricity. While solar cells are readily available and rapidly improving in efficiency, there are issues that make them impractical for large-scale use in an expeditionary setting. Typical solar systems have a large footprint, they can be fragile, and they require supplemental power sources to meet demands during non-daylight hours. There is promise in flexible solar panels that can be applied to fabrics, although efficiencies are still quite low.

- *Improved power management.* There are efforts to develop systems to simplify grid management. The goal is a system that (a) allows for easy integration of mixed power sources (generators, renewables, and battery banks), (b) provides intelligent startup and shutdown of power sources to best meet energy demands, and (c) offers managed energy storage to efficiently address peak and off-peak loads. Software and planning tools have been developed to assist with tailoring facility layout and the power grid to efficiently meet power demands.

- *Other innovative power sources.*

  — Various engine designs (e.g., Stirling engines, microturbines) are being evaluated as efficient, lightweight alternatives to small diesels generators.

  — Thermoelectric devices convert heat directly to electric power. Systems being evaluated can convert exhaust heat from a small generator set to an additional 500w of usable electrical output.

  — Radioisotope generators can serve as very long-lived power sources. Widely used by NASA, they convert thermal energy from radioactive decay directly into electrical energy. They pose some risk of contamination if the container leaks, but there should otherwise be little risk from radiation.

Conservation in energy use. Primary areas of interest include the following:

- *Insulation.* Insulation of tents with spray foam has been shown to reduce energy use by up to 50 percent. There have been efforts to develop more portable insulation, including innovative aerogel products that offer five times better thermal performance than traditional materials.
- *Improved environmental control units (ECUs).* A new line of improved ECUs already developed promises efficiency gains of 15- to 25 percent over current systems. Further advances in efficiency using commercial technologies seem possible.
- *Vehicle and aircraft.* For ground transportation, the emphasis will be on hybrid power systems, electronic controls, alternative fuels, and vehicle weight reduction. Aircraft efficiency will rely on improvements to power plants and aerodynamic features.
- *Electronics and electric motors.* There are ongoing efforts to reduce the startup surges associated with electric motors. Although there are aggressive commercial efforts to reduce the power demands of electronic modules, the competing needs for extra capability often outweigh the gains made.

Estimated technology cost for power production

In table 5, we show the capital cost and fuel operating costs for some alternative means of producing power (in cost per kilowatt). The table was adapted from a 2004 Army report [15] and costs have not been updated.

Diesel generators are the cheapest power producers, in terms of upfront costs. Solar systems with battery banks are expensive to purchase, but the fuel is free. Small turbines and fuel cells do not offer savings yet, although potential efficiency gains may change that.

It is important to realize that the costs shown here are based on rated peak capacity. For solar systems, it typically requires 5kw of nominal capacity to meet a steady load of 1kw over the entire day (charging batteries during daylight and drawing on them later). Thus, it would cost at least $50,000 to replace a 1kw diesel generator with a photovoltaic solar system. The military requirements for ruggedness and mobility add further to costs, so that prices of over $100,000 for systems capable of meeting a 1kw constant load seem to be typical.

Table 5. Estimated technology costs

Power generator type	Capital cost ($/kw)	Fuel cost ($/kwh)
Tactical diesel	$500	$.07
Microturbine (250kw)	$1,500	$.07
Wind (1mw peak)	$2,000	$.00
Biomass (1mw)	$2,500	$.03
Microturbine (100kw)	$3,000	$.07
Methanol fuel cell (210kw)	$6,800	$.03
Photovoltaic w/ battery bank (1kw peak)	$10,000	$.00
Microturbine (30kw)	$13,000	$.07
Solid oxide fuel cell (200kw)	$20,000	$.27
Hydrogen fuel cell (1kw)	$160,000	$.08

Source: Adapted from Center for Army Analysis [15].

Evaluating fuel savings options

In this section, we assess the potential fuel savings and other significant attributes for some of the primary options for reducing fuel use. We consider (a) generator improvements, (b) solar power, and (c) insulation. For each, we calculate savings based on a megawatt of generator capacity operated at 40-percent load, with 70 percent of capacity linked to air conditioning. The loads are typical of levels observed in Afghanistan. Then, we extrapolate from the 1mw case to consider overall savings if options were applied across Afghanistan.

Generator efficiency and power management

In table 6, we address the payoff to improving generator efficiency and to optimizing generator capacity to better match power load.

Our baseline fuel use is based on 1000kw of generator capacity operating at 40-percent load. The mix of generators used to calculate fuel use was based on those used at a battalion-size base in Afghanistan. We estimate baseline fuel use by generators at just over 1000 gallons a day, or 365,740 gallons a year. (Information on tactical generator fuel consumption and efficiency can be found in appendix B.)

Improve generator efficiency. The first option considered is to improve generator fuel consumption rates by 20 percent. This corresponds roughly to replacing the current tactical generator with new Advanced Medium Mobile Power Sources (AMMPS) generators. The result is the 20 percent reduction in generator fuel use. Extrapolated to Afghanistan as a whole, this would correspond to yearly fuel savings of 2.1 million gallons, or 6 percent of total USMC annual fuel consumption (the savings are less than 20 percent because generators account for only about a third of total fuel use).

Any further improvements to the efficiency of power sources, whether from improved diesel generators or alternative technologies (e.g., fuel cells) would add proportionately to savings. For example, suppose that fuel cells eventually match the peak efficiency of current 100kw diesel generators, meeting any load at this same efficiency. That proves to be equivalent to a 32-percent improvement in fuel consumption rates for power generation and would lead to yearly fuel savings of 3.3 million gallons, or 10 percent of total consumption.

Table 6. Generator efficiency and power management options

	Baseline	Improve generator efficiency 20%	Optimize generator capacity	Optimize and improve efficiency
Generator capacity (kw)	1000	1000	444	444
Power load (kw)	400	400	400	400
Daily generator fuel use (gal)	1,077	862	808	646
Yearly generator fuel use (gal)	393,150	314,520	294,870	235,900
Yearly fuel savings (gal)	-	78,630	98,280	157,250
Savings in generator fuel use (%)	-	20%	25%	40%
Afghanistan: overall yearly fuel use (gal)	32,393,750	30,313,250	29,793,280	28,232,875
Afghanistan: yearly fuel savings (gal)	-	2,080,500	2,600,470	4,160,875
Afghanistan: overall fuel savings (%)	-	6%	8%	13%

Optimize generators. The second option is to optimize the number of generators to better match power load. We reduced the number of generators (while maintaining the same mix of sizes) to allow them to run at 90-percent load. The result is a 25-percent reduction in generator fuel use. This, extrapolated to Afghanistan as a whole, would correspond to yearly fuel savings of 2.6 million gallons, or 8 percent of total annual fuel consumption. These gains, of course, depend on the assumed excess capacity. The MEAT assessment found even greater excess capacity when they visited Camp Leatherneck. However, subsequent efforts to centralize power production at the larger bases may have already taken some of this potential gain.

Combine improved efficiency and optimized capacity. The final option combines the previous two, improving generator efficiency and reducing excess capacity. The result is a 40-percent reduction in generator fuel use and potential overall fuel saving of 4.16 million gallons, or 13 percent overall. The capital cost of replacing 440kw of generator capacity with higher efficiency models would be about $300,000 in total. Annual fuel savings from the efficiency improvements would be about $940,000, when valued at the $6 a gallon delivery price relevant for the larger bases.

Solar power

Here, we look at replacing generators with solar photovoltaic panels backed up by battery banks. The power, cost, and weight data are based on a Deployable and Renewable Energy Alternative Module (DREAM) system developed for the Marine Corps [16].[5] Each unit generates a peak power of 7.2kw from 36 solar panels. The battery bank provides 50kwh of energy storage when fully charged. Total system weight is over 2 tons and the deployed footprint is over 500 square feet. Details on the DREAM system components can be found in [16]. The cost of a single unit is $200,000, with a quarter of that being for

5. Specifications are based on the phase II version of the DREAM system [16]. A newer version, now in testing, incorporates a small diesel generator to help overcome the shortcomings of solar systems. The new version uses military standard rechargeable radio batteries and flexible solar panels, resulting in increased battery weight, a larger solar footprint, and higher cost. The overall system weight is lower, however.

batteries. Prices for lithium-ion batteries are about $1,000 per kwh. The high cost of the system is driven up by military requirements for mobility and robustness.

In table 7, we explore two options. One is to replace all the generators with solar systems. We then, out of curiosity, looked at using similar batteries as a backup for the generators, without the solar panels. The batteries would be charged by the generators.

Table 7. Solar and battery options

	Diesel generator baseline	Solar system	Batteries without solar
Power capacity (kw)	1000	2,000	1000
Power draw (kw)	400	400	400
Battery storage capacity (kwh)	-	14,000	5,100
Daily generator fuel use (gal)	1,077	0	691
Yearly generator fuel use (gal)	393,150	0	252,330
Yearly generator fuel savings (gal)	-	393,150	140,820
Generator fuel savings (%)	-	100%	36%
Total system weight (tons)	38	576	72
Battery weight (tons)	--	94	34
Solar panel area (sf)	--	140,000	--
Capital cost	$688,000	$55,550,000	$5,770,000
Yearly fuel savings (@ $12/gal)	-	$4,717,770	$1,689,790

The solar option results in 100-percent reduction in generator fuel used. The downside is cost, weight, and footprint. The 10,000 solar panels would cover more than 140,000 square feet, almost three football fields. The system would weigh 576 tons and cost over $55 million. The corresponding fuel savings would be worth about $4.7 million, when valued at the $12 a gallon cost of fuel at the tactical edge.[6] It makes no fiscal sense, particularly given the risk of power shortfalls on cloudy days. The solar option would take about 10 years of constant

6. The fuel savings shown in table 7 depend on the excess generator capacity. Savings would be lower when replacing an optimized generator layout.

use to pay for itself, depending on maintenance costs which we have not considered. Only carefully selected smaller scale applications could possibly make financial sense.

Battery backup to generators. We were curious whether storage batteries were an effective means of addressing generator overcapacity. In this option, we use the batteries from the solar option, but retain the generators. We optimize the number of batteries to get the greatest reduction in fuel use. The batteries allow the generators to be run 9.5 hours a day, with battery power used for the remainder of the day. The result is a 36-percent fuel savings.

The savings result because the generators now run more efficiently, at close to full load (86-percent load). While the savings are significant, this is not really a sensible option; there are much cheaper ways to address excess capacity (e.g., better planning). At a smaller scale, though, battery backup systems may well be a valuable element of an intelligent power management system; they can help address peak loads and variations in power demand over the day.

Insulation and air conditioning

Here we look at insulation of tents. The cost and effectiveness data are based on spray foam insulation applied to tents in Djibouti. Costs include material and installation. It is assumed that 70 percent of generator power is used for air conditioning. This is slightly less than the 75 percent observed at Camp Leatherneck, but a little more than is found at battalion-size bases.

Foam insulation. In table 8, we look at the spray foam option. The spray foam insulation can yield savings of up to 50 percent on fuel used for air conditioning. For our example, that would be equivalent to a 35-percent reduction in generator fuel use. The capital cost for the 1mw base would be about $488,400. The annual fuel savings, valued conservatively based on $6 per gallon delivered cost of fuel, would be $825,600. The effort pays for itself in less than a year. Extrapolated to Afghanistan as a whole, the yearly fuel savings would be 3.6 million gallons, or 11 percent of total annual fuel consumption.

While improvement of 50 percent may not be easily available with other forms of insulation, the combination of improved ECU systems with insulation should be able to achieve such gains.

Table 8. Structure insulation

	Baseline	Foam insulation
Power capacity (kw)	1000	1000
Daily generator fuel use (gal)	1,077	700
Daily fuel use for ECU (gal)	754	377
Fuel savings on ECU (%)	-	50%
Generator fuel savings (%)	-	35%
Yearly fuel savings (gals)	-	137,600
Capital cost	-	$488,400
Annual fuel cost savings (@ $6/gal)	-	$825,600
Afghanistan: yearly fuel savings (gal)	-	3,640,800
Afghanistan: overall fuel savings (%)	-	11%

This page left intentionally blank.

Gaps and issues related to fuel use

Here we summarize key issues and capability gaps related to fuel use at forward deployed bases. Our focus is on improving efficiency in power production and conservation in expeditionary facilities energy use.

Issue areas of concern

Power production efficiency

Issues

For the foreseeable future, forward bases will rely on traditional generators to produce electrical power. The technology is robust, reliable, reasonably portable, and well understood. Generators currently account for a third of the fuel used in sustained operations. At most forward bases, where there is little aviation activity, the generators account for even higher percentages of fuel use.

The next line of tactical generators, AMMPS, already promises efficiency gains of 15 to 25 percent over current systems [17]. Advances such as permanent magnets allow significant weight savings and increased efficiency. Variable speed operation allows for improved efficiency when operating at less than full load. Further improvements in the efficiency of generators are possible with advanced fuel injection systems, the incorporation of ultracapacitors as energy storage devices, and thermoelectric devices that convert exhaust heat directly to electricity. The decision to replace current generators with newer models that are 20 percent more efficient would pay for itself in fuel savings within a year, if fuel is valued at the $6 a gallon delivered price.

Gaps

- There is a need for continued improvement in the fuel efficiency, weight, and noise levels of generators.

- Prompt fielding of more efficient generators, particularly at the tactical edge where fuel delivery cost is high, is important if USMC is to accomplish fuel and cost savings. Any reluctance to replace current working generators will slow efficiency gains.
- There is a need for continued attention to the development of fuel cells and alternative engine designs as potentially higher efficiency replacements for inefficient small diesel generators.

Energy efficient structures

Issues

As much as 75 percent of the fuel used to generate electricity at forward bases goes to air conditioning or heating poorly insulated tents and structures. This is of most concern at the larger bases, where air conditioning is prevalent. Currently, more attention goes to ensuring adequate power delivery to these bases rather than to reducing energy demands.

The effective use of spray foam insulation has already been demonstrated in Iraq and Afghanistan. It can reduce energy use by as much as 50 percent [7]. The problem is that foamed tents are not reusable. While that may be appropriate when facilities are to remain in place, it is problematic for the Marines who require mobility. There are ongoing efforts to explore other approaches to insulating structures. There is also a new line of improved ECUs coming soon that promises a 15-percent improvement in fuel consumption [18]. Our analysis suggests that better insulation and more efficient air conditioning could reduce overall fuel use by more than 11 percent, the highest payoff to any single alternative.

Gaps

- There is a need for effective, robust, lightweight, easy-to-install, and portable insulation for air conditioned tents.
- There is a need for continued improvements in the efficiency of heating and air conditioning systems.

- There is a need for training to emphasize responsibility for energy efficiency and conservation.
- There is a need for improved training of camp commandants to help them better manage energy resources.
- There is a need to ensure that base support and acquisitions contracts require and reward energy efficiency.

Power management

Issues

Camps are set up quickly, with more attention to establishing the foothold, than to planning for efficiency. Each group is provided with its own generator, often oversized for the load. Generators are frequently observed running at less than 50-percent load. This is wasteful and leads to maintenance problems (due to accumulation of unburned fuel). Generators may be oversized due to unavailability of appropriate units or cautious anticipation of future growth. The problems have been exacerbated by a shortage in distribution equipment and trained manpower. Our analysis suggests that a more tailored layout of the power grid, one that would reduce excess capacity and better manage loads, can reduce generator fuel use by more than 25 percent (also see [6] and [19]). That corresponds to an 8-percent reduction in overall fuel use.

There have been attempts to develop systems to simplify grid management. For now, though, the devices are too complex and expensive for widespread use in an expeditionary setting. Simpler systems and approaches to addressing overcapacity and inefficient grid design are called for.

Gaps

- There is no small-scale, low-cost architecture capable of simplifying power management. Such a system should allow for easy integration of small clusters of generators and renewable power sources, with automatic startup and shutdown, and managed energy storage to efficiently address peak loads. It should be portable and easily adaptable to changes in grid size.

- There is a need for integrated energy storage capability in standalone generators. Storing energy during off-peak times to be delivered to meet peak demands would allow for smaller generators to be used, each running more efficiently.

- There is insufficient emphasis on efficient base layout and grid design when camps are first established. Better use of planning software or standard templates for base design would be helpful.

- More attention needs to be paid to deployment planning in order to ensure that the switching equipment and wiring harnesses that are needed to link power sources and combine loads are available.

- There are too few trained electricians and technicians to setup, manage, and maintain power distribution systems in distributed operations. A battalion may have just one person covering several outposts and patrol bases.

Renewable power sources

Issues

Renewable energy systems for generating electric power have become readily available and more affordable in recent years. They offer the possibility of greater self-sufficiency because they produce power without fossil fuel. However, renewable systems are not yet ready for widespread application in an expeditionary setting. They can be fragile, intrusive in their footprint, bulky, costly, and unreliable as a steady source of power. Solar systems, in particular, require significant supplemental power sources to meet demands during non-daylight hours. Solar power is perhaps suited to some small-scale and niche applications.

Of growing concern are the piecemeal efforts being used to evaluate and acquire solar energy systems. Such approaches can lead to difficulties with interoperability, maintenance, training, and logistics support. This is an issue particularly with respect to the variety of electronic controls used to manage these power systems.

Gaps

- There is a need for more efficient, robust, small renewable energy systems to improve self-sufficiency at forward bases.
- There is a need for a standard power distribution architecture that allows renewable energy power to be easily integrated with existing generator systems.
- There needs to be a more centralized approach across DOD to the evaluation and design of renewable energy systems in order to ensure that interoperability, logistics, and maintenance needs are being addressed.

Final observations

We recommend that the Marine Corps become more actively involved in promoting the development and effective use of energy solutions relevant to the expeditionary role. Specifically, we suggest the following:

- Establish a permanent experimental FOB at 29 Palms where Marines can gain training in energy, water, and waste management.
- Establish a comprehensive requirements document that will spur commercial development of relevant energy solutions.

This page left intentionally blank.

Appendix A: Energy technologies

We conducted a survey of currently funded RDT&E projects and acquisitions to identify products and technologies that might improve the energy self-sufficiency of forward deployed USMC forces. Over 50 products and projects, identified in references [20] to [50], were reviewed. Roughly half of them describe products in the pipeline or technology projects that will likely produce products by 2015. The others are longer-term projects with the objective of producing products that will likely become available between 2015 and mid-century. We review these with the understanding that some may be useful to the USMC and some may not.

We categorized the products and technology projects according to their end-use objective: (1) more efficient power generation with fossil fuels, (2) improved power management and distribution, (3) fossil fuel alternatives, (4) reduced electricity consumption, and (5) improved delivery system performance.

Introduction

In addition to technology investments, there are two fundamental issues that will impact the demand for fossil fuels. The first is that electrical power generation for forward deployed forces will depend, well into the foreseeable future, on tactical generator sets powered by fossil fuels. This is reflected in the large generator inventory and in the continuing technology investment to improve the fuel efficiency and performance of these generators. The DOD generator set is estimated as 125,000 units, with the USMC fielding just over 6 percent of this total [20]. These generators are widely used because the technology is reliable, robust, mobile, power dense, and well understood.

A second fundamental issue that will impact the demand for fossil fuels is the application of system design techniques to optimize base layout and equipment selection to reduce fossil fuel needs. The DOD

Project Manager for Mobile Electric Power (PM-MEP) [20]–[22] has sponsored a systems integration approach and each of the services is now engaged in efforts to conduct system level experimentation and develop the tools needed to improve self-sufficiency at forward locations.

One of the base planning tools is the Auto Distribution Illumination System Electrical (AutoDISE) [23]. It helps in the selection of generator sets, renewable energy options, environmental control unit (ECU) options, shelter improvements, and efficient lighting systems. The Net Zero Plus Joint Concept Technology Demonstration (JCTD), involving the Army and Marine Corps, is evaluating energy efficiency technologies at an experimental forward operating base (FOB) at Fort Irwin, California [24]. The Air Force Research Laboratory is exploring solar power, fuel cells, and efficient shelter systems at the Renewable Energy Tent City on Tyndall Air Force Base, Florida. These system-level experiments provide the opportunity to identify potential operational problems and technology investments.

Others across the DOD research community, including the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR), are seeking advances in energy technologies that might better support deployed forces.

Our survey of RDT&E investments clearly indicates that improvements to the power generator sets and operating base layout and design are being aggressively pursued.

Improved power generation efficiency—fueled systems

The DOD PM-MEP directs an aggressive program to improve power generation efficiency. The Army provides major support in executing the PM-MEP program. ONR and the Marine Corps System Command contribute to its execution. The projects and product descriptions discussed immediately below are part of that program [20] [22] [25] [26] [27].

Conventional generators

Advances to the conventional diesel engine generator such as variable speed operation, permanent magnets, advanced fuel injection, integrated energy storage, automatic paralleling, and waste heat recovery are expected to improve fuel efficiency, power density, reliability, ease of setup, and noise levels.

Advanced Medium Mobile Power Sources. The Advanced Medium Mobile Power Sources (AMMPS) program will lead to a new family of diesel engine generators that produce between 5kw and 60kw of electrical power [25] [26]. AMMPS will replace the current Tactical Quiet Generator (TQG) generator sets in the same power range, with production beginning in 2010. Generators in this power range represent about two-thirds of the total inventory. The new generators improve on the fuel efficiency of the TQG generator by 15 to 25 percent.

Large Advanced Mobile Power Sources. The Large Advanced Mobile Power Sources (LAMPS) development project is scheduled to begin in 2010. The goal is to replace the large (100kw and 200kw) TQG generator sets with more efficient systems.

Lightweight 100kw diesel generator. A concept generator is being developed that uses a turbocharged aero-diesel (a lightweight diesel developed for aviation use) to drive an advanced permanent magnet alternator, with variable speed operation, and ultracapacitors for energy storage. The goal is a towable system weighing 4200 lbs or less.

Small Tactical Power Systems. The Small Tactical Electric Power (STEP) program is scheduled to start development in 2012. The interest is in lightweight generators that produce 3kw or less. A number of potential options are being evaluated. For small diesels, there is interest in the following:

- *Advanced fuel injection.* Advanced electronic fuel injection systems are being evaluated. They are expected to improve fuel efficiency and lower noise in small diesel generators.
- *Integrated energy storage.* An experimental system is integrating energy storage devices with a variable speed generator. Ultra-

capacitors serve to meet peak loads, with the advantage being that a smaller generator can be used to meet power demands.

Combustion alternatives to conventional generators

A number of nonconventional approaches to small tactical electric power production are under consideration [20][29][30].

Modified gasoline engines. Research is being conducted on modifying lightweight spark ignition gasoline engines to operate on JP-8 fuels. Advances in fuel injection technologies allow this. A portable 1kw generator weighing less than 15 lbs is expected.

Microturbines. Small gas turbines, operating at 24-percent efficiency and weighing about 22 lbs are in development. Microturbines offer a high power to weight ratio and are slightly more efficient than small diesels. They can be noisy, however.

Stirling engines. Researchers are investigating Stirling engines to produce 160w to 3kw of power. Compared to a diesel, the external combustion Stirling engine is expected to be quieter, cleaner, more reliable, and more efficient.

Advanced thermoelectric power sources. Thermoelectric materials convert heat directly to usable electrical power.

- *Heat recovery systems.* These materials can convert engine exhaust heat to electrical output, adding to the efficiency of generators and vehicle engines. Projects are underway using advanced thermoelectric devices in a small tactical generator and in the Stryker vehicle [28].
- *Small power source.* The devices are also being evaluated as small, lightweight power sources. In the long term, thermoelectric devices may replace combustion engines, if conversion efficiencies can be improved to 35 percent. Efficiencies of 10 percent are available now and 15-percent efficiency is expected soon [28].

Fuel cells

Fuel cells convert the chemical energy of fuels directly to electrical power, through a reaction between a fuel and an oxidant. There is a wide variety of fuel cells, but the principles are the same. They are made up of three elements: the anode, the electrolyte, and the cathode. At the anode, a catalyst oxidizes the fuel into a positive ion and negative electrons. The electrolyte allows the ions to pass through to the cathode, but not the electrons. Instead, the electrons flow through a wire, creating the electrical current. The electrical circuit returns the electrons to the cathode, where, in the presence of another catalyst, they react with the ions and oxygen to create water and carbon dioxide.

Fuel cells differ in type of electrolyte, fuels, and catalysts. They are classified according to the type of electrolyte. Proton exchange membrane fuel cells (PEMFC) are the classic hydrogen-oxygen fuel cell. Generally, to use other fuels than hydrogen, the fuel must first be reformed to produce hydrogen. Solid oxide fuel cells (SOFC) have the advantage of running on a variety of fuels including hydrogen, hydrocarbons, or alcohols. A major disadvantage of the SOFC is a very high operating temperature. The high operating temperature requirements mean that SOFC technologies cannot start up fast and are not reliable for frequent start and stop operations.

A number of fuel cell projects are underway across DOD.

- *Man portable systems (20–1000w).* Several products are being developed to provide the soldier with “on-the-move” battery charging systems. It is anticipated that their success will reduce the logistic load and battery resupply demand. The reformed methanol PEMFC and the SOFC have been demonstrated. ONR is also looking at a novel high temperature PEM fuel cell that will operate on reformed JP-8 fuel [31]. The use of JP-8 fuels in fuel cells has been problematic because sulfur poisons the catalysts and high carbon monoxide levels in reformate interfere with the electrolyte.
- *Auxiliary power units (.5-15kw).* There is an ONR program to develop solid oxide fuel cells that can provide auxiliary power to military vehicles [29]. The system aims to produce 15kw of power at greater than 30 percent efficiency using reformed JP-8.
- *Tactical power units (5-60kw).* ONR is seeking to create solid oxide fuel cells that can serve as high efficiency replacements for

the tactical electrical power generators [32]. The requested systems would operate on JP-8 fuel. They might consist of a fuel reformer, solid oxide fuel cell, and integrated energy storage. Efficiencies of close to 50 percent are expected, once exhaust heat recovery systems are included.

Improved power management and distribution

The Mobile Electric Power Distribution Replacement System (MEPDIS-R) is the Marine Corps' approved tactical power distribution system. It is a flexible, modular system consisting of portable power distribution boxes and interconnecting power cables. Related improvements that will help with grid layout and ease of setting up and efficient design are available or in development.

AutoDISE software. AutoDISE [23] is used to help design a power grid layout. It assists in correctly sizing equipment, determining electrical equipment and cable needs, and connecting and balancing loads across generators. The software accounts for shelters, electrical consumers, distribution equipment, and power generators.

Intelligent Power Distribution system. The Intelligent Power Distribution system is expected to be fielded in 2011 by PM-MEP [25]. This system is designed to simplify power distribution and reduce training needs by introducing automatic load balancing. It is compatible with current MEPDIS-R equipment.

Hybrid Intelligent Power. In the longer term, a project that appears promising is Hybrid Intelligent Power (HI-POWER) [16] [19], which is a power management architecture. It is intended to minimize the use of fossil fuel by dispatching and synchronizing multiple power inputs. The inputs can be generators, solar, wind, energy storage systems, and local electrical grids. It is suitable for combining power systems of up to 200kw, an appropriate grouping for many expeditionary bases.

Electronic Power Conditioning and Control. Another power management project is the Electronic Power Conditioning and Control (EPCC) [19]. This is a containerized unit (20 ft ISO container) designed for power grids of 250kw to 1mw. Although the idea is promising, the size, scale, and cost ($560,000) of this unit make it unclear what role it might play in an expeditionary setting.

Fossil fuel alternatives

This section describes renewable energy technologies and substitute fuel concepts that have the potential to either replace fossil fuels or reduce fossil fuel demand. We also include power storage technologies in this section.

Solar energy

Deployable and Renewable Energy Alternative Module. One near-term project is the Deployable and Renewable Energy Alternative Module (DREAM), sponsored by the USMC Program Manager for Expeditionary Power Systems and ONR. It is packaged to be HMMWV towable and includes solar-photovoltaic panels that produce over 5kw of peak electrical power [16] [35]. The system uses commercially available solar- photovoltaic panels and lithium-ion batteries. A large footprint and high cost make the system of doubtful value for extensive use. The lithium-ion batteries are significant cost drivers. In an early demonstration, the system failed to meet goals for continuous power, and it is, therefore, being reevaluated [16].

Ground Renewable Expeditionary Energy System. ONR is sponsoring the Ground Renewable Expeditionary Energy System (GREENS) program to develop and demonstrate a portable renewable power system using solar collectors [36]. The system produces 1.6kw of peak power and costs almost $35,000. It is ruggedized for expeditionary use and can be packed into 80 lb cases.

Solar shades and flexible photovoltaics. Solar shades can reduce the heating load on tents. A variety of commercially available systems now integrate flexible photovoltaic panels into solar shades [24]. Systems ranging from 750w to 2kw have been demonstrated and have undergone technical and user testing at the Net Zero Plus JCTD [37].

Flexible organic solar cells. ONR and the Naval Research Laboratory are sponsoring research to improve the efficiency of flexible organic solar cells [36]. These are thin solar cells that can be applied to material (e.g., tents, uniforms) and other flexible substrates. Efficiency levels are now less than 8 percent for most commercially available products using flexible solar cells, well below the 20 percent available from solid cells. Efficiencies of closer to 13 percent are expected soon.

Very High Efficiency Solar Cells. DARPA and the National Renewable Energy Laboratory (NREL) are seeking to develop and demonstrate very high efficiency multi-layer solar cells (VHESC). The goal is an affordable, manufacturable module that can achieve power efficiencies of 40 percent. Efficiencies of over 40 percent have been demonstrated, more than double what is now commercially available [38].

Other renewables

Wind. Although smaller wind turbines are perhaps attractive for isolated military bases, wind power is not ideally suited to expeditionary bases. Wind is inconsistent; the wind systems can be a hazard to aviation and interfere with radar; large towers require expensive construction and transportation efforts; and the systems may be visible from far away, making for an inviting target.

Biomass. The Central Intelligence Agency is proposing development of small scale biofuel processors for distribution in Afghanistan. The goal is to create a highly distributed local biofuel industry that would serve to create a market for oil crops that might replace opium [39].

Waste-to-energy. Waste-to-energy projects have the potential to address the base waste disposal problem and simultaneously produce fuels.

- *Tactical Garbage to Energy Refinery.* The Tactical Garbage to Energy Refinery (TGER) system is a waste-to-energy system that combines advanced fermentation and thermal gasification processes to produce ethanol and synthetic gas from food and packaging waste [40] [41]. The ethanol, gas, and additional diesel are mixed to run a 60kw generator. A ton of garbage will run the generator for a day. The generator uses 5 gallons of diesel an hour during the 6 to 12 hours the TGER takes to warm up; once fully operational, only 1 gallon of diesel an hour is required. The TGER fits inside a standard shipping container. The system is not yet fully viable for expeditionary use, due to reliability problems, scale, and operational complexity [41].

- *Mobile Integrated Sustainable Energy Recovery.* The containerized Mobile Integrated Sustainable Energy Recovery (MISER) system uses the supercritical water gasification conversion process to produce a gallon of diesel from each 22.7 pounds of waste processed. Reliable long-term operation has not been demonstrated yet [42].

Alternative energy sources

Radioisotope power sources. Radioisotope generators can serve as very long-lived power sources. Widely used by NASA, they convert thermal energy from radioactive decay directly into electrical energy. Researchers in the DARPA Micro Isotope Power Sources (MIPS) program are looking at extremely high energy density radioisotopes as long-lasting alternatives to conventional batteries for unattended sensor applications. Larger systems do pose some risk of contamination if the container leaks, but there is otherwise little risk from radiation.

Energy storage

Batteries. DARPA is exploring a variety of materials that may increase the capacity of lithium-ion batteries. Their Micro Power Sources (MPS) project is investigating new battery architectures, new materials, and their chemistries in order to provide increased energy densities in smaller packages.

Ultracapacitors. ONR researchers are seeking further advancement in the power density of ultracapacitors [30][43]. An ultracapacitor can provide the power density (w/kg) of a standard capacitor in combination with an energy storage density (wh/kg) approaching that of lead-acid batteries. Advanced ultracapacitors will be of high value as lightweight energy storage devices in hybrid vehicle and power generators, improving the handling of peak electrical loads.

Conservation—reducing electricity consumption

This section reviews technologies that reduce electricity consumption by making products already in use more efficient or by transferring demand to more efficient fuel-using energy sources. Generally, these projects focus on shelter improvements and ECU efficiency.

Shelters

A number of projects already in progress aim to improve the efficiency of shelter systems. The Army Natick Shelter Technology, Engineering, and Fabrication Directorate leads a comprehensive RDT&E program focused on energy management systems (solar photovoltaic, lighting, insulation) [24]. The Net Zero Plus JCTD program has evaluated several of these shelter concepts. Of interest are the following:

- *Aerogel insulation.* Aerogels are a nano-silica material with the lowest thermal conductivity of any known solid. The remarkable thermal properties of this material have been incorporated into a flexible insulation for military shelters [24][44]. The insulation has demonstrated a 40 percent improvement in thermal resistance, while not affecting packing size and only increasing tent weight by 3 percent. The technology is still maturing; there have been problems with the insulation powdering.
- *Honeycomb insulation liners.* These tent liners are made of heat reflecting outside layers and thermal insulating interior layers [45]. The honey-combed interior lays flat during transport and is inflated with air when deployed. The product is still in development; there can be problems with air leaks when the outside layers are torn.
- *Solar shades.* A number of products that integrate flexible photovoltaics in tent material have been evaluated [24]. When integrated into solar shades for tents, these systems serve two purposes: reducing heat absorption and providing electric power. Army research and development efforts are looking to lower the unit cost of incorporating flexible solar-photovoltaic panels into solar shades.

Environmental Control Units

Improved Environmental Control Units. A family of Improved Environmental Control Units (IECU) is currently under development. These new systems are designed for reduced power consumption, with a soft-start capability that limits current surge. Fuel savings of 15 percent are expected [17].

Improved Integrated Trailer Environmental Control Unit Generator. The Marine Corp has developed an improved HMMWV towable Integrated Trailer Environmental Control Unit Generator (ITEG) to support highly mobile activities [23][46]. An ITEG unit integrates a generator set and environmental air conditioning. The improved ITEG will use the engine flywheel to directly drive the compressor, eliminating an inefficient mechanical-to-electrical-to-mechanical conversion process. This will result in a 20-percent efficiency gain.

Evaporative cooling. An evaporative cooler is a device that cools air through the evaporation of water. Air conditioners that rely on evaporative cooling are widely available commercially. They are well suited to climates where temperature are high and the humidity is low. Power savings can be over 50 percent as compared to compressor-based units [47]. However, with water use of 4 to 10 gallons a hour (as compared to fuel savings of perhaps a gallon an hour), the systems are not going to be cost effective where water must be delivered by convoy.

Geothermal heat pump. Energy alternatives include a geothermal heat exchanger. The Army has experimented with a prototype that will circulate cooler temperatures from underground to reduce shelter air conditioning demands [22].

Cogeneration/waste heat recovery

Thermal fluid cogeneration. The Army is looking at options to recover heat generated in power production for use in kitchens, laundry, or shower facilities. The project explores the use of a central burner and thermal fluid heat transfer system to drive power generation and provide heat for food processing. They are exploring various engine technologies for the power generators (Stirling engines, gas turbines, or steam turbines). The cogeneration system will operate at significantly higher overall efficiency than standalone systems (potentially exceeding 75 percent) and reduce fuel consumption [22].

Thermoelectric devices. As previously discussed, thermoelectric devices that allow direct conversion of waste heat to electricity are under development.

Delivery system trends

In terms of delivery system trends, in the near term, there will be a continuing tendency to reduce fossil fuel dependency. For ground transportation, the emphasis will be on hybrid power systems, alternative fuels, advanced engine and fuel controls, heat recovery, and vehicle weight reduction. Aircraft efficiency will rely on turbine improvements and better system integration of airframe, power plant, control, and aerodynamic features [48].

In the longer-term (2015 and beyond) ground transportation systems may be powered by fuel cells. Aircraft systems may use unducted fan engines and ceramic gas turbine blades that allow for higher engine operating temperatures and efficiencies [48].

We also note that the increasing use of unmanned air and ground vehicles may significantly influence future operating base designs and energy consumption. While the limits of this trend and its impact on future force levels have not been defined, it is important to keep it in mind.

Appendix B. Tactical generator fuel use

In table 9, we list annual fuel consumption rates for tactical generators of various sizes, showing how fuel use depends on power load. Table 10 provides efficiency data, with efficiency measured in terms of kilowatt hours (kwh) produced per gallon of fuel. The larger generators operate more efficiently than smaller ones, and there is greater efficiency at higher loads.

Table 9. Tactical generator yearly fuel consumption rates (gals)

Generator size	Percent load on generator 100%	75%	50%	25%
3kw	3,013	2,427	1,927	1,551
10kw	8,060	6,480	5,340	3,680
30kw	23,215	18,310	13,930	10,250
60kw	41,520	32,850	23,566	16,995
100kw	66,925	53,260	40,910	27,860

Note: Fuel use calculated based on 24-hour-a-day operation. Actual use will be less, due to maintenance downtime. Data on hourly fuel use provided by the Marine Corp Warfighting Lab.

Table 10. Tactical generator efficiency (kwh/gal)

Generator size	Percent load on generator 100%	75%	50%	25%
3kw	8.7	8.1	6.8	4.2
10kw	10.9	10.1	8.2	6.0
30kw	11.3	10.8	9.4	6.4
60kw	12.7	12.0	11.2	7.7
100kw	13.1	12.3	10.7	7.9

This page left intentionally blank.

References

[1] Defense Energy Support Center. *Fact Book 2008*. https://www.desc.dla.mil/DCM/Files/DESC Fact Book FY 2008.pdf

[2] Defense Energy Support Center. *Fact Book 2006*. https://www.desc.dla.mil/DCM/Files/FactBook_FY06.pdf

[3] Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. Report of the Defense Science Board Task Force on DOD Energy Strategy. *More Fight – Less Fuel*. Feb 2008

[4] Commanding General, Multi-National Force-West (MNF-W). Joint Staff Rapid Validation and Resourcing Request, *Renewable Energy System*. 25 Jul 2006

[5] USMC Energy Summit. "Lightening the Load – Reducing the Footprint in the Expeditionary Environment – A National Security Imperative for Success." Washington, D.C. 13 Aug 2009

[6] Marine Energy Assessment Team. *Afghanistan Assessment Outbrief*. 21 Oct 2009

[7] B. Frounfelker and T. Wilke. Army Material Systems Analysis Activity (AMSAA). *Spray Foam Insulation Information Brief*, presented to Army Senior Energy Council. 30 Jul 2009

[8] Bureau of Transportation Statistics, Research and Innovative Technology Administration. *Airline Fuel Cost and Consumption*. http://www.transtats.bts.gov/fuel.asp?pn=1

[9] Energy Information Service. *Annual Energy Outlook 2010: Early Release Overview*. DOE/EIA-0383. 14 Dec 2009. http://www.eia.doe.gov/oiaf/aeo/overview.html

[10] Energy Information Service. *Annual Energy Outlook 2009.* DOE/EIA-0383. http://www.eia.doe.gov/oiaf/forecasting.html

[11] Army Environmental Policy Institute. *Sustain the Mission Project: Casualty Factor for Fuel and Water Resupply Convoys.* Sep 2009

[12] "How the US army protects its trucks – by paying the Taliban." *The Guardian,* 13 Nov 2009. http://www. guardian.co.uk/world/2009/nov/13/us-trucks-security-taliban

[13] Defence Technology and Innovation Centre, UK Ministry of Defence. *Reducing Operational Dependence on Fossil Fuel Capability Vision The Self Sustaining Forward Operating Base.* 19 Jun 2009

[14] E. Blankenship and R. Cole. Headquarters Marine Corp PA&E. *Fuel and Water for OEF: Towards Developing "Fully Burdened Costs*, presented at MORS Power and Energy Workshop. 30 Nov 2009

[15] Center for Army Analysis. *Strategic Energy Resource Investment Optimization for the US Army.* Aug 2004

[16] *A Mobile Hybrid Power Source with Intelligent Control.* Rick Silva, CME. Joint Service Power Expo. 7 May 2009. http://www.dtic.mil/ndia/ 2009power/2009power.html

[17] Paul Richard, PM-MEP. *Mobile Electric Power for Today and Tomorrow*, presented Joint Service Power Expo. 25 Apr 2007. https://www.pm-mep.army.mil/pdffiles/Joint_Service_Power_Expo_25Apr07.pdf

[18] Jeff Taylor, PM-MEP. *Improved Environmental Control Unit (IECU) Program Overview,* presented at JOCATA Technical Working Group Meeting. Nov 2009. http://www.natick army. mil/Soldier/jocotas/Nov09/taylor improved environmental control unit (iecu) program ov.pdf

[19] CERDEC, U.S. Army REDECOM. *Hybrid-Intelligent Power "HI-POWER".* http://www.nist.gov/eeel/high_megawatt/upload/Holcomb-2.pdf

[20] DOD Project Manager Mobile Electric Power (PM MEP). *DOD Mobile Electric Power Systems Command Brief to EGSA*. Mr. Paul Richard. Mar 2009

[21] Marine Corps Warfighting Lab. *USMC Energy Efficiency: Brief to LtGen Flynn*. 26 Aug 2009

[22] U.S. Army Combined Arms Support Center White Paper. *Tactical Electric Power (TEP): Emerging Technologies and Initiatives That Influence Organizational Power Needs*. Jan 2009

[23] *AutoDise 6.2.0 User's Manual*, prepared for Army CECOM Power Generation Branch by BRTC Inc. 2009

[24] U.S. Army Natick Soldier RD&E Center. *Shelter Technology Engineering and Fabrication Directorate: Technologies Overview*. Aug 2009

[25] DOD Project Manager Mobile Electric Power (PM-MEP), *EGSA Government Relations Session: Army R&D Efforts*. EGSA Fall Meeting. C. Bolton. 14 Sep 2009

[26] Oak Ridge National Laboratory. *Developments of Proof of Concept Units for the Advanced Medium-Sized Mobile Power Source (AMMPS) Program*. ORNL/TM-2001/222. Mar 2002

[27] National Defense Industry Association (NDIA)Marine Corps Expeditionary Power and Energy Symposium, various industry exhibit brochures. Jan 2010

[28] U.S. Department of Energy. *Thermolectric Developments for Vehicular Applications*. Diesel Engine-Efficiency and Emmisions Research Conference, Detroit. 24 Aug 2006

[29] Office of Naval Research. *Power and Energy Overview Brief to MajGen Robert E. Shmidle*. Paul Gido and Richard Carlin. 30 Apr 2008

[30] Office of Naval Research. *Naval S&T in Support of USMC Energy Futures*, presented at the USMC Energy Summit 2009. George Solhan. 13 Aug 2009

[31] *Person Portable JP-8 Fueled Fuel Cell Power Generator (PJF-Gen).* http://www.virtualacquisitionshowcase.com/document/627/briefing.

[32] Office of Naval Research. *Solid Oxide Fuel Cell Based Tactical Electrical Power Demonstration.* ONR BAA Announcement Number 09-034. 22 Jul 2009

[33] U.S. Army Rapid Equipping Force (REF) briefing, Jul 2007

[34] Department of Defense Energy Security Task Force (OUSD(AT&L)). *Department of Defense report to Congress on Energy Security Initiatives.* Oct 2008

[35] AeroVironment, Inc. *Deployable Renewable Alternative Energy Module, Operators Manual.* Jul 2008

[36] Office of Naval Research. *Power and Energy Overview,* briefing to MGen Schmidle. 30 Apr 2008

[37] U.S. Army Natick Soldier RD&E Center. *Net Zero Plus JCTD: Evaluation of Energy Savings Technologies for Expeditionary Shelters.* JOCOTAS. 4 Nov 2009

[38] "University Of Delaware-Led Team Sets Solar Cell Record." *Science Daily.* 30 Jul 2007. http://www.sciencedaily.com/releases/2007/07/070726210931.htm

[39] Office of the Chief Scientist, Central Intelligence Agency. *Afghan Energy Project: Presentation to LtGen George Flynn.*

[40] "Trash Tactics in Iraq." *Biomass Magazine.* Oct 2008.

[41] U.S. Army RDECOM, Edgewood Chemical Biological Center. *Tactictal Garbage to Energy Refinery.* ECBC-TR-713. Oct 2009

[42] U.S. Army RDECOM. *Minimizing the Footprint of Deployed Bases: Army Approaches to Waste to Energy Conversion.* Patrick Taylor. 7 May 2009

[43] Marine Corps Warfighting Lab, CSS Branch. *Expeditionary Power Overview. Brief for CG MCWL.* 7 Aug 2009

[44] U.S. Army Natick Soldier RD&E Center. *High Performance Aerogel Insulation For Shelters*. Elizabeth Swisher. 13 Jan 2008

[45] U.S. Army Natick Soldier RD&E Center. *Fabric Structure Team Overview: Shelter Technology, Engineering, Fabrication Directorate.* Jean Hempel. Nov 2009

[46] Michael A. Gallagher, Marine Corps Systems Command, "Innovations in United States Marine Corps Expeditionary Power Systems." *The WSTIAC Quarterly*, Vol. 9, No.1 Mar 2009

[47] U.S. Department of Energy, Federal Energy Management Program, "Coolerado Cooler Helps to Save Cooling Energy and Dollars." *Technology Installation Review.* DOE/GO-102007-2325. http://www1.eere.energy.gov/femp/pdfs/tir_ coolerado .pdf

[48] Professional Pilot, pp 54-62. *Technology Timelines 2010: A Look Ahead for the Next 30 Years from an Assortment of Industry Leaders*, M. Cetron, President, Forecasting International, Dec 2009

[49] Responses to Office of Naval Research Request for Information 10-RFI-0003, Topic: Forward Operating Bases

[50] National Defense Industry Association (NDIA)Marine Corps Expeditionary Power and Energy Symposium, various Naval Research Laboratory exhibit brochures. Jan 2010

This page left intentionally blank.

List of figures

This page left intentionally blank.

List of tables

This page left intentionally blank.

CRM D0022638.A2/Final

4825 Mark Center Drive, Alexandria, VA 22311-1850 703-824-2000 www.cna.org