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Soldier-Portable Battery Supply

Foreign Dependence and Policy Options

Richard Silberglitt, James T. Bartis, and Kyle Brady

Key findings

- The primary driver of battery development and manufacture is civilian demand.
- Most of the rechargeable batteries procured by the Department of Defense are assembled from critical components manufactured outside the United States, principally in Asia, where many consumer devices containing such batteries are manufactured.
- Research found that government and battery industry representatives expressed concerns about the security and surge capability of the soldier-portable battery supply chain, the potentially unmanageable cost of establishing a U.S. production base, and the potential incompatibility of commercial batteries with military requirements.
- Unless the U.S. manufacturing base were to become competitive in the much larger market for consumer devices, fully domestically produced batteries for military applications will remain expensive compared to those using cells produced in Asia.
- Policymakers must make their decisions based on the predicted future power needs of soldiers and the risks associated with a foreign-dependent battery supply chain balanced against other supply chain risks and the costs of risk mitigation.

SUMMARY While batteries are crucial for military operations, their development and manufacture is primarily driven by the much greater civilian demand, especially for hand-held and portable electronic applications such as mobile phones, laptop computers, and, most recently, tablet computers. For consumer electronics, rechargeable lithium-ion batteries now dominate the market due to their ability to store large amounts of energy per unit weight and per unit volume, as compared to all other commercial options. Just as Asia is the source of manufacture of most consumer hand-held and portable electronic applications, it is also the center of manufacture for the associated batteries and battery components. This applies to both consumer and military applications.

During this study, it quickly became clear from discussions with government managers and researchers and representatives of the battery industry that most of the rechargeable batteries procured by the Department of Defense (DoD) are assembled from critical components manufactured outside the United States, principally in Asia.

Both DoD and the Department of Energy (DOE) have active programs aimed at developing a production base within the United States for rechargeable lithium-ion batteries—the former for space-qualified applications and improved soldier-portable batteries (SPBs) and the latter for electric and hybrid vehicles. However, because of the much greater demand for batteries for consumer devices (billions per year as compared to millions for military applications), a domestic manufacturer of SPBs will not benefit from the economies of scale enjoyed by the Asian battery manufacturers. This will result in DoD paying a premium, unless that manufacturer can also serve the consumer market.

Additionally, current policy is to use rechargeable batteries whenever practical and to procure such batteries from the lowest-cost supplier that meets military specifications. Add the fact that the number of SPBs is anticipated to increase significantly as the Army's Brigade Combat Teams rely increasingly on wireless devices, and this situation gives rise to concerns with respect to the security and surge capability of the SPB supply chain, the potentially unmanageable cost of establishing a U.S. production base, and the potential incompatibility of commercial batteries with military requirements.

In this report we outline three alternative policy options that address these concerns, in addition to the current policy:

1. **Strengthen the Supply Chain**: Develop and implement a logistics plan and infrastructure capable of delivering a sufficient number of non-rechargeable batteries to forward-based operating units to replace rechargeable soldier-portable batteries (RSPBs) in the event of a disruption within the supply chain; require all materials and components to be obtained from secure sources; require a surge production capacity across the entire supply chain; or establish a stockpile.
2. **Strengthen the Nexus Between Soldier-Portable Research and Development (R&D) and Manufacturing**: Increase support to production-related R&D and/or increase coordination with participants in the DOE Vehicle Battery Program.
3. **Promote Domestic Production of RSPBs**: Require DoD procurements to have all key components and advanced materials be manufactured within the United States; provide investment or production subsidies to firms that manufacture batteries with high domestic content; or incentivize domestic production using non-monetary measures, such as establishing technical specifications that promote the manufacture of advanced RSPBs.
4. **Maintain the Current Policy:** Continue to pursue the current policy of buying lowest-cost RSPBs that meet the military specifications, but are assembled from commercial cells.

If DoD decides that it wants to take action concerning foreign dependence of the SPB supply chain, then the minimum approach would be elements of Policy Option 1: Strengthen the Supply Chain. If DoD could establish a vendor certification process and establish secure sources for all soldier-portable cell and battery components, as well as cell production and battery assembly, whether in the United States or with its allies, it would have a reliable supply chain.

Policy Option 2, Strengthen the R&D-Manufacturing Nexus, also has potential benefits. It would leverage the R&D investments of both DoD and DOE, and could lead to some U.S. production of RSPBs. However, unless the U.S. manufacturing base were to become competitive in the much larger market for consumer devices, the fully domestically produced batteries for military applications will remain expensive compared to those using cells produced in Asia.

The most direct approach to establishing a reliable soldier-portable battery supply chain would be Policy Option 3: Promote Domestic Production. However, this would likely be the most expensive option. Its pursuit would likely also not be based solely on defense concerns, because of the potential contribution of a strengthened domestic manufacturing base to economic and employment goals.

The benefit of Policy Option 4, Maintain the Current Policy, is the current system's low cost and the access it affords to the constant market-driven innovation occurring in the private sector. The trade-off is that military equipment must be either designed or adapted to use batteries assembled from cells that were manufactured with consumer applications in mind. Maintaining this policy may be a viable option, considering the cost of the other three options and other demands on DoD funds, including possible supply-chain problems with other critical military equipment. Cost-benefit analysis of the first three policy options, versus doing nothing, requires both technical data and information on the feasibility of supply arrangements that were unavailable to us, and was beyond the scope of this study.

INTRODUCTION

For want of a nail the shoe was lost,
for want of a shoe the horse was lost;
and for want of a horse the rider was lost;
being overtaken and slain by the enemy,
all for want of care about a horse-shoe nail.
Benjamin Franklin, 1758

Franklin's proverb reminds us of the importance of detail in military logistical planning. Obviously, horse-shoe nails are no longer a major focus of military procurement; if Franklin were writing today, however, he could reframe his proverb around the importance of soldier-portable batteries (SPBs). Batteries enable radio communication among combat squad members and field headquarters. They provide the power to obtain accurate location data essential for maneuver and combat air support. Laser range finders and night-vision goggles are two more examples of battery-powered capabilities that give U.S. troops battlefield superiority.

While batteries are crucial for military operations, their development and manufacture is primarily driven by the much greater civilian demand, especially for hand-held and portable electronic applications such as mobile phones, laptop computers, and, most recently, tablet computers (billions per year as opposed to millions for military applications).[1] For consumer electronics, rechargeable lithium-ion batteries now dominate the market due to their ability to store large amounts of energy per unit weight and per unit volume, as compared to all other commercial options. Just as Asia is the source of manufacture of most consumer hand-held and portable electronic applications, it is also the center of manufacture for the associated batteries and battery components. This applies to both consumer and military applications.

In 2012, the Office of the Assistant Secretary of Defense for Research and Engineering asked the RAND National Defense Research Institute to examine the dependence of the supply chain for current and emerging SPBs on capabilities that currently are not or may not be available within the United States or its allies. This supply chain begins with the raw materials needed to produce battery components and covers the full spectrum of manufacturing required to assemble a finished product meeting military specifications. Specifically outside the scope of our study were the logistics issues associated with delivering batteries to forward-based units and the management of batteries once they are received by such units.

During the study, it quickly became clear from discussions with government managers and researchers and representatives of the battery industry that most of the rechargeable batteries procured by the Department of Defense (DoD) are assembled from critical components manufactured outside the United States, principally in Asia. This strong dependence on manufacture within Asia then became the focus of the study. After collecting information on this dependence from available literature and discussions with subject-matter experts in government and industry from the organizations listed below, we outlined three possible new policy goals for increasing the security of the SPB supply chain and drew up the broad outlines of policy options aimed at achieving these goals. Our intention in this effort was not to recommend any particular policy, but rather to illuminate the potential paths forward should DoD decide that the current dependence on manufacture within Asia represents too great a supply-chain risk and thus the current policy should be changed.

How This Study Was Conducted

The RAND research team began this study by reviewing the literature covering current and emerging battery performance, applications, and suppliers. This literature review was followed by interviews with government researchers and program managers involved in the research and development (R&D) and acquisition of SPBs. The government organizations covered span the R&D and acquisition organizations with primary responsibility for SPBs, and include developers of advanced batteries that might be adapted toward soldier-portable use. These meetings included representatives from the following offices:

- Army Research Laboratory
- Air Force Research Laboratory
- Office of Naval Research
- Naval Research Laboratory
- Army Communications-Electronics Research, Development, and Engineering Center
- Army Program Executive Office Soldier—Project Manager Soldier Power
- Office of the Assistant Secretary of Defense for Operational Energy Plans and Programs
- Office of the Deputy Assistant Secretary of Defense for Manufacturing and Industrial Base Policy
- U.S. Department of Energy, Vehicle Technologies Program

- U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability.

For each of the above organizations, the representatives included the senior official responsible for and knowledgeable of battery development or acquisition issues. Most of the above meetings were in-person, with an average duration of over two hours.

Additionally, RAND researchers held structured discussions with representatives of several private-sector firms involved in the development and/or manufacture of batteries for military applications. These firms taken together supply the majority of batteries procured by DoD, and include developers of advanced battery designs and those among the top ten suppliers of batteries to the Defense Logistics Agency (DLA):[2]

- Bren-Tronics
- Dow Kokam
- PolyPlus
- Quallion
- SAFT America
- Thales
- 3M
- Ultralife
- Yardney.

The representatives of the above firms were senior managers responsible for battery development and/or sales to DoD. To facilitate frank and open discussion, the meetings with industry representatives were held on a not-for-attribution basis. Most of the industry discussions were by phone, with an average duration of over one hour.

Definitions

While this is not a technical report on batteries, we do need to introduce a few technical terms. For example, we will discuss both single-use and rechargeable batteries. Following common practice, we designate single-use batteries as *primary* batteries. Once they are discharged, they must be discarded. Rechargeable batteries are generally referred to as *secondary* batteries.

In general, a battery is collection of cells. A conventional automobile battery used for starting, lighting, and ignition, for example, generally contains six lead-acid cells. Some batteries consist of a single cell, which is the case for the familiar alkaline batteries (e.g., AAA through D cells). A multi-cell battery basically consists of three components: the cells, the battery packaging that holds the cells, and the wiring and electronics that connect the cells and assure safe charge and discharge.

The cell is the basic working element of a battery; it is where chemical energy is converted into electrical energy. Each cell consists of a negative and a positive electrode. When operating (i.e., discharging), electrons flow from the negative electrode, through an external circuit, to the positive electrode. The negative electrode is also called the *anode,* and the positive electrode is called the *cathode*. Separating the anode and cathode within a cell is the *electrolyte*. The electrolyte is a liquid or semi-porous solid through which ions can move between the two electrodes during battery discharge and, in the case of secondary batteries, recharging.

OVERVIEW OF SOLDIER-PORTABLE BATTERIES

SPBs are a subset of the larger military battery market, which covers power storage for vehicles, weapon systems, and numerous specialty requirements. This variety in battery applications leads to variety in the types of batteries that the military acquires; a battery cell designed to periodically provide small amounts of power to a flashlight is built differently than a large, one-shot cell inside a missile, which may lie dormant for many years and then be expected to provide a large amount of power at a moment's notice. The following sections provide a very brief overview of current and emerging SPBs. They do not, and are not intended to, provide a comprehensive listing of the characteristics, properties, and costs of such batteries.

The Characteristics of Soldier-Portable Batteries

DoD provides soldiers with both primary and secondary batteries. In some cases, a soldier will carry both types. Primary batteries produced in the United States include the familiar commercial alkaline cells commonly used to power flashlights, smoke alarms, and numerous devices within homes and businesses. Within the past few years, primary lithium metal batteries have become commercially available and are now used in soldier-portable applications. All primary batteries store and recover energy by way of an irreversible chemical reaction. Once the reaction has been allowed to run to completion, the battery has no further value as an energy storage device.

Compared to secondary batteries with similar chemistries, primary batteries have the advantage of lower unit costs and higher specific energy—the amount of energy a battery is able to store per unit weight, measured in watt-hours per kilogram (Wh/kg). Because the chemical reaction used to generate the power in a primary cell is not required to be reversible, battery designers have more freedom to utilize materials and component structures that allow them to increase the specific energy of a cell or battery. This characteristic of primary batteries appeals to the military, which has spent a great deal of effort attempting to reduce the weight and volume of the batteries that soldiers are required to carry.[3] High specific energy is one of the major reasons that primary batteries have previously been so widely used in military applications.

Figure 1 shows the gravimetric energy densities (specific energies) of current and emerging primary and secondary battery cells of the various chemistries that are currently used or could be used in the future in SPBs.

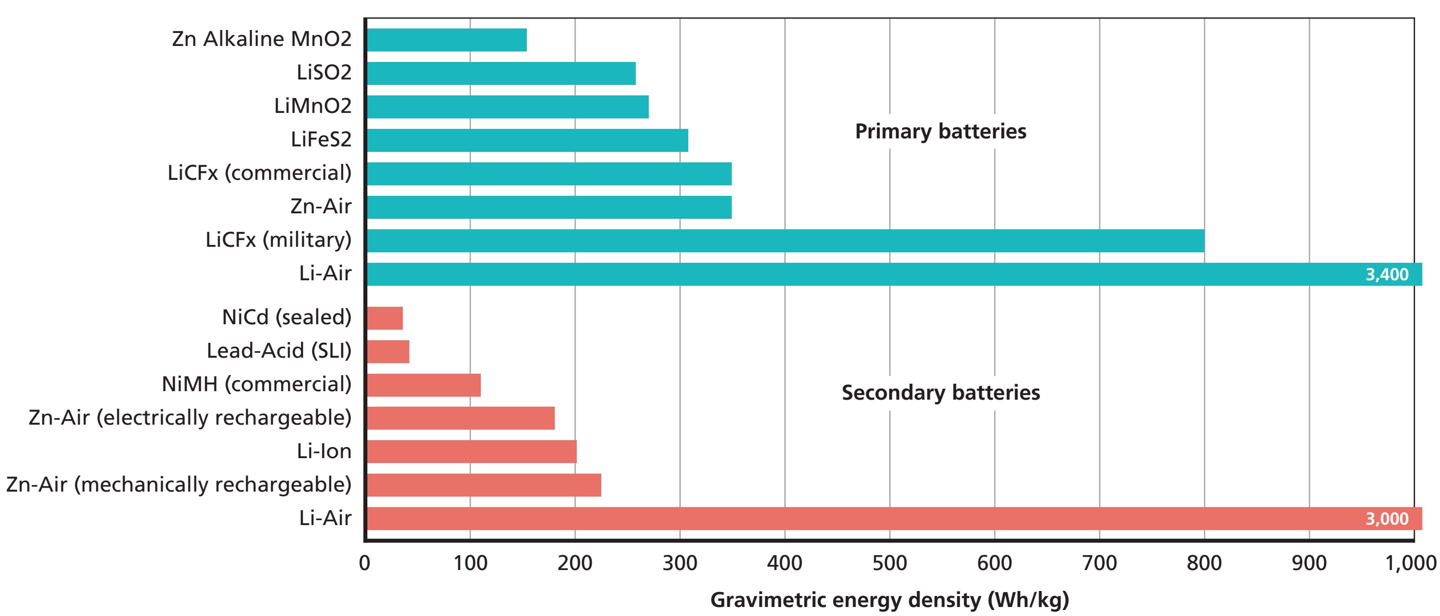
The major advantage of secondary batteries is that they dramatically reduce the logistical burden of supplying batteries to forward-based soldiers. A rechargeable lithium battery can undergo more than a thousand charge/discharge cycles during its operating life, thereby eliminating the need to purchase, store, and deliver many hundreds of primary lithium batteries. For military efforts to streamline logistics and reduce waste, secondary batteries are clearly superior to primary batteries. Current military thinking reflects this, and Army acquisition policy explicitly states that rechargeable and reusable batteries will be used in new-fielded equipment unless this is "not practical."[4]

Currently, many primary and secondary batteries that are used in military and commercial applications are made using lithium. Lithium-based primary batteries are generally referred to as "lithium metal" or simply "lithium" batteries. Lithium-based secondary batteries are typically referred to as "lithium-ion" batteries.

Battery Performance Requirements

SPBs are often embedded within devices such as radios or night-vision goggles, and a soldier must carry sufficient spares to replace or recharge these batteries as needed. If an embedded battery is of the secondary type, it needs a source of energy from which to recharge. For most cases, this energy source will

Figure 1. A Comparison of Gravimetric Energy Densities for Current and Emerging Battery Cells



SOURCE: Thomas B. Reddy (ed.), *Linden's Handbook of Batteries*, 4th ed., New York: The McGraw-Hill Companies, Inc., 2011.
NOTES: Li-Air numbers are estimations, and should be regarded as unproven. The abbreviations appearing in this figure correspond to the following elements: C (Carbon), Cd (Cadmium), F (Flourine), Fe (Iron), H (Hydrogen), Li (Lithium), Mn (Manganese), Ni (Nickel), O (Oxygen), S (Sulfur), and Zn (Zinc). CFx and MH represent Carbon monoflouride and Metal-hydride, while O2 and S2 are referred to as "dioxide" and "disulfide," respectively. SLI stands for starting, lighting, ignition—the applications of automotive lead-acid batteries.
RAND *RR500-1.1*

> Because mission success and soldiers' lives often depend directly on a military battery's performance, the military is willing to pay somewhat higher prices to ensure that its batteries will be effective in combat situations and rugged environments.

be a petroleum-powered generator located at the base camp. Recharging equipment can also operate using military vehicles. For certain operations, however, soldiers may be on extended missions without vehicular support. These soldiers need to be able to replace or recharge their embedded batteries with other batteries, increasing the load that they must carry.

There are non-battery solutions for collecting the power necessary to recharge an embedded battery. Portable solar photovoltaic panels,[5] including those embedded in blankets,[6] have recently been fielded for the purpose of recharging SPBs. Researchers are also investigating piezoelectric materials that can be implanted in the soles of boots, where they generate power as soldiers walk.[7] These solutions have not yet been widely adopted, though, and using larger SPBs to recharge smaller embedded batteries is still a standard practice.

Battery performance optimization is always application-dependent, and it involves balancing many different concerns and characteristics. Although specific energy is one of the more desirable characteristics of battery performance, it is only one part of the total package. The instantaneous power that the battery can provide per unit of weight (measured in watts per kilogram) is another crucial characteristic. The military also places a premium on a battery's energy density, namely, the amount of energy that can be stored in a specified volume (often expressed as watt-hours per liter).

SPBs generally make use of the same types of chemistries as do commercial batteries, though they often emphasize different characteristics of performance. In some commercial applications, lowering unit cost is the primary goal of battery research. This is the case for the DOE-sponsored battery development efforts in support of electric vehicles and for stationary storage of electricity. For military purposes, however, battery cost is secondary to dependability. Because mission success and soldiers' lives often depend directly on a military battery's performance, the military is willing to pay somewhat higher prices to ensure that its batteries will be effective in combat situations and rugged environments.

Military specifications for battery dimensions, capabilities, safety, storability, and other characteristics are set to meet the needs of particular weapons or support systems in many cases. In others, a standardized performance specification established by DoD can be used. For example, requirements for rechargeable batteries used in many soldier-portable applications are set forth for all DoD agencies in Military Performance Specification (MIL PRF) 32383, a list of requirements drawn from specifications throughout government and industry.[8]

In addition to requirements for characteristics of battery performance, requirements are established for battery survivability in harsh conditions. Among other qualities, SPBs must be able to operate in both high and low temperature environments; MIL PRF 32383 specifies a range of -20°C (-4°F) to 50°C (122°F), though certain types of lithium cells may be subject to more stringent requirements. Because the rate at which chemicals within a battery react is dependent on temperature, reactions proceed more quickly as temperature increases. This means that, for military batteries, great care has to be taken to ensure that the power generated in a cold-weather environment is sufficient to meet a soldier's needs. The linkage of temperature and rate of reaction also affects battery storage, as the slow self-discharge that affects all cells runs more quickly at high temperatures. In the case of secondary batteries, high temperatures can also increase the rate at which a cell recharges.

MIL PRF 32383 also mandates a number of tests to determine a potential military battery's resistance to physical damage. Because a battery is an energy storage device, by definition a good battery contains large amounts of energy in a confined space. Safety, therefore, is a paramount concern, and it must be established that SPBs will fail gracefully, i.e., without damaging other components of an electrical system or posing a danger to operators. Graceful failure must hold in the face of many different types of possible abuse: Requirements cover the testing necessary to establish the battery's response to explosive decompression, submersion, thermal and mechanical shock, sand and dust storms, and numerous other environmental hazards that a military battery might encounter during its service life.

CURRENT AND EMERGING SOLDIER-PORTABLE BATTERIES

SPBs are made up of a wide variety of different chemistries. In addition to the lithium cells mentioned earlier, the military makes use of nickel-based cells, as well as air-breathing batteries that pull oxygen from the outside air. In this section, we review some of the more common battery chemistries currently used to power soldier-portable devices, as well as those emerging chemistries relevant for soldier-portable applications. This section is not a comprehensive review, but rather a brief description of those chemistries discussed in the interviews we conducted.

Primary Batteries

The military maintains a supply of primary batteries, many of which make use of lithium chemistries. Lithium primary cells are those that use lithium or lithium compounds to form their anodes. The cathode can be formed from any of a number of different materials, two of the most common structures currently in use being FeS_2 and SO_2.

$LiFeS_2$, lithium iron disulfide, is a commercial "workhorse" battery. A single $LiFeS_2$ cell is made up of a lithium anode, an iron disulfide cathode, and separator material between them. $LiFeS_2$ cells are designed to provide their power at a lower voltage than many other lithium cells, operating at 1.5V as opposed to the more common 3V. This allows them to be easily substituted for the 1.5V alkaline batteries commonly used in personal electronics, with which they are meant to compete. Because of their much greater specific energy (Energizer advertises a value of 297 Wh/kg for their AA-size cell[9]), $LiFeS_2$ cells can be made about one-third lighter than their alkaline competitors or yield greater energy at roughly the same weight and volume. Moreover, they can be stored for much longer due to their lower self-discharge rate. $LiFeS_2$ cells excel in applications requiring high electric current loads. Motor-driven tools, high-current electronics, and similar devices are all common applications for $LiFeS_2$ batteries.[10] The iron disulfate cathode material is cheap, and is intermixed with copper in some variants of this chemistry.

$LiSO_2$, lithium sulfur dioxide, batteries consist of a lithium metal anode and a liquid cathode. $LiSO_2$ cells can be used over a wide range of operating temperatures. Like $LiFeS_2$ batteries, they have low self-discharge rates allowing storage for long periods of time. $LiSO_2$ boasts a high energy capacity as well, though it is designed to operate at higher voltages than $LiFeS_2$. In some variants of this battery chemistry, the sulfur dioxide cathode is replaced with less costly manganese dioxide at the expense of some low-temperature performance.

An "air-breathing" battery structure has long been a goal of the R&D community, and has great potential for use in military applications. The military has started to deploy a limited number of batteries based on zinc-air chemistry. A Zn-air cell pulls oxygen from the air to use as a cathode reactant, and has a porous zinc structure filled with electrolyte as its anode. Because the cathode material is external to the cell, Zn-air batteries can be designed with high specific energy. Zn-air cells can also be stored for a very long period of time, so long as they are completely sealed. Once air is allowed in, however, they self-discharge very quickly.

Secondary Batteries

Li-ion rechargeable batteries have been the focus of considerable military and commercial energy storage research, and are well entrenched in soldier-portable applications. As a military acquisition, Li-ion batteries have the distinct advantage of being heavily used in the consumer market, developments in which can be leveraged by the military. Li-ion batteries are now the most popular batteries used in laptops, cell phones, and other electronics. Li-ion batteries boast high gravimetric energy density, operating between approximately 100 and 200 Wh/kg,[11] and a low self-discharge rate compared to other rechargeable batteries. These advantages are reduced, however, when a Li-ion battery is used in high-temperature environments or is forced to generate large currents for extended periods of time.

Two nickel-based chemistries are also used in rechargeable batteries: nickel-metal-hydride (NiMH) and nickel-cadmium (NiCd). Both chemistries involve positive electrodes made of NiOOH (nickel oxyhydroxide) but differ in the materials used in their negative electrodes. NiMH has largely replaced NiCd because of its much greater specific energy and lower toxicity.[12]

NiMH batteries are competitive with Li-ion technology in some applications, and can match the lower end of the Li-ion battery spectrum in specific energy. When compared to Li-ion technology in other respects, though, NiMH batteries have several disadvantages. For example, their high self-discharge rate keeps them from being stored for any length of time without needing to be recharged. Battery structures with lower self-discharge have been introduced, but generally have lower capacity than standard varieties.[13]

Emerging Battery Chemistries

Lithium carbon monofluoride (LiCFx) is an emerging chemistry for primary batteries. The LiCFx chemistry's theoretical specific energy is much higher than that of either $LiFeS_2$ or $LiSO_2$, for which it is a potential replacement.[14] On an open circuit, it operates reliably and safely at around 3.2 to 3.7 volts. LiCFx batteries are currently in production and commercial service, and were estimated to account for about 9 percent of the 2009 world battery market, with Panasonic producing 50 percent of LiCFx batteries worldwide as of that year.[15] The market is currently dominated by small button cells, because of the expense of the CFx cathode. However, hybrid cells with a less-expensive cathode incorporating MnO_2 have been developed that demonstrate improved performance as compared to standard D cells.[16] Active development programs on LiCFx primary batteries aimed at military applications are underway at several battery manufacturers in the United States and abroad.[17]

Lithium-air (Li-air) is another possible next-generation battery chemistry. Li-air cells utilize many of the same principles as do current Zn-air cells. Oxygen from the air is used in the reaction at the cell's positive terminal, and the negative terminal is made of lithium or a lithium compound. There are many different groups trying to make this type of battery feasible using a wide variety of different structures, some of which claim to have Li-air primary cells approaching commercialization. One of these organizations, the Berkeley-based battery research firm PolyPlus, has reported the successful test of a cell with specific energy in excess of 700 Wh/kg.[18]

Thus far, efforts to create a Li-air secondary battery have run into many of the same roadblocks that keep secondary Zn-air cells from becoming practical, such as the formation of lithium dendrites and the high cost of separator materials designed to prevent short circuits from forming. The problems are being addressed by a number of research organizations, all of which are motivated by the possibility of developing a secondary battery with a very high specific energy and energy density.[19]

> The federal government takes an active role in the development of energy storage technologies, both through traditional research funding . . . and through technology development programs.

Government Research and Development on Soldier-Portable Batteries

The federal government takes an active role in the development of energy storage technologies, both through traditional research funding for basic science and through technology development programs. Much of this R&D is relevant to current and emerging SPBs. The discussion below is based on a report by the GAO in August 2012, which identified 39 major federal battery-related R&D projects that had received $1.3 billion in funding between 2009 and 2012.[20] DoD obligated $430 million in 14 different projects, while the DOE obligated $852 million in 11. NASA and a few other organizations also undertook research, though at much smaller overall funding levels.

The majority of the DOE's programs were focused on basic research and on applications that are only tangentially related to SPBs. However, advances in battery chemistry and materials made in these programs could be transferable to soldier-portable applications. Over a third of the money that DOE spread among its 11 projects went toward the Vehicle Technologies Energy Storage Research and Development Initiative, which was designed to improve the competitiveness of electric vehicles in the automotive market.[21] This broad goal involved funding for exploratory materials research; applied battery research; battery development; and testing, analysis, and design. A number of companies received awards to develop high–specific-energy cells and cell components, as well as materials that could be incorporated into next-generation cells.[22]

These efforts met with some notable successes. Awardees ensured that cost reductions in rechargeable Li-ion batteries were on track, and were able to extended battery lifetimes. New targets for R&D were identified, notably in efforts to develop alloy materials and cells. In addition, several new research programs focused on "beyond-lithium-ion" batteries were initiated under DOE vehicle technology efforts.[23]

A second focus area that received a large amount of DOE funds was the improvement of the U.S. power grid's energy storage capability. This program was carried out in the Office of Electricity Delivery and Energy Reliability, which obligated $241 million through its Energy Storage Program.[24] This program explores and implements new battery designs in anticipation of advancements in the electrical grid. Among the Energy Storage Program's goals are the development of unique Li-ion batteries made from cost-effective materials and the development of air-breathing batteries.[25] The program is ongoing, and is slated to shift its focus to the wider scaling up of production and system design through collaboration with industrial partners. Like the vehicle technology program, it has the potential to deliver new battery chemistries and production capabilities that could support the SPB industrial base.

DoD's battery development programs span all branches of the armed services. Many of these programs are directed toward vehicle and weapon battery technology, but there are also several efforts aimed at improving the performance of SPBs. The Army Research Laboratory has pursued a broadly based research program on both primary and secondary lithium batteries, including work on improved electrolytes, increased capacities, higher voltages, and improved overall battery performance.[26] The Army's Communications-Electronics Research, Development and Engineering Center is pursuing applied research, testing, and evaluation, as well as system integration efforts to transfer emerging technologies to soldier-portable power systems.[27] One of the military's overarching goals is the creation of a convenient, wearable battery from which all of a soldier's devices can be charged. To this end, the Army developed the Soldier Wearable Integrated Power System (SWIPES), which provides power from conformal battery cells integrated into a soldier-wearable vest. This device, which was one of the top ten U.S. Army Greatest Inventions in 2010, has the potential to reduce the batteries that soldiers are required to carry on a 72-hour mission by up to 12 lbs.[28] Continued R&D of such integrated power systems could reduce the number of secondary batteries that a soldier would need to carry, which could be a factor in alleviating some of the supply concerns discussed in this report.

DEPENDENCE OF SOLDIER-PORTABLE BATTERIES ON FOREIGN SUPPLIERS

This section reviews information on the current status of the SPB supply chain obtained from our discussions with government researchers and program managers, as well as representatives of domestic suppliers of batteries to the military. Based on this information, as well as that readily available from open sources, we identify areas of concern related to the dependence of the domestic suppliers on cells manufactured in Asia that are used to assemble SPBs.

The Current Soldier-Portable Battery Supply Chain

SPBs are assembled from cells that are composed of components such as electrodes and electrolytes, which in turn are fabricated from raw materials. In this section, we review where the raw materials, cells, and cell components are sourced and where batteries are assembled, with an eye toward identifying capabilities that currently are not or may not be available within the United States or its allies.

Raw Materials

Battery production begins with mining of raw materials, only two of which were identified in our discussions with domestic suppliers of SPBs as potential areas of concern: lithium and cobalt.

A secure supply of raw lithium is essential to the production of any type of advanced SPB. Because of the global interest in electric cars, and Li-ion batteries to power them, the lithium-mining industry has been closely scrutinized in recent years.

The majority of raw lithium production takes place in South America. Chile, the world's largest lithium producer with the largest reserves, is home to the massive Salar de Atacama salt flat, which is managed primarily by a private firm, the Sociedad Quimica y Minera (SQM) de Chile. Across the border in Bolivia, the Salar de Uyuni, which is the largest salt flat in the world, is currently under development by the Bolivian state, but not yet producing. An equally large amount of lithium to that produced from evaporation pools built into the

> There has been some discussion of the mining industry's continuing ability to supply the market with sufficient lithium.

Chilean salt flats is produced from pegmatite ores mined in Australia. Chile and Australia together account for 70 percent of global lithium production and control 65 percent of world reserves of lithium.[29]

There has been some discussion of the mining industry's continuing ability to supply the market with sufficient lithium. This could become a problem in the future, some argue, because of the trend toward wider adoption of electric vehicles throughout the world. However, the vast majority of scholarship that we have encountered while researching this report seems to indicate that this concern is unfounded. The DOE has undertaken several analyses of lithium availability and electric vehicle demand, which have concluded that the lithium supply will be sufficient to meet production needs far into the future.[30] Many non-governmental analysts have independently come to the same conclusion.[31]

However, there are other researchers that disagree. One prominent example is the Swedish team of Vikstrom, Davidsson, and Hook from Uppsala University. While their study uses many of the same data sources as does the DOE,[32] their conclusions differ in their assessment of the speed at which production can be scaled up to meet increasing demand. Using a bell-curve model of production capability, Vikstrom et al. found several points between 2010 and 2050 during which their estimations of electric vehicle demand surpass the projected ability of the mining industry to provide lithium.[33] This model comes with a number of caveats, though, and it is only their highest estimations of demand that show potential difficulties. Considering these mitigating factors, the large number of researchers that remain unconcerned about lithium availability, and the relatively small size of the SPB market compared to electric vehicle demand, it seems safe to assume that lithium is not a cause for concern in the SPB supply chain. It would be prudent, however, for military planners to maintain an awareness of the state of the lithium market and be ready to adjust their lithium battery acquisition practices if it becomes necessary to do so.

The concerns associated with the supply of cobalt, which is widely used in some lithium battery cathodes, focus on its main source: the Democratic Republic of the Congo. In addition, a large part of the raw Congolese cobalt passes through China, the world's largest producer of refined cobalt. There has been a drive in recent years to establish some measure of U.S. production; among other interested organizations, the Idaho Cobalt project is in the process of opening a mine dedicated solely to cobalt, as opposed to the usual practice of processing it as a secondary product of copper and nickel mining.[34] Regardless of whether these efforts are successful, however, cobalt's modest role in the SPB market suggests that the supply of batteries based on other chemistries will be able to accommodate any interruptions in cobalt production.

Cells and Cell Components

Commercial production of high-performance cells is presently driven by consumer electronic applications, most notably cell phones, smart phones, tablets, and portable computers. These are also the applications that drive private-sector investment in advanced battery development. To a large degree, what the military wants in an SPB overlaps with what consumers want in their batteries: high specific energy, storability, long operating life, reliability, and safety.[35] For that reason, SPBs acquired by the military have been able to incorporate certain cells that also serve civilian applications. This is an important feature of the DoD acquisition strategy for SPBs. The demand for cells for SPBs is roughly three orders of magnitude smaller than the demand for consumer applications. By following a dual-use acquisition strategy, the cells used in SPBs are produced with economies of scale that would be impossible if the cell designs were exclusively directed at military applications.

Our discussions with representatives of companies that currently supply batteries to DoD strongly suggest that if the military moves away from this dual-use strategy, it will pay a premium price for its batteries. This is in fact already the case for certain batteries that are used for specialized military applications, including space-based systems, avionics, and weapons. It then stands to reason that if DoD develops a superior SPB that is not also of commercial interest, the specialty manufacturer of such a battery would likely need to charge a premium as well.

The cells that are the basis of this dual-use strategy are produced primarily in Asia.[36] For example, Korea's Samsung

SDI and LG Chem had a combined share of 40 percent in the 2011 global rechargeable battery market. Three Japanese companies, Sanyo, Panasonic, and Sony, accounted for a further 35 percent. Large Asian producers such as Hitachi feature prominently in the remaining 25 percent as well. It is known that Japanese and Korean producers manufacture some of these cells in China,[37] but the precise fractions are not publicly available. Our discussions with battery industry representatives suggested that China's role in this industry is significant.

As a general rule, cathode materials are produced in Korea, as well as by the companies Nichia and Toda Kogyo in Japan. The synthetic graphite used to make some varieties of anode is most commonly produced by Japanese firms, while the natural graphite market is dominated by China. Our discussions suggested that China performs the majority of its component manufacturing for lower-end batteries, because of concerns about lack of quality control. Both electrolytes and separators are produced in large numbers in Japan, though Korea and other countries are attempting to create more local electrolyte production capacity. The United States has some separator production capability; though companies in Japan control a large share of production, North Carolina–based Polypore and its subsidiary, Celgard, are also counted among the major producers.[38]

Battery Assembly

The final part of the manufacturing process is the packaging of cells into battery casings. This can be done fairly easily by electrically connecting a stack of cells and then placing them in a container, but most batteries include extra intra-battery electronics that monitor various aspects of cell performance as well. These electronics connect to various safety mechanisms and performance enhancements to insure that a battery meets military or commercial performance requirements. The electronics and packaging for an SPB involves a trade-off between hardness, flexibility, and other characteristics that must meet military specifications and be matched to a soldier's mission.[39]

We draw a distinction here between primary batteries, for which there are large producers that maintain manufacturing divisions in the United States,[40] as well as U.S.-based specialty manufacturers for whom the military is a primary client,[41] and secondary batteries, in particular rechargeable Li-ion batteries. From our discussions with battery manufacturers we learned that the vast majority of Li-ion batteries sold to the U.S. military are assembled from commercial cells that, as discussed above, are manufactured in Asia, hence the dependence of SPB supply on a supply chain based in Asia that includes a component in China.

Government Programs Aimed at Establishing Domestic Manufacturing

Recognizing the dependence of the supply chain for Li-ion batteries on foreign sources, DoD has established two separate programs under the Defense Production Act, Title III, to build a Li-ion battery production base in the United States. The first involves an award to Quallion for the domestic production of spacecraft-qualified Li-ion batteries, as well as critical materials and components for these batteries (cathodes, cathode precursor materials, and anodes).[42] The second, which had just begun as this report was written in the first half of 2013, is specifically targeted to SPBs, with the goal of increasing the maximum gravimetric energy density to greater than 250 Wh/kg at 250 W/kg discharge rate. Potential applications for these batteries include unmanned aerial vehicles, dismounted soldiers, and autonomous vehicles. A Broad Agency Announcement (BAA) under this program was issued in July 2011.[43] The program is structured in two phases, with awards in Phase I of up to $500,000, with each awardee expected to provide equal matching funds and required to deliver five cells for performance testing in a government laboratory, as well as a technical, business, and marketing plan, and to conduct cost analyses relevant to building a low-rate but expandable manufacturing capability. The plan for Phase II is that one of the Phase I awardees will be

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The demand for SPBs is projected to increase rapidly in coming years. . . . A secure supply chain for rechargeable batteries with surge capacity will be required to meet these needs.

selected to receive a $21.9 million government award, and again expected to provide equal matching funds, to build a domestic production capability.

The DOE is attempting to establish a U.S. manufacturing base for electric vehicle batteries, and has directed a large amount of funding to that end in recent years. Awardees selected for these efforts included Johnson Controls, A123 Systems (an unsuccessful investment—the company has since gone bankrupt and been purchased by Chinese automaker Wanxiang Group[44]), EnerDel, and General Motors, among others. These companies all received financial support for developing component production, cell manufacturing, and battery assembly capabilities in various locations throughout the United States.[45]

If the DOE is successful in establishing U.S. component and cell manufacturers, this could contribute to a more secure supply chain for SPBs, despite the primary intention of the funding being the development of electric vehicles. This does not mean to suggest that SPBs are simply scaled-down versions of the batteries used in vehicles; SPBs emphasize different performance characteristics and require somewhat different engineering processes. The DOE's funding, however, has the potential to build up the infrastructure and human capital that would benefit U.S. battery production efforts across all applications. Such an infrastructure that is oriented directly toward commercial applications would be much better suited to competing with commercial sources of cells for SPBs than the current infrastructure that supplies DoD with cells for primary and special purpose batteries.

Areas of Concern for Soldier-Portable Battery Supply

There are three major concerns for the supply of SPBs: (1) the security and surge capability of the supply chain for the manufacturing of the cells from which these batteries are assembled; (2) the potentially unmanageable cost of establishing a U.S. manufacturing capability for these cells; and (3) the possible incompatibility of the safety and reliability requirements of SPBs with the commercial production of the component cells.

Security and Surge Capability

Several U.S. companies currently produce primary (non-rechargeable) SPBs, including Bren-Tronics, SAFT America, and Ultralife. This manufacturing base has been in existence for decades, has filled surge requirements for overseas combat operations in Iraq and Afghanistan, and would be the means to fill a surge requirement that happened now. However, the shift in military preferences toward secondary (rechargeable) batteries represents a departure from the usual means of doing business. Moreover, the demand for SPBs is projected to increase rapidly in coming years as an increasing number of the Army's Brigade Combat Teams field networking equipment such as smartphone-type devices, software-controlled radios, and satellite communications devices.[46] A secure supply chain for rechargeable batteries with surge capacity will be required to meet these needs.

As described above, the current supply of rechargeable soldier-portable batteries (RSPBs) is based on cells that are manufactured almost exclusively in Asia for commercial devices such as mobile phones, laptops, tablets, and other consumer electronic devices. This is so for a very practical business reason—demand for batteries for these devices is in the billions per year, and they are manufactured in close proximity to where the devices themselves are manufactured, in many cases by highly vertically integrated companies such as Panasonic, Sanyo, and Sony in Japan and Samsung and LG Chem in Korea.[47] While the parent companies are headquartered in countries that are strong U.S. allies (Japan and Korea), these could become unavailable in the event of a serious Asian military contingency. In addition, some of these batteries and the cells from which they are assembled are manufactured in China. This presents a potential vulnerability in the supply chain for RSPBs in the event of any type of economic, political, or military conflict with China. As the Army transitions to a greater fraction of rechargeable batteries to implement its acquisition policy, and the demand for these batteries increases to satisfy the increased networking requirements of its Brigade Combat Teams, it will become increasingly reliant on a foreign supply chain that includes Chinese manufacturers.

Cost of Establishing a U.S. Production Capability

The military demand for (soldier-portable) rechargeable batteries tops out in the millions per year, roughly three orders of magnitude less than that provided by the commercial market for electronic devices. Moreover, these batteries are procured by the DLA on an as-needed basis, which can result in difficult to predict timing and quantities. Thus, in the current situation, in which there is no significant domestic manufacturing of the commercial electronic devices that would provide a larger market for domestically produced rechargeable batteries, there is no business case for investment in a domestic production capability for cells—and U.S. manufacturers remain assemblers.

U.S. battery manufacturers buy rechargeable cells from Asian manufacturers because it is economically infeasible for them to produce these cells. The manufacturing facilities that are used by companies that supply batteries for consumer electronics required substantial capital investment, which is justified by the large demand for these batteries. We can get a rough idea of the order of magnitude of the necessary investment from the size of the U.S. government programs aimed at establishing a domestic manufacturing base for rechargeable batteries for electric vehicles and the power grid, which amounted to $1.3B dollars between 2009 and 2011.[48] Under the American Recovery and Reinvestment Act (ARRA), the DOE invested an additional $1.5B to develop an entire domestic manufacturing supply chain for rechargeable batteries for electric and hybrid vehicles, from raw materials to components to cells to batteries to recycling capability.[49]

It is clear from the programs cited above, as well as our discussions with manufacturers of RSPBs, that the type of sophisticated manufacturing facility that would be capable of producing the cells that are currently used to assemble these batteries at a price competitive with the current Asian manufacturers would require capital investment of hundreds of millions or perhaps billions of dollars. This would either require a dual-use capability to serve a commercial market in the United States or the willingness of DoD to pay a higher price for SPBs containing U.S.-manufactured cells, compared with the current batteries containing Asian-manufactured cells. This would require a change from the current DLA practice of procuring the cheapest batteries that meet the published requirement.

Potential Incompatibility of Commercial Batteries with Military Requirements

To meet military specifications, the current suppliers of SPBs assemble the commercial cells that they use in hardened cases and use designs that are engineered to meet military requirements. Without a domestic cell production capability, there is no guarantee that this will continue to be possible with cells that are developed to meet commercial cost and performance requirements.

This issue was brought to the forefront by the failure of Li-ion batteries made by the Japanese company GS Yuasa Corp. on Boeing 787 Dreamliners, which led to the grounding of the entire 787 fleet.[50] GS Yuasa is a large company that has substantial experience in space and aviation, and in fact was chosen by NASA to supply Li-ion batteries for the International Space Station.[51] GS Yuasa was selected in a competition against the much smaller U.S. firm, Quallion, which was building on the results of a DoD Title III program, following the down-selection of these two firms from five original potential suppliers.[52] This example shows how sometimes the U.S. government chooses foreign commercial sources over U.S. firms qualified under a program overseen by DoD. Such commercial sources are driven by market requirements, whereas DoD-qualified firms must meet military requirements. This example provides a warning of the potential vulnerability associated with continued exclusive use of a foreign commercial supply chain for components of important defense items such as the cells that are assembled into RSPBs.

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SOLDIER-PORTABLE BATTERY SUPPLY CHAIN POLICY OPTIONS

This section outlines and discusses three policy options for addressing the SPB supply chain concerns described in the previous section, in addition to the option of doing nothing, i.e., continuing the current policy of procuring batteries from the lowest-cost source that meets specifications, regardless of the source of cells and components. For each policy option, we present possible components of an implementation plan. The first policy option focuses on strengthening the supply chain for SPBs. Here we suggest measures that can reduce the consequences of a disruption of the Asian supply chain stemming from potential economic, social, political, or military developments. The second policy option focuses on promoting the development and production of improved RSPBs. For this option, we suggest measures that offer to strengthen the nexus between DoD-supported R&D and domestic manufacturers. For the third policy option, we move from a strictly DoD perspective to a broader national perspective by focusing on measures that would establish a domestic supply of RSPBs and possibly a domestic capability to compete in the global marketplace for powering portable electronic devices.

Policy Option 1: Strengthen the Supply Chain

This policy option covers actions required to address the vulnerabilities in the supply chain for RSPBs and consists of one or more of the following components:

1. *Replacement plan*: Developing and implementing a logistics plan that would replace RSPBs with non-rechargeable batteries in the event of a disruption within the RSPB supply chain.
2. *Secure sourcing*: Requiring all materials and components of RSPBs to be obtained from secure sources.
3. *Surge production*: Requiring a surge production capacity across the entire RSPB supply chain.
4. *RSPB stockpile*: Establishing a RSPB stockpile.

As compared to the alternative of promoting domestic production of RSPBs, each of these components is likely to have low implementation costs and each component could be structured to fully address supply chain vulnerabilities.

Replacement Plan

The push toward rechargeable and away from non-rechargeable SPBs is driven not only by cost savings and operational flexibility, but also the greatly reduced wartime logistics burden afforded by rechargeable batteries. An effective replacement plan requires that a logistics infrastructure be in place so that a sufficient number of non-rechargeable batteries can be obtained and delivered to forward-based operating units. Obtaining non-rechargeable replacement batteries would require that private firms capable of producing non-rechargeable batteries that meet military specifications maintain a surge production capability that might be much greater than their routine (i.e., peacetime) sales to the military. As non-rechargeable SPBs are phased out of the inventory, implementing this requirement on DoD vendors will be costly, if not impractical.

Additionally, implementing a replacement plan negates the operational advantages of RSPBs at the very time when they may be most needed, namely, during an Asia-centered crisis or conflict. And soldier training would need to include operational protocols for rechargeable and non-rechargeable batteries. For both of the above reasons—availability and operations—a replacement plan may not be a practical approach for addressing vulnerabilities in the RSPB supply chain.

One possible way to reduce the number of RSPBs that might be needed, and hence the severity of these problems, would be to employ a mixed-use strategy in which rechargeable batteries are used primarily by outlying units, while non-rechargeable batteries are reserved for units close to major bases, and hence easier to resupply.

Secure Sourcing

A secure sourcing policy would require that DoD suppliers of RSPBs certify that all components (cells, electrodes, electrolytes, advanced materials) are manufactured in the United States or obtained from countries that are determined to be secure sources from a national security perspective. A secure

> The more restrictive the definition of secure suppliers, the higher the implementation costs.

sourcing policy requires that DoD define “secure suppliers” and establish a verification and vendor certification process. The more restrictive the definition of secure suppliers, the higher the implementation costs of this approach will be. The least-restrictive definition is to exclude the few nations of concern that are already subject to export controls. Most of the nations on the current export control list are highly unlikely to be in the RSPB supply chain, with the notable exception of China and Vietnam. This minimal approach, however, may not be effective in securing the RSPB supply chain in the event of an Asia-centered conflict, since manufacturing facilities in Japan and South Korea might be targeted.

An alternative approach could be a DoD RSPB purchasing plan that not only avoids nations of concern but also requires that an appreciable fraction of RSPBs purchased by DoD be associated with a supply chain that is independent of Asia.

The costs to DoD of implementing a secure sourcing policy for RSPBs is highly uncertain. Specifically, we do not know the extent to which the major manufacturers of rechargeable lithium cells and batteries in Japan and South Korea are dependent on components and advanced materials manufactured in China. Moreover, these major cell/battery manufacturers may be resistant to complying with any DoD-driven certification/verification process. After all, DoD purchases of RSPBs represent a miniscule fraction of their production for commercial applications. This problem could require bilateral agreements between the United States and the governments of Japan and South Korea.

Forcing a portion of DoD’s RSPB procurement to be independent of Japan and South Korea could result in appreciable cost increases because these two nations dominate the commercial market for small rechargeable lithium batteries.

Military allies of the United States may be willing to adopt a secure-sourcing policy for RSPB procurements. If so, the global demand for secure-sourced RSPBs would increase, and some cost savings might be achieved. But still, a concerted procurement policy for defense applications would affect a very small fraction of the global demand for rechargeable lithium-based cells and batteries.

Surge Production

Presently, a very small portion of the supply chain for RSPBs is within the United States. Moreover, the current vendors of RSPBs are not affiliated with the foreign firms that manufacture all of the cells that are currently used within RSPBs procured by DoD. Our discussions with representatives of those vendors indicate that they also have limited leverage with these foreign firms, which stems from the relatively small purchases made for DoD applications. Considering this situation, the present capability to surge production of RSPBs is highly uncertain.

A secure-sourcing policy is a necessary prerequisite to a surge production capability. Further analysis is required regarding how an effective surge production capability can be achieved when nearly all of the RSPB supply chain is outside of the control of the vendors of RSPBs procured by DoD.

RSPB Stockpile

Maintaining a stockpile of RSPBs, or of the cells that can be assembled into an RSPB, offers an ability to significantly reduce both supply chain vulnerabilities and surge production limitations. Our discussions with government and private-sector experts on battery technology indicated that an RSPB stockpile must be actively managed to prevent cell/battery performance deterioration during prolonged storage.[53] Additional technical work is required to develop and test protocols for managing a stockpile. It is likely that the final protocols will depend on the details of the composition and structure of the cells or batteries being stored.

The viability and maintenance costs of an RSPB stockpile cannot be determined until storage protocols are developed and tested. Our research did not reveal an ongoing effort directed at resolving this issue.

Policy Option 2: Strengthen the R&D-Manufacturing Nexus

Our meetings with DoD researchers and program managers revealed that a major goal of DoD-conducted or sponsored research in RSPBs is directed at developing batteries that have greater energy and power densities, improved reliability, and reduced risks to the health and safety of troops during training and combat operations. Considering that U.S. firms do not manufacture the cells used in RSPBs, it is uncertain whether DoD-supported research in RSPBs has or will result in improved (or next-generation) RSPBs. Assemblers of RSPBs frequently mentioned that they received useful technical information from the extensive battery research and development programs sponsored by the DOE; in particular, research conducted at the national laboratories. This technical information was often transferred to their Asian-based suppliers of cells.

Through its program to develop a U.S. manufacturing base capable of manufacturing high-performance and low-cost secondary batteries for automotive applications, the DOE has put in place a domestic secondary battery manufacturing capability. In doing so, it has established within the United States a cadre of world-class scientific and technical expertise in secondary cell and battery development and manufacture. Even though RSPBs have performance requirements that are much higher and cost constraints that are much more severe than automotive batteries, we found that much of the technology and manufacturing know-how is transferable between the two applications.

If a goal of DoD R&D is to hasten the availability of improved and next-generation RSPBs, the following measures could be part of a policy for strengthening the nexus between R&D and manufacturing.

Increase Support to Production-Related R&D

Without sufficient production-related R&D, the only recipients of DoD fundamental and applied research (6.1 and 6.2) on soldier-portable secondary cell concepts will be those foreign firms that have already established themselves as market leaders.

Increase Coordination with Participants in the DOE Vehicle Battery Program

Greater involvement with the research organizations and manufacturers in DOE battery programs provides the means for DoD to leverage the major investments made by DOE and the private sector in advanced battery development. Considering the relative sizes of DoD and DOE efforts in battery R&D, this policy component would promote joint DoD-DOE research activities and favor those firms that demonstrated the technical and management wherewithal to manufacture advanced lithium-based batteries and cells within the United States. Here the DoD goal would be to focus that same expertise on next-generation RSPBs.

One potential area for DoD-DOE cooperation is the DOE's Battery Innovation Hub, the Joint Center for Energy Storage Research (JCESR), initiated in fiscal year 2013 at Argonne National Laboratory.[54] JCESR is a research partnership that joins government researchers to researchers from industry and academia. Their research spans the entirety of the innovation process, from basic science to production and market delivery. The two primary research areas mentioned on JCESR's website are electric vehicle and grid storage solutions,[55] but this could likely be expanded to include an RSPB mission with DoD participation.

Implementation of these policy components would require either increased R&D funding or a reallocation of DoD R&D support toward manufacturing and associated testing activities.

Policy Option 3: Promote Domestic Production

Under this policy option, DoD would promote or establish a domestic supply of RSPBs, including the components and advanced materials used in their manufacture. This option is the most extensive and expensive of the three we have considered. Domestic production would strengthen the supply chain for RSPBs, it would accelerate the development and production of next-generation RSPBs, and it would promote the broader national goal of revitalizing the domestic manufacturing base. While this option is also highly likely to be the most expensive, implementation costs will be highly dependent on how this policy option is formulated.

Components of this policy option could include the following:

1. *Procurement mandate*: Requiring in DoD procurements of RSPBs that all key components and advanced materials be manufactured within the United States.
2. *Subsidies*: Providing investment or production subsidies to firms that manufacture RSPBs with high domestic content.
3. *Incentives*: Incentivizing domestic production using non-monetary measures, such as establishing technical specifications that promote the manufacture of advanced RSPBs.

An important consideration in evaluating these policy components is the extent to which they offer to create a self-sustaining industry that would serve military needs as well as civilian applications. Here, the big prize would be establishment of an industry sector capable of successfully competing in the marketplace for batteries that would power portable and hand-held electronic devices. But it is important to recognize that, should this competitive industry sector be established, the benefits would accrue to the nation as a whole, and thereby only indirectly to national security, via an improvement in the overall prosperity of the nation.

Procurement Mandate

DoD could change its procurement policy for RSPBs (or for that matter, all batteries) by mandating domestic production of battery cells. Recognizing that the RSPB supply chain is only as strong as its weakest link, the domestic production requirement must extend not just to battery cells, but rather to all components and advanced materials used within those cells. Alternatively, imported components and materials could be allowed if they originated from a nation designated as a secure supplier and a firm that agreed to certification/verification and surge production (see the preceding sections on “Secure Sourcing” and “Surge Production”).

There are two major issues associated with implementing this policy component. First, what will be the nature of the resulting industrial base? And second, how would unit costs change? In the near term, the domestic firms capable of competing in this arena would likely be those that are already major participants in the DOE vehicle battery program. Our discussions with industry representatives indicated that a number of firms that are in the DOE program would be interested in manufacturing cells for RSPBs. Some representatives suggested that a DoD market would positively impact their other business lines, such as manufacture of specialty cells for biomedical, aviation, aerospace, and certain industrial applications. However, none of our industrial respondents would give credence to the concept that a domestic production mandate for RSPBs would drive the establishment of a domestic industry capable of competing within the commercial marketplace for powering consumer electronics. Rather, they maintained that much larger economic and institutional forces would dominate any business decision to move the manufacture of batteries for consumer electronics to the United States. At best, a small manufacturing base directed at DoD applications might be a seed for a domestic consumer-oriented industry, but only if the larger forces are moving in the right direction.

The foregoing suggests that a domestic cell manufacturing base will not have the economies of scale that are in effect for the dominant Asian cell and battery producers. Higher production costs are extremely likely. Some useful information on costs might be forthcoming from firms selected for the Title III program on SPBs described in the previous section. Pending receipt of detailed engineering and business assessments, there is no analytic basis for estimating the cost impact of a procurement-driven domestic production mandate.

Subsidies

An alternative to mandating is subsidizing. For example, DoD procurements could specify a premium that DoD would allocate to bids for RSPBs with high domestic content, versus imported cells. Basically, this would be a production subsidy. Unlike a production mandate, a production subsidy allows the government to limit the maximum amount of additional costs that it will incur. If properly constructed, a production subsidy also maintains competition.[56] The downside of a production subsidy is that it does not guarantee the development of a domestic industrial base. Building and equipping facilities for domestic manufacture of cells for RSPBs is likely to be a three- or four-year endeavor. The large investments required to build a domestic manufacturing capability for RSPBs will not be made unless private firms are confident that DoD will maintain a steady policy course and not leave them with stranded investments and no markets.

Investment subsidies are a common tool within the DoD Title III and ManTech programs. The major advantage of the investment subsidy is that it is up front, thereby addressing the reluctance of private firms to rely on DoD maintaining a steady policy course. The major disadvantages of investment subsidies are that they require DoD to pick winners and losers based on potential, versus actual, performance. To the extent that investment subsidies form a large fraction of the total investment required, they also present a serious moral hazard, in that the subsidized companies will not bear risk concomitant with their importance to the enterprise.

Incentives

In the course of our meetings with government and private industry experts, we received a number of suggestions for incentivizing innovation and promoting domestic production by modifying DoD policies for procuring RSPBs. One approach would be to change the technical specifications for RSPBs so that they exceed those of cells and batteries that are currently in the commercial marketplace. The argument in favor of this approach is that the large Asian firms producing secondary cells are unlikely to invest in a specialized, high-performance product, thereby opening an opportunity for domestic manufacture. There is precedent for this. A number of U.S. firms manufacture secondary cells for specialty applications, although the market for each of these specialty applications is much smaller than that for RSPBs.

Counting on technical specifications as a means of building a domestic production base is perilous. First, the continuing demand for improved secondary cells for consumer electronics suggests that we will see a steady stream of improvements in lithium-based secondary cells. It is uncertain whether a small domestic manufacturer can keep up with these improvements. What constitutes a tight specification today may be the commercial standard within a few years. The second problem is that domestic cell manufacture does not guarantee a secure supply chain. That only occurs if all major components and advanced materials are from secure sources. For these two reasons, we suggest caution in adopting any policy that would attempt to secure the supply chain by tightening performance specifications of RSPBs.

Policy Option 4: Maintain the Current Policy

In addition to the three policy options described above, two of which are directed at strengthening the supply chain (Policy Options 1 and 3), there is of course a fourth possibility: Do nothing—namely, continue to pursue the current policy of relying on rechargeable cells produced outside the United States. This may be a reasonable option, at least until further information is available. First, any attempt to strengthen the SPB supply chain will likely result in additional costs to DoD for battery procurement or stockpiling. Before changing to a new policy, further analysis is required to ascertain prospective costs. Second, it is not clear that there is a near- to mid-term threat to the supply chain. Our finding is that the supply chain is centered in Asia and may have critical components within China. Further examination is required to determine the circumstances that might allow China or other nations to disrupt the supply of rechargeable batteries to the U.S. military, how the logistics system would respond to any shortfall, and whether there would be an appreciable loss of military capability. Even if there is a finding of a threat, judgment is required as to whether addressing this threat is a worthwhile allocation of limited defense funds. For example, there may be supply chain problems with other critical military equipment that are more important to address, or there may be defense priorities unrelated to supply chain issues. Another possibility within the current option is R&D aimed at reducing the number of batteries that a soldier must carry, e.g., continuation or expansion of current programs on integrated power systems that can recharge many batteries from a single source, on systems that use locally available power, and on improved power management.

REFLECTIONS ON THE POLICY OPTIONS

As noted in the previous section, Policy Option 4, Maintaining the Current Policy of procuring RSPBs containing cells made in Asia, may be a reasonable option. However, DoD may want to evaluate what soldiers' power needs are likely to become in the future, and factor that assessment into its consideration of the battery supply chain. DoD may decide that a future supply chain with the potential of containing a significant Chinese component is unacceptable. In that case, DoD could then investigate the costs and feasibility of implementing a secure sourcing policy, as described under Policy Option 1. If DoD could establish a vendor certification process and establish secure sources for all soldier-portable cell and battery components, as well as cell production and battery assembly, whether in the U.S. or its allies, it would have a reliable supply chain.

Policy Option 2, Strengthen the R&D-Manufacturing Nexus, also has clear benefits. It would leverage the R&D investments of both DoD and DOE, and would likely lead to some U.S. production of RSPBs. However, unless the U.S. manufacturing base were to become competitive in the much larger market for consumer devices, the fully domestically produced batteries for military applications will remain expensive compared to those using cells produced in Asia.

DoD may want to evaluate what soldiers' power needs are likely to become in the future and factor that assessment into its consideration of the battery supply chain.

Unless DoD can successfully establish secure sources for RSPBs, the cells from which they are assembled, and the components and raw materials from which those cells are built, a domestic production base would be needed to ensure a completely reliable supply chain. This is Policy Option 3, Promote Domestic Production. Whether it is pursued via a production mandate, subsidies, or incentives, this will likely be the most expensive option, at least over the short to mid-term. Over the long term, this option could be cost-effective, but only if it resulted in a competitive domestic manufacturing base serving both civilian and military demand for portable batteries. Its pursuit would likely not be based solely on defense concerns, because of the potential contribution of a strengthened domestic manufacturing base to economic and employment goals.

NOTES

[1] Due to the variety of processes utilized by each branch of the armed forces in procuring batteries, it is very difficult to judge the exact size of the SPB market. A 2010 report by the U.S. Government Accountability Office (GAO) placed the investment by the armed forces in all types of batteries, capacitors, and fuel cells between $200M and $400M per year between 2006 and 2010. These figures include battery science and technology and purchases by the Defense Logistics Agency (DLA), which are believed to account for the majority of logistical support battery acquisitions. Compare these numbers to the larger U.S. battery market, which was evaluated at $13.2B in a 2011 report by the Freedonia Group.

See GAO, *Defense Acquisitions: Opportunities Exist to Improve DoD's Oversight of Power Source Investments*, Washington, D.C., GAO-11-113, December 2010 (as of November 22, 2013: http://www.gao.gov/new.items/d11113.pdf); and Freedonia Group, *Batteries*, Industry Study 2781, September 2011 (as of November 22, 2013: http://www.freedoniagroup.com/industry-study/2781/batteries.htm).

[2] The Ultralife Corporation, Thales Communications, and Bren-Tronics were ranked in the top ten battery suppliers to the DLA, by value of sales, in a 2010 Bidlink assessment. See "Batteries are big business for defense contractors," Bidlink.com, December 8, 2010 (as of November 22, 2013: http://www.bidlink.net/news/2010/12/batteries-big-business-defense-contractors/); and Troy O. Kiper, Anthony E. Hughley, and Mark R. McClellan, *Batteries on the Battlefield: Developing a Methodology to Estimate the Fully Burdened Cost of Batteries in the Department of Defense*, thesis, Monterey, Calif.: Naval Postgraduate School, June 2010 (as of November 22, 2013: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA524719).

[3] The Army Research Laboratory (Aberdeen) stated in a recent report: "In a typical 72-hour mission in Afghanistan, U.S. Soldiers carry seven types of batteries, or 70 individual batteries in all adding almost 20 pounds. . . . A typical infantry battalion spends more than $150,000 on batteries alone each year, the second highest expense next to munitions. Battery weight is a fifth of the total weight a Soldier typically carries in theater." (Army Research Laboratory [Aberdeen], "Unburdening the Soldier through innovations in battery, power component technology," Army Research Laboratory website, March 15, 2011 [as of October 17, 2013: http://www.arl.army.mil/www/?article=564])

[4] Army Regulation 70-11, *Army Acquisition Policy*, Headquarters, Department of the Army, Washington, D.C., July 22, 2011, pp. 59–60.

[5] John W. Lyons, Richard Chait, and James Valdes, *Assessing the Army Power and Energy Efforts for the Warfighter*, Washington, D.C.: National Defense University, Center for Technology and National Security Policy, 2011 (as of November 22, 2013: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA539876).

[6] For an example, see Lee Patrick Sullivan, "The Solar Blanket," *Energy Now*, November 22, 2011 (As of April 18, 2013: http://www.energynow.com/video/2011/07/21/solar-blanket).

[7] Kathy Eastwood, "Harvesting Energy While Walking," U.S. Army website, June 23, 2011 (as of April 18, 2013: http://www.army.mil/article/60272/Harvesting_energy_while_walking/).

[8] MIL-PRF-32383, Performance Specification: Batteries, Rechargeable, Sealed, General Specification for, Defense Logistics Agency, June 16, 2011 (as of September 6, 2013: http://quicksearch.dla.mil/basic_profile.cfm?ident_number=277787&method=basic).

[9] *Lithium Iron Disulfide: Handbook and Application Manual*, Energizer Battery Manufacturing, Inc., 2013 (as of March 13, 2013: http://data.energizer.com/PDFs/lithiuml91l92_appman.pdf).

[10] Winn Rosch, "Batteries: History, Present, and Future of Battery Technology," *PC Magazine*, June 8, 2001 (as of March 3, 2013: http://www.pcmag.com/article2/0,2817,1155272,00.asp).

[11] "Lithium-based batteries," Battery University, 2013 (as of March 13, 2013: http://batteryuniversity.com/learn/article/lithium_based_batteries).

[12] NiCd batteries are still used in certain types of older military equipment used in training by National Guard and reserve units. See John Keller, "Army Eyes Universal Battery Charger for Platoon-Level Use in Remote Locations," *Military and Aerospace Electronics*, April 1, 2013 (as of April 18, 2013: http://www.militaryaerospace.com/articles/2013/04/universal-battery-charger.html).

[13] For example, Sanyo's eneloop line of rechargeable consumer batteries.

[14] Arek Suszko, "Lithium Carbon Monofluoride: The Next Primary Chemistry for Soldier Portable Power Sources," Fort Monmouth, N.J.: RDE-COM, CERDEC, Army Power Division, November 1, 2006 (as of March 13, 2013: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA481761).

[15] Schmuel De-Leon, "Li/CFx Batteries: The Renaissance," presentation by Schmuel De-Leon Energy, Ltd., August 6, 2011 (as of March 13, 2013: http://www.sdle.co.il/AllSites/810/Assets/li-cfx%20-%20the%20renaissance.pdf).

[16] Thomas B. Reddy, (ed.), *Linden's Handbook of Batteries*, 4th ed., New York: The McGraw-Hill Companies, Inc., 2011, pp. 14.73–14.74.

[17] De-Leon, 2011.

[18] "Advanced lithium battery technology," PolyPlus, 2009 (as of April 18, 2013: http://www.polyplus.com/liair.html).

[19] For example, see Peter G. Bruce, Stefan A. Freunberger, Laurence J. Hardwick, and Jean-Marie Tarascon, "Li-O2 and Li-S batteries with high energy storage," *Nature Materials*, Vol. 11, No. 1, 2012, pp. 19–29.

[20] Note that the report focused on rechargeable battery development programs. GAO, *Batteries and Energy Storage: Federal Initiatives Supported Similar Technologies and Goals but Had Key Differences*, Washington, D.C., GAO-12-842, August 2012 (as of April 18, 2013: http://www.gao.gov/assets/650/647742.pdf).

[21] GAO, 2012. A major player in government investment in electric vehicle battery technology is ARPA-E, which manages the Batteries for Electrical Energy Storage in Transportation (BEEST) Program. See ARPA-E, "BEEST: Batteries for Electrical Energy Storage in Transportation," undated (as of December 3, 2013: http://arpa-e.energy.gov/?q=arpa-e-programs/beest).

[22] David Howell, "Overview of Battery R&D Activities," briefing, Department of Energy Vehicle Technologies Program, May 15, 2012.

[23] Howell, 2012.

[24] GAO, 2012.

[25] DOE, Office of Electricity Delivery & Energy Reliability, *Energy Storage: Program Planning Document*, February 2011 (as of December 3, 2013: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/OE_Energy_Storage_Program_Plan_Feburary_2011v3.pdf).

[26] For details, see the summaries from "Battery Day 2011," (Army Research Laboratory, "Battery Day Fact Sheets," Army Research Laboratory website, February 22, 2011 (as of April 19, 2013: http://www.arl.army.mil/www/default.cfm?page=556).

[27] For an overview of the Army soldier power program, see Terrill B. Atwater, "Army Power Division Overview," briefing, August 2007 (as of April 19, 2013: http://www.11ecpss.betterbtr.com/pdf%20folder%20monday/M6-Army%20Power%20Efforts%20July07.pdf).

[28] Dan Lafontaine, "Improved batteries, SWIPES to lighten Soldiers' load," U.S. Army website, May 7, 2012 (as of March 13, 2013: http://www.army.mil/article/79388/Improved_batteries__SWIPES_to_lighten_Soldiers__load/).

[29] The information in this paragraph is from U.S. Geological Survey, *Mineral Commodity Summaries 2013*, Reston, Virginia, 2013, pp. 94–95 (as of April 19, 2013: http://minerals.usgs.gov/minerals/pubs/mcs/2013/mcs2013.pdf).

[30] Jeremy Neubauer, "The Impact of Lithium Availability on Vehicle Electrification," presentation at *Plug in 2011*, National Renewable Energy Laboratory, 2011 (as of December 3, 2013: http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/52393.pdf).

[31] See, for example, R. Keith Evans, *An Abundance of Lithium* (Parts 1 and 2), March and July 2008 (as of December 3, 2013: http://www.che.ncsu.edu/ILEET/phevs/lithium-availability/An_Abundance_of_Lithium.pdf and http://www.evworld.com/library/KEvans_LithiumAbunance_pt2.pdf); Seth Fletcher, *Bottled Lightning*, New York: Hill and Wang, 2011; and Camille Grosjean, Pamela Herrera Miranda, Marion Perrin, and Philippe Poggi, "Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry," *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 3, April 2012, pp. 1735–1744 (as of July 28, 2013: http://www.sciencedirect.com/science/article/pii/S1364032111005594).

[32] Namely, U.S. Geological Survey figures for historical lithium supply and production and the International Energy Agency's "Blue Map Scenario" for electric vehicle demand. It is worth noting that, though the Blue Map Scenario is used as the input to both DOE's National Renewable Energy Laboratory and Vikstrom's models, it is only a target for electric vehicle penetration, not an actual projection.

[33] Hanna Vikstrom, Simon Davidsson, and Mikael Hook, "Lithium Availability and Future Production Outlooks," *Applied Energy*, Vol. 110, No. 10, 2013, pp. 252–266 (as of December 3, 2013: http://uu.diva-portal.org/smash/get/diva2:621281/FULLTEXT02.pdf).

[34] Alison Snyder, "High-Tech Demand Sparks Return of Cobalt Mines," *MIT Technology Review*, August 30, 2011 (as of March 13, 2013: http://www.technologyreview.com/news/425273/high-tech-demand-sparks-return-of-cobalt-mines/).

[35] In general, military specifications are met through selection of appropriate commercially available cells and appropriate assembly of those cells to form a battery.

[36] Ralph J. Brodd, "Synopsis of the Lithium-Ion Battery Markets," in Masaki Yoshio, Ralph J. Brodd, and Akiya Kozawa (eds.), *Lithium-Ion Batteries*, New York: Springer, 2009, pp. 1–7.

[37] See, for example, LG Chem Power, Inc., "LG Chem," 2008 (as of December 3, 2013: http://lgcpi.com/chem.shtml); and Panasonic, "Major Sites," 2013 (as of December 3, 2013: http://panasonic.net/ec/company/location.html).

[38] The information for this and the previous paragraph was derived primarily from the following reports: "Rechargeable battery industry," WOORI Investment & Securities, November 18, 2011; and "Rechargeable Batteries: Chapter 1, Mobile device batteries," Daishin Securities Research Center, April 19, 2012.

[39] For details on assembly of batteries from cells, see Reddy, 2011, Chapter 5.

[40] For example, see Energizer Holdings, Inc., "Locations," 2011 (as of December 16, 2013: http://www.energizerholdings.com/company/locations/Pages/default.aspx).

[41] For example, SAFT America, Ultralife, Yardney, Quallion, and Eagle Picher all manufacture various types of lithium and other high-performance military batteries.

[42] Defense Production Act, Title III, "Lithium Ion Battery Production for Space Applications (LISA)," undated (as of April 19, 2013: http://dpatitle3.com/dpa_db/project.php?id=67).

[43] Department of the Air Force, Air Force Materiel Command, "Defense Production Act Title III, Lithium Ion Battery Production for Military Applications Project," BAA 11-17-PKM, July 8, 2011 (as of April 22, 2013: https://www.fbo.gov/index?s=opportunity&mode=form&id=08871c6175d2a243e1deeec07732ed70&tab=core&_cview=0).

[44] Bill Vlasic, "Chinese Firm Wins Bid for Auto Battery Maker," *New York Times*, December 9, 2012 (as of March 13, 2013: http://www.nytimes.com/2012/12/10/business/global/auction-for-a123-systems-won-by-wanxiang-group-of-china.html?_r=0).

[45] Howell, 2012.

[46] See, for example, Joe Gould, "Army to field new network tools to 8 BCTs," *The Army Times*, July 3, 2012 (as of December 3, 2013: http://www.armytimes.com/news/2012/07/army-network-tools-fielding-8-brigade-combat-teams-070312w/).

[47] Ralph J. Brodd, *Factors Affecting U.S. Production Decisions: Why Are There No Volume Lithium-Ion Battery Manufacturers in the United States?* Gaithersburg, MD: National Institute of Standards and Technology, ATP Working Paper 05-01, June 2005 (as of December 4, 2013: http://www.atp.nist.gov/eao/wp05-01/wp05-01.pdf).

[48] GAO, 2012.

[49] Christopher Johnson, "ARRA Battery Manufacturing for Electric Vehicles," presentation, U.S. Department of Energy 2012 Merit Review, Electrochemical Storage, May 15, 2012.

[50] See, for example, Yuki Noguchi, "Grounding of 787s Creates Doubt About 'Business As Usual' at Boeing," *NPR News*, January 30, 2013 (as of December 5, 2013: http://www.npr.org/2013/01/30/170667934/grounding-of-787s-creates-doubts-about-business-as-usual-at-boeing); and "GS Yuasa Working Closely with Boeing to Get 787s Flying Again: Chief," *The Japan Times* (Osaka,) March 5, 2013 (as of December 5, 2013: http://www.japantimes.co.jp/news/2013/03/05/business/gs-yuasa-working-closely-with-boeing-to-get-787s-flying-again-chief/).

[51] See GS Yuasa Lithium Power, "GS Yuasa Li-ion Battery Cells Selected to Power International Space Station," press release, November 29, 2012 (as of December 5, 2013: http://www.gsyuasa-lp.com/content/gs-yuasa-li-ion-battery-cells-selected-power-international-space-station).

[52] See Quallion, "Satellite Batteries," undated (as of December 5, 2013: http://www.quallion.com/sub-ms-satellites.asp).

[53] Battery storage protocols could include, for example, maximum and minimum temperature limits, acceptable humidity levels, maximum storage duration, methods for handling and transfer, safety procedures, and accident response. Active management involves establishing an electrical connection to the stored batteries or cells and appropriately maintaining or varying the voltage between the electrodes.

[54] DOE, Office of Science, "DOE Energy Innovation Hubs," March 25, 2013 (as of December 5, 2013: http://science.energy.gov/bes/research/doe-energy-innovation-hubs/).

[55] JCESR, "The National Mission," 2013 (as of December 5, 2013: http://www.jcesr.org/research/the-national-need/).

[56] For example, the procurement could be structured so that technically qualified bids offering imported cells would be evaluated by increasing bid unit prices by 20 percent when compared to technically qualified bids offering domestically produced cells. Assume $100 is the lowest-bid unit price from vendors offering imported cells. With a 20-percent bias for domestic production, the lowest-price vendor offering high domestic content would win the competition so long as the bid unit price is under $120. Otherwise, the award goes to the vendor offering imported cells.

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