SAND2020-1436B

Adapting SOCOM to an Electrified World

Karen Swider Lyons, U.S Naval Research Laboratory, Washington DC

Joshua Lamb, Sandia National Laboratory

Yet-Ming Chiang, Massachusetts Institute of Technology, Cambridge MA

Introduction

SOCOM envisions its future with Hyper Enabled Operators[1] empowered by "data assets, adaptive and flexible sensors, scalable tactical communications, edge computing, embedded algorithms, and tailorable human-machine interfaces… integrated into architectures that will sense, monitor, transport, process, and analyze and aggregate data." [2] Many of these technological advances are possible due to the rapid pace of microelectronics development, which has famously increased in capability following an exponential curve with time, or doubling twice every two years.

Underlying the execution of fielding advanced communication, computing, and sensors is the need for adequate electrical power and energy. Vast technological changes have occurred since the 1980's in electrochemical power sources, particularly with lithium-ion battery technology for mobile devices, automobiles and energy storage. Fuel cell technology is also being steadily commercialized. The capacity of batteries is fixed on their chemical composition, but has been doubling once every ten years as new materials are discovered and developers can cram more "energy in the can." For fuel based systems, the progress is slower as the energy content of fuels is fixed, but improvements are made through creating lighter and more efficient conversion devices. To accommodate additional energy requirements for microelectronics, developers of commercial electronic products simply use more space and weight in devices for the power sources, a design luxury that SOCOM might not have.

We assert that continued progress in electrochemical energy technologies in the next 30 years will affect SOCOM significantly, as electric-powered unmanned systems become more effective, assuming that SOCOM manages the resources appropriately. Power requirements will increase for communication in GPS denied areas, as the distance between receivers and transmitters increase and signals must overcome clutter in the environment. Electrical energy is poised to have even a broader impact as the DOD moves to directed energy weapons, plus demands increase for high quality power at its temporary installations for electronics and communications. New technologies are trending toward increased electrification of even traditionally non-electric devices, with the gap for implementation often being the lack of a suitable power source. Maintaining technological supremacy in the future will require the development and adoption of power sources capable of powering new advances. The US might also depend on new countries to keep access the materials needed for new energy sources, and rely less on oil-producing countries. This chapter will attempt to project how the movement to electric power sources,

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such as batteries and fuel cells, may affect SOCOM's technological and geopolitical outlook for the next 30 years.

Electrochemical energy systems

Lithium ion batteries for energy storage

Rechargeable lithium ion batteries (Li-ion) for portable electronics were first commercialized by Sony in Japan 1991. Since then, the capacity of lithium ion batteries has increased by more than three times. Their cost has decreased by 85% since 2010. Such increases in capacity and decreases in costs are forecast to continue as Li-ion batteries are now ubiquitous in everything from tools to automobiles. And as their manufacturing and safety continues to improve, they are finding applications in on-grid and off-grid energy storage when coupled with wind or solar power. The market prospects for lithium ion batteries and related energy storage systems is in reference. [3] Investments in battery-related technologies were $13.7B in 2016-2017, and such investments continue to grow.

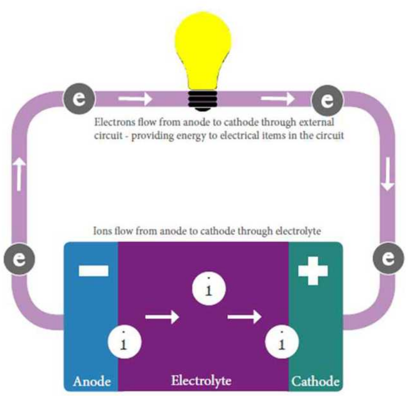

Figure 1. Schematic of battery charging and discharging, from Ref 3. The cycle is about 90-95% efficient.

Rechargeable Li-ion batteries are electrochemical energy storage devices that store energy produced by another source (e.g. natural gas/turbines, diesel/generators, solar panels). The materials in the cathode and anode of the batteries shuttle lithium ions between them upon charge and discharge. As the battery is charged, the cathode transition metal oxides (containing typically cobalt, nickel and manganese) release electrons and positively charged lithium ions to the carbon/graphite anode as the battery. The reverse process occurs on discharge, and they release the potential energy of the stored electrons to an external device. Li-ion batteries store more energy than their lead-acid or Nickel-Cadmium counterparts mainly because their chemistry yields a higher voltage (nominally 4 Volts vs 1.5 Volts for lead acid). Power, in Watts is equivalent to the product of voltage and current (P = V*I Watts). Energy is power over time (E = V*I*t). Li-ion batteries also feature much higher cycle life than other rechargeable technologies, with commercially available technologies able to achieve 500 full charge discharge cycles or more before losing energy storage capability. The materials in lithium ion batteries are also lighter than in their traditional counterparts, giving them higher power and energy per unit weight and even volume. New materials and manufacturing methods have been developed to make batteries that are lighter and denser, so more Watts and Watt-hours are produced per unit weight or volume of the batteries, with more projections for improvements. Further details of lithium ion battery materials and technology plus future prospects including environmental impact and lifecycle costs can be found in reference. [4]

Even lithium ion batteries however have not fully broken the relationship between power and energy (typically increasing power capability leads to a reduction in stored energy and vice versa), making battery selection highly dependent upon the application. A careful consideration of power, energy and operating conditions (particularly temperature) must be considered when selecting a battery for an application. Li-ion for example typically has a narrow operating window of ~5-55 ˚C. Selecting the wrong battery for an application can lead to a device unable to complete its mission, or even present a safety hazard to users. The stored energy in batteries always carries an inherent risk, described in greater detail below.

Fuel cells

Fuel cell technologies are also poised to change how energy is distributed worldwide. Like batteries, fuel cells produce electricity directly via electrochemical reactions at the cathode and anode, however the fuel cells are open and use air for the oxidizer and they do not store energy (the energy resides in the fuel). The reactions are facilitated by electrocatalysts, typically containing platinum, and the electrolyte is a perfluoronated polymer, such as Nafion®.

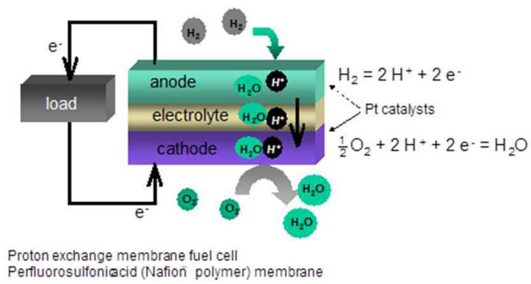

Figure 2. Schematic of a hydrogen fuel cell mechanism.

Hydrogen fuel cells are the most advanced type of fuel cell, and are being used for automobile propulsion, materials handling (fork lifts) and back-up power. Hydrogen fuel cells operate at low temperatures (e.g., less than 100 °C) and around 60% efficiency. Hydrogen fuel cells fill some niches well. Because they efficiently convert the high energy of hydrogen gas to electricity, they typically have more energy than large-scale batteries. They refuel quickly, keeping equipment in use longer than those powered by batteries, a key attribute for warehouse forklifts and fleet vehicles. The cost of fuel cell development is mainly in manufacturing rather than raw materials, so their costs are projected to decrease.[11] While the investment in fuel cells is far smaller than into batteries, fuel cell automobiles are being developed worldwide and Japan, South Korea and China are setting ambitious goals to have millions of fuel cell cars on the road by 2030 and are also targeting long-haul trucking. Amazon recently bought a large stake in Plug Power for its fuel cell forklift business. Cummins recently bought a large stake in Hydrogenics for hydrogen fuel cells and hydrogen production for back-up power.

Hydrogen fuel is the main detraction for fuel cells, as it must be made by reforming natural gas or electrolyzing water by processes that are marginally efficient. The hydrogen is typically stored at high pressures, and the infrastructure has been too sparse to make it convenient for most consumers. More recent demonstrations have shown that hydrogen is an asset as renewable energy plants are able to make it “for free” with excess solar and wind. Excess electricity is provided to electrolyzers to produce hydrogen from water. The hydrogen is either fed into natural gas lines or compressed and stored as fuel. Hydrogen can also be stored indefinitely, with no loss of energy (unlike batteries, which will self-discharge).

Other types of fuel cells include direct methanol fuel cells, which are limited to small sizes due to thermal restrictions with heat rejection, and solid oxide fuel cells, which operate near 800 °C typically on natural gas, but have not been as successful on liquid fuels such as JP-8. As discussed below, these types of fuel cells have some niche markets for the military.

Electric power for SOCOM missions

Portable power

The heavy load of batteries required for the dismounted soldier is a well-known problem. US Marines refer to them as one of the 3 B's needed for survival: "Beans, Bullets, and Batteries." The US Government has spent hundreds of millions of dollars seeking new energy systems for new energy systems in the 20 to 50 Watt range, or adequate to power radios and communication systems. The Army is also striving to network all of the power loads on the soldier so that only one type of battery must be carried. A range of technologies have been explored such as lithium batteries, energy harvesting devices (e.g., heel strikes) and direct methanol fuel cells. Solid oxide fuel cells and Sterling engines were also explored due to their promise of operating only on JP-8.[5] While this investment by the government clearly "energized" the interest in small power sources, the main technology now in this power range is rechargeable lithium ion batteries.

Table 1. Specific energy and energy density of 20-50 Watt battery and fuel cell systems, and DOE energy targets. Fuel cell systems assume 1200 Wh missions.

	Systems (20 to 50 W)	Specific energy Wh/kg	Energy density Wh/L	Notes
Rechargeable batteries	Lead acid battery	30-40	60-75	Well established high power battery
	Li-ion – standard for soldier	170	274	Brentronics BB2590
	Conformal wearable rechargeable Li-ion battery	120	184	Palladium CWB-150
	US DOE vehicle battery goals	235	500	Target for system level batteries [6]
Primary batteries	Primary battery - Li-CFx/MnO2	266	325	Eagle Picher - not rechargeable
Portable fuel cells	Direct methanol fuel cell	273	126	UltraCell XRT-25
	Direct methanol fuel cell	275	181	SFC Energy, Jenny 1200
	PEM fuel cell with 5000 psi H2	515	205	estimated

The specific energy and energy density of state-of-the art batteries is given in Table 1, along with values for some small commercial fuel cells, and the target for the next generation of automotive battery systems. The military have adapted lithium ion batteries to solider needs by making them conformal to the body, and thus more volumetrically efficient to carry. Methanol fuel cells (using liquid or reformed methanol) had some successes as did propane fueled solid oxide fuel cells. However, no energy harvesting devices beyond solar blankets have been deployed for the military. Sterling engines never received enough investment to get beyond the prototype stage. PEM fuel cells with compressed hydrogen are the most effective for energy per unit weight (specific energy) although they are not energy dense. Compressed hydrogen is unappealing for a soldier to carry. Using solid forms of hydrogen (uncompressed) is also possible. Metal hydride canisters are commercially available, but have low hydrogen storage per weight. More hydrogen-rich solutions such as alane or making hydrogen from Aluminum in water, but these systems are less mature, expensive, and have less energy than compressed hydrogen.

The development of cost effective, reliable power sources can cost in the billions of dollars once all the materials development, manufacturing and systems integration, so it is unlikely that the US Government can fund a technology alone, and dual use, with a broad commercial acceptance is ideal. A significant boon is the level of investment in battery technology from both commercial and public funded research and development. Significant funding for advanced battery development is currently in place through the Department of Energy's Vehicle Technology Office and a consortium of US auto manufacturers, the United States Advanced Battery Consortium (USABC).[6] They have provided targets performance targets for near term (CY 2023) battery development for electric vehicles. This represents a significant investment made by both commercial and public funded R&D as well as showing what performance targets may be commercially available in the near term. Developments made for the EV market represent significant resource if they can be adequately adapted to the needs of the special forces mission.

Progress is also being made at managing the electric loads better, and new iPower software is being implemented to better match new technologies to existing power sources.[7] The recommendation still stands that the SOF community must wisely manage its power loads effectively[5] and not expect an advanced power/energy source to become available.

Back-up power and remote sensors

The specific energy and volume of batteries is essentially linear with sizing. Fuel cells become more compelling for longer missions because the weight and size of the fuel cell power plant stays the same over time, with the requirement to only add more fuel. Diesel generators are state of the art, and used successfully, however they are noisy and the electric power is somewhat noisy. Both methanol fuel cells and propane- fueled solid oxide fuel cells scale favorably with size, and as the mission endurance increases from 24 to 72 hours, as shown in Table 2. The fuel cells are still relatively expensive compared to batteries, and while commercial vendors exist, the required propane and methanol fuels are a specialty fuel for the DOD, complicating logistics.

Table 2. Estimated specific energy of 110 and 275 W fuel cells vs batteries for 24 and 72 h missions compared to Lithium ion battery.

	Rated power, Watts	24 h Specific energy, Wh/kg	72 h Specific energy, Wh/kg	notes
Ultraelectronics D300	275	350	750	solid oxide fuel cell/propane fuel, limited cycle life
SFC EFOY 2400	110	110	900	direct methanol fuel cell
Solider Li-ion battery	100-275	170	170	Brentronics BB2590 - Batteries can be added in series to increase power

Unmanned air systems

Electric power brings many advantages over combustion technologies for unmanned air systems (UASs), as it directly compatible with electronics, plus brings low electric noise, instant starting, decreased maintenance, reduced vibrations, and negligible thermal signatures.

Small toys, robotics, and air vehicles have proliferated with the introduction of lithium polymer batteries, e.g., LiPo batteries, which are a form of Lithium-ion batteries with a gelled interior electrolyte. LiPos tend to have less strict manufacturing than cells used for cell phones, computers, etc., but can be designed in very small sizes and with very high power. Drones, or quad copters, are one technology that have particularly benefitted from LiPo batteries. The precise control of the drones is enabled by the electric power to the electric motors on each propeller, so that they can dynamically adapt with the wind and fatigue on the motors and keep the vehicle level.

Small quadcopters (or multicopters) are now commonplace due to the confluence of advanced Lithium-ion batteries, electric motors, and small electric cameras and payloads. Sophisticated mapping can be carried out with drones that can be purchased for a few thousand dollars. Most notably, the DJI Phantom and other drones are affordable to consumers and are now being used for jobs ranging from wedding photography to electric power line monitoring. The batteries on these vehicles last on the order of 20 to 30 minutes, making them inadequate for complex over-the-horizon surveillance.

The endurance of commercial drones is expected to increase incrementally as new battery technology is developed. While the commercial drones might be considered too simplistic for advanced SOCOM missions, the SOCOM community should expect that their adversaries will be equipped with this technology, for both surveillance and carrying out attacks. Without longer endurance, the systems can still be made more lethal by grouping the systems together in swarms for more complex attacks and/or decoys. This threat will only grow in the next 30 years as the technology continues to develop with the shared commercial market.

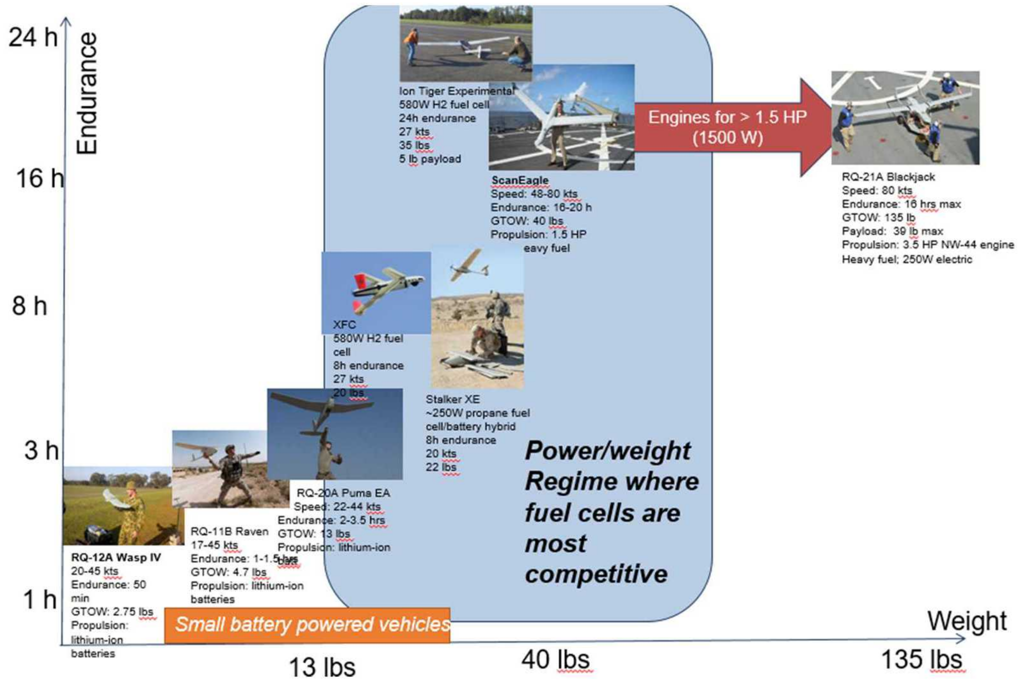

Figure 3. Comparison of battery, fuel cell and engine powered UASs, from Tier 1 to Tier 3.

Hydrogen fuel cells have been demonstrated to drastically increase the endurance of small, Tier 2 (15 to 50 lb) unmanned air vehicles with a 4 to 8 x increase over Li-ion batteries. The Naval Research Laboratory has demonstrated 24-hour flights of 35-pound vehicles with hydrogen fuel cells, and envision adding endurance with solar panels and autosoaring so that the vehicles can stay up for days at a time and serve as communication networks or provide persistent surveillance.

Other countries are also actively pursuing hydrogen fuel cells for long endurance small UASs. Such vehicles are likely to become a threat, as these quiet, long endurance vehicles are more frequently deployed.

Other special-forces missions

Power requirements for exoskeletons, such as the Tactical Assault Light Operator Suit (TALOS) were assessed as too demanding for electrochemical power sources.[8] However, new exoskeleton concepts are arising with reduced electronic loads and swappable Lithium-ion batteries.[9] As researchers learn to decrease the power needed for the loads, and battery and/or fuel cell technology improves, exoskeletons are likely to become an aid on the battlefield.

There is also a wish to upgrade wet SEAL delivery systems to dry systems, with longer range. The program to develop the Advanced SEAL Delivery System (ASDS) failed with a failure of the lithium ion batteries, resulting in a spectacular fire and complete destruction of the vehicle. This sobering accident effectively halted the use of advanced lithium ion batteries for the Navy. However progress is being developed toward the adaption of new Lithium-ion commercial batteries with better safety pedigrees. There are also numerous programs to extend the endurance of unmanned undersea vehicles with lithium ion batteries.

Risks of advanced battery sources

All stored energy carries an inherent risk, particularly if the stored energy is released uncontrollably. Currently, the largest forms of stored energy on the US electric grid are in the form of pumped hydroelectric reservoirs, where water is cycled between reservoirs at different elevations to store electrical energy. The uncontrolled stored energy in this case is potentially catastrophic, particularly for those living downstream from the dam. Batteries carry this risk like any form of stored energy but present some particular challenges. Looking at batteries in terms of the fire triangle, a fully charged battery holds fuel and oxidizer in intimate contact with one another. The only other places this is common is in high explosives and rocket fuel. While battery failure is certainly less catastrophic than the risk presented by an explosive, advanced electrochemical systems present an increasingly energy dense component of many systems. Not only can a failure render the device inoperable, but a severe enough incident can lead to damage beyond the power source and even injury to the user in extreme cases.

Lithium ion presents a modern case study of this problem. The specific concerns of lithium ion cells are well known. They are intolerant of abusive conditions, the active materials exhibit energetic breakdown, the inactive components (the electrolyte in particular) are flammable, and flammable gasses are often produced as part of the decomposition. Much the same could also be said of chemical fuels. Gasoline and other fuel fires happen routinely, yet the hazards inherent to the fuel are rarely seen as a reason to prohibit its use. The difference ultimately is familiarity with risks inherent to the technology. We have 100+ years of dealing with liquid fuel fires and most organizations feel they are well equipped to safely handle liquid fuels and respond to any emergency situations surrounding them. Lithium ion batteries by comparison have been in common use for around 20 years, and in most of that time have been relegated to single cell consumer electronic devices. Applications using more than three or four small cells have only become common in the last 7 or 8 years (largely thanks to the commercialization of electric vehicles).

The current solution to field high energy density batteries is to rely on sophisticated engineering of the battery pack, including both active and passive controls to mitigate a potential failure. These solutions add significantly to the size, weight and cost of the system, effectively reducing the energy density of the underlying technology. Research and development is underway for advanced battery reliability, including more sophisticated diagnostics, cell level improvements for better safety and pack level improvements.

While DOD has been slow to adopt new battery technologies due to safety concerns, potential adversaries may be less reticent. A higher tolerance for risk presents other countries with an opportunity to leapfrog our own technologies by adopting new power source technologies where the safety concerns have not been fully addressed. The use of lithium-ion batteries in the new stealthy Russian submarines was revealed when a vehicle was destroyed at sea, possibly due to a lithium-ion battery fire. The Japanese,[10] Australians and Chinese (and others) continue to develop submarines with lithium ion batteries. Howaldtswerke-Deutsche Werft AG has built a fuel cell based submarine for years for the German and Italian navies, and others. The adoption of advanced power sources by SOCOM will be critical to maintaining a technological advantage. This requires 1) a better understanding of the potential consequences so that users can appropriately assess the risks of a technology and 2) improved technologies to mitigate risks when they are deemed unacceptable.

GeoPolitical Concerns for Manufacturing and Raw materials and new Electric Microgrids

Li-ion batteries were first invented in the U.S., and the materials were discovered in the U.S., Europe, and Japan. However, Sony in Japan led the first effort to commercialize and manufacture the technology. The centers of manufacturing then moved to South Korea, but now China dominates 73% of the manufacturing market as part of their government strategic efforts to become leaders in new energy technologies and electric vehicles, much like the path that China took for solar energy. Meanwhile, the US has 12% of the world manufacturing capability for Li-ion batteries today, and with no national plan for electrification, its worldwide share is forecast to drop.

Up to 70% of the cost of lithium ion batteries in their raw materials. [11] Lithium batteries require lithium for their anodes, plus an assortment of transition metal oxides for their cathode. The original cathodes contained cobalt (as lithium cobalt oxide), but these have been replaced by higher capacity and higher voltage materials containing nickel and manganese. The majority of cobalt (69%) is mined in the Democratic Republic of Congo, however China holds 62% of the cobalt chemical supply, as shown in Figure 1. [12] Nickel is primarily mined in Indonesia (26%) and the Philippines (17%),[12] where it is also causing significant environmental damage.[13]

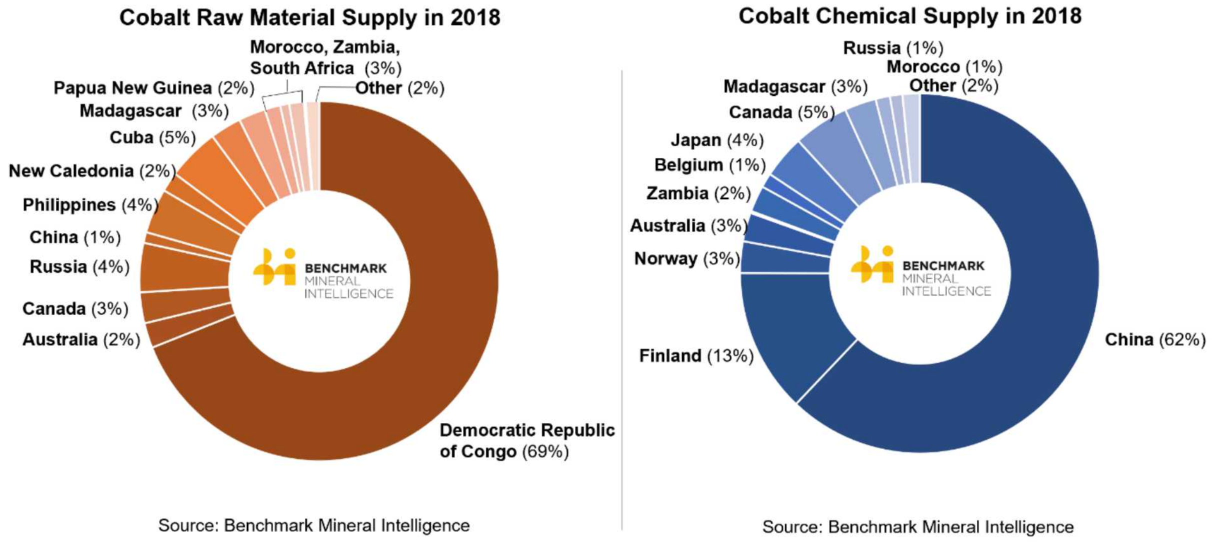

Figure 4. Distribution of cobalt as a raw material (left) and chemical (right) from reference 12.

Benchmark Mineral Intelligence, a company that tracks markets for Li-ion batteries, briefed the U.S. Congress in Feb 2019 to raise concerns about the US losing its manufacturing and technological lead. The number of Li-ion battery “mega” or “giga” factories increased from 17 in 2017 to 70 in 2019, 46 of which are based in China with only five currently planned for the US.[12] A RAND study raised similar concerns about the US maintaining a ready manufacturing source of batteries for soldier portable battery supply,[14] and would likely impact SOCOM as well. A challenge for low-volume manufacturers for soldier-specific or custom batteries will be whether they have enough clout to affect the purchase of the materials needed for batteries, as the giga-factories dominate the purchasing. And would it be possible to have a surge of battery production for soldiers in war time?[15] The recent proposal of the U.S. Executive Branch to purchase Greenland from Denmark could be seen as a means for more reliable access to the raw materials in batteries and fuel cells and electric motors, as the ice shelves melt and allow new mining projects, such as the Magmatic Massive Sulfide project for nickel-copper-platinum-cobalt.

SOCOM should also expect that the use of batteries and fuel cells in microgrids in combination with renewable energy (solar and wind) will provide power to thousands of communities world wide that were previously without stable sources of power. Microgrids are being implemented now in Pacific island communities where all power is generated by imported fuel from generators. As the technology costs continue to decrease, stable electric power will likely come to Africa, India and third-world communities. The availability of stable electric power from hybrid microgrids will undoubtedly improve living conditions for hundreds of millions of people world wide. While peace typically follows improvements in living conditions and economic stability, thirty years from now, SOCOM might find some emerging communities with aggressive ambitions.

Summary

The world is presently experiencing a revolution in electric power sources, as lithium-ion battery and fuel cells becoming ubiquitous, reliable, and cost-effective for portable electronics, vehicles, tools, and homes. The technologies are expected to proliferate with the growing demand for electric vehicles and grids, and will likely affect SOCOM missions at both the technical and geo-political levels. SOCOM must manage the deployment of electronic loads around realistic expectations of the capabilities of commercial power sources, and work to integrate new technologies effectively into their missions. Despite that the energy of batteries and fuel cells will not improve at the rate of microelectronics, the electrification of unmanned systems will unleash new, small technologies that can be used effectively both by and against the US. SOCOM will also have to consider relationships with countries that hold the raw materials for batteries, fuel cells and electric motors. New economies might emerge around micro-grids in less-developed countries.

Acknowledgements

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
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