Optimized Energy Storage

Thirty-six percent reduction in FOB generator fuel use

by Capt David J. Chester, USMC; LtCol Torrey J. Wagner, USAF; & Douglas S. Dudis

>Capt Chester was commissioned in 2010 from North Carolina State's NROTC. He is currently working toward a Master's Degree in Environmental Engineering and Science to earn the MOS 8831. His research is in DOD Waste Management with a focus on Waste-to-Energy technologies.

>>LtCol Wagner was commissioned in 2000 from the University of Minnesota's AF ROTC. LtCol Wagner's current research interests within AFIT's Department of Systems Engineering and Management include finding optimized solutions to meet DOD energy requirements in a cost-effective manner. He recently finished teaching the first rendition of his newly developed graduate-level Future DOD Energy Systems Engineering course.

>>>Dr. Dudis is the Director of the AFRL Energy Office and provides guidance to professional societies and strategic energy forums at the USAF, DOD, interagency, and international levels. He has experience leading research in an active laboratory and has supervised and mentored numerous masters and doctorial students, faculty, and postdoctoral researchers.

The DOD energy policy is to increase energy security resiliency, and mitigate costs in the use and management of energy.[1] Forward operating bases (FOBs) are remote, austere base camps that support an operationally defined mission with a limited or no ability to draw from an energy grid and have historically relied on diesel-powered generators for the primary production of energy.[2] Generators are sized to meet a theoretical peak demand, but steady state loads are far below this peak, resulting in under-loaded generators.[3] Under-loaded diesel generators decrease efficiency and increase the need for maintenance, affecting the lifespan of the systems.[4 5]

This article analyzes the coupling of current power generation technology with energy storage. The addition of optimized energy storage to current diesel generators reduces fuel consumption by 36 percent and reduces energy system costs by 24 percent. Decreased fuel requirements at outlying FOBs equates to fewer resupply convoys, reducing operational fuel use, time spent outside the wire by service members and associated combat casualties.

Background

Military operations involve the projection of military power beyond the sovereign boundaries of the United States. Base camps are evolving military facilities that support deployed units executing military operations by providing the necessary services and support to sustain operations. The primary purpose of a base camp is mission support—providing survivability and protection to the deployed forces, managing resources and critical infrastructure, and maintaining facilities.

At a minimum, a forward base must be able to power and support a combat operations center (COC) that houses the radio equipment, laptops, and minimal lighting required to command and control battlefield operations and support the warfighting capability of the unit.[6] Additional energy can be used to power billeting and personnel support measures, including climate control and lighting. The average power demand for an Afghanistan COC is approximately 2.2 kW, with a 4.5 kW peak power demand and a daily energy requirement of 53 kWh.[7] The average power demand for climate control for the same platoon patrol base is 1 kW, peaking mid-day at 1.6 kW, with a daily energy requirement of 24 kWh.[8]

Figure 1 (see next page) displays the combined COC and climate control power demands that are combined to create the energy requirement used in this analysis. The daily energy requirement totals 77.5 kWh with 3.2 kW average power and 5.4 kW peak power.

Engineering an energy system to provide power to an austere forward base requires more than just selecting a generator that can meet power demands. It is essential to apply a life-cycle analysis on the generator and consider its total cost of ownership including logistics and disposal, requirements for use, and maintenance. The selected energy system for an austere forward base must meet the minimum COC power demands but must also be rugged and resilient, as forward deployed platoons and companies are often not staffed with generator mechanics. Fuel requirements are an equally important

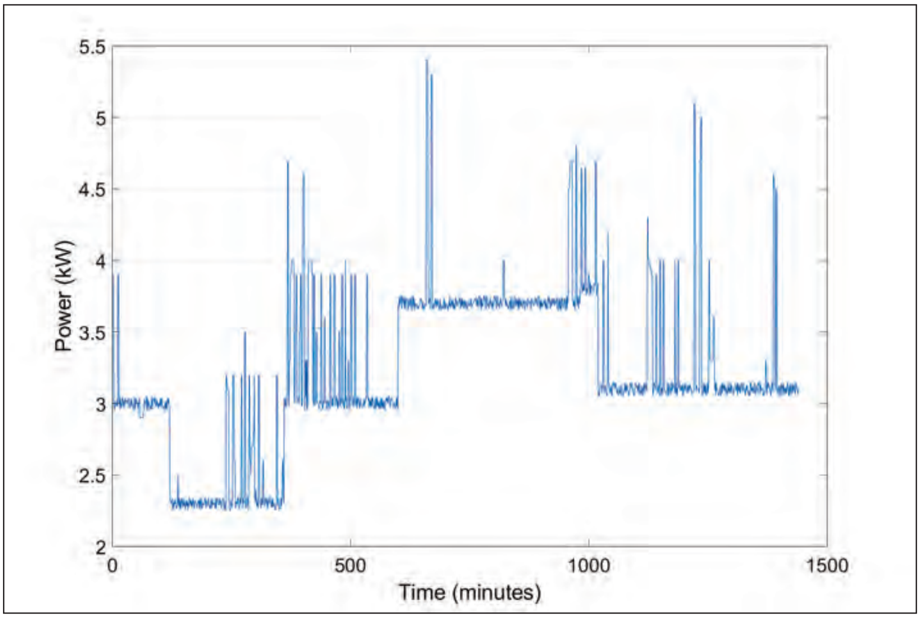

Figure 1. Combined platoon patrol base power demand.

	Generator	Battery	Inverter/charger
Component Cost	$1,120 / kW[9]	$490 / kWh[10]	$900[11]
Replacement	-	600 cycles[12 13]	-
Weight (lbs)	800[14]	300[15]	100[16]
Fuel Cost ($/gal)	10[17]	-	-
Peak efficiency	26 percent	-	-
Power Output (steady state / max)	5 kW / 5 kW[18]	5 kW / 7 kW[19]	6 kW / 6 kW[20]
Max Storage	-	13.5 kWh[21]	-

Table 1. Cost and performance model parameters.

consideration, as resupply to austere locations is considered a combat operation and requires significant commitment of personnel and resources.

Method

The energy system modeled consists of a generator and battery controlled by an inverter/charger. This configuration allows the generator to run at full load, where it is most efficient, and store the excess generated power in a battery. Once the battery is full, the excess energy is discharged from the battery, allowing the generator to shut down to conserve fuel and wear. When the battery has discharged to its minimum-allowable level, the generator turns back on, and the cycle repeats.

Cost and performance values used in the system model for representative generator, battery, and inverter/charger components are shown in Table 1.

The generator efficiency curve is modeled from the manufacturer's specification, with an efficiency of 26 percent at 5 kW output and 10 percent at 1 kW output.[22] It was assumed that the cost of starting the generator was ten seconds of fuel use. The representative battery is advertised to fully discharge during each cycle with a lifespan of 10 years,[23] but literature shows lithium-ion batteries have an expected life between 300 and 600 discharge cycles at 100 percent depth of discharge.[24 25] The model accounts for eight percent round-trip battery energy loss and replacement of the battery if it exceeds the above-noted number of discharge cycles and increases the battery cost accordingly. The ten-dollars-per-gallon fuel cost is an average calculated from historical fuel usage from Camp Leatherneck to outlying FOBs.[26] The model used 37.9 kWh/gallon of energy available in diesel fuel, which was converted from 46 MJ/kg.[27]

Generator performance was modeled based on the daily load from the 45-Marine patrol base shown in Figure 1 and the model parameters shown in Table 1. The first simulation used the 26 percent maximum efficiency of the 5 kW advanced medium mobile power sources to calculate fuel consumption for a 24-hour period. With constant efficiency, the daily required diesel fuel to power the patrol base was 12.2 gallons, or $122. The second simulation added battery storage and the inverter/charger. The daily required diesel to power the COC was then reduced to only 7.9 gallons, or $79, a dramatic 36 percent reduction in fuel requirements because of intermittent generator use at peak efficiency.

Optimization

The total cost is defined as the cost of components and fuel over the period of the deployment, and we assumed a 180-day operation. The model tracked the parameter "minutes not met" (MNM) if the combined generator and battery could not meet the power demand for a specified minute. The analysis considered zero tolerance for any MNM. This section examines variations in battery size, generator size, and then the battery and generator optimally sized for the lowest cost.

As battery capacity increased, the price of the battery also increased, but fewer battery replacements were required to meet the 180-day deployment demand. This created a saw-tooth variation in battery cost, as shown in Figure 2 (see next page). The cost of diesel was relatively stable for all battery sizes. This makes intuitive sense, as the battery is directly charged from excess power from the generator, and that stored power is eventually used while the generator is off, which does not require additional fuel.

As generator size increased, there was a gradual increase in generator cost; however, the battery cost increased with larger generators. This is because the larger generators charged batteries quicker, allowing more frequent discharge cycles of the batteries, hastening their replacement. Similar to the batteries, smaller generators were unable to maintain the base load and charge the battery, eventually unable to meet demand.

Both battery capacity and generator size were varied and the resulting cost and MNM were calculated and are displayed in Figure 2. The saw-tooth variations in Figure 2 are because of the cost of battery replacements, and optimal configurations are shown in red.

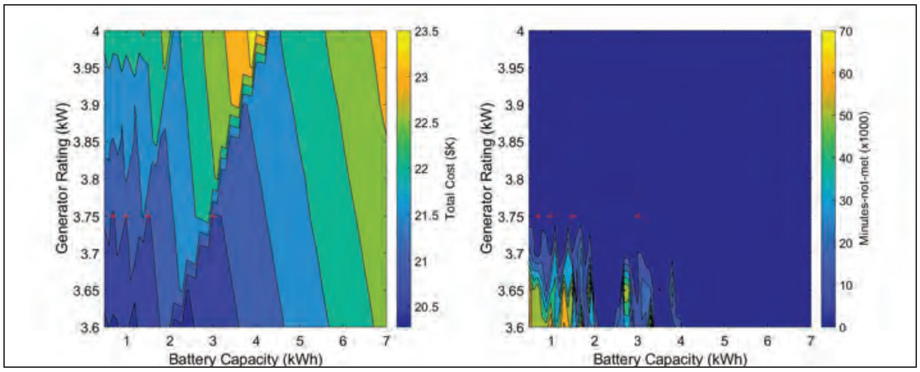

Figure 2. Total cost (left) and MNM (right) while varying generator size and battery capacity.

The optimal configuration is to meet the requirement with the smallest generator and the smallest battery that doesn't require replacement.

The left side of Figure 2 shows that the lowest cost (dark blue) is a 3.6 kW generator paired with either 0.7, 1.1 or 2.2 kWh battery capacities. However, this does not account for whether the generator can meet system demands—the right side of Figure 2 shows unacceptable levels of MNM in these configurations. The optimal configurations shown in red avoid regions with high MNM and use a 3.75 kW generator paired with either 0.7, 1, 1.5 or 3 kWh battery capacities. For those configurations, the battery needs to be replaced three, two, one and zero times, respectively.

The optimal configuration is to meet the requirement with the smallest generator and the smallest battery that does not require replacement. The 3.75 kW generator was the smallest possible generator still able to meet steady-state demand and contribute energy to the battery. The 3 kWh battery was large enough to handle any large spikes in demand to not require replacement across a 180-day deployment, and to power the FOB for an hour of generator-free operation, and it was small enough to limit costs. For this configuration, Figure 3 plots the COC power demand, the power output of the generator, and the charge of the battery for two days of operation.

Conclusion

This proof-of-concept showed that energy storage coupled with current power generation technology for a FOB can reduce fuel use by 36 percent while saving 24 percent of the energy system cost. The diesel fuel required to meet an actual Marine patrol base energy requirement for 180 days—relying solely on a 5 kW advanced medium mobile power sources and accounting for the inefficiency of under-loading a generator—is nearly 2,200 gallons, with a combined fuel and generator cost of $27,600. It saves 760 gallons of fuel and $6,600 to power the same FOB using a 3.75 kW generator, a 3 kWh battery, and a 6 kW inverter/charger. Decreased fuel requirements at outlying FOBs will also equate to fewer resupply convoys, reducing fuel use further, and reducing time spent outside the wire by service members.

Running generators at optimal efficiency has the additional benefit of reducing maintenance and replacement costs. As the cost of fuel continues to rise and technology improvements reduce battery costs, this cost difference will only continue to improve.

Notes

1. Department of Defense, *Department of Defense Instruction 4180.01, DOD Energy Policy*, (Washington, DC: 2017).

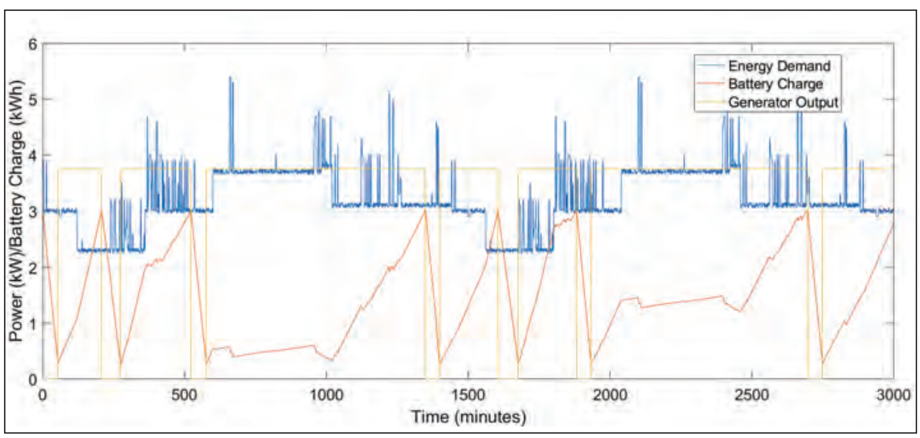

Figure 3. Power demand, 3.75 kW generator power production, and 3 kWh battery discharge at the cost-optimized configuration.

2. Department of the Army, *Field Manual 3-34.400, General Engineering*, (Washington, DC: 2008).

3. B.H. Newell and E.B. Shields, *Expeditionary Energy Data Collection within Regional Command Southwest, Afghanistan*, (Washington, DC: USMC Expeditionary Energy Office, 2012).

4. Ibid.

5. Kevin E. Garcia, *Optimization of Microgrids at Military Remote Base Camps*, (Monterey, CA: Naval Postgraduate School, 2017).

6. *Expeditionary Energy Data Collection within Regional Command Southwest, Afghanistan.*

7. Ibid.

8. Ibid.

9. "Advanced Medium Mobile Power Sources Brochure," TESLA Cummins, Inc., (Columbus, IN: 2017).

10. "Powerwall," TESLA Cummins, Inc., (Online: 2018), available at https://www.tesla.com.

11. *1.5KW to 6KW Any Power Combi Pure Sine Wave Inverter/Charger User's Manual*, Sigineer Power, (Midvale, UT: 2015).

12. "BU-808: How to Prolong Lithium-Based Batteries," Battery University Group, (Online: 2018), available at https://batteryuniversity.com.

13. Ioannis Hadjipaschalis, Andreas Poullikkas, and Venizelos Efthimiou, "Overview of Current and Future Energy Storage Technologies for Electric Power Applications," *Renewable Sustainable Energy Review*, (Nicosia, Cyprus: 2009).

14. "Advanced Medium Mobile Power Sources Brochure."

15. "Powerwall."

16. *1.5KW to 6KW Any Power Combi Pure Sine Wave Inverter/Charger User's Manual*.

17. *Gasoline and Diesel Fuel Update*, (Washington, DC: U.S. Energy Information Administration, 2018).

18. "Advanced Medium Mobile Power Sources Brochure."

19. "Powerwall."

20. *1.5KW to 6KW Any Power Combi Pure Sine Wave Inverter/Charger User's Manual*.

21. "Powerwall."

22. John G. Sprague, *Optimal Scheduling of Time-Shiftable Electric Loads in Expeditionary Power Grids*, (Monterey, CA: Naval Postgraduate School, 2015).

23. "Powerwall."

24. "BU-808."

25. "Overview of Current and Future Energy Storage Technologies for Electric Power Applications."

26. Sean R. Dubbs, "Estimating the Fully Burdened Cost of Fuel Using an Input-Output Model—A Micro-Level Analysis," (Monterey, CA: Naval Post Graduate School, 2011).

27. David J. Cookson, C. Paul Lloyd, and Brian E. Smith, "Investigation of the Chemical Basis of Diesel Fuel Properties," *Energy & Fuels*, (Mulgrave, Australia: 1988).

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