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Renewable energy and energy storage to offset diesel generators at expeditionary contingency bases

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Abstract

Expeditionary contingency bases (non-permanent, rapidly built, and often remote outposts) for military and non-military applications represent a unique opportunity for renewable energy. Conventional applications rely upon diesel generators to provide electricity. However, the potential exists for renewable energy, improved efficiency, and energy storage to largely offset the diesel consumed by generators. This paper introduces a new methodology for planners to incorporate meteorological data for any location worldwide into a planning tool in order to minimize air pollution and carbon emissions while simultaneously improving the energy security and energy resilience of contingency bases. Benefits of the model apply not just to the military, but also to any organization building an expeditionary base—whether for humanitarian assistance, disaster relief, scientific research, or remote community development. Modeling results demonstrate that contingency bases using energy efficient buildings with batteries, rooftop solar photovoltaics, and vertical axis wind turbines can decrease annual generator diesel consumption by upward of 75% in all major climate zones worldwide, while simultaneously reducing air pollution, carbon emissions, and the risk of combat casualties from resupply missions.

Keywords

Expeditionary/contingency base planning, renewable energy and storage, energy efficiency

1. Introduction

The US Department of Defense (DOD) is the single largest consumer of fuel worldwide.[1,2] In 2011 alone, the US military spent a reported $20 billion on air conditioning in Iraq and Afghanistan.[3] Much of this cost was merely for transporting energy:

> To power an air conditioner at a remote outpost in landlocked Afghanistan, a gallon of fuel has to be shipped into Karachi, Pakistan, then driven 800 miles over 18 days to Afghanistan on roads that are sometimes little more than ''improved goat trails ... and you've got risks associated with moving the fuel almost every mile of the way.''[3]

In fact, for every gallon of fuel used in Afghanistan, seven gallons were needed to transport it there.[4] Moreover, 18% of all US Army casualties in Iraq and Afghanistan were related to ground resupply operations, and between 2003 and 2007 alone, attacks on logistics convoys resulted in over 3000 wounded or killed in action.[5,6] In addition, the logistics required to assure energy security at military contingency bases (often called forward operating bases, or ''FOBs'') is no small measure. In the first months of 2008, over 241,000 troops and over 200,000 contractors were deployed to the US Central Command theater of operations, and, at various times, over 500 FOBs existed in Iraq and Afghanistan.[7–9] Approximately one-third of all wartime fuel is used by generators at FOBs, so there exists an opportunity to reduce the inefficiency of current energy consumption.[10] As one general implored: ''unleash us from the tether of fuel.''[11]

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After nearly 20 years, the United States still has FOBs in both Iraq and Afghanistan. Based on this commitment, the US Congress has enacted laws regarding the fully burdened cost of fuel, energy resilience, and energy security.[12] Briefly, the fully burdened cost of fuel is the commodity price plus the total cost of all personnel and assets required to move and protect the fuel from point of purchase to point of use; energy resilience is the ability to avoid, mitigate, and/or recover from anticipated and unanticipated energy disruptions; and energy security is having assured access to sufficient energy for mission essential requirements when and where it is needed.[12] Given this mandate and limited resources in general, new methods are needed to substantially reduce energy consumption and cost for expeditionary bases.

The authors' hypothesis is that significant reductions in required diesel resupply at expeditionary bases can be achieved by incorporating renewable energy, energy efficiency, and energy storage. Benefits include improved energy security and resilience, as well as reductions in capital and operations costs, air pollution, carbon emissions, and fuel-related convoy casualties. This paper presents a new optimization model that uses input data for base parameters (e.g., size, level of service, and climate), energy storage, solar photovoltaics (PV), Vertical Axis Wind Turbines (VAWTs), and the US Army's new energy efficient building (''hut'') design based on Structural Insulated Panels (SIPs). The model provides planners the capability to study the impacts of building construction, commercial energy storage systems, solar PV, wind turbines, Air Source Heat Pumps (ASHPs), and scale at any climate location worldwide.

Previous studies have investigated only specific aspects of energy use at FOBs or unique non-military applications. One study found that reducing energy demand, removing the requirement for a spinning reserve, and allowing generators to operate at 100% of their rated load produced the best results, while energy storage systems had effectively no impact on generator run-hours or fuel consumption.[13] This study drew conclusions from assessments of 2- or 24-h periods modeled using a theoretical optimization based on efficiency curves for a common military generator.[13] A related theoretical optimization study concluded that using multiple sizes of generators, adding energy storage systems, and incorporating solar PV arrays all produced significant fuel savings.[14] The US Army has invested in model FOBs where it can study innovative applications, such as the Future Capabilities Integration Laboratory (formerly the Base Camp Integration Laboratory) at Fort Devens, Massachusetts. One study used both theoretical modeling and tests at this FOB laboratory to conclude that the most impactful technologies were smart microgrids and energy efficient shelters, while noting that the assumed improved baseline conditions of larger FOBs resulted in lower savings.[10] Other studies from both academic institutions and government suggest that microgrids with energy storage and scheduling management alone can reduce fuel consumption at FOBs by 20%–30%.[15,16] In addition, researchers are developing optimization models for non-military applications, such as the Food-Energy-Water Microgrid Optimization with Renewable Energy (FEWMORE), which is meant to minimize capital, maintenance, and operations costs for remote Arctic communities.[17] These studies are useful, but they are limited in that they investigate a specific scenario or package of technologies. What remains missing is a tool where military planners can define their own combinations of available technologies to be employed in a desired location, be able to quantify potential benefits versus cost, and determine the best solution for an FOB before it is built.

This study is unique from previous studies in that it develops a new optimization model to take input data for contingency base parameters and quantify benefits from reduced fuel consumption to include reductions in costs, air pollution, carbon emissions, and fuel-related convoy casualties. Energy storage, solar PV, and climate parameters are found in other studies, but this model goes further to also investigate the use of VAWTs, new ''SIP huts,'' and expands the climates considered to include the polar region. The model provides planners the capability to study the impacts of building construction, commercial energy storage systems, solar PV, wind turbines, ASHPs, and scale. Rather than being limited to a specific time frame, the model uses year-long meteorological data for each of 8760 h in a year and allows planners to test their own solutions for a potential contingency base located anywhere in the world.

Results demonstrate the imperative of bridging the gap between generalized planning factors and previous research with limited time scales or pre-defined technology packages. This model relies only on common and/or open-source software to facilitate knowledge transfer and use by both planners and researchers alike. Ultimately, the intent is to develop rules of thumb for manuals such that planners can better use energy efficiency, storage, and renewables at expeditionary bases to improve energy resilience while reducing air pollution, carbon emissions, and combat casualties. For a list of nomenclature and an in-depth description of all focus areas, methods, assumptions, derivations, and calculations, please refer the Supplementary Information.

2. Methods

There are three major parts to this analysis: pre-processing, the optimization process, and post-processing. Pre-processing uses Microsoft Excel to receive model input for key design parameters and data files. The optimization process reads specific data from the pre-processing spreadsheets and uses IBM's CPLEX solver within an optimization code written using the Julia programming language. The Julia code then passes results from the optimization process to another Excel spreadsheet for compilation, post-processing analysis, and graphing of results.

2.1. Pre-processing

2.1.1. FOB parameters. The pre-processing process begins in Microsoft Excel by allowing user input for FOB parameters. Data for the FOB's location come from Typical Meteorological Year version 3 (TMY3) data files. The model includes an example location for each of the five major Köppen Climate Classification Zones (A–E), but it also has a tab where users can input TMY3 data for any other desired location. Critical information from the TMY3 data file includes the location's latitude and longitude and hourly values for outdoor dry bulb temperature, ground reflectance (albedo), air pressure, and wind speed.[18] Data for planning factors, to include size, building square footage requirements, and peak power requirements, come from military publications.[19–22] FOB size is based on the unit, population, and land area needed. From small to large, contingency base sizes include platoon, company, battalion, brigade, and support area (see Table 4 in Supplementary Information). Building square footage requirements include needs for billeting, tactical operations' centers, dining facilities, gymnasiums, shops, medical aid stations, laundry facilities, and so on. Peak power estimates depend upon the level of service provided at the FOB, typically referred to as basic, expanded, or enhanced. Data for construction type and energy efficiency of buildings come from studies on experimental buildings and test facilities at the US Military Academy and the US Army Corps of Engineers.[23,24] These data permit calculation of the thermal index of construction options using established methods, which involves calculating the R-values for all windows, doors, walls, ceilings/roofs, and floors comprising the building envelope, as well as using blower door test data to calculate infiltration.[25,26] The unimproved South West Asia (SWA) Hut serves as the baseline structure and the model calculates the cost of additional lumber and insulation for improved SWA Huts as well as the cost of specialty panels for SIP Huts.

2.1.2. Electrical load. Next, the model generates a mock load for the analysis, relying upon previous studies with a 24-h load profile.[10] However, rather than repeat the same load every day throughout the year, this model introduces a randomized variable that serves to vary the load from the baseline profile within established boundaries. Furthermore, the model decreases this load profile to make it represent lighting and plug loads, but then also introduces Heating, Ventilation, and Air Conditioning (HVAC) loads that increase the load profile even further, while ensuring the FOB's location and climate impacts overall load requirements. The model allows for a user-defined building internal temperature set-point, which, when combined with TMY3 data for ambient temperature and construction type thermal index values, facilitates the calculation of space conditioning requirements. Rather than military-grade Environmental Control Units, this model considers the use of more efficient civilian ASHPs. Manufacturers of ASHPs publish values for the Heating Seasonal Performance Factor (HSPF) and the Seasonal Energy Efficiency Rating (SEER), which relate the average coefficient of performance over the heating and cooling seasons, respectively. This model applies a correction to HSPF and SEER values to reflect the impact of climate on ASHP performance based on the 99% heating and 1% cooling design temperatures for each location.[27–29] This calculates a more accurate HVAC load that is currently absent from most planning factors.

2.1.3. Renewable energy resources available. The model next calculates the renewable energy resources, namely, solar and wind, available at a specified location. For the solar resource analysis, a user can define an analysis year, from which the model calculates the Julian day and century (2000 standard epoch). The model uses this time data, the location's latitude and longitude, and astronomical equations[30] to calculate the Sun's position at every hour of the year. The model uses three different methods to calculate solar position;[31–33] example results are compared in the Supplementary Information. The model then calculates the total insolation on a collector, which is the summation of direct, diffuse, and reflected radiation, for both clear- and all-sky insolation scenarios. By comparing the three methods and two scenarios, one can draw conclusions about model complexity versus precision of results. Furthermore, future application of this model to an experimental FOB will allow the analysis of that precision against measured data to assess model accuracy. To determine solar PV electricity production, this model adopts the National Renewable Energy Laboratory's (NREL's) PVWatts methodology for calculating transmittance through anti-reflective coatings and the glass of PV panels, as well as a correction for the cell operating temperature.[34] The model adopts the same efficiency levels (module and inverter efficiencies and other system losses like soiling, shading, snow, mismatch, wiring, connections, light-induced degradation, nameplate rating error, age, and availability) and PV characteristics (nominal operating cell temperature and power temperature coefficient) as used in NREL's

PVWatts program for premium PV panels. The model also allows for user input on both rooftop and utility solar installations. For rooftop installations, this study uses buildings oriented with panels facing solar south (if in the Northern Hemisphere, opposite for the Southern Hemisphere) and the panels have tilt angles equal to the roof pitch. Cost estimates use published data for residential installations and include the capital cost of panels, mounts, inverters, wiring, and all balance of plant equipment, less any tax benefits generally included in such reported values.

For the wind resource analysis, a user can select a wind turbine and input manufacturer's published data for the power curve; rotor swept area; height; rated and maximum power output; cut-in, cut-out, and survival wind speeds; and efficiency.[35] This study uses VAWTs, as opposed to Horizontal Axis Wind Turbines (HAWTs), due to their ability to achieve higher wind farm power densities and lower hub heights.[36] Using gin poles and winches, it is likely possible to erect VAWTs in the field without lift assets, even with turbines weighing several hundred pounds. Alternatively, the US Army has cranes and trained operators that could help install VAWTs. Users of the model can define a friction coefficient from a pre-defined drop-down list to account for surface ground conditions, although this study uses the "1/7th rule-of-thumb" for open land throughout the analysis for all locations. The model takes hourly air pressure and wind speed data from the TMY3 files to calculate the hourly corrected air density and wind speed at turbine mid-point height. Using an estimated number of turbines (user-defined with consideration of total FOB land area requirements from published planning factors), spacing, an estimated utilization factor, and an aerodynamic loss factor, the model calculates the annual wind farm energy production and capacity factor. Cost estimates use published manufacturer catalog prices for turbines, controllers, inverters, towers, and ancillary equipment.[37]

2.1.4. Energy storage. For energy storage, the model allows for input on battery characteristics, to include energy capacity, continuous and peak power, and charge/discharge round-trip efficiency. These parameters can reflect either centralized or distributed energy storage solutions. This study uses data for distributed batteries installed in buildings that can be connected to rooftop solar;[38] however, in either case, the model treats all batteries as being fully connected on an FOB microgrid. In addition, this paper takes manufacturer-reported "useable capacity" to mean 100% of the modeled battery's range of charge/discharge. However, users of the model can just as easily input their own maximum depth of charge/discharge in order to model the use of controls that can help prolong the lifetime of batteries, which may or may not be important to planners based upon the FOB's purpose.

2.1.5. Diesel generators. The model uses 60-kW diesel generators for platoon- and company-sized FOBs and 840-kW prime power diesel generators for battalion-, brigade-, and support area-sized FOBs.[39,40] Users can define a percent overage of diesel generator capacity in order to allow for redundancy, specifically to facilitate repairs, maintenance, and downtime. In addition, users can input minimum and maximum load fractions to define allowable generator loading conditions. The cost of diesel is based on current prices, historical trends, and studies on (and the legal requirement to use) the fully burdened cost of fuel.[12,41–44] The fully burdened cost of fuel is highly dependent upon the costs of transport, personnel, sustainment, and air and ground force protection in addition to the cost of the fuel itself. Due to the large sensitivity this has on the cost analysis, this study adopts a conservative approach and uses a dollar per gallon value that reflects only the fuel commodity, transport, sustainment, and ground force protection components. This value is just 1/3rd the estimated base case fully burdened cost of fuel in Iraq in FY07 (or 1/4th that value when adjusted to FY20 dollars).[45] Nevertheless, sensitivity in fuel cost only affects the estimated simple payback results. When considering resilience, the model's reported percent reduction in the volume of diesel consumed is unaffected by cost, which is further explained in section 2.2.

2.2. Optimization process

A text editor (Atom), runs integrated development environment (IDE) software (Juno), which itself uses a statistical programming language (Julia), to execute IBM's optimization solver software (CPLEX).[46–49] All programs are open-source, with the exception of IBM's CPLEX, which is offered free of charge to students and academics.

The Julia code pulls data from the pre-processing spreadsheets for use in mixed-integer linear programming (MILP) with binary variables for diesel generators (on/off). The optimization program seeks to minimize the total cost of diesel and any curtailment, subject to the following constraints, variable constraints, and expressions (see the Supplementary Information for mathematical representation and code):

Constraints:

1. The overall FOB energy balance at every hour is such that that summation of the battery energy used, the total energy produced by all diesel generators that are on, the energy from solar PV, and

the energy from wind turbines is equal to the summation of energy demand (load), energy stored in batteries, and energy curtailed.

2. The initial battery energy storage starts at the minimum (i.e., zero).
3. The battery energy balance is such that the energy stored at the beginning of the next hour is equal to the battery energy stored at the beginning of the current hour, plus battery energy stored in that hour, less battery energy used in that hour.
4. The battery energy stored in any hour cannot exceed the summation of the energy produced by the diesel generators, solar PV, and wind turbines in that hour.
5. The battery energy used in any hour cannot exceed the battery energy stored at the beginning of that hour.
6. The diesel generators can run only within a user-specified minimum and maximum load fraction to avoid wet stacking and severe underloading of generators.

Variable constraints:

1. Diesel generator on/off is binary.
2. The energy stored in the batteries at any hour must be greater than or equal to the minimum (zero, a positivity constraint) and less than or equal to the maximum battery capacity.
3. Limitations on battery charging/discharging rates limit the energy stored/used from the batteries in any hour.
4. Energy produced in any hour by the diesel generators and energy curtailed have positivity constraints (the model changes the sign for curtailment to negative later in post-processing for graphing purposes).

Expressions calculate the:

1. Hourly energy produced by all generators turned on.
2. Hourly diesel cost of all generators turned on.
3. Total penalty cost for any curtailment.
4. Total fuel cost and curtailment penalty.

Output from the optimization process includes hourly energy produced by diesel generators, the energy storage level in batteries at the beginning of the hour, the battery energy consumed in that hour, and energy curtailed (if any) as well as the annual volume of diesel consumed and the corresponding annual fuel cost. The optimization program also serves to transfer key data needed from pre-processing spreadsheets to post-processing spreadsheets for further analysis, to include the hourly power load, solar and wind power production, and the additional upfront costs for more energy efficient buildings, battery energy storage, solar PVs, and wind farms used in each scenario.

2.3. Post-processing

Post-processing involves compiling output data from multiple runs of the optimization process in order to graph the results. The results for each climate zone shown in section 3 required compiling a minimum of 51 different iterations, 17 per hut type (unimproved SWA Hut, improved SWA Hut, and SIP Hut). To get a general sense of possible solutions, this study assumes maximum limits for battery, solar, and wind nameplate installations:

1. Up to 10 batteries (13.5 kWh storage capacity each) can be installed in each building (hut).
2. Solar PV can only be installed on hut roofs with industry-recommended offsets from roof edges.
3. Wind farms can take up no more than 10% of the prescribed land area for each contingency base size.

These assumed maximum installations are then divided into quarter increments to run simulations using zero, ¼, ½, ¾, and 100% for batteries alone, solar alone, and wind alone. Additional simulations use all three added to an FOB's energy portfolio simultaneously in the same incremental amounts. Depending upon the comparison examined, a baseline scenario (generally unimproved SWA Hut construction) defines what improvements can occur. The calculation of simple payback lines uses projected Consumer Price Index (CPI) values for the next 2 years.[50] The model does not change the cost of diesel in future years because data show that, for the 10 years between 2009 and 2018, the annual average global price of diesel fluctuated (both positive and negative) between a low of \$3.22 gal^{-1} and a high of \$4.35 gal^{-1}.[43] The uncertainty in diesel cost, even without considering the fully burdened cost of fuel, makes forecasting a diesel cost value over the short term have little to no useful meaning.

3. Results

Figure 1 consolidates results for a battalion-sized FOB with an expanded level of service, representing a middle FOB size and median level of service. Figure 1 shows three graphs for each of the five major Köppen Climate Classification Zones (A–E), each corresponding to a selected building construction type. Graphs at left illustrate the baseline condition of unimproved SWA Huts (what the military typically builds in expeditionary environments), in the middle are improved SWA Huts (with additional insulation), and at right are very energy efficient SIP Huts (a new design being tested by the US Army).

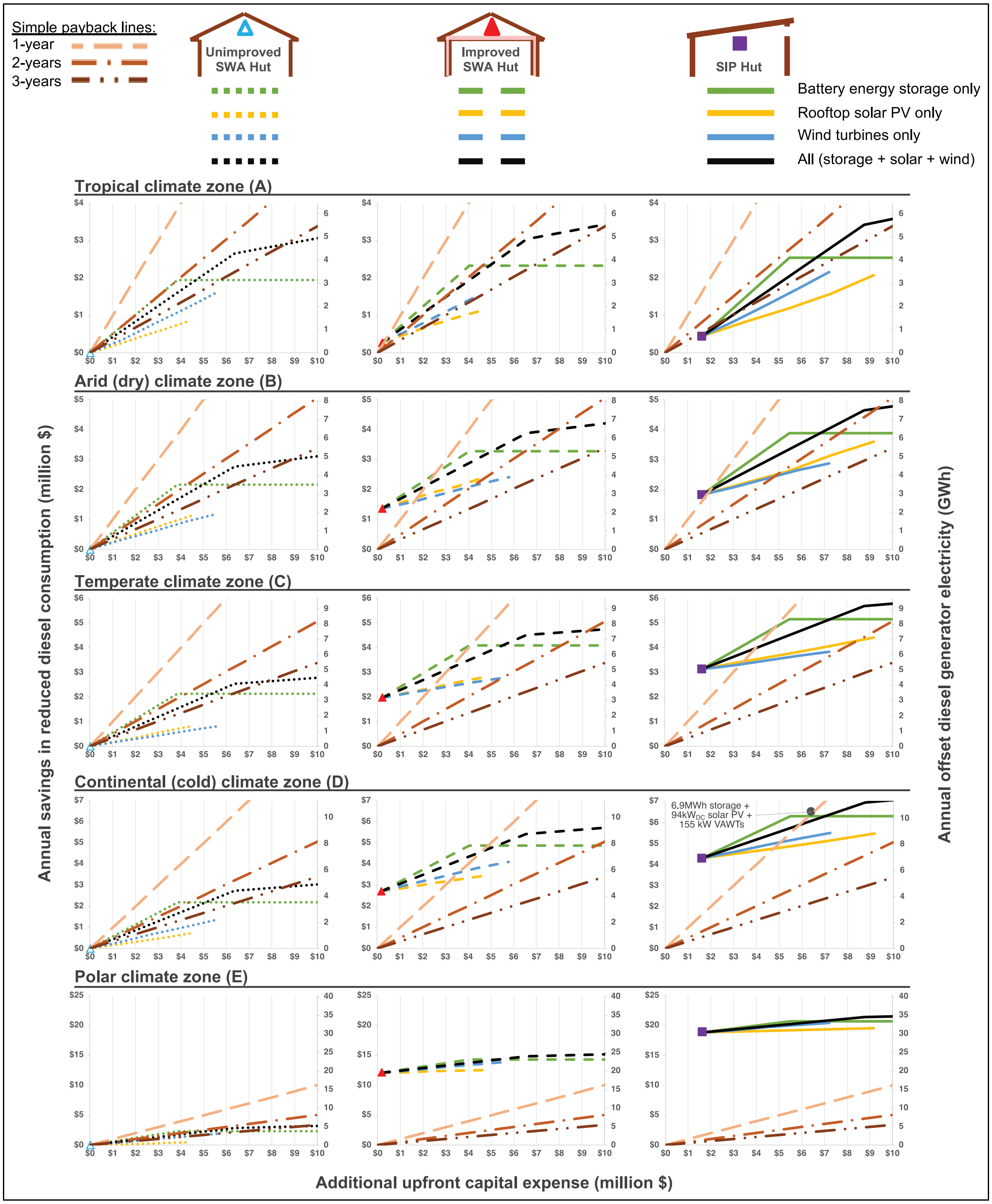

Figure 1. Potential for increased energy resilience as measured by reduced reliance on diesel generators for electric power. Results are for a battalion-sized FOB with an expanded level of service arranged by climate zone and construction type. The baseline business-as-usual scenario uses only diesel generators for power production and unimproved SWA Hut construction. The cost of diesel uses a fully burdened cost of fuel of \$8.32 gal^{-1}. Simple payback lines use a CPI of 2.4% at 2 years and 2.6% at 3 years with no change in the cost of diesel due to typical ± price fluctuations. Solutions above (to the left) of simple payback lines represent positive ROI within the defined time period. *y*-axis values change between climate zones.

The left vertical axis reflects annual savings in diesel fuel consumed in millions of dollars. The right vertical axis converts this value to the annual offset of energy demand from diesel generators. The horizontal axis reflects estimates for additional upfront capital cost. In general terms, increasing along the x-axis translates to more money invested upfront, while increasing along the y-axis translates to more money saved. The lines radiating from each baseline condition describe the potential benefits of incorporating battery energy storage alone (green), rooftop solar PV alone (amber), wind turbines alone (blue), or all three in combination (black). The length of the amber and blue lines indicate design-specified limits on nameplate installations, namely, available rooftop area for PV and 10% of estimated FOB land area requirements for wind farms. The green lines have a point at which their slope flattens, representing the point at which additional battery nameplate installations continue to cost more upfront but do not provide additional benefit in reducing diesel consumption (batteries can only store energy, not generate it). In addition, yearly simple payback lines indicate that solutions above (to the left) of each line represent options with a positive return on investment (ROI) within that timeline. Only 1-, 2-, and 3-year simple payback lines are shown, although planners may or may not know an anticipated lifetime for a contingency base.

Full explanations of all assumptions are in the Supplementary Information; however, there are three major considerations that deserve note here. First, although the US Army estimated the fully burdened cost of fuel in Iraq as between \$9 and \$45 depending upon delivery distance and type of protection (ground or air) used,[51,52] this study uses a fully burdened cost of fuel of just \$8.32 gal^{-1}, which reflects only some of those costs converted to FY17 dollars.[44] This model does not include component costs for materiel and personnel; it is assumed the Soldiers are already deployed, their salaries are already paid, and the military vehicles are already purchased and transported to the theater of operations. Although there is an opportunity cost in that the Soldiers and materiel could be used to accomplish other tasks if they were not conducting resupply convoy missions, that is beyond the scope of this study. Second, construction labor costs are not considered. SIP Huts are faster to build than SWA Huts,[24] but additional labor is required for unpacking and installing batteries, solar PV, and wind turbines. Third, the additional upfront transportation costs of additional building materials, batteries, PV panels, wind turbine components, and all ancillary equipment are not covered here. All of these factors are highly dependent upon the actual location of an FOB and are best left for further analysis, if desired. The focus here is on the energy resilience of an FOB once it is established. The model uses cost valuation only as a proxy for resilience due to its usefulness in the optimization process and its proportionality to the amount of fuel that must be purchased, transported, delivered, and stored at an FOB in a reliable manner.

Figure 1 shows that the energy efficiency of buildings is critically important for bases outside of the tropics, although even the tropics can expect a positive ROI depending upon how long the FOB is in use (see simple payback lines). In addition, incorporating battery energy storage is the next best investment if done alone. In each scenario, there is a point at which additional energy storage is no longer useful in reducing diesel consumption because, without renewables, diesel generators must still produce power for the FOB. The batteries provide a benefit by allowing generators to work at their optimal capacity rather than be forced to follow a load or even dump load. However, once sufficient batteries are installed to reach the potential of this benefit, additional batteries simply result in more upfront cost with no return. Batteries can store and release energy, but they cannot generate energy. In addition, batteries have a round-trip (charging, discharging, and inverter) efficiency which introduces energy loss.

The results shown allow for a maximum load of 100% rated capacity for each generator, although the model facilitates imposing a limit (e.g., 80%) in order to leave a spinning reserve for peak loads as done by many microgrid management systems.[13,16] Rather than underloading a generator, microgrid management software can divert excess energy generation to battery storage for use later on when generators are turned off, and batteries can serve the role of providing peak power within their discharge limits. One can also see in Figure 1 that the benefits of PV and wind turbine installations are location-specific with wind performing better in some locations and solar in others. Which resource performs best depends upon the FOB's specific location (not necessarily the climate zone) and is determined using data from each location's TMY3 data file. For the SIP Hut FOB in a continental climate, an independent solution reflects nameplate installations of 6.9 MWh storage, 94 kW_{DC} solar, and 155 kW wind. Combinations of batteries, solar, and wind need not adhere to the proportional increases shown by the black line stretching from zero to the assumed maximum. This independent solution achieves an ROI within 1 year and offsets 60% of annual diesel consumption. Planners can use this model to test different scenarios and find a solution to fit any given situation.

From any of the simulated scenarios, one can produce graphs like those shown in Figure 2 to investigate the FOB's energy portfolio balance over a desired time period. Figure 2 shows a support area-sized FOB with an

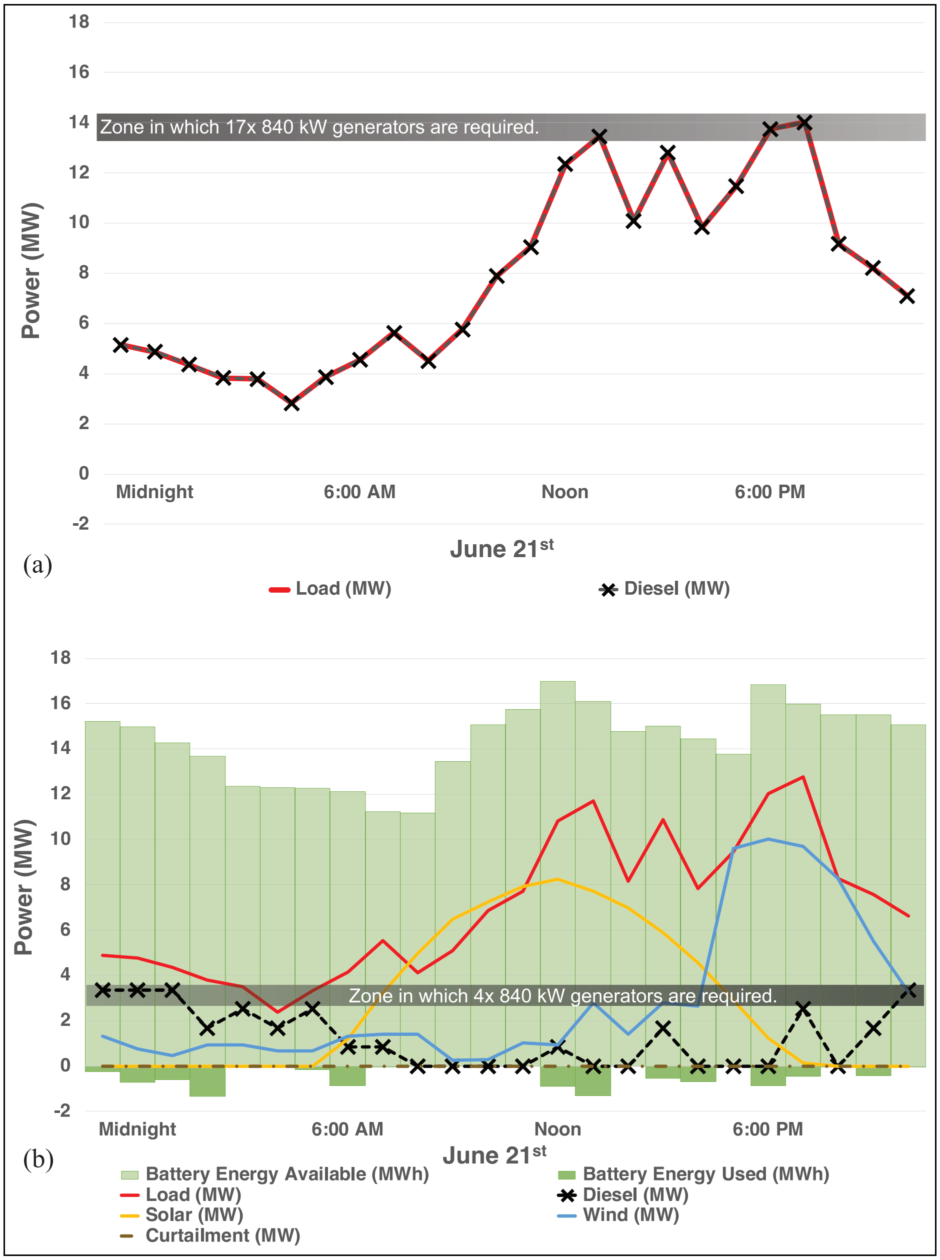

Figure 2. Potential for increased energy resilience as measured by reduced reliance on diesel generators for electric power. Results are for a support area-sized FOB (6000 + people) with an enhanced level of service in an arid (dry) climate on 21 June. (a) Uses unimproved SWA Huts and only diesel generators for power, resulting in load following with a requirement of 17 × 840 kW generators for several hours of the day. (b) Uses energy efficient SIP Huts, which decreases energy demand due to lower HVAC loads. Adding 41 MWh battery energy storage, 11.3 $\mathrm{MW}_{\mathrm{DC}}$ solar PV, and 9.3 MW wind turbines results in a significant reduction of diesel generators required with zero generators required for ten of 24 h.

enhanced level of service in an arid (dry) climate on 21 June, on or about the summer solstice. The time, in hours of the year, is on the horizontal axis and power, in megawatts, is on the vertical axis. Lines denote the power whereas shaded areas represent the product of power and time, that is, energy in megawatt-hours. Figure 2(a) shows the business-as-usual scenario, which would require up to 17 × 840 kW generators running for at least 3 h of the day to follow and meet loads. Figure 2(b) shows that this same FOB can reduce to a maximum of just 4 × 840 kW generators running for 4 h of the day with zero generators needed for ten of 24 h. The reduction in needed generators

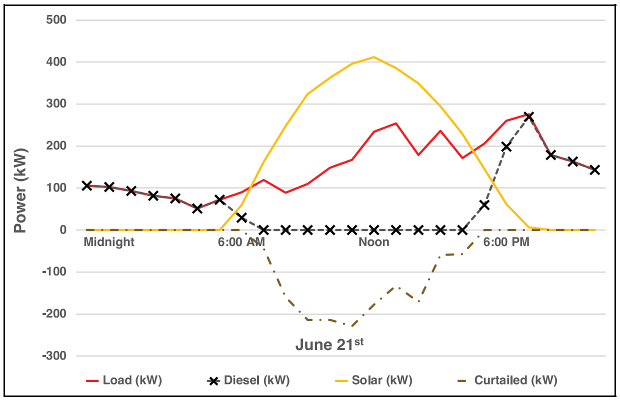

Figure 3. The "duck curve." Results are for a company-sized FOB with a basic level service in an arid (dry) climate on 21 June. The incorporation of solar PV without energy storage creates a scenario where the FOB cannot use excess production and must curtail it.

is due to three factors: first, a decreased load from more energy efficient SIP Huts, which decreased HVAC requirements; second, the application of both solar and wind power to meet load requirements; and third, battery energy storage facilitating the management of generators switching on or off. Furthermore, it is interesting to note an occurrence of wind power production exceeding the total wind farm nameplate rating. This occurrence is the result of wind speeds within that favorable range of the wind turbine power curve (see Figure 12 in the Supplementary Information) where output power exceeds the nameplate rating, which can actually be 35% higher for some wind turbines.[35]

Figure 3 illustrates a potential pitfall when incorporating renewables without energy storage. In this case, a company-sized (300-person) FOB with a basic level of service is in an arid climate on 21 June with 570 kW_{DC} PV and no battery energy storage. The result is similar to the "duck curve" first shown by the California Independent System Operator in 2013,[53] so-called because the line showing net load on the generators looks like the silhouette of a duck with its tail on the left, its back in the middle, and its neck, head, and bill on the right. In situations where renewable power production exceeds load requirements and there is no energy storage available, the result is curtailed energy—a reduction in energy output from what could have been produced. Also problematic is the combination of a setting sun during the hours of typically increased loads, which requires a rapid ramp rate for diesel generator-supplied power in the late afternoon/evening.

Figure 4 shows the impact of scale and energy efficiency of buildings for platoon, company-, battalion-, brigade-, and support area-sized FOBs with an expanded level of service in a continental (cold) climate with zero renewables or energy storage. The size of each marker reflects the comparative size in FOB population. Shown are three scenarios: going from unimproved SWA Huts to improved SWA Huts, going from unimproved SWA Huts to SIP Huts, and going from improved SWA Huts to SIP

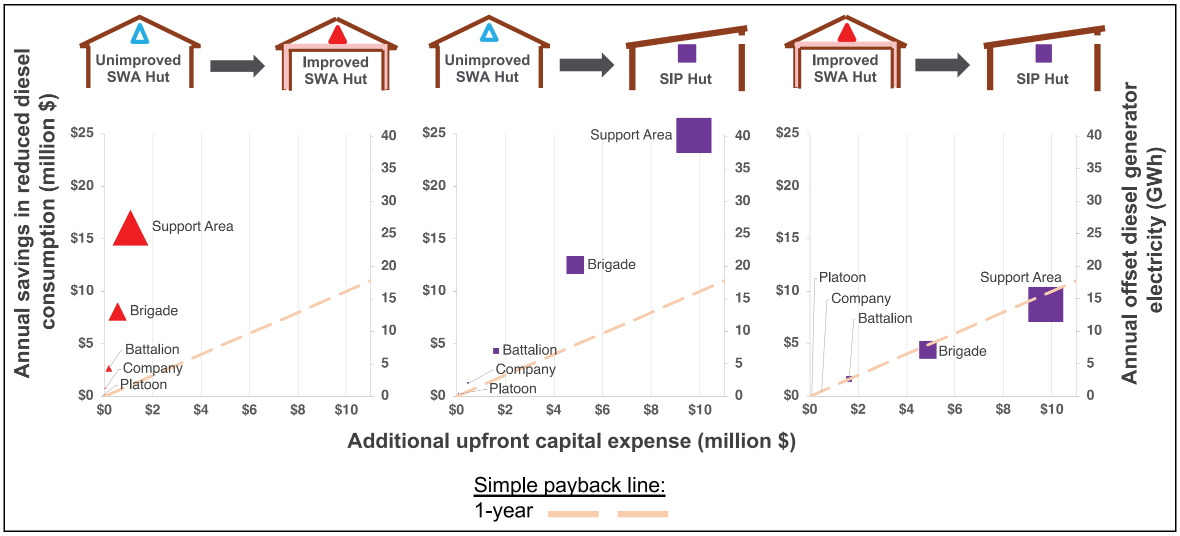

Figure 4. The impact of scale and energy efficient construction on savings. Results are for platoon-, company-, battalion-, brigade-, and support area-sized FOBs with an expanded level service in a continental (cold) climate, each with reference to an FOB of the same size using the baseline construction type shown. Solutions above (to the left) of the simple payback line represent positive ROI within 1 year. Although this study uses different buildings, the concept illustrated by the difference between the middle and right graphs agrees with PNNL's findings in Engels et al.[10] that savings will be less when a higher baseline scenario is assumed.

Huts. For an FOB located in a continental (cold) climate, the extra energy efficiency of SIP Huts results in annual savings over both the unimproved and improved SWA Hut construction options. These graphs illustrate two important concepts. First, savings from energy efficient buildings scale with base size. Second, the relative degree of savings decreases when the energy efficiency of baseline construction improves, which correlates with Pacific Northwest National Laboratory's (PNNL) study where they assumed the largest bases start off with an improved baseline condition and, consequently, their modeled savings for the largest bases were lower than all the others. In order to maintain a constant point of comparison, this study maintains a baseline of unimproved SWA Huts using only diesel generators for all scenarios.

Table 1 illustrates the capabilities of this model to predict offset energy demand and reduced costs, air pollution, carbon emissions, and casualty prevention for a specified scenario and climate. Shown are results for a battalion-sized FOB with an expanded level of service, SIP Hut construction, and nameplate installations of 6.86 MWh storage, 1.89 MW_{DC} solar PV, and 1.55 MW VAWTs. Such installations require significant additional upfront transportation. Of the styles modeled in this paper, it would take about 508 batteries, 6100 solar panels, and 774 wind turbines, all with associated equipment (foundations, poles, mounting hardware, inverters, wiring, etc.) to satisfy these specifications. The extra building materials for SIP Huts alone would require 121 additional 20 ft shipping containers. Nevertheless, reduced diesel consumption means fewer vehicles and convoy missions later. Using values from Eady et al.[54] for the volume of fuel per truck and considering an FOB in an arid climate, 131 fewer fuel trucks would be required over the course of a year, and this does not include the numerous additional force protection assets required to support those trucks on multiple convoys. Also, this value is largely dependent upon the fuel trucks used and their volumetric capacity. If the trucks used were a standard military fuel servicing tanker carrying 2500 gallons of fuel, the result would increase to 322 fewer fuel trucks. In any case, additional transport upfront reduces reliance on resupply later.

4. Discussion

With regard to previous work, these findings largely confirm those in the PNNL[10] and Naval Postgraduate School (NPS)[13,14] studies, except for the conclusion in the NPS study[13] that energy storage systems have little impact. The findings here suggest that, depending upon the climate zone, incorporating energy storage is the second best improvement after implementing energy efficiency measures.

With regard to energy security and energy resilience, the findings suggest some qualitative benefits. This study assumes that the current solution, using diesel generators, will remain the primary means for electric power production with little to no change in total generator nameplate rating or on-FOB fuel storage. Once FOB commanders gain confidence in the reliability of sustainable energy and as storage costs decline, the military can expand this solution, potentially up to 100% clean, renewable energy. In the meantime, if FOBs consume fuel at a slower rate by incorporating energy efficiency and renewables, then multiple benefits will result, including the following:

1. Energy security will improve due to the additional power generation assets on hand and the ability to maintain fuel storage tanks at or near their full capacity; that is, generators can be shifted from a primary (or only) means of electricity production to backup or peaking roles.
2. The time between mandatory fuel resupply missions will lengthen, which reduces:
   (a) The risk of enemy attacks on logistics convoys or transportation infrastructure (bridges, roads) to disrupt resupply.
   (b) The amount of fuel consumed to deliver (and protect the delivery of) fuel, which contributes to the fully burdened cost of fuel.
   (c) The risk of injury or loss of life for those conducting dangerous resupply missions.
   (d) Operations and maintenance costs for logistics, to include freeing up personnel for other missions, and reducing wear and tear on logistics vehicles, vehicle maintenance, and so on.

Furthermore, incorporating additional energy storage and renewables results in power generation and energy storage distributed across the FOB yet managed through a microgrid. Together, the proposed system decreases the likelihood of outages due to generators being down for maintenance, fuel shortages, or enemy attacks destroying critical power nodes using spot generation configurations.

This model is at the macro level with a focus on the microgrid's total load. The model assumes all loads and phases are properly balanced, and it neglects transmission losses since generators are located near their loads. As shown in Figure 2(b), the model does not penalize generators for having to start-up or shut-down, which would require additional time and fuel and would increase fuel consumption in both the baseline and diversified energy portfolio scenarios. The model uses a constant value for fuel consumption (gal hr^{-1}) as reported by generator manufacturers, which reflects approximate consumption at optimal or rated load. Since the baseline scenario has generators following the load, this assumption overestimates

Table 1. Benefits of implementing energy efficient buildings, energy storage, and renewables at FOBs in terms of offset energy, diesel savings, reduced air pollution and carbon emissions, and avoided casualties. Results are for a battalion-sized FOB (1000 people) with an expanded level of service (a median estimated load requirement) using 840 kW diesel generators. Improvements include energy efficient SIP Hut construction (+ \$1.62 million), and nameplate installations of 6.86 MWh battery storage (+ \$3.86 million), 1.89 MW_{DC} solar PV (+ \$7.55 million), and 1.55 MW wind turbines (+ \$5.60 million), for a total of \$18.6 million in additional upfront capital expense. All table values are in terms of annual offset FOB-only diesel requirements for a single FOB with 1000 people. For reference, in 2QFY08, there were over 441,000 military and civilian contractors deployed in support of contingency operations. In practice, savings will be even greater due to reduced vehicle fuel consumption for logistical transport requirements, which will vary significantly dependent upon the fuel's point of purchase and the FOB's location.

Savings per 1000-person FOB, that is reductions in ...		Units	Köppen climate zone				
			Tropical	Arid	Temperate	Continental	Polar[a]
Energy	Energy demand	GWh $year^{-1}$	9.29	10.8	11.7	14.1	37.2
Diesel and cost	Diesel required	% $year^{-1}$	83	80	75	80	88
		gal $year^{-1}$	691,000	804,000	873,000	1,050,000	2,770,000
	Diesel cost, low[b]	FY20 USD $year^{-1}$	\$1.84 million	\$2.14 million	\$2.32 million	\$2.79 million	\$7.37 million
	Diesel cost, this paper[c]	FY20 USD $year^{-1}$	\$5.75 million	\$6.70 million	\$7.26 million	\$8.74 million	\$23.0 million
	Diesel cost, high[d]	FY20 USD $year^{-1}$	\$22.5 million	\$26.2 million	\$28.4 million	\$34.2 million	\$90.1 million
Air pollution[e]	Non-methane hydrocarbons, NMHC	ton $year^{-1}$	1.76	2.05	2.23	2.68	7.07
	Nitrogen oxides, NO_X	ton $year^{-1}$	6.22	7.24	7.86	9.46	24.9
	Particulate matter, PM[f]	ton $year^{-1}$	0.28	0.32	0.35	0.42	1.12
	Carbon monoxide, CO	ton $year^{-1}$	32.5	37.8	41.1	49.4	130
Carbon emissions[g]	Carbon dioxide, CO_2	ton $year^{-1}$	7050	8210	8910	10,720	28,300
	Methane, CH_4	ton $year^{-1}$	0.28	0.33	0.36	0.43	1.14
	Nitrous oxide, N_2O	ton $year^{-1}$	0.06	0.06	0.07	0.08	0.22
	Combined carbon dioxide equivalent, CO_{2e}[h]	ton $year^{-1}$	7080	8240	8940	10,760	28,400
Casualties	WIA or KIA[i]	# people $year^{-1}$	0.20	0.23	0.25	0.30	0.80

FOB: forward operating base.

[a] Uses unimproved SWA Huts as the baseline, like all other climate zones, in order to provide consistency of the compared scenario; however, it is unlikely uninsulated buildings would ever be used in such a climate.

[b] Uses of the Defense Logistics Agency's (DLA's)[42] FY20 United States Dollar (USD) standard purchase price for diesel # 2 (fuel only).

[c] Uses the FY20 USD for DLA purchase price of diesel #2, plus transport, sustainment, and force protection (ground) costs.[42,44]

[d] Uses the fully burdened cost of fuel from a FY07 Iraq base case adjusted to FY20 USD and includes costs used in this paper (see [c]) along with personnel and force protection (air) costs.[44,55]

[e] Assumes generators meet minimum US Environmental Protection Agency (EPA)[56] Tier IV standards.

[f] Assumes all particulate matter (PM) ≤ 10 μm (PM10) and 97% of PM is smaller than 2.5 μm (PM2.5) in accordance with US EPA[57] non-road compression-ignition engine modeling.

[g] Uses US EPA[58] values for direct emissions from stationary combustion sources, diesel #2.

[h] Uses 100-year global warming potential values from the Intergovernmental Panel on Climate Change (IPCC).[59]

[i] Uses an Army Environmental Policy Institute (AEPI)[54] report and FY07 values for Wounded In Action (WIA) and Killed In Action (KIA) fuel-related convoy statistics in Iraq and Afghanistan.

fuel usage. However, because the model does not require generators to leave a spinning reserve, the model simultaneously underestimates fuel usage in the baseline scenario. In the diversified energy portfolio scenario, batteries can reduce or even potentially eliminate the need for a spinning reserve. Further refinement of the model may include functions for decreasing generator fuel consumption at lower loading and incorporating generator controls, specifically to reduce the frequency of start-up and shut-down and force more storage from excess generation.

The model addresses several gaps in military planning factors. First, peak power is currently estimated based on peak power per person planning factors, which vary according to expected level of service (basic, expanded, or enhanced).[20] However, as shown in Figure 1, building energy efficiency and climate also have large impacts on energy requirements. To get a better estimate of actual load requirements, the model takes planning factors and separates the total load into two parts: lighting + plug loads and HVAC loads (see section 2 and Supplementary Information). Second, there are no planning factors for incorporating renewables on FOBs. This model allows for planners to download open-source solar and wind data from online databases[18,60–62] and better design FOB energy portfolios for any desired location.

The optimization model has "perfect foresight" because it solves using a known load demand profile and known environmental conditions (insolation, wind speed, temperature, etc.) with data for every hour of the year. The model reduces computational time required by breaking the optimization of 8760 h a year into 12 discrete optimization problems, one for each month, of about 730 time steps each. One drawback to this method is that the optimization strives to use stored battery energy by the end of each month. However, this also serves to limit perfect foresight to 1-month at a time. To maximize resilience, it is conceivable that the best course of action might be to keep batteries near their full state of charge with variation only to avoid curtailment of renewables or to turn off underloaded generators. Nevertheless, in order to share the model and facilitate planners running it on their assigned workstations, managing computational time is imperative.

5. Conclusion

The results suggest three rules-of-thumb for planners when incorporating energy storage and renewables for resilience on expeditionary bases:

1. Efficiency is number one. Additional upfront capital expense for improved building construction can significantly reduce fuel demand with rapid payback. Planners should consider the local climate and expected FOB lifetime when determining a strategy.
2. Invest in energy storage next. FOBs can either centralize or distribute batteries. Compatibility with microgrid controls, deployability, and operations/maintenance requirements may dictate the appropriate choice. Even if a FOB uses no renewables, energy storage allows for the reduction (or elimination) of a spinning reserve for peak loads; allows for generators to work at their optimal capacity; and reduces underloading, wet stacking, and other maintenance issues. Energy storage is also critical for incorporating renewables, next, to avoid curtailment.
3. Adding renewables will help eliminate nearly all reliance on diesel generators. Wind and solar are complementary in nature and their combined installations increase the annual number of hours of renewable power production.

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Supplementary material

Supplemental material for this article is available online.

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