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N. Judson
A.L. Pina
E.V. Dydek
S.B. Van Broekhoven
A.S. Castillo

4 October 2016

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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Massachusetts Institute of Technology
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N. Judson
A.L. Pina
E.V. Dydek
S.B. Van Broekhoven
Group 73

A.S. Castillo

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EXECUTIVE SUMMARY

Critical mission operations on domestic military installations for the Department of Defense (DoD) use backup sources of power to protect against the failure of the domestic electric utility grid. This report examines the life cycle costs and availability and reliability[1] of the current backup power solutions at military installations and compares them to alternatives for future deployments to reduce life cycle costs or to increase the availability of energy to critical mission operations.

The recently released Department of Defense Instruction (DoDI) 4170.11 [1] defines energy resilience as “the ability to prepare for and recover from energy disruptions that impact mission assurance on military installations.” In order to quantify resilience, the metric used in this report is the availability of power to on-site critical energy loads during times of grid outage. Defining which loads are critical on installations is an important part of assessing resilience options and requires close collaboration between the mission operators and installation support personnel. This assessment reviewed Service or Defense Agency warfighting missions, life, health, and safety capabilities, critical infrastructure and facilities, and other supporting installation infrastructure to better understand critical mission operations for consideration in a more comprehensive resilience framework.

In order to understand existing resilience solutions and procedures for the Air Force, Army, Marines, and Navy, site visits were conducted at four installation. These site visits were performed by the study team over the course of two to four days. Backup power sources at these installations generally comprise small building-scale diesel generators with the number of generators ranging from approximately 50 to over 350 generators at a single installation. Backup generators are purchased either by the base organization responsible for electricity infrastructure (Civil Engineering, the Department of Public Works, or Naval Facilities, collectively referred to as the DPW) or by mission operators or other tenants at the installation. They are generally maintained and tested by the installation utility staff, but could also be maintained and tested by mission operators and other tenants. Because there are a number of entities involved in the procurement, operation, maintenance, testing, and fueling of the generators, detailed inventory and cost data is difficult to obtain. The DPW is often understaffed, leading to uneven testing and maintenance of the equipment despite their best efforts. The reliability of these generators is typically below industry standards; the maintenance and failure rates of generators during startup and operation is not always recorded. The study used actual data where it was available, but also developed assumptions based on subject matter expertise and engineering estimates to develop a business case

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[1] Availability is defined as “the ability of an item – under combined aspects of its reliability, maintainability, and maintenance support – to perform its required function at a stated instant of time or over a stated period of time.” Reliability is defined as “the ability of a component or system to perform required functions under stated conditions for a stated period of time,” as per the Institute of Electrical and Electronics Engineers (IEEE) Standard 493 (commonly referred to as the IEEE Gold Book). For purposes of this study, the availability metric was measured in annual unserved energy in megawatt-hours (MWh), which measures the amount of energy not serviced to the critical load throughout the year. This annual unserved energy is an important energy resilience metric since it would align to a disruption or an associated downtime impacting mission performance. Reliability metrics and models were also used throughout the study to help determine the overall annual unserved energy to the critical load. As an example, the failure rates of generators versus other system designs were part of reliability modeling and were used as input variables to the Monte Carlo simulations that determined the overall amount of unserved energy (availability metric).

analysis framework to assess resilience options at each installation. The actual data provided from each installation was combined with engineering estimates from staff at the installations and with industry data sources such as the Institute of Electrical and Electronics Engineers (IEEE) Gold Book [2] to develop a baseline life cycle cost and availability metric for backup generators. This baseline was then used to conduct an analysis of alternatives to compare across over forty different energy resilience solutions.

An analysis and simulation tool was developed to enable the DoD to establish an energy resilience baseline for military installations. The tool allows the DoD to perform an analysis of alternatives and to consider tradeoffs between life cycle costs and the availability of varying energy resilience solutions. The tool examines over forty potential architectures for each site, including both centralized and distributed energy solutions. The tool has the capability to examine a large number of prospective technologies, including diesel and natural gas generation, solar photovoltaics (PV), energy storage, and fuel cells. The modeling and simulation tool also determines reliability metrics and performs system reliability modeling for these different generation sources. The reliability metrics and modeling is an input to a Monte Carlo simulation that allows the DoD to predict the amount of unserved energy (the availability or resilience metric) for the critical energy loads identified at each military installation. When combined with life cycle cost predictions, the modeling and simulation tool provides a comparison of the cost and availability (energy resilience metric) of the different potential energy resilience solutions at each military installation. This allows mission owners and installation personnel to determine how much they are willing to spend to achieve different levels of energy resilience.

For the four sites visited, the study found that energy resilience solutions exist to reduce life cycle costs and to increase resilience to critical mission operations. These solutions include larger distributed and centralized generation in combination with PV at the electrical distribution feeders that service critical energy loads. Resilience can also be added at specific critical facilities by using uninterruptible power supplies (UPS) for critical energy loads that cannot tolerate any unserved energy. The study found that often, critical energy loads were clustered at a limited number of electrical distribution feeders, providing an opportunity to increase resilience and lower costs by centralizing generation.

Consolidating generation into a smaller number of 1 megawatt (MW) or larger diesel, natural gas, or other cost-effective fuel source generators at the substation eliminates a large number of smaller generators at the building level. For the most critical facilities, a generator can still be colocated at the facility, but with the generator able to operate in parallel with the centralized source to maximize system efficiency. The benefits of this type of configuration include cost and logistic efficiency improvements such as reductions in the maintenance, testing, and fuel resupply needs of existing generators during normal and grid outage scenarios. The centralization of the generation could also provide a more robust and flexible option to service multiple missions and to increase redundancy to those missions. The resilience to each mission improves as each additional generator at the centralized generation source provides redundancy for all of the loads it services, while increasing redundancy at the building level requires doubling the total amount of generation at each building. Centralizing generation also allows for revenue-generating opportunities with the local utility or participation in demand response, where these opportunities are available.

Further, either building-level solar PV on the critical electric distribution feeders or a centralized PV array could be incorporated into an energy resilient design with the appropriate protection equipment and switchgear. In order for large amounts of PV to be used during off-grid operation, more advanced inverter functionality will be required, such as high- and low-voltage ride through capabilities and dynamic curtailment of PV output. The addition of PV that directly provides power to the electrical system during normal or outage scenarios also helps the installation levelize its cost of electricity. In regions where there are opportunities to pursue more affordable PV options, solar energy could help offset the installation's electric bill and provide a source of savings to reinvest into more resilient energy options.

The study found that while an on-base centralized energy solution can provide more resilience, military installations should first consider improving the reliability of their existing electrical distribution system. Currently, a primary cause of outages on some military installations is the lack of reliability of the existing base electrical distribution system. This is problematic for any existing or future energy resilience solution. Critical missions will continue to experience outages if the reliability associated with the base's electrical distribution system is not addressed. In some cases, a base receives a high level of reliability from the commercial electric system, only to see it degrade as the power makes its way onto the base and to the critical energy load in question. In order to address reliability at the base level, military installations must know when and where system failures or outages are occurring. This information is important to mitigate reliability issues and prior to investing in distributed or centralized energy resilience solutions. It should be noted that military installations are required to report system outage data per Title 10, Section 2925(a). The energy resilience solutions suggested through this study for each installation can be used as the starting point for a more detailed exploration to address the remediation of these base electric distribution system reliability issues.

There is a growing interest in the DoD to use large-scale batteries combined with solar PV as a potential energy resilience solution. The study analysis shows that at existing prices, large batteries (>1 megawatt hour [MWh]) sized for peak critical energy loads are not cost effective. The challenge with a renewable energy source plus energy storage system is that the energy storage system needs to be sized for the longest expected outage duration at the worst time of the year for solar production (and one that provides continuous power through nighttime operations). This could mean sizing batteries for multiple days, weeks, or months. This leads to a system design severely oversized for the critical energy load to ensure the remediation of outage risks. As battery prices continue to become competitive, however, the DoD could use the modeling and simulation tool to reassess energy storage as a cost-effective energy resilience option.

The policy elements that the DoD should consider resulting from this study include: (1) aligning mission and energy resilience requirements; (2) designing and installing energy resilience systems, infrastructure, equipment, and fuel; (3) operations, maintenance, and testing (OM&T) of installed energy resilience systems; and (4) how to appropriately justify business case decisions to execute energy resilience projects (whether paid for with appropriated or alternative financing). While the focus of this study was to develop the business case framework to support budget and alternative financing decisions, a resilience framework is difficult to implement without addressing all of these policy elements.

Guidance on the alignment of mission and energy requirements would help military installations to better clarify and identify their critical energy requirements and align critical energy loads to performance metrics such as energy availability and reliability. Regular communication between the mission owners on an installation and the DPW is critical to ensure that critical mission operations are prioritized for restoration during grid outages. Further, it allows for energy resilience solutions at the installation to be developed holistically to provide the most cost-effective and resilient overall design. This is particularly challenging at larger installations and at Joint Bases with multiple tenants and where varying processes and procedures are used to identify critical mission operations and critical mission requirements. The alignment of mission and energy resilience requirements could be encouraged at both the Office of the Secretary of Defense and the Service-level, where processes for energy resilience improvements could include both a mission and an energy champion.

The DoD should also consider guidance on planning measures to assist in the development of outage scenarios. This would better guide the development of critical energy requirements and their associated critical energy loads. The DoD could consider the establishment of performance metrics, such as availability and reliability metrics, to ensure mission assurance and to better quantify business case decisions. The establishment of performance metrics would reinforce the accurate collection of performance and outage data recommended by this study, which are already required through Title 10, 2925(a). The DoD presently collects and tracks this data through its Annual Energy Management Report, and has been asked through the Fiscal Year 2017 National Defense and Authorization Act (NDAA)[2], Senate Armed Services Committee (SASC) Report to provide an additional report "with established metrics to evaluate the costs, risks, and benefits associated with energy resilience and mission assurance against energy supply disruptions on military facilities and installations." The DoD can leverage cost, availability, and reliability analysis in this study, and those of other institutions such as the IEEE and the U.S. Army Corps of Engineers Power Reliability and Enhancement Program to help shape energy resilience planning factors and metrics.

To improve the design of energy resilience solutions (individual generators, centralized or distributed generation, etc.), the DoD could improve its guidance for sizing energy systems and conducting energy load analysis. For single generators, it is important to ensure that they are appropriately sized to the loads they service. It is not uncommon for single generators to be sized relative to the building transformer, which is often well oversized to the building peak load. Better design considerations for energy systems and infrastructure are needed to improve both the cost effectiveness and the reliability of system designs for more energy-resilient systems. DoD could also consider guidance on design considerations to appropriately island distributed energy systems and should refer to IEEE Standard 1547.4, *Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, to appropriately design energy-resilient systems for continuous operations when a disruption occurs.

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[2] At the time of this study, the FY2017 NDAA was not passed by Congress. The DoD should monitor the FY2017 NDAA to appropriately implement any of its Congressional requirements.

Each of the Services is in the process of integrating advanced metering infrastructure into their installations. Only limited meter data was available at the time of the site visits; however, this resource will be very valuable for future assessments. In order to appropriately size backup generation capabilities on an installation, independent of the chosen architecture, it is important that the energy needs (electrical and thermal) of critical facilities are available. In addition, in order to compare existing solutions against potential new designs, it is important that the installations begin to electronically track information about their generators' cost and performance (outage data, run time, failure rates, and maintenance logs). Further, ensuring that energy resilience is built into the design process would allow for more cost-effective and integrated designs to service critical energy loads on military installations and to prioritize investments to ensure the continuity of critical mission operations.

The DoD should consider improving OM&T criteria for energy-resilient systems. In the FY2017 NDAA SASC Report, the DoD is required to report "a comprehensive strategy, including a development and implementation plan that replaces or improves emergency power generation readiness, reduces system maintenance, and improves fuel flexibility to ensure the sustainability of all Department emergency power generation systems in operation." By improving guidance on OM&T, the DoD will align itself to this Congressional requirement. More importantly, the guidance will help improve mission assurance on its military installations. Specifically, this study found that not all installations were conducting routine or full load testing on existing backup generators; this testing helps ensure that backup generators operate as intended during an outage. The DoD should continue to raise awareness to ensure that routine and full load testing is accomplished at military installations for backup generators. These policy requirements already exist under DoDI 4170.11, *Installation Energy Management*. The DoD could also continue to encourage the appropriate processes to ensure OM&T is occurring and that those processes include a clear inventory of backup generators on the base, a schedule of when maintenance and testing occurred, and the costs associated with purchasing, maintaining, as well as testing backup generators and any energy resilience systems. This would not only ensure systems operate as intended, but would help support and justify investment decisions future for energy-resilient systems.

Further, the study found that supporting energy resilience infrastructure, such as UPS is not centrally managed by installation facility staff; they are often owned and operated by mission operators at the facility level. The study also found that the maintenance and testing for UPS and other facility-level energy resilience infrastructure could be improved. The DoD could consider developing a process to ensure that these systems are appropriately maintained and incorporated into integrated testing procedures.

Lastly, the focus of this study was to develop a business case framework to compare different energy resilience solutions. It analyzed tradeoffs between life cycle costs and the availability of a baseline (backup generators). Then, an analysis of alternatives was pursued to compare other energy resilience technologies. The study has created a quantifiable framework that the DoD can use to justify investment decisions across its military installations. Compared to the baseline of backup generators that are presently used to supply DoD energy resilience, the study found that there are more cost-effective energy resilience solutions that improve the availability of power to critical mission operations at the four military installations reviewed. The DoD should consider establishing guidance that applies the framework in the study across other military installations to evaluate other energy resilience opportunities. The DoD could also consider pursuing energy resilience projects at the four military installations investigated based on the opportunity to save money and to improve mission assurance.

For energy resilience projects that generate the appropriate savings, a variety of funding opportunities can be considered, such as Service and Defense Agency appropriations, alternative financing, and the DoD's Energy Conservation and Investment Program (ECIP). The business case framework in the study was aligned to existing guidance for life cycle cost analysis pursuits (ten-year life cycle cost), and the recommended energy resilience projects would fall within existing life cycle cost guidance and savings-to-investment ratio (SIR) criteria. This means that Services and Defense Agencies should have a strong justification to compete for and prioritize energy resilience projects within their current programming, planning, budgeting, and execution (PPBE) cycle based on cost effectiveness and their direct support to critical mission operations. Services and Defense Agencies should also be able to establish alternative financing arrangements to support energy resilience projects and compete energy resilience projects within ECIP. Further, in the FY2017 NDAA, Congress has authorized the DoD to pursue energy resilience under Title 10, Section 2811 and to include energy resilience as part of ECIP. The DoD should consider incorporating energy resilience guidance within ECIP, which reflects a prioritized and structured approach for projects that focus on critical energy loads and incorporates the business case framework within this study. The Services and Defense Agencies could also consider the pursuit of similar guidance for their PPBE and alternative financing processes.

Since there are opportunities to generate life cycle savings through the pursuit of energy resilience projects, the DoD could investigate how to incentivize military installations to pursue these projects. One possible area that can be investigated is to use the authority within Title 10, Section 2912, *Availability and use of energy cost savings*. This authority allows military installations to retain energy savings generated by projects and reinvest those savings back into energy projects or other mission needs of the military installation. Guidance on this authority can also be found in DoD's *Financial Management Regulation* (FMR) 7000.14-R, Volume 12, Chapter 12 [3]. At the time of the study, there was one Agency within the DoD that had issued a memorandum to establish an account to implement this authority.

The goal of the study was to develop and demonstrate an energy resilience framework at four DoD installations. This framework, predominantly focused on developing a business case, was established for broader application across the DoD. The methodology involves gathering data from an installation on critical energy load requirements, energy costs, and usage, quantifying the cost and performance of the existing energy resilience solution (generators) at the installation, and then conducting an analysis of alternatives to look at new system designs. Improvements in data collection at the installation level, as recommended in this report, will further increase the fidelity of future analysis and the accuracy of the recommendations. And most importantly, increased collaboration between the facility personnel and the mission operators at the installation will encourage holistic solutions that improve both the life cycle costs and the resilience of the installation's energy systems and supporting infrastructure.

ACKNOWLEDGMENTS

The study team received significant support at all four installations, despite the significant time pressures on the installation personnel. We were impressed by the knowledge, dedication, and capabilities of the engineering staff.

Many people have been instrumental in helping us gather information and ideas for this work. In particular we would like to thank the people at the participating installations and the many members of the public works departments, civil engineering, and Naval facilities departments for their help. Along with the installation support community, we would also like to thank the many members of the mission assurance community, and the mission operators who participated at each military installation. In addition, we would like to thank those who helped set the study on the right track at Service regional/Command offices and headquarters organizations for their continuous involvement and collaboration. Lastly, we would like to thank the participating utility providers and industry partners who helped support the study.

ACRONYMS

DCI	defense critical infrastructure
DoD	Department of Defense
DoDI	Department of Defense Instruction
DPW	Department of Public Works
DSCA	defense support to civil authority
ECIP	Energy Conservation and Investment Program
IEEE	Institute of Electrical and Electronics Engineers
kW	kilowatt
LCC	life cycle cost
MW	megawatt
MWh	megawatt hour
NDAA	National Defense and Authorization Act
PPA	power purchase agreement
PPBE	programming, planning, budgeting, and execution
PV	solar photovoltaic
SASC	Senate Armed Services Committee
SIR	savings-to-investment ratio
UPS	uninterruptible power supply

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1. ENERGY RESILIENCE: ENERGY AND MISSION ASSURANCE

The Department of Defense (DoD) increasingly supports critical time-sensitive national security, warfighting, and life, health, and safety capabilities from its domestic DoD installations. For a majority of these installations, the primary power source to these critical mission operations is the domestic electric grid. Therefore, it is imperative that the critical facilities on these installations are resilient to power outages on the bulk grid. The recently updated Department of Defense Instruction (DoDI) 4170.11 [1] states that "DoD Components shall plan and have the capability to ensure available, reliable, and quality power to continuously accomplish DoD missions from military installations and facilities." The purpose of this study is to examine the life cycle costs and the availability and reliability of different energy resilience options for critical mission operations on DoD domestic installations.

The DoDI defines energy resilience as "the ability to prepare for and recover from energy disruptions that impact mission assurance on military installations." Therefore, metrics to quantify energy resilience should align to mission assurance when considering energy investments on a military installation. To align to mission assurance, it is important to quantify the availability and reliability[3] of power for critical facilities and associated energy loads on the military installation. Availability and reliability [2] provide measures to ensure continuous critical mission operations and allow for the quantification, design, and comparison of different energy resilience solutions.

The study approach was to quantify and assess tradeoffs between life cycle costs and the availability of the existing energy resilience solution (typically, backup diesel generators at the building level) and to perform an analysis of alternatives to compare to other energy resilience solutions. The result is an analysis and quantification that helps establish a forum to allow installation personnel and mission operators to consider tradeoffs between cost and risk to mission assurance when pursuing energy resilience projects.

DoDI 4170.11 requires alignment of energy requirements to critical mission operations on military installations. The ability of DoD to define and characterize these critical mission operations is an essential step to establish a resilience framework and to quantify critical energy requirements and energy loads on military installations. DoDI 4170.11 defines critical energy requirements as, "those critical mission operations on military installations that require a continuous supply of energy in the event of an energy disruption or emergency."

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[3] Availability is defined as "the ability of an item – under combined aspects of its reliability, maintainability, and maintenance support – to perform its required function at a stated instant of time or over a stated period of time." Reliability is defined as "the ability of a component or system to perform required functions under stated conditions for a stated period of time," as per the Institute of Electrical and Electronics Engineers (IEEE) Standard 493 (commonly referred to as the IEEE Gold Book). For purposes of this study, the availability metric was measured in annual unserved energy in megawatt-hours (MWh), and measures the amount of energy not serviced to the critical load throughout the year. This annual unserved energy is an important energy resilience metric since it would align to a disruption or an associated downtime impacting mission performance. Reliability metrics and models were also used throughout the study to help determine the overall annual unserved energy to the critical load. As an example, the failure rates of generators versus other system designs were part of reliability modeling and were used as input variables to the Monte Carlo simulations that determined the overall amount of unserved energy (availability metric).

To implement an energy resilience framework, installation personnel and mission operators must define and prioritize their critical energy requirements to determine critical energy loads on a military installation. While the DoD has a well-established process for identifying defense-critical infrastructure (DCI), a resilience framework requires a more comprehensive understanding of Service or Defense Agency warfighting missions, life, health, and safety capabilities, and the supporting installation infrastructure that support critical mission operations on military installations.

Defining consistent critical mission operations has been difficult for DoD because a Service, Defense Agency, or a customer on a military installation (critical mission operators and tenants) not only have varying mission requirements, but also have mission requirements that change and adapt over time. Each Military Service has unique mission requirements that are critical to them. For example, the Army may designate its deployable soldiers, training of those soldiers, and supporting installation infrastructure as critical. The Navy may designate its installation infrastructure supporting carrier strike groups as critical. And, the Air Force may designate its installation infrastructure supporting air operations as critical.

Further, at the installation or facility level, functions that look similar could also have varying criticality designations. As an example, a data center that aligns to intelligence, surveillance, or reconnaissance may be considered critical, while a data center that aligns to administrative operations may not be critical. There also may be installation functions that seem critical, but are not when investigated fully. An example may be a critical air operations mission supported by an air traffic control tower and a runway. The installation functions (air traffic control tower and runway) may not be critical if they are no longer supporting the critical enterprise mission (air operations mission), as designated by the Service or the Defense Agency. This could occur if a critical mission operation is moved to another area of the military installation or there are plans to move the mission to an alternative location. This is important because a facility-level function must align to an enterprise critical mission operation in a disruption scenario in order for it to also be considered critical in a resilience framework.

Resilience acknowledges that changing conditions cause the deployment of critical emergency, recovery, and response missions. This can be seen most directly with defense support to civil authority (DSCA) missions. An emergency event such as Hurricane Sandy requires DSCA, and these become important recovery and response missions in an energy resilience framework. Often, these could be described as life, health, and safety missions, which are performed by organizations within and outside the military installation boundaries.

Lastly, supporting installation infrastructure necessary to support DCI, warfighting missions, or emergency, recovery, and response missions should also be considered when defining critical energy requirements. Emergency, recovery, and response missions and supporting installation infrastructure become even more important to identify for extended power outages. The duration of a power outage could also cause these missions to adapt and expand in real-time, hence the importance of “recovery” or “adaption” in a resilience framework.

To appropriately develop a resilience framework and to consider future energy resilience solutions, a more comprehensive understanding of critical energy requirements on military installations is required. The following information should be considered to determine critical energy requirements and for the appropriate development of a resilience framework:

- Defense Critical Infrastructure (DCI): Those assets identified by the Defense Critical Infrastructure Program. DCI is the composite of DoD and non-DoD assets essential to project, support, sustain military forces and operations worldwide. DCI is a combination of task critical assets and defense critical assets.

- Service and Defense Agency Warfighting Capabilities: These could impact force readiness and projection, and a variety of other Service or Defense Agency warfighting capabilities. They could also include missions such as the maintenance of DoD aircraft, ships, and ground vehicles, the manufacture of certain key components, and the training of forces.

- Emergency, Recovery and Response Missions: These include life, health, and safety missions, and other missions such as those that provide important capabilities to support DSCA. During Hurricane Sandy, Joint Base McGuire-Dix-Lakehurst in New Jersey played a critical role as a staging area for the disaster response. Facilities at DoD installations, particularly airfields, ports, and assets related to command and control infrastructure, also serve secondary missions and become important resources during national emergencies.

- Supporting Installation Infrastructure: These facilities or infrastructure become particularly important during extended outages. Included in this category are items such as wells, water treatment and pumping stations, wastewater treatment facilities, food storage and distribution, and any other emergency services (not captured in the previous item). For outages lasting longer then several days, it may become difficult to maintain a significant presence on the installation without these services and the criticality could depend on the location and situation. Isolated desert facilities could be particularly vulnerable to water supply issues, for example.

As described, the duration and the extent of a power outage may also influence the scope of critical energy requirements and the associated critical energy loads on military installations. Specifically, emergency, recovery, and response missions or supporting installation infrastructure become important considerations during extended power outages (such as life, health, and safety and water distribution systems). As the length of an outage increases, the scope of what is considered critical could also adapt to meet extended power outage needs. An energy resilience framework realizes that flexibility and adaptability are important elements to appropriately consider critical energy requirements and their associated energy resilience solutions. An energy resilience framework should be built with adaptation in mind to meet changing conditions and the mission needs of the DoD.

For the purpose of this study we have used the historical outage data for each installation as a baseline for our analysis (where available). While some planning guidance for outages exists today in the DoD, a more robust and clearer understanding may be needed. Currently, Unified Facilities Criteria 3-

540-01 states that facilities shall “provide seven days of fuel storage either in a dedicated on-site main fuel tank or from a confirmed delivery source” [4]. It is most common for installations to store 24–72 hours of backup fuel located for individual generators, but bulk fuel storage and delivery capabilities vary widely between installations. The DoD could consider planning measures and guidance that appropriately consider risks associated with historical and future outages, and that appropriately balance the investments needed to mitigate those risks.

Two steps can be considered to help establish a framework for developing critical energy requirements and to better understand the level of investment needed for energy resilience solutions. The first is to identify what is critical by considering the length and duration of the outage based on a reasonable risk and investment profile. This can be accomplished by establishing benchmarks so installation personnel and mission operators can evaluate outage and disruption scenarios. For example, for a high-probability/frequency outage events (typically reliability-related issues), a planning factor of 0–3 days can be used to identify what is critical on a military installation. For medium-probability/frequency outage events, a planning factor of 3–7 days can be used to determine what is critical. And, for low-probability/frequency outage events, 7+ days can be used to identify what is critical [5].

The DoD can also consider outage events that extend beyond historical norms, but those would need to be carefully balanced with the feasibility of the outage occurring and the level of investment needed to mitigate unknown risks (the unknown risks would also need to be well quantified to survive a business case analysis). It should be noted that extended duration outages would likely extend beyond the military installation’s boundaries. These extended duration scenarios would need to be communicated with the broader community outside of the military installation. An energy resilience framework should also be built with flexibility to help shape and accept multiple DoD needs and requirements as they evolve and mature over time.

Second, once the DoD can clearly define and prioritize what is critical, performance metrics such as availability and reliability can be considered to help prioritize investment decisions and to ensure mission assurance. DoD could establish the level of availability and reliability needed for critical mission operations to help achieve mission assurance. For example, for those critical energy requirements and energy loads identified, DoD could strive to achieve n% of availability and/or reliability, which would align to mission requirements.

It should be noted that this study focuses solely on infrastructure within the installation boundaries and did not examine how solutions at the installation could impact surrounding municipalities. For some bases, much of the critical infrastructure may be located on the installation, allowing for a clearer division with the external community. For bases in heavily populated regions, the interdependencies of critical infrastructure are much greater. It is common for bases with larger interdependencies to share water, wastewater, natural gas systems, and living quarters with the surrounding municipalities. The interdependence of many different systems requires discussions between all stakeholders to develop comprehensive plans that increase the resilience of the whole system to known and unexpected events [6].

The focus of this effort is on the resilience of critical mission operations on DoD military installations to outages on the bulk power grid. The term “critical” is broadened in the course of this effort to examine additional supporting infrastructure on the installation that will likely be required for outages longer than the typical 0–3 days currently used for planning purposes. For longer duration outages, the DoD will need to engage with the broader community beyond the installation’s boundaries. While it is outside the scope of this study, it is recommended that the DoD engage with external stakeholders, including utilities and municipalities, to better establish the appropriate planning factors if remediating risks from extended power outages becomes a requirement.

2. STUDY APPROACH

The DoD has an existing backup generation option for most critical missions on DoD installations: building-level backup diesel generators. There is a cost and availability associated with these generators that the study captured and then compared to other options. To do that, there are two parts to the business case analysis. The first is to determine current availability and costs for existing backup power for the critical energy loads identified in the study. The second part is to determine what can be done differently that either reduces costs or increases resilience. To address the first part, the Army, Navy, Marine Corps, and Air Force each nominated one installation to determine the existing critical loads, and existing backup generation systems, costs, and availability. To address the second part, the study took the information from the installations, along with information from other sources, and conducted an analysis of alternatives of other possible backup and primary power sources in different combinations of devices to meet the existing critical energy loads. The result was a comparison of life cycle cost and availability metrics that can used for tradeoff decisions across multiple energy resilience solutions. Specifically, the study results at each installation indicate that cheaper and more resilient power system options

The goal of the study was to follow a standard analysis methodology for each of the installations so that the approach is reproducible for other installations. Therefore, the resulting recommendations for an installation are based on a framework which uses a standard set of input information. As each location was visited, the study team improved the quality of the data through site observations and follow-up subject matter expert surveys and questions. These improvements in data quality helped shape modifications to the inputs in the modeling and analysis tool.

Over the course of the study, the study team had an introductory meeting with each of the Services to brief Secretariat-level members of the Services; teleconferences with each of the installations to coordinate pre-visit information exchanges; two- to four-day site visits to ascertain information on the ground; follow-up calls and correspondence to check information and ask for additional details; follow-up draft reports sent to each of the installations for comment; teleconferences with each of the installations to present the study's findings; and in-person briefings to Assistant Secretariat-level members of the Services. These detailed coordination efforts with all organizational stakeholders across the Military Services were accomplished in conjunction with the delivery of this report.

2.1 INFORMATION REQUESTED

A wide range of information was requested from each of the installations to determine costs and availability metrics of the baseline and future energy resilience solutions. The information was also used to better understand any infrastructure interdependencies. Information on the electrical system, the utility provider, data on energy and power use, how the installation manages energy, existing generation assets and uninterruptable power supply systems, alternative energy systems, interconnected infrastructure (steam, chilled water, water, natural gas, wastewater), mechanisms of communication about power needs, and development plans for the installation served as the basis for our analysis.

Often, actual data was not available to determine the availability, reliability, or cost metrics of the evaluated systems. When these data were not available, the study relied on generally accepted cost and engineering practices to help inform development of the energy resilience framework. These techniques included parametric estimating techniques, engineering estimates, surveying, or even subject matter expert opinion. Reliability data gaps were also filled by information provided by the U.S. Army Corps of Engineers (ACOE) Power Reliability and Enhancement Program and aligning with the Institute of Electrical and Electronics Engineers (IEEE) Gold Book [2]. The information provided and collected was used to ground the assumptions in the modeling portion of the study, as outlined in Section 2.3.

2.2 ANALYSIS TOOL

The analysis was conducted through MATLAB R2014b, which was used to perform Monte Carlo simulations on the data and/or assumptions generated for each installation. General concepts for the code framework were taken from simulation code developed for a previous program at MIT Lincoln Laboratory [7]. That study included a Monte Carlo simulation on reliability distributions from energy architectures made of combinations of continuously running or standby generator classes with variations in the models and capacities available, different battery size and operational modes, and an option for connection to the electricity grid. The model for this study also required renewable technologies, thermal loads, and simultaneous use of different generator sizes – all of which were added to the existing code framework. A block representation of the general analysis tool framework for this study is shown in Figure 1; each block represents a major component of the software code.

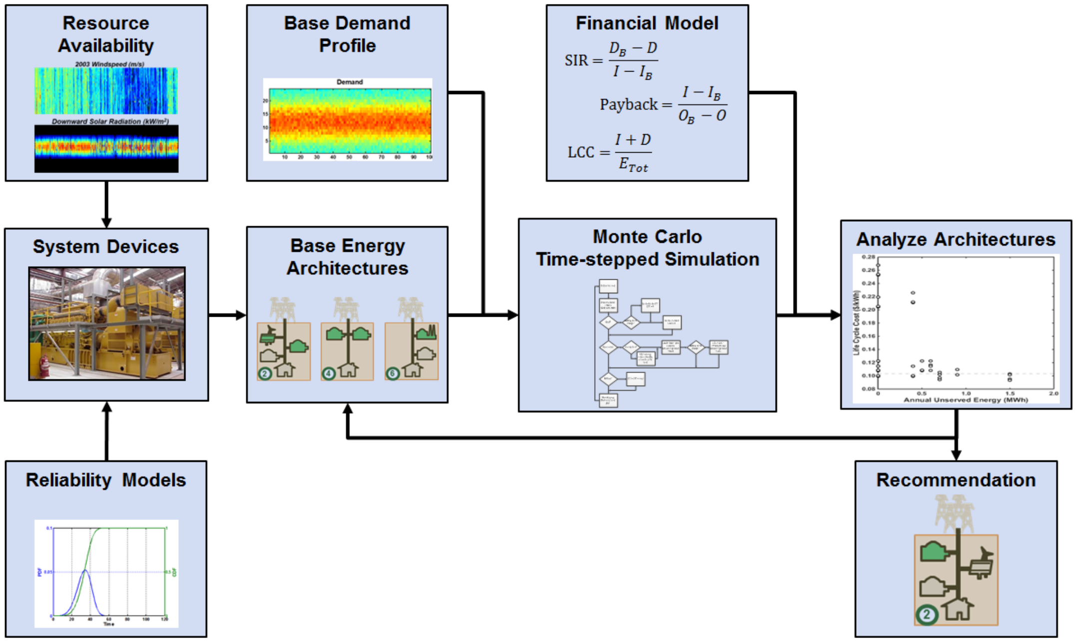


Figure 1. Block diagram of software analysis tool framework.

2.2.1 Technologies Considered

The system devices, or the technologies assessed, were considered foundational in the development of the software analysis tool framework. The resources required for operation and the reliability of the individual system devices are combined in a model for the system devices that is then used to create the different possible energy architecture solutions at each installation. In the study, technologies were chosen based on their technology readiness and commercial availability, along with input from installations about the feasibility of technologies on each site. Eleven technologies were ultimately selected. Some technologies that were not included in the analysis (due to site-level evaluations), but could be added in the future, include: wind turbines (the installations we visited were not interested due to mission compatibility issues); geothermal (sources require a highly detailed site analysis and large capital investments); and pumped hydro (there is limited availability of commercial systems).

TABLE 1

Technologies Considered in the Study

1	Building-scale diesel generators (175kW to 300kW) for backup generation
2	Building scale diesel generators (175kW to 300kW) for continuous operation (this option was not deployed in the modeling)
3	Centralized generators (2MW) for backup generation
4	Centralized generators (2MW) for continuous operation (this option was not deployed in the modeling)
5	Decentralized solar generation on rooftops (<1MW)
6	Large-scale solar PV generation through a PPA (islandable)
7	Small UPS systems
8	Large-scale battery systems sized for one-day energy storage
9	Microgrid controls and switchgear to allow operation in an islanded mode
10	Combined heat and power production
11	Fuel cells (solid oxide fuel cells powered by natural gas)

2.2.2 Diesel Generators

The most common technology employed by the Services for backup power is building-scale diesel generators that are sized based on engineering estimates for the facility's peak electrical load. As such, a majority of the tool's options centered on variations of generator sizes (ranging from 175 kilowatt [kW] building generators to 2 megawatt [MW] centralized generators) and operational modes (focusing on continuous operation or standby backup operation). The result is four different generator "technologies" where the capacity is modified for each installation and determined by the existing number and size of generators (in the case of building-scale generators) or by the substations and critical feeders (in the case of centralized generators). As there were many generators on each installation that ranged widely in size, to simplify the analysis, the average size of all critical generators was determined and then used as a proxy for the many different generator sizes and combinations.

2.2.3 Solar Photovoltaic Systems

There are two varieties of solar photovoltaic (PV) systems that are commonly used on military installations: 1) small-capacity systems – less than 1 MW – that are purchased or leased and installed on facility rooftops or 2) large-capacity systems – greater than 1 MW – that are leased and installed in open areas on the installation. Typically, these systems are dependent on a live electrical grid to produce electricity and are often referred to as "grid-tied solar PV." The inverters used in these systems have been configured to check for grid electricity (or a voltage and frequency within 5% of nominal value [8]) before converting the DC voltage provided by the solar cells to AC voltage useable by the grid and AC circuits. An alternative system design that is becoming more common can produce electricity during an outage from the electrical grid and is referred to as "islandable solar PV." This type of solar requires that bidirectional inverters are integrated with small battery banks that produce an AC voltage that simulates connection to the grid and enables the inverter to then convert DC voltage to AC voltage. Our modeling tool incorporates both grid-tied and islandable solar PV types into the large-capacity system framework and incorporates a below market rate for electricity through a power purchase agreement (PPA). This agreement would need to include arrangements for grid-tied or islandable inverters to be installed along with outage operation requirements to ensure electricity is provided during the appropriate circumstances. The amount of capacity for the system varies by installation and was sized according to existing PV already installed as well as future plans for PV installations.

2.2.4 Uninterruptable Power Supply Systems

Less widely used are uninterruptable power supply (UPS) systems. These are typically located at the building level and are sized to maintain either the entire building electrical power or a subset of determined critical loads during a grid power outage for 15–45 minutes. These systems vary widely and our modeling only handles the power not covered by the generator during startup (instead of the potential to power the building for a much longer time). The UPS system in the modeling tool is designed to carry the critical building load for 30 minutes and the resulting UPS capacity and number of units varies by installation due to the size and number of critical loads, respectively.

2.2.5 Large-Scale Battery Systems

Large-scale battery systems sized to provide electricity for all critical loads on the installation are rarely employed, but the desire to use intermittent renewable resources to meet electrical demand – and thereby needing storage to serve the load throughout the day and night – has increased the possibility of their use. The battery system in the tool is sized to store the unused electricity generated from planned solar PV fields on the installation to meet a single day's worth of demand when the electrical grid experiences an outage and the PV is not producing electricity. It is possible to use these large battery systems – sometimes multi-megawatt hour (MWh) storage capacity – for frequency regulation and other demand response programs. Even though the tool did not incorporate specific financial programs for battery systems, it did include a specific installation generation and load-shedding demand response financial incentive when those programs were available.

2.2.6 Microgrids

While not widely implemented, there are some microgrid demonstrations on military installations. Since the implementation of microgrids on installations is not mature, there are still a number of different definitions for what constitutes a microgrid or even the necessary functionality required by them. A previous study by MIT Lincoln Laboratory used the following microgrid definition, "A DoD installation microgrid is an integrated energy system consisting of interconnected loads and energy resources which, as an integrated system, can island from the local utility grid and function as a stand-alone system" [9]. The microgrid technology in the tool conceptually enables the installation to electrify and operate a portion of its distribution network separately from the grid in an islanded mode. It also increases the connectivity between the critical infrastructures on the installation and changes how the generators operate – from meeting loads individually to sharing the load collectively. The microgrid implementation in our model does not include the ability for automatic load shedding or some of the more advanced power management solutions. The study had these limitations to lower the estimated capital cost for the microgrid. Before implementing a solution at an installation, a detailed design study is necessary to determine the critical loads, switchgear, protection, generation resources, and electrical interconnection to allow these loads to be served.

Batteries are costly, but there is the potential for them to be cost-effective. However, to take into account the cost and complexity of the controls associated with battery integration, the study ran two different analyses. In the first scenario, batteries can be used to provide power in islanded mode, much like existing UPS systems. In a second scenario, the batteries can also be used in islanded mode, but there is a significant cost to implementing the control logic for the microgrid that operates the batteries, the generators, and other equipment. There are no existing commercial military microgrids; existing systems are either demonstration research projects, or have been developed through multiple technology integration demonstrations over many years. These technology demonstration projects have been expensive (>$10M). The study priced the microgrid design and controls from $1.5M to $3M at the four sites. The result for the energy architectures that include an advanced microgrid design is that it will be more expensive than the existing baseline backup generator design. However, there are opportunities for less advanced or non-automated microgrid designs at lower costs. Microgrids will also offer benefits such as improved the availability, less unserved energy to the critical loads, and improved mission performance. Microgrids are an example of when a risk tradeoff between increased resilience versus life cycle costs becomes very important. While the study resulted in energy resilience solutions that incorporate a certain level of microgrid designs that improved both life cycle costs and resilience, future installation level determinations may not yield similar results. A risk-based tradeoff will become important in cases where the DoD may need to increase life cycle costs in order to improve resilience; the modeling tool captures those scenarios as well.

2.2.7 Combined Heat and Power Generation

An alternative to centralized generators are cogeneration systems that produce electricity along with heating or cooling for thermal loads on the installation. These systems are generally on the multi-megawatt scale and can be economically advantageous for an installation that has a relatively constant thermal load and a robust natural gas supply infrastructure. The tool used a cogeneration plant (a natural gas-fired combined-cycle gas turbine) that could produce 3 MW of electricity with twenty million British thermal units of usable thermal energy. Cogeneration was only an option for those installations with a constant thermal load and the number of plants was sized to fit the thermal load, with the electrical generation considered a secondary benefit of the plant.

2.2.8 Fuel Cells

Fuel cells are another alternative to centralized generators that are best suited to work continuously and serve the electrical "base load" of the installation. Typically fueled by natural gas or hydrogen, these systems need a robust infrastructure to maintain fuel supply and must be designed to operate in parallel with the grid to take advantage of utility incentive programs or to reduce the overall electrical demand in order to be competitive with other generation resources. The tool used a 1 MW fuel cell farm – solid oxide fuel cell technology – that was fueled by natural gas, and the total capacity was sized according to the minimum constant load at each installation. Although fuel cell penetration at the installations could be higher, the demand fluctuation on the fuel cell would result in high maintenance costs.

2.2.9 Reliability Models

Another fundamental component of the framework is the reliability model for each of the system devices. These dictate how the technologies will perform under given assumptions at an installation. Every technology was required to have a mean-time-to-failure and a mean-time-to-repair value that were derived from manufacturer's estimates or the IEEE Gold Book [2]. These values were then combined with a Weibull distribution to determine the hourly failure rate for the technology. Failures were assumed to be uncorrelated, so each system device was modeled independently for failures. Current industry standards are to use a Weibull distribution, as it provides an appropriate representation of device failure and repair rates [2]. Figure 2 is the probability distribution function and cumulative distribution function for the Weibull distribution that describes a sample grid outage of 7 hours. The mean outage time of the distribution is 7 hours with a long tail that does allow more "severe" outages to be simulated consistent with those experienced in the real world (based on probability and frequency of occurrence), as seen for installations that had outage data available. The parameters that affect the shape of the distribution can be modified within the analysis tool to better match installation data once it becomes available. Similarly, repair times also follow a Weibull distribution. Maintenance costs are included in the model, but the time for regular maintenance was not modeled, as the simulation time steps are hourly and as it was assumed that regular maintenance (not repairs) can be finished rapidly or postponed in the event of a grid outage and would not be concurrent with grid failures.

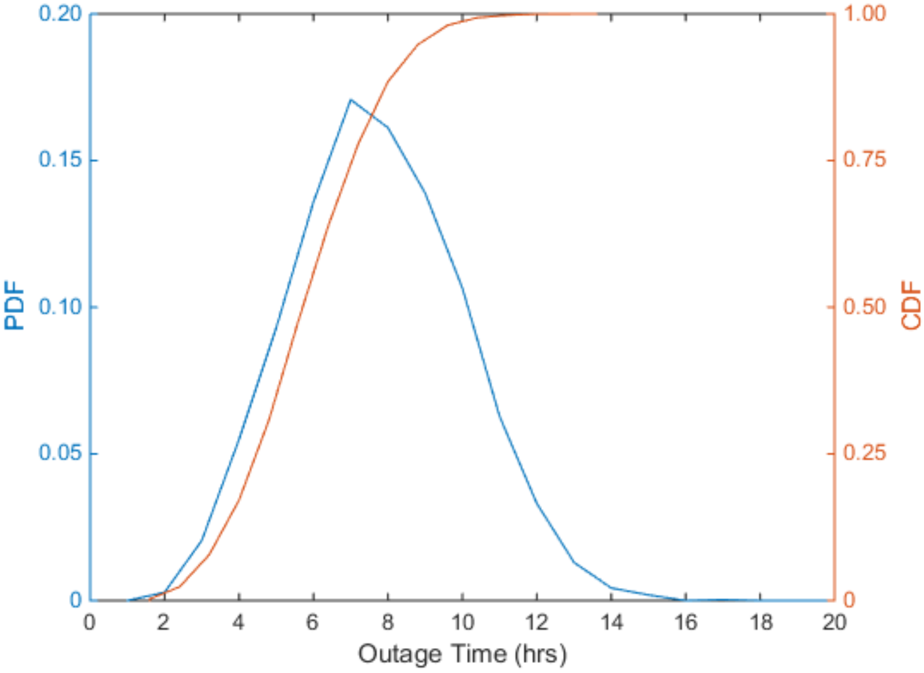


Figure 2. Weibull distribution of sample outage time for the grid.

In cases where there were multiple devices of the same technology, each device's hourly failure potential was determined independently to ensure a proper probabilistic distribution. Reliability for the technologies was defined as whether the system device failed during that hour of the simulation. From this definition, an hourly index of system performance was created. Figure 3 shows an example of hourly outages for one device modeled for a year (in this case, the electrical grid feeding one of the installations).

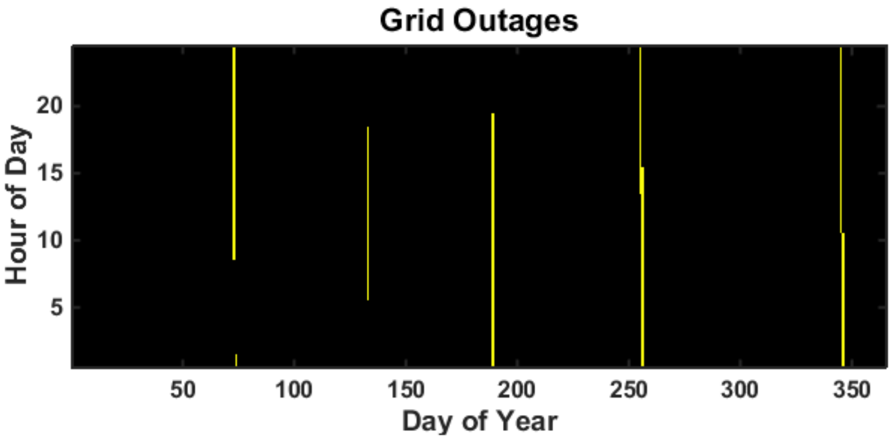


Figure 3. Example of the reliability of the grid with failures indicated in yellow.

2.2.10 Resource Availability

In addition to the reliability models integrated into the system devices, certain technologies also had resource availability constraints that determined performance during the simulation. For this analysis, the only technology that was limited by resource availability was grid-tied and islandable solar PV, although there are a number of other technologies – including wind, geothermal, etc. – that would have similar constraints in future studies. The solar resource generator requires latitude, annual percentage of sunlight reaching the ground, and annual number of days when clouds cover at most 30% of the sky during daylight hours. These values varied by installation and assumptions for military installations were derived from the nearest cities from the National Climatic Data Center Climate Data Online portal mean values. The tool incorporates these mean values with a random number generator to probabilistically create solar resource availability for every hour of the year and plots the availability results in an image similar to that shown in Figure 4.

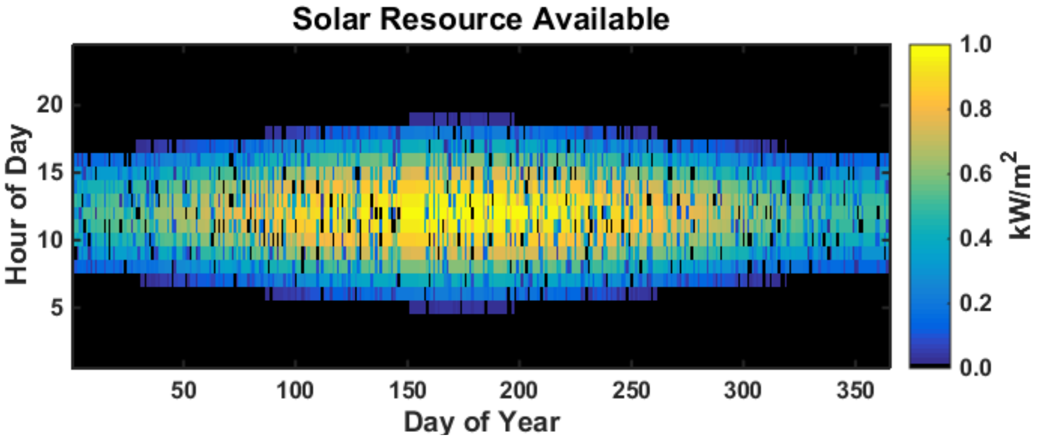
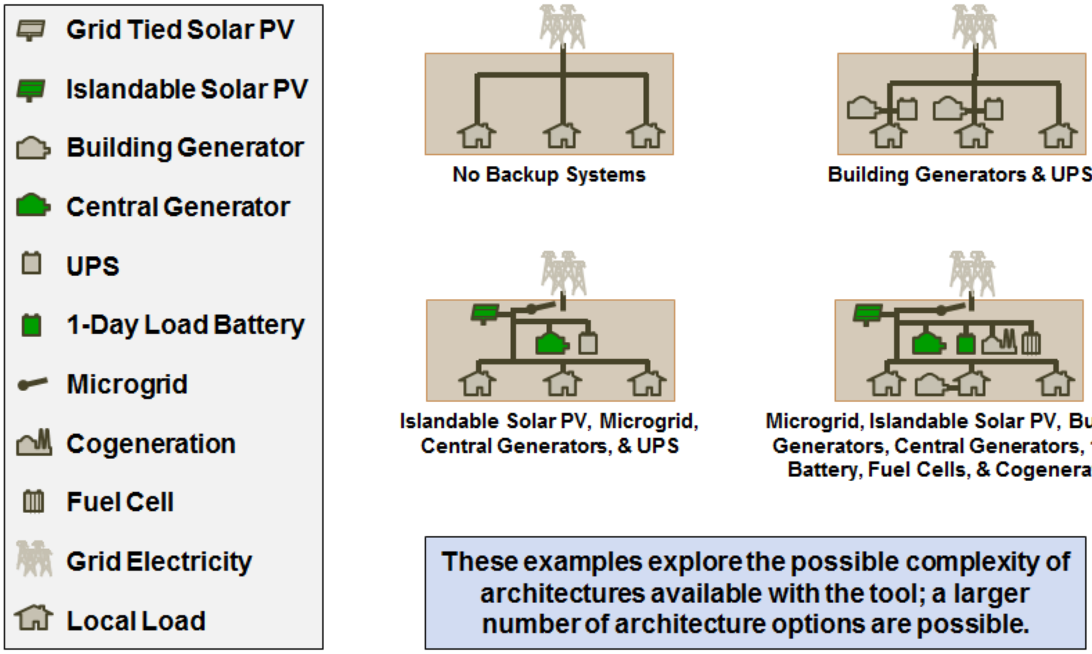


Figure 4. Example solar resource availability.

2.2.11 Energy Architectures

After the system devices have been updated with their reliability modeling and resource information, the next step in the framework is to develop energy architectures – intelligent combinations of the system devices – to serve as potential solutions to the installation availability and life cycle cost requirements. These architectures can range from a solution using none of the system devices and relying solely on the electrical grid to solutions using multiple devices in an attempt to be fully self-sufficient. Figure 5 displays the system devices included in the study along with a few examples of the potential energy resilience architectures that can be considered to meet the military installation requirements.



These examples explore the possible complexity of architectures available with the tool; a larger number of architecture options are possible.

Figure 5. Technologies used in the tool with possible architecture combinations.

For this study, forty-eight different energy resilience architectures were analyzed. These architectures were selected based on the ability of the system devices to work in a coherent manner, and to evaluate their availability and life cycle costs. There are three main decision categories influencing the development of integrated energy resilience architecture designs: (1) whether they are centralized versus building-level backup generation systems (generators), (2) the type of energy source required to generate electricity, and (3) the level of energy storage available. A flowchart decision tree of how the various technologies are integrated and how microgrids enable a greater range of technology control options is shown in Figure 6.

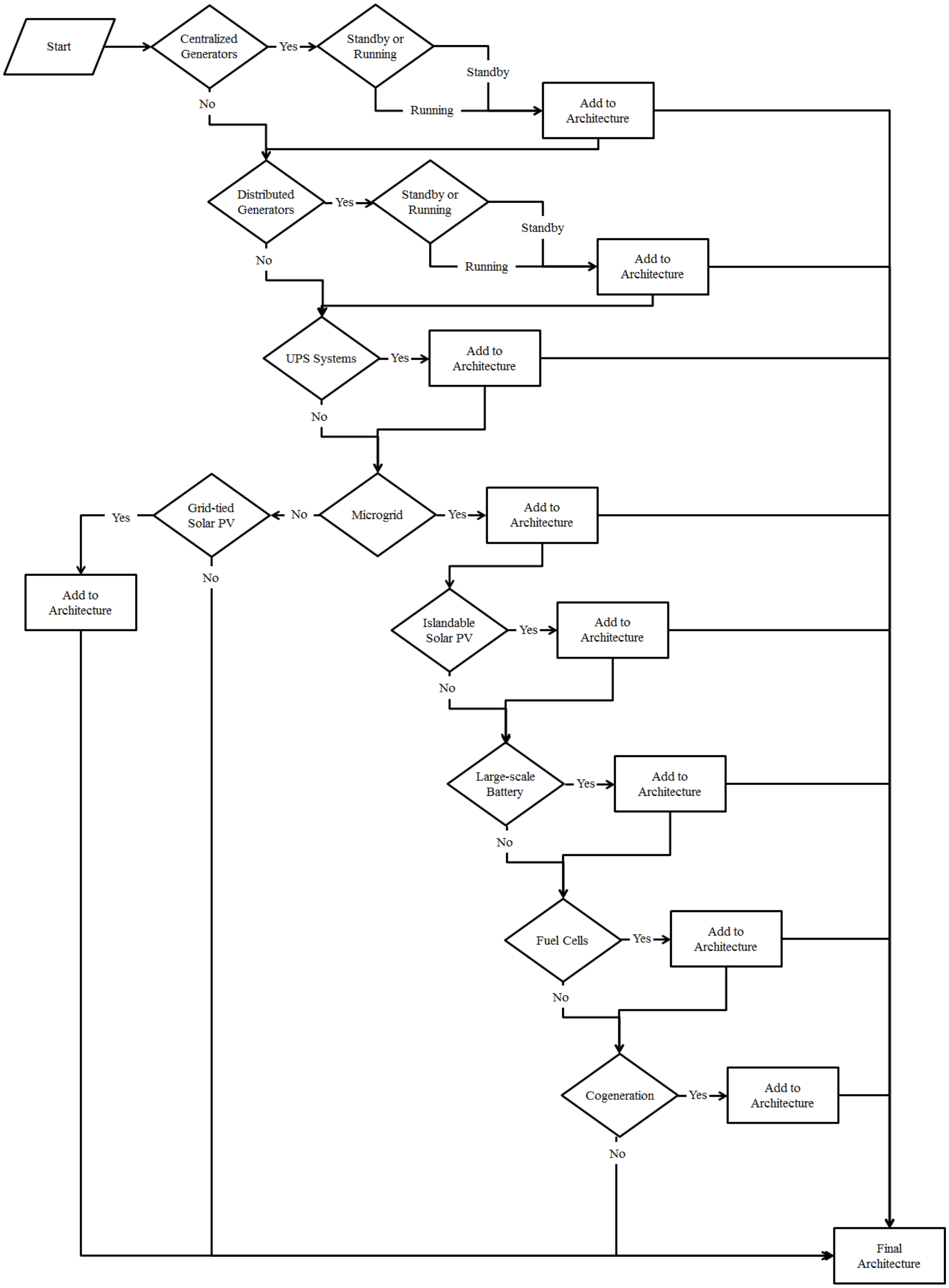


Figure 6. Architecture and technology decision tree.

Centralized generators significantly reduce the amount of maintenance required for the installation while also enabling other technologies to be aggregated in a microgrid, since they provide a stable voltage source that stands in for the electrical grid. These larger generators have synchronization controls built in to operate in parallel with other sources, and by centralizing the backup power for the installation, a smaller total generation capacity is needed to meet the peak demand. In order for these systems to meet the demand, the installation's distribution network must be reliable to ensure power is provided to critical facilities that are not in the immediate vicinity of the generators. On the other hand, distributed building-level generation enables the installation to bypass the distribution network and provide power to facilities individually. At large installations, this choice has led to numerous diesel generation assets that cannot be maintained properly, which leads to an increase in generator failure rates. Additionally, these assets must be sized to meet the peak load of each building and has resulted in almost twice as much generation capacity than necessary to meet the combined buildings' peak demand.

The type of energy sources available to each installation determined which technologies were feasible and helped assess the costs of implementing various technologies at each military installation. Diesel fuel is a common energy source across installations. Large amounts of storage are required to ensure that installations can provide power in an extended-duration outage, or that installations must rely on fuel deliveries. Natural gas pipelines that run to an installation could increase the availability of multiple, integrated technology solutions for energy resilience, since natural gas would provide opportunities to reduce fuel costs associated with operating current generation assets. As pipelines are fed from production and storage facilities located off the installation, storage tanks and scheduled refueling are not required. Using solar PV can provide a large cost saving over electricity from the grid when the installation is able to negotiate for a lower PPA rate. However, the military installation would also need to consider energy resilience in those arrangements for continuous power needs in case of an energy disruption. Historically, DoD has not included energy resilience in its renewable energy development or in its PPA agreements. Another consideration for solar and other renewable energy sources is that they are an intermittent resource that need to be paired with other generation assets to ensure the critical load demand is met for an entire disruption period (and for normal operations when it is financially prudent and technically feasible).

Energy storage can increase the resilience of the installation's electrical supply by supplying energy during the startup time of other assets and assist by increasing the availability of intermittent energy resources. Adding storage to the mix of technologies for an installation can reduce the amount of fuel consumed, which either reduces the volume of fuel storage required to meet the installation's demand during outages or increases the duration that missions can maintain operations. UPS systems and large-scale batteries are currently expensive to purchase, which limits their applications to domains where the alternative electrical backup solutions are nonexistent or more costly than the energy storage system. The increasing number of incentive programs provided by states and utilities may decrease the financial burden on military installations in the future.

2.2.12 Electrical and Thermal Demand

Following the construction of the architectures based on available technologies, the electrical and thermal demand for each installation was determined based on the critical load information provided by the installation requiring servicing. The primary piece of information requested to determine the loads was facility meter data, with a preference for fifteen-minute intervals covering at least one continuous month. In most cases, however, this data was not available. Therefore, critical peak electrical loads were estimated based on the sum of the capacity of all the critical backup generators on the installation and then halved, since there were numerous instances of backup power loading at 50% or less under maximum operating conditions (the rationale for this assumption is explained in detail in Section 2.3. Critical thermal loads were more difficult to estimate, as they were normally powered by a central steam system where the thermal output was not measured. In these cases, the amount of fuel consumed by the plant was determined by a base's utility bills, an overall efficiency of the system estimated, and the resulting average thermal supply calculated.

Once either actual or estimated critical load data was gathered from the base, a modeling tool used that information and assumed a type of profile modifier (i.e., flat, diurnal, spiked, weekend and diurnal, weekend and diurnal and seasonal), along with an element of random noise to generate an hourly demand for the installation over the course of the year. This profile was then crosschecked against any actual data received from the installation to ensure the overall characteristics were consistent. When plotted, the critical load profiles result in the hourly, average, and peak critical electrical demand for an installation (Figure 7).

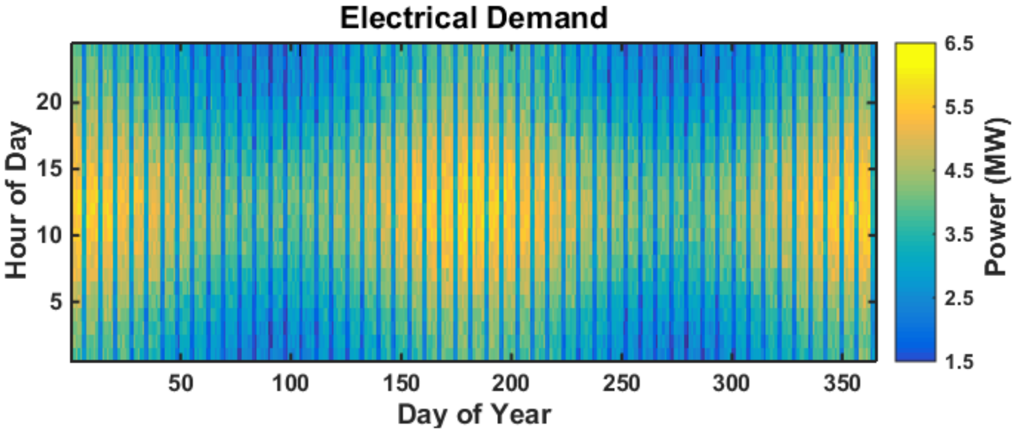


Figure 7. Example weekend, diurnal, and seasonal electrical demand profile for an installation.

2.2.13 Monte Carlo Simulation

All of the information from the previous components of the analysis framework (i.e., system devices, reliability models, resources availability, energy architectures, and demand profiles) was fed into the Monte Carlo simulation to perform the hourly time-step simulation of architecture performance. The Monte Carlo simulation works by computing the total critical electrical and thermal demand for an hour and attempts to meet that critical load using a proposed integrated energy architecture design. Normally, the process of selecting which technology should be used to meet the critical energy load is determined through optimization, but the precision gained from selecting the optimal answer for each hour comes at a large computational cost.

Another approach is to use a dispatch order by defining the order in which technologies are used to meet the critical energy load. This significantly reduces the amount of computational power needed to perform the simulation and can provide comparable results to an optimization when the dispatch order is appropriately determined. The simulation tool uses the dispatch order method for meeting the available load and the following is the order used for the study: cogeneration, boilers, fuel cells, grid-tied solar PV, islandable PV, grid electricity, central generation, building generation, UPS systems, and large batteries. This order can be modified within the tool to meet desired technology use or microgrid controller designs. Figure 8 shows the order in which the technologies are dispatched based on the thermal or electrical load remaining to be served.

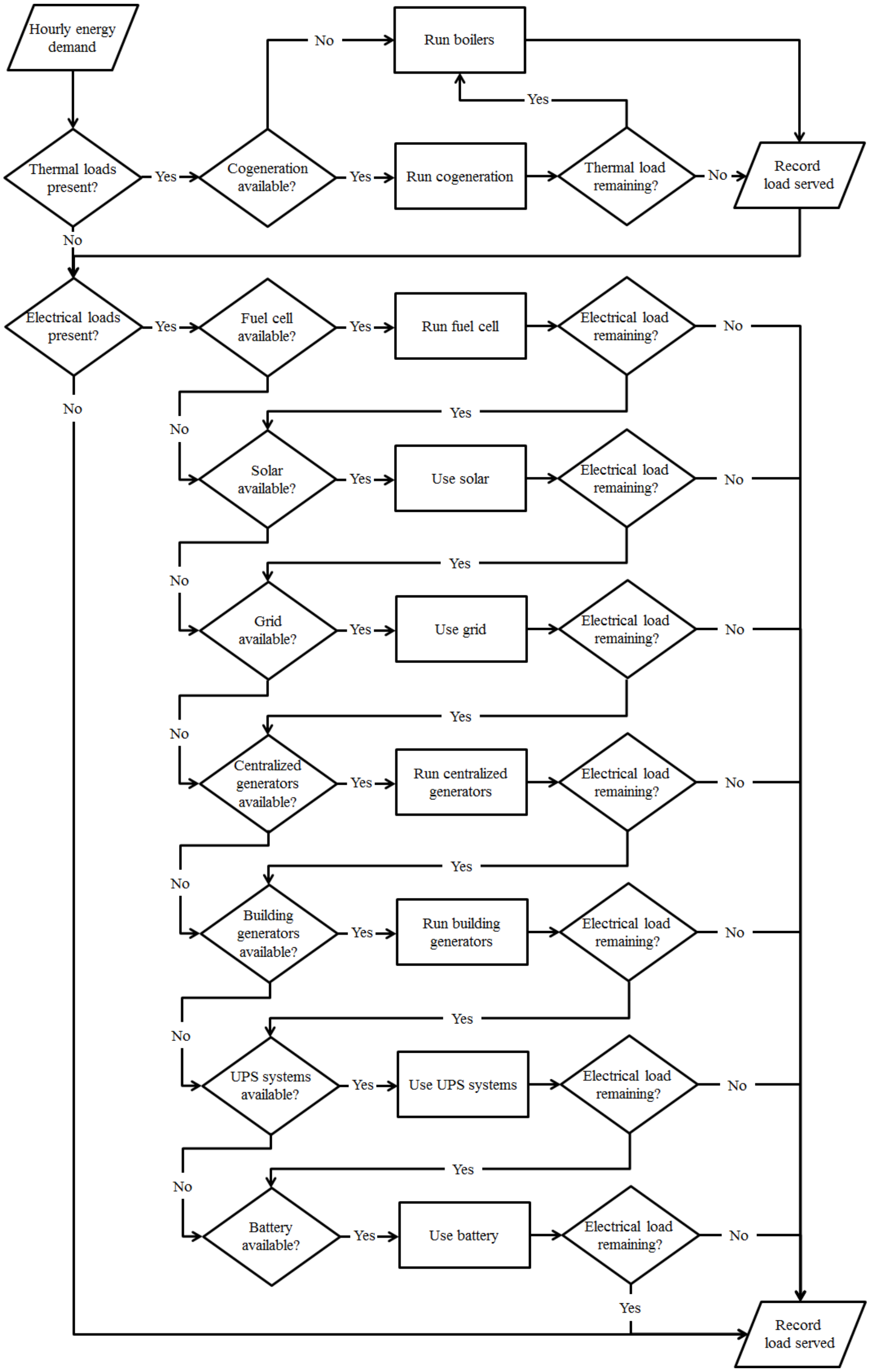


Figure 8. Logic diagram for technology dispatching to meet demand.

After using this dispatch order for the first hour, the analysis tool checks the load and available power using the same dispatch order and then loops over the remaining hours, architectures, and simulation runs for the desired analysis. This Monte Carlo simulation engine results in a distribution of potential demand outages for the architectures based on the hourly variations in load and technology failures. This distribution can be seen when plotting a histogram of the architecture outages (Figure 9). Additionally, the tool records the amount of diesel fuel and natural gas used, the amount of energy supplied by each available technology, the number of hours during which there was a power outage, and what amount of load was unserved over the course of the year (the availability metric chosen for this study). Currently, the analysis tool displays the mean of the distribution when providing a value for the simulated values and uses the mean of those values to determine an architecture's cost and unserved energy. This was a decision made to simplify the results of the analysis for this study, but the analysis tool can be modified to display the data ranges and values in a number of different ways.

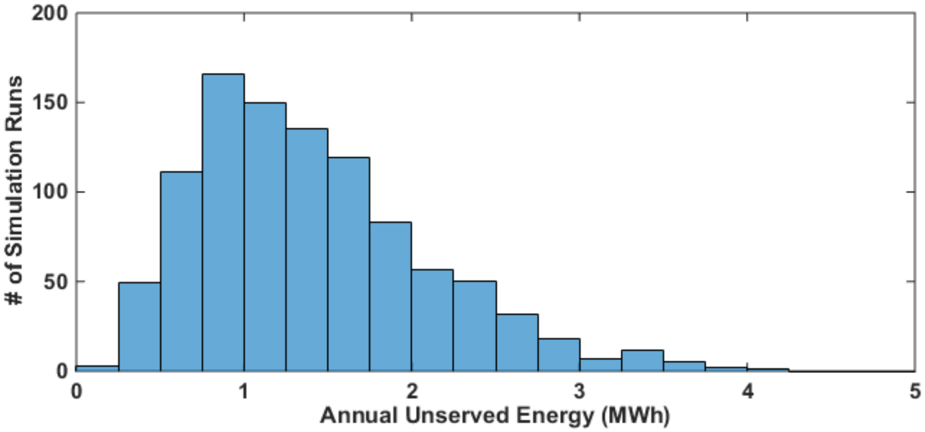


Figure 9. Example performance distribution for a single architecture over the course of 1,000 simulations.

2.2.14 Financial Calculations

For this study, the financial calculations focused on determining the life cycle cost (LCC) for each of the existing and proposed architectures. The analysis tool has the flexibility to calculate any number of different financial metrics, including savings-to-investment ratio (SIR) and simple payback, depending on the preferences. LCC was selected since it provided an easy visualization to compare the cost of future investment decisions with those currently in place. The LCC calculated in the tool considered the capital, maintenance, and energy costs for the technologies and then projected that annual value across the defined operational lifetime of the systems.

The capital cost for the architectures is determined by calculating only the new upfront costs for any remaining technology systems that the installation would need to purchase and complete the proposed architecture design. If the installation already owns existing components of a proposed architecture design (e.g., building generators), those existing items do not add capital costs.

The study assumes that existing generators are a "sunk cost" and do not provide a financial gain from salvaging, nor do they result in a financial loss from disposal. While this assumption is appropriate for this analysis, generators and other technologies can often be resold for a portion of their original value, which would provide a small offset to the new devices purchased to replace these systems. Still, the value of partially used generators is difficult to determine as the market is underdeveloped, without clear pricing examples. Another simplifying assumption is that the existing assets do not need to be replaced during the lifetime of the analysis. Often, assets on the installation need to be replaced, but the rates of replacement and when those replacements occur vary greatly from year to year and installation to installation.

The maintenance costs for the architectures are determined by calculating the annual maintenance cost for each technology and combining them to create a single yearly value. These costs are separated out as funds for maintenance and are typically allocated from the installation's annual budget, whereas the capital expenditures can be from the installation's annual budget or an alternative financing mechanism. The analysis tool assumes that annual maintenance costs are the same year after year. While they likely vary depending on the preventative maintenance schedule and while unexpected failures could lead to spikes in repair costs, over the long term, these variations should trend towards the average, so it simplified calculations to assume constant costs.

The energy cost for an architecture is determined by calculating the total amount of energy used in the simulation and then multiplying that energy consumption by the corresponding energy cost for the energy type. The different energy types were: diesel fuel, natural gas, solar energy, and grid electricity. The energy consumption was determined based on the usage profiles of different technologies during the simulation (e.g., solar energy was consumed when islandable or grid-tied solar was available). These individual energy costs were then combined to create a single, total annual energy cost for a proposed energy resilience architecture.

The annual cost to provide energy for the installation is applied to the life cycle of the technologies with the appropriate inflation factors and discount rates for projected future expenses. For this analysis the 2016 White House Office of Management and Budget standard inflation rate of 1.9% and a discount rate of 2.9% for ten-year projects was used [10]. While these factors provide a useful benchmark, we recommend that DoD consider inflation and discount rates that are in line with the private sector (i.e., 3% inflation rate and 7% discount rate) since they align more directly to actual system implementation costs. These inflation and discount rates will more heavily penalize systems with large capital expenditures and reduce the out-year costs and benefits of the technologies. The study assumed a ten-year system life cycle to align with government and DoD guidance and to provide life cycle costs in this range. However, many systems have quoted life cycles from the manufacturer that are fifteen years or longer. DoD should consider aligning the appropriate system life cycles as part of future considerations.

After applying the appropriate factors to determine system life cycle costs, this value is combined with the capital costs to develop a total cost. The total cost is then divided by the total life cycle amount of energy met by using a proposed architecture design. This results in the life cycle cost ($/kWh) metric used to compare the 48 energy resilience architectures in this study. Figure 10 plots each energy resilience architecture life cycle cost as a stacked bar plot to show the cost categories reviewed in this study. The figure provides a visual that allows cost comparisons across each energy resilience architecture and the associated cost categories.

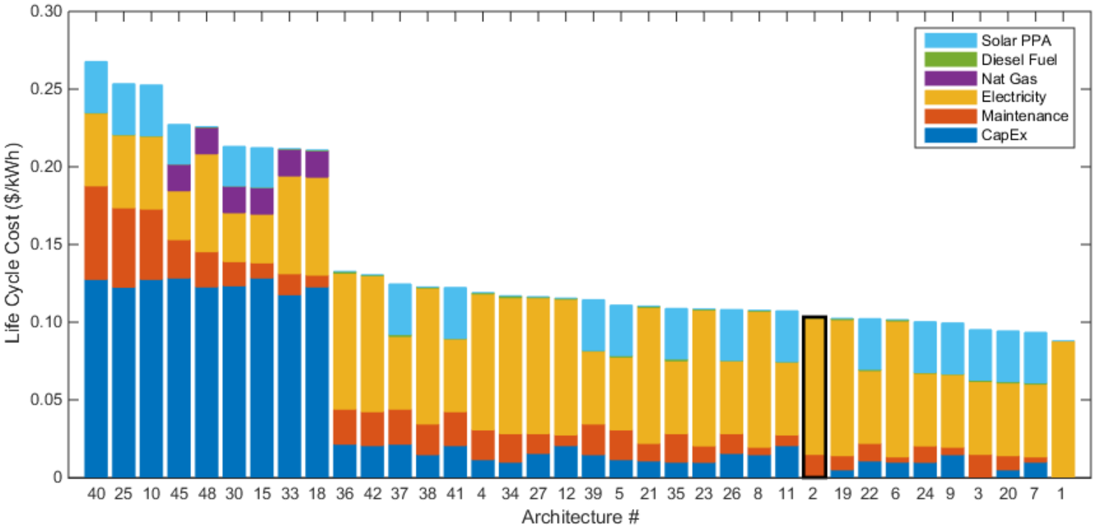


Figure 10. Example cost breakdown for each architecture with the existing architecture highlighted in black.

It should be noted that many of the financial assumptions in the study were conservative to align to existing DoD guidance and authorities. The life cycle costs could very well be more attractive in any future modification of this analysis. For example, the study found more cost effective energy resilience solutions exist at each of the four locations. This means that modifications to the stated financial assumptions could improve life cycle cost calculations further and could improve uniformly across each energy resilience architecture. While future analysis may be warranted, the DoD should carefully balance the need to accomplish more detailed analysis with the importance of implementing energy resilience projects that can mitigate known risks cost effectively today.

2.2.15 Architecture Analysis

The analysis tool also allows for risk-based decision making and tradeoffs. It can assist in the determination of energy resilience architectures to help meet military installation mission requirements. The two primary factors analyzed for the architectures were the life cycle cost and the annual unserved energy (or availability). Cost and availability can be used in energy resilience decision making processes and in energy resilience project selections. The use of cost and availability metrics also allow DoD to prioritize investment decisions to both cost and mission attributes. This study has built a framework to quantify both cost and mission metrics for risk-based tradeoff decisions.

The tradeoff between cost and availability across the range of explored energy resilience architectures is depicted in Figure 11, left panel. This is an example of a visual that quantifies tradeoffs for decision-makers to better understand the availability and cost implications across energy resilience projects. When tradeoff decisions become clustered or too close for interpretation by decision-makers, filtering the architectures to display only those on the Pareto optimal frontier (the set of solutions that has less unserved energy or is lower cost than other solutions) alleviates that challenge (Figure 11, right panel). Reducing the trade-space in this fashion also simplifies the decision making process by displaying only the most optimal solutions for key stakeholders. The existing or baseline energy resilience architecture can also be displayed against the most optimal energy resilience architectures to visualize improvements (as is represented by the dotted line in the right hand panel).

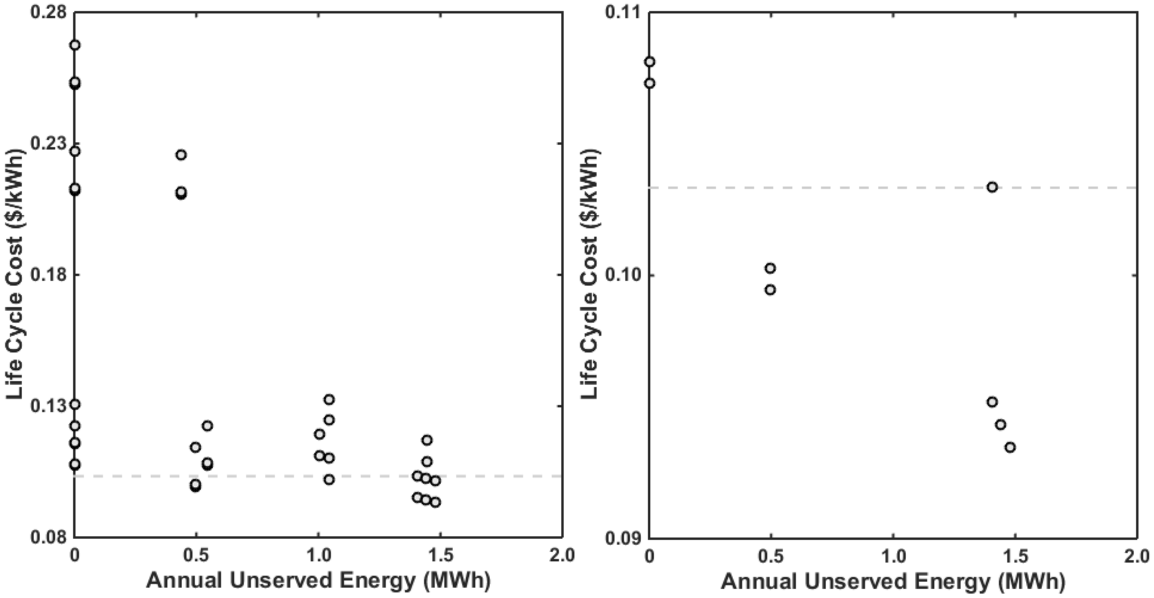
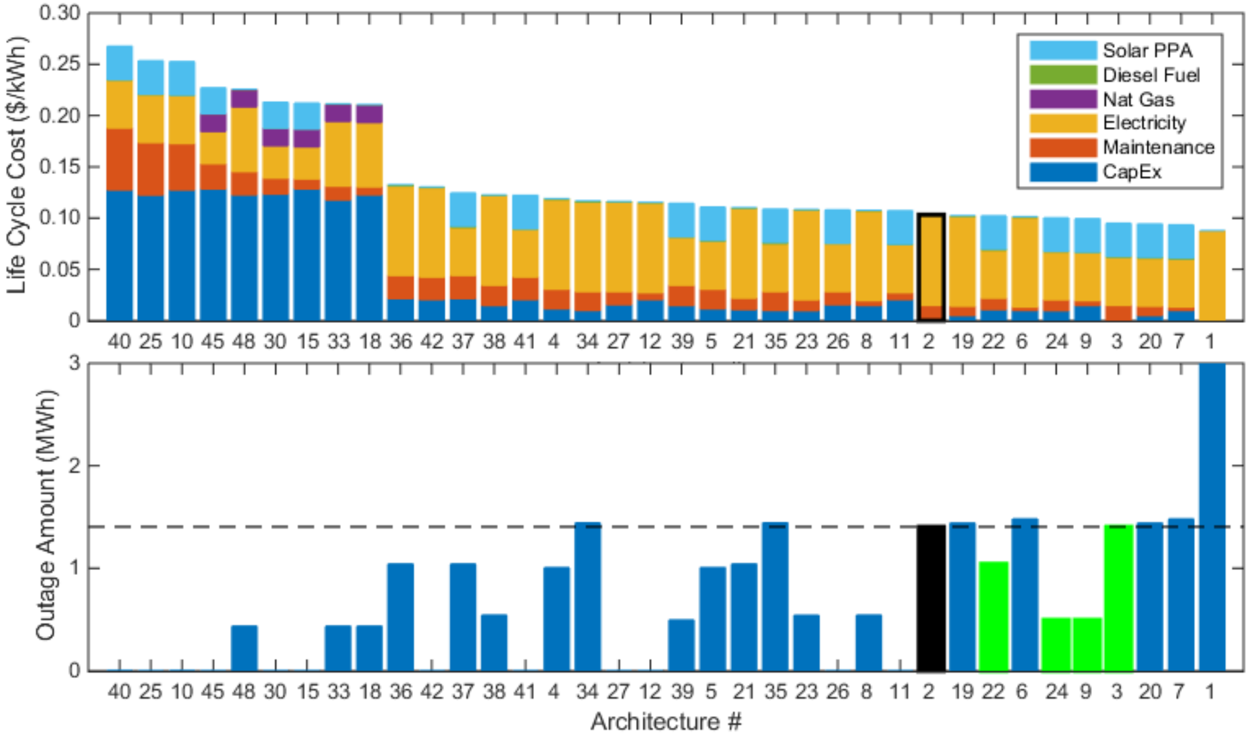


Figure 11. Example architecture tradespace (left) and reduced Pareto frontier solution space (right).

Another method for visualizing the results of the analysis is to separate the architecture costs from the architecture availability (Figure 12). The top bar chart represents the life cycle costs of the energy resilience architectures, while the bottom bar chart represents the amount of unserved energy for each energy resilience architecture. This separation of the two primary factors enables the decision-maker to visualize which specific architectures meets the installation availability requirements and/or have the desired cost attributes.



Each architecture in the analysis is shown with the existing architecture highlighted in black. Lower cost and more reliable solutions are highlighted in green on the bottom plot.

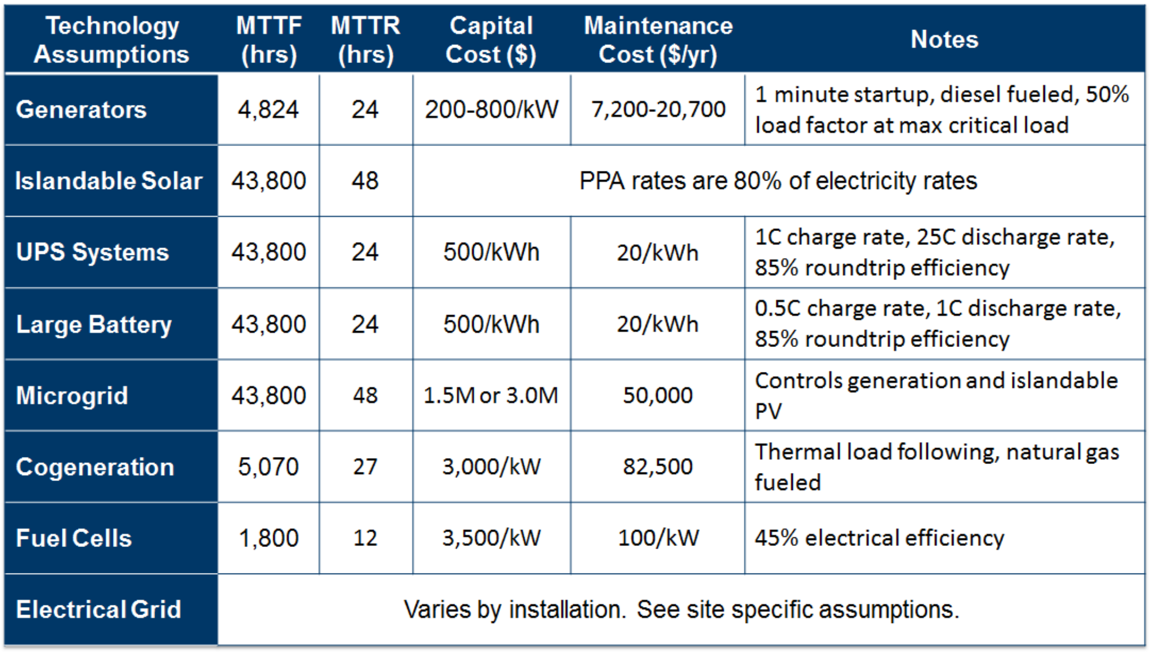
Figure 12. Example cost and performance comparison chart.

2.3 TECHNOLOGY ASSUMPTIONS

Feeding the analysis tool were a number of inputs gathered from an installation questionnaire sent prior to the site visits, the site visits themselves, and data gathered to verify responses from the site visits. Whenever there was a gap in data or information, the study used industry standards or comparable data from DoD sources to generate its assumptions. A major benefit of the tool is that it is customizable, flexible, and dynamic: many of the values can be changed to meet a desired situation or updated when new information becomes available. It is important for stakeholders to understand all the inputs within the analysis tool to make a risk-informed decision and to take the appropriate action on a recommendation. Some of the general assumptions are shown in Table 2. As described, the resulting values for the assumptions were determined by the best data available at the time of the study. They were generally generated by either actual information the installations provided, generally accepted cost and engineering practices, based on MIT Lincoln Laboratory previous experience or other subject matter expertise, or generated through manufacturer or DoD data and reports.

TABLE 2

General Technology Assumptions for the Study



Technology Assumptions	MTTF (hrs)	MTTR (hrs)	Capital Cost ($)	Maintenance Cost ($/yr)	Notes
Generators	4,824	24	200-800/kW	7,200-20,700	1 minute startup, diesel fueled, 50% load factor at max critical load
Islandable Solar	43,800	48	PPA rates are 80% of electricity rates		
UPS Systems	43,800	24	500/kWh	20/kWh	1C charge rate, 25C discharge rate, 85% roundtrip efficiency
Large Battery	43,800	24	500/kWh	20/kWh	0.5C charge rate, 1C discharge rate, 85% roundtrip efficiency
Microgrid	43,800	48	1.5M or 3.0M	50,000	Controls generation and islandable PV
Cogeneration	5,070	27	3,000/kW	82,500	Thermal load following, natural gas fueled
Fuel Cells	1,800	12	3,500/kW	100/kW	45% electrical efficiency
Electrical Grid	Varies by installation. See site specific assumptions.				

It should be noted that much of the actual information requested through surveying the military installation was not available; specifically, actual numbers for the cost and reliability of generators, the actual loads for critical missions, and the time-varying nature of those loads. This resulted in assumptions to be made for this information. The study assumed that generators were purchased according to industry standard costs that were not location-specific and also assumed that all generators had the same failure rate. The study assumed that generators were oversized by a factor of 2. This assumption is supported by subject matter expert opinions, and crosschecked with information obtained at the sites where it was available. For example, the study team reviewed data from their required semiannual generator tests under full building load, and this was one of the data sources used to validate generator size and load assumptions.

The study also assumed that all mission demand profiles matched the profile shown in Figure 7 (this assumption would need to be reviewed for higher load profiles such as missions that include data centers). The study also used outage information obtained from the installations when it was available, or assumed that the reliability modeling would impact the availability of power to the critical load. It is likely that the outage information collected at a military installation requires improvement to better justify a business case decision based on the study's findings and other related studies [11]. However, it is important to specifically understand what outage information is needed to better guide energy resilience decisions and to collect the right outage data in the future. An important step for the DoD to better guide outage related data collection or analysis is to augment the understanding of terms such as availability and reliability, since their unique differences are not well understood across the DoD. Therefore, it is important to ensure that technical capabilities aligned to availability and reliability, as well as cost and mission analysis, are encouraged throughout the DoD to implement energy resilience decisions.

The study team was able to assess and analyze availability and reliability, as well as cost and mission requirements to help inform military installation decision making and to validate the assumptions in this study. For example, the study team explored the effect of not knowing the critical load on the costs and reliability of the system architectures. Additional sensitivity analysis highlights the importance of understanding the integrative nature of multiple variables in energy resilience decision making, such as how critical load information and variations in demand profiles impact the cost and performance for the proposed energy resilience solutions. As energy resilience initiatives continue across the DoD, it will be important to determine how to appropriately embed these integrative energy resilience capabilities to better inform this multidisciplinary decision space.

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Critical mission operations on domestic military installations for the Department of Defense (DoD) use backup sources of power to protect against the failure of the domestic electric utility grid. This report examines the life cycle costs and availability and reliability of the current backup power solutions at military installations and compares them to alternatives for future deployments to reduce life cycle costs or to increase the availability of energy to critical mission operations.

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