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Evaluation of an Energy Resilienc5e Analysis Tool for Army Installations

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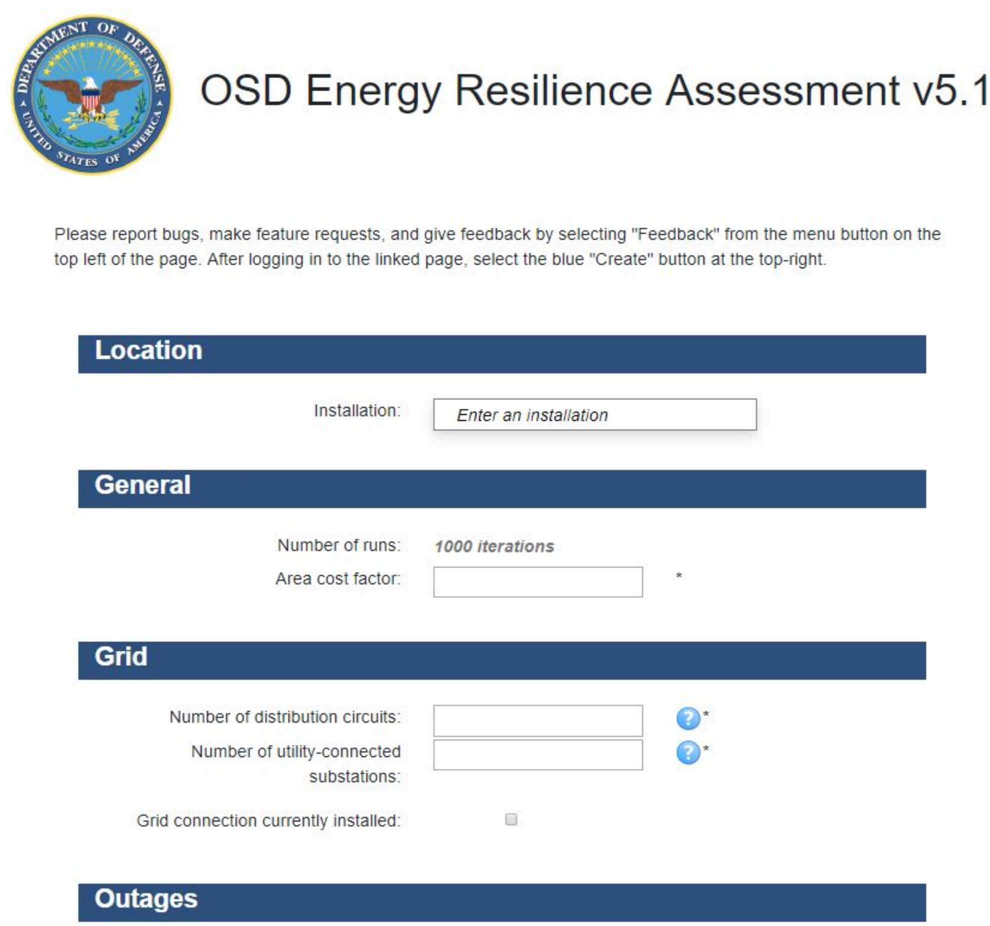
July 2019



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Abstract

This report is an evaluation of the Energy Resilience Analysis (ERA) tool developed by the Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) to explore its capabilities and its potential for implementation across U.S. Army installations. The project delivery team (PDT) reviewed the tool's functions and documentation, ran simulations, and reviewed data inputs required from installations. The PDT found that the ERA Tool does provide a user-friendly automated analytical framework for installation staff to perform energy resilience assessments with a focus on availability and reliability of energy with life cycle cost as a primary decision criterion. However, the ERA Tool does not account for the flexibility and redundancy of distribution networks, the quality of power supplied by the energy infrastructure at an installation, or the ability of an installation's energy infrastructure to prepare for and recover from specific energy disruptions. Also, the current methodology does not take into account a minimum resilience requirement to guide decision makers through the selection process. The PDT acknowledges that MIT-LL's approach was to develop a high-level planning tool for energy resilience assessment, which they did successfully. This report explores the potential consequences of this analysis approach and makes recommendations for improvements to the ERA Tool.

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Preface

This study was conducted for the Assistant Secretary of the Army (Installations, Energy and Environment) ASA(IE&E) under Project "Evaluation and Implementation of an Energy Resilience Analysis and Simulation Tool for U.S. Army Installations," funded via Military Interdepartmental Purchase Request (MIPR) 11097982, "ERA Tool from MIT-LL." The technical monitor was Mr. Paul Volkman, Office of the Deputy Assistant Secretary of the Army for Energy and Sustainability (*ODASA* (E&S)).

The work was performed by the Energy Branch (CFE) of the Facilities Division (CF), of the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Giselle Rodriguez was Chief, CEERD-CFE, and Donald K. Hicks was Chief CEERD-CF. The Associated Technical Director was Kurt Kinnevan, CEERD-CZT. The Deputy Director of ERDC-CERL was Dr. Kumar Topudurti and the Director was Dr. Lance D. Hansen.

COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

1.1 Background

Department of Defense Instruction (DODI) 4170.11 (USD[AT&L] 2016) defines resilience as, "the ability to prepare for and recover from energy disruptions that impact mission assurance on military installations." DODI 4170.11 requires U.S. military installations to "have the capability to ensure available, reliable, and quality power to continuously accomplish DoD missions." This instruction also tasks U.S. Department of Defense (DoD) Components with performing, "periodic vulnerability assessments and audits to assess the risk of energy disruptions on military installations, and implement remedial actions to remove unacceptable energy resilience risks … These energy projects shall be pursued based on life cycle cost effectiveness or if they remove unacceptable energy resilience risks."

Army Directive 2017-07 (OSA 2017) establishes energy requirements to, "ensure available, reliable, and quality power … to continuously sustain critical missions." Key energy-related requirements are to:

- *Secure Critical Missions*. The Army will reduce risk to critical missions by being capable of providing necessary energy and water for a minimum of 14 days.
- *Sustain All Missions*. The Army will improve resilience at installations, including planning for restoration of degraded energy and water systems and reducing risks of future disruptions, by addressing the following attributes:
  - *Assured Access to Resource Supply*, i.e., redundant and diverse sources of supply, including renewable energy, which meet evolving mission requirements during normal and emergency response operations.
  - *Reliable Infrastructure Condition*, i.e., infrastructure capable of onsite energy storage along with flexible and redundant distribution networks that reliably meet mission requirements.
  - *Effective System Operations*, i.e., trained personnel who conduct required system planning, operations, and sustainment activities for energy security.

The Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) developed the Energy Resilience Analysis (ERA) tool to support DODI 4170.11 by providing an automated analytical framework for installation energy managers and planning personnel to perform energy resilience assessments with a focus on the availability and reliability of energy with life cycle cost as a primary decision criterion. Specifically, the ERA Tool was designed to enable the DoD to "perform an analysis of alternatives and to consider tradeoffs between life cycle costs and the availability of varying energy resilience solutions" (Judson 2016).

This work was undertaken to review the ERA Tool and its documentation; to test and evaluate the tool's algorithms by using the tool to run simulations while varying input parameters; to review the data inputs required from installations; and to evaluate the tool implementation methodology used by MIT-LL during site visits.

During the course of this project, MIT-LL has continued development of the ERA Tool by creating a web application user interface, limiting the parameters available to the user, and generally streamlining the analysis process. The initial version of the tool available to the PDT was labeled the ERA Tool Version 3.0 by MIT-LL and will be called the "ERA MATLAB V3.0" for the remainder of this report. The recently released web application was labeled OSD ERA Tool Version 5.0 by MIT-LL and will be called the "ERA Web App V5.0" for the remainder of this report. Any time both versions are being simultaneously referenced, they will be referred to as the "ERA Tool." Since the code from the ERA MATLAB V3.0 is available to the PDT, this version is used to assess the backend algorithms governing the analytical engine of the ERA Tool. Since the code from the ERA Web App V5.0 is locked from the PDT, the PDT focused on assessing the user interface, data input, and version control capabilities of the ERA Web App V5.0.

1.2 Objectives

The primary objective of this project was to verify that the ERA Tool is actionable and the results are valuable at U.S. Army installations. To fulfill the primary objective, the PDT pursued these secondary objectives:

1. Verify that the ERA Tool criteria metrics used to compare alternatives are appropriate for quantifying energy resilience as defined by DODI 4170.11 and Army Directive 2017-07 (ERA MATLAB V3.0).
2. Verify that the ERA Tool algorithms used to produce the criteria metrics are appropriate for quantifying energy resilience as defined by DODI 4170.11 and Army Directive 2017-07 (ERA MATLAB V3.0).
3. Verify that the current implementation methodology is appropriate for resilience analysis under U.S. Army requirements by demonstrating the data collection and simulation process at a large military installation (referred to hereafter as "Installation A").
4. Recommend potential areas of improvement to the tool and the implementation methodology, if applicable.

1.3 Approach

The project delivery team (PDT) met the objectives of this work through the following steps:

1. Reviewed DODI 4170.11 (USD[AT&L] 2016) and Army Directive 2017-07 (OSA 2017) to determine the Army requirements for the ERA Tool.
2. Reviewed the technical reports and documentation that MIT-LL produced after implementing the tool at military installations to clearly delineate the methodology currently being used and the data collection required to operate the tool.
3. Reviewed the backend code and ran the ERA MATLAB V3.0 to explore and test the algorithms used to produce criteria metrics for comparing alternatives.
4. Met with the MIT-LL development team to investigate how the tool was being used and how the tool was likely to be modified.
5. Conducted a case study at Installation A, including a data collection trip.
6. Ran both ERA Tool versions with real world data from Installation A.
7. Reviewed the user interface and functionality, data input process, and version control capabilities of the ERA Web App V5.0 to determine how effective the tool would be for different levels of users.

8. Reviewed the recommendations supplied to Installation A by the ERA Web App V5.0 to evaluate the actionable benefits provided by the analysis.

2 Technology Evaluation

2.1 User interface and workflow

2.1.1 ERA MATLAB V3.0 user interface and workflow

To use the tool, the ERA MATLAB V3.0 requires users to have MATLAB installed on their computer and to have the ability to read code. The closest thing to a user interface that this program has is the ERA function, which gives the user the ability to define which architecture to simulate, the length of the black sky outage, if solar, electrical, and thermal loads will be imported or generated, etc. (Figure 2-1).

Figure 2-1. ERA MATLAB V3.0 user interface.

```
function results = ERA(alpha,scenario,endurance,black_sky,FuelDays,Repair)
%% User Inputs

%  Scenario and Simulation Selection -- Set up the Monte Carlo simulation
% alpha          = 1;    % critical load scaling factor
% scenario       = 2;    % select the installation variables to use
% endurance      = 1;    % 1 = black sky outage, 0 = standard outages
BaselineArch     = 2;    % baseline for cost delta
Nruns            = 1000; % select the number of simulations to perform

%  Black Sky Analysis -- a long duration outage to simulate HILF events
% black_sky          = 60;   % number of days for the black sky outage
% FuelDays           = 3;    % days of peak consumption fuel stored on base
% Repair             = 1;    % 1 = component failures are repaired,
                             % 0 = no repairs are made during extended outages
DieselTanks      = 1;    % 1 = additional tanks req, 0 = unlimited off-site fuel
LNGtrucks        = 0;    % 1 = LNG truck only, 0 = functional pipeline

%%%% ***DO NOT MODIFY*** %%%%%
blacksim         = 0;    % 0 = regular outage events, normal fuel usage;
                         % 1 = black sky event, fuel cutoff once reserve depleted
%%%% ***DO NOT MODIFY*** %%%%%

%  Generator Repurchasing -- repurchase portion of components annually
gen_rebuy        = 0;    % purchase new generators as old ones fail
                         % 0 = no rebuy, 1 = rebuy at rebuy_rate
rebuy_rate       = 0.05; % percentage repurchased on an annual basis

%  Import Existing Data
SolarImport      = 0;    % 1 = import solar site data, 0 = generate data
LoadImport       = 0;    % 1 = import load site data, 0 = generate data
ThLoadImport     = 0;    % 1 = import load site data, 0 = generate data
```

The user must also define the existing energy architecture and all alternative energy architectures at their target installation. For example, Figure 2-2 shows how seven different energy architectures are defined for Joint Base Andrews by inputting the number (e.g., 52 generators for architecture 2) or existence (e.g., 1 = The “GRID” connection exists in architecture 1) of different types of equipment into a matrix.

Figure 2-2. Joint Base Andrews energy architectures.

```
case 6          % JB Andrews - 2MW Gen Analysis
    %[#GEN1 #GEN0 #SGEN1 #SGEN0 NET BAT UPS ISOL GSOL FC CHP BOIL GRID];
    Circuits = [...
        0     0     0      0     0   0   0    0    0   0  0    0    1   %1
        0     0     0     52     0   0   0    0    0   0  0    0    1   %2
        0     4     0      0     1   0   0    0    0   0  0    0    1   %3
        0     5     0      0     1   0   0    0    0   0  0    0    1   %4
        0     6     0      0     1   0   0    0    0   0  0    0    1   %5
        0     7     0      0     1   0   0    0    0   0  0    0    1   %6
        0     8     0      0     1   0   0    0    0   0  0    0    1]; %7
    %[#GEN1 #GEN0 #SGEN1 #SGEN0 NET BAT UPS ISOL GSOL FC CHP BOIL GRID];
```

Then, once the baseline energy architecture and the alternative energy architectures are defined, the user must input relevant information for each piece of equipment in the energy architecture. For example, Figure 2-3 shows how the user must input the capacity, purchase cost, annual operations and maintenance (O&M) cost, and fuel use curve for a generator.

Figure 2-3. Generator input variables.

```
case 2 %100 kW TQG
    GEN.SCap        = 100;      % electrical capacity (kW)
    GEN.SCost       = 28600;    % Cost of unit [$] (From Nost Nation)
    GEN.SOMCost     = 7200;     % O&M cost per unit per year [$/yr]
    Sgencurve = [0 1.77
                 25  3.18
                 50  4.67
                 75  6.08
                 100 7.64 ];
```

Several other steps may be required to properly run the ERA MATLAB V3.0. Some possibilities include:

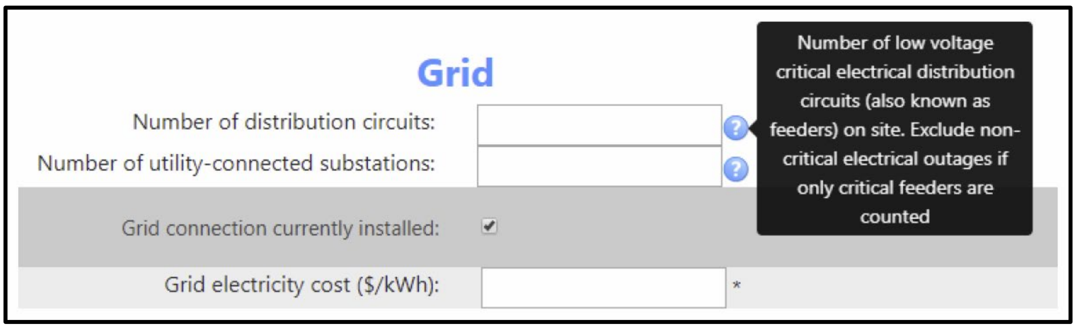
1. Updating the mean time to failure (MTTF) and mean time to repair (MTTR) parameters that are unique to each technology in the ERA Tool. This is particularly important for grid reliability.

2. Inputting solar availability data in comma-separated values (CSV) format or through other solar parameters (i.e., latitude, clear days, sunny days, etc.).
3. Inputting electric and thermal load profiles. Either CSVs or average load values with a load profile type (e.g., weekend, diurnal, and seasonal).

2.1.2 ERA Web App V5.0 user interface and workflow

The ERA Web App V5.0 has a dedicated user interface that is accessible through an Internet browser, which constitutes a defining improvement over the ERA MATLAB V3.0. This interface allows the user to streamline the data input process. The interface also provides "tool tips" for most input parameters to help the user understand the data requirements (Figure 2-4). In addition to the user interface, MIT-LL provides a data collection spreadsheet to help users consolidate the required data in an easy-to-input format (see Appendix A).

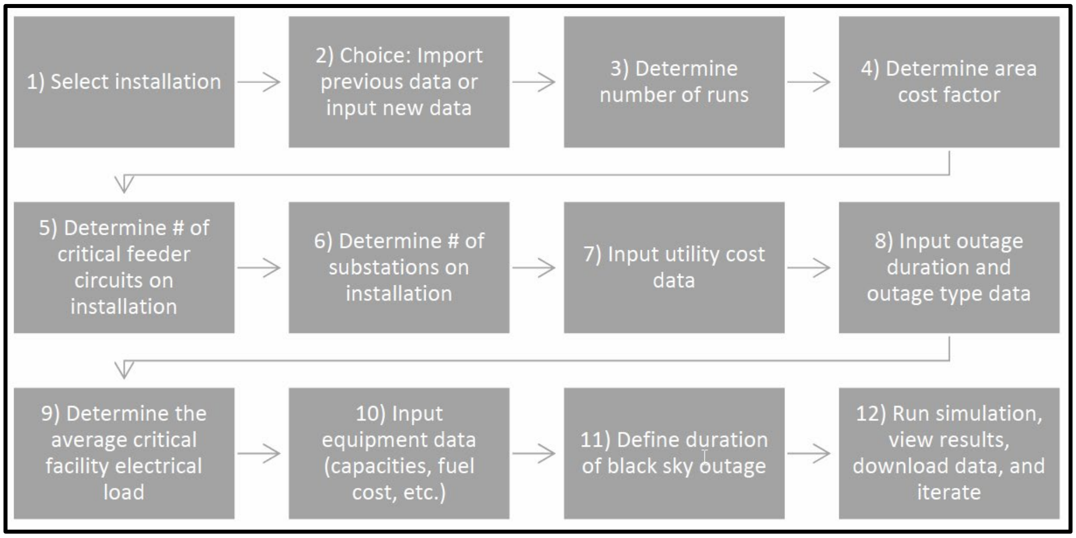
Figure 2-4. ERA Web App V5.0 tool tips example.



The ERA Web App V5.0 has a straightforward simulation process (see Figure 2-5). However, the PDT has some concerns regarding the following steps:

- Step 2: The user cannot name or add notes to a simulation run. Because of this, the user does not know the source of the previous data.
- Step 2: The tool will not run unless both primary and standby generators have input data. It is very possible that an installation will not have both types of generators, so this could add a barrier to running the simulation.
- Step 2: The user is only able to select the most recent data associated with an installation.
- Steps 2 & 12: The user cannot copy, replace, update, or delete previous simulation runs.

Figure 2-5. ERA Web App V5.0 simulation steps.



- Steps 4, 9, and 10: Location and technology-specific parameters are hidden from the user. This could have a detrimental effect on simulation accuracy and the installation's ability to reflect improvements in cost, operations, and efficiency.
- Steps 5 & 6: The user cannot determine the relationship between grid outages and the MTTF and MTTR for the grid.
- Steps 10 & 12: For each technology the user is asked to check a box indicating that the technology is currently installed on the installation. Each box that the user checks appears to impact the dispatch of equipment that will be analyzed in the tool. The PDT believes that there should be a dynamic field on the input page that describes the technologies that will be included in the simulation alternatives based on the input data.
- Step 12: The user cannot rerun a previous simulation, instead, they must run a new simulation with the same data. This could lead to a crowded workspace of many similar simulation runs listed in the tool's "run history."
- Step 12: There is no description of the alternative architectures on the results page.
- Step 12: The resilience metric on the outputs page is not necessarily comparable across installations due to differences in scale and inherent issues with aggregating critical load explained in section 2.2.1.2 .
- Step 12: The user cannot determine whether the energy architectures meet a minimum resilience standard. The tool highlights the architectures that are both more cost effective and more resilient, but installations may

want to define a minimum acceptable resilience standard for their energy infrastructure rather than simply being better than the status quo.

- Step 12: The user cannot review a table of outputs in the ERA Web App V5.0 unless they download a data zip file.
- Step 12: The user cannot drill down into the actual values on the results page.
- Step 12: The user cannot resize axes in the ERA Web App V5.0. This can be an issue when there is a large difference in unserved energy between alternative architectures. Data can be downloaded and manipulated in Microsoft Excel, but this slows down analysis time and renders the ERA Web App V5.0 less effective.
- All Steps: The tool lacks a tiered input structure with casual users seeing first level of inputs, then a 2nd tier of inputs for more advanced user to control installation-specific inputs.

The analytical backend of the ERA Web App V5.0 is still based in MATLAB and it appears that many of the algorithms have remained intact through the version update; however, additional functionality to improve user-friendliness and to limit the amount of required input data to run the tool has sufficiently changed the analytical engine to make a direct comparison between the ERA MATLAB V3.0 and the ERA Web App V5.0 impractical.

Of the complete list of variables that could reasonably vary between installations (see Appendix A), the majority of the variables are locked from the user in the ERA Web App V5.0. Appendix B includes a list of user-defined variables, and Appendix C includes the list of important variables over which the user no longer has control in the ERA Web App V5.0.

There is a balance between opening up access to these variables to increase the tool's precision and keeping these variables locked from the user to maintain ease of use and consistency. The PDT believes that the correct balance will become clear over time as more installations use this tool and identify its strengths and shortcomings. This list of parameters can serve as a glimpse into the inner workings of the ERA Web App V5.0 so that users are able to choose the parameters over which they may want greater control.

2.2 Resilience analysis

To determine the extent to which the ERA Tool is capable of quantifying energy resilience it is important to understand what the DoD and the

Army see as the important components of energy resilience. According to DODI 4170.11, energy resilience is defined as, "the ability to prepare for and recover from energy disruptions that impact mission assurance on military installations." Army Directive 2017-07 goes further by specifying requirements to, "continuously sustain critical missions," which include the following components:

- at least 14 days of available energy to critical missions
- redundant and diverse sources of energy supplied
- flexible and redundant distribution networks
- trained personnel for system planning, operations, and sustainment activities.

2.2.1 Analysis criteria

2.2.1.1 Defining the baseline

MIT-LL defined a set of energy production, distribution, and storage equipment on an installation as an "energy architecture" (Judson 2016). At a DoD installation, electricity is typically supplied by the grid, a set of backup diesel generators that are distributed around the installation such that each generator serves one facility, and potentially uninterruptable power systems (UPSs) for critical operations that cannot handle a momentary loss of power. In the ERA MATLAB V3.0 methodology, this is the **baseline** energy architecture used to support energy loads on the installation. This baseline energy architecture is used as the benchmark against which to compare alternative energy architectures, which means that an alternative energy architecture that has lower life cycle cost and better resilience than this baseline will be seen as a better solution. It is important to note that the implementation methodology only focuses on the aggregate **critical energy load** at each installation, which is an input supplied by the installation staff.

2.2.1.2 Resilience metric

Currently, the metric calculated by the ERA Tool for comparing the resilience of different energy architectures is the aggregate "annual unserved energy (MWh)" to critical loads on the installation. This is determined by comparing the energy demand and the available energy supply for each hour of the year. The annual unserved energy is determined by the following factors:

1. The technologies that make up the energy architecture
    a. Energy produced or stored by each technology
    b. The reliability of each technology (see technologies in Table 2-1)
2. Resource availability to operate each technology
    a. Solar resources
    b. Fuel availability (natural gas, diesel, etc.)
3. Electrical and thermal demand profiles for the installation.

This metric does not consider if critical loads in individual buildings are served or if the quality of power served is sufficient to meet mission requirements. This also means that the tool is not configured to analyze any network failures or dependencies. This tradeoff leads to a simplified Energy Resilience Analysis that can be performed quickly with relatively limited data; however, this analysis will also fail to accurately model realistic power failures.

To illustrate the potential shortcomings associated with aggregating the critical load and available backup generation in the ERA Tool we have put together the following hypothetical, yet realistic, scenario:

- Installation X has 10 critical facilities, all with an average load of 10kW.
- Each critical facility has a backup generator oversized by 2X (20kW capacity, each) with no microgrid or load-sharing capability.
- The ERA Tool would show that there is a total load of 100kW and a backup generator capacity of 200kW.

In this scenario, four of the 10 building-level generators could fail at the same time during a grid outage and the total backup power supplied in the ERA Tool would still be 120kW, which is greater than the demand of 100kW. In this scenario, there would not be any unserved energy, i.e., no loss of resilience. However, in reality those four facilities with failed generators would have zero power supplied to them for the duration of the grid outage.

2.2.2 Algorithms

2.2.2.1 Overview

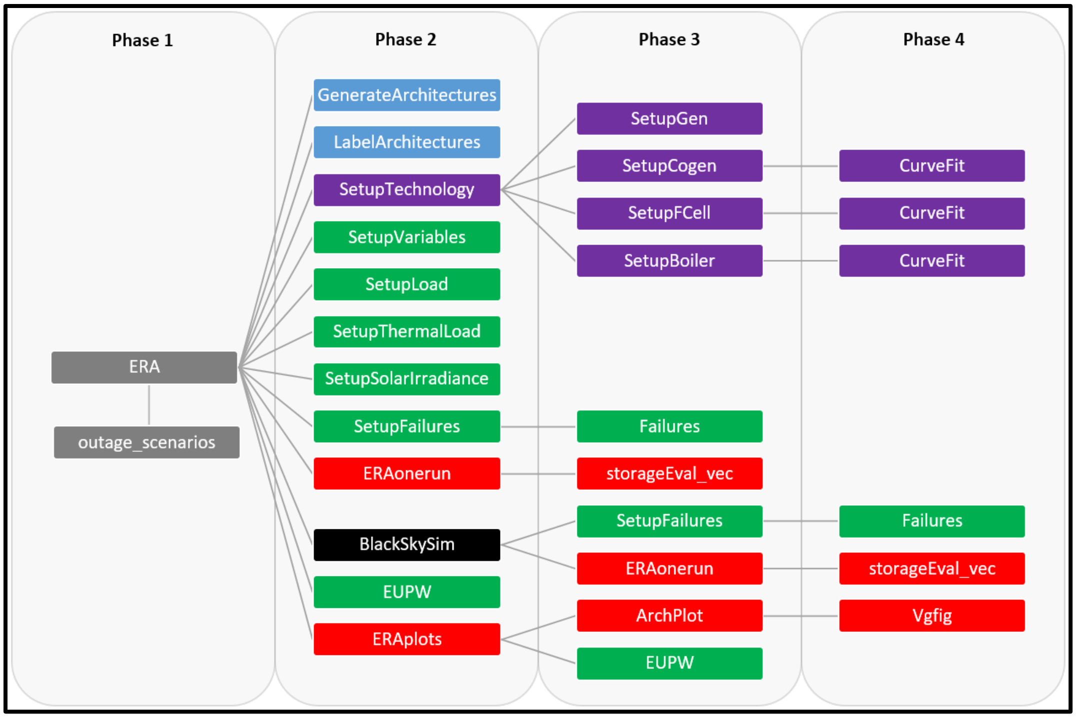
A previously published technical report from MIT-LL (Judson 2016) does not describe the algorithms that comprise the ERA Tool in significant detail. To better understand the ERA Tool, the PDT performed a thorough code review of the ERA MATLAB V3.0 to ensure that the ERA Tool logically quantifies resilience in the way that MIT-LL intended by focusing on availability and reliability. As stated in the MIT-LL tech report, “availability and reliability provide measures to ensure continuous critical mission operations and allow for the quantification, design, and comparison of different energy resilience solutions” (Judson 2016). The rest of this section explains the algorithms behind the ERA MATLAB V3.0 in further detail and notes when there have been obvious changes between the MATLAB and Web App Versions.

The ERA MATLAB V3.0 is comprised of 20 functions, three scripts, and several optional spreadsheets for inputting real world data for improved simulation accuracy. Figure 2-6 shows the order in which the various functions and scripts are called by organizing them into four phases of function calls where each connection (gray line) signifies a function calling another function from left to right. Figure 2-6 also shows how the functions that comprise the ERA Tool can all be grouped into one of six functional groups based on the over-arching task they are involved in performing. The color coding of the functional group heading is shown in the blocks in Figure 2-6. The six functional groups are:

- **Functional Group 1**: These functions allow the user to run the tool with the option to perform a sensitivity analysis. These functions have been rendered obsolete by the ERA Web App V5.0’s user interface.
- **Functional Group 2**: These functions set up the baseline energy architecture and alternative energy architectures. These functions have been changed in the ERA Web App V5.0 such that they programmatically create alternative architectures based on limited user inputs.
- **Functional Group 3**: These functions set up the simulation parameters, including:
    - Installation annual electrical load
    - Installation annual thermal load
    - Annual solar resource
    - Device failure rates
    - Current costs and cost escalation.
- **Functional Group 4**: These functions run the Monte Carlo simulation and produce output figures.
- **Functional Group 5**: This function replicates the Monte Carlo simulation assuming a high-impact low-frequency “black sky” outage event.

- **Functional Group 6**: These functions set up technology parameters for:
    - Boilers
    - Cogeneration
    - Fuel Cells
    - Generators.

Figure 2-6. ERA MATLAB V3.0 functional diagram (ordered left to right and top-to-bottom).



2.2.2.2 *Algorithm detailed summary*

Within the functions defined above, the user can manipulate dozens of variables (Appendix A). In the ERA MATLAB V3.0, only six of these inputs can be defined by the user when calling the ERA function in Functional Group 1. The rest of the inputs must be changed within the body of the code, which requires an understanding of both computer programming and the MATLAB language; however, the ERA Web App V5.0 has improved this process by providing a user interface that makes many of the most important input parameters readily available to the user with built-in explanations and guidance.

Once the user inputs have been specified and the ERA function is called, the ERA Tool selects the architecture for analysis, which are user-defined in the ERA MATLAB V3.0 and automatically generated in the ERA Web

App V5.0. Each architecture is a combination of the available technologies in the tool (Table 2-1).

Table 2-1. Available technologies in ERA MATLAB V3.0. Adapted from Judson (2016).

Technology	Description
GEN1	Centralized generators for primary power (2 MW)
GEN0	Centralized generators for backup power (2 MW)
SGEN1	Building-scale diesel generators for primary power (175 – 300kW)
SGEN0	Building-scale diesel generators for backup power (175 – 300kW)
NET	Microgrid that enables generators to share loading
BAT	Large-scale battery for long duration outages
UPS	UPS battery systems for momentary outages
ISOL	Islandable solar photovoltaic (PV) – provides power during outages
GSOL	Grid-tied solar PV – does not provide power during outages
FC	Fuel cells that supplement baseload generation
CHP	Cogeneration plant
BOIL	Natural gas steam boilers
GRID	Connection to electricity grid

In the ERA MATLAB V3.0, each of the technologies that comprise the energy architectures must have their technical specifications input into the tool by the user (see phase 3 “Setup” functions in Figure 2-6) and the number of each technology must be input into the GenerateArchitectures function (see Figure 2-6). This means that the user is responsible for correctly sizing the technologies. Judson (2016) outlines the methodology MIT-LL used for sizing each technology. Appendix D provides more details.

In the ERA Web App V5.0, a limited amount of technical specifications for the technologies are available for the user to input into the tool. The number of each technology is only a relevant input for generators in the ERA Web App V5.0; everything else is based on the aggregated generation capacity.

A baseline energy architecture, the existing energy architecture on the installation, and multiple alternative energy architectures can be compared based on energy availability and life cycle cost. Once the desired architectures have been selected, the ERA Tool creates all the performance and cost variables for each technology, which form the basis of the energy architectures. Next, the tool goes on to build the necessary variables for the Monte Carlo simulation, namely, the electrical, thermal, and solar load profiles that are present at the installation. In the ERA MATLAB V3.0, these profiles can either be supplied via spreadsheet by the user, or they will be generated based on the average load at the installation and by one of several user-specified load profiles listed in Table 2-2. In the ERA Web App V5.0, the user is only able to input the average load profile, leading the PDT to assume that there is an assumed load profile used for every installation.

Table 2-2. Load profiles generated by the ERA Tool.

Profile No.	Description
1	Flat
2	Spike
3	Diurnal
4	Weekend and Diurnal
5	Weekend, Diurnal and Seasonal
6	Diurnal and Summer
7	Diurnal and Seasonal

The Monte Carlo simulation is set up to run an hourly analysis (8760 hours/year) over an assumed 10-year system life cycle. In each hour, all the technologies are checked for failures. Based on the available technologies (i.e., those that have not failed) during each hour, and how much energy each of the technologies can produce, the ERA Tool determines if the energy architecture is able to supply the electrical and thermal demand defined by the load profile. The ERA Tool assumes that individual technology failures are not related so each device is modeled independently for failures using a Weibull distribution. The Weibull distribution is a probability density function that allows the user to define the shape of the failure or repair distribution, and that uses either the MTTF or MTTR to scale the distribution. It is described by the equation:

$$f(x) = \frac{\lambda}{k}\left(\frac{x}{k}\right)^{\lambda-1} e^{-\left(\frac{x}{k}\right)^{\lambda}} \tag{1}$$

where:

λ is the shaper parameter, or else known as the Weibull slope, and
k is the scale parameter.

If the user calls for it, the ERA Tool is able to perform the same basic analysis under a black sky outage event (i.e., when the grid and potentially fuel delivery are unavailable). This step is important because it allows the tool to satisfy the Army Directive 2017-07 requirement that an installation should be able to supply at least 14 days of energy.

Once that is completed, the ERA Tool performs financial calculations used to compare how well each alternative energy architecture performed against the baseline. Next, new technology and maintenance costs are calculated, as well as the yearly amount of demand response income (note that demand response is not an available input in the ERA Web App V5.0 and an investigation of the ERA Web App V5.0 parameters shows that demand response income is set to zero). Lastly, a life cycle cost analysis is performed, which meets the DODI 4170.11 requirement to use life cycle costs analysis. The PDT has reviewed and documented each function in detail, but any deeper analysis is beyond the scope of this report.

2.3 Economic analysis

2.3.1 Background

The ERA Tool is capable of examining the life cycle costs and the availability and reliability of different energy architectures for critical mission operations on DoD installations. It quantifies and assesses tradeoffs between life cycle costs and the availability of energy for the existing energy architecture and performs an analysis of alternatives to compare against other energy architectures.

Financial calculations are focused on determining the life cycle cost (LCC) of each architecture for comparison between each of the proposed architectures and the existing architecture. The LCC calculated in the tool considers the capital, maintenance, generator rebuy rate, and energy costs for the technologies and then projects that annual value across the defined operational lifetime of the systems using the Office of Management and Budget inflation and discount rates. In the ERA Web App V5.0 the operational lifetime of the systems is locked at 10 years, which may be concerning since the "FY 2019/FY 2020 Energy Resilience and Conservation Investment Program and Plans for the Remainder of the Future Years Defense Program Guidance"* suggests the following estimated useful life spans:

- Boiler Plant Modifications: 20 years

* https://www.acq.osd.mil/eie/Downloads/IE/FY2019_FY2020%20ERCIP%20Guidance.PDF

- Electrical Energy Systems: 25 years
- Solar (photovoltaic, and thermal): 25 years.

To further support an extended analysis timeframe, Marqusee et al. (2017) uses a 20-year investment horizon to reflect the expected life of generators and microgrids.

The capital costs for the architectures are determined by calculating only the new upfront costs for any remaining technology systems that the installation would need to purchase to complete the proposed energy architecture. 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. The analysis tool assumes that annual base maintenance costs are the same year after year. While maintenance costs likely vary depending on the preventative maintenance schedule and unexpected failures, over the long term, these variations should trend toward the average, so the ERA Tool simplifies the 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 unit cost for the energy type (e.g., $0.12 / kWh of electricity). This is a simplified energy cost approach that does not take into account the intricacies of utility tariffs, but considering the high-level nature of the ERA Tool, this approach is reasonable. Based on the MIT-LL report (Judson 2016), fuel consumption for testing of the equipment or for refreshing diesel fuel in storage was not considered.

As stated in the previous section, demand response income appears to be zeroed out in the ERA Web App V5.0, and users cannot edit demand response income. Additionally, there is no consideration for load-shedding capabilities that may improve the life cycle costs associated with microgrids and centralized generation assets. Again, considering the high-level, simplified analysis approach taken by the ERA Tool, these simplified cost assumptions are reasonable. If the ERA Tool is modified to perform a more detailed resilience analysis, then the LCC analysis should also be modified to take into account utility tariff, demand response, and load-shedding details for a more realistic assessment.

2.3.2 Baseline, Base Case, and a minimum resilience requirement

The current ERA methodology has the following high-level steps:

1. Define the baseline (existing) energy architecture in the ERA Tool.
2. Define alternative energy architectures (this step is automatic in the ERA Web App V5.0).
3. Compare the baseline energy architecture to the alternative energy architectures to determine the architecture that is the best option.

This current methodology of comparing alternative architectures to the existing baseline could be problematic because the baseline architecture may be significantly less resilient than what is required by the mission. For example, there may not be any alternatives that have both a lower LCC and lower annual unserved energy than the baseline architecture; however, the baseline architecture may not be resilient enough to sufficiently protect critical infrastructure from power failures. In this example, the ERA Tool would suggest that the installation keeps its current insufficient infrastructure.

To rectify this issue, the ERA Tool could be configured to establish a Base Case in addition to the baseline. In installation master planning the concept of a Base Case is the baseline plus any improvements planned to meet a minimum requirement. For example, an installation may have 10 existing buildings in their baseline, but they might need two more buildings over the next 5 years to accommodate an expected increase in personnel. The 5-year Base Case would then have 12 buildings.

To ensure that the comparison being carried out by the ERA Tool is appropriate, it makes sense that the installation should define a minimum resilience requirement and create a Base Case architecture that is comprised of the equipment that would most easily meet this minimum requirement (e.g., minimum power quality requirements, minimum downtime requirements (UPS systems), minimum renewable energy requirements, etc.). Then, when the alternative architectures are created by the ERA Tool they will be compared to the minimum resilience requirements defined in the Base Case rather than whatever happens to exist at the installation. The resilience of the energy supply system in the Base Case scenario would be brought up to minimum requirements and the LCC would increase compared to the pre-renovation baseline to meet the resilience requirement.

This new LCC would be the standard to beat. In the rare case where an installation's current energy infrastructure is sufficient to meet their minimum resilience requirement, the baseline will be equal to the Base Case and no further work be necessary.

According to DoD and Army guidance, senior commanders are tasked to, "use a consistent methodology to work with mission owners and tenants to assess and prioritize installation-critical energy and water requirements needed to support the missions of an installation" (OSA 2017). This required action would help installations establish a Base Case.

2.3.3 User access to LCC components

When MIT-LL began to conduct site visits and implement this tool at military installations they were aware that there would be difficulties with accurately assessing life cycle costs:

> The lack of comprehensive information on the costs of generation assets, the total number of generators on an installation, the lack of easily accessible information on how much maintenance individual systems require, and what the cost of that maintenance is makes it difficult to efficiently and accurately assess the actual costs of current systems. This leads to various assumptions influencing the life cycle cost analysis (Judson 2016).

Since LCC is one of only two decision metrics, it is important for the user of the tool to understand where the components of the LCC number are coming from. Now that this tool can be in the hands of installation subject matter experts, it makes sense that these individuals would have visibility into cost components and the ability to override these cost components where they have documentation to back up their numbers. This is an area where the ERA Web App V5.0 is lacking. When inputting information for an installation, the user is asked to input an "area cost factor," which is then used to escalate equipment costs accordingly. This means that the user is not able to input equipment costs that they know to be true in their region and they are never given a report that includes these constituent costs. For example, if the user wants to see what the cost assumption is to purchase a new generator they would need to:

1. Purchase, download, and install MATLAB
2. Run the ERA Web App V5.0 and download the "Download Results" zip file
3. Open the "Results.mat" file in MATLAB

4. Look through the 106 variables in the “Results.mat” file and identify the “BldgEmgGen” if they wanted to see the purchase cost of the distributed backup generators or the “CentEmgGen” if they wanted to see the purchase cost of the centralized backup generators.

This process makes it prohibitively cumbersome to simply see the costs used by the ERA Web App V5.0. The users are unable to influence equipment costs, which will likely result in overly simplistic cost assumptions that will negatively influence the LCC metric.

2.4 Simulation results (ERA Web App V5.0)

The ERA Web App V5.0 produces three graphical outputs shown in Figures 2-7, 2-8, 2-9, and 2-10. Across all of the figures each column represents one energy architecture. Each of these architectures has an ID number associated with them, which, in this case, is between 1 and 38. The order of energy architectures (from right to left) is consistent across each of the three graphics, so it is easy for the user to compare.

The simulation outputs presented below are based on data collected from a site visit to Installation A. (Chapter 3 provides further details.) The stacked column chart in Figure 2-7 shows the 10-year life cycle costs associated with each alternative energy architecture and the color-coded components of each bar represent the cost categories. The architectures are sorted from right to left with the lowest cost architecture on the far right and the highest cost architecture on the far left. The baseline architecture is identified with a black box surrounding its column, which in this case is architecture 2. The horizontal dotted line indicates the simulated LCC of the baseline architecture so it is easy for the user to see how much each alternative energy architecture deviates from the baseline.

Figure 2-7. LCC stacked column chart.

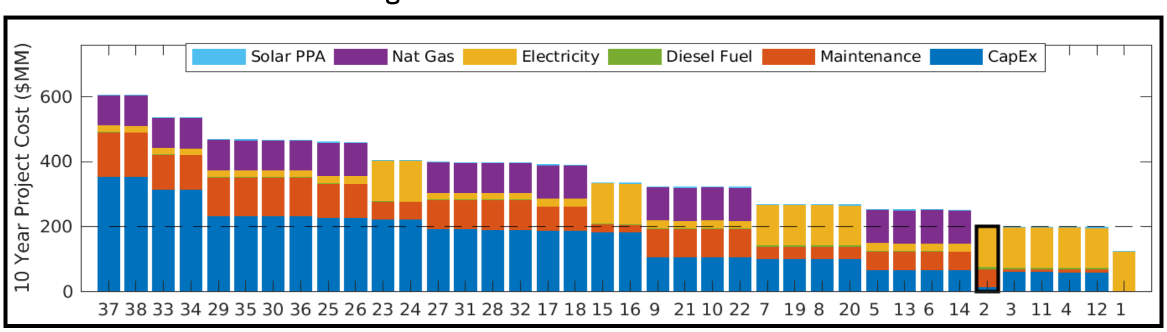


Figure 2-8 is a column chart showing the total unserved energy (MWh) over the 10-year analysis period, which is the energy resilience metric employed by MIT Lincoln Laboratory. The baseline architecture is identified with black shading, the lower cost and higher performance architectures are identified with bright green shading, and architectures that do not fulfill both lower cost and higher performance have blue shading. The horizontal dotted line indicates the simulated total unserved energy of the baseline architecture so it is easy for the user to see how much each alternative energy architecture deviates from the baseline. The shading in this graphic makes it very clear to the user which alternatives show a simulated improvement over the existing baseline architecture.

Figure 2-8. Energy resilience column chart.

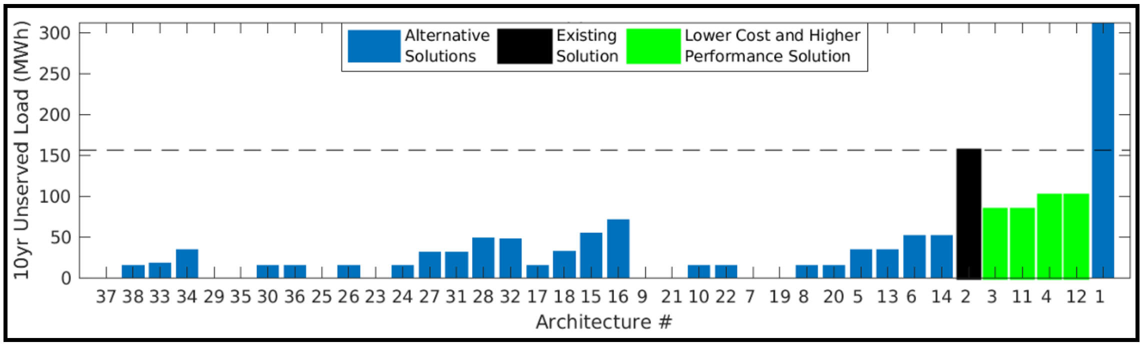


Figure 2-9 shows how the preceding charts are presented in the ERA Web App V5.0 outputs. The stacked method allows the user to see how each architecture compares on LCC and resilience metrics and the highlighted columns help the user quickly identify the alternatives that perform better on both metrics.

Figure 2-10 shows the same data as Figure 2-9, with the addition of a black sky scenario (in this case, a 14-day total grid outage). The blue portions of the columns in the top chart of Figure 2-10 simply represent the sum of the 10-year life cycle cost components shown in Figure 2-9. The red portions of the columns in the top chart of Figure 2-10 are the additional life cycle costs incurred during the black sky scenario (typically comprised primarily of backup fuel consumed by generators while the utility connection was compromised). The MIT-LL report (Judson 2016) gives more detail regarding these graphical outputs.

Figure 2-9. Life cycle cost and energy resilience comparison chart.

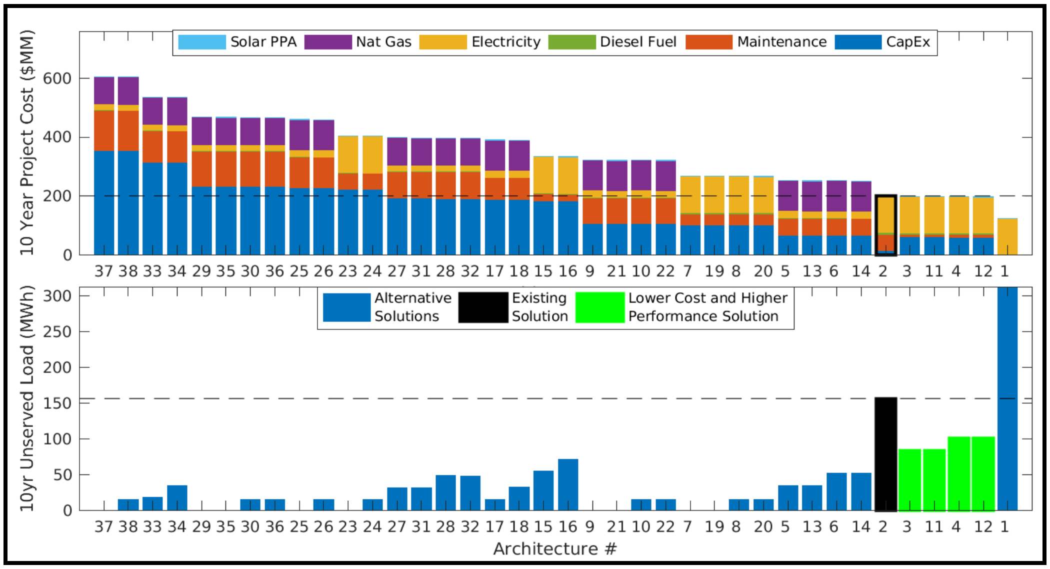
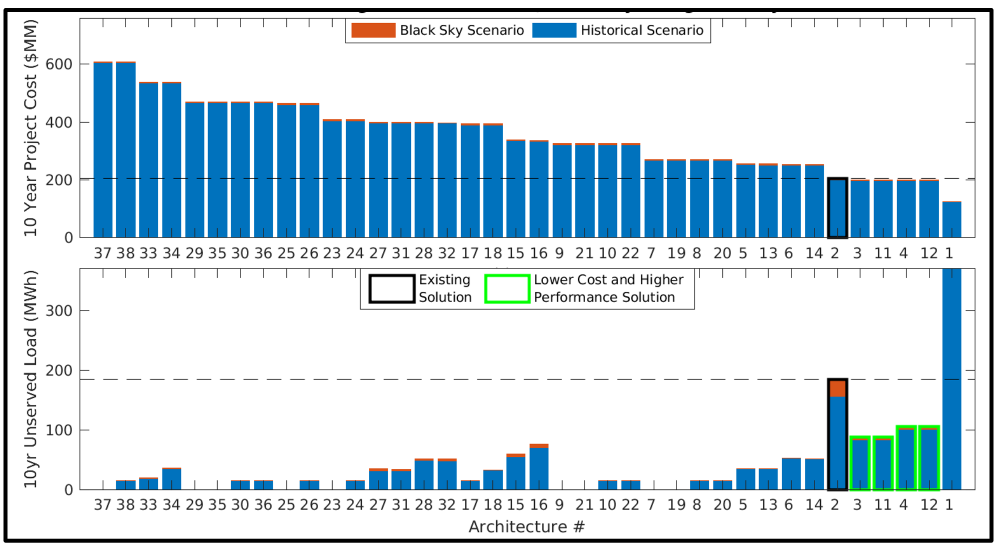


Figure 2-10. Black sky outage life cycle cost and energy resilience comparison chart.



3 Use at Military Installations

The primary means of providing electric backup power for the most critical mission capabilities at DoD facilities is through the use of building-level diesel generators. The MIT-LL analysis (Judson 2016) included four installation studies (Installations B-E) and ERDC-CERL did its analysis at one installation (Installation A). For each study, the goal was to determine additional options to enhance backup generation capability and to perform a comparison of life cycle costs and energy availability metrics. Specifically, the study from each installation determined that several options exist to provide cheaper and more reliable power systems.

3.1 Limitations of data availability at military installations

The ERA Tool uses a wide variety of necessary information from each military installation to determine baseline costs and resilience solutions. In areas where data is unavailable, the tool has built-in assumptions to address gaps. Table 3-1 lists the basic information requested from all of the sites, including the work at Installation A that ERDC-CERL performed to gather electrical usage, costs, and outages from the grid, along with information on the backup diesel generator inventory.

Table 3-1. Data available by installation.

Information	Installation A	Installation B	Installation C	Installation D	Installation E
Single-line Electrical Diagram	Privatized, not known			Not updated, leading to confusion	
Electrical Usage Data	Installation-level data + 1/4 building-level	Only installation-level data available, not known at the building level, lending difficulty to right-size generation assets for critical loads. Tendency is to oversize 2-10 fold.			
Electrical Outage Data			Individual electrical feeder-level outage data not tracked		
Current electrical Costs					
Generator Inventory			Some missions not tracked		No central list
Generator priority List		Different contracts per fuel type; Not prioritized		Many generators on non-critical loads	No master list; Priority groups in individual lists
Generator Capital Costs	Costs of existing systems are not tracked. Some generators purchased with MILCON, some by mission owners, some are owned by facilities				
Generator Maintenance Costs			Time is tracked, not parts	Time is tracked, not parts	Estimated O&M costs provided
Generator Operational Costs		Not available			
Generator Failure Rate	Not tracked		Tracked only for some generators	Not tracked	Tracked by AF, not by Navy
Future Development Plans					In process
Action Rating	73%	55%	64%	50%	55%

Legend		
Has all actionable information	Has some actionable information	Has no actionable information

Source: Adapted and updated from (Judson 2016).

The information gaps place limitations on the overall analysis. Two important conclusions drawn from these gaps include:

1. Determining the true cost of backup power was challenging because none of the installations tracked capital or O&M costs for the existing backup generators.
2. All of the installations track electricity consumption from the grid, but only in the case of Installation A was there some level of building-level metering, so the consumption from critical loads was not available.

The Action Rating is an average score to assess the availability of information collected at each site (green=1, yellow=0.5, red=0). This gives an indication of the lack of data typically available at DoD installations, which is one likely reason why the ERA Tool was created to operate at a planning level, rather than a detailed engineering level.

Energy architecture comparisons are directly impacted by the amount of information available. In the case of this study, the usage data were important to ensure the correct size backup solutions (since an overestimate results in higher capital costs and oversized generators). The lack of information on UPS systems also leads to uncertainty regarding the readiness of those systems.

3.2 Data collection approach at Installation A

3.2.1 Approach

Similar to the site investigations that MIT-LL performed for the initial study, four engineers from the ERDC-CERL Energy Branch visited Installation A in July 2018. Much of the information necessary for the ERA Tool, such as power bills, grid outage reports, and generator lists, can be collected before performing a site visit, but being onsite provided additional insight not available through email and phone communication. The site visit consisted of meetings with the following Installation A agencies:

- Directorate of Public Works (DPW): Primary information facilitator, who coordinated assistance with other agencies.
- Directorate of Plans, Training, Mobilization, and Security (DPTMS): Resource for discussions on emergency response, preparedness, and risk assessment.

- Privatized Utility: O&M provider for Installation A distribution lines and diesel generators, diesel fuel provider.
- Privatized Energy Services Company (ESCO): O&M provider for Installation A boilers, cogeneration systems, microgrid and Energy Savings Performance Contracts (ESPC) projects.
- Several other critical mission owners on Installation A.

Section 3.6 gives specific details of the input parameters used for ERA Tool.

3.3 Installation A electrical grid infrastructure and outages

Meetings with the Privatized Utility provided insight on the electrical grid infrastructure and backup generation. DPW provided 36 months of grid outage reports (Figure 3-1). During that timeframe, the department documented a total of 99 outage events, with an average outage duration of 2.97 hours. The vast majority of these outages (92 of 99) would have been categorized as feeder outages (defined as less than 500 facilities), while six were likely substation outages (affecting between 500-1,500 facilities), and one, for a hurricane, was at the utility scale affecting a reported 1,756 facilities. The primary risks to the electrical grid are tree limbs falling on the above ground lines. Figure 3-2 shows the categorized causes of outages. While technical issues and animal encounters accounted for 30.6% and 25.0% of the outage causes, respectively, weather related issues (hurricane, thunderstorm, ice, wind, etc.) collectively accounted for 34.7% of the outages. The Installation Design Guide (IDG) states that all new electrical lines are to be installed underground, and this is one of the main priorities the Privatized Utility prioritizes whenever a line is disrupted.

3.4 Installation A backup generation

3.4.1 Generator assets

The Installation A DPW provided a “Generator List” spreadsheet with details on the building-level backup generation. The list changed multiple times during the data collection period due to added capacity, but at the time of this writing, the installation had a total of 299 building-level generators with a total capacity of 109.9 MW. The provided spreadsheet also notes that a total of 125 generators with rated capacity of 73.8MW were located at critical facilities. Figure 3-3 shows the breakout of generators at critical and non-critical facilities.

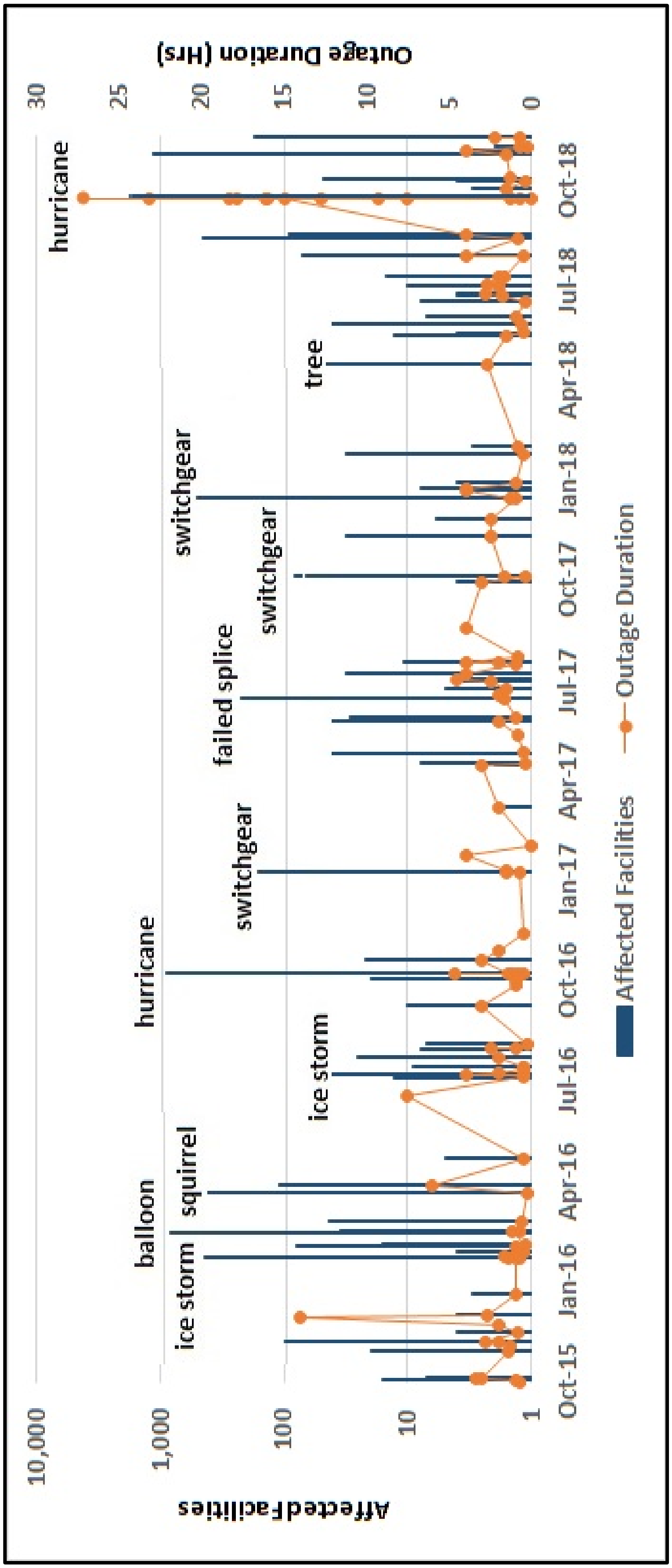


Figure 3-1. Installation A electrical grid outage frequency and duration.

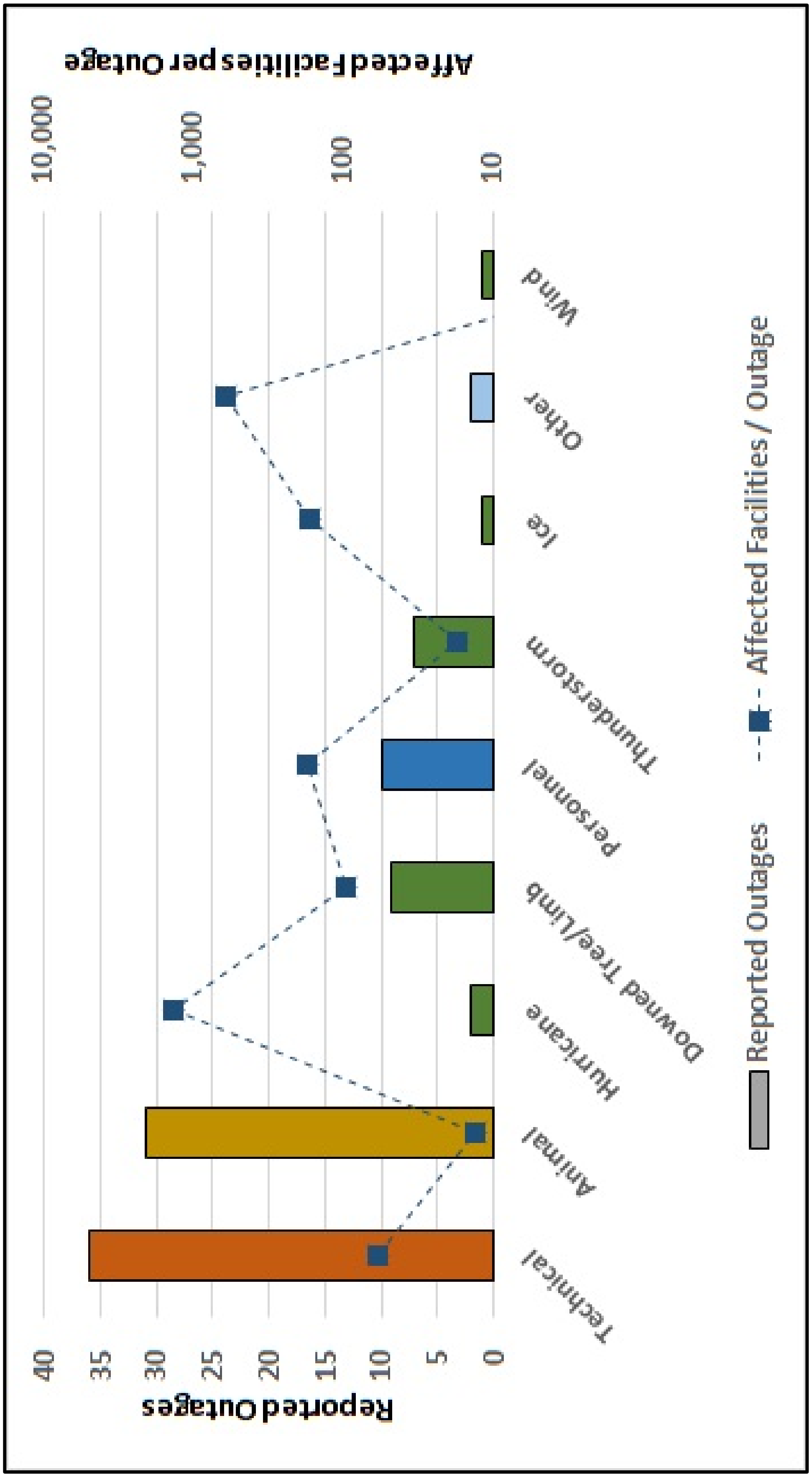
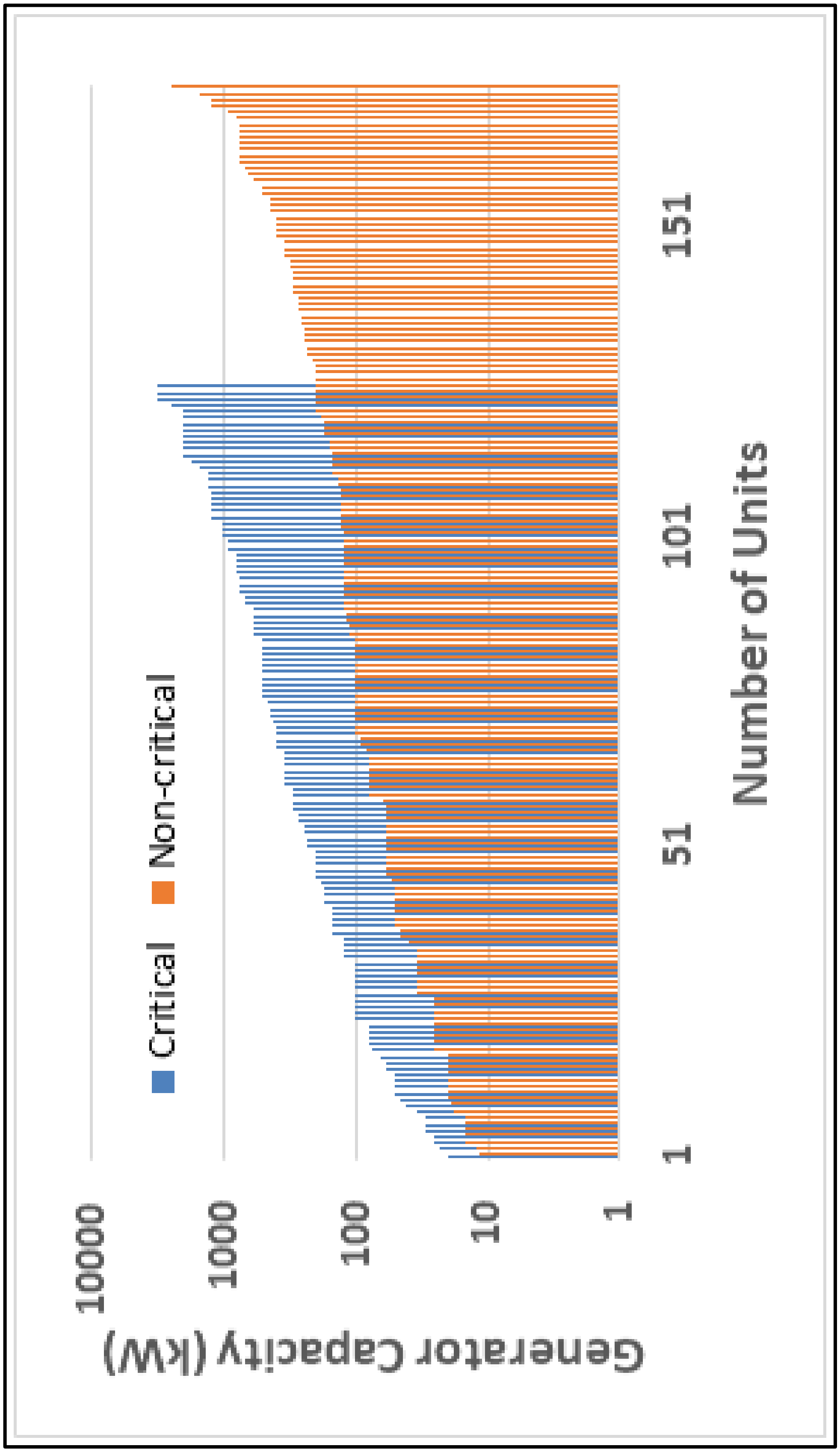


Figure 3-2. Categorized outage causes during 36-month reported timeframe at Installation A.

Figure 3-3. Breakout of critical and non-critical facility generators at Installation A.



The ERA analysis focused on the critical facilities so the study incorporated cross-checking the generators located at a critical facility in the "Generator List" with the "Critical Facility List." Some discrepancies between the two lists are:

- Total facilities listed in the "Critical Facility List": 183
- Total number of facilities on the "Critical Facilities List" noted to have a backup generator: 100
- Total backup generator units located at a facility listed as critical on the "Master Generator List": 125
- Facilities listed to have a generator on the Critical Facilities List", but not in the Master Generator List: 52.

Note that these discrepancies likely contributed only to some minor errors that are largely corrected in the rollup of the generator assets in the ERA Tool previously described in the discussion on the algorithms in section 2.2.2

Installation A DPW indicated that the majority of the generators are owned and operated by the Privatized Utility, with the exception of a handful of classified areas that own and maintain their own generators. All new generators installed have 48 hours of runtime capacity based on 100% load. Other than a few critical facilities, the Privatized Utility noted that there is very little redundant capacity.

Shortly after the site assessment from ERDC-CERL, a hurricane hit the U.S. East Coast and greatly impacted Installation A. Follow-up conversations with DPW revealed the vulnerability of the diesel re-fueling infrastructure. Approximately 3 days before the hurricane struck, the Privatized Utility went around the installation to refill any of the generators that were below capacity to get to 48hr runtime. The Privatized Utility eventually began to run out of spare fuel, so DPW had to look for places offsite, but they could not buy fuel with the government credit card due to the fact that the cost of 2,300 gallons exceeded the credit card purchase limit. They worked out an agreement to have the Privatized Utility go to their fuel supplier to buy two truckloads of fuel during the hurricane with the understanding that DPW would reimburse the Privatized Utility on the power bill.

3.4.2 Storage assets

Spreadsheet data that the DPW provided showed that the liquid fuel storage capacity is approximately 1.5 million gallons for the entire installation, including facility and vehicular applications. The generators are noted to have 1,134,000 gallons of capacity, fueled by diesel (710,000 gallons), No. 2 Oil (419,000 gallons) and gasoline (5,000 gallons). Analytical calculations determined that the installation had operational run time of approximately 13 days with the current level of generator and fuel capacity; however, Section 3.7 describes the ERA simulations that provide a significantly more detailed analysis.

3.5 Installation A thermal generation infrastructure

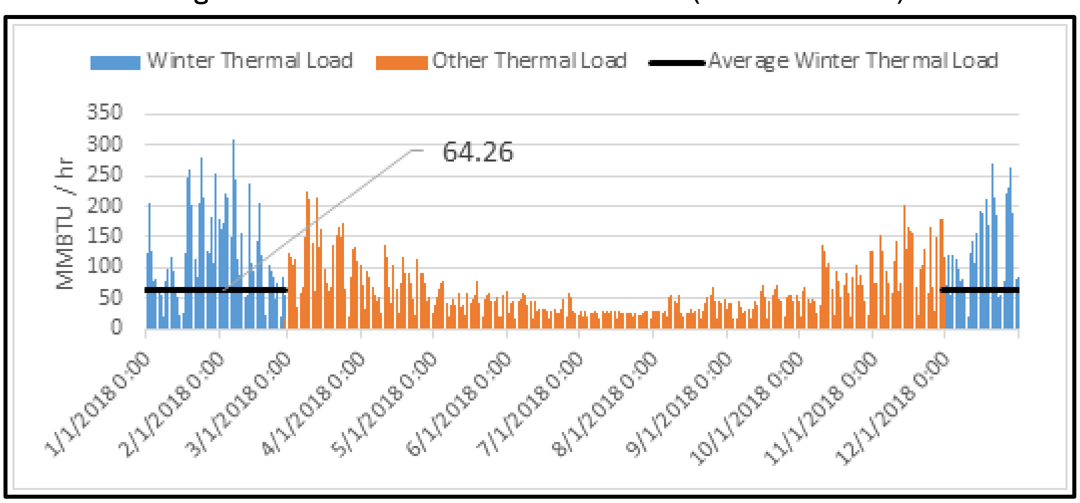
Installation A supplied the PDT with a list of buildings served by central energy plants (central boilers and cogeneration). Of these, only three critical facilities (<2%) matched with these buildings. Since the vast majority of critical facilities at Installation A do not appear to be served by central energy plants, the PDT modeled the critical facilities as having distributed boilers.

To model the thermal needs of the installation, the ERA Web App V5.0 called for the following parameters:

- Average winter thermal load (MMBTU/hr)
- Whether cogeneration is currently installed
- Whether centralized heating is currently installed
- Installed centralized heating thermal capacity (MMBTU).

Figure 3-4 shows the average winter thermal load, extracted from the System Master PLanner tool (SMPL) data.

Figure 3-4. Installation A critical thermal load (modeled in SMPL)



Since <2% of critical facilities had a central heating component and the PDT was not able to determine the quantity of central heating for these facilities, the simulation was run assuming 100% of thermal generation came from building-level distributed boilers.

3.6 ERA Tool input parameters

Table 3-2 shows a few of the main ERA Tool inputs, with all of the details noted in the ERA Web App V5.0 data collection spreadsheet in Appendix A. Installation A personnel had many of the inputs readily available in forms or spreadsheets, such as the utility and outage data along with the generator and fuel storage capacities. However, it was more challenging to obtain information about the electrical distribution system. The electrical grid distribution circuits (44) and utility-connected substations (5) were counted from simplified one-line diagrams supplied from the DPW, so it is possible that there is some detail left out regarding the electrical distribution infrastructure.

Table 3-2. ERA input parameters at Installation A.

Parameter	Metric	Unit
Grid electricity cost	0.05416	$/kWh
Natural gas cost	6.03	$/MMBTU
Total planned and installed solar capacity	1500	kW
Average electrical load	28979	MW
Diesel cost	2.11	$/gal
Diesel fuel storage capacity	1523839	$/yr
Number of distribution units	44	
Number of utility-connected substations	5	
Primary generator capacities	1000	kW
Standby generator capacities	See Fig. 13	
Outage data	See section 3.4	

Additionally, the ERA Web App V5.0 only allows the user to input both installed and planned solar capacity at the same time, so the PDT entered 1500 kW to allow for future solar expansion.

The average electrical load of 28.9 MW noted in Table 3-2 was a specific parameter in the ERA Tool that could potentially have a high degree of inaccuracy. Most Army installations are metered, at best, at the substation level, so getting an accurate estimate on average building load is challenging. The authors created an estimate using the CERL-developed SMPL Tool, which provides a consistent approach to estimating critical loads.

3.7 Installation A ERA results

The PDT chose to run the ERA Tool once with just the electrical infrastructure and a second time with a combination of electrical and thermal infrastructure. This choice was made to see how the addition of thermal infrastructure can impact the tool outputs.

3.7.1 Analysis of electrical infrastructure

The ERA Tool ran 38 energy architectures for the electrical infrastructure at Installation A. Appendix D includes details of each architecture. Figure 3-5 shows the lifecycle cost and resilience for the baseline, 4-day and 14-day black sky scenarios. Of the 38 alternative energy architectures analyzed, four architectures stood out as both less costly and more energy resilient than the baseline energy architecture in all three of the outage scenarios. These scenarios, along with the baseline, are as follows:

- Architecture 2: Existing System on Site (baseline)
- Architecture 3: Central Backup Generators, Microgrid, Grid
- Architecture 4: Central Backup Generators, Building Backup Generators, Microgrid, Grid
- Architecture 11: Central Backup Generators, Microgrid, Islandable PV, Grid
- Architecture 12: Central Backup Generators, Building Backup Generators, Microgrid, Islandable Solar PV, Grid.

Table 3-3 lists and Figure 3-6 shows the architectures that have the potential to have lower life cycle costs and increased resilience. Every alternative scenario incorporated the existing grid and some amount of centralized diesel generation capacity using 1MW units (at a cost of $462K each). A major takeaway is the decrease in lifecycle costs ranging from 2.4%–2.9% for each of the more affordable alternatives, while the amount of unserved energy decreased from 38.6%–47.1% relative to the baseline. Another notable comparison shows how higher use of centralized generators realized about a 9% increase in resiliency, specifically when comparing Architectures 3 and 11 with 39 central generators to Architectures 4 and 12 with only 18.

Figure 3-5. Installation A lifecycle and energy resilience scenarios for (a) baseline (b) 4-day black sky, and (c) 14-day black sky.

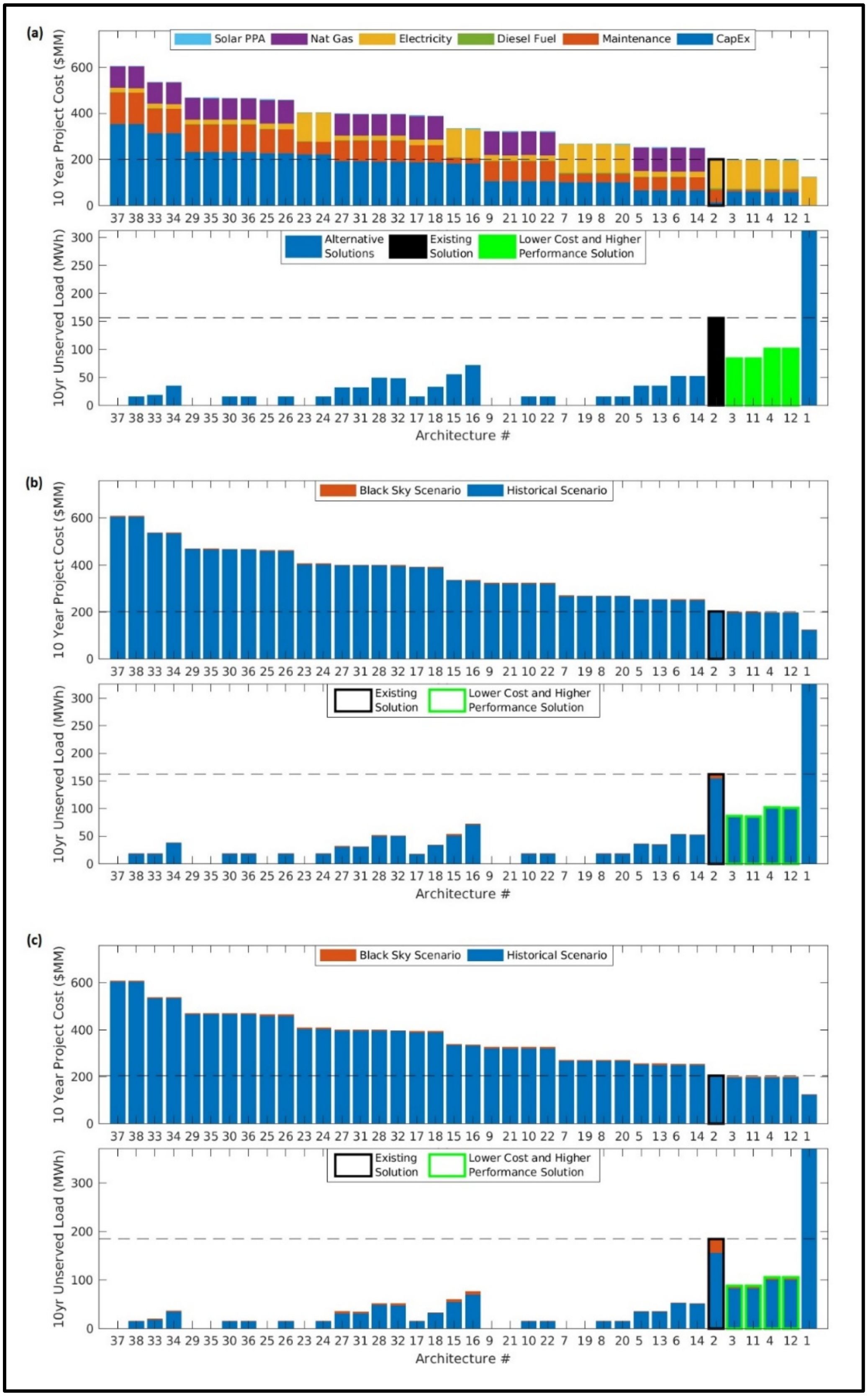
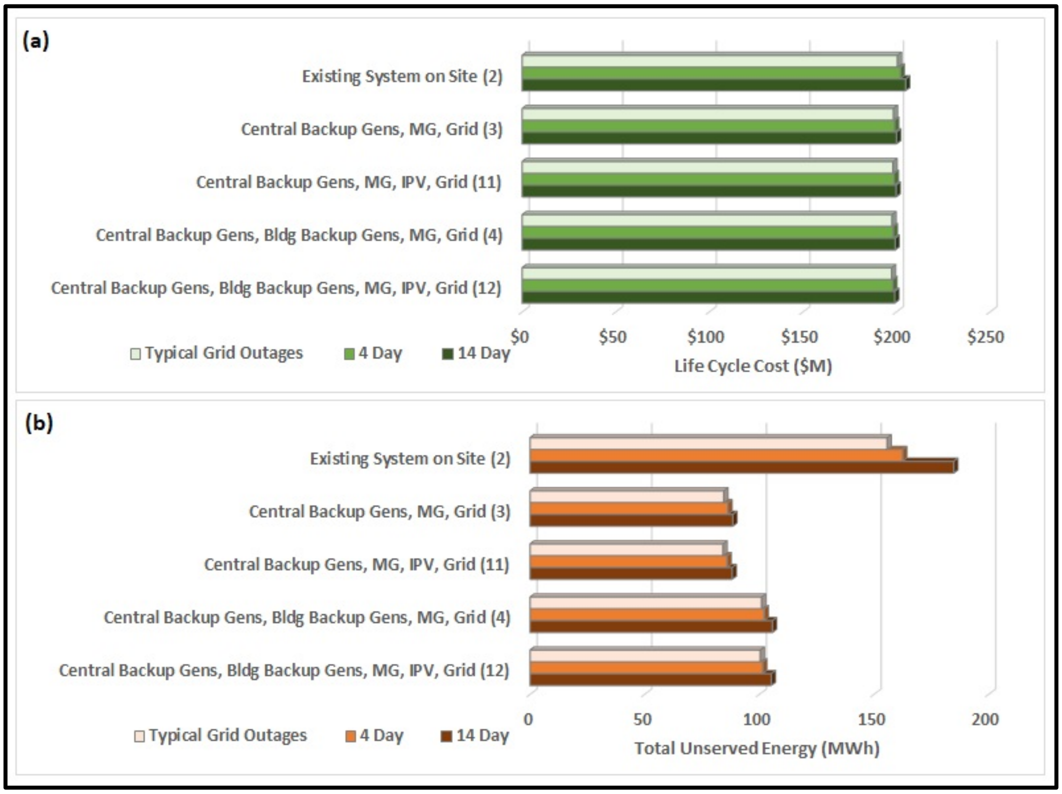


Table 3-3. Equipment and parameters for LCC saving architectures

Equipment	Architecture 2	3	4	11	12
Existing grid	Yes	Yes	Yes	Yes	Yes
Microgrid	Yes	Yes	Yes	Yes	Yes
Islandable solar PV (MW)	0		0	1.5	1.5
Number of central generators (1 MW each)	0	39	18	39	18
Number of building generators (125kW each)	299	0	167	0	167
Life cycle cost ($M)	200.7	198.5	197.8	198.3	197.6
LCC % decrease from baseline	—	2.4%	2.7%	2.5%	2.9%
Unserved energy	162.5	86.3	102.1	85.9	101.4
Unserved energy % decrease from baseline	—	47%	38.6%	47.1%	38.8%

Figure 3-6. (a) LCC and (b) unserved energy of various electrical alternative architectures for typical grid outages, along with 4-day and 14-day black sky outages. Specific architecture numbers are noted in parenthesis.



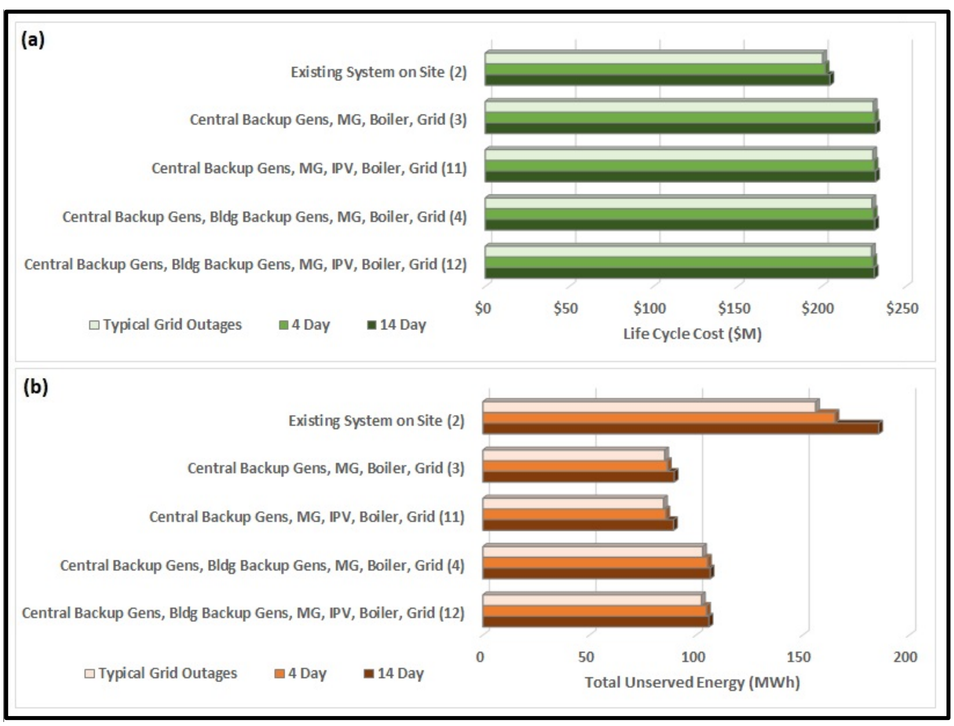
The four alternative architectures with lower LCC still have the possibility of unserved energy, and would likely not meet all critical loads during a 14-day black sky scenario. If achieving zero unserved energy is a requirement, the two most cost effective architectures that meet this requirement are:

- Architecture 19:
  - Central Backup Generators, Microgrid, UPS, Islandable Solar PV, Grid
  - Total LCC \$270.9M or \$66.0M higher than the existing system
- Architecture 7:
  - Central Backup Generators, Microgrid, UPS, Grid
  - Total LCC \$271.2M or \$66.3M higher than the existing system.

3.7.2 Analysis of electrical and thermal infrastructure

The ERA Tool ran 62 alternative energy architectures for the electrical and thermal infrastructure. Appendixes E and F include details of these architectures. In addition to the alternatives in the electrical analysis, this analysis also incorporated central boilers. Figure 3-7 shows the results of this analysis in which the same four basic architectures (3, 4, 11, and 12) have the lowest lifecycle cost, but the incorporation of central boilers into the architecture made them approximately 15% more expensive on a LCC basis compared to the existing system onsite (Figure 3-7a). Figure 3-7b shows that the alternative architectures, which range from 43%–52% more effective in reducing unserved energy compared to the existing infrastructure, are the same effectiveness as the electric-only architectures.

Figure 3-7. (a) Life cycle cost and (b) unserved energy of various electrical and thermal alternative architectures for typical grid outages, along with 4-day and 14-day black sky outages.



4 Methodology Recommendations

4.1 Leverage the SMPL tool for critical loads

One of the most important input parameters for the ERA Tool is the critical load required at an installation. To get this information, the installation will need to have each critical facility's critical circuit (sometimes the whole facility load and sometimes a subset of the facility load) individually metered and have that data readily available for the assessment team to compile. At Installation A, the DPW had only 45 of 183 critical facilities metered and only 25 of those facilities had electric meters. Evidence from the MIT-LL report supports our experience that the installation-critical load can be difficult to measure or estimate (Judson 2016). One method to resolve this, as used by MIT-LL, was to assume that each generator was oversized by 2X and to then use the generator capacities to estimate building loads (Judson 2016). Since this estimate of 2X capacity is an approximation, it could lead to poor performance from the tool. For example, Marqusee et al. (2017) analyzed the feasibility of microgrid adoption at U.S. military installations and found that, for one military installation, "on average, the generator capacity exceeds the peak demand of the corresponding load by 427 percent." The PDT suggests using the SMPL tool to estimate unknown critical loads to more closely approximate the critical load.

At this writing, there is currently an Environmental Security Technology Certification Program (ESTCP) project* also doing a resilience analysis using a building-by-building approach, which would entail co-locating the backup generation and the building load. This approach will help to more closely approximate the energy actually consumed by backup generation during a power outage by geolocating the infrastructure to ensure more realistic analysis. The tool resulting from this ESTCP project will integrate with the SMPL tool.

4.2 Approach to analyzing adverse events

Energy disruptions to mission critical operations on military installations can result from different threats and hazards. Energy supply failures can result from breakdown of external electric utility grids, damage to energy

* ESTCP Fiscal Year 2018 Energy and Water (EW) Project 18-5281. "Technologies Integration to Achieve Resilient, Low-Energy Military Installations." A summary may be found at: https://www.serdp-estcp.org/Program-Areas/Installation-Energy-and-Water/Energy/Conservation-and-Efficiency/EW18-5281.

generation and conversion equipment installed at the installation, and/or damage to internal distribution networks. Failures of certain equipment to perform reliably (e.g., energy generation and conversion equipment and distribution grids) can be attributed to inadequate maintenance or to end-of-equipment-life performance degradation.

Mission critical operations and facilities hosting these operations have significant impacts on the Combatant Commanders' ability to execute their operational plans in a timely manner. In addition to critical facilities identified in the Defense Critical Infrastructure Protection (DCIP) program, which are related to warfighting missions, other critical assets are those that provide life, health, and safety capabilities, that support installation infrastructure, and that support any other critical functions that may be required based on the facilities mission. Requirements for availability, reliability, quality, and type of energy required for mission critical operations and facilities may differ by facility and by mission type.

The approach used in the methodology developed by MIT-LL is based on the analysis of combined energy assets available on the installation. It quantifies their reliability and availability to provide adequate power needs for continuous critical mission operations. Since different threats can disrupt not only external grid operation, but also energy assets and power and thermal grids within the installation boundaries, this tool can have a broader application when enhanced with the following capabilities:

- analysis of impacts from different threats and hazards on performance of assets at a specific location (e.g., loss of transformers, generators and other equipment due to floods, tornados, wild fires, etc.)
- analysis of the power quality required for different mission critical facilities and selection of appropriate technologies based on these needs
- analysis of the impacts of different threats and hazards on distribution system components between specific assets and buildings served by these assets
- enhancement of the tool's database to include more thermal conversion and generation equipment, distribution networks, and thermal storage systems.

4.3 Site visit methodology

During the site visit, it is important to collect as much information for the simulation as possible. It is critical to meet and talk with mission operators who know capabilities required by the mission. During the process of interviewing, it is important to determine if the information is confidential and unavailable, if the information is classified, or if the information is not available because nobody has collected the information. If the information is not available, determine if it can be predicted through modeling and, if so, what assumptions can be used (e.g., as-built drawing for thermal loads, types of operation and lighting systems used, etc.). Among the most critical information required for Energy Resilience Analysis is that data used to determine the mission requirements of energy systems:

- Type of energy required for mission critical operations.
- The length of time power or thermal energy supply can be interrupted without damage to equipment used for the mission. For example, sudden loss of power and power surges can cause damage to computers, but refrigerator will keep food safe for up to 4 hrs and a full freezer will hold the temperature for approximately 48 hrs (24 hrs if it is half full); buildings in Alaska can lose heat for not longer than 4 hrs.
- Power quality metrics based on specific mission requirements.

To plan and analyze different scenarios, it is important to determine:

- What equipment is currently used for the building, and what additional equipment supports the resilience of energy systems serving critical missions (baseline)
- Short-term energy projects, with equipment and services planned and budgeted (to build the Base Case)
- Long-term plans to improve energy systems that support critical missions and the rest of the installation (which may be available through installation's energy plan)
- Different prior emergencies that the installation energy systems have experienced, and any potential threats.

During the site visit, it is important to brainstorm with stakeholders potential architectures to be considered in the analysis. Operation managers and operators, energy managers, and other local team members have a better idea about feasibilities and constraints for different scenarios, experiences with energy-related problems they already had, and perceived threats that will be accounted for when architectures are selected and analyzed.

5 Evaluation Summary for the ERA Web App V5.0

5.1 Strengths

The ERA Tool focuses on ranking projects based on the LCC effectiveness of the project and the project's ability to remove unacceptable energy resilience risks. This meets the DODI 4170.11 requirement to "utilize LCC analysis in making decisions about their investment in products, services, construction, and other projects to lower the Federal Governments' costs and to reduce energy and water consumption."

The analytical strengths of the ERA Tool are:

- The tool has the built-in capability to produce semi-realistic load profiles based on a relatively easy data point, average demand.
- The tool can perform a rough analysis of the Army Directive 2017-07 requirement to "reduce risk to critical missions by being capable of providing necessary energy and water for a minimum of 14 days," by performing a black sky analysis. This analysis determines the installation's resilience based on its ability to supply power when grid power to the installation is cut off. If the user chooses to perform this analysis, the outputs are included in summary figures for comparison of energy alternatives.

Since the ERA Tool has been modified as a web application, **the specific strengths of the ERA Web App V5.0 are:**

- The tool is a web application that can be easily accessed by anyone with valid credentials.
- The tool processes the simulation in the cloud, making the simulation run very quickly.
- The tool tips, limited input parameters, and user-friendly interface make the tool very easy to use (especially compared to the older ERA MATLAB V3.0).
- Users have the option to either choose existing data for an installation or to input new data.
- Users have the option to type in Installation Search.
- Most of the currently required data is appropriate for casual users.
- Data collection spreadsheet is available to guide users in data collection process.

- The tool provides easy-to-read, succinct output graphics for casual user.
- Users have the ability to download input parameters, plots, and results in a spreadsheet format.
- In addition to other download capabilities, power users have the ability to download all of the backend MATLAB parameters for the simulation engine and to view results in depth.

5.2 Weaknesses

The analytical weaknesses of the ERA Tool are:

- All of the generation and storage equipment is rolled up to a single value before the simulation takes place:
  - Generator capacity is rolled up to one number even though distributed generators only serve one load. The implicit assumption is that load sharing is always possible and this is not true.
  - Solar capacity is rolled up to one number.
  - UPS capacities are rolled up to one number. The implicit assumption is that UPS capacity can be shared across the installation's critical infrastructure. This is never the case.
- All of the critical loads are rolled up to a single value before the simulation takes place:
  - The tool uses average load and load profiles.
  - The tool does not allow the user to upload individual loads from their buildings.
- Having rolled up loads and equipment will allow any deficiency at a building, i.e., no backup generation, to not show up in the analysis since excess rolled up capacity could cover those loads even though this could not happen in reality.
- Since there is no geospatial relationship between equipment, such as electrical distribution connections or interconnections, it is not possible to realistically simulate unserved energy.
- The tool could benefit from enhancements to the current database of architectures with state of the art thermal and electrical energy technologies related to energy conversion, distribution, and storage; their combinations; their technical characteristics; costs of installation; and costs of operation. This information should be regularly updated.
- The tool uses a 10-year lifespan for LCC analysis. This is much shorter than the published ERCIP equipment lifespans and unrealistically penalizes technologies with high upfront costs.

- The current list of technologies and measures does not include those related to non-energy solutions that can significantly enhance resilience against different threats, e.g., building a wall around equipment to protect from floods, moving equipment to higher floors, building a shelter around this equipment, burying cables, and connecting power distribution lines in loops. However, in some cases these measures can be incorporated indirectly through changing the MTTF of certain equipment and re-running the simulation (only possible in the ERA MATLAB V3.0).
- The current methodology for operating the tool has no minimum requirement for energy resilience. Operating under the assumption that anything is better than the status quo could lead to unsatisfactory investments.
- Since there is no Base Case specified for the minimum resilience of an installation, there is no way to compare one installation to another based on resiliency. Unserved hours could be a metric if the value from the ERA Tool was not rolled up in the aggregate for the entire installation, and if the varying ability of critical facilities to handle power disruptions was taken into account during the analysis.
- DODI 4170.11 calls for DoD Components to plan for and to have the capability to, “ensure available, reliable, and quality power to continuously accomplish DoD missions from military installations and facilities.” Army Directive 2017-07 calls for “The Army to prioritize energy and water security requirements to ensure available, reliable, and quality power and water to continuously sustain critical mission.” The ERA Tool lacks the ability to analyze the power quality of alternative energy architectures and it does not consider critical loads in *individual buildings* that may be necessary to sustain critical missions.
- The ERA Tool does not take into account:
  - the flexibility and redundancy of distribution networks
  - the quality of power supplied by the energy infrastructure at an installation
  - the ability of an installation’s energy infrastructure to prepare for and recover from specific energy disruptions (e.g., a hurricane, earthquake, or terrorist attack) at a military installation.

The specific weaknesses of the ERA Web App V5.0 are:

- Poor version control process:
  - Users cannot copy, replace, update, or delete previous simulation runs.
  - Users cannot name or add notes to simulation runs.

  - Users cannot rerun a previous simulation, instead they create a new simulation with the same inputs (this will lead to a very crowded workspace in "your run history" with heavy use).
  - User is only able to use the most recent data associated with an installation.
- The tool does not have the built-in capability to run a sensitivity analysis. This would help solidify project rankings when important data are missing or unverified.
- Users are required to input data for primary and standby generators. It is possible that an installation would not have both primary and standby generators.
- The tool lacks a tiered input structure that would allow casual users to see first level of inputs, then a 2nd tier of inputs for more advanced users to control inputs that are installation specific.
- Location and technology-specific parameters are hidden from all users. This could have a detrimental effect on accuracy and the installations ability to reflect improvements in cost, operations, and efficiency.
- Users cannot determine the relationship between inputs from outages and the MTTF and MTTR for the grid and other equipment.
- There is no description of the different architectures on the results page.
- Users cannot review a table of outputs in the ERA Web App V5.0 without having to download the data.
- There is no ability to resize axes. This comes into play with the large differences in unserved energy between architectures.
- The user does not have the ability to manipulate the load profile or output the load profile that the tool develops.
- The user must input installed and planned solar photovoltaic capacity in a single parameter, which causes the tool to assume that planned solar photovoltaic resources reduce grid purchases for the whole life span of the project even though they are likely years from being installed.
- Input page does not clarify that users should only include solar photovoltaic that can be configured to contribute output to critical loads during grid outages.
- It is unclear how the dynamics between centralized generators and feeder level outages are modeled and how this impacts unserved energy in the ERA Web App V5.0.
- The tool does not allow the user to input secondary cost savings from certain technologies or operational changes (e.g., demand response and load-shedding).

5.3 Conclusion

The extent to which these strengths and weaknesses are addressed will depend on the goal of the ERA Tool. If the tool is meant to provide a realistic assessment of installation energy resilience, then the tool would benefit from more detailed LCC analysis and resilience analysis approaches. If the tool is meant to provide a "back of the envelope" roll up report to help installation staff identify new project ideas, then the ERA Web App V5.0 of the ERA Tool is a user-friendly platform for installation staff to perform this high-level analysis; however, the tool could still benefit from some minor improvements in the user interface.

In either case, there will be a tradeoff between user-friendliness and analytical value. The findings from this report can be used to better understand how the tool currently works and to see what improvements are available to either make the tool more analytically robust, user-friendly, or both.

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Acronyms and Abbreviations

Term	Definition
ACSIM	Assistant Chief of Staff for Installation Management
AFB	Air Force Base
ANSI	American National Standards Institute
ASA(IE&E)	Assistant Secretary of the Army for Installations, Energy and Environment
BAT	Large-scale battery for long duration outages
BOIL	Natural gas steam boilers
CCE	Cloud Computing Environment
CERL	Construction Engineering Research Laboratory
CHP	Combined Heat and Power
CHP	Cogeneraton plant
CPG	Comprehensive Procurement Guide
CSV	Comma-Separated Values
DCIP	Defense Critical Infrastructure Program
DHS	U.S. Department of Homeland Security
DLA	Defense Logistics Agency
DoD	U.S. Department of Defense
DODI	Department of Defense Instruction
DPW	Directorate of Public Works
ERA	Energy Resilience Analysis
ERCIP	Energy Resilience and Conservation Investment Program
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
ERDC-ITL	Engineer Research and Development Center, Information Technology Laboratory
ESTCP	Environmental Security Technology Certification Program
FC	Fuel cells that supplement baseload generation
GEN0	Centralized generators for backup power (2 MW)
GEN1	Centralized generators for primary power (2 MW)
GFEBS	General Fund Enterprise Business Systems
GRID	Connection to electricity grid
GSOL	Grid-tied solar PV – does not provide power during outages
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
ISOL	Islandable solar PV – provides power during outages
ISOL	Islandable solar PV – provides power during outages
ISR	intelligence, surveillance, reconnaissance
JB	Joint Base
JBPHH	Joint Base Pearl Harbor–Hickam
LCC	Life Cycle Cost

Term	**Definition**
LCCA	Life Cycle Cost Analysis
LID	Low Impact Development
LNG	Liquefied Natural Gas
MATLAB	**Mat**rix **Lab**oratory
MCDA	Multi-Criteria Decision Analysis
MDMS	Maintenance Data Management System
MILCON	Military Construction
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair/Replace
MW	Megawatt
NET	Microgrid that enables generators to share loading
NET	Microgrid that enables generators to share loading
NIBS	National Institute of Building Sciences
NSN	National Supply Number
O&M	Operations and Maintenance
OMB	Office of Management and Budget
OSA	Office of the Secretary of the Army
OSD	Office of the Secretary of Defense
PAVE PAWS	Precision Acquisition Vehicle Entry Phased Array Warning System
PDT	Project Delivery Team
PPA	Power Purchase Agreement
PV	PhotoVoltaic
RH	Relative Humidity
SAIFI	System Average Interruption Frequency Index (used her to indicate number of outages per year)
SAR	Same As Report
SCE	Southern California Edison
SF	Standard Form
SGEN0	Building-scale diesel generators for backup power (175 – 300kW)
SGEN1	Building-scale diesel generators for primary power (175 – 300kW)
SIR	Savings to Investment Ratio
SMPL	System Master Planner
SMPL-NZP	System Master Planner-Net Zero Planner
SMS	Sustainment Management System
TR	Technical Report
UESC	Utility Energy Service Contract
UPS	Uninterruptible Power System
UPS	UPS battery systems for momentary outages
USD(AT&L)	Office of the Under Secretary of Defense for Acquisition, Technology and Logistics
VTIME	Virtual Testbed for Installation Mission Effectiveness

Appendix A: ERA Web App V5.0 Example Data Collection Spreadsheet

Figure A-1. Data Collection Sheet 1 "General Information"

2	Date	2/13/2019
3		
4	Average critical electrical load (kW)	28979
5	Average hourly thermal load (MMBTU/hr)	0
6	Cost of diesel ($/gal)	2.11
7	Miles to run new gas pipeline	10
8	Fuel storage on base (gal diesel)	1523839
9	Base latitude	35
10	Area Cost Factor	0.89
11		
12		
13	**Generation Technologies**	
14	**Cogeneration**	
15	Installed Thermal Capacity (MMBTU)	0
16		
17	**Large Centralized Boilers**	
18	Installed Thermal Capacity (MMBTU)	0
19		
20	**Fuel Cell**	
21	Installed Electrical Capacity (kW)	0
22		
23	**Solar**	
24	Total solar PV capacity (kW)	335
25	Solar PPA or owned?	Owned
26		
27	**Storage Technologies**	
28	**Batteries**	
29	Installed battery capacity (kWh)	0
30	**UPS**	
31	Total installed UPS capacity (kWh)	0
32		

Installed Technologies	
Natural Gas Service	Installed
Electrical Grid tie-in	Installed
Prime Generators	Not Installed
Microgrid	Not Installed
Large Batteries	Not Installed
UPS	Not Installed
Islandable Solar	Not Installed
Grid-Tied Solar	Installed
Fuel Cells	Not Installed
Combined Heat and Power	Not Installed
Boilers	Not Installed

Gas Conversion Calculator			
1	BTU	0.00	MMBTU
1	cubic ft (cf)	0.00	MMBTU
1	Ccf	0.10	MMBTU
1	Mcf	1.04	MMBTU
1	Therm	0.10	MMBTU

	Electrical Bills	Total Billed Amount ($)	Total Electrical Consumption (kWh)
34	January	3065103.006	57973850
35	February	2776379.486	53274844
36	March	2728279.808	53081230
37	April	2623783.078	51365165
38	May	2849329.113	56882699
39	June	3771225.198	64692996
40	July	4336850.281	73156080
41	August	4207293.202	72545673
42	September	3661338.983	62869445
43	October	2932951.035	53749284
44	November	2692771.013	49303622
45	December	2807797.321	52983344
46	**Average rate ($/kWh)**	0.054786001	

Gas Bills	Total Billed Amount ($)	Total Gas Consumption (MMBTU)
January	1085220.07	205925.3
February	924666.8848	180773.6
March	560479.9612	117546
April	396530.8254	96045.8
May	327279.1915	75070.5
June	262744.1324	57436.8
July	290875.914	51828
August	277235.1996	51671.2
September	300263.3359	54815.3
October	389871.4657	72790.5
November	689255.0021	118133
December	1157585.095	180874.6
Average rate ($/kWh)	5.275121673	

Figure A-2. Data Collection Sheet 2 “Grid Reliability”

	A	B	C	D	E	F
1	Number of Electrical Substations	5				
2	Distribution Circuits	44				
3	Years of Data input	3				
4	Outage Date	Location	Location Description	Duration (hours)	System	Type 1= feeder outage, 2=substation outage, 3= utility outage
5				2.75		1
6				0.83		1
7				2		1
8				14		1
9				2.67		1
10				1		1
11				0.98		2
12				1.38		3
13				0.75		1
14				1.6		2
15				1		1
16				0.5		1
17				1		2
18				0.33		1
19				1.17		3
20				0.68		1
21				0.55		1
22				0.25		2
23				6		3

Figure A-3. Data Collection Sheet 3 “Generation."

	A	B	C	D	E	F	G	H	I	J
1	Backup Generation			Prime Generation						
2	Capacity list (kW)	Facility Number		Capacity list (kW)	Facility Number					
3	7			1000			Power Conversion Calculator			
4	10						1	hp	0.7457	kW
5	11						1	Btu/hr	0.000293	kW
6	12									
7	12									
8	12									
9	15									
10	15									
11	15									
12	15									
13	17									
14	18									
15	19									
16	20									
17	20									
18	20									
19	20									
20	20									
21	20									
22	25									
23	25									
24	25									
25	25									
26	25									
27	25									
28	25									

Appendix B: ERA MATLAB V3.0 User-Defined Variables

Table B-1. User-defined variables.

Function	User-Defined Variables
ERA	• alpha: scaling factor that is applied to electrical load. The baseline estimated load is in the technology setup file. • scenario: selects which installation parameters to simulate. • endurance: enables the code to perform simulation of black sky events and their effect on unserved load and architecture costs. 1 = standard outages with a black sky outage, 0 = standard outages. • black_sky: duration of the black sky outage in days (i.e., 14 days). • FuelDays: amount of diesel fuel reserves stored on the installation, which can be number of days of operation (1-365) or total number of gallons stored (i.e., 5e4). Any number greater than 365 will be treated as a gallon amount. • Repair: simulates the effect of having limited or no additional personnel on the installation to repair failed components. 1 = component failures are repaired, 0 = no repairs are made during extended outages. • BaselineArch: baseline for cost delta. • Nruns: select the number of simulations to perform. • DieselTanks: 1 = additional tanks required, 0 = unlimited offsite fuel. • LNGtrucks: 1 = Liquefied natural gas (LNG) truck only, 0 = functional pipeline. • blacksim: 0 = regular outage events, normal fuel usage. 1 = black sky event, fuel cutoff once reserve depleted. ▪ NOTE: comment says "DO NOT MODIFY" • gen_rebuy: purchase new generators as old ones fail. 0 = no rebuy, 1 = rebuy at rebuy_rate • rebuy_rate: percentage repurchased on an annual basis • SolarImport: 1 = import solar site data, 0 = generate data • LoadImport: 1 = import load site data, 0 =generate data • ThLoadImport: 1 = import load site data, 0 = generate data

Function	User-Defined Variables
GenerateArchitectures	• All of the architecture variables for each installation • Centralized generators that are always running (primary power) • Centralized generators that are in standby mode (backup power) • Building generators that are always running (primary power) • Building generators that are in standby mode (backup power) • Microgrid that enables generators to share loading • Large-scale battery for long duration outages (primary power) • UPS battery systems for momentary outages (backup power) • Islandable solar PV (provide power during outages) • Grid-tied solar PV (non-functioning during outages) • Fuel cells that serve as baseload generation asset • Cogeneration plant that is thermal load following • Natural gas steam boilers that serve thermal load • Connection to the electricity grid
Outage_scenarios	• alpha: scaling factor that is applied to electrical load. The baseline estimated load is in the technology setup file. • scenario: selects which installation parameters to simulate. • endurance: enables the code to perform simulation of black sky events and their effect on unserved load and architecture costs. 1 = standard outages with a black sky outage, 0 = standard outages. • black_sky: duration of the black sky outage in days (i.e., 14 days). • FuelDays: amount of diesel fuel reserves stored on the installation, which can be number of days of operation (1-365) or total number of gallons stored (i.e., 5e4). Any number greater than 365 will be treated as a gallon amount. • Repair: simulates the effect of having limited or no additional personnel on the installation to repair failed components. 1 = component failures are repaired, 0 = no repairs are made during extended outages.
SetupBoiler	• Boil = structure of boiler parameters ○ Therm = Rated capacity (MMBTU) ○ Cost = overnight cost of boiler ($) ○ OMCost = annual O&M cost ($) ○ Curve = Fuel use curve [50 x 2] (MMBTU heat V. MMBTU fuel)

Function	User-Defined Variables
SetupCogen	• Cogen = structure of cogeneration parameters ○ Cap = rated electrical capacity (kW) ○ Therm = Rated thermal capacity (MMBTU) ○ Cost = Overnight cost of cogeneration ($) ○ OMCost = annual O&M cost ($) ○ .Curve = Fuel use curve [50 x 3] (kW v. MMBTU fuel v. mmBTU heat)
SetupFailures	• Wshape: shape of the Weibull distribution for failures
SetupFCell	• FCell = structure of fuel cell parameters ○ Cap = Rated electrical capacity (kW) ○ Cost = overnight cost of fuel cell ($) ○ OMCost = annual O&M cost ($) ○ Curve = Fuel use curve [50 x 2] (kw v. MMBTU fuel)
SetupGen	• Gen = structure of boiler parameters ○ Cap = Rated electrical capacity (kW) ○ Cost = Overnight cost of generator ($) ○ OMCost = annual O&M cost ($) ○ Curve = Fuel use curve [50 x 2] (kW v. gallons fuel) ○ SCap = Rated electrical capacity (kW) ○ SCost = Overnight cost of generator ($) ○ SOMCost = annual O&M cost ($) ○ SCurve = Fuel use curve [50 x 2] (kW v. gallons fuel)
SetupLoad	• loadfilename: the name of the load data file to be imported into the tool • sheet: the sheet number with relevant data in the excel file • xlrange: the cell range with the relevant data in excel
SetupSolarIrradiance	• solfilename: the name of the solar data file to be imported into the tool • sheet: the sheet number with relevant data in the excel file • xlrange: the cell range with the relevant data in excel
SetupTechnology	• Load.avg: Average load [kW]. • Load.type: 1=flat, 2=diurnal, 3=spikes, 4=real, 5=weekend&diurnal, 6=weekend&diurnal&seasonal. • Load.rand: sigma on load (scaled to max load). • Load.depth: amplitude of diurnal pattern (normalized). • Thermal.avg: Average load [MMBTU].

Function	User-Defined Variables
	• Thermal.type: 1=flat, 2=diurnal, 3=spikes, 4=real, 5=weekend&diurnal, 6=weekend&diurnal&seasonal. • Thermal.rand: sigma on load (scaled to max load). • Thermal.depth: amplitude of diurnal pattern (normalized). • Cost.fuel: $/gallon. • Cost.natgas: $/million BTU. • Cost.NGint: $/mile natural gas pipeline. • Cost.grid: $/kWh. • Cost.solar: $/kWh *found that roughly 20% discount applied to most states. • Cost.Life: Lifetime of devices (years). • Cost.ri: Inflation rate from 2016 Office of Management and Budget (OMB) 10 year. • Cost.dr: Discount rate from 2016 OMB 10 year. • Cost.fueltank: [$ gal] cost for new fuel storage from Defense Logistics Agency (DLA) Military Construction (MILCON) search. • Cost.LNGtruck: [$ MMBTU] cost and capacity for LNG truck from Internet search. • Cost.fuelstor: gallons of diesel fuel stored on the installation. • Cost.DRrate: demand response rate for large generation assets [$/kW/year]. • SAIFI: number of outages per year. • Grid.MTTF: Mean time to failure [hr]. • Grid.MTTR: Mean time to repair/replace [hr]. • Grid.IntCost: Cost to wire in grid [$]. • Grid.OMCost: O&M cost of grid per year [$/yr]. • Grid.DistCost: Distribution system cost [$]. • Grid.DistOM: Distribution O&M cost [$/yr]. • BGenModel: Which centralized generator to use. • SGenModel: Which building generator to use. • Gen: Make generator efficiency curve: • Gen.MTTF: Mean time to failure [hr] (IEEE 493-2007 p.238). • Gen.MTTR: Mean time to repair/replace [hr] (IEEE 493-2007 p.238). • Gen.Fraction: % Startup time for generator(1 minute) [dt]. • SGen: Make generator efficiency curve: • GenPairs: joining the two gen structs into one struct. • Gen: Renaming the combined struct to match convention. • Bat.Charge: charge rate of battery.

Function	User-Defined Variables
	• Bat.Discharge: discharge rate of battery. • Bat.Days: number of days battery can sustain base. • Bat.Hours: number of hours battery will sustain. • Bat.Eff Round trip efficiency (incl. rect/invert). • Bat.Cap Capacity [kWh]. • Bat.MTTF: Mean time to failure [hr] (IEEE 493-2007 p.227) but changed to be more realistic. • Bat.MTTR: Mean time to repair/replace [hr] (IEEE 493-2007 p.227) changed to be more realistic. • Bat.Cost1: Cost of unit [$/kWh]. • Bat.OMCost1: O&M cost per unit per year [$/yr/kWh]. • Ups.Charge: charge rate of UPS assuming LiPo. • Ups.Discharge: discharge rate of UPS assuming LiPo. • Ups.Eff: Round trip efficiency (including rect/invert). • Ups.Cap: Capacity [kWh]. • Ups.MTTF: Mean time to failure [hr] (IEEE 493-2007 p.227) but changed to be more realistic. • Ups.MTTR: Mean time to repair/replace [hr] (IEEE 493- 2007 p.227) but changed to be more realistic. • Ups.Cost1: Cost of unit [$/kWh]. • Ups.OMCost1: O&M cost per unit per year [$/yr/kWh]. • Sol.MTTF: mean time to failure [hr]. • Sol.MTTR: mean time to repair/replace [hr]. • Sol.Avg: average available solar energy [kW/m^2]. • Sof.Eff: efficiency of solar panel. • Sol.Cap: [kW] solar capacity is set to 10x the mean load by default. • Sol.Cost: cost to install solar panels [$]. • Sol.OMCost: O&M cost per unit per year [$/yr]. • Sol.Latitude: latitude of location (Boston, MA is the default). • Sol.Clear: number of clear days. http://www.currentresults.com/Weather/US/average-annual-sunshine-by-city.php • Sol.Cloud: number of fully cloudy days (search for "cloudy days in [city] per year" and use Current Results website). • Sol.Sunny: percentage of annual possible sunshine. http://www1.ncdc.noaa.gov/pub/data/ccd-data/pctposrank.txt • Net.MTTF: mean time to failure [hr]. • Net.MTTR: mean time to repair/replace [hr]. • Net.IntCost: Cost to wire in microgrid [$].

Function	User-Defined Variables
	• Net.OMCost: O&M cost of microgrid per year [$/yr]. • CHPModel: Which cogen plant. • Cogen: Make cogen efficiency curve: • Cogen.MTTF: Mean time to failure [hr] (IEEE 493-2007 p.241). • Cogen.MTTR: Mean time to repair/replace [hr] (IEEE 493-2007 p.241). • FCellModel: Which fuel cell. • FCell: Make fuel cell efficiency curve. • FCell.MTTF: mean time to failure [hr]. • FCell.MTTR: mean time to repair/replace [hr]. • BoilerModel: Which boiler. • Boil: Make boiler efficiency curve. • Boil.MTTF: mean time to failure [hr] (IEEE 493-2007 p.228). • Boil.MTTR: mean time to repair/replace [hr] (IEEE 493-2007 p.228).
SetupThermal-Load	• thloadfilename: the name of the thermal load data file to be imported into the tool • sheet: the sheet number with relevant data in the excel file • xlrange: the cell range with the relevant data in excel
SetupVariables	• dt: time step [hr] • Tdays: total sim time [days] • NOTE: comment says “DO NOT CHANGE” • Tfinal: number of timesteps in the simulation • noiseseed: 0 = “shuffle” random number generation, any other number = set seed for repeatable range 713691030
Vgfig	• font • linewidth • sizefig

Appendix C: ERA MATLAB V3.0 Variables No Longer User-Accessible in the ERA Web App V5.0

Table C-1. Variables no longer user-accessible in the ERA Web App V5.0.

Impacted Technology or Parameter	Locked or Automatically Generated Variables
Boilers	• Purchase cost ($) • Annual O&M cost ($) • Fuel use curve (efficiency) • Boiler model • Mean time to failure (MTTF) (hr) • Mean time to repair/replace (hr)
Cogeneration	• Rated electrical capacity (kW) o Note: Tool does not distinguish between cogeneration generators and other types of backup generators • Purchase cost ($) • Annual O&M cost ($) • Fuel use curve (efficiency) • Cogen model • MTTF (hr) • Mean time to repair/replace (hr)
Fuel Cells	• Purchase cost ($) • Annual O&M cost ($) • Fuel use curve (efficiency) • Fuel Cell Model • MTTF (hr) • Mean time to repair/replace (hr)

Generators	• Purchase cost ($)
	• Annual O&M cost ($)
	• Fuel use curve (efficiency)
	• Centralized generator model
	    o Note: Tool no longer handles centralized and building generators separately
	• Building generator model
	    o Note: Tool no longer handles centralized and building generators separately
	• MTTF (hr)
	• Mean time to repair/replace (hr)
	• Startup time for generator (min)

Impacted Technology or Parameter	Locked or Automatically Generated Variables

Load (Electric and Thermal)	• Electric load file upload
	  ○ Note: Tool no longer allows user to upload actual load data
	• Electric load profile (flat, diurnal, spikes, real, weekend & diurnal, weekend, diurnal, & seasonal)
	• Electric load depth (amplitude of diurnal pattern)
	• Thermal load file upload
	  ○ Note: Tool no longer allows user to upload actual load data
	• Thermal load profile (flat, diurnal, spikes, real, weekend & diurnal, weekend, diurnal, & seasonal)
	• Thermal load depth (amplitude of diurnal pattern)

Solar PV	• Solar insolation file upload
	  ○ Note: It appears that the solar insolation data may be stored in the tool based on the installation's location.
	• Average available solar energy (kW/m^2)
	  ○ Note: It appears that the solar insolation data may be stored in the tool based on the installations location.
	• Solar electricity cost ($/kWh)
	• MTTF (hr)
	• Mean time to repair/replace (hr)
	• Solar panel efficiency
	• Purchase Cost ($)
	• O&M cost per unit per year [$/yr]
	• Latitude of installation
	  ○ Note: This may be stored in the tool based on which installation is selected
	• Number of clear days.
	  ○ Note: This may be stored in the tool based on which installation is selected
	• Number of fully cloudy days
	  ○ Note: This may be stored in the tool based on which installation is selected
	• Percentage of annual possible sunshine
	  ○ Note: This may be stored in the tool based on which installation is selected

SetupVariables	• Total simulation time (days)
LCC Assessment Parameters	• Lifetime of devices (years) • 10-year Inflation rate from OMB (2016) • 10-year Discount rate from OMB (2016) • Cost for new fuel storage ($/gal)

Impacted Technology or Parameter	Locked or Automatically Generated Variables
Electricity Grid	• MTTF (hr) o Note: Most likely calculated from a combination of "outage type," "outage duration," "number of distribution circuits," and "number of utility-connected substations" • Mean time to repair/replace (hr) o Note: Most likely calculated from a combination of "outage type," "outage duration," "number of distribution circuits," and "number of utility-connected substations" • Cost to wire in grid [$] • Annual grid O&M cost [$/yr] • Distribution system cost [$] • Annual distribution O&M cost [$/yr] • Demand response rate [$/kW/year]
Natural Gas Infrastructure	• Natural gas cost ($/million BTU) • Natural gas pipeline cost ($/mile natural gas pipeline) • LNG truck cost ($ MMBTU)
Batteries	• Battery charge rate • Battery discharge rate • Time battery will sustain charge (hours or days?) • Round trip efficiency (incl. rect/invert) • MTTF (hr) • Mean time to repair/replace (hr) • Cost ($/kWh) • Annual O&M cost ($/yr/kWh)
UPS	• Charge rate (assuming LiPo) • Discharge rate (assuming LiPo) • Round trip efficiency (including rect/invert) • MTTF (hr) • Mean time to repair/replace (hr) • Cost ($/kWh) • Annual O&M cost ($/yr/kWh)
Microgrid	• MTTF (hr) • Mean time to repair/replace (hr) • Cost to wire in microgrid ($) • Annual O&M cost of microgrid ($/yr)

Appendix D: Equipment Sizing Methodology in ERA MATLAB V3.0

D.1 Diesel generators

"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)" (Judson 2016).

"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" (Judson 2016).

D.2 Solar photovoltaic systems

"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" (Judson 2016).

D.3 Uninterruptable power supply systems

"The UPS system in the 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" (Judson 2016).

D.4 Large-scale battery systems

"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" (Judson 2016).

D.5 Combined heat and power generation

"The tool used a cogeneration plant (a natural gas-fired combined-cycle gas turbine) that could produce 3 MW of electricity with 20 million British thermal units (BTU) 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" (Judson 2016).

D.6 Fuel cells

"The tool used a 1 MW fuel cell farm – solid oxide fuel cell (SOFC) technology – that was fueled by natural gas, and the total capacity was sized according to the minimum constant load at each installation" (Judson 2016).

Appendix E: ERA Electrical Architectures Analyzed for Installation A

Table E-1. ERA electrical architectures analyzed for Installation A.

Architecture Number	Technologies
1	Grid
2	Existing System on Site
3	Central Backup Gens,MG,Grid
4	Central Backup Gens,Bldg Backup Gens,MG,Grid
5	Central Primary Gens,Central Backup Gens,MG,Grid
6	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,Grid
7	Central Backup Gens,MG,UPS,Grid
8	Central Backup Gens,Bldg Backup Gens,MG,UPS,Grid
9	Central Primary Gens,Central Backup Gens,MG,UPS,Grid
10	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,UPS,Grid
11	Central Backup Gens,MG,IPV,Grid
12	Central Backup Gens,Bldg Backup Gens,MG,IPV,Grid
13	Central Primary Gens,Central Backup Gens,MG,IPV,Grid
14	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,IPV,Grid
15	Central Backup Gens,MG,Batt,IPV,Grid
16	Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,Grid
17	Central Primary Gens,Central Backup Gens,MG,Batt,IPV,Grid
18	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,Grid
19	Central Backup Gens,MG,UPS,IPV,Grid
20	Central Backup Gens,Bldg Backup Gens,MG,UPS,IPV,Grid
21	Central Primary Gens,Central Backup Gens,MG,UPS,IPV,Grid
22	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,UPS,IPV,Grid
23	Central Backup Gens,MG,Batt,UPS,IPV,Grid
24	Central Backup Gens,Bldg Backup Gens,MG,Batt,UPS,IPV,Grid
25	Central Primary Gens,Central Backup Gens,MG,Batt,UPS,IPV,Grid
26	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,Batt,UPS,IPV,Grid
27	Central Backup Gens,MG,FC,Grid
28	Central Backup Gens,Bldg Backup Gens,MG,FC,Grid
29	Central Backup Gens,MG,UPS,FC,Grid
30	Central Backup Gens,Bldg Backup Gens,MG,UPS,FC,Grid
31	Central Backup Gens,MG,IPV,FC,Grid
32	Central Backup Gens,Bldg Backup Gens,MG,IPV,FC,Grid
33	Central Backup Gens,MG,Batt,IPV,FC,Grid
34	Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,FC,Grid
35	Central Backup Gens,MG,UPS,IPV,FC,Grid

Appendix F: ERA Electrical and Thermal Architectures Analyzed for Installation A

Table F-1. ERA electrical and thermal architectures analyzed for Installation A.

1	Grid
2	Existing System on Site
3	Central Backup Gens,MG,Boiler,Grid
4	Central Backup Gens,Bldg Backup Gens,MG,Boiler,Grid
5	Central Primary Gens,Central Backup Gens,MG,Boiler,Grid
6	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,Boiler,Grid
7	Central Backup Gens,MG,UPS,Boiler,Grid
8	Central Backup Gens,Bldg Backup Gens,MG,UPS,Boiler,Grid
9	Central Primary Gens,Central Backup Gens,MG,UPS,Boiler,Grid
10	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,UPS,Boiler,Grid
11	Central Backup Gens,MG,IPV,Boiler,Grid
12	Central Backup Gens,Bldg Backup Gens,MG,IPV,Boiler,Grid
13	Central Primary Gens,Central Backup Gens,MG,IPV,Boiler,Grid
14	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,IPV,Boiler,Grid
15	Central Backup Gens,MG,Batt,IPV,Boiler,Grid
16	Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,Boiler,Grid
17	Central Primary Gens,Central Backup Gens,MG,Batt,IPV,Boiler,Grid
18	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,Boiler,Grid
19	Central Backup Gens,MG,UPS,IPV,Boiler,Grid
20	Central Backup Gens,Bldg Backup Gens,MG,UPS,IPV,Boiler,Grid
21	Central Primary Gens,Central Backup Gens,MG,UPS,IPV,Boiler,Grid
22	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,UPS,IPV,Boiler,Grid
23	Central Backup Gens,MG,Batt,UPS,IPV,Boiler,Grid
24	Central Backup Gens,Bldg Backup Gens,MG,Batt,UPS,IPV,Boiler,Grid
25	Central Primary Gens,Central Backup Gens,MG,Batt,UPS,IPV,Boiler,Grid
26	Central Primary Gens,Central Backup Gens,Bldg Backup Gens,MG,Batt,UPS,IPV,Boiler,Grid
27	Central Backup Gens,MG,FC,Boiler,Grid
28	Central Backup Gens,Bldg Backup Gens,MG,FC,Boiler,Grid
29	Central Backup Gens,MG,UPS,FC,Boiler,Grid
30	Central Backup Gens,Bldg Backup Gens,MG,UPS,FC,Boiler,Grid

31	Central Backup Gens,MG,IPV,FC,Boiler,Grid
32	Central Backup Gens,Bldg Backup Gens,MG,IPV,FC,Boiler,Grid
33	Central Backup Gens,MG,Batt,IPV,FC,Boiler,Grid
34	Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,FC,Boiler,Grid
35	Central Backup Gens,MG,UPS,IPV,FC,Boiler,Grid
36	Central Backup Gens,Bldg Backup Gens,MG,UPS,IPV,FC,Boiler,Grid
37	Central Backup Gens,MG,Batt,UPS,IPV,FC,Boiler,Grid
38	Central Backup Gens,Bldg Backup Gens,MG,Batt,UPS,IPV,FC,Boiler,Grid
39	Central Backup Gens,MG,CHP,Boiler,Grid
40	Central Backup Gens,Bldg Backup Gens,MG,CHP,Boiler,Grid
41	Central Backup Gens,MG,UPS,CHP,Boiler,Grid
42	Central Backup Gens,Bldg Backup Gens,MG,UPS,CHP,Boiler,Grid
43	Central Backup Gens,MG,IPV,CHP,Boiler,Grid
44	Central Backup Gens,Bldg Backup Gens,MG,IPV,CHP,Boiler,Grid
45	Central Backup Gens,MG,Batt,IPV,CHP,Boiler,Grid
46	Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,CHP,Boiler,Grid
47	Central Backup Gens,MG,UPS,IPV,CHP,Boiler,Grid
48	Central Backup Gens,Bldg Backup Gens,MG,UPS,IPV,CHP,Boiler,Grid
49	Central Backup Gens,MG,Batt,UPS,IPV,CHP,Boiler,Grid
50	Central Backup Gens,Bldg Backup Gens,MG,Batt,UPS,IPV,CHP,Boiler,Grid
51	Central Backup Gens,MG,FC,CHP,Boiler,Grid
52	Central Backup Gens,Bldg Backup Gens,MG,FC,CHP,Boiler,Grid
53	Central Backup Gens,MG,UPS,FC,CHP,Boiler,Grid
54	Central Backup Gens,Bldg Backup Gens,MG,UPS,FC,CHP,Boiler,Grid
55	Central Backup Gens,MG,IPV,FC,CHP,Boiler,Grid
56	Central Backup Gens,Bldg Backup Gens,MG,IPV,FC,CHP,Boiler,Grid
57	Central Backup Gens,MG,Batt,IPV,FC,CHP,Boiler,Grid
58	Central Backup Gens,Bldg Backup Gens,MG,Batt,IPV,FC,CHP,Boiler,Grid
59	Central Backup Gens,MG,UPS,IPV,FC,CHP,Boiler,Grid
60	Central Backup Gens,Bldg Backup Gens,MG,UPS,IPV,FC,CHP,Boiler,Grid
61	Central Backup Gens,MG,Batt,UPS,IPV,FC,CHP,Boiler,Grid
62	Central Backup Gens,Bldg Backup Gens,MG,Batt,UPS,IPV,FC,CHP,Boiler,Grid

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14. ABSTRACT
This report is an evaluation of the Energy Resilience Analysis (ERA) tool developed by the Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) to explore its capabilities and its potential for implementation across U.S. Army installations. The project delivery team (PDT) reviewed the tool’s functions and documentation, ran simulations, and reviewed data inputs required from installations. The PDT found that the ERA Tool does provide a user-friendly automated analytical framework for installation staff to perform energy resilience assessments with a focus on availability and reliability of energy with life cycle cost as a primary decision criterion. However, the ERA Tool does not account for the flexibility and redundancy of distribution networks, the quality of power supplied by the energy infrastructure at an installation, or the ability of an installation’s energy infrastructure to prepare for and recover from specific energy disruptions. Also, the current methodology does not take into account a minimum resilience requirement to guide decision makers through the selection process. The PDT acknowledges that MIT-LL’s approach was to develop a high-level planning tool for energy resilience assessment, which they did successfully. This report explores the potential consequences of this analysis approach and makes recommendations for improvements to the ERA Tool.

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