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A METHODOLOGY FOR RISK ASSESSMENT TO IMPROVE THE RESILIENCE AND SUSTAINABILITY OF CRITICAL INFRASTRUCTURE WITH CASE STUDIES FROM THE UNITED STATES ARMY

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ABSTRACT

Reliable performance of energy and water infrastructure is central to the mission readiness of the United States Army. These systems are vulnerable to coordinated attacks from an adversary as well as disruption from natural events. The objectives of this work were to investigate Army installations in North America, identify best practices for improving the resilience and sustainability of critical energy and water infrastructure, and develop a framework and methodology for analyzing the resilience of an installation under varying outage scenarios. This work was accomplished using a multi-layered decision process to identify unique case studies from the 117 active-duty domestic Army installations. A framework for analyzing and assessing the resilience of an installation was then developed to help inform stakeholders. Metered energy and water data from buildings across Fort Benning, GA were curated to inform the modeling framework, including a discrete-event simulation of the supply and demand for energy and water on the installation using ProModel. This simulation was used to study the scale of solutions required to address outage events of varying frequency, duration, and magnitude, the combination of which is described as the severity of outages at a given site. This project helps develop a framework to inform how installations might meet Army Directive 2020-03, which states that installations must be able to sustain mission requirements for a minimum of 14 days after a disruption has occurred.

Keywords: Energy, Water, Resilience, Infrastructure

1. INTRODUCTION

Army Directive 2020-03 establishes the requirement that installations be able to sustain mission critical operations for 14 days in the event of an outage. The impetus for this directive is the recognition that the United States Army will be impaired if installations are denied energy and water resources. In partnership with the Office of the Deputy Assistant Secretary of the Army for Installations, Energy, and Environment (ODASA IE&E), a team at the United States Military Academy (USMA) has investigated opportunities to improve the resilience of installations. This body of work describes some of the initial findings and methodologies from the research effort.

The 2021 Texas power outage serves as a prime example of the cascading effects of outages [1]. The outage stemmed from an extreme cold weather event that, among other things, froze water pipes across the state. The lack of water flow created an immediate issue for citizens due to the lack of running water, but it also caused a follow-on issue by shutting down natural gas power plants therefore cutting off electricity to millions of consumers [2]. The isolation of the Texas power grid prevented electricity from being allocated from other states. Prior to the event, many energy stakeholders in the state of Texas had not prepared equipment for the possibility of extreme low temperatures that persisted for numerous days, resulting in devastating effects. These stakeholders include the Electric Reliability Council of Texas (ERCOT), natural gas suppliers, power plant operators, electricity and water utilities, local municipalities, residential and commercial building owners, and nearly every other major institution in the state that is tasked with sourcing, managing, and delivering energy to consumers. A "black swan event," as described by Nassim Nicholas Taleb, "lies outside the realm of regular expectations, carries an extreme impact," and is "retrospective," as "humans concoct explanations for its occurrence after the fact, making it explainable and predictable [3]." If such an outage occurred on an Army installation, the potential impact could be immense, showcasing a necessary change in how such events are considered in measuring resilience standards. As will be described herein, this body of work resulted in the modeling of

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diverse outage scenarios, the assessment of how changes to energy infrastructure could improve resilience, and the development of a framework for measuring outage costs at Army installations.

2. LITERATURE REVIEW

Resilience can be broadly defined as a system's ability to recover from failure, with two nuanced definitions. Engineering resilience draws attention to "efficiency, constancy, and predictability" which represent the core values of fail-safe engineering design [4]. Ecological resilience emphasizes the importance of "persistence, change, and unpredictability" as critical to the definition of a resilient system. A deviation from these two base definitions is the concept of adaptive resilience which assumes that a system undergoes constant change and will never "return" to a state of equilibrium after a disruption [5]. United States Code Title 10 defined military installation resilience as the "capability of a military installation to avoid, prepare for, minimize the effect of, adapt to, and recover from extreme weather events, or from…changes in environmental conditions, that…adversely affect the military installation or essential transportation, logistical, or other necessary resources…that are necessary in order to maintain, improve, or rapidly reestablish installation mission assurance and mission-essential functions" [6]. This definition of system resilience adequately encompasses all the nuances in US Army doctrine and published orders. It is narrowly tailored to meet the strictest definition of resilience, to ensure the goal of consistent mission readiness.

To meet the goal of increasing energy resilience one must understand the basic sources and definitions of energy and power. The majority of primary energy supply in the United States is sourced from fossil fuels; however, deployment of renewable sources such as wind and solar has grown [7]. The Energy Information Administration (EIA) defines renewable energy as "energy from sources that are naturally replenishing but flow-limited; renewable resources are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time [8], [9]." In the case of an energy outage, "critical mission operations on domestic military installations for the Department of Defense (DoD) use backup sources of power to protect against the failure of the domestic electric utility grid [10]." Most Army installations use diesel generators for backup power, but renewables offer additional appeal for they are often grid-connected [11]. The connection to the grid allows for redundancy of energy production capability, and an opportunity to net meter power production and generate income in the event the renewable asset is producing excess power at a given moment. A greater employment of renewables could help increase the net resiliency gain of installations across the country [12].

Emergency Diesel Generators (EDGs) are the most common form of backup power used for critical loads in the event of a grid failure [13]. On an Army installation, the reliability of EDG varies based on size of post due to differing critical loads of energy that must be produced. The reliability of an EDG is directly affected by the state of maintenance and measurable by operational availability, probability that the generator will fail to start, the mean time until failure, and the mean time between failures [13], [14].

A battery energy storage system (BESS) may be deployed to prevent the loss of critical loads and reduce electrical demand charges by providing load shifting, dynamic local voltage support, short-term frequency smoothing, grid contingency support, and reduce the need for fossil-fuel-based energy generation [15], [16]. In some cases, a BESS can act as a direct replacement of an EDG; however, BESS are limited in terms of duration compared with an EDG if ample supply of diesel is available. The configuration of a BESS is a key factor to assessing its reliability and resilience within specific systems. The total reliability of a traditional BESS is less than the reliability of its individual components since traditional BESS designs connect components in series [17]. In a reconfigured BESS (RBESS) the failure of one battery module does not cause the entire BESS to fail. In an RBESS, each battery module is controlled by its own individual converter module. In the event of a failure, the battery module can be isolated or replaced without causing system failure [17]. These BESS are used in partnership with traditional energy generation such as EDGs. Aggregated BESS are used for renewable energy sources and consist of multiple BESS [18]. The reliability of an ABESS is determined by "up" and "down" time, defining operational time. This type of system is designed to be connected to a microgrid. The usage of a BESS system depends heavily on the requirements of the system, which will yield differing levels of reliability and value towards resiliency.

Microgrids (MG) are "electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded" [13]. Adding MGs to Army installations would allow the system to remain functional in the case of an event where the system lost connection to the main power network.

The reliable access to potable water through water treatment systems is of primal importance for human life and Army operations. Throughout all factors of the water system, there were two general findings on how to improve resilience. The use of backup generation and system redundancies were the two strongest ways to improve water system resiliency [18], [19]. In practice, this could be a decentralized system with multiple small-scale plants that are individually more vulnerable to breakdown or attack, but produces a more resilient system the system is stronger [19].

The electric grid in the United States is characterized by three main subsections: generation, transmission, and distribution. Energy generation encompasses traditional fossil fuel generation in addition to opportunities for the use of alternative fuels. U.S. electricity markets have wholesale and retail components. Wholesale markets involve the sale of electricity among electric utilities and electricity traders before it is sold to consumers. Retail markets involve the sale of electricity to consumers. Wholesale and retail markets can incorporate regulated and competitive structures. Competitive market structures typically use price signals to incentivize electricity production and may allow customers to choose between competitive suppliers. In ERCOT, the energy market is composed of day-ahead and the real-time markets. The real-time market involves transactions that take place at varying frequency (e.g. once every hour versus once every five minutes) to help match supply and demand. Energy markets and capacity markets differ in that capacity markets use regulated pricing and incentives to ensure sufficient spare generation capacity is available to meet variations in electricity demand. Customers in regulated markets typically face higher prices for renewable energy than those in competitive markets [20].

3. MODELING METHODOLOGY

The objective of modeling outages is to assess the overall energy resilience of an Army installation. Fort Benning, Georgia was used as a case study while developing the modeling methodology. The ability to model the resilience of the installation was done by leveraging the discrete event simulation capability of *ProModel*. High resolution energy data, in terms of spatial and temporal details, were curated for Fort Benning. The use of the dataset as well as the simulation constructed in *ProModel* allowed for discrete simulations of Fort Benning's energy supply, energy demand, and a history of outage events. The simulation within *ProModel* treats generation assets and buildings as supply and demand nodes, respectively (i.e. as sources and sinks of energy). The nodes are connected by simulated transmission lines which deliver discrete packets of energy to balance supply and demand. The four model input variables are electricity demand, electricity supply, normal outages, and black swan outages. In the event of an outage, the supply side is cutoff, resulting in a deficit of energy for the remaining sources of demand. Outages of varying severity could be modeled by changing the frequency, magnitude, and duration of the energy deficit.

In the absence of an outage, the electricity supply and demand at the installation is assumed to be equal, as would be expected for any functional electric grid. Thus, the consumption dataset that was collected from Fort Benning allowed for a quantification of the necessary supply requirements for the installation. Some critical assumptions for the energy structure of Fort Benning are as follows: each month out of the year has a distinct hourly demand curve, which is created using both monthly metered data from each building on Fort Benning between the years 2014-2019 and hourly consumption from the EIA for the southeastern region of the United States [21]. The metered monthly data is converted into average monthly consumption for each of the 60 months within the data set. Next, the average monthly consumption is filtered to an average daily consumption value for each of the 60 months by dividing by the number of days in the month. Lastly, the average daily consumption by month throughout the entire five years is created. The average daily consumption value is then applied on a fractional basis to the hourly consumption curve for each month of the year using the demand data from the EIA. The final product is 12 distinct, 24-hour consumption curves representing an average day for each month of the year at Fort Benning. These average days were repeated for every day of the relevant month with the inclusion of stochastic variations in the magnitude of the demand curves to capture similar behavior to what is seen day-to-day as a result of changes in weather, for example. Notional examples of the consumption curves for February and July are provided in Figure 1 showing the summer-peaking behavior due to large air conditioning loads and more mild winters in Georgia.

The inclusion of outage information and modeling of more severe outages is one of the valuable contributions of this work. Fort Benning's normal outage are based on empirical data that quantifies three different outage variables – frequency, duration, and magnitude – from the year 2020. While these outages are important, the model developed herein focuses on the potential impact of a black swan event affecting Fort Benning. A sensitivity analysis approach was used to consider the wide-ranging possibility of what a large, unforeseen outage event might do to the installation. The goal of the sensitivity analysis was to illustrate the methodology for assessing energy resilience by altering the three critical variables that define the outage event: duration, frequency, and magnitude.

The outage event variables are input into the model with separate informed probability distributions. Figure 2 illustrates three potential probability distributions for each outage variable: frequency, duration, and magnitude. The exponential distribution, PDF1, represents the most likely scenario in terms of all three variables. For example, for most outages, the duration of that outage will be very small. Similarly, for the large majority of outages, the damage of that outage will be relatively minuscule. However, a small percentage of outages have the potential to be a black swan event, where the duration and magnitude of those events are abnormally large, creating catastrophic energy shortage circumstances for an Army installation. Each case explored by the modeling methodology will illustrate how an installation's energy is impacted given a certain outage variable condition.

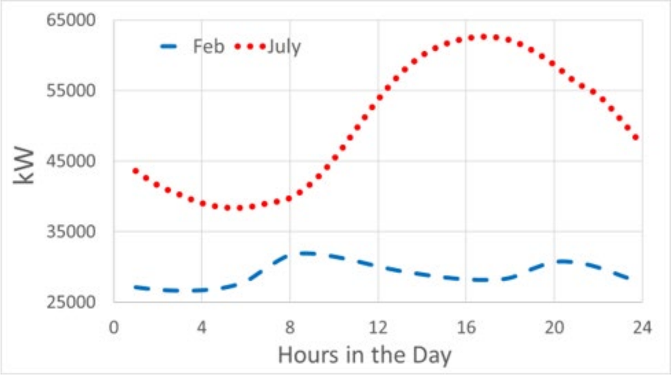

FIGURE 1: NOTIONAL EXAMPLE OF FORT BENNING MONTHLY ENERGY DEMAND CURVES FOR FEBRUARY AND JULY.

The potential damage caused by a large hurricane was used to help scale the average magnitude of a hypothetical black swan events. For clarity: hurricanes are not black swans because the storms are a well understood risk. However, hurricanes do provide abundant data in terms of the potential scope of damage that can be caused from a catastrophic weather event. While the probability of a hurricane directly hitting Fort Benning is low, the possibility of a catastrophic event is still possible, whether it be natural or manmade.

Based on National Oceanic and Atmospheric Administration (NOAA) data displayed in Figure 3, the return period for a major hurricane striking along the Georgia-Alabama border is about once every 40 years [22]. The potential for a major storm event to occur once every 40 years was thus defined as the 50th percentile of each frequency distribution. Furthermore, the 50th percentile for each magnitude distribution was approximately 56% of installation energy being wiped out by a potential outage based on normalized damage data from category 5 hurricanes in the United States over the past 100 years. Lastly, given the recent winter storm event in Texas that affected power for about a week, the 50th percentile for duration of outage was defined as one week. Based on these 50th percentile values, probability distributions were developed for each of the outage variables (e.g. exponential decay for magnitude of a possible outage event).

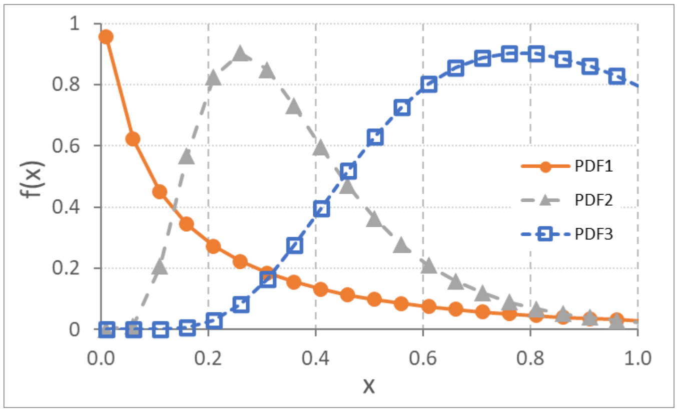

FIGURE 2: NOTIONAL AND NONDIMENSIONALIZED PROBABILITY DISTRIBUTION FUNCTIONS TO COMPLETE SENSITIVITY ANALYSIS OF FREQUENCY, DURATION, AND MAGNITUDE OF OUTAGE EVENTS.

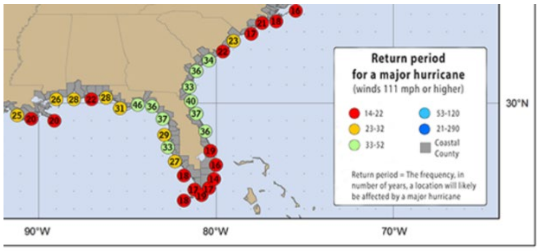

FIGURE 3: MAJOR HURRICANE RETURN PERIOD [22]

4. MODELING RESULTS

One hundred years of energy supply and demand at Fort Benning were modeled using the discrete event simulator. Figure 4 shows an overview of these 100 years. In this figure, energy supply is shown in green, energy demand is shown in blue, and outage impact is shown in orange. Three black swan events are highlighted in red boxes. In these large events, outage impact affects over 50% of installation energy supply. It is also possible to examine their large duration when zooming in to these specific instances.

Figure 5 shows year 19 (i.e. hours 166,440—175,200) of the 100-year simulation, zoomed in on the left most black swan event from Figure 4. This shows greater resolution of the energy supply and demand curves and the outages affecting them. Each month has varying energy demand based on input demand curves as described in Section 3, and this difference is more pronounced here. The difference between supply and demand is also more visible. Figure 5 is meant to provide further context on what is being modeled on a monthly and yearly basis.

Figure 6 shows the same black swan event as Figure 5 zoomed in to a two-week period. This figure shows what happens in the model once an outage occurs. Prior to an outage, demand equals supply. When an outage happens, supply decreases based on whatever the magnitude of the outage is that has appeared stochastically. Figure 6 shows the literal gap between supply and demand once an outage occurs by showing that supply no longer matches demand.

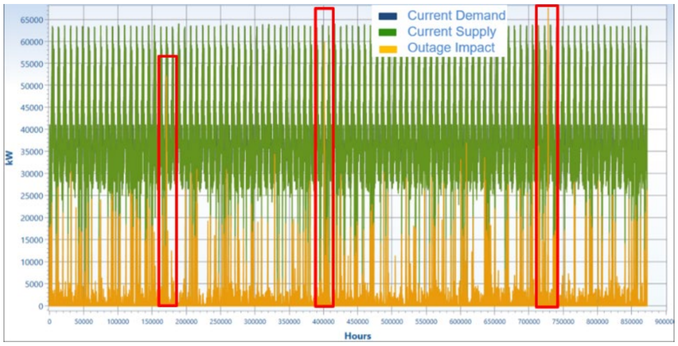

FIGURE 4: 100-YEAR SIMULATION OF ENERGY SUPPLY AND DEMAND AT FORT BENNING, INCLUDING BLACK SWAN OUTAGE EVENTS.

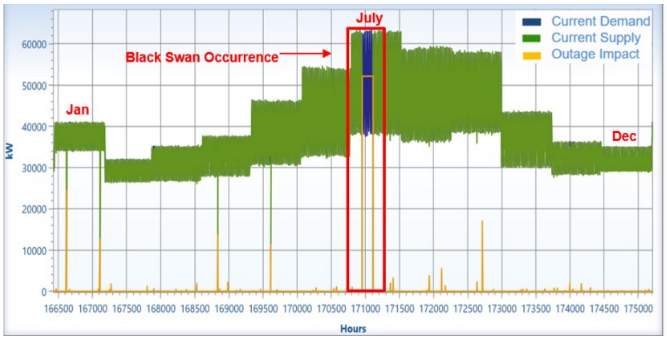

FIGURE 5: ONE YEAR OF 100-YEAR SIMULATION AT FORT BENNING.

Figure 7 shows the same two-week span as Figure 6 with an added example generator. In the model, the amount of energy needed to make supply and demand equal again during an outage is calculated and displayed, shown by the gray curve. While this happens, the amount of cumulative backup energy required to close the gap between supply and demand for the duration of the outage is shown by the black curve. With these outputs, it is possible to further investigate energy and fuel requirements to cover simulated outages.

Figure 8 demonstrates a plausible method for achieving the requirements outlined in Army Directive 2020-03. This method involves decreasing energy demand when a large outage occurs to the level needed to only cover the requirements for the installation's most critical facilities. In the case of this model, critical facilities were assumed to account for 25% of normal demand. The same outage event that was depicted in Figure 5 is shown here. However, in the example provided in Figure 8, it is assumed the installation electricity demand also decreases to the level needed to only cover critical facilities when an outage occurs. This strategy would involve actively cutting load to ensure that critical facilities remain operational. Installation energy managers using this modeling methodology in the future would be able to make more informed assumptions regarding the proportion of critical energy needs on an installation.

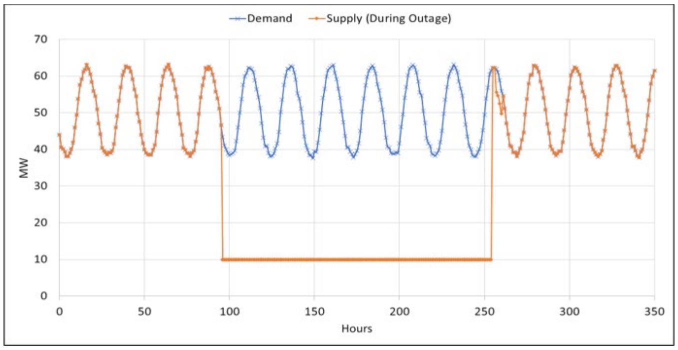

FIGURE 6: TWO WEEK SPAN EXPERIENCING 156 HOUR BLACK SWAN EVENT.

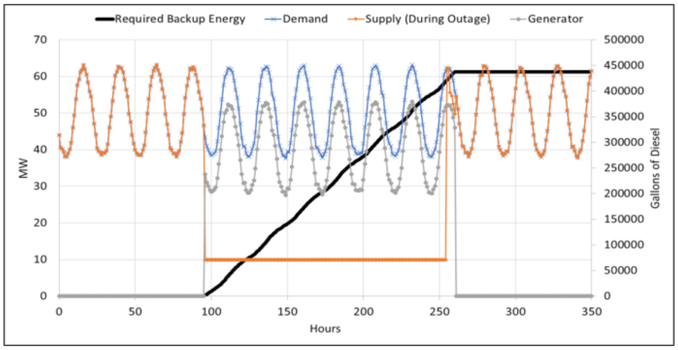

FIGURE 7: TWO WEEK SPAN EXPERIENCING 156 HOUR BLACK SWAN EVENT WITH GENERATOR AND REQUIRED BACKUP ENERGY NEEDED TO COVER OUTAGE.

Figure 9 shows the energy generation and fuel requirements for covering an outage where demand is decreased. This example is meant to demonstrate the potential effectiveness of decreasing energy demand to only cover critical facilities when a large outage occurs while simultaneously operating backup generation assets. Doing so significantly decreases the amount of generated energy and cumulative fuel needed to cover the outage. For this example, generation and fuel requirements were less than a tenth of what was needed to cover an outage when energy demand beyond critical facilities was also included (i.e. the example shown in Figure 7). As a reminder, all of the modeled results shown in Figures 6—9 are based on the magnitude of the outage that was identified in the 100-year simulation from Figures 4 and 5. The only difference in Figures 6—9 is the exploration of how an installation might respond to the outage event by either providing greater backup generation assets or by cutting loads that are not critical to meeting missions requirements.

Figure 10 shows the notional relationship between energy reliability and marginal cost as informed by the results of the model. For this figure, only the marginal cost of fuel is considered; fuel storage infrastructure, distribution, and maintenance costs are not included. As reliability increases from 95% to 98%, the increase in cost is nearly linear. However, above 98% the increase is exponential. This relationship is expected as marginal benefits would decrease as

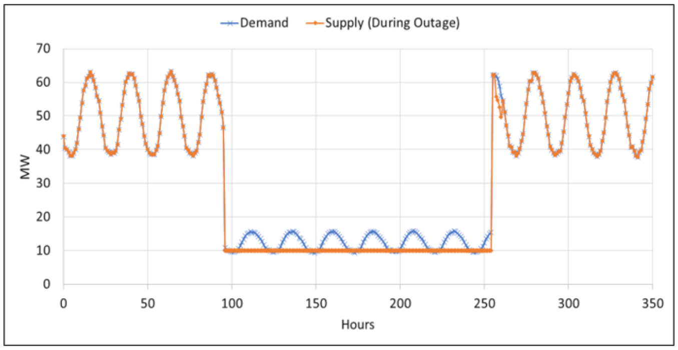

FIGURE 8: TWO WEEK SPAN RESPONDING TO 156 HOUR BLACK SWAN EVENT BY DECREASING DEMAND TO ONLY COVER CRITICAL FACILITIES.

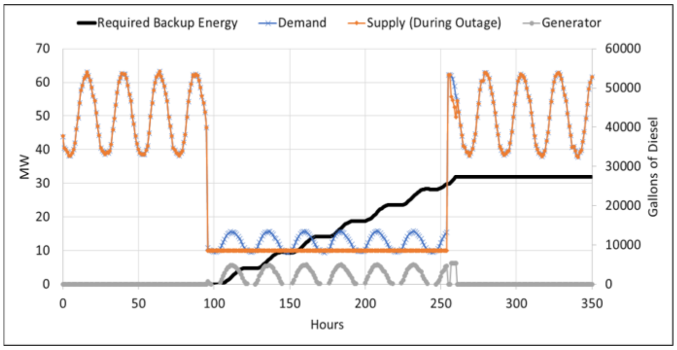

FIGURE 9: GENERATOR AND REQUIRED BACKUP ENERGY NEEDED TO RESPOND TO 156 HOUR BLACK SWAN EVENT WHILE DECREASING DEMAND TO ONLY COVER CRITICAL FACILITIES.

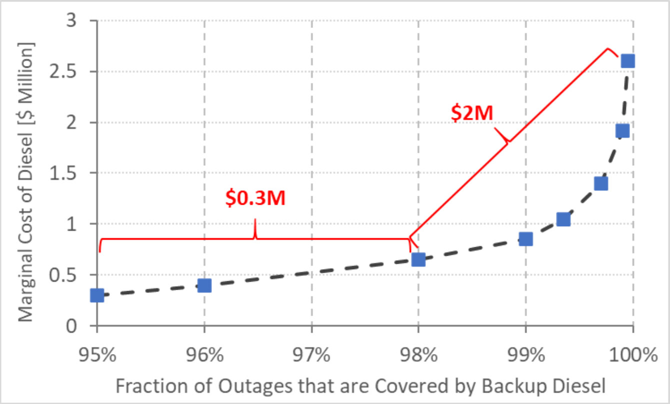

FIGURE 10: NOTIONAL RELATIONSHIP BETWEEN RELIABILITY AND FUEL COST BASED ON OBSERVED RESULTS FROM MODEL.

an installation's energy system becomes more reliable. Factoring in infrastructure, distribution, and maintenance in future work would yield a similar, albeit more drastic, relationship due to the significant costs these factors would add.

The purpose of this outage model is to provide a methodology for simulating possible outages and unplanned events and informing recommendations for responding to them. Several assumptions could be refined in future work. The three distributions for black swan events could be refined for various worse case scenarios that an installation energy manager would like to plan for their given installation. Furthermore, the amount of demand needed to cover critical facilities could also be improved with installation-specific insight. Of note, the results presented here often depicted gallons of diesel as the fuel requirement to cover outages. This was used as a point of reference. The model can be used to calculate the necessary energy (or water) required to cover an outage, and a number of alternative fuels or technologies could be applied in the same way diesel was used here.

5. OUTAGE COST METHODOLOGY

The objective of the outage cost methodology is to create a better understanding of the cost of outages to the mission of the United States Army and the Department of Defense. Current cost design methodology devalues the most extreme outage events by using probabilities of occurrence when measuring cost [23]. Creating projects that solve these black swan events are often not deemed cost effective. Due to the mission of the Army, these events must be considered and, in some cases, prioritized. Army Directive 2020-03 outlines the expectation of maintenance of operations in the event of a 14-day outage event, which would fit the classification of a black swan event. This framework will be a generalized approach to gauging the costs to infrastructure failure and to weigh the benefits of applying alternatives.

5.1 Pre-Outage

1: Determine the total cost of operations at an installation.

The first step is to determine the cost of operations on a dollars per soldier per day basis (i.e. $Cost_{daily}$). This will achieve the goal of determining the level of resources that go into producing the defense ability of the Army. The broadest way to determine this value is to divide the annual budget of the installation and its units, $Cost_{annual}$, by the number of soldiers on the installation and then by the days in a year, as shown below.

$$Cost_{daily} = \frac{Cost_{annual}}{\text{\# of soldiers} \times 365\ \text{days/yr}} \qquad (1)$$

Ideally, the total cost should be split among the various sectors or nodes on the installation. This can be done multiple ways, with one possibility being levels of 'critical,' 'essential,' and 'enhancing,' to describe the importance of a particular node to the overall mission of the installation.

2: Map infrastructure relationships.

With available information, the relationships of the infrastructure systems on the installation can be determined. This includes the routing of power, water, and telecommunication utilities across an installation, allowing managers to determine the full extent of an outage on an installation.

3: Assign cost-time relationships.

For each node, there will be a cost-time relationship, $f_i(t)$. This relationship will depend on the function of the node and its relative importance. The cost of an outage may increase linearly, exponentially, or even logarithmically over the course of an outage and must be developed with an understanding of the mission of the installation.

5.2 Post-Outage

4: Track extent and duration of outage.

For the outage, consider all the nodes that are affected by the outage event. This will include the level to which performance is degraded. In this respect, performance can be degraded to varying levels depending on the setup of the infrastructure systems to include complete loss of function.

5: Sum the costs of all affected nodes.

With the established time functions and cost per hour of operation, the costs over the entire outage event, $Cost_{total}$, can be summarized. The end state of this step is a single value dollar amount. An example for how the calculations would be organized is shown in the following function.

$$Cost_{total} = \sum_{i=1}^{n} f_i(t) \qquad (2)$$

6: Establish the parameters of an alternative.

With an alternative, one must establish the parameters under which it will function. This includes the costs of construction and operation, as well as how the alternative will function to change the magnitude, duration, or frequency of outages.

7: Measure impact of alternative on outage event.

Using the same outage event, determine the change in the outage. Changes in the magnitude, duration, or extent of the outage will influence what the final cost of the outage is. The difference between the cost before the alternative and after is the benefit of implementing the alternative.

8: Determine the Benefit-Cost ratio for an alternative.

For the implementation of an alternative, it will be viewed as beneficial if the benefits of the alternative outweigh the costs. As previously stated, the benefit is defined as the difference in the cost of the outage before and after the alternative is introduced (i.e. $Cost_{outage}$ minus $Cost_{outage\ with\ alternatives}$). The benefit-cost ratio, $\frac{B}{C}Ratio$, is then defined as

$$\frac{B}{C}Ratio = \frac{Cost_{outage} - Cost_{outage\ with\ alternatives}}{Capital\ Costs + O\&M\ Costs} \qquad (3)$$

where $Capital\ Costs$ include capital expenses (e.g. cost to purchase and install hardware) and $O\&M\ Costs$ are operation and maintenance costs.

The complete methodology is displayed in the graphic of Figure 11. Each box represents a step associated with the numeric order of the steps discussed in Sections 5.1 and 5.2 (i.e. the yellow numbers in the bottom right corners of each box are the corresponding sequence).

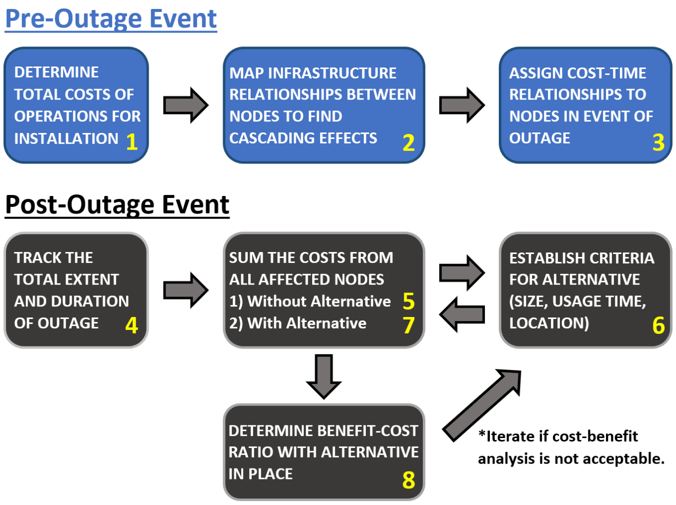

FIGURE 11: GRAPHICAL REPRESENTATION OF THE METHOD TO DETERMINE THE COST OF AN OUTAGE WITH AND WITHOUT IMPLEMENTATION OF ALTERNATIVES.

6. CASE STUDY RESULTS

The methodologies and results presented in Section 3, 4, and 5 focused on the supply and demand of energy (e.g. kWh) to showcase functionality of how to measure and respond to an outage event. The same methods can be applied to water infrastructure, except instead of measuring kWh the model might be focused on millions of gallons (MG). This section provides three case studies to showcase hypothetical results of the methodology when applied to two energy-focused scenarios and one water-focused scenario. For clarity: these case studies are not intended to provide a detailed assessment of the interrelated nature of energy and water that can result in cascading failures of infrastructure.

Case Study #1- This case study mimics the black swan event that was modeled in *ProModel*. Interpreted as a real-life event, this is 50-year, severe weather event that directly hits Fort Benning, damaging ~56% of electricity capacity for a duration of seven days. This magnitude corresponds to 39 MW of electric power removed from the system. Informed by knowledge of the Fort Benning energy demand, it is assumed that 20 MW are removed from normal operations that are not mission essential (e.g. housing), another 15 MW from mission enhancing (e.g. dining facilities), and the final 4 MW from mission critical nodes (e.g. telecommunications). The alternative will be 15 MW of mobile generation, to be emplaced within 10 hours of an outage.

Case Study #2- A coordinated attack by foreign actors damages both water treatment plants that feed to Fort Benning. Repair time is estimated at seven days. There is assumed to be a total of 4 MG of water located in water tanks throughout Fort Benning, enough for one day of average consumption. The alternative in this situation is purchasing 11 3,000gph reverse osmosis water purification units (ROWPUs) to satisfy 15% of the water demand on post. This amount of water is assumed to meet the basic human consumption and operational requirements, the most critical operations.

Case Study #3- Outages occur intermittently on post due to acts of nature and downed power lines. On average there are 10 events annually, at an average magnitude of 5 MW. The alternative for this case study is routing 3 MW from a solar field in the event of outages. It is assumed that these outages do not influence the performance of mission-critical nodes. The alternative would decrease the magnitude of a given outage, but not the duration.

Table 1 shows the breakdown for each of these case studies, to include their outage costs, implementation costs, and benefit-cost ratio. In all three case studies, the benefit to cost ratio was greater than 1, signifying that all alternatives would bring a positive impact on the installation. The case studies were evaluated without probability, in that it is assumed that the outage magnitude will happen. As previously stated, traditional cost estimation for outages factors in the probability of an event, such as a 150-year storm. For the Army, considering events as a definite event may be a necessary step to build secure infrastructure systems. Using probability to determine whether to implement resilient infrastructure would be akin to using the

TABLE 1: CASE STUDY RESULTS

	#1 15MW of Mobile Generators	#2 11-3,000 gph ROWPUs	#3 3-MW Solar Power
Outage Cost (1)	$763,000,000	$415,000,000	$210,000,000
Outage Cost (2)	$260,000,000	$166,000,000	$126,000,000
Benefit	$503,000,000	$249,000,000	$84,000,000
Implement. Cost	$20,000,000	$21,000,000 [24]	$17,000,000
B/C Ratio	25:1	12:1	5:1

probability of an attack in combat on whether to build defenses. As a result, it is likely that probability-based cost estimation undervalues implementing alternatives to improve energy and water resilience.

These case studies were simplified by setting specific frequencies and magnitudes of outages. They were manufactured using knowledge of the installation, but also kept vague to not cause security issues. The manipulation of outage variables and parameters is at the discretion of those most familiar with the situation of the installation. To determine costs, the amount of energy or water lost was treated as a percentage of functionality. In case study 2, the assumption was made that a percentage decrease in water availability corresponds to a same percentage decrease in functionality. For all nodes this would not be the case, but in this case study it made the most sense from a security perspective.

The benefit to cost ratio of the different case studies are clearly influenced by the time-cost functions. Case studies 1 and 2 both include exponential functions for elements of the outage. Case study 1 was particularly extreme, given the outage scenario and the assumptions made in locating the impacts of the outage. This was not the case with the periodic minor outages in case study 3, with the outages not being located in a mission-critical area. In practice, determining the time-cost relationships for nodes on an installation are not the job of a single person. It requires knowledge of both the essential missions of the installation and the status of power and water distribution. If costs were only estimated by the magnitude of an outage, there would be the possibility of overlooking the critical nature of specific infrastructure nodes that could have disproportionally high impacts on the mission readiness of an installation even if the magnitude, duration, or frequency of the outage event was small.

The case studies and alternatives discussed herein also demonstrate the necessity for planned fuel storage. Both the generator and ROWPU use diesel as fuel, with each having a set rate of consumption to produce its necessary output on an hourly basis. For the mobile generation, the fuel requirement is a product of the power production, the fuel consumption rate, and the hours that the generators are online. For case study #1, the diesel requirement is gallons. In practice, the fuel does not need to be stored completely on Fort Benning, as long as a supply chain can be maintained. Furthermore, auxiliary fuel storage (e.g. two-weeks of diesel consumption for ROWPU) kept onsite at Fort Benning could be considered to help address concerns regarding interruption of the supply chain.

7. CONCLUSIONS

Army installations must have energy and water resilience to successfully project force to fight and win the Nation's wars. In the event of a large outage or damaging event, energy and water can become limiting factors to mission readiness. This work helps develop a framework for analyzing the infrastructure requirements and associated cost of addressing outage events of varying frequency, duration, and magnitude. A case study approach was used to further highlight how resilience can be understood in the context of maintaining mission readiness for the Army. While historical outage data can be used to predict the probability of future outages, robust planning should also consider events that are unforeseen. The chance of a black swan event remains a threat for all installations. A different manner of estimating outage costs can help to demonstrate the true impact of extreme outage events. In the Army, the ability to deploy and defend the Nation is the produced good; the cost of metered electricity is not the true cost of an outage. By factoring in the impact of an outage over time and weighing it against an alternative, energy managers and installation commanders can make better decisions about securing their ability to function during an outage event. The methods developed in this study can help inform the decision-making process for installations across the Army, and may be applied more broadly to other critical infrastructure in the civilian and public sectors.

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