Electric Power Resilience Metrics for Grid-Tied Military Installations

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***Abstract*—This paper proposes quantitative resilience evaluation metrics to drive informed investment on U.S. military installations. Metrics evaluate utility feeder redundancy, on installation electric power generation, the fuel mix of that generation, the power and energy capabilities of energy storage systems, the resilience of the distribution system, and the ability to form microgrids to serve critical load. These metrics are applied to provide a baseline for a notional military installation developed from real-world and hypothetical data, and to four scenarios to see the impacts of generation, energy storage, fuel storage and microgrid capabilities. The proposed resiliency metrics can be applied with commonly available information without detailed models and simulation of distribution systems. As a result, this approach is suitable to inform project selection and investment in projects to achieve resiliency goals.**

***Index Terms*—Distributed generation, energy infrastructure resilience, microgrids, power system resilience, resilience metrics**

I. Introduction

A. Background

There are a myriad of laws and policies emphasizing the significance of resilient electrical power systems for U.S. military installations. In recent years, the Department of Defense has emphasized the importance of energy and water resilience, highlighting the need for installations to assess and mitigate risks associated with electricity supply disruptions [1]. Furthermore, 10 U.S. Code § 2911 emphasizes the development and implementation of energy resilience measures, including the establishment of plans to demonstrate energy flexibility and the cost-effectiveness of micro-reactors at domestic military installations. More specifically, 10 USC 2911 directed establishment of metrics and standards to assess energy resilience of U.S. military installations in 2024 [2]. There is also a requirement for U.S. military installations to maintain energy independence for 14 days as outlined in [3].

B. Intent

Many DoD energy resilience projects are funded through the DoD Energy Resilience and Conservation Investment Program (ERCIP) [4]. Assessing resilience improvements on proposed projects is a challenge, impacting how to best direct funding for the greatest impact. To the author's knowledge, there are currently no resilience evaluation tools in use across the DoD for this purpose. In ERCIP projects, for example, each project proposal is evaluated on economic viability, improvement of energy resilience, and use of innovative technologies. This paper proposes a quantifiable framework to assess the resilience of military installation's electrical power systems. This framework will drive effective project proposal evaluation and quantify improvement of energy resilience at the proposal stage. The framework also enables quantifiable comparison of projects to better assess investment in energy resiliency. While designed for the unique requirements of military installations, it is potentially widely applicable.

C. Current state of the art for resilience metrics

There are numerous works that evaluate resilience of power systems. However, military installations are fundamentally different than most commercial entities and require different energy resilience assessment strategy. In [5] the authors applied a tiered load priority scheme coupled with a quantitative assessment of the value of lost load. This approach is quite applicable, but does not hit the overall goal of quantitatively determining energy system resilience to drive investment from the DoD. In [6] the authors develop resilience assessment models as inputs to optimization models for power system operation. Unfortunately implementing this method requires the creation of optimization models, which do not exist for the comparably small military installations. Developing them would be expensive and time consuming. In [7], the authors have a robust resilience assessment framework. However, it requires extensive modeling and simulation to implement. This would be challenging for the DoD, which requires a simpler framework for funds allocation. Literature also offers many suggestions for improving the resilience of power systems. From these suggestions, concepts of metrics to assess and drive that improvement can be derived. In [7] the authors recommend creating microgrids and installing advanced metering to improve resilience. This work proposes a similar approach to the one used throughout [8], but these metrics are designed for large fixed military microgrids and not permanently islanded nanogrids. Impact to energy resilience improvement and resiliency contribution to mission requirements at an installation is a key selection criteria. However, there is not clear guidance on how to quantify this and it must be evaluated prior to project selection. A key contribution of this work is providing a process to quantify resiliency of proposed projects without

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detailed system design or simulation, which will improve proposals and selection of DoD energy resilience projects.

D. Current state of military installation power systems

Before delving into the details of the proposed metrics, it is important to present some background on the current state of military power systems. Today's permanent military installations in the United States are dependent on local utilities for electrical power [3]. There are limited renewable generation projects on these bases and the vast majority of energy production comes from utilities off the installation [3]. Most critical loads on military bases feature non-prime rated backup diesel generators, many with automatic transfer switches. None of these systems are capable of cooperative operation to form islanded microgrids in the event of a grid outage [3].

The rest of the paper is organized as follows: Metrics and methodology for overall installation resiliency are presented Section II. Section III presents example resilience evaluations. Concluding remarks are made in section IV.

II. Metrics

Various metrics were developed and combined to evaluate the overall energy resiliency of an installation: installation feeders, generation capacity, fuel requirements, energy storage, monitoring, distribution system, and microgrid capabilities are included. These factors are combined and related to energy demand to provide a single numerical metric representing overall resilience of an installation. Some metrics are calculated over a 14-day period. The worst-case scenario for meeting critical demand over a 14-day period should be used to provide safety margin in resilience.

A. Defining Common Terms

Key terms associated with the proposed metrics are defined here:

$P_{critical}$: The installation hourly critical power demand, in MW over a 14-day period
$P_{critical}[i]$: The average installation critical power demand, in MW, for its mission critical operations over hour i.
$E_{critical}$: The energy required to support installation critical load, in MWh, for 14 days.
For metrics requiring hourly iteration, i is used as the hourly index variable.

These metrics assume categorization of generation fuels into two broad categories, fueled generators and non-fuel generators. Fueled generators include diesel generators, hydrogen fuel cells, and natural gas turbines, as they require a continuous supply of fuel to produce electricity. These fuel streams are subject to disruption during resilience events. Non-fuel generators include nuclear generators and renewable generation systems such as wind and solar PV. The index values used for generators:

N: integer number of fueled generators on an installation.
n: index term for fueled generators.
M: integer number of non-fueled generators on an installation.
m: index term for non-fueled generators.
$P_r(n), P_r(m)$: rated capacity for fueled and non-fueled generator, in MW, respectively.
$P(n,i), P(m,i)$: generator output for fueled and non-fueled generator, in MW, at hour i respectively.
$CF(m)$: Estimated capacity Factor of non-fueled generator m.

Terms for other installation information:

T: the number of medium voltage (>5kV) and larger transformers on the installation.
T_R: the number medium voltage and larger transformers with redundancy (e.g. dual transformer substation with transfer switch).
G: the number of generation sources on an installation (fueled and non-fueled).
B: the number of buildings on an installation.
S: the number of substations on an installation.
T_M, G_M, B_M, S_M: number of transformers, generators, buildings, and substations with power monitoring equipment installed.

B. Installation Feeder Resilience Metric, IFR

The Installation Feeder Resilience Metric quantifies the resilience of an installation's utility provided power supply by evaluating the capacity and resilience of the utility feeders entering from off the installation. Military installations rely almost exclusively on feeders to meet their energy requirements; they are a critical vulnerability, and feeder redundancy is a system resiliency strategy, as discussed in [7]. These feeders are beyond the physical and cyber security bubbles of military installations and are thus more vulnerable to disruption. The Installation Feeder Resilience (IFR) Metric compares total feeder capacity to the installation's critical load against the contingency of a lost feeder. The score ranges from 0 - 1. If IFR is 1, then there is sufficient N-1 redundancy on feeder supply to the base's critical load. A score of zero indicates there is no N-1 redundancy on feeders. To encourage balanced investment of resources, a score exceeding 1 is rounded down to 1. IFR is calculated using:

$$IFR = Min\left(\frac{\sum_{k=1}^{N-1} P_F(k)}{Max(P_{critical}[i])}, 1\right) \quad (1)$$

where $P_F(k)$ is rated power of feeder k in MW, N is total number of feeders for the installation, and k is each individual utility feeder for the installation.

C. Installation Generation Capacity Metric, IGC

The installation generation capacity metric, IGC, quantifies an installation's resilience with respect to the critical load profile $P_{critical}$. The value of IGC is calculated hourly based on

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critical load data. It includes fueled and non-fueled generation. Capacity factors are used to estimate the intermittent nature of renewable energy generation. The IGC is calculated over a 14 day period (336 hours) using Algorithm 1.

Algorithm 1 Installation Generation Capacity

Require: $0 \leq i < 336$
  if $P_{Crtitical}[i] \leq \sum_{n=1}^{N} P_r(n) + \sum_{m=1}^{M} P_r(m) \times CF(m, i)$ **then**
    $P_C[i] = 1$ ▷ there is sufficient power
  else
    $P_C[i] = 0$ ▷ there is not sufficient power

$$IGC = \frac{\sum_{i=1}^{336} P_C(i)}{336} \tag{2}$$

IGC will have a value between 0 and 1. 1 indicates there is generation capacity to serve all critical load, a value less than one indicates insufficient generator capacity to serve all load.

D. Installation Fuel Mix Metric, IFM

Diversity in electrical power generation fuel sources is foundational for a resilient power system on military installations. Fuel streams for fueled generators can be disrupted, while non-fueled generators are not dependent on a constant supply of fuel from a logistics system and are less likely to be disrupted. Capacity factor for renewable generation estimates the intermittent nature of renewable generation. The range of the IFM is 0-1. A 1 indicates that all generation does not rely on a fuel supply system and a zero indicates that it is totally dependent on fuel storage or delivery. The IFM is calculated by the ratio of estimated non-fueled generator production to estimated energy production of all generation sources:

$$IFM = \frac{\sum_{m=1}^{M} [P_r(m) \times CF(m)]}{\sum_{m=1}^{M} [P_r(m) \times CF(m)] + \sum_{n=1}^{N} P_r(n)} \tag{3}$$

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E. Installation Fueled Generator Resilience, FGR

Most installation electric power generation falls under the fueled generator category. DoD policy requires installations to operate for 14 days without external power generation from utilities. This metric assumes that assumption extends to include the non-availability of external fuel re-supply. Thus, installation energy resilience policy requires 14 days of fuel on hand and the generation capacity to meet the critical demand. The Installation Fueled Generator Resilience metric (FGR) compares the available fuel to critical power demands at hourly intervals for 14 days. This metric assesses the ability of the installation fuel stores, fossil fuel based generators, and non-fuel based generators, to meet $E_{critical}$. This metric requires hourly load and generator fuel consumption data for the critical load over a 14 day period and an hourly estimate of non-fuel based generation. The latter can be obtained from historical data or estimated based on available resources and system design (e.g. typical meteorological year data with a photovoltaic plan design). The metric produces a result between 0 and 1, where a value of 1 indicates sufficient fuel and generation to meet critical load for 14 days. The FGR is calculated using Algorithm 2 and Equation (4).

Algorithm 2 Installation Fueled Generator Resilience Algorithm

Require: $0 \leq i < 336$
  Initialize $Fuel[0]$ to starting fuel amount
  for $i = 0$ to 335 **do**
    if $P_{critical}[i] \leq \sum_{n=1}^{N} P_r(n) + \sum_{m=1}^{M} P(m, i)$ **then**
      $P_C[i] = 1$ ▷ Sufficient power
    else
      $P_C[i] = 0$ ▷ Insufficient power
    $Consumed[i] = \sum_{n=1}^{N} F(P(n, i))$
    $Fuel[i+1] = Fuel[i] - Consumed[i]$
    if $Fuel[i+1] \geq 0$ **then**
      $F_C[i+1] = 1$ ▷ Sufficient fuel
    else
      $F_C[i+1] = 0$ ▷ Insufficient fuel

$$FGR = \frac{\sum_{i=0}^{335} F_C(i) \wedge P_C(i)}{336} \tag{4}$$

where, $F(P(n, i))$ is the fuel consumption per hour of generator n at the load level at hour i, and $Fuel[0]$ is the installation fuel storage capacity (e.g. in gallons for liquid fuel or cubic feet for gas).

F. Installation Energy Storage Resilience Metrics, ESR_P and ESR_E

The installation Energy Storage Resilience Metrics quantify the resilience of an installation with respect to its energy storage systems in the event of a loss of all other sources of electrical power. The metrics are used to quantify the impact of energy storage systems on installation energy resilience during resilience events. Both power and energy capacities must be considered. Energy Storage Resilience (power), ESR_P, quantifies the resilience of energy storage systems with respect to their rated power output. The Energy Storage Resilience (energy), ESR_E does the same with respect to energy. The score ranges from 0 - 1 and is calculated using:

$$ESR_P = Min\left(\frac{\sum_{n=1}^{N} P_{ESS}(n)}{Max(P_{critical})}, 1\right) \tag{5}$$

and

$$ESR_E = Min\left(\frac{\sum_{n=1}^{N} E_{ESS}(n)}{E_{critical}}, 1\right) \tag{6}$$

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where, $P_{ESS}(n)$ is the rated power of ESS n in MW, $E_{ESS}(n)$ is the rated energy of ESS n in MWh, and N is the total number of ESS systems on an installation.

G. Installation Monitoring Capacity Metric, IMC

The metering of power systems provides essential information to system operators and developing requirements for resiliency projects. For example, detailed load profile data can help explicitly define critical load requirements ahead of designing for resilience. During a resilience-inducing event, this information is even more important. This extends to monitoring power systems on military installations. The installation monitoring capacity metric, IMC, quantifies an installation's power system monitoring capabilities. Visibility into the state of the electric grid is essential for operations under difficult conditions. These monitoring systems must be accessible on the base by operations managers. The IMC is calculated using,

$$IMC = \frac{\frac{B_M}{B} + \frac{S_M}{S} + \frac{G_M}{G} + \frac{T_M}{T}}{4} \tag{7}$$

The IMC score ranges from 0 to 1. Metering of all transformers, buildings, generators, and substations results in 1, while a score of zero indicates there is no metering.

H. Installation Distribution System Resilience Metric, DSR

Military installations are similar to towns and cities with their medium voltage distribution networks. These networks are vulnerable to disruption and without them, it is impossible to move energy from generation the load. Therefore, a resilience metric is required to quantify the impact of distribution system resilience. This metric explores two components to distribution system resilience, transformers and location of feeders. Transformers have long lead times and are primarily made overseas, making them potentially difficult to acquire in the event of a significant disruption. Therefore, it is advisable to design redundancy in a distribution system. For example, substations with dual transformers, both having capacity to serve load, with a transfer switch. The remaining transformer can serve load in the event of a transformer failure. Distribution systems are either above or below ground. Underground distribution systems, while more expensive, are inherently more resilient to natural disasters and physical attack [7]. This metric promotes the underground installation of distribution cabling to increase the systems resilience. The Installation Distribution System (DSR) resilience weighs each of these factors evenly and is calculated using,

$$DSR = \frac{\frac{T_R}{T} + \frac{D_U}{D_U + D_A}}{2} \tag{8}$$

where, D_U is the length of under ground distribution cabling on the installation and D_A is the length of above ground distribution cabling on the installation.

I. Installation Microgrid Formation Metric, IMF

The ability to form and operate microgrids is essential to energy resilience for military installations. Electricity distribution, generation, and storage assets are not effective without a microgrid control systems. If a disruption event occurs, the installation will need to operate an islanded microgrid to support critical operations. Islanded microgrids operate independent of a larger power system, self regulating voltage and frequency through generation, load, and storage management. Thus, a metric is needed to assess a military installation's ability to form and operate an islanded microgrid. Specifically, installation microgrid formation IMF metric assess the percentage of $P_{critical}[i]$ that can be served by an islanded microgrid. It is calculated using,

$$IMF = Min\left(\frac{P_{\mu grid}}{Max(P_{Critical})}, 1\right) \tag{9}$$

where, $P_{\mu grid}$ is the rated power of all generation under the islanded microgrid control system. It is calculated using,

$$P_{\mu grid} = \sum_{o=1}^{O} P_{rated}(o) + \sum_{p=1}^{P} P_{rated}(p) \times CF(p), \tag{10}$$

where o an p are the subset of n and m, respectively, that are under the control of the islanded microgrid controller. Spot generators are not be included in $P_{\mu grid}$ as they are not connected to the microgrid. IMF ranges from 0 to 1 where a 1 indicates that all of $P_{critical}$ is supported by a microgrid.

J. Installation Energy Resilience Metric, IER

The IER metric combines the proposed metrics into one resilience metric. This evaluation is a weighted $(\alpha, \beta, \gamma, \delta)$ and normalized score based on: generation capacity to serve critical load (α), energy capacity to serve critical load (β), instrumentation (γ), and infrastructure resilience (δ). The latter encompasses metrics on main feeders, distribution network, and non-fuel based sources which contribute to resilience from power network and fuel supply disruptions. IER ranges from 0 to 1, with a higher score indicating a higher electrical energy resilience score:

$$\begin{aligned} IER = \alpha \left(\frac{Min(IGC + ESR_P, 1) + IMF}{2}\right) \\ +\beta \left(Min(ESR_E + FGR, 1) + \gamma \left(IMC\right)\right. \\ +\delta \left(\frac{IFR + IFM + DSR}{3}\right) \end{aligned} \tag{11}$$

weights must be positive and are constrained by:

$$\alpha + \beta + \gamma + \delta = 1 \tag{12}$$

The constraint on these weighted values normalizes their overall effect resulting in a standardized score from 0-1, but allows emphasis on different metrics at the installation level. Meeting critical power or energy demands independent of grid

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availability will result in an unweighted value of 1 for the first two terms respectively. As such, these first two terms should generally be weighted higher than the second two terms.

III. Example Metric Application

Due to the sensitive nature of military power systems, this work presents results for a notional military base to demonstrate the proposed resiliency evaluation. Details were derived from a mix of real-world and hypothetical data. The installation is a training base focused on force generation. Load data was obtained from [9] and critical load derived as a subset of this data. Nearly all building and substations were monitored, feeder redundancy exists, most of the substations have redundant transformers, and nearly all distribution cables are underground. Table I provides information on the facility baseline and four scenarios examined in this work. For this example, $\alpha = \beta = 0.4$ and $\gamma = \delta = 0.1$ to provide more emphasis on meeting critical load power and energy requirements as this was deficient in the baseline scenario.

TABLE I
Infrastructure Architectures

	Baseline	A	B	C	D
Natural Gas Gen.(MW)	0.00	6.00	6.00	6.00	6.00
Solar PV Gen. (MW)	0.40	4.00	4.00	4.00	4.00
Microgrid Control	No	No	Yes	Yes	Yes
Energy Storage (MW)	0.00	0.00	0.00	5.00	5.00
Energy Storage (MWh)	0.00	0.00	0.00	30.0	30.0
Natural Gas Supply	No	No	No	No	Yes

Table II shows metric and resilience scores for baseline and four scenarios studied using equations (1) through (11). The worst case 14-day energy and power requirements for the installation were used. Peak critical load is approximately 11 MW and 14-day critical load energy consumption is approximately 2400 MWh. PV generation was simulated at the installation location based on a standard PV system design and available solar resources. For scenarios with microgrid control, it was assumed all generation and energy storage assets were included in the microgrid. Lastly, for scenario D it was assumed sufficient fuel supply to operate the natural gas generator over the 14-day period. As expected, adding generation, energy or fuel storage, and microgrid control contributed to higher resiliency scores. IER sensitivity to weighting parameters is shown in Table III. Each parameter was adjusted across a wide range while uniformly adjusting the other paramters constrained to (12). Sensitivities were relatively constant, varying ± 0.03, within a given scenario, and scenarios which modified terms with a negative sensitivity generally improve IER (shaded cells indicate architecture change in each scenario). These results show that using sensitivity analysis this technique can be generalized to a variety of installations and help select scenarios for study.

TABLE II
Baseline and Scenario Scores

Score	Baseline	A	B	C	D
IFR	1.00	1.00	1.00	1.00	1.00
IGC	0.00	0.40	0.40	0.40	0.40
IFM	1.00	0.11	0.11	0.11	0.11
FGR	0.00	0.00	0.00	0.00	0.40
ESR_P	0.00	0.00	0.00	0.47	0.47
ESR_E	0.00	0.00	0.00	0.01	0.01
IMC	0.88	0.88	0.88	0.88	0.88
DSR	0.95	0.95	0.95	0.95	0.95
IMF	0.00	0.00	0.63	0.63	0.63
IER	0.19	0.24	0.36	0.46	0.62

TABLE III
Average Weighting Parameter Sensitivities

Sensitivity	Baseline	A	B	C	D
$\Delta EIR/\Delta\alpha$	-0.618	-0.320	-0.004	0.225	0.091
$\Delta EIR/\Delta\beta$	-0.618	-0.587	-0.693	-0.758	-0.356
$\Delta EIR/\Delta\gamma$	0.547	0.577	0.434	0.393	0.257
$\Delta EIR/\Delta\delta$	0.693	0.330	0.396	0.393	0.007

IV. Conclusion

This paper derived a novel methodology to assess resiliency on military bases without the need for detailed power system models or simulation results. A suite of metrics were developed, along with an overall resiliency score, suitable for evaluation of projects at the proposal stage. This methodology can drive informed investment to prioritize funding towards projects. Future work will include refining these metrics based on actual project designs and results.

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