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Defining, Measuring and Assigning Resilience Requirements to Electric and Thermal Energy Systems

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ABSTRACT

The resilience of the energy system impacts the primary functionality of critical facilities, such as military installations, hospitals, and education campuses, during disruptions. Throughout the history of energy systems, major disruptions of energy supply (both electrical and thermal) have degraded critical capabilities and caused significant social and economic impacts to private and public communities. Therefore, resilience must be an integral goal of the community-wide energy master planning (EMP) process, and application of energy resilience principles is important during the design of new and the upgrade of existing energy systems. The integration of resilience goals into the EMP process on the campus level is discussed in detail by Jeffers et al. (2020). Best practices for resilient electric and thermal energy systems favor the use of installed energy sources rather than emergency generation for short durations and promote the use of multiple and diverse sources of energy, favoring energy resources originating within the community (DOD 2020). Examples of best practices of such systems implementation will be described in the planned International Energy Agency Energy in Buildings and Communities Programme (IEA EBC) Annex 73 case studies book (IEA n.d.).

The energy system options that can be used for power supply, heating, and cooling of campuses vary by their architectures and technologies used, including for individual buildings, building clusters, the campus-wide level, and the community level. Design and evaluation of system resilience should be based on requirements established by mission operators, which are currently not well understood.

Metrics for energy resilience fall into two broad categories: attribute based and performance based (Vugrin et al. 2017; Roege et al. 2014). Attribute-based metrics can be counted or populated via checklists or surveys. They often describe the characteristics that make a system resilient, such as robustness or reliability (NIAC 2009). However, these metrics are difficult to integrate into the EMP process because they are not easily compared with performance-based metrics in other categories, such as cost-effectiveness (e.g., overall net present value of the energy system) or sustainability (e.g., kilograms of carbon dioxide equivalent emissions) (Jeffers et al. 2020).

This paper provides a definition of resilience metrics and offers a methodology to address site-specific requirements for resilience based on the level of mission criticality, the remoteness of the site which results in the time for system repair, and whether the mission is duplicated and can be executed at any other sites. The paper also describes a quantitative approach that allows for evaluation of both the ability of a system to absorb the impact of a disruption (robustness) and its ability to recover. The definition of resilience *and the methods to quantify resilience used in this paper allow it to be directly integrated via performance-based metrics within alternative designs of energy systems.*

While there have been more discussions and research related to resilience of electric energy systems, resilience of thermal energy systems is also important, especially for extreme climate locations. This paper addresses requirements to resilience for both electric and thermal systems comprised of energy conversion, distribution, and storage components. Additional information on requirements for resilience of thermal energy systems can be found in the work by Zhivov et al. (n.d.).

This paper is based on research conducted under IEA EBC Annex 73 and the Environmental Security Technology Certification Program (ESTCP) project Technologies Integration to Achieve Resilient, Low-Energy Military Installations (Zhivov n.d.).

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INTRODUCTION

A resilient energy system (electric or thermal) is one that can prepare for and adapt to changing conditions and recover rapidly from disruptions, including deliberate attacks, accidents, and naturally occurring threats (WH 2013; HQDA 2015). The concepts of *reliability* and *resilience* of energy systems are often confused. The primary difference between reliability-focused planning and resilience-focused planning is the type of events included in the process and the methods used to quantify the impact of the events.

Reliability-focused planning limits itself to high-probability events with relatively low consequences (DOE 2017). System reliability is the desired level of system performance. Commonly used indices to measure electric system reliability are the Customer Average Interruption Index (CAIDI), which gives the average outage duration that any given customer would experience, or the average restoration time System Average Interruption Duration Index (SAIDI) (IEEE 2012).

For resilience-focused planning, in addition to the information on statistical system element failure, system reliability should be adjusted for expected low probability, high-consequence threats, and hazards expected for the locality of interest, which are called Design Basis Threats (DBTs).Therefore, resilience of energy systems is threat-informed rather than threat agnostic, as systems that are resilient to one threat type may not be resilient to another threat type. For example, an area that is exposed to high winds and earthquakes would not be considered resilient if it only hardened the energy system to wind but ignored ground acceleration. Threat probabilities may change over the planning horizon and hazard magnitudes may need to be represented differently over time. To mitigate threats that have trends over the planning horizon, planners should use data to inform a simulation model and project magnitude vs. probability for future years. For more details regarding DBT, see the work by Jeffers et al. (2020).

QUANTIFYING ENERGY SYSTEM RESILIENCE

The quantitative approach described in this paper supports the U.S. Department of Defense (DOD) memorandum on metrics and standards for energy resilience at military installations (DOD 2020) and allows for evaluation of both the ability of a system to absorb the impact of a disruption (robustness) and its ability to recover. Critical missions may employ extensive redundancy and protect vital system components to ensure continuity of the mission even when faced with a significant natural or man-made disaster. Some critical missions can withstand small disruptions as long as the system can recover quickly. In either case, overall resilience of the system can be quantified as a deviation in mission availability from baseline operations to some degraded system state following a disturbance.

A comprehensive literature review of energy system resilience conducted by Willis and Loa (2015) identified 154 metrics currently used by the energy industry. Ayyrub (2015) also conducted a comprehensive review of resilience definitions and the metrics relevant to energy systems and buildings. These practical and simplified proposed metrics capture the entire attribute set in the resilience definition. The quantitative approach to resilience of systems supplying energy to buildings proposed in this paper is limited to the following metrics: Energy System Robustness (ER), Energy System Recovery Time—Maximum Time to Repair (MaxTTR), Energy Availability (EA), and Energy Quality (EQ).

The first three parameters are critical for selection of the energy supply system architecture and technologies that comprise the system to satisfy requirements related to energy system resilience. As is discussed later in his paper, requirements to EA and MaxTTR depend on 1) the criticality of the mission being served by the system, 2) the system repairability, which has significant dependence on the remoteness of the facility hosting the mission, and 3) the redundancy of facilities that can serve the same critical function.

Requirements for ER depend on mission-critical load; they can (first) be measured as the percentage of the load that is available to mission-essential loads from the total mission essential load requirements and (second) also be related to the overall building energy load under normal (blue sky) conditions. These loads are illustrated using a notional example shown in Figure 1.

EQ is another important quantitative metric for energy systems serving critical functions and should be considered a design parameter for internal building energy systems. Most of the mission-specific energy quality requirements, including limitations on short-term power interruptions, voltage and frequency variations, harmonics, etc. (see Performance Class Transient Limits in UFC 3-540-01 [NAVFAC 2019]), can be handled by building-level energy systems. Building-level electric systems (nano-grids) generally include redundant or backup components and infrastructure for power supply, uninterruptible power supply (UPS), automatic transfer switches, data communications connections, environmental controls (e.g., air conditioning, fire suppression), and various security devices that can be designed to provide power with severe demands on the stability and level of the frequency, voltage, and waveform characteristics of the uninterruptable electrical power to mission-critical equipment and can operate in an islanded mode between 15 minutes and several hours. It is important to account for the latter capability when requirements to the maximum energy supply downtime are established.

For resilient thermal energy system planning, a well-insulated and airtight building envelope of a massive building may be considered capable of maintaining habitable indoor air temperature for several hours after heat or cooling supply to the building is interrupted. The internal electrical and thermal systems of mission-critical facilities are designed based on the class or tier of such facilities. Therefore, requirements that EA, MaxTTR, and EQ be specified for energy systems that provide energy to the building will differ from those required by the critical equipment and personnel.

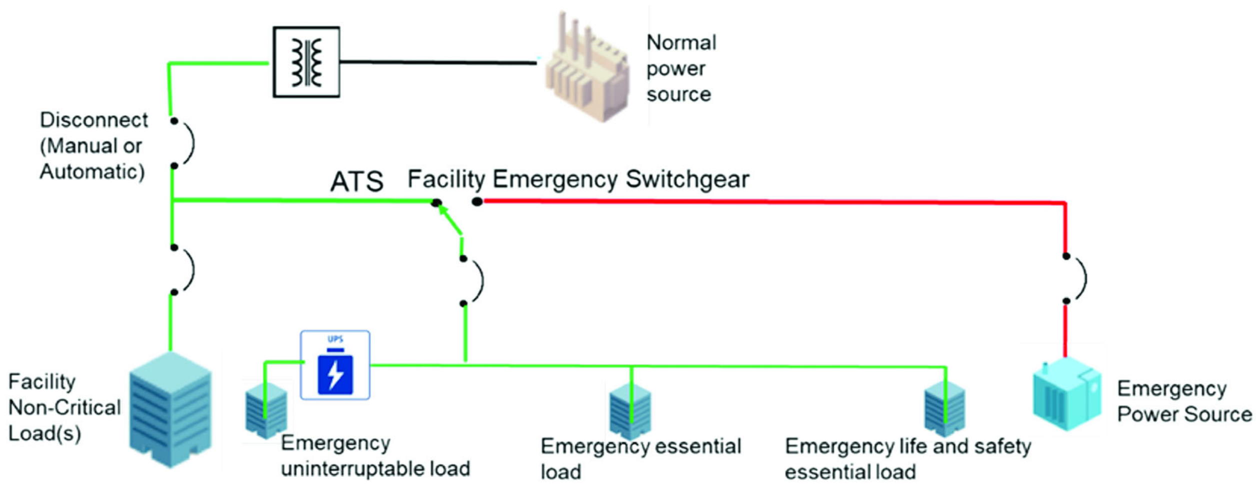

Figure 1 *Schematic of the one-line diagram for a notional facility.*

ENERGY SYSTEM ROBUSTNESS

Robustness is defined as "the ability to absorb shocks and continue operating" (NERC 2018). For many critical facilities, there may be mission assets that are considered uninterruptible, critical but interruptible, or life and safety related. Because it is imperative to the mission that these assets remain online, any undelivered load to such facilities or assets would be considered mission failure. ER is a metric that shows the power availability P (in kW and/or kBtu/h) needed to satisfy critical mission loads over a period of time immediately following a disruptive event, measured as a fraction of the mission-critical requirement or a fraction of the baseline energy requirement.

Using the ER metric, we can quantify the overall resilience of a system in two phases: absorption of the event and recovery. Consider the event shown in Figure 2; immediately following this event, there is a drop in the load available to mission. Duration of phase one for electric energy systems is much shorter than phase one duration for thermal energy systems unless thermal systems are used for processes that use steam or hot water. This change from the baseline to the degraded state represents the robustness of the system in response to that particular event. The time required to restore the system to its baseline state is referred to as *recovery*. The smaller the change in load available to mission and the shorter the recovery time, the more robust the system.

The robustness R of the system to any particular event can be quantified using Equation 1 and is illustrated in Figure 2 by the area between the line showing the baseline mission availability and the curve representing the actual mission performance over time. The smaller the area between the baseline and the curve, the more resilient the system. Robustness is measured on the scale between 0 and 1, where 1 is the most resilient system.

$$R_{\text{m.c.}} = \frac{E_{\text{event}}}{E_{\text{m.c.}}} \tag{1a}$$

$$R_{\text{baseline}} = \frac{E_{\text{event}}}{E_{\text{baseline}}} \tag{1b}$$

where $R_{\text{m.c.}}$ and R_{baseline} are system robustness measured against the mission-critical load and the baseline load; E_{event}, $E_{\text{m.c.}}$, and E_{event} are energy supplied to the building during the period of time between t_o and t_f with the baseline load, mission-critical load and degraded due to even load:

$$E = \int_{t_o}^{t_f} P(t)dt \tag{2}$$

Depending on mission needs, it may be more important to prioritize either absorption or recovery. For example, Figure 3a shows two systems with different levels of absorption. The two systems have the same recovery time, but System 2 has a lower initial decrease in power available to the building. System 2 is more resistant to the postulated event and is more robust than System 1 despite having the same recovery time. In other cases, it may be more important to prioritize recovery from an event as opposed to absorption. Figure 3b shows two systems with similar absorption to an event but different recovery times. Though both systems have the same ability to absorb the shock from the event, the shorter recovery time for System 2 yields a larger area under the curve such that System 2 can be said to be more resilient than System 1.

Energy System Recovery

In the recovery phase, the system is stabilized and no further damage or degradation is expected. The system may be operating in alternate or emergency modes with a reduced load. At the beginning of this phase, energy may be provided to critical systems by the internal building system with the

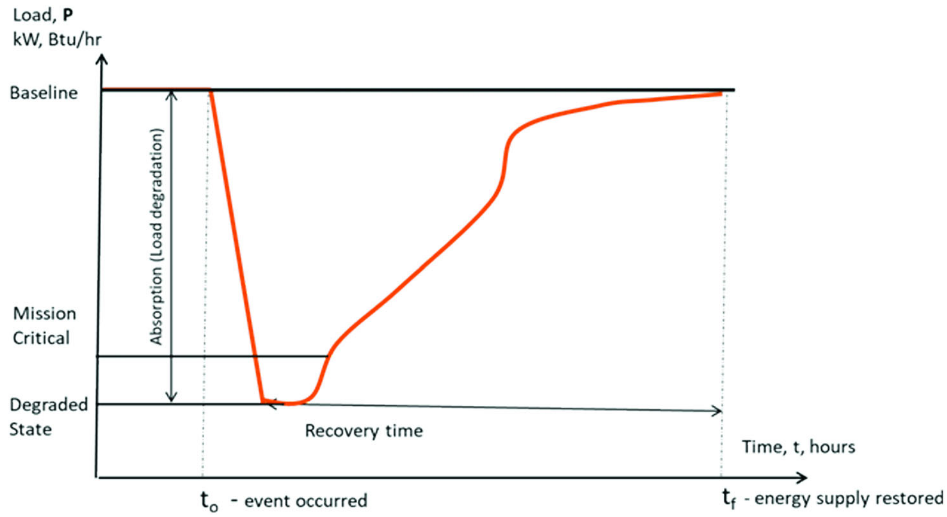

Figure 2 *System response to a disruptive event.*

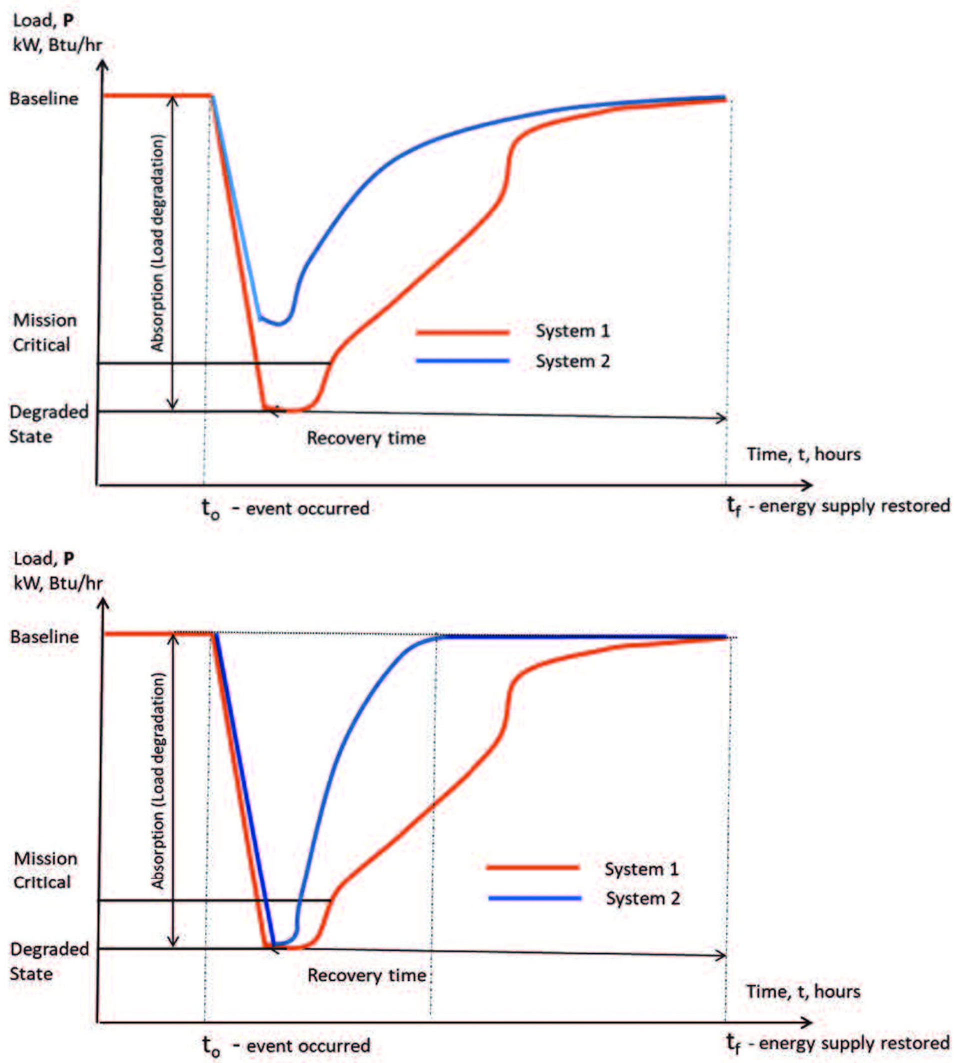

Figure 3 *Two systems with (a) different absorption and (b) different recovery times.*

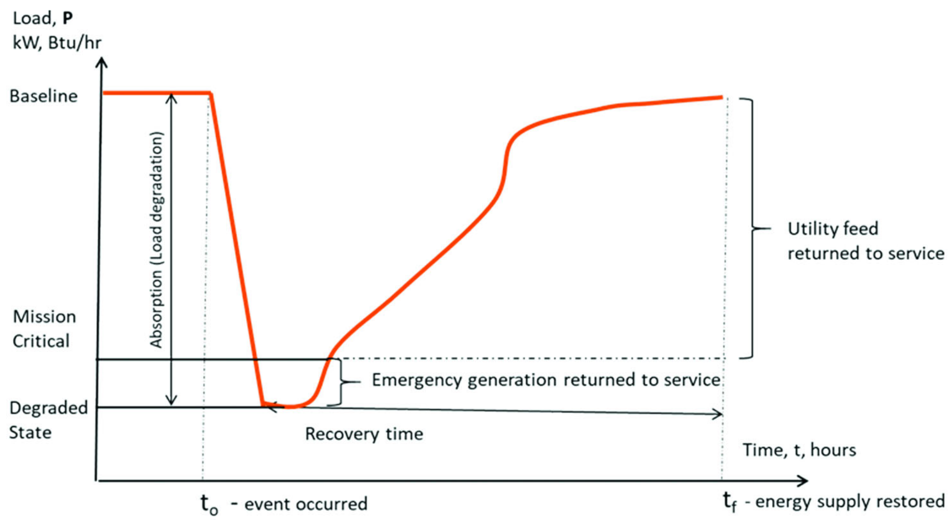

Figure 4 *Stepped recovery of power system assets.*

power storage capacity followed by standby generators, emergency boilers, alternative utility feeds, or distributed energy resources. In this phase, the emphasis is on restoring the system to its baseline operation.

As previously discussed, the shorter the recovery time, the more robust the system. Recovery time is determined by the average length of time required to return damaged components to service. In general, the availability of energy for the mission increases as assets are recovered. For large or complex systems, availability during the recovery phase may change continuously. For smaller systems, or where fewer redundant paths exist, it can be more useful to consider the change in availability during the recovery phase as a step function. That is, there are discrete step changes in availability as components or success paths are returned to service.

Figure 4 shows an example of this concept in which an event has disabled both the on-site generation as well as one of two redundant utility feeders. The on-site generators are quickly returned to service, resulting in a large step increase in availability to support mission-critical loads. During generator unavailability, power to mission-critical assets is provided by UPSs integrated into the nano-grid. After some time, the redundant utility feed is returned to service, resulting in a second step increase in availability. It is important to note that for a single success path to be restored, all series components must be fully restored before improvements in availability are realized. For example, if an event disables a backup generator and its associated fuel tank and fuel lines, all of these assets must be repaired before that feed is considered back on-line.

If one considers the step-change model in Figure 4, it becomes apparent that the recovery time for the system can be approximated using the Mean Time to Repair (MTTR) for the various affected components. However, designers, planners, and facility managers must use caution when using MTTR to anticipate recovery time following a contingency event, as MTTR data are typically based on failure modes that occur during normal operation. Contingency events may cause different failures to occur, and additional logistics delays must be considered based on the nature of the event and the location of the site. To determine the recovery time for a system, MTTR data should be used as inputs to an evaluation of the disaster recovery plan.

Following a contingency event, the facility or site should have a plan in place to adapt to and recover quickly from its affects. Due to limitations of personnel, resources, and logistics, repairs for all components cannot occur simultaneously. It may also be required that some assets be restored in sequence. Priority must be given to restoring power to the level that satisfies the needs of mission-critical loads. In this case, the MTTR of the system providing mission-critical load will be smaller than the Maximum Single Event Downtime (MaxSEDT) assigned based on the configuration and the storage capacity of the nano-grid.

Defining Energy Availability (EA)

Energy Availability (EA) is a measure of the readiness of a system or component to perform its required function and is usually expressed as a function of equipment downtime, as shown in Equation 3:

$$EA = \frac{\text{Uptime}}{\text{Uptime + Downtime}} \quad (3)$$

This metric is used to evaluate the performance of the energy in terms of the percentage of time it is available for the mission. For example, if an event occurs that reduces energy availability to 0.99, then the average expected weekly downtime of the mission is about 100 minutes. If a more resistant system only reduces energy availability to 0.999, the expected weekly downtime for the mission is about 10 minutes. This essentially represents a tenfold difference in system performance. There are two principal measures of availability: inherent availability A_i and operational availability A_o.

Inherent Availability. When only reliability and corrective maintenance or repair (i.e., design) effects are considered, we are dealing with inherent availability. Inherent availability is calculated based on the failure rate and MTTR for system components, without considering any logistical delays or preventative maintenance factors. This level of availability is solely a function of the inherent design characteristics of the system.

Operational Availability. In a real-world consideration of repair times, etc., availability is determined not only by reliability and repair but also by other factors related to preventative maintenance and logistics. When these effects of preventative maintenance and logistics are included, we are dealing with operational availability. Operational availability is a real-world measure of availability and accounts for delays such as those incurred when spares or maintenance personnel are not immediately on hand to support maintenance.

System operational considerations and the nature of events to be considered may dictate the preferred measure of availability for evaluating a given event. In practice, it is important to consider the impact of an event on both the inherent and operational availability of the system. For the purposes of this discussion, the examples in the following sectionrefer to operational availability. Technical Manual (TM) 5-698-1 (HQDA 2007) provides additional information on basic availability concepts and definitions.

Traditional reliability and availability analysis methods such as reliability block diagrams, state-space modeling, and Monte Carlo simulations, may be used to evaluate mission availability during base-case and contingency operations. Additional information on each of these methods, as well as general availability concepts, can be found in TM 5-698-1.

Reliability is concerned with the probability and frequency of failures (or more correctly, the lack of failures). A commonly used measure of reliability for repairable systems is the mean time between failures (MTBF). The equivalent measure for non-repairable items is mean time to failure (MTTF). Reliability is more accurately expressed as a probability of success over a given duration of time, cycles, etc. For example, the reliability of a power plant might be stated as 95% probability of no failure over a 1000-hour operating period while generating a certain level of power.

Evaluating Energy Reliability

According to TM 5-698-1 (HQDA 2007), reliability of the system with components installed in series can be calculated by

$$R_s = R_1 \times R_2 \times \ldots \times R_i \times \ldots \times R_n \tag{4}$$

where R_i is the reliability of component i.

Figure 5 shows an example of calculation reliability of a system with two components installed a) in series and b) parallel.

Reliability with Redundancy. The system shown in Figure 5b has the same components (1 and 2) in series denoted by one block labeled 1&2, but two of each component are used in a configuration referred to as *redundant* or *parallel*. Two paths of operation are possible: top 1&2 and bottom 1&2. If either of the two paths is intact, the system can operate. The reliability of the system is most easily calculated by the following equation:

$$R = 1 - (1 - R_s) \times (1 - R_s) = 0.9994 \tag{5}$$

where R_s is the reliability of the system of components 1 and 2 installed in series. Adding a component in parallel, i.e., redundancy, improves the system's ability to perform its function.

For the purposes of evaluating resilience, this paragraph focuses on the reliability block diagram/Boolean algebra methodology. Constructing a reliability block diagram requires translating the system topology into a set of discrete elements and logic gates. Items connected in series are typically combined with AND operators; parallel objects and strings are typically combined with OR operators. Each element in a block diagram has an associated availability statistic, which is derived from statistical data collected from similar components.

Figure 6 shows an example of a typical utility system translated into a reliability block diagram. Note that combining redundant paths with an OR operator significantly increases the mission availability. Incorporating contingency event data into availability modeling allows for a quantifiable difference in performance between base-case and contingency operations. This can be accomplished using a deterministic

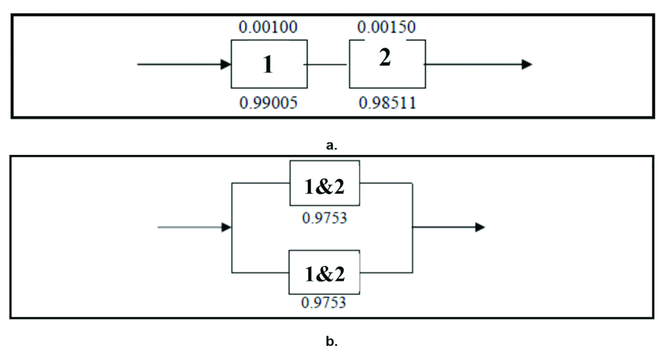

Figure 5 *Reliability block diagram of components installed a) in series and b) parallel. For the in-series diagram, the number above each block is the failure rate in failures per million operating hours and the number below each block is the component reliability. The system reliability shown in this example is* $R_s = R_1 \times R_2 = 0.99005 \times 0.98511 = 0.9753$. *For the parallel diagram, each block represents the series configuration of components 1 and 2. The number below is the reliability calculated using Equation 4.*

approach, similar to traditional Failure Mode, Effects & Criticality Analysis (FMECA) analysis. This method assumes that an event of a certain magnitude has occurred and evaluates the effect that the event has on overall system availability.

Evaluating Energy System Robustness

The following steps can be used in the deterministic method for robustness evaluation of a typical distribution system as illustrated in Figure 6.

Step 1: Determining events for which the energy availability should be assessed. An all threat/all hazard assessment is conducted for the area of interest with identified critical assets. Threats may come in the form of natural disasters, accidents, and man-made threats, the most common of which are listed in Table 1. Threats and hazards to be addressed in the resiliency analysis integrated into the Energy Master Plan are called Design Basis Threats (DBTs). It is important to include the threats that occur with low frequency but pose a potentially high consequence. DBTs should be evaluated individually but may also be evaluated in combinations depending on anticipated impacts to the given area. While the area of interest may not be directly affected by a threat or hazard, the secondary or tertiary effects caused by events elsewhere may prove impactful to the mission at some level and therefore must be considered during the threat analysis.

The methodology of all threat/all hazard assessment developed by U.S. Army North (ARNORTH) includes the following criteria: operational capability, intentions/likelihood, activity, and operating environment (ARNORTH n.d.). It was designed primarily to assess man-made threats and is not applicable for addressing other types of threats and hazards. The CARVER method is another well-documented method that has been applied to several domains. This methodology focuses on the following six metrics: criticality of the

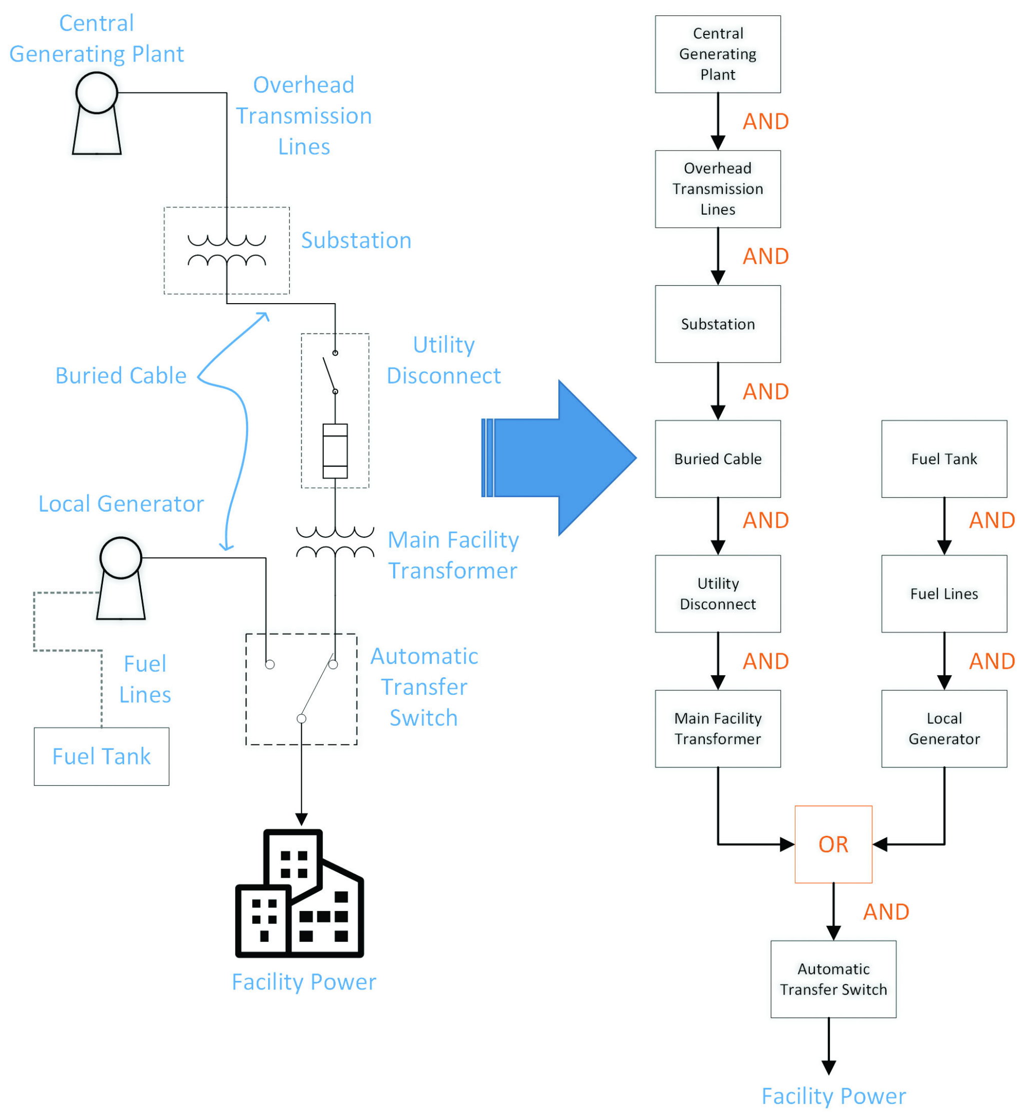

Figure 6 *Reliability block diagram for a typical distribution system.*

Table 1. Typical Threats and Hazards

Natural	Unintentional and Technological	Man-Made
Hurricanes and tropical storms	Unintentional spills of hazardous materials	Conventional bombs/IEDs
Landslides and debris flows	Nuclear power plant failures	Biological agents
Thunderstorms and lighting	Failure of supervisory control and data acquisition systems	Chemical agents
Tornados	Explosions	Nuclear bombs
Tsunamis	Workplace fires	Radiological agents
Wildfires	Industrial accidents	Arson/incendiary attacks
Water and ice storms		Armed attacks
Sinkholes		Cyberterrorism
Earthquakes		Hazardous material releases (intentional)
Extreme heat		
Floods and flash floods		
Hail		
Damaging winds		
Droughts		

Table 2. Ranking Threats

Threat	Threat Probability	Threat Severity	Threat Rating	Threat Rank

asset, accessibility of the target to the adversary, recoverability time to repair/replace the asset, vulnerability of the asset to attack, effects the threat would have on the area, and recognizability of the target in different weather conditions and distances (Labaj and Bencie 2018). Similar to the ARNORTH method, the CARVER method addresses a combination of a threat and its impact on the asset and was designed primarily to address man-made threats. It seems the most applicable to prioritization of different threats for a given locality is a modification of the above methodologies developed at Fort Bragg in combination with the All Hazard Threat Assessment (ATHA) methodology (USACE 2019). This site-specific threat matrix ranks different threats (Table 2) based on a combination of threat probability and threat severity as

$$\text{Threat Rating} = \text{Threat Probability} \times \text{Threat Severity} \tag{6}$$

There are four categories of threat and hazard probability ratings (low, medium, critical, and high). The threat and hazard probability ratings can be found in the Mission Assurance Assessment Stand-alone Tool (MAAST) (USACE 2019). The use of these ratings and definitions will facilitate the uniform assessment of the likelihood or probability of any individual threat or hazard occurring. *Probability* is defined as the estimate of the likelihood that a threat will cause an impact to the mission or a hazard within the area of interest. The likelihood or probability of threats and hazards for the area of interest can be determined using the metrics presented in Table 3.

For typical hazards and threats, numerical probability ratings based on frequency of occurrence are listed (USACE 2019). The information is based on authoritative data sources for continental United States locations. Other threat data for the analysis can be obtained from various open-source databases, the most common of which for the United States are those by Federal Emergency Management Agency (FEMA), National Oceanic and Atmospheric Administration (NOAA), and United States Geological Survey (USGS). Additionally, countries or agencies may have their own threat databases and maps that can be used for certain areas.

Threat Severity

Threat or hazard severity may be similar to the term *consequence*. When assessing a potential threat or hazard one asks, "what would be the psychological, economic, sociolog-

Table 3. Threat and Hazard Metrics

Linguistic Value	Low	Medium	Critical	High
Description	Indicates little or no credible evidence of a threat to the asset or the immediate area where the asset is located. For the identified threat, there is little or no credible evidence of capability or intent and no demonstrated history of occurrence against the asset or similar assets. For the identified hazard, there is a rare history, or no documented history, of occurrence in the immediate area or region where the asset is located.	Indicates a potential threat to the asset or the immediate area where the asset is located. Also indicates there is a significant capability with low or no current intent, which may change under specific conditions, and there is low or no demonstrated history. For the identified threat, there is some evidence of intent. There is little evidence of a current capability or history of occurrence, but there is some evidence that the threat could obtain the capability through alternate sources. Alternatively, the identified threat evidences a significant capability, but there is little evidence of current intent and little or no demonstrated history. The identified hazard has a demonstrated history of occurring on an infrequent basis in the immediate area or region where the asset is located.	Indicates a credible threat against the asset or the immediate area where the asset is located. The identified threat has both the capability and intent, and there is a history that the asset or similar assets are, or have been, targeted on an occasional basis. The identified hazard has a demonstrated history of occurring on an occasional basis in the immediate area or region where the asset is located.	Indicates an imminent threat against the asset or the immediate area where the asset is located. The identified threat has both the capability and intent and there is a history that the asset or similar assets are being targeted on a frequent or recurring basis. The identified hazard has a demonstrated history of occurring on a frequent basis in the immediate area or region where the asset is located.
Numerical rating	0.1-0.25	0.26-0.50	0.51-0.75	0.76-1.00

Table 4. Threat Severity Metric

Numerical Value	0–4	5–8	9–12	13–16	17–20
Linguistic Value	Negligible	Minor	High	Extreme	Catastrophic

ical, or military impact if this hazard were to occur?" Because the severity of a threat or hazard can be very difficult to assess, we suggest applying the effect metrics used for criticality assessment presented in Table 4.

For selected DBTs, the higher-intensity events have a greater chance of causing energy system component failure, but they occur less frequently. Figure 7 shows a fragility curve for a particular component that shows the probability of component failure according to the intensity of an event.

From the probability of failure determined from fragility curves for a design-based threat (event), the resulting probability of component failure (given that the event occurrence is above the threshold) and the reliability of the system for that event should be evaluated. For other events, the severity of risk may be more subjective. For contingencies such as wildlife damage (e.g., from squirrels), cyberattacks, or terrorist attacks, the probability of occurrence may be unknown or is subject to change. Consequently, a threshold value for conditional probability of failure may not exist, and a different means of event selection is warranted.

Step 2: Determine what components are likely to fail as a result of the event. All components in a system are uniquely vulnerable to a set of events. For example, exterior generators may be vulnerable to flooding, whereas supervisory control and data acquisition (SCADA) controlled switchgear may be more vulnerable to cyberattacks. If fragility

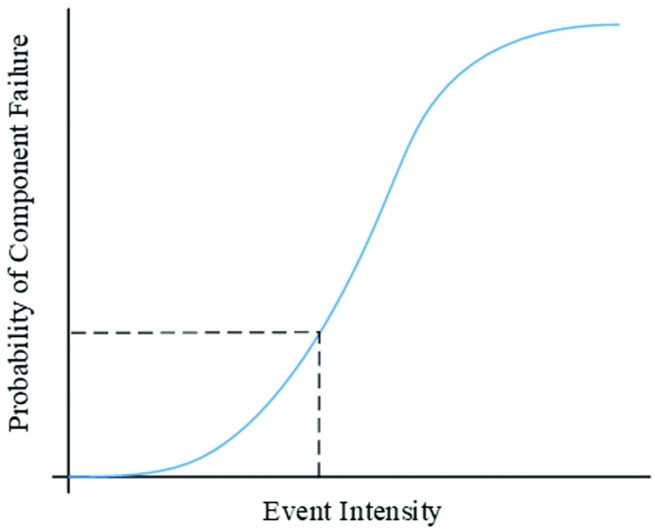

Figure 7 *Example fragility curve for the notional event.*

curves for individual components are available, then the probability of component failure associated with an event can be incorporated into the system availability model. However, in many cases it may be more practical to consider certain key components as having failed due to the event. For the deterministic approach, this clearly identifies single points of failure or areas that require additional hardening measures (e.g., burring cables, raising steam lines and equipment, creating meshed networks for hot- and cold-water pipes, erecting flood walls). These system alterations need to be designed, installed, and commissioned, and performance of these systems must be tested on a regular basis, especially in preparation for events that would improve the absorption and reduce the recovery time. Information collected in TM 5-698-5 (HQDA 2006) shows significant changes in probability of failure of systems that are well maintained and regularly tested. Benefits of maintenance and testing of energy systems on the life of equipment and its reliability are discussed by the Office of the Assistant Secretary of Defense (OASD 2017).

Step 3. Analyze the degraded system state. As previously mentioned, functionality for critical missions that are considered uninterruptible must be maintained. In these cases, the change in system performance can be measured by the change in mission availability from the baseline state. In other words, a contingency event is considered to affect mission availability, not overall mission success. For example, in the postulated power system shown in Figure 8, a wind event disables only overhead transmission lines. Since backup power can be immediately supplied by emergency generators, mission loads can continue to operate. However, until the transmission lines are restored, the likelihood of failure is significantly increased.

Similar methods can be used to evaluate the degraded mission availability for other alternatives using reliability block diagrams, the Monte Carlo method, etc. However, the

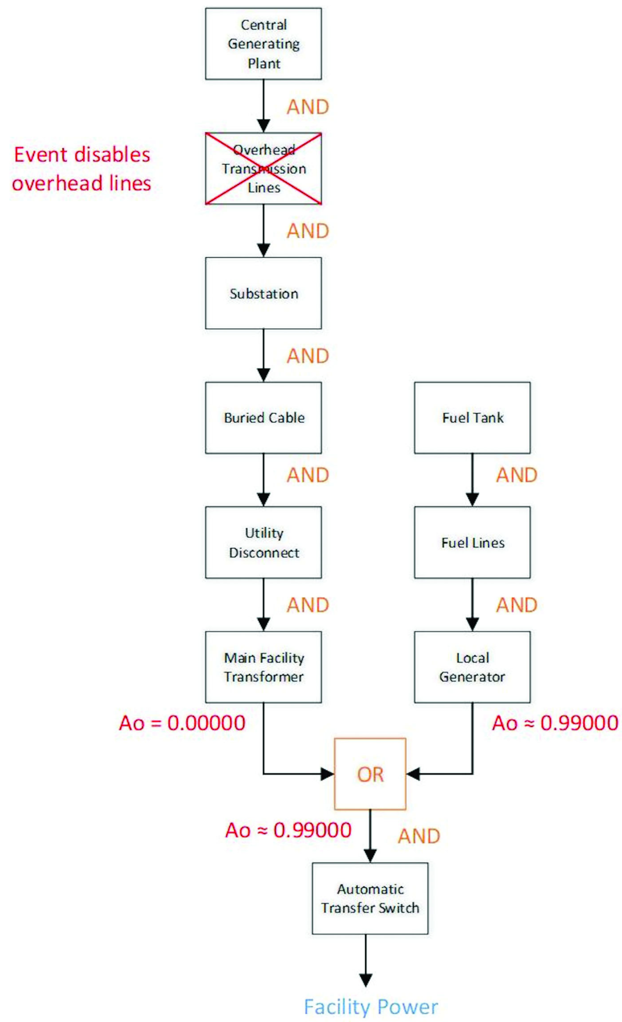

Figure 8 *Distribution system model in degraded state.*

input data must be modified to reflect the impact of the event being considered. The simplest method is to consider failed components as having an availability of zero. If equipment fragility curves are available, the resulting equipment reliability can be incorporated into the existing availability model.

POWER AND THERMAL ENERGY SYSTEM REQUIREMENTS FOR RESILIENCE METRICS

Power and thermal requirements for resilience metrics can vary from site to site and depend on a multitude of factors. As previously discussed, certain sites may need prioritization of either robustness or recovery, depending on their specific needs.

Power Systems

To evaluate requirements for energy system availability, it is important to apply a realistic time scale to the baseline and degraded availability states. Typically, availability is related to equipment downtime on a yearly scale; a "six nines" system relates to about 30 seconds of downtime per year. However, contingency scenarios are more likely measured in hours or days. When assessing the minimum acceptable level of degraded state availability, it is also important to consider the site-specific requirements for availability, as well as requirements for system topology.

For example, consider the difference between a system with *N*+1 redundancy in which a single success path (*N*) is provided with a single independent backup, and a system with *N*+2 redundancy in which a single success path (*N*) is provided with two fully independent backups. A baseline availability requirement of six nines (0.999999) can be achieved using an *N*+2 redundant arrangement of three elements each with an availability of 0.99 or using an *N*+1 redundant arrangement of two elements each with an availability of 0.999. If an event occurs that incapacitates only one feed, the *N*+2 system will have a degraded state availability a full order of magnitude higher than the *N*+1 system. Naturally, systems with higher levels of required redundancy should have more stringent requirements for resilience than those with less design redundancy (see Figure 9). Site-specific requirements for resilience should also be decided by weighing several major factors. Ultimately, the required level of resilience is based on the level of mission criticality, the remoteness of the site, and whether or not the mission is duplicated and can be executed at any other sites.

Criticality. At many government agencies (including DOD installations), public and private enterprises serve a range of missions, some of which are more critical than others. In a perfect world, designers would be able to protect all levels of critical missions from the effects of any possible event. However, due to funding and design constraints, some assets must be prioritized over others.

A *critical mission function* is defined as a function that is vital to the continuation of operations of the organization or agency (HQDA 2008). Such functions include those required by statute or executive order as well as other functions deemed essential by the head of each organization and must be performed without interruption to execute critical missions including during and after a disaster. In addition to core critical facilities and operations, there are critical facilities that, if not maintained, impact the safety of the public during and after a disaster. The priority of each critical mission function and corresponding facility asset must be identified by tenants and customers and documented and approved by community leadership.

The methodology of criticality analysis in this section uses a modified version of the metrics from ARNORTH's *Risk Management Process* (ARNORTH n.d.), where "importance" is the sum of all of the following metrics: effect, recoverability, substitutability, mission functionality, and repairability. Based on this methodology, facility criticality can be classified as low, moderate, significant, or high.

Remoteness (System Repairability). Critical facilities and other critical assets exist in a variety of locations. This can have a significant effect on the time of recovery for a mission following an extreme event when there is limited availability of a qualified repair crew on site and limited access to spare parts. Remoteness is primarily related to the geographical location of a facility or installation but can be further influenced by other accessibility factors. Topographic features such as bodies of water or mountainous terrain, as well as the number and condition of access roads, can also impact the remoteness of a site. For example, if a site can only be accessed via a single bridge, it would be considered more remote than a similar site with several access points. Similar to the level of criticality, the remoteness of a site can be categorized in rela-

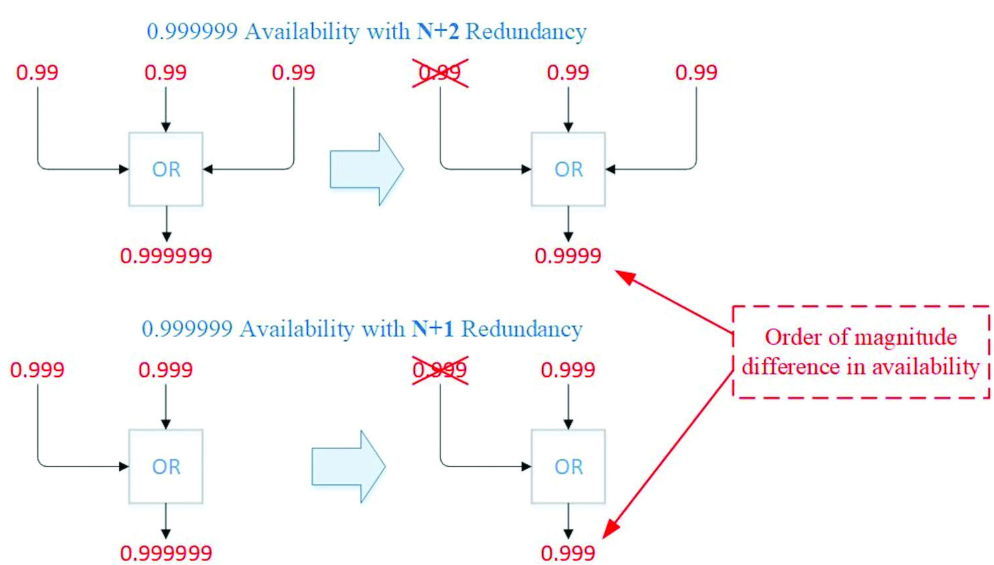

Figure 9 N+*2 vs* N+*1 system resilience.*

Table 5. Remoteness/Reparability Metric

Numerical Rating	Low (0–6)	Moderate (7–12)	Significant (13–160)	High (17–20)
Description	Immediate/low cost or short-term/moderate cost to repair (0 to 72 hours)	Mid-term repair/ significant cost to repair (more than 72 hours, less than 7 days)	Long-term/high cost to repair (more than 7 days, less than 30 days)	More than 30 days or no repair possible

tive terms. For the purposes of resilience planning, sites should be considered to have low, moderate, significant, or high remoteness (see Table 5).

Typically, more remote sites should prioritize the robustness phase of resilience, as recovery may be limited by physical constraints. This maximizes overall resilience by prioritizing the ride-through ability for these missions. Major factors that affect system repairability are availability of spare parts and the personnel with specified skill levels required for prescribed levels of energy system maintenance and repair. A commonly used measure of a system repairability is the MTTR.

Facility Redundancy. Some missions can be carried out at geographically diverse sites such that a contingency event at one is unlikely to affect mission success at any of the other sites. Also, at the same site, buildings can provide different levels of service to different mission functions. This creates additional mission redundancy and can reduce resilience requirements at an individual site. Multiple functions may be served by a single asset, and multiple assets can all serve a single function. To allocate different assets to different mission-critical functions, stakeholder input is helpful, especially when assets operate differently in day-to-day scenarios as opposed to emergency situations. Functions and their criticality may change during emergencies as infrastructure is used in different ways from normal operations. Emergency plans should be consulted to understand how infrastructure asset uses are expected to change during disruptive events.

Infrastructure assets can be buildings (e.g., a cafeteria), system components (e.g., water pumps, pipes, and valves), or loads within buildings (e.g., computing resources). In addition to buildings, assets may also be point loads such as communications towers or networks such as water distribution systems. When functions are provided by networks—a potable water system or a communications network, for example—the critical function performance is a complex function of asset performance that should be calculated using a system model. However, when functions are provided by collections of point assets, estimating the fraction of necessary critical function that the assets as a whole can provide is sufficient.

The output of this step is a matrix that associates infrastructure assets with critical functions (Jeffers et al. 2020). Table 6 lists the elements of a generic asset-to-function mapping matrix. Planners should fill out Table 6 for all assets and buildings that provide or enable critical functions and map them based on the relative capability of providing their functions. For instance, if Asset 1 is able to provide 100% of Function A's requirements, it would score 1.0. Similarly, if Asset 2 and Asset 3 are each capable of providing 50% of Function B to the area of interest (AOI), they would each score 0.5. It is not necessary for the rows to add to 1.0. Some critical functions have redundant assets—for instance, Asset 1 and Asset 3 could each have capability of providing 0.75 of the requirements for Function C.

Table 6. Building to Critical Function Mapping Matrix

Critical Function	Assets and Buildings			
	Asset 1	Asset 2	Asset 3	…
Function A				
Function B				
Function C				

In the notional system shown in Figure 10, each of the four buildings provide different services to five critical functions. Building A is a dormitory with a dining facility. Building B is a student center with a bank, convenience store, small coffee shops/cafes (assumed to be closed during emergencies), and a basement that can serve as a storm shelter. Building C is a second dormitory. Building D is a data center with servers for research laboratories and campus administration files.

The data in Table 7 map each asset to the community and mission functions it provides. Building A can provide 100% of the required shelter since it already serves as housing and can provide 75% of the required food if the dining facility stays open. Food may be limited to supplies on hand and will naturally decline the longer the emergency lasts. Building B is providing food and bottled water at a low level to those who can purchase items at the convenience store and cannot support by itself the needs of the entire campus for these functions, especially for extended disruption durations. The bank in Building B can provide financial services at a medium level through branch services and an ATM, but not enough to serve the entire campus. During an extended event, some individuals will need to rely on off-campus financial services even if Building B is operational. Building C is another dormitory, providing shelter at a high level with no additional functions. Building D is the only building on the campus that can serve as a data center for the campus.

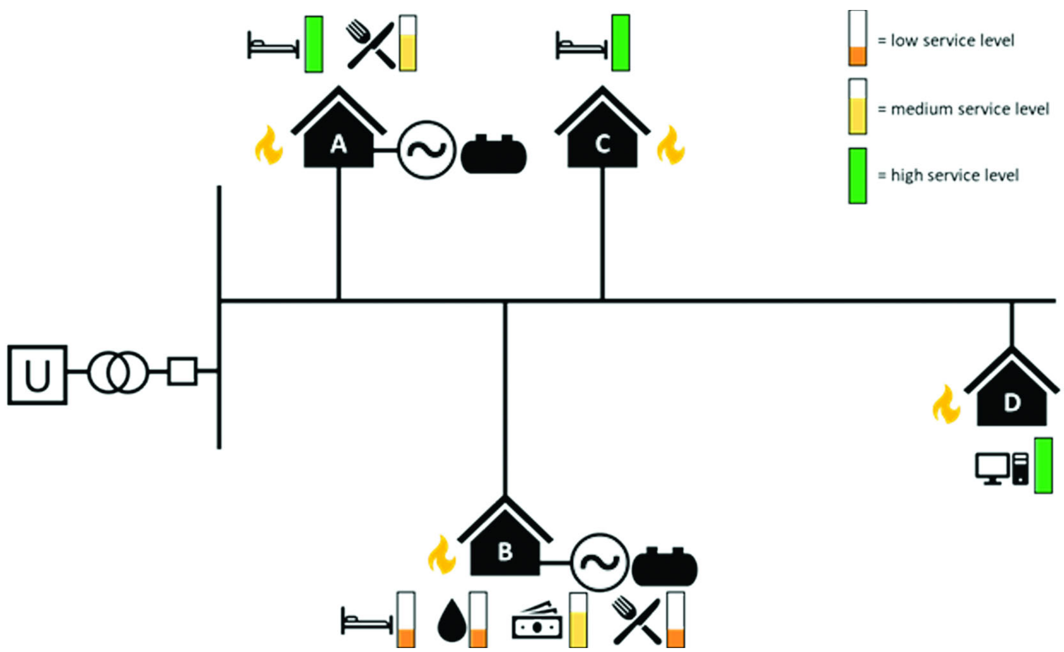

Figure 10 *Critical functions and their service levels applied to the notional system (Jeffers et al. 2020).*

Table 7. Mapping of Buildings to Functions for Notional System

Critical Function	Building A	Building B	Building C	Building D	Redundancy
Shelter	1.0	0.5	1.0		150%
Food	0.75	0.25			0%
Finance		0.5			0%
Water		0.25			0%
IT and data				1.0	0%

It is important to evaluate the practical considerations in mission duplication; several questions must be answered. Will the mission be transferred to an alternate site automatically? Will personnel be available at the alternate site to process the mission? Can the mission be transferred in anticipation of a foreseen event? In the interest of simplicity, the ability of a mission to be carried out at alternate sites should be considered as a simple yes or no. This information will help to select the facility redundancy score from Table 8.

Categories for Energy Availability and Recovery

Once these three factors (mission criticality, facility remoteness/repairability, and redundancy) have been evaluated, the results can be used to determine the requirement categories for both availability and recovery (see Table 9). As previously discussed, these two aspects of resilience should be considered independently due to the unique needs of individual sites.

Using the data in Table 9, the three factors can be applied to place a mission or asset in prioritized categories for both robustness and recovery. The result is a low-moderate-significant-high index for each resilience phase. For example, a mission with moderate criticality, significant remoteness, and moderate facility redundancy would have a significant robustness requirement and a moderate recovery requirement.

Note: The process of assigning resilience requirements is based on three factors: mission criticality, facility remoteness/repairability, and redundancy. This process needs to be executed by mission operators, not energy planners. This process may include information classified as secret or top secret if the asset or supporting infrastructure is classified. Typically, the list of an installation's critical assets is for official use only (FOUO) and not classified unless the assets are designated as Defense Critical Assets (DCAs), Task Critical Assets (TCAs), or supporting infrastructure for DCAs or TCAs. In any case, this process can be executed internally, and results can be kept for internal use as backup information.

Table 8. Facility Redundancy Metric

High (0–6)	Significant (7–12)	Moderate (13–16)	Low (17–20)
Not difficult to accomplish mission using facilities providing similar capabilities (redundancy >150%)	Difficult to accomplish mission using facilities providing similar capabilities (redundancy 60% to 150%)	Very difficult to accomplish mission using facilities providing similar capabilities (redundancy 35% to 55%)	Limited substitutes for facilities providing similar capabilities are available (redundancy < 30%)

Table 9. Determination of Resilience Requirements

Resilience Metric Requirement	Resilience Phase	
	Availability	Recovery
Low	Criticality: Low–Moderate Remoteness: Low Facility redundancy: Yes	Criticality: Low Remoteness: Low–Moderate Facility redundancy: Yes
Moderate	Criticality: Low–Moderate Remoteness: Moderate–Significant Facility redundancy: Yes	Criticality: Low–Moderate Remoteness: Moderate Facility redundancy: Yes
Significant	Criticality: Moderate–High Remoteness: Significant–High Facility redundancy: No	Criticality: Moderate–Significant Remoteness: Significant–High Facility redundancy: No
High	Criticality: Significant–High Remoteness: High Facility redundancy: No	Criticality: High Remoteness: Significant–High Facility redundancy: No

Table 10. Examples of Allocation of Different Facilities to Mission-Based Resilience Requirement Categories (May be Different at a Particular Site)

Resilience Metric Requirement			
Low	Medium	Significant	High
Offices, administrative, housing, recreation facilities, etc.	Intelligence processing, district office buildings, etc.	Medical centers, logistics warehouses, etc.	Warfighting facilities, intelligence mommunity (IC), hospitals, continuity of government operations, critical communications facilities, nuclear command and control, etc.

Based on this process, operators will identify requirements to energy systems, which can be provided to energy planners (without any background information).

Table 10 lists examples of facilities that can be affiliated with different levels of requirements to energy systems resilience for low remoteness and low redundancy factors.

The following subsection provides recommendations to mission operators on how to select energy requirements of their mission-critical facilities-based metrics presented in Table 11.

Recommended Requirements for EA and MaxSEDT

The resilience requirements listed in Table 11 stratify each resilience metric in Table 9. Each resilience metric in Table 9 is split into two levels of facilities, primary and secondary, which in turn have two levels of requirements for energy system resilience ranging from low (0) to high (4). Such stratification of each resilience metric creates more accurate scenario-fitting to the facility and mission requirement.

Over the four category ranges that make up a resilience metric requirement category, the resilience variables increase with progression through the ranges. Improvement in degraded state availability and Maximum Single Event Downtime (MaxSEDT) will depend on the metric of low, moderate, significant, or high. MaxSEDT also improves throughout the primary and secondary categories; it is the one variable that is unique in every category. This results in MaxSEDT being the differentiating variable when there is an overlap in the

Table 11. Recommended Resilience Requirements to Power Systems Serving Mission-Critical Facilities

Resilience Metric	Facility Level	Resilience Submetric	Category	Degraded State Availability	Acceptable Average Weekly Downtime (Minutes)	Maximum Single Event Downtime (Minutes)
Low	Primary	Low	LP/1	0.92	806.4	2419
		Moderate	LP/1+	0.95	504	1500
	Secondary	Low	LS/0	0.9	1008	3024
		Moderate	LS/0+	0.92	806.4	2419
Moderate Primary	Primary	Low	MP/2	0.99	100.8	302
	Secondary	Moderate	MP/2+	0.995	50.4	150
Secondary	Primary	Low	MS/1	0.95	504	1500
	Secondary	Moderate	MS/1+	0.99	100.8	302
Significant Primary	Primary	Moderate	SP/3	0.999	10.08	30
		Significant	SP/3+	0.9995	5.04	15
	Secondary	Moderate	MS/2	0.95	504	1500
		Significant	MS/2+	0.99	100.8	302
High	Primary	Significant	HP/4	0.9999	1.008	3
		High	HP/4+	0.99999	0.1008	0.3
	Secondary	Significant	HS/3	0.9995	5.04	15
		High	HS/3+	0.9999	1.008	3

where

P = Primary facility/mission	0 = Lowest resilience metric range
S = Secondary facility/mission	1 = Resilience metric range
L = Low resilience metric	2 = Resilience metric range
M = Moderate resilience metric	3 = Resilience metric range
S = Significant resilience metric	4 = Highest resilience metric range
H = High resilience metric	+ = Highest 10% of a specific resilience metric range

degraded state availability and average weekly downtime variables.

Power delivery can be thought to have three delivery mechanisms. The first delivery mechanism resides internally to the facility; it is the building-level power infrastructure. The second delivery mechanism is the emergency, or backup, power directed to the facility—from outside of the building but sourced from local infrastructure power generation. The third delivery mechanism is the full power load delivered to the facility under normal operating conditions; this is commonly prime power, or power delivered from an electric utility. Power from the first delivery mechanism will be referred to as layer one power. Power from the second and third delivery mechanisms will be referred to as layers two and three, respectively.

Two facility load levels are defined. The full electrical power load is provided by layer three power and serves the entire electrical load of the facility. The critical electrical power load is provided by layers one and two, also referred to as *backup power*, and only serves the facility critical infrastructure. The facility critical infrastructure load results from the load shedding of all power connected equipment that is not critical for the continuity of the mission or missions housed in the facility.

Layer one power for a facility is the electrical backup power that resides inside of the facility. Common components are a UPS and an automatic transfer switch (ATS). Layer one backup power is the shortest duration of electrical power capacity of the three layers. The power delivery capacity can be from several minutes to several hours typically.

Layer two power for a facility is the electrical backup power that resides outside of the facility but at minimum is partially dedicated to supplying the facility. Common components are generator sets and renewable energy systems such as solar arrays. Layer two backup power is of variable duration. The electrical power delivery capacity can be several hours to days in duration. Electrical power delivery capacity is only limited by factors such as fuel storage capacity, battery rectifier capacity, etc. The layer two power can also be supplied for an installation-wide or campus microgrid system. In such a case, the facility power is supplied from a microgrid system that also provides power to other facilities that reside at the same location as the facility in question.

Layer three for a facility is the electrical power that resides in the infrastructure of the prime power utility. Common components of the utility that provide electrical power to the facility are substations and the medium voltage power distribution system. Layer three is the supplier of electrical power under normal conditions. Unlike layers one and two, layer three is not maintained or repaired by the facility. An exception to this structure is the use of installation or campus distributed power generation in conjunction with connection to the prime power utility, the primary goal of which is to lower the cost of the distributed power generation or to provide opportunities to sell into the utility grid for a positive cost differential. Failure at layer three requires relying on layers one and two for continuity of mission operations.

MaxSEDT is presented as a more critical metric for design parameters than Mean Time to Repair (MTTR). MTTR is a mean, or average, of the total repair time of the mean value of all single event repair times. For a normal distribution curve, this results in one-half of all single event repair times less than the MTTR and one-half of the single event repair times greater than the MTTR. Every single event downtime will vary in severity. While some incidents will require days to repair, others will take minutes.

MaxSEDT is a more appropriate critical metric in design of a mission-critical facility. Long repair time is not desirable for mission-critical facilities. Mission-critical facilities have a limit of the maximum time the mission can endure an interruption of electrical power. MaxSEDT is an important metric because it tells you how efficiently you can respond to and repair the worst-case downtime event. Ideally the electrical power system will be designed to achieve the mission requirement for MaxSEDT.

Thermal Systems

Thermal energy systems are composed of both demand and supply sides (Figure 11). The demand side is composed of mission-related active and passive systems, including thermal demand by the process, HVAC systems maintaining required environmental conditions for the process and comfort for people, and a shelter/building that houses them. Requirements to thermal or environmental conditions in the building or its part housing critical mission-related processes and people include criteria for thermal comfort and health, process needs, and criteria preventing mold, mildew, and other damage to the building materials or furnishings. These requirements for normal (blue sky) and emergency (black sky) operations are described in detail by Zhivov et al. (2021), who specify requirements for building thermal conditions under normal and emergency operations for occupied and temporarily unoccupied spaces. Thermal comfort conditions in a mission-critical facility during normal operations differ from the cold stress threshold limits or heat stress threshold limits within which mission operators are able to conduct mission-critical tasks. This results in a difference between the total heating or cooling loads during normal operations and critical loads during emergency operations. This affects requirements for Energy Availability (EA) provided by the supply system. The time to restore the system to its baseline state is another requirement to the energy supply system. EA and MaxSEDT are two critical metrics of the thermal system characteristics of any asset affected by an event and may be affected by several factors, including site remoteness, event severity, and environmental condition.

MaxSEDT for Thermal System. Maximum downtime for a thermal system can be defined in terms of how long the

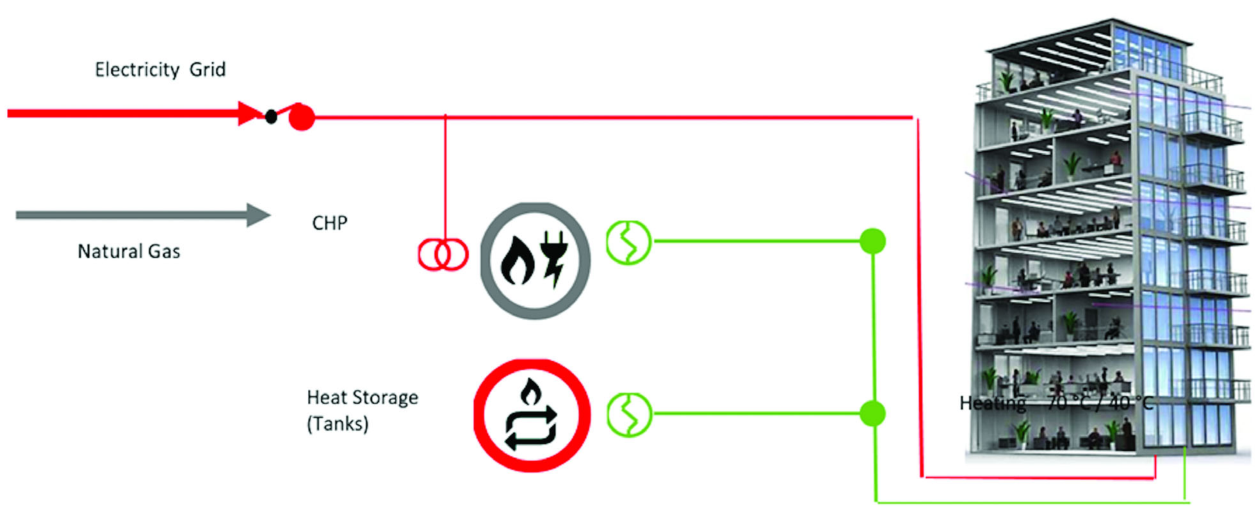

Figure 11 *Component of the notional thermal system.*

process can be maintained, how long the building remains habitable (habitability threshold), or how long the thermal environment can be maintained above the sustainability threshold level to protect sensitive content and to protect the building against damage from freezing of water pipes, sewer pipes, or the fire suppression system and from the start of mold growth during extended loss of energy supply in extreme weather events (e.g., 40°F [4.4°C]). Zhivov et al. (2021) define threshold limit values for building habitability for the heating season as the room air temperature being above 60°F (16°C) and for the cooling season as wet bulb global temperature (WBGT), accounting for a combination room air temperature and relative humidity below 88°F (31°C). Mission operators may select different thresholds based on the age, health, or level of training of inhabitants.

The major factors affecting the heat flow rate and therefore the time when the internal temperature reaches a threshold based on building habitability/survivability or sustainment include: difference between indoor and outdoor air temperatures; building envelope leakage rate; building envelope insulation properties, including insulation levels of its components; and thermal bridging and internal thermal load (people and appliances/equipment connected to electric power).

Also, the thermal mass of building structures composed of concrete, masonry, or stone materials that constitute a high level of embodied energy enables the building to absorb and store heat to provide "inertia" against temperature fluctuation. Figure 12 shows how these factors will influence the time when the building reaches its habitability (t_h) and sustainment (t_s) thresholds.

A one of the first of its kind, a thermal decay study attempting to address thermal decay in cold environments was conducted at Fort Wainwright, AK, and Fort Greely, AK (Oberg et al. 2021). The tests occurred with outdoor air temperatures ranging between –20°F and –40°F (–28.9°C and –40°C) allowed in order to obtain building-specific data on temperature change in different building areas and different surfaces of tested buildings to identify critical areas with significant temperature degradation compared to other building areas.

These tests found that air temperature in mechanical rooms located in the basement, in a semi-basement, or on the first floor having an opening for makeup air, fenestration, or a large open stairway column located nearby deteriorated more quickly than that in other parts of the building; therefore, mechanical rooms can be used as representative locations for identifying the time when a building reaches sustainability thresholds. Typically, the longest time to reach the habitability threshold occurs on the middle floors, which can be recommended for hosting mission-critical operations and which have therefore been used as representative locations for this purpose. EnergyPlus-based building energy modeling was used in this study, combined with the weather data corresponding to the test locations and dates, which allowed the building models to be calibrated for use in parametric studies of representative buildings.

The parametric studies of indoor air temperature decay (Liesen et al. 2021) were conducted using the geometry of one of the studied buildings that has two floors and a basement and houses office and meeting spaces, medical examination facilities, and medical laboratories. The following parameters were changed in the study:

- *Building mass:* 1) high-mass building (concrete masonry unit and poured concrete slabs) and 2) light-frame buildings.
- *Thermal envelope characteristics:* ranging from 1) pre-1980 code construction, 2) current minimum energy

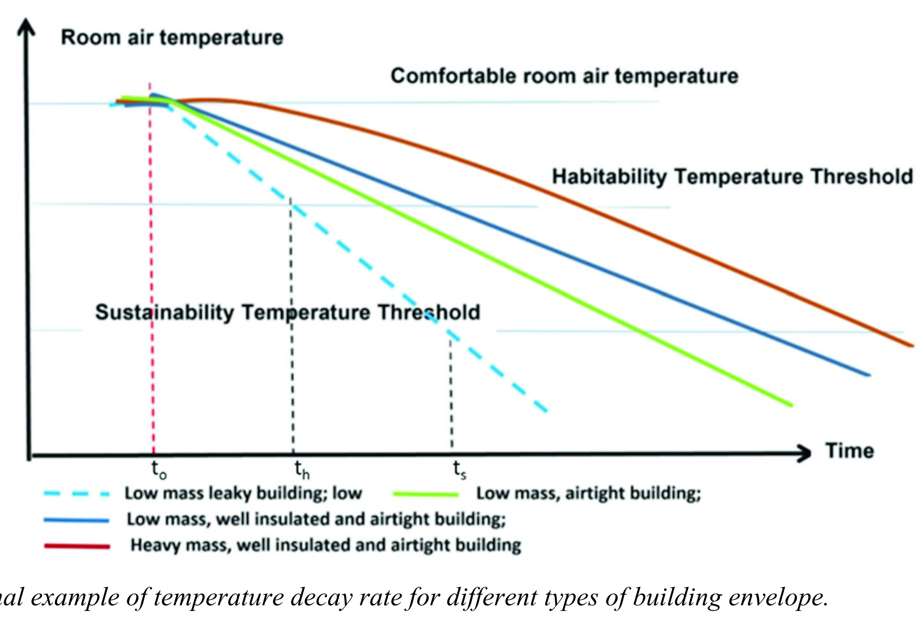

Figure 12 *Notional example of temperature decay rate for different types of building envelope.*

efficiency requirements (lower efficiency), and 3) state-of-the-art energy-efficient building characteristics (high efficiency) for buildings constructed in U.S. Department of Energy (DOE) climate zone 8. Table 12 lists specific characteristics for these three building categories.

- *Outdoor dry-bulb air temperature (ODB):* –60°F, –40°F, –20°F, 0°F, 20°F, and 40°F (–51°C, –40°C, –29°C, –18°C, 7°C, and 4°C). Typical meteorological year (TMY3) weather files used in the parametric study were adjusted to steady-state temperature files.

The results of these studies presented in Table 12 clearly show that high building mass contributes significantly to the thermal resilience of the building, along with greater building airtightness and higher thermal insulation. In a building with a mass structure and a more energy-efficient building envelope design, the indoor air temperature approached the habitability level of 60°F (16°C) 7 hours later than a similar building with a less energy-efficient building envelope and 6 hours later compared to similar arrangements with a framed (i.e., lower thermal mass) building structure. Intersection of the indoor air temperature decay line with the building sustainability threshold of 40°F (4°C) occurred 31 hours and 27 hours later, respectively, for the same scenarios. When mass high-performance buildings are compared with buildings built using pre-1980 codes (such buildings constitute the majority of existing buildings), the difference in the maximum time to repair calculated until the building air temperature reaches habitability and sustainability threshold values is much more significant. With the current trends in climate change, similar studies to obtain time until the building air temperature reaches habitability and sustainability threshold values after power supply interruption to the HVAC system can be critical for buildings located in hot/humid climates.

Blue Sky and Black Sky Energy Demands. During a normal (blue sky) scenario, energy generated on site or imported from outside the area of interest (AOI) can be consumed by *all* end uses (mission-critical and non-mission-critical building functions, industrial processes, and central services such as compressed air, water, sewer, etc.). This quantity of energy will also include distribution losses (hot water, chilled water, and steam network) and on-site conversion losses (from turbines, boilers, and engines).

During emergency (black sky) scenarios, some generation, distribution, and thermal storage system components

Table 12. Parametric Study Results for Maximum Single Event Downtime

Building Parameters	ODB Temp.	Mass Building			Frame Building		
		Typical/ Pre-1980	Low Efficiency	High Efficiency	Typical/ Pre-1980	Low Efficiency	High Efficiency
Walls (R-Value I-P)		20.5	40	50	20.5	40	50
Roof (R-Value I-P)		31.5	45	60	31.5	45	60
Air Leakage (ACH)		0.4	0.25	0.15	0.4	0.25	0.15
Window (R-Value/U-Factor)		Double Pane; R = 1.78/U = .56	Double Pane; R = 3.34/U = .3	Triple Pane; R = 5.25/U = .19	Double Pane; R = 1.78/U = .56	Double Pane; R = 3.34/U = .3	Triple Pane; R = 5.25/U = .19
MaxSEDT Hab. (60F)	–60°F	< 1 hour	2 hours	5 hours	< 1 hour	1 hour	2 hours
MaxSEDT Sust. (40F)	–60°F	9 hours	28 hours	41 hours	4 hours	14 hours	21 hours
MaxSEDT Hab. (60F)	–40°F	1 hour	3 hours	10 hours	< 1 hour	2 hours	4 hours
MaxSEDT Sust. (40F)	–40°F	20 hours	36 hours	51 hours	10 hours	18 hours	24 hours
MaxSEDT Hab. (60F)	–20°F	2 hours	6 hours	15 hours	1 hour	3 hours	6 hours
MaxSEDT Sust. (40F)	–20°F	31 hours	46 hours	60 hours	15 hour	22 hours	28 hours
MaxSEDT Hab. (60F)	0°F	3 hours	13 hours	29 hours	2 hours	5 hours	9 hours
MaxSEDT Sust. (40F)	0°F	43 hours	59 hours	90 hours	21 hours	28 hours	33 hours
MaxSEDT Hab. (60F)	20°F	10 hours	28 hours	45 hours	3 hour	8 hours	15 hours
MaxSEDT Sust. (40F)	20°F	60 hours	78 hours	95 hours	28 hours	35 hours	40 hours
MaxSEDT Hab. (60F)	40°F	29 hours	54 hours	72 hours	8 hour	17 hours	23 hours
MaxSEDT Sust. (40F)	40°F	93 hours	112 hours	123 hours	41 hours	47 hours	50 hours

may be compromised, e.g., components may be out of order or fuel supply to the campus can be limited. To maintain critical functions, the need for energy by both critical and noncritical functions can be reduced by shedding noncritical thermal loads. To do this, loads must be prioritized (to denote where and how energy will be used). Priority for energy supply must be given to buildings and their areas with mission-critical uninterruptable or interruptible processes. These mission-critical areas may include the whole building or, in some cases, as little as 5% to 10% of the total building area. For example, this strategy would dictate that a data center keep computer room air conditioners (CRACs) online while shutting down some office-only area air-conditioning systems. This example reduces the demand on backup supplies of generator fuel, providing longer run times of on-site supplied power.

The amount of thermal energy to be supplied to noncritical areas of a building or to noncritical buildings can be significantly reduced by using direct digital control (DDC) (or manual operation) to control space temperature to extend the use of limited resources without jeopardizing mission-critical, life, or safety functions or building sustainability. While the room air temperature in a mission-critical area of a building must be maintained close to the normal temperature, air temperatures in surrounding areas can be reduced to the level of survivability. Air temperatures in non-mission-critical facilities can be temporarily dropped to the level above the sustainability threshold. If possible, ventilation systems should be designed and adjusted to accommodate zonal control to reduce airflow rates in non-mission-critical zones to the level required for building pressurization. In occupied areas with reduced ventilation, care must be given to not violate air change per hour requirements of codes. When outside environmental conditions warrant, systems such as economizers may be used to maintain indoor air temperature. Nevertheless, due to their specific use in emergency scenarios, some buildings (e.g., shelters, dining facilities, etc.) may use more energy.

CONCLUSION

Power and thermal energy delivery can be thought to have three delivery mechanisms. The first delivery mechanism resides internally to the facility; it is the building-level power infrastructure for electric energy systems and building envelope and its mechanical systems for thermal energy supply. The second delivery mechanism is the emergency, or backup, energy systems directed to the facility from outside of the building but sourced from local infrastructure power and thermal energy generation. The third delivery mechanism is the full load delivered to the facility under normal operating conditions; this is commonly prime power, or power delivery from an electric utility for electric systems and steam, hot water, and chilled water delivered from the campus, building cluster, or outside the campus plant. Two facility load levels are defined. The full electrical and thermal energy load is provided by a layer three energy source and serves the entire electrical and thermal load of the facility. The critical electrical and thermal energy load is provided by layers one and two, also referred to as *backup power*, and serves only the facility critical infrastructure.

This paper introduces a quantitative approach to resilience of electric and thermal energy systems supplying energy to a building's mission-critical areas that includes the following metrics: Energy System Robustness (ER), Maximum Single Event Downtime (MaxSEDT), Energy Availability (EA), and Energy Quality (EQ). The first three parameters are critical for selection of the energy supply system architecture and technologies that comprise it to satisfy requirements related to energy system resilience. EA and MaxSEDT depend on 1) the criticality of the mission being served by the system, 2) the system repairability, which has significant dependence on the remoteness of the facility hosting the mission, and 3) redundancy of facilities that can serve the same critical function. Requirements for ER depend on the load that is critical to the mission; this can be measured as 1) the percentage of the load that is available to mission essential loads from the total mission essential load requirements, which can also be related to 2) the overall building energy load under normal (blue sky) conditions. EQ is another important quantitative metric for energy systems serving critical functions and should be considered as a design parameter for level one building energy systems.

To prevent significant damage to noncritical buildings, minimum thermal requirements (in cold climates) and air humidity above the dew point (in hot/humid climates) must be maintained in these buildings, which will require that thermal energy still be supplied to these buildings, but at a significantly reduced rate. These variations in type, magnitude, and schedule of critical energy requirements are essential considerations when developing resilience system performance metrics such as energy availability and Maximum Single Event Downtime (MaxSEDT).

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