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Integration of Resilience Goals into Energy Master Planning Framework for Communities

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ABSTRACT

This paper describes in detail a process for integrating resilience goals within the Energy Master Planning Process. Focusing on the district scale, methodologies are discussed to quantify the resilience benefits of energy system designs and determine trade-offs between resilience and blue-sky performance. Systems are aggregated to a mission function level with the goal of keeping critical functions online during emergency events. We outline how to down-select the top threats for the area, how to apply the corresponding threat profiles and fragility curves to the system's infrastructure elements, and how to evaluate resilience metrics using systems modeling techniques. Design options to improve the system's resilience to the selected threats are suggested by the process. All steps of the process are applied to a notional example. The paper concludes with a discussion of the capability gaps and a path forward for implementing this process for energy master planners. This paper is based on research performed under the International Energy Agency's Energy in Buildings and Communities Program Annex 73, focusing on development of guidelines and tools that support the planning of Net Zero Energy Resilient Public Communities as well as research performed under the Department of Defense Environmental Security Technology Certification Program project EW18-D1-5281, "Technologies Integration to Achieve Resilient, Low-Energy Military Installations."

INTRODUCTION

The Energy Master Planning (EMP) process is useful for guiding long-term energy development plans that address goals of multiple stakeholders at the district scale. The EMP process provides a holistic approach to long-term planning for achieving energy needs cost-effectively, reliably, and sustainably (Zhivov et al. 2014). Although the EMP process can be applied to communities with multiple owners, the process described in this paper focuses on communities with a single-owner or single developer that can coordinate the implementation of energy generation, distribution, and building technologies; such as university and hospital campuses, military installations, or urban redevelopment projects. The EMP process described in this section is built on previously developed concepts (OSD 2016; ESTCP 2015; Zhivov et. al, 2014; IEA Annex 51), but differs in such a way that in addition to meeting an installation or community's day-to-day energy goals (herein: blue-sky goals), it integrates development of a highly resilient "backbone" of energy systems that allows maintenance of critical missions and lifeline services during extended outages over a range of emergency scenarios, caused by natural and man-made events as well as aging infrastructure.

To date, EMPs have been based on a community's blue-sky energy goals and constraints, such as site and source energy use reduction, reduced emissions, lower operational cost, and positive return on investment (Sharp et al. 2020). Resilience goals often received secondary consideration within EMP, if considered at all. A recent survey of energy master plans for zero-energy districts found that while resilience was often cited as a driver or goal for planning, resilience benefits were not quantified at the same level of rigor as efficiency or sustainability benefits (Zaleski et al. 2018). Currently, with a growing attention to energy systems resilience, many planners incorporate resilience independently of the EMP process. Sandia National Laboratories has developed the Energy Surety Microgrid™ (ESM) design methodology

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that focuses on resilience in energy system design oriented toward energy systems supporting critical facilities (Jensen et al. 2015). However, the ESM methodology has not been fully integrated into the EMP process to date, nor does it take advantage of the cost-savings, resilience gains, and efficiencies offered by integrating thermal loads into the design process. Incorporation of resilience into the EMP process can help planners achieve resilience goals at a lower overall cost, with a potentially positive impact on performance in other categories such as system efficiency and sustainability.

We define a resilient energy system as one that can prepare for and adapt to changing conditions, and recover rapidly from disruptions including deliberate attacks, accidents, and naturally occurring threats (PPD-21, U.S. Army 2015). Extending this definition, a resilient energy system prioritizes and maintains performance of important services such as food, water, and shelter, as well as economic or mission-oriented functions that relate to the purpose of the district. This system resilience can be enabled by holistically designing systems that explicitly account for threats and improve energy delivery to critical functions subject to these threats. Therefore, an EMP process that integrates resilience will decrease the probability of unacceptable consequences from a host of threats to the people and critical activities of a district.

This paper describes in detail a methodology that integrates resilience into the EMP process. Throughout the paper, we use a hypothetical district system with a mix of critical-service-providing load and non-critical energy load, as well as thermal and electrical energy load. While smaller than most districts, this system will capture a wide range of challenges that planners are likely to face. The resilience-inclusive EMP methodology is presented step-by-step and is intended for use as a guide for energy master planners.

MEASURING AND IMPROVING RESILIENCE

To integrate resilience into the EMP process, it must be measured. A lack of quantifiable resilience measures has been highlighted as a critical gap in energy system planning (National Academies of Sciences, Engineering, and Medicine 2017). 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. kg of CO_2 equivalent emissions). Performance-based resilience metrics are directly measured or forecasted via systems models and describe how well the overall system performs subject to disruptions.

Figure 1 shows a graphical description of system performance subject to a single event. In this figure, an event occurs that degrades overall system performance. In the district undergoing EMP design, system performance may be measured by the effort that people must expend to achieve their basic needs (e.g., food, water, shelter), and/or the level to which that district achieves its purpose (e.g., economic output or mission performance). System 1 and System 2 are two alternative energy system designs, subject to the same disruption. This overall system performance is highly dependent on the energy system's performance during the event. Energy system performance at key loads in the system enable the system performance, for example a water treatment plant enabling drinking water for the community. The performance-based resilience metric "system impact" (SI) is the integral over time of the actual system performance minus the target (or nominal) system performance, as shown:

$$SI = \int_{t0}^{tf} [TSP(t) - SP(t)]dt \tag{1}$$

where *TSP(t)* is the targeted system performance through time – the nominal performance of the system without a disruption, and *SP(t)* is the system performance subject to the disruption (Vugrin et al. 2010). The goal of a resilience-inclusive EMP process is to decrease the projected SI as much as possible for as little cost as possible, while balancing trade-offs with other goals such as efficiency and sustainability. The goal of this paper is to add rigor to how resilience is quantified so planners can compare resilience across various solutions and find holistic solutions that benefit sustainability and efficiency while achieving resilience.

INTEGRATION OF RELIABILITY-FOCUSED PLANNING

Because the EMP process uses a performance-based metric to describe resilience, it can be extended to include reliability-focused planning. The primary difference between

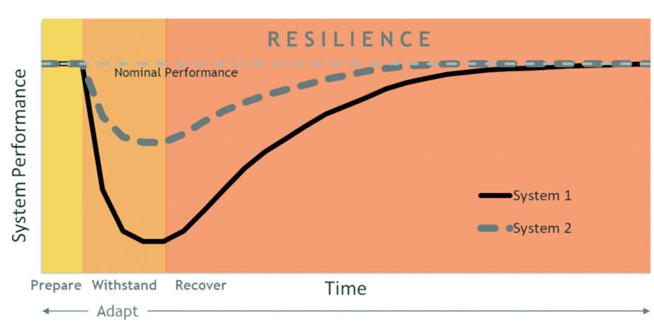

Figure 1 *Hypothetical system performance over time during a disruption for two alternative system designs.*

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 (U.S. DOE 2017). These are events that often occur several times a year such as wildlife intrusion/ damage, storms, car-hit-poles, and other accidents. Because these events occur frequently, there can be a wealth of historic data on how the energy system performs subject to them. The historic data enables direct calculation of performance-based reliability metrics such as mean time between failures (MTBF) and mean time to repair (MTTR) for energy system assets, as well as kilowatt-hours not served per year for the energy system as a whole (Brown 2009; Torell and Avelar 2004). Therefore, reliability-focused planning often relies on historic data to estimate where upgrades to the system would best improve reliability. In contrast, resilience-focused planning includes a much wider range of events – including but not limited to the low-probability events that could pose a very high consequence to the energy system and the district. Because these events occur infrequently, there is not enough historic data to gauge how the energy system will perform. System modeling must be included to forecast the consequence of low-probability events. To incorporate the full range of events from low-to high-probability, data-driven reliability calculations are combined with model-driven resilience calculations (Vugrin et al. 2017).

The resilience-inclusive EMP process we describe here is threat-inclusive 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. Assuming failures occur independently from one another is another factor separating reliability-focused planning from resilience-focused planning. Judson et al. (2016) offer an approach to threat-agnostic resilience planning for military installations that focuses on improving the energy availability at critical facilities but does not directly incorporate the effects of known threats to the system.

METHODOLOGY—RESILIENCE-INCLUSIVE ENERGY MASTER PLANNING

This paper details a step-by-step process for resilience planning for single-owner systems such as military installations, campuses, hospital complexes, and public housing. The proposed methodology includes distinctive steps along with their inputs and outputs, which can be well understood by energy master planners. This process is designed as an ideal and rigorous integration of resilience planning within EMP, which means that some of the methods and processes require

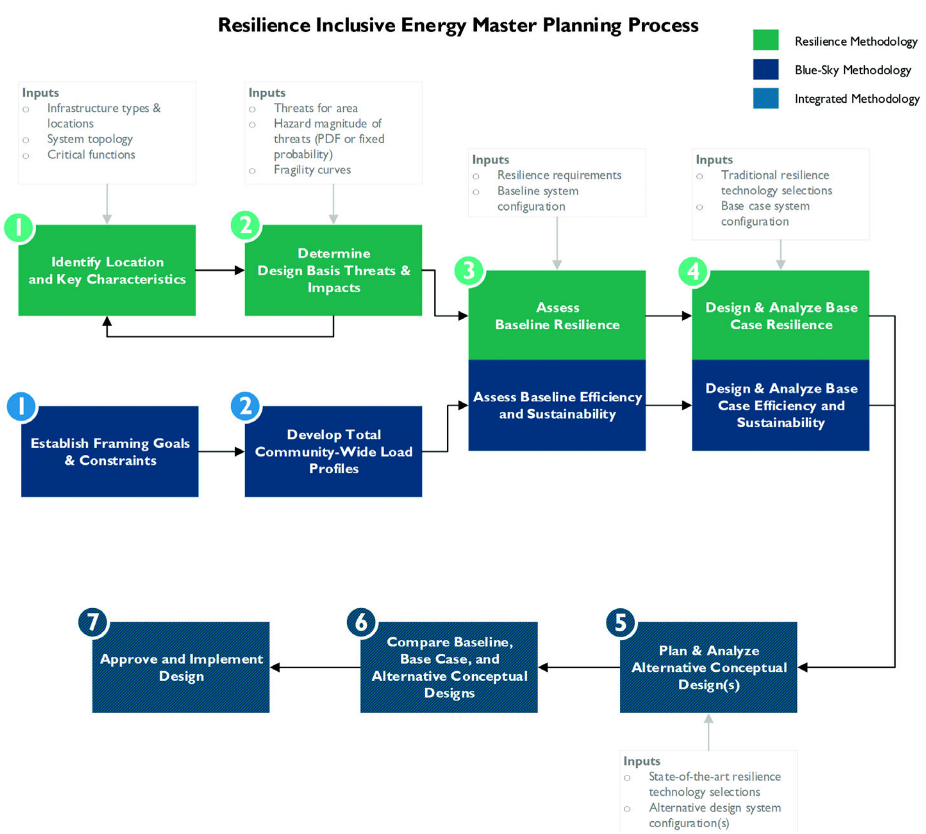

Figure 2 *Resilience process for energy master planning.*

systems modeling and/or optimization capabilities. Not all energy master planners possess such capabilities, so wherever possible, we have noted compromises in the process that can allow planners to move forward without them. In the long-term, this ideal process can serve as a design guide for easy-to-use computational tools that will be available to energy master planners.[1]

An Overview of the Planning Process

The process shown in Figure 2 has been developed to incorporate resilience goals into the EMP process. Each step, along with inputs, methods, and outputs is discussed in detail in the following sections.

At a high level, energy master planners should familiarize themselves with the area of interest (AOI) and its critical operations, identify high-consequence threats affecting the area, quantify the probabilistic system impact of the existing system, quantify the probabilistic system impact of a standardized base case improvement alternative, develop holistic designs for alternatives that improve on the base case in one or more categories, and compare probabilistic system impact across the baseline, base case, and alternatives. Finally, planners should compare resilience performance to performance in other categories, optimizing designs to balance trade-offs between cost, resilience, sustainability, and efficiency. In the following sections, we will introduce a notional system and apply each of these steps to show how a planner would work through the process. Steps one through six will be broken down into a series of subtasks that are detailed in Figure 3. Desired data will be described, but compromised processes for completing steps are suggested when data is unavailable or incomplete.

Applying the Process to a Notional Energy System

The remainder of this paper uses the notional system shown in Figure 4a to illustrate the resilience planning process.

This system includes a simple radial distribution electrical system design with four buildings. The left-hand side of the diagram shows an electrical bus representing a substation, with a facility transformer and breaker switch to the electric utility. Buildings A and B have backup generators and fuel storage. All buildings have their own boiler for heat fueled by a natural gas distribution system (not shown).

Step 1: Identify Location and Key Characteristics

The first step in the Resilience-Inclusive EMP Process, shown in Figure 3a, is the characterization of the AOI undergoing resilience-inclusive EMP. The type of AOIs considered for this process include, but are not limited to: military installations, hospitals, campuses, and public housing developments. The AOI has designated purposes – for example a university campus supports higher education as well as the health and wellness of the students, faculty, and staff that live and work on the campus. The most important purposes for a given AOI should be considered critical operations – herein designated as "critical functions" – that must be performed for the location to serve its purpose. The planner's goal will be to keep these critical functions online as much as is required by the AOI. In disruption events, the performance of these functions is the System Performance (SP) term in Equation 1. Planners should also understand the overarching blue-sky and resilience goals for the AOI, especially whether the goals include direct constraints, such as a fixed percentage of energy from renewable resources or a facility-wide efficiency target. For this process, blue-sky performance is defined as the total overall life-cycle cost of energy for an AOI, combined with the achievement of sustainability goals such as reduction in greenhouse gas emission associated with the AOIs energy system.

At the end of step 2, a risk equation will be populated that will enable ranking of the highest priority threats for further analysis. This risk equation is only to be used for ranking threats and should not be used for the final design prioritization described in steps 3 through 5. We introduce the risk equation here to preface how criticality will play a role in the ranking of risks. The prioritization risk equation is as follows:

$$R_t = p_t \sum_f v_{t,f} c_f \tag{2}$$

where R_t is the risk index of threat t, p_t is the approximate likelihood of threat t occurring in a given year, $v_{t,f}$ is the approximate vulnerability of mission function f to threat t, and c_f is the approximate criticality of mission function f. The goal of step 1 is to quantify the critical functions such that the criticality term for the risk equation is populated. The likelihood of threat t occurring and the vulnerability to that threat will be described in later sections.

1a: Identify Infrastructure and Location

All energy demands within the AOI should be mapped and well-understood; including buildings as well as other assets that have electrical or thermal load. For this step, a geospatial information system (GIS) is helpful to incorporate the multiple data sets that will be integrated throughout the process. Similarly, the energy supply system including thermal and electrical assets such as transformers, switchgear, conductor, piping, boilers, etc. should be mapped and well-understood. This includes any expected upgrades to infrastructure within the planning horizon.

1b: Identify Critical Functions

The concept of "critical function" serves as an intermediary between the AOI's (community/campus/military installation) mission or purpose, and the function of individual

[1] For example, as a part of the ongoing Environmental Security Technology Certification Program (ESTCP) project EW18-D1-5281, a software tool will be developed for planners to integrate this methodology into the Energy Master Planning process.

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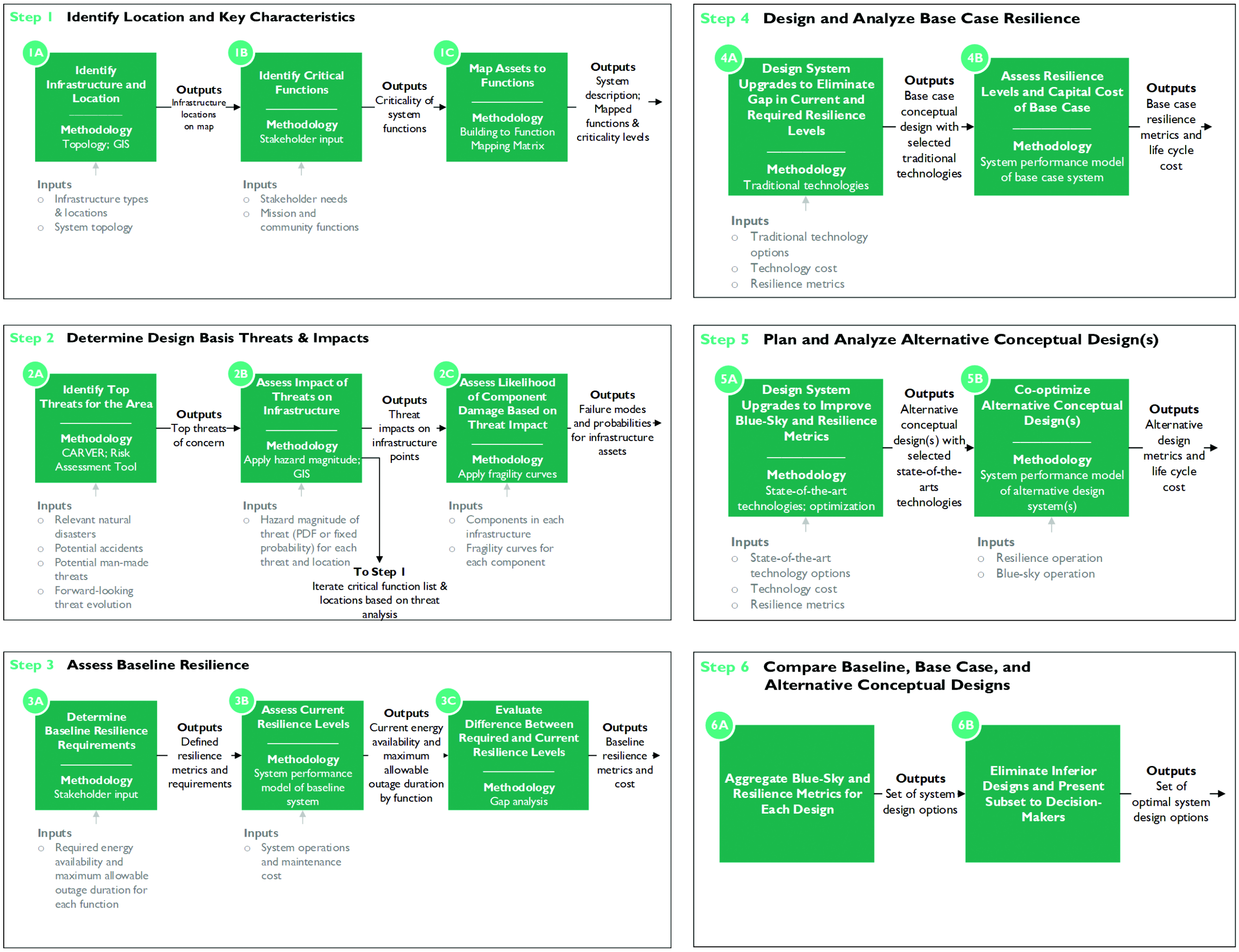

Figure 3 *Subtasks for energy resilience process: (a) Step 1, (b) Step 2, (c) Step 3, (d) Step 4, (e) Step 5, and (f) Step 6.*

buildings or assets. Concentrating on providing resilience to the critical functions instead of to critical buildings or assets builds flexibility into the resilience investment plan and ultimately reduces cost in most applications. Many functions can be enabled by more than one building, and many buildings provide or can be adapted to provide multiple functions.Human shelter is a good example of a function that could be provided by a large number of buildings. Alternatively, a function may be supported by a small part of a single building and thus resilience for critical loads would not require building-wide backup power. Finally, different threats or scenarios can dictate that certain buildings are used to provide a function over others – for instance when a subset of buildings are flooded or damaged. This fungibility of load to provide an overall function to the AOI is not well-represented by current design tools and presents a capability gap for planners.

Critical functions enable the AOI to serve its purpose and can be further separated into life-sustaining functions and mission functions. Table 1 provides a non-exhaustive list of functions that may be considered in each category. Life-sustaining functions provide people with services such as food, water, and shelter during emergency events. Mission essential functions support an important purpose for the AOI that is not directly necessary for human life but is nonetheless vital, such as important research or national security purposes (FEMP 2013). For the U.S. Army, a critical mission function is defined as a function that is vital to the continuation of operations of the organization or agency (U.S. Army 2006). A risk management process has been developed by U.S. Army North that guides planners through a prioritization of assets with focus on mission execution (USARNORTH 2019). For life-sustaining functions, a description of how functions enable overall success of a community or installation is provided by Clark et al. (2018). Stakeholder engagement with community planners and/or mission owners is commonly necessary to assess the functions that are critical and the assets that can provide those functions.

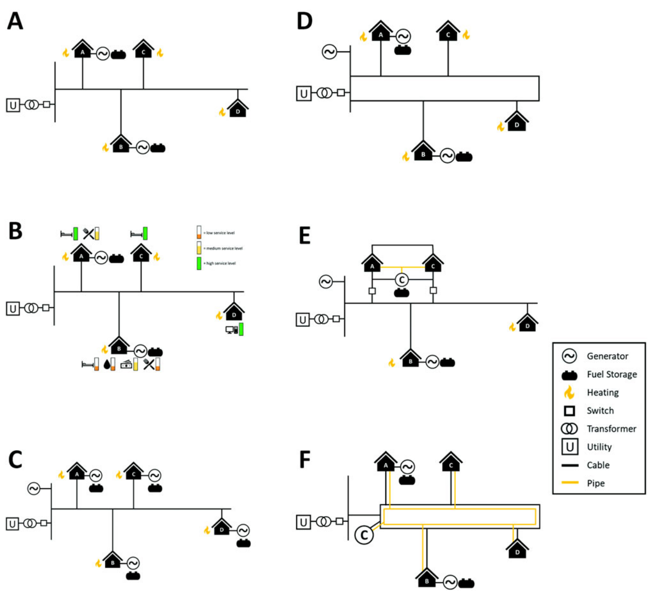

Figure 4 *Notional energy system configurations: (a) Baseline system, (b) Critical functions and their service levels, (c) Base case system, (d) Alternative conceptual design #1, (e) Alternative conceptual design #2, and (f) Alternative conceptual design #3.*

Critical functions may need to be further refined for some AOIs. For example, transportation may include alternative means, each with separate energy requirements, such as personal vehicles, trains, and buses. In this case, transportation would be an overall community function, but each mode of transportation would constitute a sub-function with unique energy resilience requirements. Even within one building, multiple functions with multiple levels of criticality can be numerated.

At the end of this step, the planner should have a list of all critical functions, and the approximate criticality rating of these functions that will populate c_f in Equation 2. Criticality ratings may be assessed based on consequence of loss. The largest criticality rating should be 1.0, whereas a purely non-critical function would hypothetically be assigned a value of 0.0. A suggested criticality ranking methodology is that outlined by DoD O-2000.12-H (DoD 2004) where criticality is the normalized sum of the following metrics: Effect, Recoverability, Substitutability, Mission Functionality, and Reparability.

1c: Mapping Infrastructure Assets to Functions

Once critical functions are identified, and their criticality quantified, infrastructure assets mapped in step 1a are associated with one or more functions determined in step 1b. The topology of the system is important for evaluating current and future system states since placement of resources within the

Table 1. Common Critical Functions for Communities and Missions

Life-Sustaining Functions	Mission Functions
Communications	Communications
Emergency Logistics	Cybersecurity
Evacuation	Data Management and Storage
Finance	Force Mobilization and Deployment
Food	Intelligence
Fuel	Logistics
Medical Services	Manufacturing and Maintenance
Medications	Operational Support
Restoration	Research and Development
Safety	Secure Storage
Security	Security and Force Protection
Shelter	Strategic Command
Transportation	Surveillance and Reconnaissance
Waste Management	Training
Water	

system and distances between infrastructure assets can impact the resilience of the system as a whole. This is a point at which 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 a disruptive event.

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). 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 which that asset can provide is sufficient.

The output of this step is a matrix that associates infrastructure assets with critical functions. In addition to buildings, assets may also be point loads such as communications towers, or networks such as water distribution systems. Table 2 lists the elements of a generic asset to function mapping matrix. Planners should fill out the table for all assets and buildings that provide or enable critical functions and map

Table 2. Building to Critical Function Mapping Matrix

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

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 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.

Calculating Emergency and Blue-Sky Energy Demands

For the AOI to be resilient, it is necessary to serve the most critical energy demands that will be present during the disruption scenarios. The planner must understand the dynamic demand of each asset or building in the disruption scenarios and scale up to demand for each critical function in order to develop and evaluate resilient designs. This contrasts with standard EMP process that uses historic data or models to calculate energy demands for a blue-sky day. The characteristics of the critical energy load can vary significantly between functions. For example, a communications function may require a large but steady supply of power to meet its equipment and conditioning needs. A shelter, on the other hand, may have little to no critical electrical power demand, but have a large variable heating demand to protect occupants from environmental conditions. Figure 5a gives an overview of how critical and non-critical loads are broken out within buildings, while Figure 5b illustrates 24-hour load profiles for the disruption scenario. Profiles for blue-sky scenarios could be drastically different.

There are also large variations in energy demand profile based on the function's location. For example, a critical administrative function in Phoenix, AZ would likely require a cooling system to maintain operation, but that same function in San Diego, CA could meet that demand by opening the windows and taking advantage of natural ventilation. Similarly, the acceptable system description period will be significantly shorter for a heating system in the depths of an Alaskan winter compared to Seattle, WA. 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 quality, discussed later in more detail.

Mapping Buildings to Functions in the Notional System

Using the notional system, Figure 4b shows that each of the four buildings in the AOI 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 lower level that can serve as a storm shelter. Building C is a second dormitory. Building D is a data center with servers for research labs and campus administration files.

The data in Table 3 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; however, 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 serves as a data center for the campus.

SELECTION AND APPLICATION OF THREATS

Resilience is contextual in that it is defined in relation to a threat or hazard (Watson et al. 2014). For example, a system that is resilient to hurricanes may not be resilient to earthquakes. Threats that an AOI has chosen to incorporate within the energy master plan are called Design Basis Threats (DBTs). Threats may come in the form of natural disasters, accidents, and man-made threats. Planners must select the threats that are most applicable to their area, to increase resilience to those threats. It is important to include the threats that occur with low frequency but pose a potentially high consequence. Provided in this section are a list of threats by type, directions for down-selecting to the appropriate DBT(s) for a given area, and data requirements. DBTs should be evaluated individually but may also be evaluated in combinations depending on anticipated impacts to the given area. Details of the subtasks associated with this section are shown in Figure 3b.

2a: Identify Top Threats for the Area

Natural disasters include events caused by nature that adversely impact communities and missions. Below is a list of natural disasters present around the globe:

- Avalanches
- Blizzards

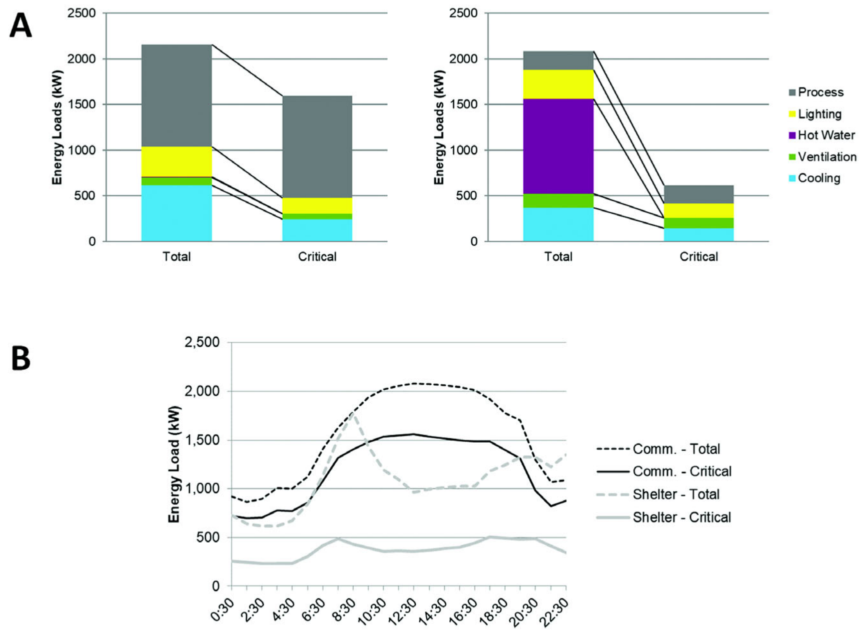

Figure 5 *Total and critical electrical demands: (a) Total and critical electrical demand load for a data center (left) and a dormitory (right), and (b) Critical electrical demand hourly profiles for communications and shelter over a 24-hour period.*

Table 3. Mapping of buildings to functions for notional system

Critical Function	Building A	Building B	Building C	Building D
Shelter	1.0	0.5	1.0	
Food	0.75	0.25		
Finance		0.5		
Water		0.25		
IT and Data				1.0

- Droughts
- Earthquakes
- Extreme Heat
- Floods
- Geomagnetic Disturbances (GMD)
- Hurricanes/Cyclones/Typhoons
- Ice Storms
- Landslides
- Lightning
- Tornadoes
- Volcanic Eruptions
- Wildfires
- Wind

Accidents are events that lead to power or thermal outages that are unintentional and may be caused by humans, animals, or infrastructure failures. A list of possible accidents is given below, though certain areas may have additional threats unique to their area. Some accidents are common events that cause only small/brief interruptions and are not the type of low-probability, high-consequence threats which are important to consider for resilience.

- Transportation accidents (car, bus, etc.) that damage electrical/thermal infrastructure
- Animals that cause power outages by climbing on equipment
- Untrimmed vegetation
- Equipment reliability failures
- Construction that inadvertently causes damage to electrical/thermal infrastructure
- Infrastructure failures/collapses (bridges, roads, etc.).

Man-made threats are deliberately planned and executed attacks aimed at taking down electrical and/or thermal infrastructure and services. Planners should also acknowledge the "insider" threat of people who have valid access to systems and choose to perform malicious attacks. A list of man-made threats is given below:

- Cyberattacks (insider and outsider)
- EMPs (Electromagnetic Pulse)
- Physical attacks on electrical/thermal infrastructure

- Riots/Wars
- Terrorist attacks

Planners are typically aware of their top threats and may already be employing risk assessment methods such as the Threat and Hazard Identification and Risk Assessment (THIRA) developed by the U.S. Department of Homeland Security (2018) that can be used to inform the selection of DBTs. However, if many threats exist for an area, planners may need a structured method to down-select to the most critical threats for their location. Multiple methods exist that may be utilized, such as the Risk Management Process developed by ARNORTH, ERDC's Risk Assessment Tool (RAT), and the CARVER method (U.S. Army North 2019; Schnaubelt et al. 2014). All planners walk through the process of identifying all threats to the area, quantifying the potential probability and consequence of threats, and ranking the threats to determine those that should have the highest focus. Planners in coastal California would almost certainly include earthquakes as a DBT for their planning, whereas planners in Minnesota would likely focus on other threats. Gulf and Atlantic Coast communities experience hurricanes, but few major earthquakes.

It's important to recognize that some threat assessment methods, such as ARNORTH's Risk Management Process and CARVER, were designed primarily to assess man-made threats and would need to be modified to include natural disasters and accidents. For example, the ARNORTH methodology includes the following criteria: operational capability, intentions/likelihood, activity, and operating environment (U.S. Army North 2019). Meanwhile, CARVER focuses on the criticality of the 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 (Schnaubelt et al. 2014). More information on determining threat probabilities and threat severities for natural disasters is given in the following section.

2b: Assess Impact of Threats on Infrastructure

Up to this point, the planner has established a list of critical functions for the AOI and has identified the top threats to the area. The planner should next understand how those threats impact the buildings and energy assets within the AOI, as well as the likelihood and duration of utility service outage. Assessing long-term predictive maps quantifies the threat intensity spatially at a set probability. Sources of threat data are publicly available from a variety of sources. FEMA, the USGS, and NOAA all provide open-source data for the United States and select international locations (FEMA 2015; USGS 2019; NOAA 2019). For natural hazards, the DHS-provided HAZUS tool offers a good starting point for numerous threats (FEMA 2019). HAZUS delivers a standardized methodology for estimating potential losses from earthquakes, floods, hurricanes, and tsunamis. Additionally, some countries have established their own databases and models for threats specific to their areas. Figure 6a shows the long-term earthquake threat map (peak ground acceleration, 2% likelihood in 50 years) for the United States as generated by the USGS (USGS 2019). Similarly, Figure 6b illustrates the location and intensity of historic events that have caused considerable consequence to energy infrastructure.

Threat probabilities may change over the planning horizon and hazard magnitudes may need to be represented differently over time. For 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. An example of using this process is shown on the map in Figure 7b. In the analysis of Jeffers et al. (2016), spatial profiles of flood depth were generated for 100-yr and 500-yr floods. For the planning horizon, additional spatial profiles were generated based on the projected 1.5 ft and 3 ft of sea level rise. These additional profiles informed planners of how flood risk is evolving at set probabilities.

The output of this step is ratings for p_t in Equation 2, the approximate probability associated with one or more specific Design Basis Threats (DBTs) within each threat category. The probability of a DBT is assessed based on its likelihood of

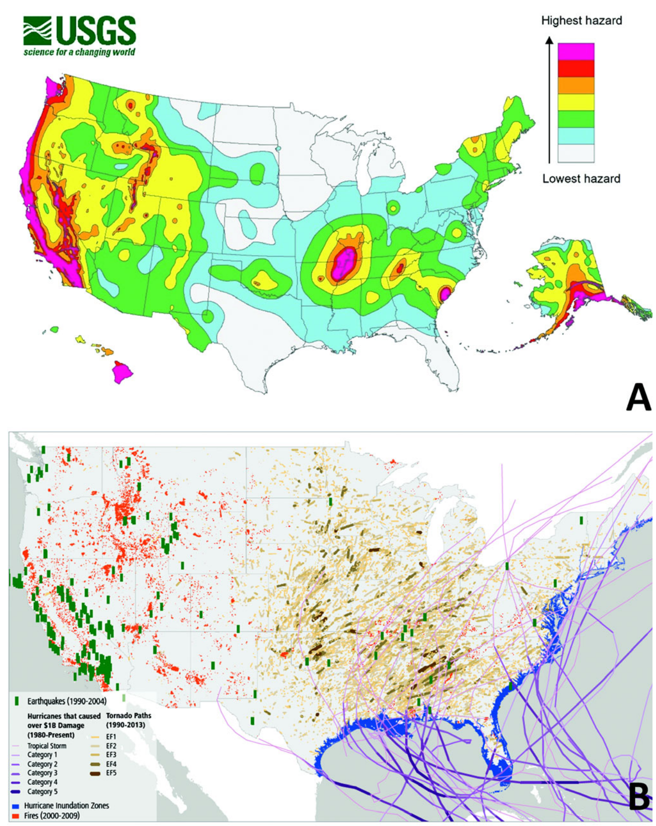

Figure 6 *Design basis threat examples: (a) Long-term earthquake threat map for United States, (b) Historic major natural disasters in United States (USGS 2019; Preston et al. 2016).*

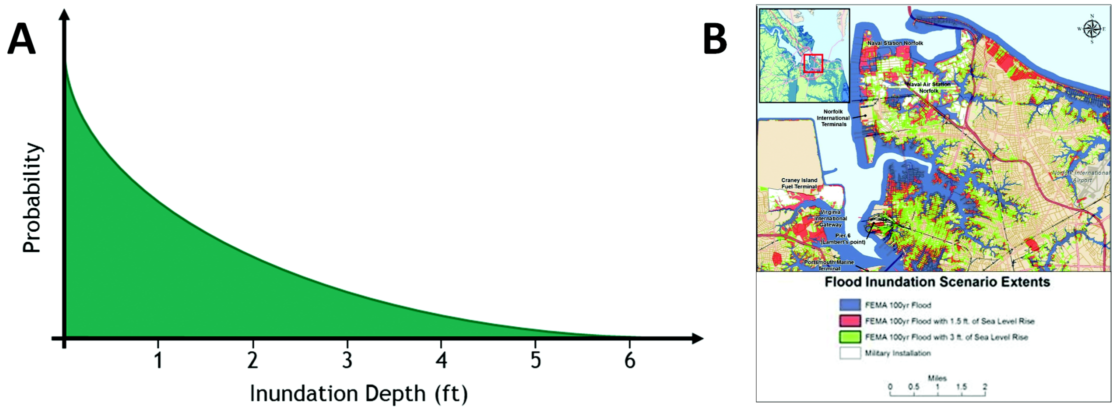

Figure 7 *Flood design basis threat: (a) Flood PDF, and (b) Flood effects on geographic area (Jeffers et al. 2016).*

occurrence within a given year, in which a value of 1.0 would indicate absolute certainty of occurrence and a value of 0.0 would indicate the threat never occurs. For this step, it's recommended to assess multiple DBT instances within each category (e.g., for flooding to assess the 100-year flood with a pt of 0.01 and the 500-year flood with a p_t of 0.002). To aid with population of pt, for each type of threat being considered for a given area, the planner should acquire or generate data on the magnitude of the threat, either as a probability density function (PDF) or at a fixed probability, for each threat and each location. An example PDF representing the inundation level at a specific location is shown in Figure 7a.

2c: Assess Likelihood of Component Damage Based on Threat Impact

Using the spatial representations of the DBTs generated in step 2b, for each DBT at multiple levels of probability planners should use GIS tools to understand the threat magnitude for each asset. The output of this step is the vulnerability rating, $v_{t,f}$ in Equation 2 for each critical function f, and each DBT. A vulnerability rating of 1.0 indicates absolute certainty of the function not providing its intended service, while a vulnerability rating of 0.0 indicates the function is sure to withstand the DBT to the point that it can provide its service.

If DBTs are represented in raster form, a geospatial intersection between the mission-function-providing buildings/assets and the threat contour will provide the threat intensity at each building/asset. In Figure 8, the notional system has been overlaid with a 100-year flood threat profile (e.g., p_t of 0.01). In this example, planners should calculate the flood depth for infrastructure points A through D, as well as depth for all energy assets. These include electrical assets such as overhead distribution lines, generators, switches, transformers, and thermal assets such as boilers, pipes, and valves. For line assets, the maximum flood depth along the length of the line or pipe should be estimated.

Once every asset has been assigned a threat magnitude, fragility curves are used to determine the probability of

Figure 8 *Flood threat profile applied to notional system.*

damage to the asset. For energy assets, fragility curves are often generated by component manufacturers, and curves generated by statistical analysis are available from the literature (Zareei et al. 2016; Shafieezadeh et al. 2012; Shafieezadeh et al. 2014; Han 2008; Eidinger et al. 2016). For buildings, fragility curves are also available for different classes of construction, primarily for wind and seismic hazards (Filliben et al. 2002, Hwang and Huo 1994). For every asset, the threat magnitude is used as input to the x-axis of the fragility curve, where the probability of failure is output on the y-axis. In the case that no fragility curve is available for a specific asset type or threat, one may be generated by working with a Subject Matter Expert to determine the level below which the asset never fails, and the level above which the asset always fails. A logistical curve is interpolated between these two values to generate a fragility curve. A hypothetical outcome of this process is shown below in Figure 9a.

In addition to failure probabilities for all assets, the failure probability and expected outage duration for the electric utility and any other utilities serving critical functions must also be determined for each DBT. The most accurate way to estimate this is to work directly with the electric utility, assessing outage durations for past events and projecting future system performance where possible. Promising statistical work such as Guikema et al. (2014) provides statistical estimates of outage likelihood and expected duration using hurricane

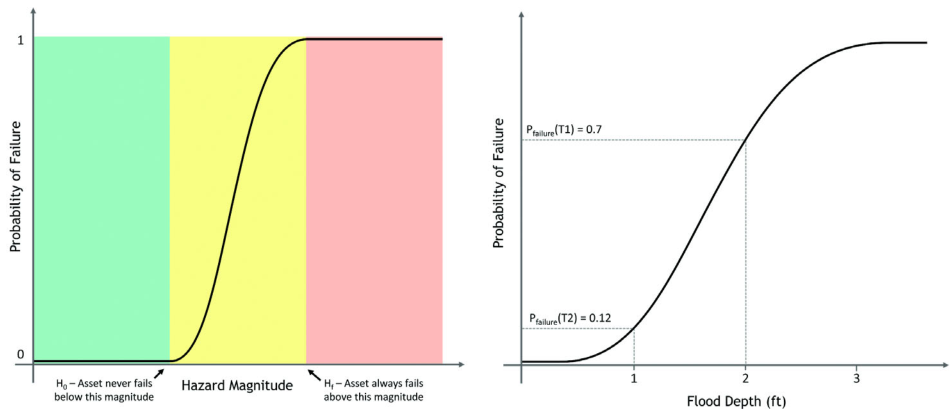

Figure 9 *Example fragility curves: (a) Hypothetical fragility curve, and (b) Transformer fragility for notional system.*

intensity as a forcing function. Similar statistical analysis has been performed for earthquakes (Liu et al. 2007).

Once all building, energy asset, and utility failure probabilities are calculated, they should be used to estimate the vulnerability of each mission function to each DBT. This vulnerability is defined as the probability that the mission function will not serve its intended purpose over the course of the event. To calculate this, planners should use the asset to function mapping developed in Table 3, entering their estimated probability that each asset would not be able to serve its intended purpose.

Application of Flooding to the Notional System

For the notional system, a 100-yr flood DBT was applied to the buildings and energy infrastructure assets, resulting in the spatial analysis illustrated in Figure 8. Building D is under 2 feet of water, building C is under 1 foot of water, and buildings A and B are not inundated. Not shown in the diagram, buildings C and D have pad-mounted transformers, which are also inundated by 1 foot and 2 feet of water, respectively. The buildings are not susceptible to this level of flooding; however, the transformers are. Using the hypothetical fragility curve shown in Figure 9b, these transformers have a probability of failure of 0.12 and 0.7, respectively. This information will be used by the systems model analysis for baseline resilience in the next step.

The asset-level vulnerability estimate is illustrated as Table 4 for our reference system. In this case, the electric utility has an estimated failure probability of 0.5 and the water utility also has an estimated failure probability of 0.5. The backup generator has a failure probability of nearly zero since it is in the non-inundated area. Because buildings A and B have robust connections to the backup generator, their estimated vulnerabilities are 0.0. Based on the fragility of the transformer serving Building D, the probability of failure to serve energy is estimated at 0.7. Subject matter experts estimate that the building is completely dependent on power to serve its function, so the estimated vulnerability is also 0.7. In contrast, building C can still provide some of its service without power, so although the failure probability for the transformer serving Building C is 0.25, the vulnerability of Building C's function is estimated at 0.1.

Iteration between Steps 1 and 2

Once all building and asset failure probabilities as well as asset-level vulnerabilities are calculated, they should be used to estimate the vulnerability of each mission function to each DBT. This is accomplished using a combination of Table 3 and Table 4. The mission function vulnerability $v_{t,f}$ in Equation 2 is the weighted sum of the asset-level vulnerabilities, as expressed in Equation 3.

$$v_f = 1 - \sum_b f_{b,f}(1 - v_b) \tag{3}$$

where v_f is the vulnerability rating for function f, $f_{b,f}$ is the function contribution of building b to function f from Table 3, and v_b vulnerability of building b from Table 4. Vulnerability cannot be negative, so if Equation 3 returns a negative value, the vulnerability of that function should be estimated as zero.

At this point, the approximate risk for the AOI subject to each DBT can be calculated using Equation 2. All DBT's should be rank ordered by this risk rating, and a cutoff should be applied based on the planner's risk tolerance. It is suggested that at least 5 major DBT's be down-selected to move on to step 3, but several more may be selected, especially if they all constitute a relatively high-risk rating.

Planners may learn new things about function criticality in the process of step 2 that change their rankings in step 1. Often, function criticality can evolve based on the type and duration of a threat. For example, during a typical short-term power outage the shelter function may not be considered critical. However, for an event such as a blizzard that lasts more than 24 hours and/or limits access to and from the campus or installation, sheltering becomes a critical operation, requiring robust power and heating supply. This dynamic requirement

Table 4. Estimates of Asset-Level Vulnerability for the Notional System

Critical Function	Building A Vulnerability	Building B Vulnerability	Building C Vulnerability	Building D Vulnerability	Water Network Vulnerability
Shelter	0	0	0.1		
Food	0	0			
Finance		0			
Water		0			0.5
IT and Data				0.7	

demands flexibility in the energy systems to be able to respond. Community and mission functions focused on reducing the threat or minimizing recovery time, such as emergency logistics and communications, increase in importance before, during, and after a threat event. An effective response of these functions to a threat, in turn, can reduce the vulnerability and recovery time of other functions.

CALCULATING BASELINE RESILIENCE

On completion of step 2, the planner has all necessary inputs to calculate baseline resilience metrics for each DBT category. The baseline resilience metrics are calculated assuming no investments are made to the energy system. This section outlines the use of resilience metrics and systems modeling to compute the baseline resilience performance, and to highlight the gap between resilience performance and resilience targets. The subtasks associated with this section are summarized in Figure 3c.

3a: Determine Baseline Resilience Requirements

Energy resilience metrics are associated with each critical function in this step. For each critical function, stakeholders populate requirements for energy availability and maximum allowable outage duration. The left side of Table 5 illustrates the information that will be gathered in this step. Energy availability is defined as:

$$\text{Energy Available} = \text{Uptime}/(\text{Uptime} + \text{Downtime}) \qquad (4)$$

where *uptime* is the amount of time during disruption events that energy is available to the critical function, and *downtime* is the amount of time energy is not available to this function during the disruption. This will equate to a fraction and may also be presented as a percentage. If simplicity is required, a suggested set for energy availability requirement is {99.995%, 99%, 95%, 80%, 50%}. Maximum allowable outage duration is the amount of time without energy the critical function can continue to provide an acceptable level of service. A suggested requirement set for maximum outage duration is {1, 30, 60, 120, 480} minutes.

Certain industries have established energy resilience requirements for critical functions, including data centers (ANSI 2019), healthcare facilities (NFPA 2019), and food storage (BC Campus 2019; USDA 2013). Similarly, the U.S. Department of Defense has established Unified Facilities Criteria for critical loads, breaking them into categories of uninterruptible, essential, and nonessential (U.S. DoD 2017). By this guidance, loads that support critical functions are likely to be categorized as either uninterruptible or essential.

Table 5. Resilience Metric Table for System Designs

	Required		Baseline	
Critical Function	Energy Availability	Max Allowable Outage Duration	Energy Availability	Max Observed Outage Duration
Function A				
Function B				
Function C				

3b: Assess Baseline Resilience Performance

The right side of Table 5 captures the baseline performance for each critical function within the two energy resilience metric categories. The baseline is the current system without any investments or enhancements. It is often impossible to fill in this data via measurement, since many locations have not experienced an exhaustive set of extreme disruptions in recent memory. Therefore, it is recommended that systems modeling be applied to generate the baseline resilience performance. The systems model describes the behavior of the AOI's energy system when disrupted for resilience assessment and also looks at the system under blue-sky conditions as a starting point for community-wide energy master planning. Several resources in the literature describe methods for performing systems modeling for calculating the resilience of electric power distribution systems (Panteli and Mancarella 2017; Billinton and Li 1994; Ubeda and Allan 1992).

The systems model is run using Monte Carlo or similar sampling methods for each DBT category with the failure probabilities generated in step 2c as input. Within each DBT category (e.g., hurricane, earthquake), the output of this activity is the energy availability and maximum outage duration to each critical function. If the DBT categories were characterized with discrete probabilities (e.g., 100-yr flood, 500-yr flood), the expected metric for each particular critical function over all DBTs is calculated as:

$$E(EA) = \frac{\Sigma_{i=1}^{n} p_i \times EA_i}{\Sigma_{i=1}^{n} p_i} \quad (5)$$

where $E(EA)$ is the expected value of the energy availability over the planning horizon and is equivalent to the baseline energy availability; n is the total number of DBT discrete probabilities, p_i is the discrete probability of DBT_i, and EA_i is the energy availability result of the systems model for this particular critical function averaged over all runs of the systems model parameterized for DBT_i. The same method is followed to populate maximum outage duration, only instead of averaging, the maximum value is captured over all runs of the systems model.

3c: Evaluate Baseline Resilience Gap

Once Table 5 is filled to completion, the resilience gap is the difference between the required metrics and the baseline metrics for each critical function. This has the advantage of being measured in the same units as the metrics themselves, which makes designing improvements more straightforward.

Note that while not included as a resilience metric, power quality should be considered during the planning process as a metric of the underlying component systems as part of the blue-sky analysis. For both resilience and blue-sky performance, power quality will become a constraint when optimizing the system, rather than an objective.

Calculating Baseline Resilience for the Notional System

The notional system has five critical functions that must be sustained at various levels during an emergency. Energy availability and max allowable outage duration requirements for each function are given in the first two data columns of Table 6. These requirements will be set by the planners and may vary between locations for the same functions based on system layout, system components, and other considerations. Energy availability and max observed outage duration values for each function are given in the last two data columns of Table 6. Values in the table are notional and for illustration purposes only.

Charting the values for both energy availability and maximum outage duration allows the planner to see where gaps exist between the baseline values and the requirements. Charts for baseline metrics are shown in Figure 10a. The baseline system configuration is already meeting the energy availability requirement for food and the maximum outage duration for finance. All other metrics exhibit a gap that must be addressed in future system designs.

DESIGN AND ANALYZE BASE CASE RESILIENCE

Gaps between required resilience levels to DBTs and current resilience levels will be addressed by planners through investments in the system (energy system improvements) or through protecting the existing system (mitigation). Proposed changes are captured in conceptual designs that can then be compared to the baseline and each other. At a minimum, planners will need to put together two conceptual designs: the base case conceptual design and at least one alternative conceptual design. The base case design is the first conceptual design developed to improve resilience and includes the most basic and common ways of improving the system. The purpose of the base case design is to serve as a cost savings comparison for the alternative designs. Though the base case conceptual design will satisfy resilience requirements, it may not be the most cost-effective way to achieve increased resilience and will not improve blue-sky metrics. A cost analysis for both total load under blue-sky conditions and critical load under DBTs should be performed for base case and alternative conceptual designs. Subtasks for designing and evaluating base case resilience are summarized in Figure 3d.

4a: Formulating the Base Case Design

The base case design only targets elimination of the resilience metric gap and does not consider blue-sky metrics for efficiency or sustainability. Base case design options include traditional technologies, such as:

- Local backup boilers
- Local backup diesel generators
- Uninterruptible power supply (UPS)
- Fuel storage
- Strengthening existing overhead lines
- Replacing existing overhead lines with underground lines
- Other physical protection for existing assets (raising, constructing walls, etc.)
- Additional assets to ensure n+1 local redundancy.

Critical function owners should consider the opportunity to mitigate the impact of each DBT through use of the base case design. If the function is relocatable, such as a flying mission at a military base, or outpatient treatment at a clinic, these protocols can be implemented to remove the function from the threat's path. Where a function is relocatable but only with significant disruption to its effectiveness, the likelihood of relocation will depend on the potential severity of the threat. Elements of the function may go through graceful shut down procedures to minimize potential threat physical damage and decrease recovery time. For unmovable functions, actions such as topping-off of fuel storage tanks and deploying physical protection can be undertaken to enhance its resilience.

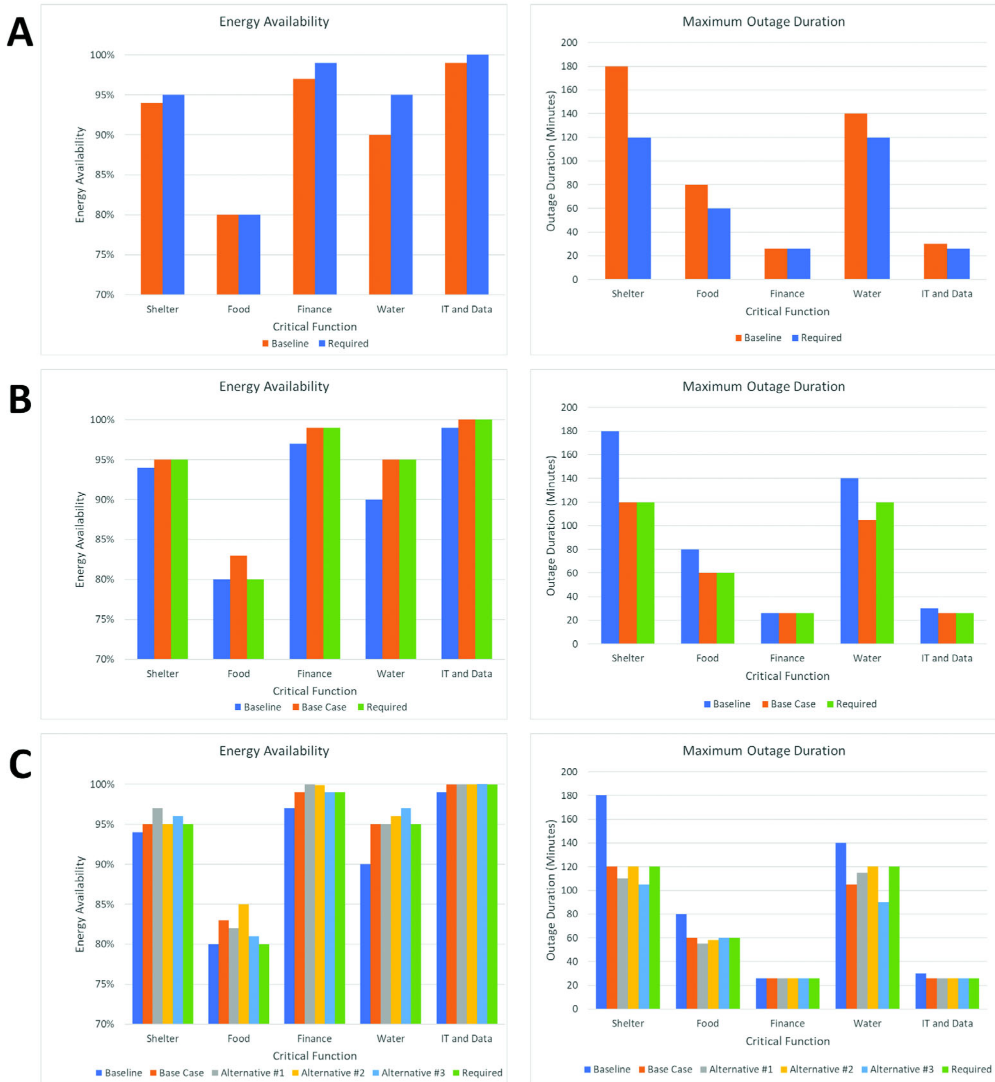

Figure 10 *Energy availability and maximum outage duration charts: (a) Baseline charts, (b) Base case charts, and (c) Summary charts of all design options.*

Table 6. Resilience metrics for notional system baseline (Avelar 2007)

	Required		Baseline	
Critical Function	**Energy Availability**	**Max Allowable Outage Duration (minutes)**	**Energy Availability**	**Max Observed Outage Duration (minutes)**
Shelter	95.0%	120	94.0%	180
Food	80.0%	60	80.0%	80
Finance	99.0%	26	98.0%	26
Water	95.0%	120	90.0%	140
IT and Data	99.995%	26	99.0%	30

4b: Assess Resilience Performance and Capital Cost of Base Case Design

These technologies are placed by the planner throughout the system to improve the energy resilience to loads within critical function categories that have a resilience gap as defined by Table 5. The planner may have to run the systems model iteratively while selecting and parameterizing the base case design, so to ensure that systems are not under- or over-built but meet the resilience metric requirements as closely as possible. Once this is complete, the planner should compute the total capital cost for the base case design based on localized cost guidance for each technology selected.

Designing the Base Case for the Notional System

For the notional system, if the main generator fails or if the main conductor of the radial distribution system fails, buildings C and D will not have any available power. We take the straightforward approach of adding backup generators and fuel storage to buildings C and D to design against loss of power. This base case system is shown in Figure 4c.

The calculated resilience metrics for this base case design are given in Table 7. Values in the table are notional and for illustration purposes only.

This base case design is only concerned with meeting the required resilience of the critical functions. It does not take advantage of the layout of the system or the potential to network buildings into microgrids. It does not take advantage of mutually beneficial designs for resilience, efficiency, and sustainability. Though this approach solves the resilience issues, it is likely not the least expensive way to ensure critical functions stay online during an emergency. The graphs of energy availability and maximum outage duration for the base case in Figure 10b show the improvement over the baseline and that all functions energy resilience requirements are now fulfilled.

PLAN AND ANALYZE ALTERNATIVE CONCEPTUAL DESIGNS

The alternative conceptual designs are the primary integration point for traditional EMP. These designs should integrate blue-sky goals with resilience goals such that performance is co-optimized for the planner. These designs should explore additional technologies beyond the base case conceptual design and should also consider alternative system configurations. Both system improvements and system mitigation may be used to develop the designs. Subtasks for designing and evaluating resilience for alternative conceptual designs are summarized in Figure 3e.

5a: Develop Initial Alternative Conceptual Designs

The alternative conceptual designs will be developed to eliminate the baseline resilience metric gap, to decrease the capital cost as compared to the base case design, and to improve the blue-sky performance as compared to the base case design from the traditional EMP process. A brief and incomplete subset of technologies that can be considered for alternative conceptual designs include:

- Low and medium temperature District Heating networks
- High temperature District Cooling networks
- Efficient electric heat pumps
- Combined cooling, heat, and power (CCHP) plants with ad-/absorption cooling systems
- Power-to-heat systems
- Large scale electrical storage systems
- Short term and seasonal thermal systems
- Microgrids
- Alternative electrical distribution topologies
- Distributed and district solar PV and hot water systems
- Centralized flexible power generation
- Distribution system automation
- Waste heat
- Regenerative technologies, etc.

Technologies considered must be feasible for the area both in footprint and in function. The conceptual designs will exhibit attributes that impact the resilience posture in a variety of ways. For example, a more efficient generation system will improve the resourcefulness of the function, a microgrid can improve sustainment capacity and recoverably, and investment into an additional power line can improve robustness. As such, these designs need to respond directly to the function requirements and determined vulnerabilities of existing systems.

5b: Co-Optimize Alternative Conceptual Design(s) to Determine Trade-Offs

To most effectively determine the viability of alternative technology solutions a planner must model their potential individual and combined performance. Beyond the resilience performance of the technical solution, enhanced resilience design solutions can exhibit additional financial justification through operation during normal blue-sky conditions.

To truly maximize performance, a system should be co-designed with both blue- and black-sky operation being considered. An example is an on-site solar and energy storage system configured in combination with a diesel-fueled generator and microgrid, to meet the demands of an installation crit-

Table 7. Resilience Metrics for Notional System Base Case Design.

	Required		Base Case Design	
Critical Function	Energy Availability	Max Allowable Outage Duration (minutes)	Energy Availability	Max Observed Outage Duration (minutes)
Shelter	95.0%	120	95.0%	120
Food	80.0%	60	83.0%	60
Finance	99.0%	26	99.0%	26
Water	95.0%	120	95.0%	105
IT and Data	99.995%	26	99.995%	26

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ical load for at least 14 days of utility outage. The campus-level systems are modeled against the demand profile to quantify the financial performance of both the consumption mitigation of the solar array and the demand-reduction capacity of the associated energy storage system. Figure 11 portrays the system's operation on a blue-sky (left) and during an outage (right).

The modeling is an iterative process between different combinations of solar, energy storage, and generator size to optimize the financial case while maintaining operational requirements. Other factors to consider are available space for generation resources, and the infrastructure management and control infrastructure required to manage the assets and curtail the interruptible loads.

Opportunities to take advantage of synergies between electrical and thermal systems should be evaluated. For example, a design option where the base case diesel generators are replaced or complemented by a natural gas generator designed to operate continuously and capture its waste heat for heating and hot water. While the critical demand may only be for electricity, the generation of heat is mitigating traditional heating costs and providing additional energy during an outage that can be used to support loads beyond what is mission-critical.

An oft-overlooked component of resilience is the impact of energy consumption reduction while maintaining full critical function performance. This can be in facility-level circuit design and controls to isolate critical loads and curtail all others in an emergency or in energy efficiency upgrades, such as lighting system replacement or specifying more efficient equipment. These improvements provide the ability to increase critical function sustainment time in an outage without consuming additional resources and can allow critical systems to be down-sized, reducing capital investment. Conservation projects often have the strongest business case for investment and can be combined with other resilience upgrades to justify the larger project.

Strategies to improve resilience range in scale from system component to overarching policy changes. Installation planning that fundamentally integrates resilience at an early stage can dramatically increase the viability and effectiveness of strategies. Designating and planning for resilient enclaves, designated areas for increased infrastructure resilience, allows targeted investment to serve the most critical functions. As critical functions evolve over time, resilient enclaves also allow for changes in demands for asset capacity and resources without requiring additional resilience investments. Pre-designing resilient infrastructure (power, water, and communication networks) to serve enclaves of flexible assets provides the required function flexibility while focusing investment. These enclaves of 'plug and play' asset foundations may have local microgrids, generation assets, fuel storage, etc. to meet resilience requirements of any potential campus function. Functions with similar requirements would all be served by that enclave, with alternative options for varying requirements. For example, a critical data storage or laboratory function may be located in an enclave with a robust power capacity and quality supported by a microgrid and dedicated substation(s). Another function with has industrial water needs may be located adjacent to the treatment plant.

Development of alternative conceptual designs within the Resilience-Integrated EMP is less straightforward than development of the base case designs because of additional considerations and technologies available to this design. Therefore, it is suggested that co-optimization tools be utilized for this process. This is an area of ongoing research and a topic for further discussion.

Alternative Conceptual Designs for the Notional System

For the notional example, three alternative conceptual designs are developed to improve system resilience. Each is analyzed for energy availability and maximum outage duration. The first alternative conceptual design is one in which the radial network is transformed into a loop system design shown in Figure 4d. Even if the primary conductor experiences a failure at some point, the buildings can be fed in the opposite direction to improve continuity of service. In the second conceptual design, buildings A and C are networked into a

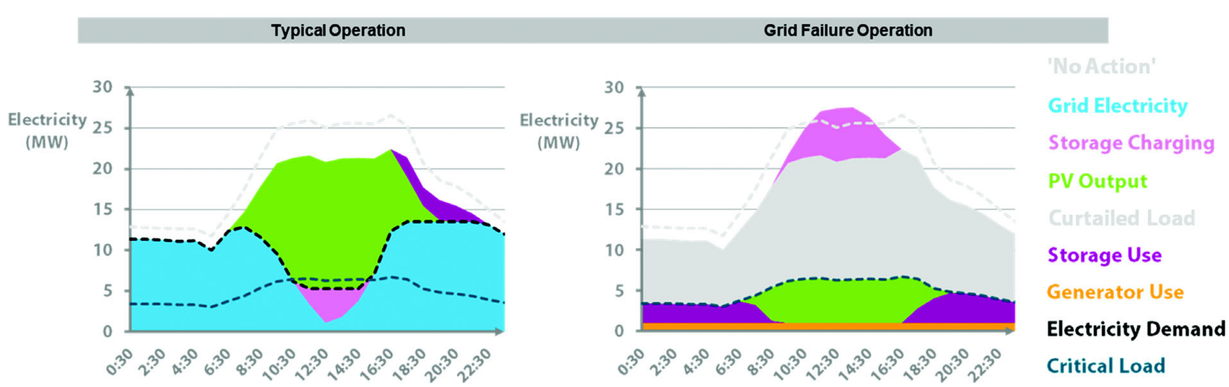

Figure 11 *Comparison of system operation during blue-sky operations and during a grid outage.*

small microgrid and are provided power and heat through a small CCHP system. This conceptual design is shown in Figure 4e. The third conceptual design expands the microgrid and CCHP to all four buildings. A larger CCHP provides the heat and power via a loop system, as was used in the first alternative conceptual design. Buildings A and B retain their original backup generators and fuel storage. This conceptual design is shown in Figure 4f.

The calculated resilience metrics for the three alternative conceptual designs are shown in Table 8. Values in the table are notional and for illustration purposes only.

COMPARING ALTERNATIVE DESIGNS AND SELECTING FINAL DESIGNS

Once planners have developed the base case and alternative conceptual designs and evaluated the associated blue-sky and resilience metrics, the options should be compared along all metric categories. This step is summarized in Figure 3f.

6a: Aggregate Blue-Sky and Resilience Metrics for Each Design

For effective comparison, blue-sky metrics from traditional EMP should be aggregated along a single dimension. Similarly, the two resilience metrics should be aggregated across all critical functions into a single dimension. Several alternative metrics are commonly used to describe blue-sky performance, such as total thermal/electrical efficiency, total net present value given all cash flows, and avoided emissions compared to baseline. It is often most straightforward to aggregate the blue-sky dimension into a single metric that is measured in units of currency.

For illustration, we assume a planner that purchases electricity and natural gas from a utility. The AOI has no fuel other than natural gas and diesel for thermal and electrical generation. This planner is not allowed to sell electrical or thermal energy to the utility. Furthermore, there is a goal of cutting emissions by 50% compared to the baseline. The planner is attempting to optimize performance over a planning horizon of 30 years. The planner uses the following metric to summarize blue-sky performance for each alternative design and the base case design:

$$\begin{aligned} & BlueSkyPerformance \\ & = EndOfLife - CapEx \\ & + NPV(-ElectricityPurchases \\ & (-GasPurchases) - O\&M - EmissionsCost) \end{aligned} \tag{6}$$

where *BlueSkyPerformance* is measured in U.S. Dollars. This metric may be populated by a Life Cycle Cost Analysis including emissions reductions as a monetary benefit (Fuller 1995). The *EndOfLifeValue* is the remaining value of all assets at the end of the planning horizon. The *CapEx* is the capital expenditure for new energy system investments beyond the baseline. The *NPV* function is a net present value of all annual cash flows using a discount rate and the planning horizon as parameters. *ElectricityPurchases* are an annual cash flow for electricity purchased from the utility by the AOI. *GasPurchases* are an annual cash flow for natural gas and diesel purchased from the gas utility and diesel distributor, respectively. *O&M* is the annual operations and maintenance cost for all energy system assets. *EmissionsCost* is the total emissions per year from the AOI assets plus the total emissions per year associated with *ElectricityPurchases* multiplied by a cost per kg CO_2 equivalent.

In this example, all alternative designs must attempt to improve the *BlueSkyPerformance* as compared to the baseline *BlueSkyPerformance*. For each design, this difference from the baseline becomes the *Blue-Sky Value* metric for the resilience-integrated EMP process. Additionally, for this example, all designs are subject to a constraint that the total greenhouse gas emissions must be less than 50% of the baseline total emissions. The planner chooses designs that increase the AOI's electrical and/or thermal efficiency while meeting the sustain-

Table 8. Resilience Metrics for Notional System Alternative Conceptual Designs

	Required		Alternative Conceptual Design #1		Alternative Conceptual Design #2		Alternative Conceptual Design #3	
Critical Function	Energy Availability	Max Allowable Outage Duration (minutes)	Energy Availability	Max Observed Outage Duration (minutes)	Energy Availability	Max Observed Outage Duration (minutes)	Energy Availability	Max Observed Outage Duration (minutes)
Shelter	95.0%	120	97.0%	110	95.0%	120	96.0%	105
Food	80.0%	60	82.0%	55	85.0%	58	81.0%	60
Finance	99.0%	26	99.99%	26	99.99%	26	99.0%	26
Water	95.0%	120	95.0%	115	95.0%	120	97.0%	90
IT and Data	99.995%	26	99.995%	26	99.995%	26	99.999%	26

ability requirement and delivering a positive return on investment when considering the *CapEx*.

To aggregate the resilience metrics, the following equation is used for the base case design and each alternative design:

$$Resilience\ Performance = \frac{\Sigma_{i=1}^{n}[FC \times 0.5[Achievement(EA) + Achievement(MD)]]_i}{\Sigma_{i=1}^{n} FC_i} \quad (7)$$

where *ResiliencePerformance* is a unitless value describing how far beyond resilience requirements the design achieves. A value of 1.0 indicates that all requirements were met exactly. The summation is performed over all critical functions up to the n^{th} critical function. *FC* is the function criticality rating for critical function *i*. *EA* and *MD* are the energy availability metric and maximum duration metric evaluations, respectively, for critical function *i*. The *Achievement(x)* function evaluates resilience performance versus the target using a functional relationship:

$$Achievement = \begin{cases} 0, \text{ metric} < \text{target} \\ 1 + \alpha \times (\text{metric} - \text{target}), \text{ metric} \geq \text{target} \end{cases} \quad (8)$$

where α is the amount, for each critical function, that the planner values exceeding targets. A value of zero for all α devolves the resilience and blue-sky co-optimization problem into blue-sky optimization with a resilience constraint. In this case, the *target* is the same as the requirement.

6b: Eliminate Inferior Designs and Present Subset to Decision-Makers

Once the blue-sky and resilience metrics for each alternative design and the base case design are aggregated into two dimensions, improvements in resilience can be weighed against improvements in blue-sky performance, as illustrated in Figure 12. In most cases, the alternative designs will improve on the base case design in at least one dimension. The designs in green in Figure 12 are Pareto-efficient, in that there are no designs that improve on one dimension without decreasing performance in another dimension. The designs in grey in Figure 12 are dominated by at least one design, meaning that there is at least one design that performs better in both dimensions. Because the base case design delivers no blue-sky gains, some designs have a higher life-cycle cost than the baseline, indicated by negative blue-sky performance.

This comparison is useful because it allows the planner to eliminate many designs that are ineffective compared to others. All grey (base case) designs in Figure 12 may be eliminated from consideration, assuming the relevant goals have been captured in the two dimensions. This helps the planner

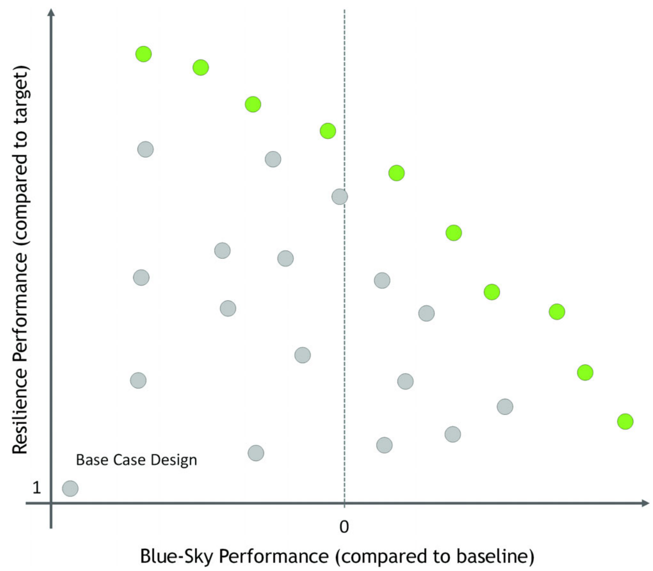

Figure 12 *Comparison of blue-sky and resilience performance.*

and the decision-makers focus on the trade-offs between resilience performance and blue-sky performance. Furthermore, because the blue-sky performance dimension is presented in units of total life cycle cost, every alternative design has a net cost savings compared to the base case design. Using this framework, resilience gains can be measured against improvements in cost savings. Planners may set a resilience gain to cost-saving ratio to further down-select designs.

Comparing Alternative Designs for the Notional System

For the notional example, a base case system design and three alternative conceptual designs were analyzed. The associated energy availability metrics and maximum outage duration metrics are shown in Figure 10c. All designs meet the resilience requirements and some of the alternative conceptual designs slightly exceed the requirements. These designs, which each meet requirements, give stakeholders a set of options for improving the resilience of their current system based on what technologies they decide to invest in and the size of their budgets.

DISCUSSION: GAP ANALYSIS OF AVAILABLE RESILIENCE PLANNING APPROACHES

The Resilience-Inclusive EMP process described here is purposefully ideal. It is intended to set requirements for tools and capabilities that will ultimately allow a wide range of planners to adequately follow this process. The authors recognize that most planners will not have the requisite capabilities to complete every step in this process today. Current processes such as the U.S. Army's Guidance for Energy and Water Plans

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begin to balance achievement of energy resilience requirements with total system life-cycle cost.

Each step in the Resilience-Inclusive EMP process. along with an estimated maturity gap. and the capabilities required to fill each gap are outlined in Table 9. The most critical gaps are in steps 3 and 5. Systems modeling platforms called out as a gap for step 3 would be necessary for steps 4 and 5, as well. The systems models that have been designed to assess resilience, such as the Performance Reliability Model (Arguello et al. 2015), cannot currently utilize a set of DBTs to map threat impacts to assets and determine component failure probabilities. Furthermore, the authors are not aware of tools that integrate electrical with thermal systems modeling in this manner. Most pressing, these tools are not integrated into a co-evaluation or co-optimization platform, as noted in the step 5 capability needs. This co-optimization platform would need to parse billions to trillions of unique design combinations to effectively explore the space of alternatives, and therefore requires advanced computational algorithms unavailable to the vast majority of system planners today.

Many energy modeling tools have been developed in the United States and Europe, where applications vary from urban energy planning to local energy planning (Zhivov et al. 2017). While these tools address specific aspects of energy planning, a comprehensive tool to evaluate blue-sky and resilience benefits is needed and is currently under development.

CONCLUSIONS AND FUTURE WORK

This paper presents a novel and broad-encompassing advancement to the EMP process called Resilience-Inclusive Energy Master Planning. The definition of resilience used and the methods to quantify resilience allow it to be directly integrated via performance-based metrics within alternative designs of energy systems. Using this integrated method, energy systems can be co-optimized to provide blue-sky performance and resilience to critical functions of an AOI at lowest overall life-cycle cost. The process includes selection of design basis threats based on risk-minimization methods. We outline the process of developing a baseline resilience metric by mapping energy resilience metrics to critical functions, quantifying how the current system without improvements meets or does not meet the planners' resilience requirements subject to the design basis threats. The paper describes development of a base case design, which only targets resilience performance separately from blue-sky performance to give the planner an understanding of the costs to meet targets if planning were performed decoupled. Finally, the paper describes co-optimizing resilience and blue-sky performance metrics such as total life-cycle cost and avoided greenhouse gas emissions to take advantage of co-benefits that can be achieved with advanced designs such as centralized CCHP systems and microgrids. We conclude with a discussion of the computational advancements that must be made for the Resilience-Inclusive Energy Master Planning process to be adopted by district-level master planners throughout the world. Although many advancements are still necessary, we describe how each of these would be approached and provide examples of how each step has been accomplished separately to date.

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Table 9. Capability Gap and Needs for Each Step in the Resilience-Inclusive EMP Process

Process Step	Capability Gap	Capability Needs
1. Identify Location, Goals, and Key Characteristics	Low	Database of location characteristics (building types, weather patterns, etc.)
2. Determine Design Basis Threats and Impacts	Med	Geospatial tool development to automate data collection and fragility analysis
3. Assess Baseline Resilience	High	Systems modeling platform for thermal + electrical blue-sky and resilience performance
4. Design and Analyze Base Case	Med	Simplified design tools and technology database that integrate with systems modeling platform
5. Design and Analyze Alternatives	High	Co-optimization capability to efficiently aggregate a multitude of asset-level design options into a set of pareto-efficient design alternatives
6. Compare Alternative Designs and Down-select Final Designs	Low	Visualization and user experience tools

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