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Characterization of Harsh Environments, At-Risk Microgrid Components, and Hardening Technologies (Report Version 0.1)

Rachid Darbali-Zamora, Melissa S. Louie, Jeewon Choi, Giovanni Ponce and Jack D. Flicker

Sandia National Laboratories, Albuquerque, NM

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

Microgrid implementation can help improve electrical service, reliability, and resilience for localized communities. However, they may be susceptible to damage from natural disasters and extreme weather events, which often coincide with times of greater community dependence on microgrids due to likely increased vulnerability of equipment on the main grid. Microgrid equipment can be protected against these hazards through various hardening techniques. The selection of hardening mitigations may depend on the actual risk of the hazard in the specific location and for the specific type of system, as well as cost and feasibility factors. This report summarizes a framework that can be used to characterize risk to a microgrid system from a list of natural hazards enumerated by FEMA. We also describe hardening techniques and mitigations that can be used for specific energy generation, storage, loads, and power delivery elements within a microgrid.

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EXECUTIVE SUMMARY

Microgrids, or systems of co-located energy generation, storage, and use, can be implemented to improve electrical service reliability for communities, especially during times of elevated vulnerability of the main grid, such as during natural disasters and extreme weather events. However, they are often also susceptible to damage, so there may be a need to harden these systems against the natural hazards that they may encounter.

In this report, we provide a literature-supported overview of hardening techniques against potential impacts of various natural hazards on common subsystems and equipment used in microgrids. The natural hazards are categorized by the type of impact. These categories are water impacts (including from events such as tsunamis, hurricanes, and potential associated riverine and/or ocean flooding), solid precipitation (e.g., hail and sleet), freezing precipitation (e.g., snow and ice), extreme temperatures (extreme heat and cold), land and seismic irregularities (landslide/avalanche, sinkhole/karst, earthquake), fire and air contamination (volcanic eruption, wildfire), and wind (high winds, such as in a tornado). There is also an "other" category for natural hazards that were not considered to fit into any of the described categories: hurricanes (specifically, the combination of rain, humidity, and high winds), lightning, and drought. The microgrid subsystems were also categorized into energy generation and storage (including combined heat and power systems, solar photovoltaics, wind turbines, and battery energy storage systems), load assets (including critical, priority, controllable, interruptible, and diversion/dump loads), power delivery elements (including power lines, transformers, switchgear, capacitor banks, circuit breakers, and disconnects), and sensing, controls, and communication equipment.

We also describe a generic risk assessment framework for evaluating natural hazard risks to microgrid equipment. This framework involves characterizing the likelihood of the hazard occurring in the location of the microgrid, the detectability of the damage that could occur to the microgrid equipment from the hazard, and the severity of the damage to the overall system. The risk characterization aspect of the framework can help users understand the most highly anticipated risks for their specific location and system. Additionally, the framework presents a method for prioritization of hardening actions for the owner-operator or other involved stakeholder to take, based on the effectiveness and cost of the solution. This framework is generic because it can be applied as needed by the risk analyst based on the needs and goals of the community or other users, and the data available.

We implemented an example application of the risk assessment framework in the Microgrid Hardening Design Toolkit, an executable application showing various aspects of risk and describing the same mitigation techniques included in this report, for census tracts in the U.S. and U.S. territories.

TACRONYMS AND TERMS

Acronym/Term	Definition
AC	alternating current
CHP	combined heat and power
DC	direct current
DER	distributed energy resource
EAL	expected annual loss
EF Scale	Enhanced Fujita Scale
EMS	energy management systems
ESS	energy storage system
FEMA	Federal Emergency Management Agency
HVAC	heating, ventilation, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers
LEE	leading edge erosion
LPS	lightning protection system
NEMA	National Electrical Manufacturers Association
NRI	National Risk Index
PV	photovoltaic
RES	renewable energy system
SPD	surge protection device
TVS	transient voltage suppression
UPS	uninterruptible power supply

1. INTRODUCTION

Extreme weather events and natural disasters have been found to cause disruptions to the electrical grid in many cases [1], often resulting in health, safety, and economic challenges for affected customers [2]. Thus, there is a need for solutions to improve resilience and reliability of electrical service in regions susceptible to these extreme weather events and natural disasters [3]. Microgrids, which are localized and energy systems with co-located energy generation, storage, and load, are increasingly being implemented for this purpose [4]. Microgrids often consist of distributed energy resources (DERs) such as solar photovoltaics (PV), wind turbines, batteries or other energy storage systems (ESS), and backup generators [5], [6]. The decentralized nature of microgrids, integration of non-fuel-reliant renewable energy resources, and ability to operate in grid-connected or islanded (isolated from the grid) modes enable microgrids to improve reliability and electrical service during events that disrupt service from the main grid.

While microgrids offer an alternative solution for electrical service in times when there are disruptions in the main grid, they are also susceptible to extreme weather conditions, natural disasters, and geophysical hazards [7], [8]. Events such as hurricanes, earthquakes, wildfires, floods, and ice storms pose significant threats to the structural integrity, operational stability, and energy supply of a microgrid [9], [10], [11], [12], [13]. Hardening of microgrid components, or the preventive actions taken in the design of the microgrid infrastructure in anticipation of natural disasters, can improve resilience and reliability of electrical service [14]. In this literature review, we summarize how different natural disasters and extreme weather events might affect components or parts of a microgrid and discuss methods of preventing the occurrence of hazards and mitigating overall risk to the microgrid through hardening techniques.

For the purpose of consistency throughout this report, the term "hazard" will be used to describe an event that could result in harm or an adverse consequence to a piece of equipment, while "risk" will be used to refer to metrics that combine the ranking or quantification of the damage inflicted by a hazard with the probability or frequency of that harm being realized [15]. "Resilience" as used here will refer to overall grid system resilience, i.e., the ability of the overall system to resist interruptions to electrical supply.

1.1. Resiliency Characteristics of Microgrids

1.1.1. Islanded Operation

The islanding capability of microgrids is one of their most crucial features in disaster prone areas. This capability allows microgrids to disconnect from the main grid and continue operating independently during emergencies [16]. Islanded microgrids enhance resilience by ensuring a continuous power supply for critical loads when the central grid fails for any reason, including natural disasters and extreme weather events as well as grid disruptions that might be caused by voltage, current, or frequency fluctuations or other interruptions internal to grid operations. Robust protection mechanisms are essential to ensure that the transition between grid-connected and islanded modes is smooth and does not add to the electrical service disturbance.

1.1.2. Renewable Energy Generation Integration

The integration of renewable energy sources (RES) such as solar, wind, and small-scale hydro is vital in disaster resilient microgrids [17], [18]. These systems reduce reliance on the supply of external fuel supplies, which can be interrupted during disasters. Microgrids with renewable energy and advanced storage systems may show improved resilience compared to central grid systems in disaster conditions, since renewable generation can continue even when centralized fuel-dependent systems fail [4].

1.1.3. Energy Storage Systems

Energy storage plays a pivotal role in enhancing the reliability of microgrids during disasters by storing excess energy from RES and supplying it when generation is disrupted [19]. ESS, particularly battery systems, allows the microgrid to maintain power during extended grid outages. Integrating larger and more efficient energy storage systems improves a microgrid's ability to remain operational for longer periods under islanded conditions [19].

1.1.4. Distributed Energy Resources

Using decentralized, distributed energy resources and redundancy can add to the resilience of a power system. Distributing storage across multiple sites within the microgrid, for example, instead of using centralized storage, means that there are backup storage assets that can continue to function even if certain areas of the system are compromised. This approach is a solution to maintain operational flexibility during disasters.

1.1.5. Black Start Capability

Black start capability, which allows a microgrid to restart independently after a total system failure or shutdown, is an essential feature for disaster recovery [20]. Microgrids with black start functionality can recover more quickly after grid wide failures. Moreover, microgrids utilizing a combination of energy storage systems (e.g., batteries and fuel cells) and small generators are able to reduce recovery times significantly [21].

1.1.6. Resilient Control Architectures

Decentralized control systems are crucial for disaster resilient microgrids [22]. In centralized systems, communication failures or control system outages can lead to cascading failures. The role of decentralized and multiagent control architectures in ensuring that microgrids remain operational during extreme weather events. These systems enable autonomous decision making, optimizing the distribution of power among critical loads and managing the microgrid more effectively during emergencies.

1.2. Hazards: Extreme Weather and Natural Disasters

In this report, we discuss several events that may cause varying degrees of damage to microgrid components and equipment. These events include extreme weather and natural disasters. The extreme weather events include heavy precipitation (including hail, sleet, snow, and ice), extreme high and low temperatures, high winds (such as from tornados and hurricanes), and lightning. The natural disasters include flooding (such as from tsunamis or hurricanes), landslides or avalanches, sinkholes or karst conditions, earthquakes, volcanic eruptions, and wildfires. These events have been observed to cause damage to various components and equipment in microgrid systems.

Each type of event discussed in this report may have different impacts on microgrid components depending on their various characteristics. For example, hurricanes may cause damage from high-speed winds, which is distinct from the damage they may cause from heavy rains and flooding. Some of these impacts may also be coupled; the combination of high winds and heavy rains may uniquely impact the infrastructure in ways that each aspect might not impact the infrastructure independently. For ease of categorization in this report, we discuss seven major categories of extreme weather or natural disaster characteristics, and each type of event falls under one or more of these categories.

The first category is water impacts and flooding, which can occur during events like tsunamis and hurricanes. Note that in this report, the term "hurricane" is used to describe tropical storms characterized by high winds and heavy rains, including cyclones and monsoons.

The second category is precipitation, which is split into mechanical and freezing characteristics. For example, solid precipitation may strike and mechanically damage equipment, while freezing precipitation may cause the ingress of cold water into equipment and cause different effects. We provide hail and sleet as examples of solid precipitation, and snow and ice as examples of freezing precipitation. While there may be some overlap in the characteristics of these four examples, we perceived through this literature review that research on mechanical impacts of hail and sleet were more well-characterized than mechanical impacts of snow or general ice, and that literature on the impacts of hail and sleet were focused on mechanical impacts rather than water impacts.

The third category is extreme temperature, which encapsulates both high and low temperatures. These extreme weather events may occur during periods characterized by terms such as heat waves or cold snaps.

The fourth category is one that describes land and seismic irregularities. This category includes landslides and avalanches. We use definitions describing landslides as events in which soil slips down a slope in a distinct occurrence (as opposed to smaller-scale erosion over time) and avalanches as events in which soil or rocks fall, collapse, or roll down a slope without constant contact with the slope, and with fragmentation [23]. Both the potential impacts of falling rocks and of soil movement on microgrid systems were included under these natural disasters. We also added sinkholes and karst conditions in the category of land irregularities; these two terms capture the potential for the formation of subterranean cavities through dissolution, collapse, or subsidence of subsurface material [24]. Finally, earthquakes and seismic activity were included in this broad category. Seismic activity and landslides/avalanches may also be somewhat connected (i.e., a seismic event could trigger a landslide or avalanche).

The fifth category is air contamination, which includes volcanic eruption and wildfires, which have both been observed to emit ash, smoke, and other contaminants that may cause long-term damage to built infrastructure. The localized heat of wildfires is also considered.

The sixth classification is a high wind category, which, in this report, only contains tornadoes.

The final category was a miscellaneous category for other weather events that did not fit directly into any of the other categories. This group included hurricanes, lightning strikes, and drought. Although, as discussed, hurricanes may involve flooding, precipitation, and high winds, which are all other categories, we decided to give it a distinct category to also incorporate other considerations not captured by the previous categories, such as the high humidity conditions and compounded effects of multiple hurricane characteristics. While there are multiple types of droughts (e.g., meteorologic and hydrologic drought), in this report, drought is used as a general and non-specific reference to an unusually long period of reduced rainfall and low humidity in comparison to baseline conditions.

The identified extreme weather events and natural disasters are also of concern for grid systems, including microgrids, because of their potential to trigger cascading failures. Disruptions in one component, such as a damaged substation or a failed communication system, can cause chain reactions, leading to instability in frequency regulation, power quality degradation, and eventual system shutdown [25], [26]. Moreover, as microgrids rely on advanced control systems and communication networks for real-time energy management, damage to sensors, controllers, or data links can severely impact their ability to island from the main grid or coordinate distributed generation effectively [27].

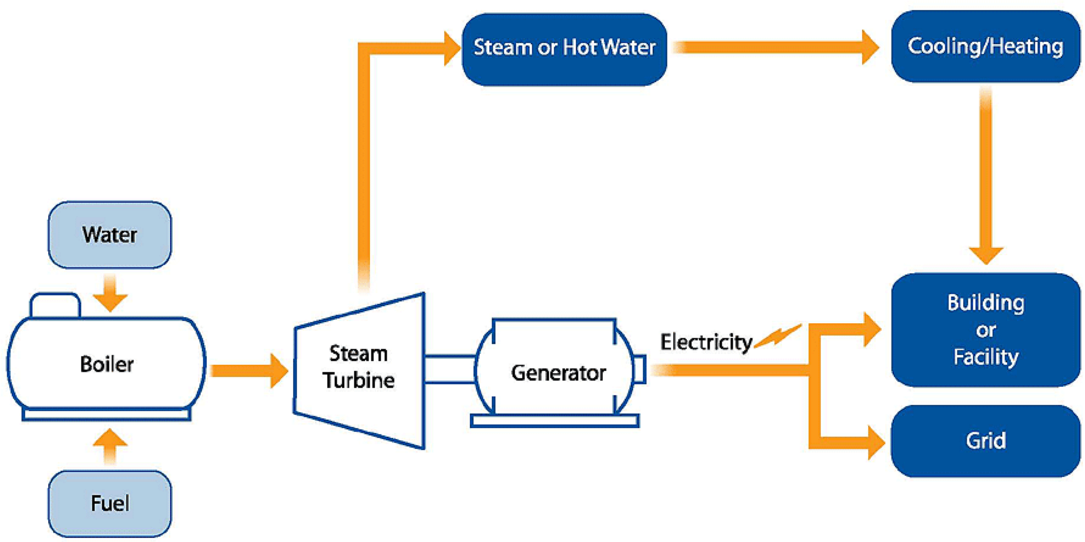
1.3. Microgrid Equipment

We categorized microgrid equipment and components into five groups based on function: energy generation and storage assets, load assets, other hardware, and controls, sensing, and communication.

1.3.1. Energy Generation and Storage Assets

Microgrids have hardware assets responsible for generating and storing energy. A mixture of renewable energy generation sources and energy storage sources can help strike a balance between generating electricity without the use of fuel and allowing for the distribution or usage of this non-dispatchable energy to be controlled through energy storage [28].

We highlight a few major energy assets that are commonly used in microgrids: combined heat and power (CHP) systems, solar photovoltaic (PV) systems, wind turbines, and battery energy storage systems (BESS). This is not an exhaustive list; other assets like hydropower turbines, wave energy converters, and hydrogen energy storage may also be included in microgrids. Figure 1-1 provides a visual overview of these energy technologies.



a)

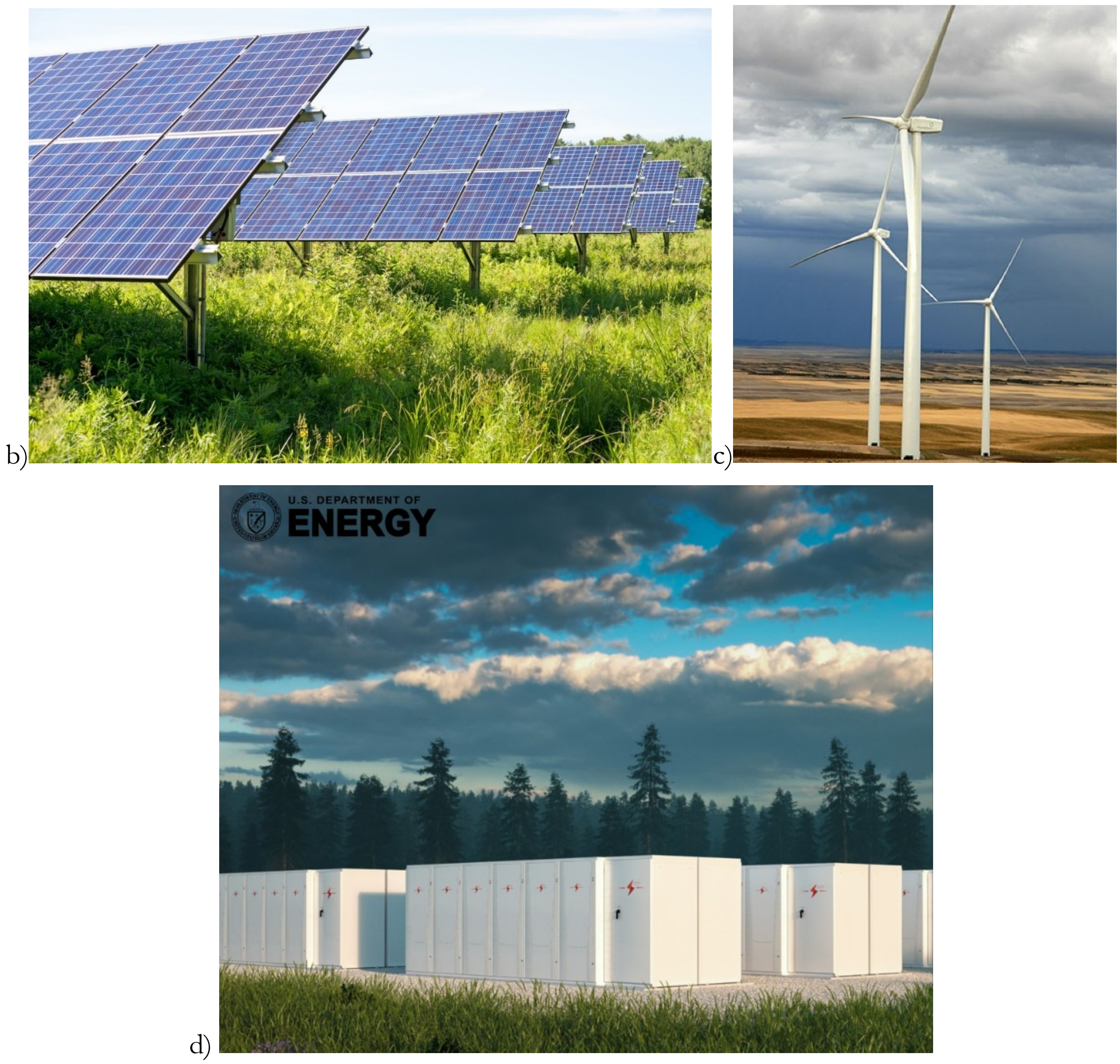


Figure 1-1. a) CHP system diagram [29], b) solar photovoltaic panels [30], c) wind turbines [31], d) BESS [32].

CHP systems use combustion of natural gas, biomass, oil, or other fuels to generate electricity through a turbine; excess heat from the exhaust is collected and used for heating or cooling of buildings [29]. The main components of a CHP system discussed in this report are the steam turbine and the generator.

PV systems utilize solar cells, which are often P-N junction diodes, to convert solar energy into electrical energy [33]. Both roof-mounted and ground-mounted solar PV systems are common. This technology does not have any moving parts, but the modules themselves, as well as supporting hardware like the cover glass for the modules and the metal supports on which they are mounted, were all discussed in this report as being susceptible to hazards from extreme weather and natural disasters. Note that this report refers to flat PV panels and not to concentrating solar or other types of solar power technologies.

There are a few different wind turbine designs, but the most common type of wind turbines, horizontal-axis wind turbines, uses three blades to spin a horizontal shaft attached to a generator to convert the mechanical energy into electrical energy [34]. The turbine blades, nacelle that houses the generator, and tower on which the generator and blades are mounted, were all included as components vulnerable to natural hazards.

For the purpose of this report, BESS will be used to refer to battery systems, which are included in microgrid systems to provide dispatchability to complement non-dispatchable sources like solar and wind, peak shaving, and load compensation, among other capabilities [35]. Batteries consist of electrodes and an electrolyte, which were all considered in this review.

1.3.2. Load Assets

"Load" describes the end usage or application for the electricity generated by a grid system. When a grid outage occurs and there is limited capacity for electrical service, a utility or other entity managing an electrical system must prioritize bringing loads back online that may be lifesaving and assign other loads to lower tiers based on their importance for short- and long-term recovery. The assignment of importance to different loads may be somewhat dependent on the community and its unique needs, but generally the loads are prioritized as follows.

Loads like hospitals, emergency response centers (e.g., fire and police stations), and communication hubs, are all considered essential services and critical loads that must be prioritized in the short term in the case of an electrical service outage or other disturbance. Critical loads are often facilities that require high power quality and reliability, while noncritical loads like residential homes are less essential to keep powered during grid outages [36].

In this report, priority loads include facilities that support recovery efforts following a natural disaster or during an extreme weather event. They are not as essential to keep continuously powered as the critical loads, and intermittency in their service is acceptable, but considering them a secondary priority to critical loads can help ensure that services that help community members during and after electrical service lapses are operational. Priority loads may include facilities like administrative buildings, schools, and commercial facilities relevant to recovery efforts.

Controllable loads are defined here as systems on a lower tier of importance, such as heating, ventilation, and air conditioning (HVAC) systems and water pumps in residential homes, as well as industrial processes. These loads often include systems that can be adjusted or curtailed in response to grid conditions or external events.

Interruptible loads are loads that can be temporarily disconnected from the grid during high-demand situations or natural disasters to protect the grid and prevent damage to infrastructure. These loads are typically large industrial processes or systems that are essential but can afford temporary disconnection without significant operational disruption.

Diversion and dump loads are used to stabilize the grid by diverting excess energy during times of low demand or by dumping surplus energy when energy storage systems are full. These systems are vital for managing the energy produced by renewable generation assets like solar and wind, preventing grid instability.

1.3.3. Other Hardware

Grid and microgrid systems also contain ancillary service equipment used for transmitting, distributing, and regulating the flow of electricity. Major equipment under this category includes power lines, transformers, capacitors, electrical switchgear, circuit breakers, and disconnects.

Power lines are the main equipment related to energy transmission in a grid system. They are often categorized as transmission, feeder, distribution, or other types of lines based on their size, length, and voltage, are cables that transport electricity between locations. Power lines may be overhead or underground, depending on location, other infrastructure, and legacy infrastructure.

Devices that regulate electrical characteristics like voltage and power quality include transformers and capacitors. Transformers are devices that regulate voltage and energy distribution within grid systems while capacitors help maintain voltage stability and provide reactive power support. Transformers may be present along power lines (e.g., between power lines of different voltages, or even for specific facility loads that may have their own transformers installed).

Some devices are used to isolate and protect electrical equipment by tripping the electrical circuit; these devices include switchgear, circuit breakers, and disconnects. Switchgear controls, protects, and isolates electrical equipment through their ability to turn sections of a grid system on or off. Similarly, disconnects are used to isolate parts of the grid system for maintenance or to isolate faults and prevent cascading failures to other devices and areas of the system. Circuit breakers protect electrical infrastructure by providing a shutdown option to interrupt the flow of electricity during fault conditions. These devices, which can also be referred to as actuators and relays, can protect the equipment from destabilizing conditions such as overcurrent, overvoltage, and poor power quality. Switchgear and circuit breakers can also be located either along power lines or for specific facilities, depending on the electrical needs and sizes of the equipment.

1.3.4. Sensing, Controls, and Communication

Sensors are used to measure grid equipment characteristics such as voltage, current, frequency, power quality, and short circuits, as well as ambient conditions, such as temperature and humidity. Sensing technologies can monitor real-time data on the status of microgrid assets, enabling informed decision-making and rapid response to cyber or physical threats [37], [38], and allowing for real-time optimization of load balancing, cost minimization, and reliable power distribution [39].

Control systems, such as energy management systems (EMS) and microgrid controllers, are the systems that actively use the sensor data to balance generation and demand while maintaining grid stability [40], [41] and minimize losses [42]. Control systems may also activate devices like relays, smart devices, and the aforementioned devices that can isolate and protect parts of the grid when a fault has been detected by sensors [43]. Robust control systems are especially important when non-dispatchable energy generation sources such as wind and solar are included in the microgrid, since their intermittent nature can cause fluctuations in current, frequency, and voltage that may act as a destabilizing force if proper controls to coordinate their power injections into the system are not implemented [44]. Smart controls can provide optimized grid responses in real-time, and can be customized for parameters that are specified as important to individual systems [45], [46].

Communication systems play a vital role in microgrid operation during natural disasters, as they enable control over DERs and grid components such as load centers and substations [47], [48], [49]. These systems must be robust enough to operate under adverse conditions and ensure continuous monitoring, control, and coordination across the power system. A reliable communication network is essential for coordinating microgrid operations, especially during a natural disaster [7].

2. MICROGRID HARDENING DECISION FRAMEWORK

2.1. Framework Overview

As extreme weather events and natural disasters become more frequent and intense, improving the resilience of microgrids has become essential to sustaining reliable power in vulnerable regions. The generalized framework, shown in Figure 2-1, offers a structured, four-phase approach to identifying, prioritizing, and implementing mitigation strategies tailored to the specific risks faced by microgrid components.

In Phase 1, regional hazards such as hurricanes, wildfires, earthquakes, or floods are identified and evaluated for their potential impact on microgrid subsystems, including generation assets, energy storage, controls, and communications. Each hazard-subsystem pair is assigned a Risk Index (RI) based on three factors: likelihood of occurrence, expected physical or operational impact, and how easily the failure can be detected.

In Phase 2, only those subsystems with an RI above a defined threshold (RI ≥ 17) are advanced for mitigation planning, ensuring resources are focused on the highest-priority risks. Phase 3 introduces mitigation strategies tailored to those risks and calculates a Priority Index (PI) based on the strategy's effectiveness, the subsystem's severity, and the cost of implementation. To enable fair comparison, these scores are normalized into a scale of 0 to 1 as the Normalized Priority Score (N_{PS}), which supports tiered decision-making. Mitigation options are then categorized into three tiers, immediate (Tier 1), near-term (Tier 2), or deferred (Tier 3), to reflect their cost-benefit priority.

Finally, Phase 4 outlines the deployment of selected strategies, following a phased approach that balances impact, urgency, and budget constraints. Tier 1 mitigations are deployed quickly with minimal barriers, while Tier 2 strategies are planned for medium-term implementation, and Tier 3 options are deferred or reassessed as conditions change. This generalized framework supports resilience planning that is regionally adaptable, scalable, and grounded in risk-based decision-making, for communities, utilities, and coops with a clear path to harden microgrid subsystems against the growing threats of natural disasters.

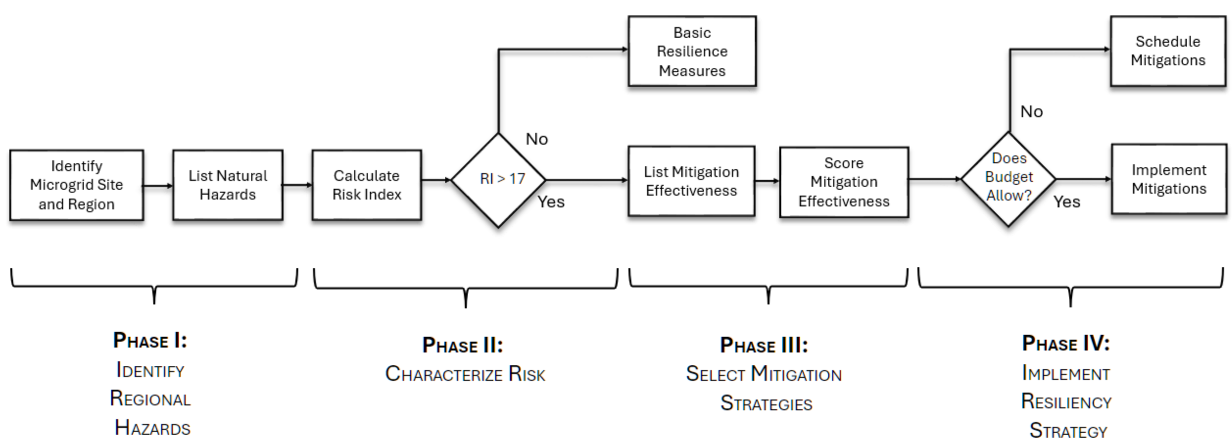


Figure 2-1. Simplified Flowchart of the Microgrid Hardening Decision Framework.

2.1.1. Phase I: Identify Regional Hazards

The first phase in the microgrid resilience planning framework focuses on understanding the unique risks posed to a specific microgrid site based on its geographic location and infrastructure condition. This process ensures that disaster planning begins with a grounded understanding of both environmental and system-based threats. Figure 2-2 illustrates the flowchart of the microgrid hardening decision framework that focuses on identification of regional hazards.

The process begins by identifying the site and regional context of the microgrid. This includes the microgrid's geographic location (e.g., coastal, inland, mountainous) and local climate, which help determine the types of natural disasters that are most relevant in the area. Common hazards considered in this phase include hurricanes, tornadoes, floods, and volcanoes. Publicly available datasets from FEMA, NOAA, USGS, and state-level emergency management agencies can be used to inform this step of the framework.

Next, the framework calls for a systematic assessment of existing infrastructure vulnerabilities. These vulnerabilities may stem from aging equipment, poor siting, or insufficient hardening.

If there are any existing vulnerabilities, then corrective measures should be recommended to address the vulnerabilities before or alongside hazard mitigation efforts. These might include replacing outdated components, elevating flood-prone equipment, or reinforcing critical infrastructure. Addressing these internal weaknesses early increases the resilience of the microgrid even before external threats are characterized.

Once vulnerabilities are accounted for, the process moves to compiling a final list of natural hazard risks. This list includes only those hazards that are geographically relevant, historically likely, and technically impactful to the microgrid's operations. These hazards are then passed to Phase 2, where they are paired with subsystems and evaluated using the Risk Index.

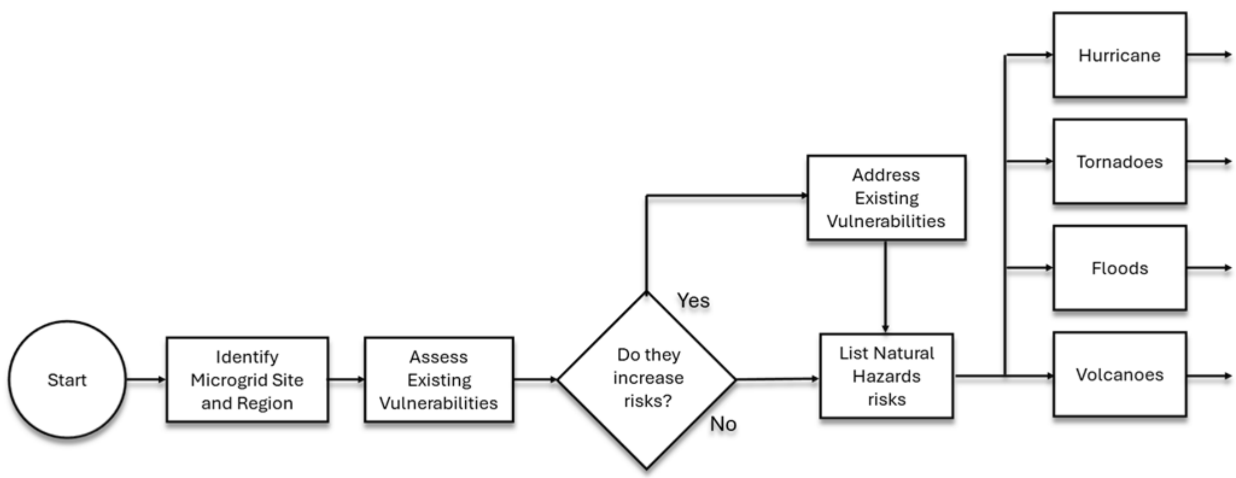


Figure 2-2. Flowchart of Phase I of the Microgrid Hardening Decision Framework (Identification of Regional Hazards).

2.1.2. Phase II: Characterize Risk Index

Once natural hazards relevant to a region are identified in Phase 1, Phase 2 focuses on evaluating how severely those hazards can impact specific microgrid subsystems. This is achieved through a qualitative scoring process that helps prioritize where mitigation efforts are most urgently needed by ranking the overall risks to a system or subsystem. Not all hazards pose equal risk to energy systems, and not all components of a microgrid are equally vulnerable. Phase 2 bridges this gap by characterizing these interactions between hazards and infrastructure.

It is important to highlight that the risk assessment framework presented here is generic and that it can be applied in multiple ways, including the one described in Section 4 of this report. The generic nature of the framework allows for it to be applied as needed to different contexts, based on the stakeholders and their goals or relevant questions. For example, the framework could be used to compare overall system risk between different locations, such as in the case of an energy project developer looking for optimal locations for implementation. This risk assessment could also be used to compare overall risk between different types of systems, such as wind turbine generators compared to combined heat and power systems; stakeholders such as communities interested in developing co-located energy generation may need to use these types of comparisons to inform their technology selection. This risk assessment framework may also help compare the relative contributions of risk from different subsystems within the same overall energy system, for example, if a project developer or energy system owner-operator were to try to prioritize hardening investments within their system. In the overall view of decision-making within projects, the operational and safety risk characterized within this framework is only one aspect of making design and operational decisions. Other factors such as permitting, cost, regulations, affected stakeholder buy-in, and commercial equipment availability are often also considered when developing, constructing, and maintaining energy projects. The goal of the framework described in this report is to present a way to evaluate one of these decision-making factors to be considered among all the relevant aspects for energy projects.

To follow the presented risk index calculation framework, we would assign heuristic levels and definitions to each parameter in the overall risk metric, for each hazard/subsystem pair (e.g., hurricanes affecting battery enclosures or floods impacting transformers). Again, these risk metric parameters are likelihood, detectability, and severity. It is important to note that these heuristic assignments are qualitative; they are informed by relative quantitative estimates but are not meant to reflect a particular dimension or physical metric. The qualitative nature of this framework further emphasizes that the framework is well-suited for comparative analyses such as those described above, rather than the numerical inputs and outputs being a measure of a particular physical dimension. The following descriptions also provide multiple potential methods for assigning these numbers, based on the goals of the research and the available data. Some of the information may be unknown or unavailable, so making reasonable approximations or justifications for different heuristic assignments may be necessary.

Likelihood (L) is the probability of the subsystem failure occurring due to the hazard in a selected region. This overall probability would ideally be informed by a combination of factors, including the frequency of the hazard occurring in the region and the probability of failure of a certain type of equipment given that the hazard occurs. A lower-likelihood event would correspond with a lower likelihood score, contributing to an overall lower RI score.

Table 2-1. Event (e.g., hazard and/or subsystem failure due to the hazard) Likelihood Classification Scale

Score	Category	Description
3	High	Likely to occur one or more times in a year
2	Medium	Potentially occurring once in a year
1	Low	Unlikely to occur
0	N/A	Will not occur

Detectability (D) is the extent to which the subsystem failure can be detected early, allowing time for response (e.g., emergency shutdown, system reconfiguration). The forecastability of a particular hazard could also potentially be used as a proxy for the detectability of a subsystem failure if pre-emptive measures can be taken to anticipate and prevent or mitigate the impacts of a hazard on a subsystem before they occur. For example, a project developer may be interested in understanding the detectability of cracked cover glass on PV modules from solid precipitation events, but there may be insufficient data available for them to appropriately characterize or assign tiers for the detectability of the system. Instead, one way to make a crude but comparable assessment would be to assume that the system would be proactively hardened, if possible, once the hazard of interest is detected. In this case, the detectability would be better described by a descriptor like "forecastability," where a hazard with little to no warning, such as an earthquake, would have a high detectability score, representing low forecastability or advance notice to harden the system, for example, through mounting of equipment. A different type of natural disaster or extreme weather event, such as a hurricane, can be predicted with varying degrees of accuracy days to weeks before they occur in a certain location, so the detectability score would be lower (indicating higher forecastability) because it would be assumed that systems could be hardened or moved to appropriate operational states in preparation for the event.

Table 2-2. Event (e.g., anticipated/current hazard presence and/or subsystem failure) Detectability Classification Scale

Score	Category	Description
3	Difficult	Unlikely detection or detection after catastrophic damage has occurred
2	Moderate	Possibly detection or detection after some damaged has occurred
1	Easy	Likely near-immediate detection

Severity (S) is a measure of the expected severity of the damage or operational disruption the hazard could cause to the system. Severity can be difficult to classify in a comparable way across different subsystems or components, and the outcome for the overall system could vary based on the component. For example, some components, such as a PV module could be redundant within a system; complete malfunction of a single PV module may only have a slight impact on the overall system's power output slightly. In another example, a faulty relay that is corroded and may intermittently work (even if not fully malfunctioning) could potentially lead to a highly dangerous situation like an unintentional islanding. Thus, one way to encompass a range of failure modes across these different components could be through a method like the example severity classification shown in Table 2-3, which frames severity of a hazard to a system in terms of its impact on overall system damage and the downstream effects on the people relying on the system. Using this high-level view of system failures can reduce the need for granular (and likely unavailable/undocumented) information needed in more detailed fragility models, where there may be a need to gather information about independent component failures, interactions between multiple failing components, and the possibility of cascading failures throughout the system.

Table 2-3. Hazard Severity Classification Scale

Score	Category	Description
3	Severe	Catastrophic damage; power outages for many customers; long-term recovery times (weeks or longer)
2	Moderate	Some damage, power outages for some customers; moderate recovery times (hours to days)
1	Minor	Damage to non-critical components or non-catastrophic damage; power outages for few or no customers; short recovery times (up to a few hours)

These three parameters are multiplied to calculate the Risk Index (RI) for each hazard-subsystem pair:

$$\boldsymbol{RI = L \times D \times S} \qquad [1]$$

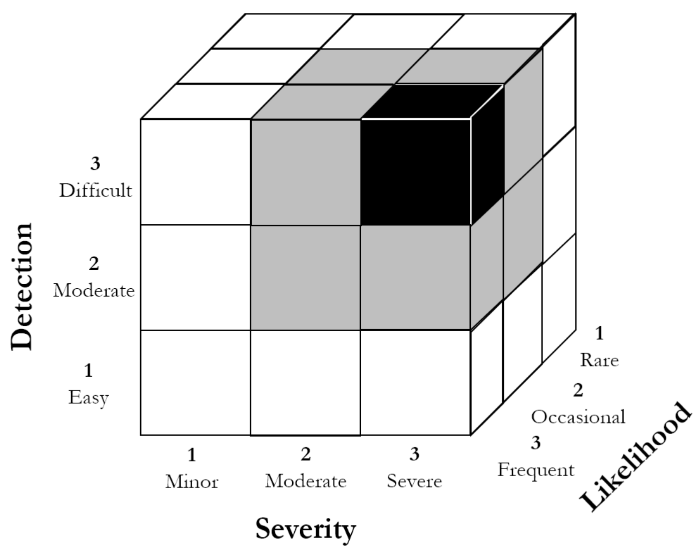


Figure 2-3. Risk ranking matrix.

The RI score ranges from 1 to 27, with a score of 0 representing a non-applicable case for a natural hazard that will not occur in a particular location (scenarios with a likelihood score of 0 are not represented on the matrix at all, since they are non-applicable situations). Higher scores represent more critical risks that demand mitigation. A threshold score of 17 was selected to distinguish which hazard/subsystem combinations warrant further action. Pairs scoring below this threshold are logged for monitoring but are not prioritized for immediate investment. For comparisons across multiple hazards and systems, the RI values can be normalized to fall within a range of 0 and 1. This is particularly useful in later phases when evaluating the relative cost-effectiveness of mitigation strategies. By the end of Phase 2, the project team has a refined list of high-severity risks that are both technically and regionally relevant. This shortlist ensures that limited budgets and resources are focused on the most vulnerable components and the most probable hazards, streamlining the pathway to strategic resilience planning in Phase 3.

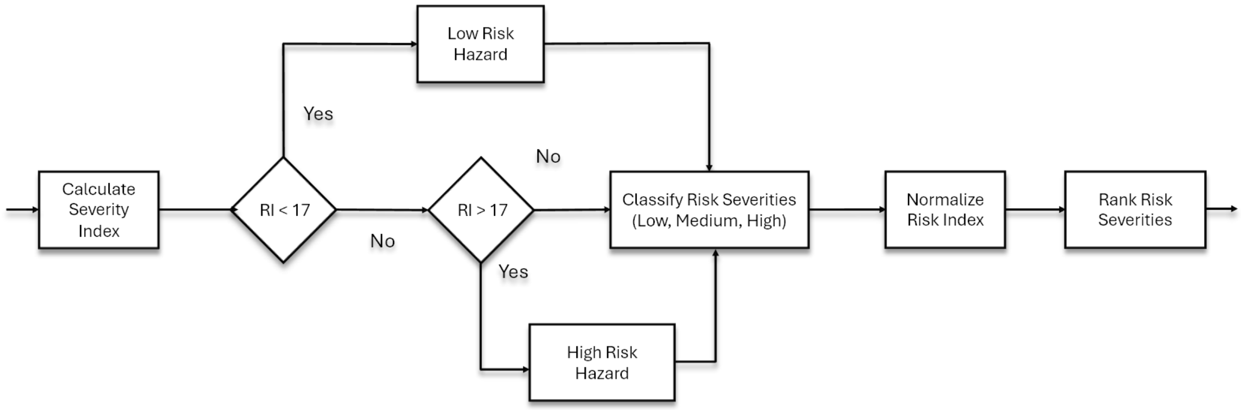


Figure 2-4. Flowchart of Phase II of the Microgrid Hardening Decision Framework (Ranking of Risk).

All three factors affect the RI, so each individual factor (for example, a high hazard rating) is not necessarily an indicator of the overall risk estimate. Designing power systems like microgrids to lower these risk ratings, through hardening techniques, can improve system resilience.

Although both frequency and consequence are involved in the calculation of the overall risk index metric, the risk index can be high for a low-frequency, high-consequence event, which is worth consideration when designing a microgrid. In these cases, **high severity hazards** demand **immediate attention**, with a focus on **hardened infrastructure**, **redundant systems**, and **backup solutions**. **Medium severity hazards** should be **monitored** for potential risks and improvements should be based on specific subsystem vulnerabilities. **Low severity hazards** may require **occasional assessments** but generally do not necessitate drastic infrastructure changes.

The approach of designing for high-consequence events can also inform decisions on **investment in specific protection measures**, such as **enhanced weatherproofing** for energy storage and **reinforced communication links** to ensure continued functionality under adverse conditions. To classify the risk indices of hazards and their impact on microgrid subsystems, we can develop a scoring system that takes into account both the likelihood and the potential impact of the hazard on key microgrid components.

The framework may also be applied differently by different stakeholders depending on the available data and the goals of the project. For example, a developer interested in making decisions about their specific system may prefer to run preliminary quantitative tests and identify or assign qualitative rankings of each risk metric to their specific equipment and setup. Another way to make the data more generically applicable to a wide range of systems, including systems that may not yet be fully designed or cases where the developer may not have the resources to do a full risk fragility assessment of the system's components, would be to aggregate historical data and use a statistical model to assign generic values for frequencies and detectability scores. This type of analysis would be rigorous, as it would require a large amount of data for various subsystems and hazards in order to reduce uncertainty, and there would need to be some way to make the data comparable across locations, hazard types, and subsystem components.

The value of using a qualitative tiered system, as alluded to throughout this section, is that it does not require the specific and potentially large amount of data that may be needed to do a more in-depth quantitative analysis, and there is no need to make definite conclusions about uncertainties or risk numbers in a physical sense. This ranking system allows for us to gain insights on the types of questions and goals described above, for projects at various levels of design, while also not overcommitting to results that may not have a highly certain quantitative basis.

2.1.3. Phase III: Select Mitigation Strategies

Once high-severity hazard–subsystem risks are identified in Phase 2, Phase 3 focuses on selecting the most effective and feasible mitigation strategies. The goal is to reduce the overall risk to microgrid infrastructure by prioritizing actions that deliver the greatest resilience improvement per dollar spent. This phase ensures that limited resources are directed toward solutions that are both impactful and cost-effective. For each hazard–subsystem pair with a high SI, potential mitigation strategies are compiled. These could include technical solutions (e.g., elevating transformers to prevent flood damage, reinforcing battery enclosures against high winds, or hardening control systems against wildfires), operational changes (e.g., adjusting load priorities), or upgrades to sensing and communication systems. Each mitigation strategy is then scored using two metrics:

- **Effectiveness (E):** The degree to which the strategy reduces risk or prevents failure.
- **Cost (C):** The financial and logistical burden of implementing the strategy.

These values, along with the previously calculated Risk Index, are used to obtain a Priority Index (PI):

$$\boldsymbol{PI} = \frac{\boldsymbol{RI} \times \boldsymbol{E}}{\boldsymbol{C}} \quad [2]$$

The values of E and C were selected based on the descriptions provided in Table 2-4 and Table 2-5, respectively. Note that these categories are broad and nonspecific to any particular type of equipment or natural hazard, to ensure that this metric is comparable across a range of scenarios.

Table 2-4. Effectiveness Categories

Score	Category	Description
5	Very High	Completely mitigates hazard impact on subsystem
4	High	Substantially reduces risk, most critical failure paths blocked
3	Low	Minor improvement; only helpful for low-intensity hazard events
2	Moderate	Somewhat reduces risk, but subsystem still partially vulnerable
1	Very Low / None	Minimal to no impact on risk

Table 2-5. Cost Scales

Score	Category	Range ($)	Description
5	Very Low	x < $10k	Uses existing infrastructure; minimal labor
4	Low	10k < x < 50k	Low complexity, fast install
3	Moderate	50k < x < 250k	Medium-scale hardware or integration effort
2	High	250k < x < 1M	Involves system redesign or major procurement
1	Very High	x > 1M	Difficult to implement

The minimum and maximum calculated PI values from the entire set are normalized to be between values of 0 and 1 using the following equation:

$$N_{PI} = \frac{PI - PI_{min}}{PI_{max} - PI_{min}} \quad [3]$$

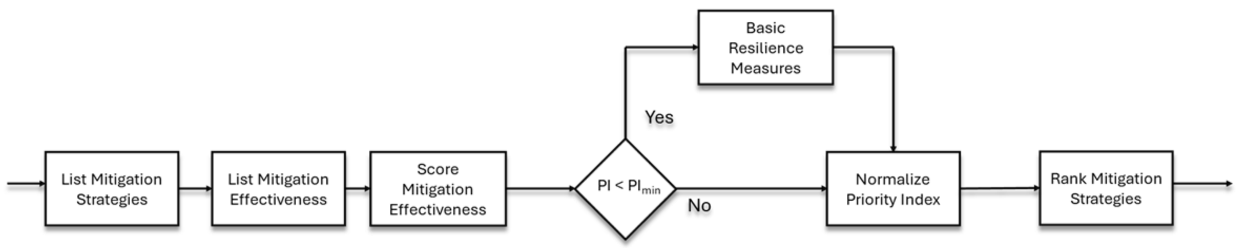


Figure 2-5. Flowchart of Phase III of the Microgrid Hardening Decision Framework (Implementation of Resilience Strategy).

2.1.4. Phase IV: Implement Resiliency Strategy

Phase 4 focuses on executing the mitigation strategies that were prioritized in Phase 3. This phase guides decision-makers through a phased deployment approach tailored to financial, logistical, and technical aspects. The ultimate goal is to harden the microgrid against the most critical threats while staying within budget and deployment constraints. Mitigation strategies are grouped by their Normalized Priority Score (N_{PS}) into three tiers:

Table 2-6. Prioritization Actions and Criteria

Tier	Criteria	Action
Tier 1	$N_{PS} \geq 0.8$	Implement immediately
Tier 2	$0.5 < N_{PS} < 0.79$	Implement next budget cycle
Tier 3	$N_{PS} < 0.5$	Keep in contingency or pilot scope

Each mitigation strategy is evaluated based on budget availability, construction feasibility, permitting, dependencies on other systems, and procurement lead times.

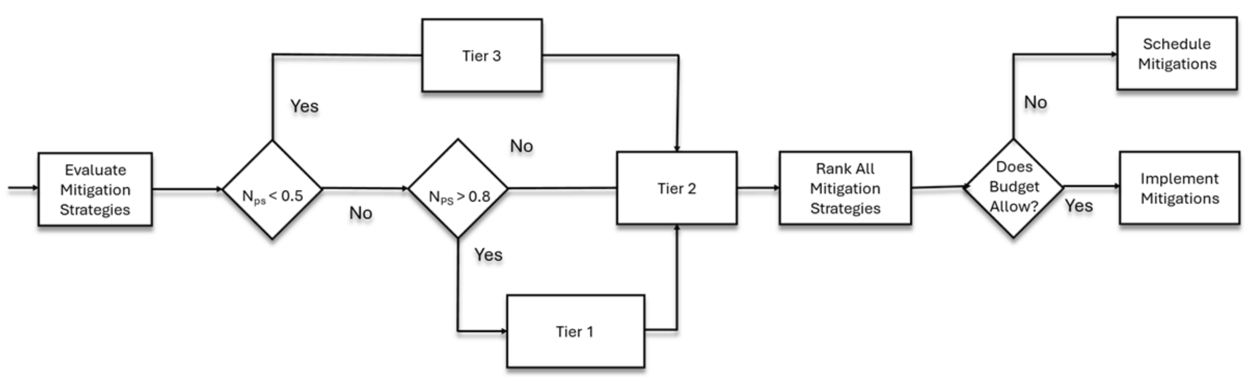


Figure 2-6. Flowchart of Phase IV of the Microgrid Hardening Decision Framework (Implementation of Resilience Strategy).

3. MICROGRID FAILURE POINTS AND HARDENING TECHNIQUES

Given the vulnerabilities of microgrids to hazards posed by extreme weather events and natural disasters, enhancing resilience requires a multi-faceted approach. To provide a couple of examples, infrastructure upgrades, such as reinforced mounting structures for solar panels, undergrounding critical power lines, and weatherproof enclosures for energy storage, can improve resilience to natural disasters. Additionally, intelligent grid management strategies, including predictive controls, adaptive protection schemes, and automated reconfiguration, can help microgrids respond dynamically to disaster conditions. Hybrid energy systems that combine diverse generation sources, along with strategic placement of backup power assets, further strengthen microgrid reliability.

One important note about general hardening techniques is that hardening may involve the system and equipment itself, as well as the general facility and surrounding area. The efficacy and need for these two types of hardening actions largely depends on the types of natural hazards that impact the specific location of interest, the flexibility of the project, and the stage of the project during which hardening actions are being taken. For example, in certain areas in the U.S., wind turbines are highly susceptible to lightning strikes. In some cases, siting a wind turbine project in areas with lower frequencies of lightning strikes may be an option, but in other cases, the wind turbines are already built or cannot be sited elsewhere. In those cases, hardening techniques to protect the turbines against lightning strikes such as implementation of a lightning protection system or a separate lightning rod may be more appropriate. These decision-making considerations are not explicitly included in the risk assessment framework, but multiple hardening techniques are offered in the following sections to account for these unique aspects of different microgrid systems.

3.1. Energy Generation and Storage Assets

The tables in this section describe specific failures that may occur for different energy assets in the event of occurrence of each of the discussed extreme weather event or natural disasters.

As shown in Table 3-1, notable failure points for CHP systems include ingress of water or particulate matter into the turbine (e.g., from precipitation, flooding, or volcanic or wildfire emissions) and damage to the blades that could lead to inefficiencies or even render the turbine unusable. The generator electrical components are also susceptible to environmental damage, such as from water impacts of precipitation or flooding, or from other causes like lightning strikes. CHP systems can be protected from these hazards using structural protection and siting in an area with low vulnerability to different environmental impacts. Siting is flexible for CHP systems, which do not depend on environmental factors for performance, the way PV systems and wind turbines do.

Table 3-2 shows vulnerabilities and hardening techniques for solar PV systems. From this literature review, it seems that the panel modules and cover glass are vulnerable to both mechanical and electrical impacts of different natural hazards. There are also environmental conditions that can reduce efficiency and performance of the panels without damaging them, particularly events that lead to potential blockage of the sun, like volcanic or wildfire emissions of ash, soot, or smoke, or snow buildup. Extreme temperatures can also have impacts on module performance and integrity. Material and electrical design, for example, through coatings and module circuit design, can be used to harden PV panels against natural hazards.

Wind turbines seem highly susceptible to hazards that may cause blade erosion (such as precipitation and/or high wind events) and structural instability in the foundation or tower (such as high wind events, seismic events, and subterranean activity), as shown in Table 3-3. The generator may also be vulnerable to temperature extremes and lightning strikes. Protective measures like retrofitting the turbine blades with coatings, building the foundation in anticipation of seismic and other land impacts depending on the selected site, implementing controls to curtail the turbine in times of potentially damaging environmental events, and using ambient controls like heating and cooling for the generator, can all help preserve wind turbine components and improve the turbine lifetime.

Table 3-4 shows vulnerabilities and hardening techniques for BESS. While batteries would likely be highly susceptible to hazards like the ingress of water or particulate matter that could cause electrical damage, they are usually located within structures that protect them from environmental hazards and prevent most of the discussed failure modes. Management of environmental conditions like temperature and mounting of the batteries on racks built to withstand seismic impacts can also be integral to the preservation of BESS within a microgrid.

3.1.1. Combined Heat and Power Systems

Table 3-1. Examples of Vulnerabilities and Hardening Techniques for Combined Heat and Power Systems

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
Water Impacts	**Flood** (e.g., tsunami, hurricane)	• Ingress of water into generator, resulting in short-circuits or other consequences resulting in electrical failure	• **Elevation or relocation:** Elevating the system or moving it to an upper floor of the building in which it is located can prevent floodwaters from reaching the major electrical components [50]. • **Dry floodproofing:** Locating the system in a structure (i.e., building, within walls/gates) that is constructed for watertightness and includes drainage or other flood mitigation measures like sump pumps can help reduce the risk of water damage to CHP systems from flooding [50].
Precipitation	**Solid Precipitation** (e.g., hail, sleet)	• Ingress of solid precipitation particles to turbine rotor blades that, in solid or liquid form, could result in efficiency losses and potential erosion or breakage of blades due to high-velocity collisions of water and equipment [51]	• **Structural protection:** Locating the system within a shelter structure can prevent precipitation impacts on the system and its major components.
	Freezing Precipitation (e.g., snow, ice)	• Ingress of precipitation particles to turbine rotor blades that, in solid or liquid form, could result in efficiency losses and potential erosion or breakage of blades due to high-velocity collisions of water and equipment [51] • Ingress of moisture to electrical components, resulting in reduced or loss of efficiency/function	• **Structural protection:** Locating the system within a shelter structure can prevent precipitation impacts on the system and its major components.
Extreme Temperature	**Extreme Heat**	• Reduced efficiency in electric power generation [52], [53]	• **Thermal management:** Locating the system in a structure with cooling capabilities can prevent elevation of system temperatures from high ambient temperatures.
	Extreme Cold	• Reduced efficiency in heating capabilities due to greater demand for heating (and potential increase in vulnerability of people relying on the heating) [52]	• **Peak power planning:** Understanding the range of extreme cold temperatures in the CHP location can help determine the appropriate five-day moving average temperature (t_{5days}) to use for design of the system [53]. • **Thermal management:** Locating the system in a structure with heating capabilities can prevent reduction in system temperatures from low ambient temperatures.
Land and Seismic Irregularities	**Landslide/ avalanche**	• Damage from debris and/or falling rock impacts	• **Siting:** Use preliminary site studies and historical data about the area to determine areas with low probability of landslides or avalanches.
	Sinkhole / karst	• Non-level orientation of facility or individual components within the facility	• **Siting:** Use preliminary site studies and historical data about the area to determine areas with low probability of sinkhole formation or karst conditions.
	Earthquake	• Turbine blade throws from seismic vibration impacts	• **Isolation system:** Implement mechanical isolation systems for the turbine or entire system that utilizes technology such as elastomeric or spring bearings to reduce vibrations transmitted to major equipment [54].

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
Fire and Air Contamination	**Volcanic Eruption**	• Ingress of ash or dust to steam turbine blades, resulting in reduced efficiency and/or breakage from high-velocity collisions of particles and equipment • Corrosion of CHP components, resulting in reduced efficiency or complete loss of function	• **Structural protection:** Locating the system within a shelter structure can prevent volcanic impacts on the system and its major electrical components.
	Wildfire	• Thermal weakening or damage of CHP system components • Propagation or ignition of new fires from combination of high heat and electrical equipment	• **Shutdown protocols:** Implementing protocols to de-energize the system when nearby wildfires are detected can help prevent damage to the system and surrounding infrastructure.
Wind	**High Wind** (e.g., tornado)	• Mechanical damage to CHP system components	• **Structural protection:** Locating the system within a shelter structure can prevent wind impacts on the system and its components.
Other	**Hurricane**	• Ingress of water into steam turbine blades, resulting in efficiency losses and potential erosion or breakage of blades due to high-velocity collisions of water and equipment [51]	• **Structural protection:** Locating the system within a shelter structure can prevent hurricane impacts. • **Emergency shutdown protocols:** Ensuring that the system has protocols and possibly automation in place to power down equipment if water has entered the system can preserve the mechanical equipment.
	Lightning	• Short-circuiting or other electrical failures of major electrical equipment • Mechanical damage to parts of the system like the turbine rotor, resulting in partially or completely reduced function/efficiency • Fire consequences from lightning striking electrical equipment	• **Structural protection:** Locating the system within a shelter structure can prevent lightning from directly striking essential electrical equipment.
	Drought	• Reduced efficiency and/or power production due to dust accumulation	• **Structural protection:** Enclosing the system within a shelter structure can prevent ingress and accumulation of dust.

3.1.2. *Solar Photovoltaic Systems*

Table 3-2. Examples of Vulnerabilities and Hardening Techniques for Solar Photovoltaic Systems

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
Water Impacts	**Flood** (e.g., tsunami or hurricane)	• Reduction in insulation resistance, resulting in high leakage voltage values and reduction in energy production [55], [56] • Poor insulation resistance [55] • Moisture penetration into modules [55]	• **Equipment drainage:** Using one-way valves to drain pull boxes and adding splice gutters can prevent accumulation of any water that has entered the electronics containers [57]. • **Site drainage:** Implementing efficient drainage around the solar modules can help remove moisture from the area [56]. • **Elevation of panels:** Elevating panels above the floodplain can reduce the likelihood of water damage from flooding [58]. Alternatively, installing floating solar installations may offer a potential solution in flood-prone areas [59]. • **Inverter placement:** Place inverters in sheltered (e.g., sealed enclosures with corrosive-resistant coatings) and/or elevated locations to prevent water ingress.
Precipitation	**Solid Precipitation** (e.g., hail, sleet)	• Breakage of cover glass [60], [61], [62] • Cracking of solar cells [60], [57], [62] • Denting of silicon [60] • Puncturing of fiber-glass substrate [60]	• **Cover glass material selection:** Thicker and/or tempered or annealed glass and polymer coatings can improve hail resistance [63], [60]. Selecting solar modules that have passed more severe hail certification tests can also help harden the solar system against larger and faster hail [63]. • **Module material:** Using thin-film modules may help prevent cracks and keep damage isolated [57]. • **Module size:** Using a higher quantity of smaller modules (fewer cells per module) can ensure that hail-impacted cells are isolated from the rest of the system [63]. • **Panel edge finish:** Grinding or finishing the edges of the glass panels can improve hail resistance since the edges are highly vulnerable [60]. • **Protective screen:** Install a wire mesh screen slightly above the panels to break apart large hailstones [60]. • **Shock mounting:** Soft- or shock-mounted solar panels can reduce hail damage. • **Tilt controls:** Use tracking systems or other tilt controls to allow panels to tilt to steeper angles to prevent hail impacts [57], [64]. • **Module orientation:** Orienting the PV module away from the most common oncoming hailstorm direction can reduce damage from hail [57], [64]. • **Module framing:** Framing PV glass modules can help contain the glass when hail impacts occur [57].

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
	Freezing Precipitation (e.g., snow, ice)	• Build-up of snow or ice resulting in reduction in solar transmittance and subsequent energy production [61] • Module or frame failure from uneven accumulation of snow on lower portion of panels resulting in module or frame infrastructural failure [57]	• **Anti-Icing coating:** Using superhydrophobic and low ice-adhesion coatings with small sliding angles and/or the ability (e.g., nano-ZnO, nanosilica and non-$CaCO_3$, composites like Y6-NanoSH) can prevent ice buildup [65], [66]. Using materials that heat up when exposed to sunlight can also prevent this ice buildup [66]. • **Frame:** Selecting modules frames with high front load ratings or good loading test performance can help them withstand heavy snow loads [57]. Alternatively, selecting frameless modules may make it easier for snow to slide off [57]. • **Multi-busbar cells:** Selecting modules with smaller widths between busbars can prevent cracks from propagating under loads like snow accumulation [67]. • **Panel tilt:** Maintaining the solar panels at a steep tilt can allow snow to slide off [57]. If using a tracker system, use a "snow stow" mode to automatically achieve this steep angle during snow events [67]. • **Module mounting:** Mounting modules in a landscape orientation may help prevent uneven snow accumulation [57]. • **Ground array mounting:** Mounting ground arrays at least two feet off the ground can provide an area for snow to slide off the panels into [57]. • **Rooftop array positioning:** Positioning solar panels to align with the top of the roof line rather than underneath can prevent snow accumulation on the roof above the panels [57].
Extreme Temperature	**Extreme Heat**	• Reduction in energy production [55]	• **Cooling:** Implementing active (e.g., air-active or liquid-active) or passive cooling (e.g., air-passive, water-passive, conductive) can reduce excessive heating [61].
	Extreme Cold	• Separation of layers due to the various coefficients of expansion of different module materials and potential freeze-thaw or general temperature cycling [57]	• **Test performance:** Select PV modules that have passed IEC 61215 ambient temperature cycling qualification tests even if not required [68].
Land and Seismic Irregularities	**Landslide/ avalanche**	• Damage from debris flow and/or falling rock impacts [69]	• **Siting:** Where possible, select PV sites that avoid regions with highly sloped/mountainous terrain and/or susceptibility to rainfall-induced landslides [69]. Consider land characteristics such as soil depth, soil area, slope, surrounding environment (e.g., presence of trees), and drainage, when selecting a site [70]. • **Preventive monitoring and maintenance:** Monitor area during rainfall (high-risk) season to anticipate and initiate landslide prevention measures [71].
	Sinkhole / karst	• Differential settlement across panels resulting in damage to modules and other hardware [72] • Increased loads or stress on PV infrastructure [72] • Development of irregular drainage and/or divots that may allow for the accumulation of water that could subsequently impact the modules [72]	• **Siting:** Use geotechnical and geophysical assessments of the area to identify sinkholes in the area and establish a sufficient buffer distance (50-100 feet or farther) for the PV array [72].

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
	Earthquake	• Horizontal movement [73] that may result in disconnection of module hardware components.	• **Rooftop solar friction:** Utilizing friction between the rooftop and the PV arrays can reduce horizontal movement [73], [74].
Fire and Air Contamination	**Volcanic Eruption**	• Decrease in voltage and/or current output and overall efficiency of PV modules based on shading of PV cells by accumulated dust/ash [75], [76], [61] • Overheating of panels from deposition of dust, potentially leading to loosening of solder points [76] • Potential exacerbation of microcracks or other manufacturing defects from deposition of dust, resulting in enlarged fractures in the module, disconnection of cells in series, and reduction in performance and lifetime [76] • Damaging of antireflection coating from dust/dirt/ash accumulation [61]	• **Hydrophobic design:** Designing solar panels to be hydrophobic or superhydrophobic and self-cleaning can make it easier for dust to be repelled off their surfaces [65], [66], [77].
	Wildfire	• Reduced solar generation due to shading from smoke [55] or elevated heat [78] • Ignition or melting of panel components (e.g., aluminum, glass components) [79] • Stress fracturing of glass from fire heat [79] • Thermal structural damage to mounting structures [79] • Thermal degradation of electronics associated with solar panels (e.g., mechanical motors for automated tracking, inverters) [79]	• **Siting:** Select solar panel locations away from areas of high risk of wildfire [79]. • **Environmental management practices:** Implement a vegetation management plan to prevent overgrowth of vegetation nearby [79]. • **PV module design:** Select panels that have been rated to be more fire-resilient (i.e., select Class A or B modules even when only C modules are required by regulation) [79]. Modules with thicker backsheets may also improve fire-resistance [79]. • **Fire-resistant containment:** Use fire-resistant containers to store electrical equipment (e.g., inverters, batteries) [79]. • **Underground cabling:** Use underground wiring where possible [79]. • **Barriers:** Install non-combustible screens or barriers in front of or behind the PV system to prevent fire spread [79]. • **Roof mounting design:** Increasing the height of the gap between PV systems and the roofs on which they are mounted (ideally with at least a one-foot gap) can prevent the spread of fire under the PV system [79]. • **Islanding:** Proactive islanding of microgrids during wildfire events [80] can prevent cascading failures and support localized power generation for evacuation centers.
Wind	**High Wind** (e.g., tornado)	• Structural fatigue damage and potential collapse due to buffeting (random fluctuating wind) or flutter (vibration) [55] • Lifting of PV modules off of their supports [55] • Power loss due to winds matching resonance frequency of modules [81]	• **Siting:** Where possible, install solar panels on rooftops rather than on mounts or tracking units [55]. If the panels area, placement (such as at the bottom rather than top of a hill) can reduce high wind effects [82]. • **Securing:** Prevent PV modules from flying by bolting modules to mounting rails [57].

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
Other	Hurricane	• Moisture ingression into panels leading to delamination and passivation loss, resulting in degradation of power output, due to high humidity conditions [61] • Swelling of encapsulant from high humidity [61] • Contribution of high humidity to discoloration of encapsulant resulting in power degradation [61] • Acceleration of corrosion of metals in PV modules from high humidity and temperature conditions, resulting in increase of series resistance, deterioration of fill factor, and reduction of power output [61] • Cloud formation leading to reduction in solar generation [83] • Shattering of PV cover glass from high winds and impacts with other objects [84] • Structural damage to metal PV supports [84]	• **Material design:** Using monocrystalline rather than amorphous PV systems can protect the system against the combination of high relative humidity and temperature [61].
	Lightning	• Over-voltage [85] and heating of PV modules from lightning electromagnetic impulse and switching magnetic impulse [86], resulting in electrical degradation and deterioration of output voltage [61] and power • High voltage discharge between cables and cells due to indirect lightning strikes [87] • Bypass diode defects [87] • Breakage of panel glass [87] • Arcing at string ribbon [87] • Introduction of holes in insulation [87]	• **Lightning protection system:** Install a lightning protection system that can protect the PV inverters from surges and other damage by terminating surges and safely directing the lightning to the ground [86]. Lightning protection systems can be external (e.g., air-termination systems, down conductors, earth-termination systems), internal (e.g., equipotential bonding) [87]. • **Surge protection:** Surge protection devices can be installed to prevent over-voltage [57]. • **Grounding:** Grounding the PV frame can prevent direct lightning strikes against the PV panel [87].
	Drought	• Reduced efficiency and power production due to dust soiling and reduced rainfall to clean panels [88]	• **Washing:** Manual or automatic washing can clean dust off panels and improve power production [88].

3.1.3. Wind Turbines

Table 3-3. Examples of Vulnerabilities and Hardening Techniques for Wind Turbines

<table>
<tr><th>CATEGORY</th><th>CONDITION</th><th>POTENTIAL FAILURE OUTCOMES</th><th>MITIGATIONS</th></tr>
<tr><td>Water Impacts</td><td>Flood (e.g., tsunami or hurricane)</td><td>• Foundation instability [89] and associated outcomes like settling and tilting</td><td>• Siting: Analyze soil characteristics and stress distribution along the ground before selecting specific points of placement for the wind turbines [89]. Where possible, avoid placing turbines in areas with large changes in elevation (which are more susceptible to flooding) or inadequate ground/soil drainage and infiltration [89].</td></tr>
<tr><td rowspan="2">Precipitation</td><td>Solid Precipitation (e.g., hail, sleet)</td><td>• Leading edge erosion (LEE) from precipitation-induced material stresses, resulting in decreased aerodynamic performance and reduced blade lifetime [90]</td><td>• Curtailment: Shutting down the wind turbine during high-precipitation events can reduce LEE and improve blade lifetime [91].
• Blade coatings: Applying blade coatings to protect blade edges can reduce LEE [92].
• Tapes: Leading edge tape can protect the blade from erosion [92].
• Metallic erosion shields: Shields like the ones that are used to prevent erosion on helicopter propeller blades may be a viable solution for wind turbine blade LEE [92] (although this method is not as common as the other mentioned solutions).</td></tr>
<tr><td>Freezing Precipitation (e.g., snow, ice)</td><td>• Pre-bending and/or imbalanced weight distribution on blade from ice accumulation [93], [94]
• Slowed rotation and reduced output [95]
• Load removal-induced vibration from ice accumulation [93]
• Deterioration in aerodynamic performance and turbine power output [93], [96]</td><td>• Blade coatings: Implement anti- and de-icing mitigations such as anti-icing blade coatings [97].
• Blade color: Painting blades black can passively facilitate ice melt [94].
• Heating elements: Implement preventive thermostat-controlled elements or heaters for wind turbine components [97], [94].
• Wind turbine spacing: Space turbines within a wind farm far enough apart so ice shedding from one turbine's blades does not damage other turbines [97].</td></tr>
<tr><td rowspan="2">Extreme Temperature</td><td>Extreme Heat</td><td>• Temperature impacts on component materials and lubrication/hydraulic system fluids resulting in declines in power production [98]
• Decline in wind turbine performance [99]</td><td>• Temperature protection control: Increasing the temperature protection setting (i.e., the temperature at which the wind turbine shuts down to prevent overheating from high ambient temperatures) can improve wind turbine performance while keeping the electrical components safe [100].
• Ventilation: Design or improve the ventilation system to make it more adequate for cooling at high temperatures [100].
• Cooling: Design the nacelle cooling system [101] to handle high heat loads if extreme ambient heat is anticipated.</td></tr>
<tr><td>Extreme Cold</td><td>• Temperature impacts on component materials and lubrication/hydraulic system fluids resulting in declines in power production [98], [100], [102]
• Losses in power production due to icing (often coupled with extreme cold) [103]</td><td>• Heating elements: Incorporating heating elements into the blades can prevent icing [104].
• Heat exchanger coating: Use protective coatings for heat exchanger coils to help maintain heat exchanger equipment for thermal management in the nacelle [105].</td></tr>
</table>

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
Land and Seismic Irregularities	**Landslide/ avalanche**	• Settlement of the turbine foundation [106] and potential resulting tilting/destabilization of the turbine (especially for offshore turbines)	• **Pile length:** Increasing pile length may reduce pore water pressure, soil deformation, and settlement of the turbine foundation [106]. • **Landslide prevention:** Use solutions such as ecomat technology to preserve soil and vegetation layer in the area and prevent erosion and landslide activity [107]
	Sinkhole / karst	• Complete collapse of the wind turbine [108] • Differential settlement, tilting and/or other destabilization of the turbine [108]	• **Pre-siting evaluation:** Use analyses such as aerial imagery, digital modeling, and visual reconnaissance to identify surface depressions or karst features within the planned site to account for the possibility of sinkhole formation when designing the site [109], [108]. • **Siting:** For wind turbine sites in areas with large amounts of gypsum, put the turbines in locations of the deepest gypsum beds (possibly with depths of at least 25 m) [108].
	Earthquake	• Excessive vibrations [110], potentially leading to structural failure • Vertical excitation resulting in damage to nacelle, rotor, blades, and pitch control mechanisms or amplification of base bending moment demand [110] • Structural failure of monopiles (especially in offshore installations) [111] • Settlement and/or tilting of turbines (especially offshore ones) mounted on mono-bucket foundations [112]	• **Foundation:** Using gravity base foundations rather than monopiles or other piled foundations would allow for slightly more flex/movement during seismic activity [111]. • **Siting:** If possible, do not put wind turbines in locations of high seismic activity or in places with ground conditions conducive to damaging seismic activity (e.g., areas with soft, loose soil). • **Damping:** Use radiation or other damping as a design consideration when designing and constructing the turbine to mitigate the impacts of seismic forces [112], [110]
Fire and Air Contamination	**Volcanic Eruption**	• Ingress and accumulation of dust, ash, or other particulate matter inside the nacelle, resulting internal temperature fluctuations (i.e., retention of heat) and reduced power production [100] • Erosion and scouring of components exposed to ash [113], potentially resulting in reduced aerodynamic performance and energy production	• **Ventilation:** Improve and modify settings for the ventilation system, including designing dust filters for high concentrations of particulate matter [100]. • **De-energization controls:** Implement controls to de-energize the system and isolate the equipment from the outside to prevent ingress of ash into the nacelle and other essential components once volcanic activity and ashfall have been identified [113]. • **Siting:** If possible, locate the wind turbine farm far enough away and out of the downwind path of volcanic ash [113].
	Wildfire	• Complete destruction of turbine construction (mechanical and electrical components) [114] • Increase in surface roughness from deposition of wildfire ash and soot, potentially resulting in blade LEE and reductions in power production [78]	• **Coatings:** Using fire-protective coatings can prevent ignition of the turbine and spread of the fire [114]. • **Barriers:** Installing a non-combustible barrier by the nacelle (e.g., made of fiber-reinforced polymer) could prevent ignition and fire propagation on the turbine [114]. • **Automatic disconnection system:** Installing a system that allows complete deactivation of the turbine's mechanical systems and electrical isolation of the tower can prevent fire damage and propagation [114]. This system should ensure total isolation of the component affected by the fire and the rest of the wind turbine;

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
			it should also have a safety device preventing reconnection of the turbine before intended [114]. • **Automatic extinguishing system:** Installing fire detection and extinguishing systems inside the nacelle can allow for early detection and extinguishment [114].
Wind	**High Wind** (e.g., tornado)	• Weakening of bolts and potential resulting structural collapse [115] • Foundation failure [115] • Buckling of tower [116] • Fracture or loss of turbine blades [116], [117] • Detrimental impacts to power quality (e.g., power factor, flicker, harmonic/interharmonic distortion) [117] • Erosion of coatings [114]	• **Feathering and curtailment:** Procedures and a design allowing angling of the pitch of the blades to prevent the blades from turning in high speeds above the turbine's rated power can help shut down the turbine during high winds and prevent damage [116]. • **Coatings:** Use anti-erosion coatings to preserve the blades [114].
Other	**Hurricane**	• Failure of pitch, yaw, and other controls from strong and directionally-changing winds [115] • Varied loads along blades, rotor, and tower due to veer (vertical variation in wind direction) [118] • Blade throw [84] or breakage [119] • Delamination [119]	• **High wind speed design:** Increasing the safety factor or other engineering design parameters above the regulatory requirements can help design for non-regular high-risk events like hurricanes [116]. • **Yaw controls:** Installing an additional power source such as batteries can allow for yaw controls to be available even during hurricane events [116].
	Lightning	• Mechanical effects from direct lightning strikes (e.g., breakage of blade) [120] • Thermal effects such as increases in temperature and even melting and steam formation and subsequent damage [120] • Electrical damage from surge currents due to either direct blade strikes or indirect strikes on power lines [120] • Induction of voltage in circuits adjacent to down-conductors on lightning protection system, resulting in damage to the blade [120] • Potential ignition of wind turbine fire and subsequent damage [114]	• **Lightning protection system:** The LPS, or lightning arrester system, generally consists of an external system (to protect the turbine infrastructure), the internal system (to convey the lightning current to ground), and the earthing system (to dissipate the remaining current) [121]. • **Height:** Where possible, consider turbine height as a design factor impacting frequency of lightning strikes [120] • **Blade tip:** Incorporating grounded exposed metal at or near the wind turbine blade tip can help guide lightning strikes to ground without going through the surface of the blade [122]. • **Nacelle bonding:** Bond the metallic nacelle to the slow speed bearing and generator base plate to protect electronics from lightning strike surges [122]. • **Wire protection and shielding:** Use wire routing and shielding (i.e., in a pipe) to protect the electrical equipment from lighting [122]. • **Lightning rod:** Adding a lightning rod that extends at least 2 m above the nacelle and that is bonded to the bed plate can protect the entire turbine [122].
	Drought	• Reduction in power due to dust accumulation or settling in electrical components	• **Ventilation:** Utilize dust filters to prevent dust accumulation in electrical components.

3.1.4. Battery Energy Storage Systems

Table 3-4. Examples of Vulnerabilities and Hardening Techniques for Battery Energy Storage Systems (BESS)

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
Water Impacts	**Flood** (e.g., tsunami or hurricane)	• Electrical shorting [123] • Contamination and possibly corrosion of internal battery components caused by ingress of water [123] • Risk of fire from exposure to salt water flooding and subsequent chemical reaction with battery fluids [124] • Battery failure from ingress of salt fog [125]	• **General flood protection** [126]**:** For example, build a clearing under the battery-containing building to allow flood water drainage. Implement property-wide flood management (e.g., shingle drainage, swales, permeable paving, retention ponds, etc.). • **Built infrastructure:** Do not build walls around the BESS, to prevent flood water accumulation. • **Elevation of storage system:** Elevate battery-containing building (i.e., on stilts) [127] or place critical BESS infrastructure in less locally flood-prone locations to prevent ingress of water.
Precipitation	**Solid Precipitation** (e.g., hail, sleet)	• Potential localized mechanical damage that could result in short-circuiting or other battery failures	• **Structural protection:** Locating the battery within an airtight structure (i.e. a shipping container or other building-type structure) or underground can protect it from mechanical impacts from solid precipitation.
	Freezing Precipitation (e.g., snow, ice)	• Ingress of moisture/ice, resulting in mechanical deformation of internal battery components [123]	• **Self-heating:** Implementing a self-heating system on the battery can help prevent counterproductively and/or damaging low temperatures in the battery and [128] the formation of ice.
Extreme Temperature	**Extreme Heat**	• Decomposition of electrolyte and solid-electrolyte interface and destabilization of cathode and anode, resulting in thermal runaway and fire outcomes [129] • Degradation of battery cells [130]	• **Thermal management:** Implementing cooling systems (e.g., passive air cooling, direct or indirect liquid cooling, or phase change material) can help maintain safe temperatures in the battery [130]. • **Heat-tolerant design:** Various battery designs (e.g., passivated Li-ion cells or graphite anode materials with low surface area, large particles, lower-voltage cathode operation) can help improve the heat tolerance of the battery [130]. • **Electrolyte selection:** Using stable salts (e.g., LiFSI) can help with thermal management of the battery [130].
	Extreme Cold	• Reduction in power performance [130] • Increase in required charging time [130]	• **Thermal management:** Implementing heating systems (e.g., resistive heating or heat pumps) can help maintain safe temperatures in the battery [130].
Land and Seismic Irregularities	**Landslide/ avalanche**	• Non-level battery orientation (i.e., if karst conditions cause ground-level changes that leave the battery slightly tilted), potentially resulting in battery acid leakage (depending on battery type) and associated outcomes like reduced battery functionality, environmental damage, and exposure of operators to battery fluids	• **Siting:** Understanding the area and its potential for landslides/avalanches can help locate the battery in areas with lower probability and frequency of these events. • **Structural protection:** Locating the battery within a structure like a shipping container can protect it from mechanical impacts of rocks if it is located near a known landslide area.

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
		• Large and sudden mechanical damage impacts from falling rocks that may	
	Sinkhole / karst	• Non-level battery orientation potentially resulting in battery acid leakage associated outcomes like reduced battery functionality, environmental damage, and exposure of operators to battery fluids	• **Siting:** Using geological analyses of the area to identify possible karst conditions can help understand areas that are more favorable for the battery.
	Earthquake	• Damage to battery racks from seismic vibrations [131], possibly resulting in mechanical damage to the battery itself • Potential decrease in discharge capacity [132] (although degradation of electrical function is not always observed [133]) • Increase in diffusion resistance [132], potentially leading to slower battery function • Internal damage to plate separators [133] • Decreased seismic ruggedness (i.e., resilience against future seismic events [133])	• **Securing of infrastructure:** Ensuring that battery equipment is secure (i.e., battery racks to foundation, and batteries to racks) can provide protection against batteries falling from seismic activity [134], [135]. • **Preventive maintenance:** Use IEEE Standard 450 (IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications) [136] or equivalent, depending on battery type, to properly maintain and operate batteries to promote seismic resistance [133]. • **Seismic testing:** Use battery systems that have been tested and certified for use in areas of high seismicity [126].
Fire and Air Contamination	**Volcanic Eruption**	• Potential corrosion from contact with ash or soot on the battery exterior or from ingress of ash into the interior • Damage to battery and functionality via ingress of dust [125]	• **Structural protection:** Locating the battery within a structure can protect it from exposure to ash or dust from volcanic activity.
	Wildfire	• Thermal abuse of the battery, possibly resulting in thermal runaway (ignition of battery fire) [137] or other thermal damage to the battery, preventing its safe use • Potential corrosion from contact with ash on the battery exterior or from ingress of ash into the interior	• **Sprinkler protection:** Implementing water-based fire protection can help control fires (whether a wildfire or battery fire induced by the wildfire or wildfire heat) and lower the battery temperature to prevent thermal runaway induced by high temperatures [138]. • **Venting:** Having adequate venting of the battery and ventilation can help maintain safe battery temperatures when there is exposure to heat from wildfires. • **Siting:** Select a location for the battery with adequate distance from combustibles [138].
Wind	**High Wind** (e.g., tornado)	• Potential ingress of dust into the battery, resulting in its failure [125]	• **Structural protection:** Locating the battery within a structure can protect it from exposure to dust from high wind conditions.
Other	**Hurricane**	• Potential ingress of moisture into battery from flooding and/or increased humidity, resulting in reduction in battery open-circuit voltage and discharge capacity [139]	• **Battery tab protection:** Using battery tab protection can prevent degradation of the battery [139].

CATEGORY	CONDITION	POTENTIAL FAILURE OUTCOMES	MITIGATIONS
	Lightning	• Lightning-induced surge resulting in overvoltage (including indirectly, from lightning strikes on equipment that is grid-connected to the BESS) [140]	• **Line surge arrester:** Line surge protectors can facilitate attenuation of the lightning surge, reduce the lightning current in the equipment, mitigate overvoltage in the BESS, and reduce electrical and thermal stresses within equipment related to the BESS [140]. • **Lightning rod:** Add ground rods near the BESS container for more protection [141]. • **Conductor:** Adding conductors to guide the surge to ground could also provide additional protection [141].
	Drought	• Drying up of battery electrolytes, potentially resulting in dendrite formation (and subsequent potential short circuits) [142] • Accumulation of dust on battery cooling systems, resulting in reduced heat dissipation capability and potential subsequent overheating and performance degradation [142]	• **Humidity/environmental control:** Locating the battery in an enclosed humidity-controlled chamber can ensure the conditions are not too dry. • **Structural protection:** Locating the battery within a structure can protect it from exposure to dust.

3.2. Load Assets

To withstand natural disasters, microgrids must harden load assets through backup power, redundancy, and environmental protection. Critical and priority loads require resilient power sources and structural reinforcements. Controllable and interruptible loads benefit from smart energy management and remote automation. Diversion loads need efficient dissipation and fail-safes to prevent instability. Strengthening these systems ensures reliability and grid resilience during extreme events.

3.2.1. Critical Loads

Critical loads must be a priority for hardening efforts since they are the most essential loads to keep in operation, even in extreme conditions. Major hardening techniques for critical loads include:

- **Resilient Power Sources:** Backup power systems such as uninterruptible power supplies (UPS) and diesel or gas generators should be implemented to provide reliable power during grid outages. These systems should be housed in waterproof and fireproof enclosures to withstand floods and fires.
- **Elevated Installations:** Elevating electrical equipment, where possible, ensures that critical loads remain operational during floods and other water-related disasters.
- **Redundant Power Paths:** Installing redundant power feeds and integrating microgrid control systems that allow automatic load shedding and switching between power sources ensures that critical loads continue to receive power even if one source fails.
- **Remote Monitoring:** Remote control systems that allow operators to monitor the health and status of critical loads help to respond quickly during emergencies. These systems should be hardened against electromagnetic interference, fire, and physical damage.

3.2.2. Priority Loads

The following strategies are useful for hardening priority loads:

- **Improved Circuit Protection:** Use of surge protection devices, circuit breakers, and reclosers ensures priority loads are protected against electrical surges caused by lightning, high winds, or other events.
- **Flexible Load Management:** Implementing advanced load controllers and sensors allows for dynamic allocation of power to priority loads. In scenarios such as hurricanes or snowstorms, power can be redirected from non-essential areas to priority loads, ensuring continued operation during emergencies.
- **Backup Power Integration:** Priority loads should be connected to backup energy storage systems like batteries or microgrid generators to provide power during grid outages. These backup systems should have the capacity to provide enough power for extended periods if required.

3.2.3. Controllable Loads

Hardening controllable loads focuses on ensuring their operation can be dynamically managed during a disaster while minimizing the risk of equipment damage. Key strategies for hardening controllable loads include:

- **Smart Load Control:** The integration of smart meters and IoT-based devices allows for remote control and load shedding of non-essential systems during peak demand or when natural disasters impact the grid. This allows for energy conservation while preventing overloading of the microgrid system.

- **Adaptive Response Mechanisms:** By implementing energy management systems (EMS) that can respond dynamically to changes in environmental conditions, controllable loads can be curtailed or shifted to non-peak hours to maintain grid stability.
- **Seismic and Environmental Protection:** Controllable loads, particularly those involved in manufacturing or industrial processes, should be housed in environments that are resistant to seismic activity, flooding, or extreme temperatures, ensuring their resilience during natural disasters.

3.2.4. Interruptible Loads

For interruptible loads, hardening measures include:

- **Automation and Remote Control:** Advanced remote-control systems and real-time communication tools allow for fast and reliable disconnection and reconnection of interruptible loads. During events like high winds or hurricanes, these systems help to mitigate the impact of load spikes.
- **Load Prioritization and Sequencing:** In cases where the load needs to be interrupted, automated systems prioritize which loads to disconnect first, minimizing the impact on business continuity. These systems should also be able to detect which loads can resume after the disaster to support recovery efforts.
- **Resilient Communication Systems:** Interruptible load control systems must be supported by communication networks that remain operational even in the event of system failures caused by lightning strikes or tsunamis. Redundant communication pathways, such as satellite or radio-frequency communication, can be used to maintain control.

3.2.5. Diversion and Dump Loads

Hardening strategies for diversion and dump loads include:

- **Energy-Resistant Dumping Systems:** These loads should be designed to safely handle large amounts of energy during peak generation periods without damaging components. For example, resistive heating systems, such as large industrial heaters, can be used to safely dump excess energy.
- **Integration with Energy Storage:** By linking diversion loads to energy storage systems, surplus energy can be stored for later use rather than being wasted. This requires energy storage systems to be resilient to extreme temperatures, flooding, and seismic activity.
- **Fail-Safe Mechanisms:** Dump loads should have fail-safe mechanisms that activate in case of equipment failure, such as backup circuits and automated systems that detect when the load is at risk of overloading.

3.2.6. Hardening of Microgrid Loads

Table 3-5: Microgrid Enhancements to Loads

Category	Condition	Critical Loads	Priority Loads	Controllable Loads	Interruptible Loads	Diversion and Dump Loads
Water Impacts	**Flood (e.g., tsunami or hurricane)**	• Elevated backup systems and power hubs	• Waterproof wiring • Secondary power feeds	• Smart controllers for load shedding	• Automated shutoff systems	• Waterproof enclosures

Category	Condition	Critical Loads	Priority Loads	Controllable Loads	Interruptible Loads	Diversion and Dump Loads
		• Waterproof enclosures and power hubs • Redundant power sources • Marine-rated equipment	• Elevated switchgear • Saltwater-resistant switchgear • Emergency isolation circuits	• Moisture-resistant enclosures • Load migration to unaffected grid zones • Early warning integration	• Protective relays • Rapid load shedding to prevent grid instability	• Rerouting options for excess power • Load redirection to alternative microgrid resources
Precipitation	**Solid Precipitation (e.g., hail, sleet)**	• Reinforced structures • Impact-resistant enclosures • Underground backup systems	• Hardened power lines • Weather-resistant switches	• Automated shutdown on impact detection • Reinforced housings	• Priority shutdown systems • Surge protection	• Resilient energy storage systems • Durable protective barriers
	Freezing Precipitation (e.g., snow, ice)	• Heated enclosures • Ice-resistant cabling • Insulated main and backup power sources • Cold-weather-rated backup systems • Redundant power sources	• Weather-resistant relays and switchgear • Ice-mitigation coatings • Heated wiring • Insulated control panels • Insulated transmission lines	• Load balancing for heating needs • Automated ice detection and removal systems • Snow load monitoring • Dynamic demand response • Component heating system	• Delayed restart procedures • Ice-resistant connectors • Emergency load-shedding protocols to prevent ice accumulation damage • Slow restart mechanisms	• Smart dumping mechanisms for load redistribution • Diversion strategies for excess energy during low demand • Heat-based diversion systems for ice mitigation
Extreme Temperature	**Extreme Heat**	• Active cooling systems • Heat-resistant materials • Additional ventilation	• High-temperature-rated insulation • Solar shielding	• Smart demand response for cooling loads • Heat-based load shifting	• Overheat protection circuits • Automatic shutdown at thresholds	• Redundant cooling solutions • Energy reallocation for HVAC
	Extreme Cold	• Cold-weather-rated components • Self-heating circuits • Battery warmers	• Insulated power conduits • Frost-resistant controls	• Adaptive heating loads • Automated temperature monitoring	• Temperature-based disconnection mechanisms	• Energy dumping for heat stabilization
Land and Seismic Irregularities	**Landslide / avalanche**	• Relocated critical infrastructure • Shock-resistant enclosures • Real-time monitoring	• Flexible power distribution systems • Rapid response planning	• Adaptive power rerouting • Smart disconnection procedures	• Quick-disconnect systems • Localized energy isolation	• Automated rerouting of power to stable areas
	Sinkhole / karst	• Seismic sensors	• Flexible connections	• Geotechnical monitoring integration	• Quick-disconnect systems	• Automated diversion to stabilize

Category	Condition	Critical Loads	Priority Loads	Controllable Loads	Interruptible Loads	Diversion and Dump Loads
		• Automatic load redistribution • Redundant feeds	• Adaptive rerouting algorithms	• Real-time load adjustment	• Priority backup shifting	surrounding loads
	Earthquake	• Seismic bracing • Shock-absorbing mounts • Redundant grid links	• Flexible conduits • Motion-resistant enclosures	• Seismic-triggered adaptive load control	• Automated shutdown to prevent cascading failures	• Emergency energy redistribution strategies
Fire and Air Contamination	**Volcanic Eruption**	• Heat-resistant enclosures • Remote operation capabilities • Redundant cabling	• Ash-resistant switchgear • High-temperature insulation	• Load reallocation to non-exposed zones • Heat-resistant circuit breakers	• Emergency disconnection from affected grid areas	• Automated load dumping to minimize failure risks
	Wildfire	• Fireproof insulation • Self-contained backup power • Underground utilities	• Flame-resistant wiring • Elevated control panels	• Heat-sensitive automatic controls • Fire-resistant housing	• Rapid isolation switches • Fire-detection integration	• Load redirection to prevent overheating in vulnerable areas
Wind	**High Wind (e.g., tornado)**	• Wind-resistant structures • Aerodynamic enclosures • Vibration dampers • Reinforced shelters for power hubs • Underground wiring • Mobile backup units	• Flexible cabling • Enhanced anchoring systems • High-impact-resistant enclosures • Rapid reconnection systems	• Dynamic load adjustment • Predictive shutdowns • Dynamic disconnection to prevent cascading failures	• Wind impact sensors, load prioritization algorithms • Fast-isolation switches • Remote grid management	• Emergency load diversion to secure systems • Load shifting to unaffected areas post-event
Other	**Hurricane**	• Underground cabling • Storm-rated enclosures • Mobile backup generators	• Elevated substations • Redundant feeders • Hardened control systems	• Adaptive load management • Storm-resilient sensors	• Emergency cut-off mechanisms • Remote isolation capabilities	• Flexible load dumping strategies • Wind-resistant storage solutions
	Lightning	• Surge suppression • Redundant grounding • Lightning-resistant enclosures	• Shielded cabling • Lightning arresters • Surge-resistant components	• Load balancing to reduce overvoltage risk • Emergency disconnects	• High-speed fault isolation • Transient voltage suppression	• Surge-absorbing load diversion circuits
	Drought	• Enclosed/ sheltered electrical components	• Enclosed/ sheltered electrical components	• Enclosed/ sheltered electrical components	• Enclosed/ sheltered electrical components	• Enclosed/ sheltered electrical components

Category	Condition	Critical Loads	Priority Loads	Controllable Loads	Interruptible Loads	Diversion and Dump Loads
		• Humidity controls for electrical components	• Humidity controls for electrical components	• Humidity controls for electrical components	• Humidity controls for electrical components	• Humidity controls for electrical components

3.3. Power Delivery

Upgrading the physical infrastructure of microgrids is critical for disaster resilience, including underground power lines. These are power lines that can be moved underground in regions prone to wind damage, like coastal areas vulnerable to hurricanes, which can improve the negative impacts of undergrounding on reducing outages during severe weather. Automated switches and real-time fault detection systems can rapidly isolate damaged sections of the grid, preventing widespread outages. Self-healing grids using these technologies can improve response times during simulations of hurricane induced failures.

3.3.1. Power Lines

As described, power lines can be underground or overhead. Both types of power lines can be vulnerable to impacts of different natural disasters, but overhead power lines tend to be more susceptible to a range of extreme events such as wildfires, high wind and precipitation conditions, and even extreme temperature. Depending on the size of the microgrid, there may not be a need for power lines at all, especially for household or neighborhood-level microgrids. However, power line hardening is still useful to discuss for larger regional microgrids. The main hardening methods for overhead power lines are summarized here, with more detail for both types of power lines provided in Table 3-6.

- **Underground Lines:** Where possible, using underground lines instead of overhead lines can reduce the need for other types of power line hardening, maintenance, and repair after the occurrence of natural hazards, depending on the expected natural hazards for a given location. However, undergrounding may be logistically and economically difficult or even infeasible, in which case some of the other listed hardening methods may be a priority.
- **Siting and Environmental Management:** Dense vegetation in proximity to overhead power lines can be damaging, especially for hazards like wildfires and high-wind events (e.g., tornados, hurricanes). Implementing protocols for rigorous vegetation maintenance, around power lines, especially in high-risk areas, can help manage this risk.
- **Implementing Equipment Redundancies:** Adding redundant power lines, with control capabilities and switches, can help improve the resilience of an electrical system.
- **Reinforcement and Updating of Existing Equipment:** Reinforcing power line poles and replacing them based on age and/or weathering can help ensure the system is mechanically robust against

3.3.2. Transformers

An overview of hardening methods for transformers is provided, with more detailed information shown in Table 3-6.

- **Enclosed and Elevated Housing:** Install weatherproof enclosures and elevate transformers above potential floodwaters to prevent water damage during storms, flooding, or tsunamis. For regions prone to extreme cold or high heat, insulated housing helps maintain optimal operating temperatures.

- **Seismic Reinforcement:** For areas prone to earthquakes or landslides, seismic bracing and shock-absorbing mounts can reduce the risk of transformer damage. These mounts help minimize movement during seismic events, preventing mechanical failure or disconnections.
- **Fire-Resistant Materials:** In areas prone to wildfires, transformers should be made from fire-resistant materials and be housed in fireproof enclosures. These enclosures should also be equipped with fire suppression systems to mitigate the risk of fire damage.
- **Corrosion Protection:** In coastal areas vulnerable to saltwater from tsunamis or hurricanes, transformers should be treated with corrosion-resistant coatings and placed in protected enclosures to prevent degradation from salt exposure.

3.3.3. Switchgear

Hardening electrical switchgear ensures continued functionality during extreme weather events. Some of the major switchgear hardening measures are provided here.

- **Waterproof Enclosures:** To protect against flooding and tsunamis, switchgear should be housed in waterproof, sealed enclosures. These enclosures prevent water ingress that could cause short circuits or equipment failure.
- **Lightning Protection:** For areas prone to lightning, surge protection devices (SPDs) and grounding systems must be installed to safely divert the energy from lightning strikes and prevent damage to switchgear components.
- **Temperature and Pressure Resistance:** Switchgear should be designed to withstand the extreme temperatures and pressure changes caused by events such as extreme heat and high winds from hurricanes or tornadoes. Thermal insulation and pressure-rated enclosures can help ensure their functionality in adverse conditions.
- **Seismic Bracing:** Similar to transformers, switchgear in seismic regions should be equipped with seismic bracing to prevent damage during earthquakes and landslides.

3.3.4. Capacitor Banks

The durability of capacitor banks can be enhanced with the following measures:

- **Enclosed and Sealed Units:** To protect capacitors from water ingress during floods or tsunamis, they should be housed in hermetically sealed enclosures with IP-rated protection against water and dust. This is essential for preventing corrosion and electrical failures.
- **Fire-Resistant Coatings:** In areas at risk of wildfires, capacitors should be coated with fire-resistant materials and placed in fireproof housings to prevent ignition and subsequent damage.
- **Over-voltage Protection:** Capacitors should be equipped with over-voltage protection devices (e.g., varistors) to protect against lightning strikes and high-voltage transients, which can damage the capacitor and disrupt the microgrid.
- **Seismic Bracing:** Capacitors, especially those installed in seismic zones, should be secured with seismic bracing to prevent displacement or mechanical damage during earthquakes or ground shifting.

3.3.5. Circuit Breakers

Enhancing the resilience of breakers is vital for ensuring system protection during natural disasters. These hardening measures may include:

- **Weather-Proof Housing:** Outdoor breakers should be housed in weather-resistant enclosures to protect against flooding, hail, and extreme temperatures. This is crucial for maintaining their functionality during storms or severe weather.
- **Enhanced Fault Detection:** Breakers should be integrated with advanced fault detection systems that can quickly identify issues such as overcurrent, short circuits, or ground faults, allowing for faster isolation of faults and minimizing system damage during disasters.
- **Seismic Mounting:** To prevent the displacement or mechanical failure of breakers during seismic events, seismic mounting brackets should be installed to stabilize the equipment in regions susceptible to earthquakes.
- **Arc Flash Mitigation:** Implementing arc flash detection systems ensures that breakers can quickly interrupt the circuit in case of an arc fault, preventing damage from high-energy events like lightning strikes or electrical malfunctions during extreme weather.

3.3.6. Disconnects

The reliability of electrical disconnects during a disaster can be enhanced through the following upgrades:

- **Flood-Resistant Design:** Disconnects located in flood-prone areas should be elevated and placed in sealed, waterproof enclosures to prevent water ingress during flooding and tsunamis.
- **Thermal Protection:** Disconnects must be designed to endure extreme temperatures from wildfires, heat waves, and ice storms. Thermal insulation and cooling systems should be integrated to prevent overheating and ensure continued functionality.
- **Corrosion Resistance:** In coastal or high-humidity regions, corrosion-resistant materials should be used for disconnects to prevent failure due to saltwater exposure or humidity from flooding.
- **Seismic Reinforcement:** Disconnects in seismic regions should be equipped with seismic anchors and shock absorbers to minimize the risk of damage during earthquakes or landslides.

3.3.7. Hardening of Power Delivery Assets

A summary of a literature review on hardening techniques for microgrid hardware is provided in Table 3-6.

Table 3-6. Microgrid Enhancements to Hardware Infrastructure

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
Water Impacts	**Flood** (e.g., tsunami or hurricane)	• Insulate or encase cables [143] • Bury cables in conduits that are sealed against water [143]	• Implement a flood mitigation strategy that considers road access maintenance to critical infrastructure to facilitate recovery [143] • Construct power lines with minimum clearance from the ground based on local anticipated flood conditions [143]	• Use weatherproof seals and gaskets • Elevate • Install flood barriers • Anchor securely • Use watertight enclosures	• Elevate [50], [144] • Dry floodproof [50] (watertight and flood-resistant enclosure [145]) • Use marine-grade materials	• Elevate [50], [144] • Dry floodproof [50] (watertight and flood-resistant enclosure [145]) • Use marine-grade materials or coatings	• Elevate [50], [144] • Dry floodproof [50] (watertight and flood-resistant enclosure [145]) • Use circuit breakers that have electronic trip units to protect against cascading failures [146] • Use marine-grade and corrosion-resistant materials (e.g., protective polymer coatings)	• Elevate [50], [144] • Dry floodproof [50] (watertight and flood-resistant enclosure [145]) or storm-rated covers • Use stainless steel or coated materials • Use floating disconnects
Precipitation	**Solid Precipitation** (e.g., hail, sleet)	Low vulnerability	• Use underground lines in areas highly susceptible to hail to prevent weighing-down of lines and power outages [147] • Implement adequate	• Put transformers in sheltered enclosures or under protective coverings to prevent damage from mechanical impacts of	• Put switchgear in sheltered enclosures or under protective coverings to prevent damage from mechanical impacts of	• Put capacitors in sheltered enclosures or under protective coverings to prevent damage from mechanical impacts of solid precipitation	• Put breakers in NEMA-rated sheltered enclosures or under protective coverings to prevent damage from mechanical impacts of	• Put disconnect switches in sheltered enclosures or under protective coverings to prevent damage from mechanical impacts of

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
			electrical isolation to minimize outage coverage if hail impacts power lines	solid precipitation	solid precipitation		solid precipitation	solid precipitation
	Freezing Precipitation (e.g., snow, ice)	Low vulnerability	• Implement monitoring of lines in forests or areas of heavy tree cover to ensure they do not bend onto power lines during snowstorms [148] • Move overhead lines to roadsides or use wide power line corridors instead of forest [148] • Use plastic-covered conductors or aerial cables [148] • Use 1 kV system technology for rural areas [148]	• Use weatherproof seals and gaskets • Install transformer inside a protective shelter • Implement de-icing or heating mechanisms • Use insulated housing	• Put switchgear in sheltered enclosures to prevent damage from moisture impacts of freezing precipitation • Add de-icing or heating elements in enclosures • Insulate switches	• Put capacitors in sheltered enclosures to prevent damage from moisture impacts of freezing precipitation • Add heated elements in enclosures	• Put breakers in insulated and sheltered enclosures to prevent damage from moisture impacts of freezing precipitation • Add de-icing or heating mechanisms	• Put disconnect switches in sheltered enclosures to prevent damage from moisture impacts of freezing precipitation • Use insulated cables • Implement heat-tracing systems • Include de-icing or heating features
Extreme Temperature	**Extreme Heat**	• Use cable materials that allow for more efficient	• Use cable materials that allow for more efficient	• Use cooling fans, forced-oil, or air-	• Implement ventilation (passive cooling) or	• Implement airflow or ventilation	• Implement ventilation and cooling mechanisms	• Implement ventilation and active cooling mechanisms

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
		conduction of electricity in high heat environments [149] • Reduce line capacity/flow of electricity through equipment [150]	conduction of electricity in high heat environments [149] • Reduce line capacity/flow of electricity through equipment to prevent overheating and associated failures (e.g., line sagging) [150], [151]	cooled systems • Monitor and implement temperature alarms • Reduce line capacity/flow of electricity through equipment [150]	active cooling to maintain ambient operating conditions [152] • Reduce line capacity/flow of electricity through equipment [150]	• Dissipate heat via heat sinks • Use capacitors rated for high temperatures if extreme heat is anticipated • Reduce line capacity/flow of electricity through equipment [150]	• Reduce line capacity/flow of electricity through equipment [150]	• Reduce line capacity/flow of electricity through equipment [150]
	Extreme Cold	Low vulnerability	• Use underground lines to prevent accumulation of ice and snapping of lines	• Monitor and implement temperature alarms • Use insulating materials	• Use insulating materials • Implement heating elements	• Use insulating materials • Implement heating elements	• Use insulating materials • Implement heating elements	• Use insulating materials • Implement heating elements
Land and Seismic Irregularities	**Landslide / avalanche**	• Run cables through conduits to relieve pressure from cables when landslides occur	• Hardening of area (rather than infrastructure itself) against landslides via slope geometry modification, slope reinforcement via chemical agents, structural protection (e.g., piles,	• Install in secure, elevated areas with slope stabilization	• Shock absorbing mounts • Flexible connections	• Install in avalanche-proof structures • Use seismic mounting	• Elevate and secure in areas with slope stabilization • Use reinforced anchoring	• Secure on stable terrain • Protect system and surrounding area from sliding

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
			retaining walls), application of grout to rock joints/fissures, diversion of debris pathways, rerouting of drainage [153]					
	Sinkhole / karst	• Ensure the area in which the lines are buried has adequate drainage • Bury lines deeper in areas where sinkholes are common or anticipated • Implement monitoring and alarm devices to be aware of sinkhole condition formation	• Remediation of sinkholes that might occur (e.g., filling of sinkhole with stone, gravel, and clay/sand layers) [154] • Compact grouting of soil around the power line poles [154]	• Relocate to stable areas • Reinforce foundations	• Relocate to stable ground • Reinforce structures	• Place in stable areas • Avoid risk zones	• Relocate to stable ground • Reinforce with deeper foundations	• Relocate to stable ground • Reinforce foundations
	Earthquake	• Use insulation material with better seismic performance (e.g., cross-linked polyethylene instead of paper-insulated lead covered	• Use underground lines to minimize earthquake damage [156]	• Use seismically qualified components, including support structure, conservator, tank, bushing, lightning arrestor, radiator, cable	• Securely mount and/or fasten the capacitor to minimize movement • Use seismic-rated designs • Use flexible connections	• Use earthquake-proof supports • Use shock absorbers	• Install using seismic-rated fasteners • Use flexible mounts	• Use seismic-rated flexible connections

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
		armored cables) [155]		box, core, and coil [157] • Use shock-absorbing mounts				
Fire and Air Contamination	**Volcanic Eruption**	Low vulnerability	• Use polymer/non-ceramic line insulators to effectively shed ash [158] • Use anti-pollution line insulator designs [158] • Orient line insulator strings non-vertically [158]	• Paint transformer with anti-corrosive material • Use ash-resistant enclosures and install air filters to prevent ash ingress • Clean after eruption events	• Seal cable penetrations with fire resistant material [159] • Install in reinforced enclosures • Use materials with resistance / tolerance to high temperatures • Implement ash filtration systems •	• Use coatings to seal the capacitor against the ingress of dust/ash • Use heat-resistant coatings • Use volcanic gas-resistant seals • Put capacitors in sheltered enclosures	• Install in sealed lava- and ash-proof enclosures • Use temperature-resistant insulation • Use dust-sealed contactors	• Install in sealed, dust-resistant enclosures • Use elevated or buried designs • Use ash-resistant contact surfaces
	Wildfire	Low vulnerability	• Maintain right-of-way for power lines in forests to reduce possibility of tree impacts on power line [148], especially in wildfire incidents • Move overhead lines to roadsides instead of forest [148]	• Fire walls [160] or fireproof casings • Appropriate separation / setback distances from exposures [160] (e.g., regularly clear vegetation near the system) • Water spray system [161] • Implement remote	• Seal cable penetrations with fire resistant material [159] • Use fire-resistant materials • Clear vegetation near the system	• Put capacitors in sheltered enclosures to protect against the ingress of dust/ash/soot/ smoke • Clear vegetation near the system	• Use fireproof enclosures • Clear vegetation near the system	• Use fireproof enclosures • Clear vegetation near the system

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
			• Use metal (e.g., steel, ductile iron) for power line poles	sensors and alarms for temperature, oil level and pressure				
Wind	**High Wind** (e.g., hurricane, tornado	Low vulnerability	• Implement monitoring of lines in forests or areas of heavy tree cover to ensure they do not bend onto power lines during high winds [148] • Move overhead lines to roadsides or use wide power line corridors instead of forest [148] • Use underground lines to prevent snapping of lines	• Paint transformer with anti-corrosive material • Anchor to stable foundations • Install underground	• Mount/anchor securely • Install underground • Use storm-rated switchgear	• Mount/anchor securely • Install underground or in reinforced cabinets	• Mount/anchor securely • Install underground	• Mount/anchor secure • Install underground or in storm-rated housing
Other	**Hurricane**	• Use protective, waterproof conduits for buried cables to prevent water damage	• Reinforce power line poles with guy wire • Use metal (e.g., steel, ductile iron) for power line poles • Replace old poles with new	• Use moisture absorbers like silica gels • Implement remote sensors and alarms for temperature, oil level and pressure	• Use storm-rated equipment • Anchor to stable foundations • Install in storm-rated housing • Implement environmental	• Use storm-rated equipment • Anchor to stable foundations • Install in storm-rated housing	• Use storm-rated equipment • Anchor to stable foundations • Install in storm-rated housing	• Use storm-rated equipment • Anchor to stable foundations • Install in storm-rated housing

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
			ones to prevent damage to weak poles from high wind conditions [162] • Add redundant power lines with open switches [162] • Create protocols for pre- and post-storm inspections of lines to ensure that any wire damage / fire hazards are addressed as soon as possible • Ensure adequate vegetation maintenance around power lines [14], [119] • If building new overhead power lines and power pole locations, ensure that placement is in easy-to-access locations for maintenance	• Anchor to stable foundations • Install in storm-rated housing	(temperature and humidity) controls			

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
			and repair (e.g., not highly vegetated) • Use underground lines [14]					
	Lightning	• Use shield wire to share the overcurrent from lightning strikes [163]	• Use parallel protection (i.e., parallel-connected gas tubes and metal oxide varistors) to short-circuit high-voltage surges • Use a protective, high-impedance coil to prevent the passage of lightning to the lines and short-circuit the voltage to ground • Use ground wires/rods in strategically-places angles to protect power lines from lightning impacts	• Lightning protection system to prevent ignition [164]	• Use passive lightning shielding system (e.g., shield wires, down conductors, lightning/ surge arresters) [165] • Use lightning rods to redirect lightning • Use surge protection • Use arc-resistant switchgear • Insulate bus bars	• Use surge protection devices (e.g., varistors, transient voltage suppressors) to minimize the impacts of voltage surges • Implement overvoltage protection devices • Implement electromagnetic interference shielding devices	• Use surge protection • Mitigate arc flashes • Use high-speed reclosers • Implement shielded control circuits	• Use surge protection circuits • Install insulated grounding systems • Use Faraday cage protection
	Drought	Low vulnerability	• Use underground lines	• Enclose in sheltered housing to prevent dust accumulation	• Enclose in sheltered housing to prevent dust accumulation	• Enclose in sheltered housing to prevent dust accumulation	• Enclose in sheltered housing to prevent dust accumulation	• Enclose in sheltered housing to prevent dust accumulation

CATEGORY	CONDITION	LOCAL DISTRIBUTION SYSTEM			INTERCONNECTION AND INTERACTION			
		UNDERGROUND CABLES	OVERHEAD POWER LINES	TRANSFORMERS	SWITCHGEAR	CAPACITORS	BREAKERS	DISCONNECTS
			• Seal cables against dust ingress					

3.4. Sensing, Controls, and Communication

This section focuses on upgrades to control systems, sensing technologies, and communication networks that enhance microgrid resilience to natural disasters. Wireless communication networks, particularly using 5G technology, are increasingly seen as a solution to ensure reliable communication during grid failures. In addition, mesh networks can provide a decentralized communication system that remains operational even if one node fails.

3.4.1. Sensing

Upgrades include:

- **Environmental Sensors:** Deploying weather stations, seismic sensors, and air quality monitors provides data on wind speed, temperature, ashfall, and ground vibrations. These sensors enable early detection of natural disasters, such as hurricanes, earthquakes, and volcanic eruptions, and facilitate proactive adjustments to system operation.
- **Structural Health Monitoring:** Implementing sensors on critical infrastructure (e.g., solar panels, wind turbines, energy storage systems) to measure stress, temperature, vibration, and other parameters. Structural monitoring systems help identify potential failures due to extreme weather conditions or seismic activity, preventing damage and optimizing maintenance schedules.
- **Grid Condition Monitoring:** Voltage, current, and frequency sensors enable real-time monitoring of grid conditions and the detection of faults or anomalies that may arise due to damage from natural disasters. Enhanced monitoring ensures that the microgrid can adjust its generation and distribution accordingly and maintain stable power delivery.
- **Advanced Battery Management Systems:** The use of smart sensors for battery temperature, charge, and voltage monitoring enables better performance in extreme temperature fluctuations, helping prevent thermal runaway or battery failure during high heat or cold caused by disasters like wildfires or extreme cold waves.

3.4.2. Controls

Upgrades for controls and EMS include:

- **Distributed and Decentralized Control Architecture:** Implementing multi-agent systems or distributed control systems ensures that individual controllers can operate autonomously during communication outages or failures. This helps maintain grid stability even when part of the system is offline due to natural disasters.
- **Seamless Integration with DERs:** Enhance control algorithms to dynamically adjust power flow, optimize load balancing, and improve resource dispatch during power outages. This integration ensures that the microgrid continues to operate even when some generation assets are offline due to environmental impacts.
- **Advanced Predictive Algorithms:** Implementing advanced algorithms that can predict demand surges and generation downtimes helps the control system proactively adjust settings and ensure efficient operation before disasters strike. These algorithms can process data from weather forecasts and sensor inputs to anticipate changes in load and generation.
- **Real-Time Fault Detection and Response:** Enhancing the system with fault detection and isolation techniques allows for faster identification of faulty components, reducing downtime and improving system recovery times after a disaster. This also includes implementing automatic reconfiguration strategies, such as self-healing capabilities, to restore power to critical loads swiftly.

3.4.3. *Communication*

Upgrades to communication systems are critical for ensuring that control systems can maintain effective oversight of microgrid components, even in the event of infrastructure damage:

- **Resilient and Redundant Communication Networks:** Implementing mesh networks and satellite communication systems provides multiple communication paths, ensuring that the microgrid can remain operational even if terrestrial networks fail. This is particularly important during hurricanes, earthquakes, and wildfires, where infrastructure damage is common.
- **Data Encryption and Security:** Enhancing cybersecurity measures with end-to-end encryption and secure protocols protects communication networks from malicious attacks or interference during a disaster. Ensuring the integrity and confidentiality of data is crucial when managing critical infrastructure under stress.
- **Real-Time Data Transmission and Remote Control:** Upgrading to 5G or fiber-optic communication ensures fast, high-bandwidth, low-latency communication between DERs, control centers, and sensors [166]. This allows for better real-time monitoring, control, and reconfiguration of the microgrid in response to natural disaster events.

Table 3-7. Microgrid Enhancements to Sensors, Controls, and Communications

Natural Disasters	Sensors	Controls and Control System (Energy Management System)	Communications
Flood	Waterproof sensors and sealed connectors	Waterproof and sealed enclosures	Waterproof equipment, enclosures, elevated communication, redundancy in communication paths
Hail	Hail-resistant covers or relocate	Reinforce against physical damage from hail	Impact resistant casing, hail resistant antennas and dishes, protective enclosures
Freezing Rain	Heating elements and insulated components	Cold-resistant materials and insulated cables	Heating, de-icing and anti-frost materials, re-enforced structure
Hurricane	Storm-resistant, hardened housings	Hardened, stormproof buildings	Wind resistant towers, flood protection enclosures
High Wind	Wind-proof designs or protective covers	Indoors or shield against high winds	Wind resistant equipment, maintenance/inspection, secure/anchored connections
Wildfire	Fireproof housings and clear vegetation	Fireproof buildings or structures	Fire-Resistant Materials, Remote Sensing and Monitoring
Snow	Heated, insulated sensor designs	Cold-resistant housing and insulation	Snow-Resistant Materials, Heating Elements, Regular Maintenance
Ice Storm	Cold-resistant sensors and storm-rated designs	Insulated and storm-resistant designs	Ice-Resistant Coatings, Reinforced Infrastructure, backup power
Extreme Heat	Heat-resistant, ventilated housings	Temperature-regulated or cooled enclosures	Heat-resistant equipment, cooling systems, shading and insulation
Extreme Cold	Cold-resistant designs and housings	Insulation for EMS devices and connections	Temperature resistant materials, heaters, and insulations.
Tornado	Wind-rated, hardened sensors	Indoors or underground in secure structures	Wind resistant infrastructure, underground communication cables, emergency communication systems
Sinkhole	Relocate to stable, non-risk areas	Install in geologically stable areas	Sturdy foundation, redundant communication
Earthquake	Shock-absorbing mounts for seismic resilience	Seismic-rated, shock-absorbent mounting, decentralized architectures, multi-agent systems for autonomous operation	Seismic-resilient infrastructures (e.g., shock-resistant designs)

Landslide/Avalanche	Install on stable, reinforced structures or areas away from avalanche risks	Place in hardened, elevated locations away from slopes	Land slide resistant towers, shelters, monitoring
Lightning	Lightning protection systems, surge protection, shielding, grounding	Surge Protection, fault detection, adaptive controls	Lighting protection systems, lightning rods, and lightning shields
Tsunami	Waterproof enclosures, elevated placement, corrosion resistance	Remote sensing, mapping tools to reroute power	Elevated communication equipment, waterproof enclosures, backup communication
Volcano	Ash resistance, high temperature resistance, redundant sensor placement, wireless and remote sensing	Ashfall monitoring, impact prediction/modelling, air quality sensors, protective shutdown	Ash resistant coating, alternative communication system
Drought	Enclosed/sheltered housing	Humidity-controlled enclosed/sheltered housing	Enclosed/sheltered housing

4. MICROGRID HARDENING FRAMEWORK APPLICATION

The framework described in Section 2.1 for qualitative assessment of microgrid risk from natural disasters and extreme weather events, as well as the microgrid mitigation strategy evaluation, was implemented in a Python-based executable application developed by Sandia National Laboratories called the Microgrid Hardening Design Toolkit (v0.22) [167]. Currently, the tool includes the analyses described in Section 2.1.1 and Section 2.1.2, which are focused on identifying potential natural hazards to energy systems and ranking and characterizing their risk in order to identify important mitigations; the mitigation prioritization decision framework was not included in this version of the tool. The definitions and data we used for the likelihood, detectability, and severity rankings to use for characterization of overall risk are described in the following sections. The risk of interest was the risk of interruptions or disturbances in electrical service.

4.1. Risk Index Values

Defining the risk index for the Microgrid Hardening Design Toolkit software required selection of a dataset with geographic diversity across the U.S. and U.S. territories, as well as extensive data for various types of natural hazards. Using a single dataset was ideal, since an established dataset would not require normalization or other types of data processing to be able to make comparisons between locations, hazard types, and microgrid equipment.

The FEMA National Risk Index (NRI) dataset provides a metric called "Expected Annual Loss," (EAL) which is a measure of the economic loss experienced by a geographic location due to the product of the frequency of the natural hazard, the community's exposure to the hazard in terms of three different consequence types (building, population, and agriculture impacts), and the historical loss ratio. The expected annual loss, which is taken from Equation 21 in [168], is provided here:

$$\boldsymbol{Expected\ Annual\ Loss}_{Hazard\ Type_{Consequence\ Type}} = \boldsymbol{Exposure}_{Hazard\ Type_{Consequence\ Type}} \times \boldsymbol{Annualized\ Frequency}_{Hazard\ Type} \times \boldsymbol{Historic\ Loss\ Ratio}_{Hazard\ Type_{Consequence\ Type}} \quad [4]$$

FEMA provides the EAL dataset for the U.S. and U.S. territories. Although it is normalized to 100 rather than a scale of 1-3, as discussed in the framework in Section 2.1, it is an appropriate proxy for the Risk Index described in this report because it contains a likelihood factor (annualized frequency) and a severity factor (both exposure and historic loss ratio are a measure of severity). While there is no explicit factor in EAL that maps directly to detectability in the framework described in Section 2.1 of this report, the detectability is somewhat incorporated, under the assumption that earlier detection of damage or even forecasting of the natural hazard beforehand would lead to appropriate preparation and pro-active damage prevention. This assumption is not perfect because decision-making and action is not only dependent on detection of a hazard before it occurs – it also depends on cost, time, labor availability, etc. – but the EAL factors together do provide a general appropriate proxy for Risk Index through direct or indirect incorporation of likelihood, severity, and detectability. It also provides an example of the types of data that can be practically observed and collected (e.g., detectability and severity, or other combinations of the factors in the risk index, may not be available as completely independent observations).

It should be noted that more specific information about specific microgrid equipment and system impacts from different natural hazards would help improve the application of this framework. However, a sufficient quantity of data, both temporally and across different hazards and equipment types, would be needed, and more in-depth fragility analyses and data processing would be needed to standardize these data for use in the framework. At the time of publication of this report, to the knowledge of the authors, this type of dataset was not found. Thus, the types of damage described by the EAL (building, population, and agricultural impacts) are used as a proxy for the risks posed by natural hazards on energy infrastructure such as microgrid equipment.

4.2. Mitigation Strategies and Prioritization

The current version of Microgrid Hardening Design Toolkit (v0.22) provides mitigation strategies, but data on effectiveness cost was not yet found to support the prioritization aspect of the framework.

3. CONCLUSION

As the frequency and intensity of natural disasters increases, the resilience of microgrids has become a crucial aspect of energy system planning and development. While microgrids offer a decentralized and flexible approach to power generation and distribution, they remain vulnerable to various natural hazards, including hurricanes, earthquakes, wildfires, floods, ice storms, tsunamis, landslides, and volcanic eruptions. These disasters can severely impact critical microgrid components such as energy generation sources, energy storage systems, communication networks, and control infrastructure. Without proper mitigation strategies, natural disasters can lead to widespread power disruptions, equipment failures, and long-term degradation of microgrid performance.

Enhancing microgrid resilience requires a multi-dimensional approach that incorporates robust infrastructure design, advanced control strategies, and proactive disaster response mechanisms. Physical reinforcements, such as underground power lines, storm-resistant solar panel mounts, and fireproof enclosures for energy storage, can mitigate structural damage from extreme weather events. Additionally, integrating real-time monitoring systems, predictive analytics, and adaptive protection schemes allows microgrids to anticipate and respond dynamically to disruptions. Hybrid energy systems, incorporating diverse generation sources such as solar, wind, and diesel backup generators, further enhance energy reliability by providing redundancy in case of generation losses.

Beyond technological advancements, policy frameworks and investment strategies play a critical role in strengthening microgrid resilience. Governments, utilities, and private stakeholders must collaborate to establish disaster preparedness protocols, incentivize resilient microgrid designs, and ensure that critical infrastructure remains operational during emergencies. Community-based microgrid initiatives, particularly in disaster-prone regions, can provide localized energy security, reducing dependence on centralized grids that may be vulnerable to large-scale outages.

Microgrid resilience depends on the integration of preventive solutions, real-time intelligence, and proactive risk management. By leveraging innovations in DERs, smart grid technologies, and advanced forecasting models, microgrids can be transformed into highly adaptive and self-healing energy systems capable of withstanding even the most severe natural disasters. Moving forward, continued research, investment, and collaboration will be essential to ensuring that microgrids not only survive extreme events but also play a pivotal role in accelerating the transition toward a more sustainable and disaster-resilient energy future.

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APPENDIX A. REGIONAL EXAMPLES OF NATURAL HAZARD IMPACTS

The following table summarizes examples of regional considerations for applying the described risk framework, although these qualitative examples are on a larger geographic scale than those displayed in the Microgrid Hardening Design Toolkit which calculates Risk Index at the level of census tracts.

Table A-1: Regional Natural Disaster Examples

Region	Disaster	Description
Puerto Rico	Hurricanes	Due to its Caribbean location, Puerto Rico is highly susceptible to hurricanes, which can cause severe damage to microgrid infrastructure [169]. On September 20, 2017, Hurricane Maria, a Category 4 storm, devastated Puerto Rico, causing the largest blackout in U.S. history and the second-longest power outage worldwide. Winds exceeding 155 mph knocked down 80% of transmission lines, and the island's power grid collapsed completely. Over 3.4 million residents were left without electricity, with restoration efforts taking nearly 11 months in some areas.
Alaska	Earthquakes	Alaska experiences frequent and strong earthquakes, posing significant risks to energy systems [170]. On November 30, 2018, a magnitude 7.1 earthquake struck near Anchorage, Alaska. The quake caused widespread power outages, damaging transformers and transmission lines. Despite Alaska's robust seismic engineering standards, the earthquake disrupted more than 50,000 customers' power supply, requiring extensive grid restoration efforts.
California	Wildfires	California's dry climate and vegetation make it prone to wildfires that can devastate power grids [171], [172]. The Camp Fire in November 2018 became California's deadliest and most destructive wildfire, destroying over 18,000 structures and killing 85 people. Pacific Gas & Electric (PG&E) admitted their equipment sparked the fire. The blaze led to massive rolling blackouts as PG&E preemptively de-energized power lines to prevent further fires. Nearly 700,000 customers were affected by planned shutoffs.
Oklahoma	Tornadoes	Oklahoma faces a high likelihood of tornadoes impacting infrastructure [173]. On May 20, 2013, an EF5 tornado tore through Moore, Oklahoma, with winds reaching 210 mph. The tornado flattened entire neighborhoods and caused extensive power infrastructure damage, leaving over 61,500 residents without power. Substations, transmission lines, and distribution poles were destroyed. The disaster underscored the vulnerability of overhead power lines in tornado-prone regions, reinforcing the argument for undergrounding power cables.
Louisiana	Floods	Low-lying areas and proximity to water bodies increase Louisiana's flood risk, affecting energy systems [174], [173]. Hurricane Katrina made landfall on August 29, 2005, as a Category 3 storm, overwhelming Louisiana's levees and flooding 80% of New Orleans. The power grid suffered catastrophic failure, leaving over 1.7 million customers without electricity across multiple states. Floodwaters submerged substations and transformers, rendering them inoperable for weeks. Diesel shortages further complicated generator use.
Minnesota	Snowstorms	Frequent heavy snowfall can disrupt power distribution and damage equipment [175]. Minnesota's infamous Halloween Blizzard of October 31 - November 3, 1991, dumped over 28 inches of snow in Minneapolis, with ice accumulation toppling power lines. The storm caused over 100,000 power outages, with many lasting days in subzero temperatures. Ice buildup on transmission infrastructure led to structural failures.
Washington State	Landslides	Hilly terrains and heavy rainfall contribute to landslide risks, threatening infrastructure stability [176]. On March 22, 2014, a massive landslide in Oso, Washington, destroyed homes and buried a portion of State Route 530, killing 43 people. The landslide took down power lines and cut off electricity to over 1,600 residents in the surrounding areas. The incident emphasized the risk of unstable terrain to power infrastructure and transmission corridors.

Region	Disaster	Description
Arizona	Droughts	Arid conditions lead to droughts, impacting water-dependent energy generation [177]. The 2020-2022 Western U.S. Megadrought was one of the worst in 1,200 years, heavily impacting Arizona's hydroelectric generation. With Lake Mead and Lake Powell at record-low levels, hydropower generation at Hoover Dam dropped by nearly 25%, affecting electricity supply across multiple states.
Hawaii	Volcanic Eruptions	Active volcanoes pose eruption risks, endangering nearby power grids [178], [179]. Hawaii's Kilauea volcano erupted in May 2018, destroying over 700 homes and severing power lines in affected areas. Lava flows damaged transmission infrastructure, cutting power to thousands of residents. Microgrids on Hawaii's Big Island helped maintain power in unaffected areas, proving the benefits of localized, resilient energy systems in volcanic regions.
Oregon Coast	Tsunamis	Coastal areas are vulnerable to tsunamis, which can inundate and damage energy infrastructure [180]. Though originating in Japan, the 2011 Tōhoku Earthquake and Tsunami sent waves reaching the Oregon Coast, damaging ports and causing localized flooding. While not as severe as in Japan, the event served as a wake-up call for tsunami vulnerability in the Pacific Northwest, where coastal power infrastructure remains at risk.

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