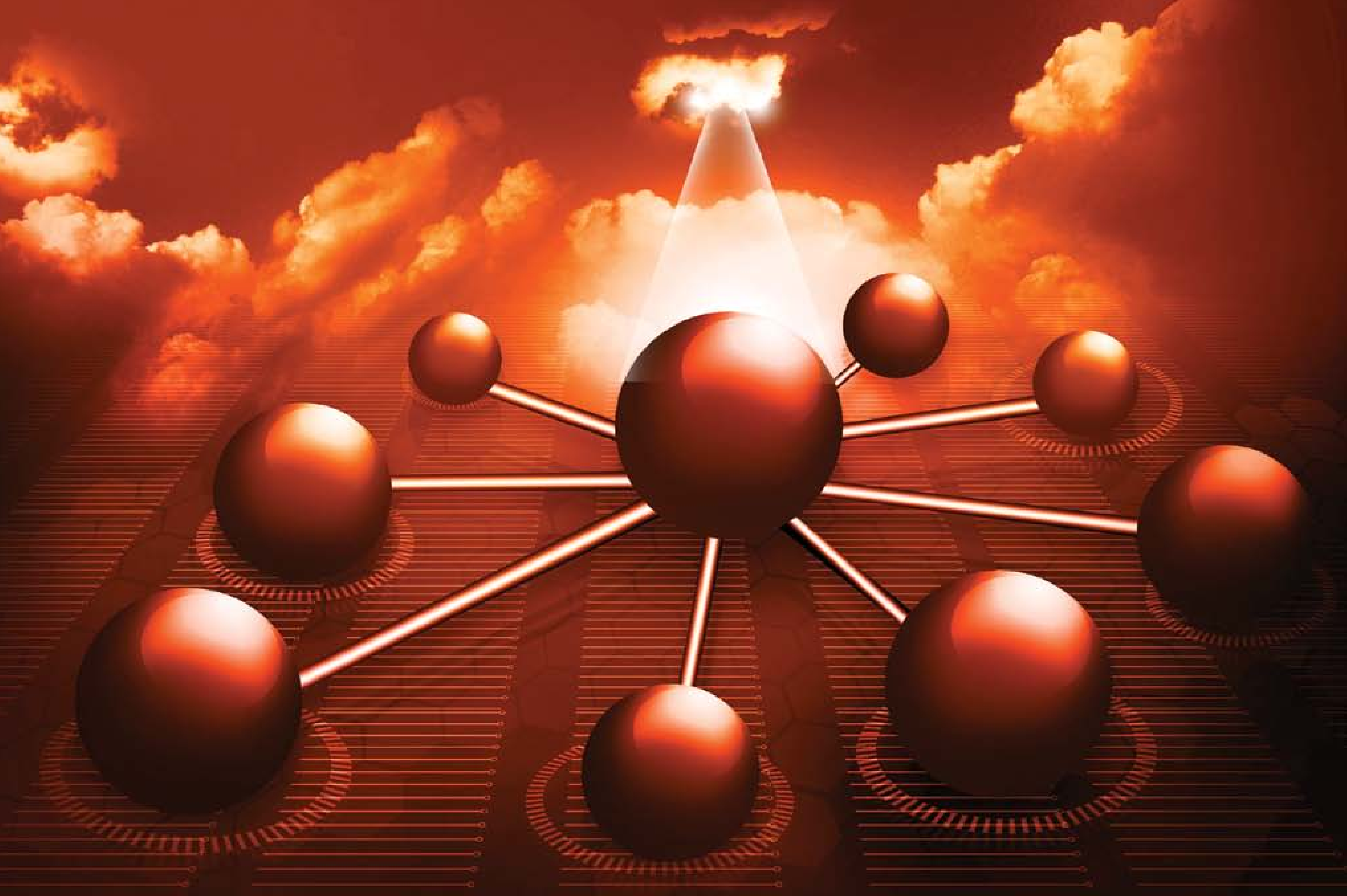


How Reliable Is Your Microgrid?

An insurer's perspective on risk drivers for distributed resources.

By Richard B. Jones, Ph.D.

For microgrid owners and operators today, there are insurers who will cover losses for some types of equipment and systems. But there is currently no insurance product that will cover the performance of the entire microgrid.

That suggests a need to uncover and pinpoint some of the complexities associated with the resilience of microgrids and distributed generation – ***from an insurer's perspective***.

This work will identify and quantify risks for microgrids and distributed generation, as may be associated with product design parameters, long-term maintenance strategies, and weather-induced outages occurring on the local utility system. Also, it will demonstrate some important resilience metrics as key underwriting variables for performance-based insurance of distributed generation and microgrid installations.

For our purposes, we can define distributed generation as electric power generation within distribution networks or on the customer side of the utility supplied network.[1] We can define a microgrid as a group of interconnected loads and distributed generation resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid – an entity that can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.[2]

And with the proliferation of renewable energy technologies and the increase in weather-related outages, these two types of power supply models are being applied in new and retrofit construction projects to improve consumer power reliability with fiscally viable business models. Since distributed generation is a hierarchal subset of microgrid operations, in this work, for brevity, the word microgrid refers to both power supply models. The findings of this research apply to both models.

Power reliability marks another variable in the analysis, and can be interpreted as a dependable resource available to reduce utility loads during high usage periods, or as a local backup source when the utility fails to meet its load requirements. However, the simplicity of these objectives is not necessarily simple to achieve in practice. In fact, the actions taken to ensure or insure these results can be extremely complex.

By the end of this analysis, we'll see that the reliability profile of the local utility will prove to be a critical element in designing a microgrid and a strategy for its upkeep and maintenance to ensure that it will operate as expected over its effective service life. Yet one cannot choose an optimal microgrid design or maintenance strategy simply by reference to the performance risk analysis given here. Rather the costs of various operation options must be compared to the potential for risk reduction, in order to yield a financial measure, such as percentage of risk reduction per dollar of expense or investment.

There is no insurance product today that covers an entire microgrid.

1. Navigant Consulting Inc. Final Report Microgrids Research Assessment for the US Department of Energy's Office of Electricity Delivery and Energy Reliability and the California Energy Commission's Public Interest Energy Research Program, May 2006.
2. 2015 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE – As of February 2015.

Richard B. Jones is senior vice president for research and engineering at The Hartford Steam Boiler Inspection and Insurance Company, Hartford, Conn., where he is responsible for the development and application of new insurance products and services for renewables and other energy resources. His work involves developing risk-based methods for insuring minimum levels of system performance. He holds a Ph.D in nuclear science and engineering from Virginia Tech.

The Utility Reliability Profile

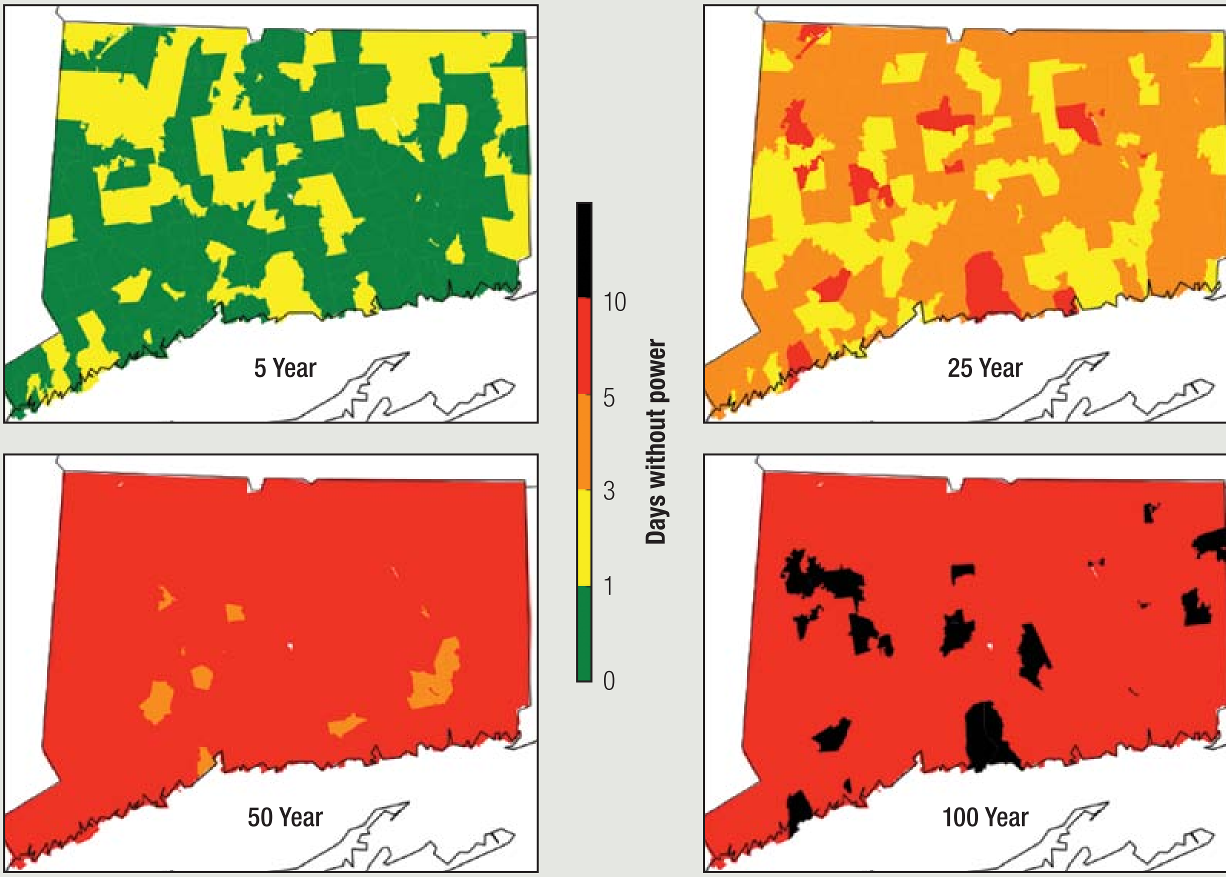
A preliminary step in microgrid design is developing the utility reliability profile for each connected facility. This profile details grid resilience: the frequency and severity of outages from specific threats or risk exposures.

And any risk analysis for microgrid reliability should address issues that are similar to standard risk exposures for property or casualty insurance, or for insurance for equipment breakdown. These classical insurances are designed to indemnify an insured in the event of a covered loss. Injuries, lightning strikes, equipment failures, for example, and the resulting loss of business are included in these types of coverages. However, the risk methodologies applied to microgrid reliability are designed not to indemnify failure, but to insure success as measured by a desired level of performance. So while microgrid owners, operators, and their insurers cover some equipment and systems for losses, there currently is no insurance product that covers the performance of the entire microgrid.

The risk analysis basics are the same for both approaches, with the differences arising in how they are applied to quantify

FEA. 1A **BLACKOUT RISK FOR CONNECTICUT SUMMER STORMS**

Outage risk from summer storms.



the risk being modeled. For the purpose of this discussion, microgrid reliability will be addressed for island or emergency mode operations where the primary utility supply has been cut off. In this manner, the microgrid must respond to the loss of external power and continue to operate at its designed load levels until the utility supply can be restored. This could be just minutes, hours, or in severe situations, several days.

The frequency and severity of island mode operations is given by the external grid reliability profile. This data contains historical utility outages and possible scenarios that could arise from location-specific threats. These events include weather, operator errors, transmission disruptions, or power generation failures. The events could occur several miles from the microgrid location or from local storms that include the microgrid environment as part of the affected weather area.

Understanding the scenarios that would place the microgrid in emergency mode, plus the threats under which the microgrid needs to function, comprise essential elements in the design and risk analysis process. For illustration of the methods used to model these risk exposures, we consider the state of Connecticut as the region for which we are planning to construct microgrid projects.

For this exercise, we examine weather threats that would cause power outages requiring a microgrid to operate in island mode. Local historical power supply reliability data are not included in this work simply because this information is site-specific.

Weather Risk Exposures

To demonstrate the weather risk exposure analysis, we assume that the location for the proposed microgrid is in Southern Connecticut. This region represents a rich collection of weather risk exposures, since power outages caused by wind, rain, snow, and ice are prevalent in Southern New England.[3, 4]

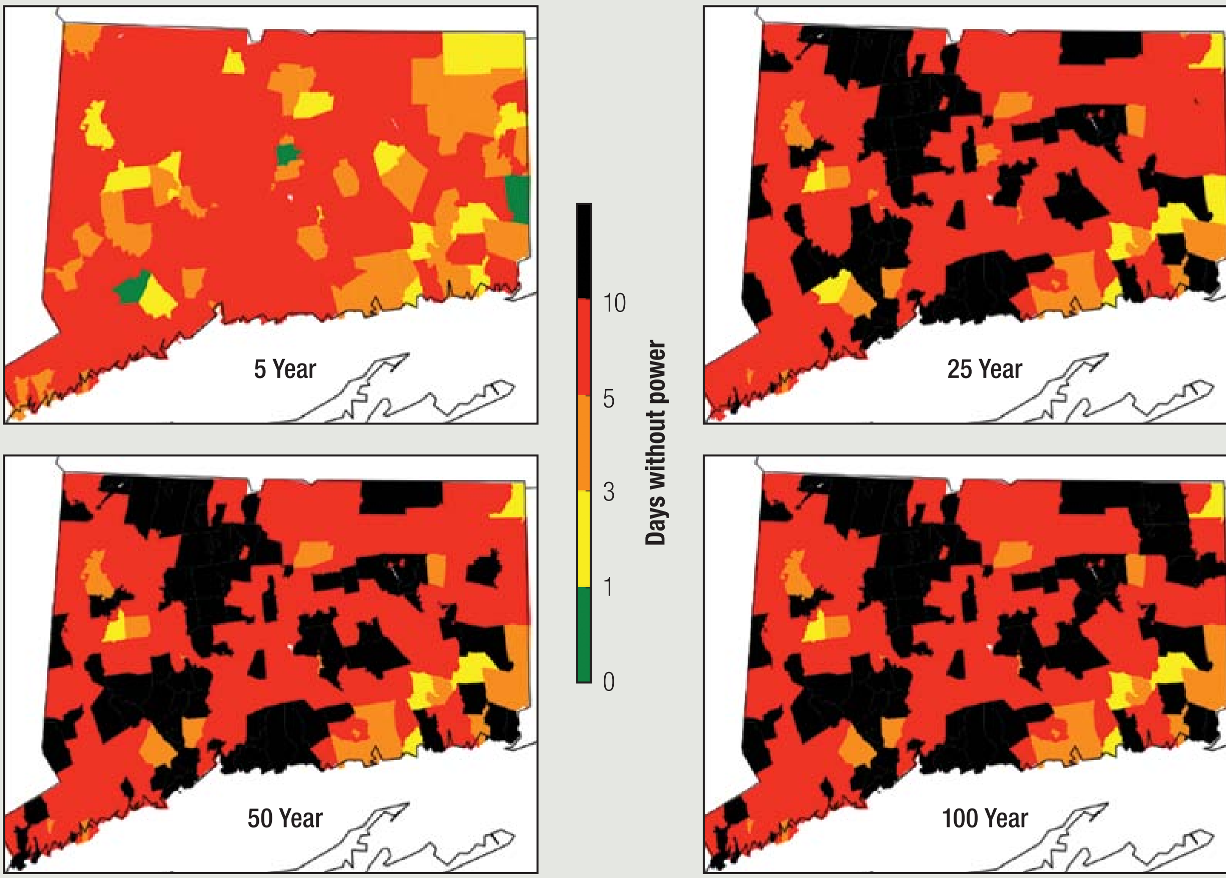
To examine the influence of weather threats on power reliability risks for this region, we utilize the Blackout Risk Model™ developed jointly by my company, Hartford Steam

---

3. IEEE Std 493-1997 - IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (Gold Book), Issue Date: June 25, 2007.
4. Additional power interruption grid exposures come from sources ranging from car accidents with electric poles, transmission failures, grid operator errors, and terrorism scenarios. These exposures would be analyzed in separate risk analyses.

FEA. 1B **BLACKOUT RISK FOR CONNECTICUT WINTER STORMS**

Outage risk from winter storms.



Boiler Inspection and Insurance Co. (HSB), and by Atmospheric and Environmental Research (AER), a unit of Verisk Climate. The new modeling technology integrates a database of possible weather conditions, satellite analysis of trees near distribution lines, proprietary knowledge of the electrical grid infrastructure, and detailed economic data. The model focuses on the U.S. power grid and incorporates extensive empirical and statistically generated data on four peril categories: hurricanes, winter storms, thunderstorms, and equipment or operator error.

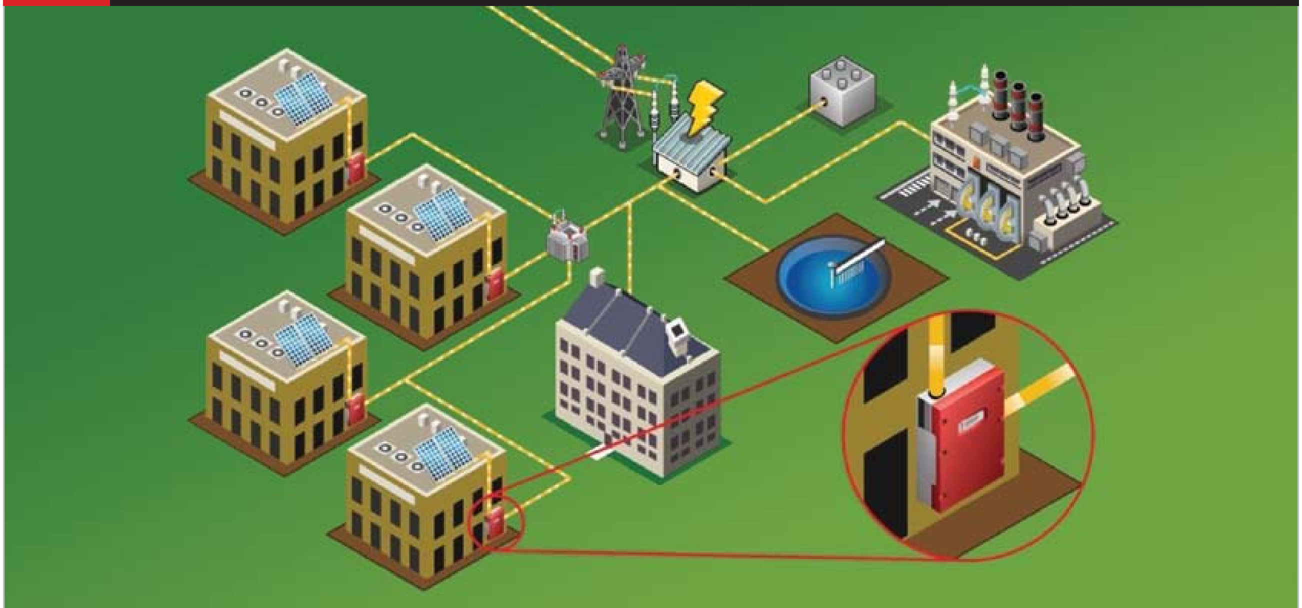
More than 95,000 actual and potential hurricane events, 68,000 winter storms, and 400,000 severe convective storms (tornados and thunderstorms) have been included in the analysis. The model's infrastructure contains more than 11,000 power plants, 64,000 substations, and 737,000 miles of transmission lines in the U.S. and Canada. The model also incorporates a U.S. country-wide, population-weighted, tree density model that accounts for the proximity of trees to power lines. Estimation of tree cover uses proprietary algorithms based on satellite data, vegetation type, and density information. Also 12,000 key substations have been classified through detailed satellite data analysis, engineering review, and/or visual inspections. Power flows of the U.S. grid are simulated down to the local substation level.

Applying the Blackout Risk Model to the state of Connecticut for winter and summer storms, we see in *Figure 1* the difference in geographic electrical power grid restoration times as a function of storm severity, as measured by "return period" and also by the type of storm. The blackout coverage areas are for zip code regions and outage durations are computed at the 75th percentile, signifying that at least 75 percent of the electrical customers in a zip code will have an outage of the following indicated durations: <1 day, 1-3 days, 3-5 days, 5-10 days, or 10+ days.

These plots display a large amount of information very succinctly, providing state planners, investors, and developers with detailed data on the areas that are either more or less susceptible to weather induced electrical blackouts. This information is important to microgrid designers also for project justification and to help determine the performance requirements for specific weather threats to ensure (and insure) reliable island mode operations for emergency situations.

Figure 1 shows that for Connecticut, winter storms have a significantly greater influence on blackout frequency and severity than summer storms. That is due in part to the high density of

FIG. 2 **A REPRESENTATIVE MICROGRID LAYOUT**



This example contains 4 rooftop solar PV systems (left side), battery storage, and a gas-fired turbine co-generation unit (far upper right).

trees in close proximity to transmission lines, the regional tree types, and that snow and ice storms generally have a larger area of influence than hurricanes.

Microgrid Configuration

Microgrid designs are highly dependent on their intended purpose, yet there are some basic attributes of their performance risk that can be identified from the illustration in *Figure 2,* which shows a representative microgrid configuration. This example contains 4 rooftop solar PV systems, battery storage, and a gas-fired turbine co-generation station as generation nodes. Load requirements are for a school, depicted as four small office-type buildings, a waste water treatment facility, and a large office building.

Microgrid performance risk is analyzed solely in island mode, where the utility feed has been interrupted. The rooftop PV units are designed to provide the required load for local building only. No cross-feed capabilities are considered. The battery storage unit and the gas turbine generator can each supply all of the required loads, with the exception of the battery storage system's limited supply duration.

In addition, however, the microgrid's island-mode performance needs to be studied for each interruption risk exposure, since the component failure frequencies and outage durations can be influenced by the threat type. For example, the outage characteristics that stem from a hurricane are different than for an outage caused by an ice storm, as indicated visually in *Figure 1.* For demonstration purposes, we will analyze microgrid island mode performance risk for summer weather exposures.

The primary performance risk variable for this model is total lost operational time (measured in hours) from equipment failures during island-mode operations. The resulting instances of lost load (measured in kWh) are easily calculated for the microgrid components, and since the individual load requirements are known, financial losses from each load loss can also be computed. However, since this configuration is solely illustrative, specific conclusions from these results are not relevant for this discussion.

Risk analysis as applied to microgrids is designed not to indemnify failure, but to insure performance.

The loss-of-load failure modes for each facility are modeled using standard reliability engineering techniques, taking into consideration the layout as shown in *Figure 2.* For the purpose of this analysis, electronic load control failures are not included, since these types of events (while extremely important) can be considered as a separate category of exposure compared to equipment failures from internal or external causes. *Figure 3* shows the types of equipment contained in the microgrid for which the model will analyze repair and restoration times.

Probabilities of Equipment Failure

Failure frequencies for the electrical components are computed from claims and exposure data compiled by HSB for the period 2008-2013. Since the type of equipment use and application can significantly influence failure probabilities, we compiled data only from the various occupancies (such as office building owners and tenants – see *Figure 4* for full list) that would reflect

FIG. 3 MICROGRID EQUIPMENT

Distribution Components
Small Circuit Breakers
Medium & Large Switchgear Breakers
Distribution Panels
Underground Cables
Building Transformers
Modeled Power Sources
Photo Voltaic Panels & Inverters
Gas Turbine Generator
Battery Storage System

FIG. 4 CUSTOMER PROFILES

Occupancies with Risk Exposure
Office Building, Owners & Tenants
Dwellings / Single and Multi-Family
Dwellings / Seasonal / Rental Vacation
Apartment Bldgs/Condominium Assoc.
Prisons / Criminal Detention Facilities
Shelters, Mens/Womens
Schools, Not Colleges
Colleges & Universities
Dry Cleaning, Laundries & Clothes Dying
Churches
Places of Public Assembly, *e.g.*, city hall
Industrial Buildings, Owner
Airline, Bus, Railroad Terminals
Marinas
Shopping Centers, Malls & Strip Hotels, Motels
Vehicle Sales - Auto, Truck, RV Dealers
Auto Service Stations/Garages, Tire Repair
Car Washes
Laundromats, Self Service

the equipment risk exposures that would occur in the type of microgrid layout described in *Figure 2.*

HSB data was used exclusively for the electrical components. The IEEE Gold Book[5] is another source of this information that could be applied given the absence of applicable data sources. For the gas turbine generation facility, industry failure and downtime data was applied.[6] At this stage in the development of commercial battery storage systems there are no data sources that can provide representative statistics and this microgrid risk analysis is not intended to specifically study their reliability attributes. For these reasons, the failure statistics used for the gas turbine generation facility were applied to the battery storage system. The benefit of the battery storage system in this microgrid analysis is to provide limited additional load supply to replace the loss of load from the gas turbine generator.

Photovoltaic system and inverters failures are also highly dependent on the equipment manufacturer, installer, and location. The data used for the PV systems are intended to represent a generic configuration in the island mode environment.

Repair and failure data are assigned per equipment type taking into consideration where it is in the system configuration. Underground cable failure probabilities are modeled to vary by their length where the HSB computed value is taken for the shortest cable. Failure probabilities for cables increase linearly by their relative length.

Repair (Restoration) Times

An important characteristic of every microgrid is the quality of the maintenance program, as exhibited by the demonstrated performance of its predictive and preventive activities to avoid unplanned outages and the speed of service restoration once a failure does occur. To model these quality characteristics, equipment repair or restoration times are expressed as lognormal distributions, defined by three percentile levels: (a) 1 percent, (b) either 50 percent or 75 percent, and (c) 99 percent, with each percentile level being assigned a value that corresponds to a particular period of time required for repair of equipment.

The choice of lognormal distributions is an assumption. Moreover, in this case, the 1 percent level operates as a practical lower limit (or best-case situation), since it is relatively simple to determine how quickly a particular piece of equipment can be repaired under perfect conditions – and that's the time value assigned to the 1-percent level. The 99 percent level operates as a worst-case situation. The 99-percent level carries a much longer time value, such that in 99 percent cases, the given repair will take less time than this value. Thus, only 1 percent of repair times are expected to exceed the time value assigned to the 99 percent level. These time values assigned to the various percentile levels represent the practical range of reasonable limits on how much time equipment repairs will require under the conditions addressed by the threats being analyzed.

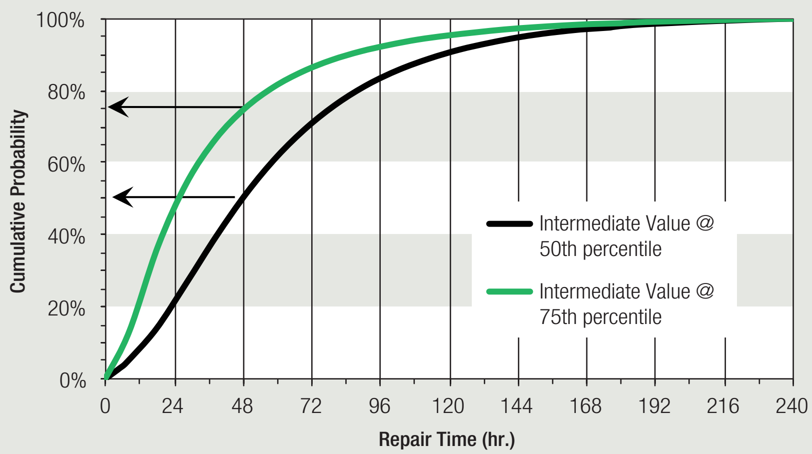
Risk for a microgrid in "island" mode depends greatly on the local utility – its reliability and outage history.

The repair-time values assigned to percentile levels were determined by HSB engineering, in combination with industry data. For the 1-percent and 99-percent levels, the repair times are reasonably straightforward to assess. But there is considerable uncertainty regarding the intermediate value (the time value for the 50-percent or 75-percent levels) required to define the

5. 2015 Münchener Rückversicherungs-Gesellschaft.
6. IEEE Std 493-199.

FIG. 5 **EQUIPMENT REPAIR MODELING**

Two alternative approaches, based on probability of required repair time.



The black curve represents **Scenario I**, assuming a 50% probability that microgrid equipment repairs can be completed within 48 hours. **Scenario II** (green curve) represents an aggressive maintenance regime, assuming a 75% probability of completing repairs in 48 hours.

FIG. 6 **EQUIPMENT REPAIR/RESTORE TIMES**

Equipment	Repair Distribution Values (hr) 1%	Intermediate Percentile	99%
Small Circuit Breakers	0.5	8	48
Medium Switchgear Breakers	4	24	72
Large Switchgear breakers	4	48	336
Distribution Panels	4	8	48
Underground Cables	4	96	336
Building Transformers	3	72	168
Photo Voltaic Panels	1	24	168
Inverters	1	24	168
Gas Turbine Co-generation	2	48	336
Battery Storage System	2	84	336

lognormal distribution of modeled repair times. For example, if a microgrid is operating in island mode, then the cause of this condition needs to be considered. It is a relatively simple manner to replace a damaged transformer under normal conditions but in island mode due to summer storm effects, the transformer may have failed due to severe flooding or wind damage. In these situations, repair time may be governed more by external conditions than the simply technical issues related to removal and installation of equipment.

Thus, by changing the middle percentile value, maintenance performance is modeled to reflect different environmental situations.

An example of this concept is shown in *Figure 5*. Consider a repair time distribution that has one hour as its 1-percent value, and 240 hours (10 days) as its 99-percent value. That means that 1 percent of the repair times will be less than 1 hour and 1 percent of the times will be greater than 240 hours. *(Editor's Note: In the model used in this article, the 99-percent level will be assigned a time value not of 240 hours, as given in the above example, but rather, of 336 hours, or 14 days.)*

Another wrinkle concerns the comprehensiveness or aggressiveness of the strategy adopted for upkeep and maintenance of the microgrid. This variable can be reflected by the selection of the intermediate percentile level – in our case, either 50 percent or 75 percent.

Suppose the time value for the intermediate percentile level is set at 48 hours. Associating 48 hours at the median level of 50 percent signifies that 50 percent of all repairs require less (and greater) than two days to complete. In practice this result could be computed from historical maintenance records or estimated by analyzing maintenance responses under the stated environmental or other identified threat conditions. This scenario represents a standard or base reference maintenance strategy and whose repair distribution is shown as the black line in *Figure 5*.

We could also consider an aggressive maintenance strategy, where 75 percent of all repair times will be less than 48 hours. That could be the result of maintenance best practices, managing an inventory program, or other maintainability activities related to equipment or system design. In this case, the 48 hours would be set at the 75-percent level to reflect the reduction in repair times due to these or other risk reduction practices. The resulting distribution of repairs for the aggressive strategy is shown by the green line in *Figure 5*.

An example of an aggressive maintenance strategy is warehousing backup components. This action could require additional capital expenses for equipment purchases and storage costs that might have no immediate value. One subjective justification for this inventory may be that the conditions that can cause a microgrid to fail may also influence commerce logistics, making routine equipment re-supply impossible for extended periods.

There are other strategies for risk mitigation of microgrid power losses that do not require major inventory expenses; *e.g.*, through insurance-related services that provide backup, quick response generation services to ensure power will be available after weather-related events. These and other scenarios can be modeled by adjusting the intermediate repair time value percentile level.

For the microgrid discussed in this example, the 50-percent values are used as a reference case representing baseline island mode response conditions and the 75-percent values represent aggressive maintenance repair and inventory strategies. The severity data used for the model is given in *Figure 6.* In other words, *Figure 6* shows the repair times assigned to the three percentile levels for individual equipment components included in our microgrid.

Fig. 7 Microgrid Operations Scenario Summary

Scenario	Description
I	Intermediate maintenance repair time value set at the 50th percentile – No battery storage
IA	Intermediate maintenance restore time value set at the 50th percentile – 12 hr. battery storage
IB	Intermediate maintenance repair time value set at the 50th percentile – No battery storage – Max restore times for generators reduced to 168 hrs.
II	Intermediate maintenance repair time value set at the 75th percentile – No battery storage
IIA	Intermediate maintenance repair time value set at the 75th percentile – 12 hr. battery storage
IIB	Intermediate maintenance repair time value set at the 75th percentile – No battery storage – Max repair times for generators reduced to 168 hrs.

Battery Storage

The desired duration of energy supply available from battery storage be dependent on the utility reliability profile and the types and sizes of other power generation sources in the microgrid design. In practice, there may be several power sources ranging from wind, PV, gas powered generators, and others. Battery storage may be used regularly in combination with renewable power sources and not just for power in the event of island mode operations.

Another possible benefit of having battery storage is in the reduction of power quality effects. Having battery storage in the circuit can reduce line disturbance events which can increase (or at least not decrease) component life. Power quality effects are the most likely causes of loss for equipment breakdown insurance claims in most commercial occupancies. Having a battery storage system "upstream" of the load components can reduce this risk and extend equipment life. This is a subtle but very real benefit of inline battery storage systems.

If the utility is subject to frequent, short-term power outages (<2 hr. for example), then battery storage systems can be effective backup power assets for island mode operations. The reliability profile provides data to help determine storage system requirements based on historical data and the other sizes and types of power generators in the configuration.

Including battery storage can be modeled based on scenarios describing various power outage causes and these results can help provide the technical justification for the type and duration of battery storage or for not including storage at all.

Microgrid Risk Analysis

Even though microgrids are composed of equipment whose operational and risk exposure characteristics are well understood, the same cannot be assumed for a microgrid system overall. They can cover many square miles and require reliable power generation and distribution capabilities under adverse conditions. This geographic diversity can provide unique weather- and system-related risk exposures – and not just for microgrid activation due to utility power failures, but for sustained island mode operation. That implies that microgrid performance risk assessments are actually the combination of several analyses each for a different threat such as a weather exposure or utility power failure scenario.

Battery storage systems are relatively new. There's no competent data on their reliability attributes.

For a specific microgrid in a specific location, performance risk can be quantified with reasonable accuracy. However, in this general analysis we are interested in identifying and estimated the overall importance of different risk drivers. Consequently, we apply a relative risk methodology that compares the risk results of different scenarios to a base case or situation.

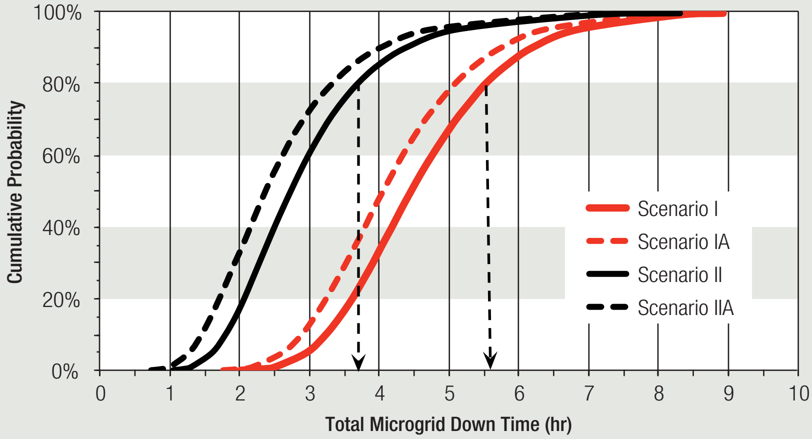
The base case, labeled Scenario I, represents a situation for summer storms for the microgrid shown in *Figure 2.* The failure probabilities, computed from HSB claims data, are applied and the equipment repair time distributions *(Figure 6)* are taken with the intermediate value at the 50 percent level. No battery storage is included.

Scenario IA adds 12 hours of full island mode power from battery storage. This situation studies the risk reduction value of battery storage for the modeled microgrid.

Scenario IB models a reduction in the extreme value of generator repair times. Notice in *Figure 6* that the 99-percent repair time for the gas turbine and battery storage generators is 336 hours, or 2 weeks of downtime. Suppose the microgrid owner could either

Fig. 8 **Microgrid Downtime Risk**

Influence of choice of repair time strategy (normal versus aggressive maintenance).



This analysis shows effect of summer storms on a microgrid located in Connecticut. The cumulative probability plots show the probability of downtime risk being less than or equal to a selected value (hours of downtime) on the horizontal axis. The Figure shows how an aggressive maintenance strategy (**Scenario II**, black curve) tends to reduce downtime risk as compared with a less aggressive strategy (**Scenario I**, red curve). The dotted-line curves show the effect of installing battery storage.

purchase insurance or another type of performance warranty from the generator operators that would limit the generator repair times either in actual time or the financial equivalent to 1 week. This scenario is used to measure the risk reduction value of this effective risk transfer.

Scenarios II, IIA and IIB are similar in content except the intermediate repair time value is set at the 75th percentile level representing a more aggressive maintenance strategy. All these scenarios are summarized in *Figure 7*.

For each load failure sequence, the component failure probabilities and failure severity distributions are combined via a system reliability model using a Monte Carlo analysis to compute downtime risk statistics. The plots shown in Figure 8 depict the distributions of downtime risk for the 50-percent and 75-percent strategies, each with no battery storage.

These cumulative probability plots show the probability of downtime risk being less than or equal to a selected value on the horizontal axis. *Figure 8* shows that the aggressive maintenance strategy (Scenario II) has a significant influence on downtime risk for most situations. This is the difference between the red and black lines. For the summer storm exposures at the 80 percent level, the total microgrid down time is about 5.6 hours or less for the standard maintenance program. For the more aggressive maintenance strategy modeled by placing this value at the 75th percentile level, the total microgrid down time is about 3.9 hours or less. That indicates a reduction in risk of about 29 percent. The closeness of the curves above the 95-percent cumulative probability level shows that very severe storms can still negate the postulated risk reduction strategies.

The difference between the solid and dotted lines for each numbered scenario depicts the risk reduction value of incorporating 12 hours of battery storage load. At the 80-percent level, Scenario I shows about a 9-percent risk reduction achieved with 12-hour battery storage, with about the same degree of improvement for Scenario II. Overall, battery storage for this sample configuration shows about a 10-percentage-point reduction in risk. This result could be a significant, considering the local utility's reliability profile.

There are several key statistics that are useful in measuring changes in risk. *Figures 9, 10 & 11* show the average and several important percentile statistics (resilience metrics) for three scenarios: Aggressive Maintenance Strategy, 12-Hour Battery Storage, and Performance-Related Insurance contract.

The first comparison in *Figure 9* contrasts the risk reduction value of an aggressive maintenance strategy. Maintenance actions are often viewed as deterministic tasks that occur on a schedule based on the type of services being applied. However maintenance response times are a stochastic process for the following reasons:

- Equipment degradation and failures can occur on a random basis.
- Human behavior is an inherent part of maintainability. Variations in timing, performance, and documentation make maintenance a stochastic process.
- Maintenance restoration times are subject to a wide range of external factors.

As discussed in the previous section, one way of modeling the restoration time variation is by changing the percentile level of the component intermediate restoration times. The changes represent different strategies on how maintenance restoration activities will be accomplished.

Figure 9 shows the risk reduction value of an aggressive maintenance strategy. The average shows overall a 36-percent reduction with decreasing effect as percentile level increases. This result is consistent with the fact that the extreme values of the restore time distributions indicate that there are threat scenarios that will still dominate the modeled aggressive maintenance strategy. However, even a 16-percent reduction at the P_{99} level can be a significant result from a risk perspective.

The influence of battery storage on microgrid island mode operations is a function of the utility reliability profile. For duration intervals of less than 12 hours, battery storage can provide an efficient alternate power supply, but if the reliability profile for the utility contains a significant potential for long-duration outages, then battery storage will have a smaller effect on outage risk reduction. *Figure 10* shows the risk reduction results for Scenarios I and II with and without 12 hours of battery power supply. Overall the risk reduction potential is between 11 to 12 percent from the 'no battery' scenarios. The decreasing risk reduction with increasing percentile levels indicates increasing outage severity consistently decreases the relatively short-term benefits of an additional 12 hours of battery supply. Thus to adequately examine the value of battery storage for microgrid island mode operations, the frequency potential for short outages must be a significant risk driver.

In the microgrid configuration shown in *Figure 2,* there are only two power sources that service the entire system. In practice there could be several distributed power sources and the reliability of these assets is critical for sustained island mode operations. The 99-percent restoration times for the battery- and gas-powered generators represent situations where it would take two weeks until power could be restored. One way to reduce this risk exposure is to transfer this risk to insurance. This option represents a financial solution that does not change the physical risk exposure for the microgrid users. Another approach is to contract alternative energy providers that have the capabilities of providing suitable backup power under the P_{99} scenarios. Severe ice or snow accumulations (in winter) or wind and storm surge (in summer) damage are possible events that can be part of the microgrid design basis.

Fig. 9 — Effect of Aggressive Maintenance

Risk Reduction from Investing in an Aggressive Maintenance Strategy

Scenarios 1 & 2
Total Microgrid Downtime/year (hr)

	Mean	P_{50}	P_{80}	P_90	P_{95}	P_{99}
Scenario 1	4.62 ± 0.02	4.45	5.52	6.19	6.85	8.35
Scenario 2	2.96 ± 0.02	2.71	3.68	4.36	5.10	6.98
% Change	36%	39%	33%	30%	26%	16%

Fig. 10 — Risk Reduction from 12 Hour Battery Storage Reserve

Total Microgrid Downtime/year (hr)

	Mean	P_{50}	P_{80}	P_90	P_{95}	P_{99}
Scenario 1	4.62 ± 0.02	4.45	5.52	6.19	6.85	8.35
Scenario 1A	4.22 ± 0.02	4.07	5.09	5.74	6.35	7.81
% Change	11%	9%	8%	7%	7%	7%

	Mean	P_{50}	P_{80}	P_90	P_{95}	P_{99}
Scenario 2	2.96 ± 0.02	2.71	3.68	4.36	5.10	6.98
Scenario 2A	2.61 ± 0.02	2.37	3.31	3.99	4.73	6.73
% Change	12%	13%	10%	9%	7%	4%

Fig. 11 — Risk Reduction from Performance Related Insurance

Or Service Contract Scenario

	Mean	P_{50}	P_{80}	P_90	P_{95}	P_{99}
Scenario 1	4.62 ± 0.02	4.45	5.52	6.19	6.85	8.35
Scenario 1B	3.72 ± 0.02	3.66	4.29	4.66	4.97	5.64
% Change	19%	18%	22%	25%	27%	32%

	Mean	P_{50}	P_{80}	P_90	P_{95}	P_{99}
Scenario 2	2.96 ± 0.02	2.71	3.68	4.36	5.10	6.98
Scenario 2B	2.55 ± 0.02	2.47	3.03	3.36	3.67	4.33
% Change	14%	9%	18%	23%	28%	38%

The question is, what is the corresponding risk reduction if financial, contractual, or physical actions are taken to reduce the P_{99} scenario effects from 2 weeks of downtime to 1 week of downtime? In our microgrid risk model the P_{99} values for the gas turbine and battery systems are reduced from 336 to 168 hours. The risk reduction results for Scenarios I & II are presented in *Figure 11.*

The overall risk reduction is between 19 and 14 percent, but the average statistics do not show the complete value of the risk mitigation measures. In this case, the risk-reduction value increases as the percentile level increases, indicating that the risk mitigation measures are most effective in reducing the high-severity, low-frequency events. For both maintenance scenarios, over a 30-percent risk reduction is obtained for the P_{99} level. This is an example of how resilience metrics[7] can be applied in practice.

7. Distributed Generation Operational Reliability and Availability Database, Oak Ridge National Laboratory, January 2004.

Conclusions and Observations

The model we've developed in this analysis leads to a number of key conclusions and observations.

1. Utility Reliability. The utility reliability profile, including weather effects, marks a critical element for designing a microgrid to ensure it will provide the required functions over its effective service life.

2. Maintenance Efforts. The maintenance program, along with its approach to inventory, spares, and proactive interventions, can provide significant risk reduction value. This part of a microgrid's design and ongoing operations should not be taken for granted.

3. Battery Performance. This analysis has assumed that the failure probabilities of the battery storage and gas-powered generators were equal. In practice, however, the actual or modeled data for the battery systems should be included to more realistically model the risk contribution from this relatively new generation source.

4. Resilience Metrics. It is clear also that different risk mitigation measures, *e.g.,* battery storage, aggressive maintenance strategies, insurance, or service contracts for example can have different valuations. Nevertheless, relying on one statistic, for example the average risk, can form an incomplete picture of the risk-reduction profile. Some measures have the ability to reduce the P_{50} risk level and others are designed to influence the P_{99} level. Resilience metrics should serve as important elements in designing a microgrid to operate in practice as intended by design.

5. Costs vs. Benefits. It is not possible to choose an optimal microgrid design or maintenance strategies from a performance risk analysis as discussed here. In order to determine which characteristics are the best design and operational choices, the costs of these options must be compared to the risk-reduction potentials. Combining costs with the risk analysis gives the statistics in the form of the per-dollar cost of a one-percent risk reduction, among other financial measures.

6. Health and Safety. A microgrid design can include assets and configurations that are not cost-effective from a financial point of view. However, there are some actions that may be taken from an ethical perspective to ensure that microgrid users are not exposed to conditions that can threaten health and safety. Thus, every project has financial limitations requiring risk-management compromises. Methods for determining the appropriate levels of funding for health and safety measures have been developed[8] and they could be applied here.

One way to reduce risk is to transfer the risk to insurance.

7. Control Systems. The performance of electronic control systems, while not discussed here, marks an essential part of overall risk analysis. Such systems contain some risk exposures and failure modes similar to equipment, due to geographical diversity, but control system operations also imply performance exposures unique to software and computer reliability.

8. Cyber Security. Microgrids share a growing operational risk exposure to cyber-attacks. The integration of legacy and new technology systems that are commonly joined as microgrids makes this risk exposure a growing concern that needs to be addressed in the overall microgrid performance risk modeling.

9. The Human Factor. Last but not least, the procedures developed to transition a microgrid to island mode need to be addressed in the risk analysis. These steps, always at some level, will require human intervention. As with the component equipment that makes up the microgrid, human reliability must certainly be addressed.

---

8. Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States, Jean-Paul Watson, et.al. SAND2014-18019, September, 2014.