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The Technical Resilience Navigator

Risk-Informed Decision Making to Support Resilience Planning

February 2023

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U.S. DEPARTMENT OF ENERGY

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Executive Summary

The Technical Resilience Navigator (TRN) helps organizations manage the risk to critical functions at a site from disruptions in energy and water services. Developed in partnership by the Pacific Northwest National Laboratory and the National Renewable Energy Laboratory, under direction and funding from the Department of Energy's Federal Energy Management Program, the TRN helps organizations enhance their resilience to a variety of disruptive events, both natural and human-caused, that could interrupt normal operations for an unknown period of time. This report provides an overview of the TRN's risk-informed approach to resilience planning and formally describes how it uses a streamlined risk model to identify effective strategies for improving resilience.

The TRN provides a holistic path through the resilience planning process, using a modular approach (Figure ES-1). The process begins with the identification of key stakeholders and defining the scope of the assessment. This serves as the foundation for the data collection and risk analysis that help users identify what factors are driving significant amounts of risk for their site's energy and water systems. This analysis can then help users focus efforts on developing resilience solutions for key risk drivers at the site. The solutions are then evaluated to determine their risk-reduction potential, their potential to provide a decarbonization benefit, and their ability to meet other important criteria for the site. Based on these evaluations, solutions are prioritized to determine which should progress to more detailed project development efforts for implementation.

Figure ES-1. Modules within the TRN that organize the holistic resilience planning process.

This report provides the technical basis for the analyses that form the core of the TRN assessment process, focusing on the semi-quantitative risk assessment methodology. This methodology follows best practices in risk science where risk is calculated for each scenario (i.e., identified pathway that something could go wrong) based on the hazard, vulnerability, consequence, and criticality associated with that scenario. In the TRN, hazards can be characterized as grouped hazards, which cause an outage only to the energy or water supply to the site, or dual-impact hazards, which have the potential to cause an outage to the supply and to onsite backup energy or water systems. These hazards are characterized in terms of their frequency and the outage duration that they would cause. Vulnerability is characterized based on the reliability of redundant backup energy or water systems. Consequence for a risk scenario incorporates the outage time associated with the hazard, the tolerable outage duration or length of time that critical loads could be lost without unacceptable interruption to a critical function, and any function restoration capabilities. The criticality weighting factor allows users to account for the level of importance of each critical function in the risk assessment.

The TRN also includes resources to help users characterize components of risk in order to reduce the user burden of this tool. For example, the TRN provides a lookup tool that can be used to identify the historical frequency with which hazards of interest have occurred at the county level, based on data from the Federal Emergency Management Agency's National Risk Index dataset (FEMA 2022). Additionally, the TRN provides calculators that can be used to estimate the duration over which redundant energy and water systems can run during an outage event (Appendices C and D).

The analysis conducted through the TRN risk assessment process supports identification of key risk drivers, development of resilience solutions, and evaluation of those solutions for their risk-reduction potential. In addition, federal agencies are required to work toward ambitious emission reduction goals. Because of this, the potential of solutions to reduce carbon dioxide emissions is a critical factor for evaluating energy projects at federal sites. To support this evaluation, the TRN incorporates an emissions impact assessment for each solution (Section 4.3.1).

Finally, the TRN combines the assessment of risk-reduction potential, emissions impact, and the ability of solutions to meet additional criteria important to the site into a solution benefit potential metric (Section 4.4). Between this metric and a high-level cost estimate, the TRN generates a prioritized list of resilience solutions evaluated through the TRN resilience planning process. This prioritized list can be used as a basis for determining solutions that should move forward to detailed project development and implementation.

The TRN process provides a framework with which sites can work through resilience planning for their energy and water systems in a systematic way. The use of a formally structured, simplified risk analysis methodology allows this process to generate robust and replicable insights. This report documents the methodologies used to evaluate risk, emission impacts, and other factors that can identify tradeoffs between resilience solutions at federal sites developed through the TRN process.

Acknowledgments

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Staff from Pacific Northwest National Laboratory who have contributed to the development of various portions of the Technical Resilience Navigator (TRN) include Sophia Dahodwala, Alison Delgado, Kathleen Judd, Erica Kilgannon, Linda Sandahl, Kate Stoughton, and Marcy Whitfield. The TRN was developed in partnership with the National Renewable Energy Laboratory; staff (current and former) who developed or informed content development include Alison Holm, Eliza Hotchkiss, Greg Guibert (former), Alexandra Young (former).

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Finally, the authors thank Arun Veeramany from Pacific Northwest National Laboratory for a thoughtful review.

Acronyms and Abbreviations

CO_2	carbon dioxide
DOE	Department of Energy
EPA	Environmental Protection Agency
FEMP	Federal Energy Management Program
NREL	National Renewable Energy Laboratory
NRI	National Risk Index
PNNL	Pacific Northwest National Laboratory
TOD	tolerable outage duration
TRN	Technical Resilience Navigator
UPS	uninterruptable power supply

Variables

A	avoided emissions (subscripts refer to the supply type generating the avoided emissions, E = electricity, NG = natural gas)
B	benefit score for solution prioritization (subscripts refer to the prioritization criterion, R = risk reduction, E = emissions reduction, i = number referring to a user-defined qualitative prioritization criterion)
C	consequence (subscripts refer to the scenario associated with the risk)
D	outage duration
E_p	present electricity use
F	time between loss of primary energy or water supply and critical function restoration
G	present emissions (subscripts refer to the supply type generating the emissions, E = electricity, NG = natural gas)
H	hazard frequency
K	time between beginning of outage and redundant system startup
J	operating runtime of redundant system
N_p	present natural gas use
P_F	probability that function restoration will be successful
R	unweighted risk
$R_{weighted}$	weighted risk
S	fractional electricity supply shift
TOD	tolerable outage duration
U	fractional change in energy use (subscripts refer to the relevant supply type, E = electricity, NG = natural gas)
V	vulnerability (subscripts refer to vulnerability associated with specific redundant systems)
W	criticality weighting factor
X	variables reflecting answers to vulnerability questions
α	prioritization criterion weighting factor (subscripts refer to the prioritization criterion, R = risk reduction, E = emissions reduction, i = number referring to a user-defined qualitative prioritization criterion)
γ	emissions factor (subscripts refer to the relevant supply type, E=electricity, NG=natural gas, and/or the type of electricity emissions factor (marginal, average, or associated with a new source of supply)

Variables Used in Appendices

$Consumption_{Daily}$	known daily electricity consumption
$Content_{Btu}$	constant that provides BTU content of fuel per gallon
$Critical_{Days}$	number of days the critical load can be met

$Critical_{DaysAdditional}$	number of additional days the critical load can be met after refueling
$Critical_{DaysTotal}$	total number of days the critical load can be met
$Critical_{Hours}$	number of hours the critical load can be met
Eff	generator efficiency
$Fuel_{Daily}$	daily fuel consumed by a generator, in BTU
$Gallons_{Daily}$	gallons of fuel consumed per day
$Gallons_{Refueled}$	number of gallons supplied during refueling
$Gallons_{Storage}$	onsite fuel storage capacity
$Generator_{kW}$	generator size in kW
KWh_{Btu}	constant that converts kWh to BTU
$Load_{Daily}$	average daily water load for water redundant system in an outage
LoadFactor	generator daily load factor
$Load_{Peak}$	peak water load
$Runtime_{Storage}$	runtime of a storage tank
$Runtime_{Secondary}$	runtime of a redundant water system that has a secondary supply with onsite storage
$Supply_{Secondary}$	flow rate that can be provided by the onsite or offsite secondary water source supply
$Vol_{Useable}$	usable tank volume
Vol_{Empty}	empty tank volume at any given point pre-outage
$wlf_{Storage}$	water loss factor for the piping between the storage tank and the load(s)
$wlf_{secondary}$	water loss factor for the piping between the onsite or offsite secondary water source and the onsite storage tank (if present) or the load(s) (if no storage tank)

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1 Introduction

The Department of Energy's Federal Energy Management Program (FEMP) works with its stakeholders to enable federal agencies to meet energy-related goals, identify affordable energy and water solutions, facilitate public-private partnerships, and provide energy leadership to the country by identifying government best practices. As a part of that work, FEMP seeks to strengthen the ability and agility of federal agencies to manage their critical missions by providing strategic energy and water management support for agencies to become resilient, efficient, sustainable, and secure.

Organizations are faced with a variety of disruptive events, both natural and human-caused, that could interrupt normal operations for an unknown period of time. While emergency management, risk management, and business continuity planning are well-established processes, resilience planning has been the subject of much interest and attention in recent years due to its holistic approach. Developed in partnership by Pacific Northwest National Laboratory (PNNL) and the National Renewable Energy Laboratory (NREL) under direction and funding from FEMP, the Technical Resilience Navigator (TRN) helps organizations manage the risk to critical functions at a site from disruptions in energy and water services.

This report provides an overview of the TRN's risk-informed approach to resilience planning and formally describes how it uses a streamlined risk model to identify effective strategies for improving resilience. Within the TRN, resilience refers to the ability to anticipate, prepare for, and adapt to changing conditions; to withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning; and to develop resilience solutions that address operational, institutional, and technical gaps. The resilience of a system can be characterized in terms of:

- **Resourcefulness:** the ability to skillfully prepare for, respond to, and manage a crisis or disruption as it unfolds
- **Redundancy:** the availability of backup resources to support the primary source in case of failure
- **Robustness:** the ability to maintain critical operations and functions in the face of crisis
- **Recovery:** the ability to return to and/or reconstitute normal operations as quickly and efficiently as possible after a disruption.

Resilience planning's holistic nature has resulted in much interest and attention in recent years, but analysis methodologies and planning approaches vary greatly. Even among risk-oriented resilience planning tools, the incorporation of risk analysis can differ significantly. The TRN uses a formal risk structure designed to have a lower burden of data collection for its users than a detailed probabilistic risk assessment. This approach quantifies risk in terms of hazard, vulnerability, consequence, and criticality weighting (Figure 1). Under each component, the metrics used to quantify that parameter are described and the approach for quantification (i.e., user input or calculated by the tool) are identified. Inputs for each of these components are collected throughout the TRN process by direct data entry and calculating parameter estimates based on user-provided information. The risk calculations within the TRN are performed automatically by the tool.

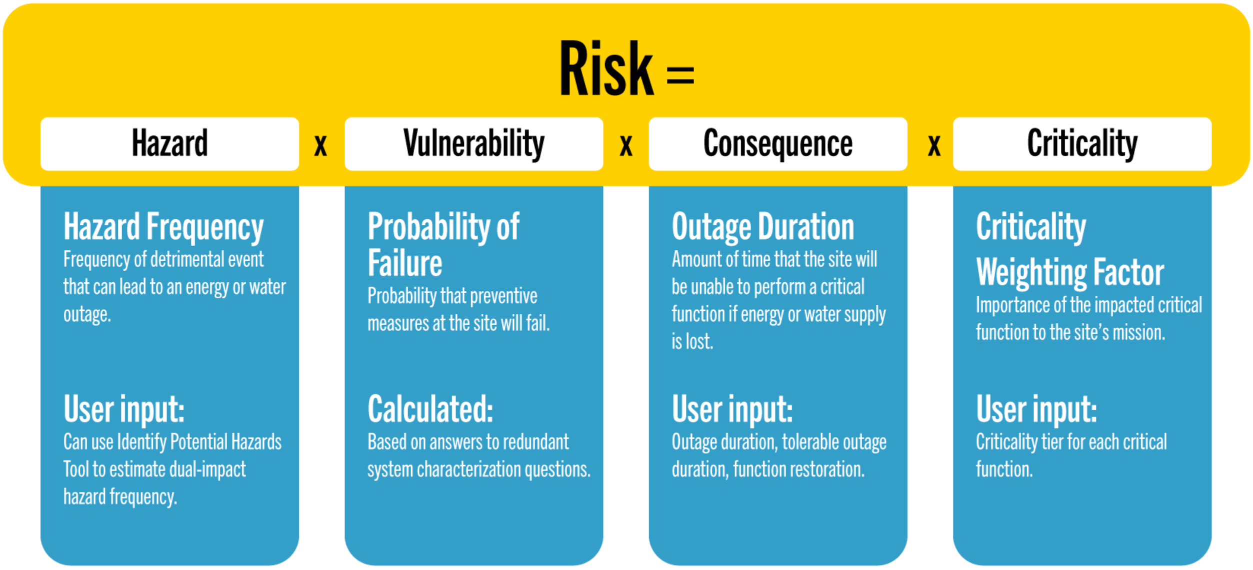


Figure 1. Components of risk that are used to characterize risk scenarios.

This report formally describes the TRN methodology to provide documentation of the calculations that drive identification of risk and guide development of resilience solutions in the tool. It also documents the methodologies related to evaluating resilience solutions as part of the TRN process. Finally, the report provides technical background related to additional support tools that have been developed to help users estimate key inputs for the TRN risk assessment.

2 Scope of the TRN

The TRN's unique focus on risk associated with energy and water systems at a site is intended to integrate with broader emergency preparedness, energy and water management, sustainability, and cybersecurity efforts, and strengthen the way those programs plan for energy and water resource availability. The TRN provides a systematic approach to identifying vulnerabilities of energy and water systems, and prioritizing solutions that reduce risk, while supporting other site priorities (see Figure 2, below). The use of a risk-informed approach to resilience planning is a key benefit of the TRN, as it provides a robust, replicable analysis framework for understanding the site's current risk posture and opportunities for risk reduction through resilience solutions. Contained within each broad step—or module—are a series of actions that lead users through information gathering, synthesis, calculation, and data analysis to understand the potential risks to critical loads and functions at the users' site.

Figure 2. The TRN process (graphic designed by NREL).

Working through this process helps a site build a detailed understanding of plans, priorities, and baseline conditions related to energy and water systems, and what types of gaps might expose the site to risk. Resilience planning is an iterative process and users may work on several actions or modules at the same time. Information revealed in later modules or through later discussions with stakeholders may result in revisiting earlier modules to update previous inputs and potentially reevaluate results. The TRN is publicly accessible at https://trn.pnnl.gov/ and is freely available to members of the public.

In the context of the TRN, the resilience planning process focuses on improving resilience of a site's critical missions in the face of disruptions to primary energy and water services. While other resilience planning tools may consider a wider range of infrastructure types (telecommunications, workforce, transportation, and other key sectors), because FEMP's mission is to enhance the energy and water performance of federal facilities, the TRN specifically focuses on that area to best match FEMP mission space.

Within the TRN, users need to define critical missions, map each critical mission to supporting critical functions, and ultimately identify the critical loads that enable the successful fulfillment of critical functions. Users define these in the Site-Level Planning and Baseline Development modules (see Figure 3).

- A ***critical mission*** is an organizational goal or set of requirements of such high importance that it must be fulfilled.

- ***Critical functions*** are the specific procedures, tasks, and decisions that ensure the critical mission will be sustained under all potential operating scenarios (normal, emergency, peak or high-tempo operations). Critical functions can include direct mission-support functions (e.g., analyze and provide intelligence, provide prison security, preserve genetic material), as well as operational support functions (e.g., provide emergency response). A TRN resource with more information about defining critical functions can be found here: https://trn.pnnl.gov/modules/quick-reference.
- ***Critical loads*** are specific systems required to sustain critical functions. Characterization of a critical load includes defining the energy and water requirements of those systems.

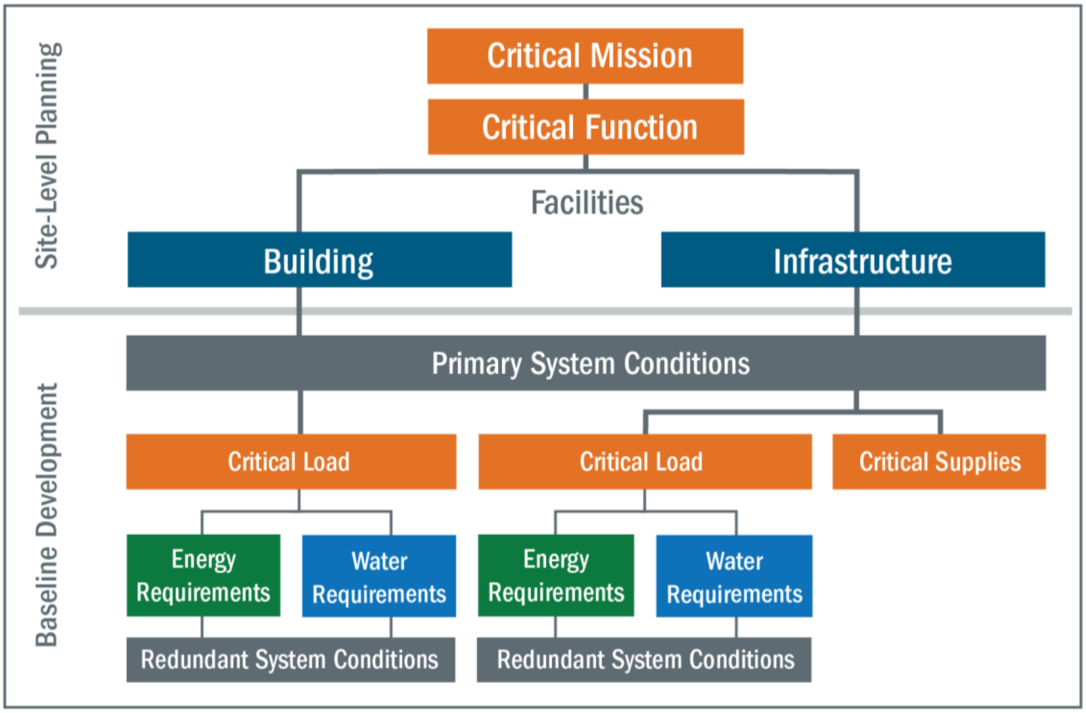


Figure 3. Relationship of critical missions, functions, and loads within the TRN process.

The TRN provides an Interview Question resource to help users gather information from critical mission and function owners to identify the critical loads, energy or water requirements, and how long a critical load could be lost without unacceptable interruption to the supported critical function (called the “tolerable outage duration” within the TRN). Additionally, the interviews help identify whether there are redundant systems that support identified critical loads and provide background on their condition (e.g., maintenance and testing information, startup information, and anticipated runtime). The TRN process refers to these data in later modules, including:

- Redundant system runtimes are used to calculate how long a redundant system can provide backup during an outage of the primary system across varying risk scenarios in the Risk Assessment module. The impact of changing these inputs as a result of a resilience solution (e.g., increasing the efficiency of critical loads, adding refueling agreements to increase the runtime of a generator, or replacing a redundant system with a longer lasting one) can be modeled in the Solution Prioritization module.
- In the Risk Assessment module, redundant system characteristics and conditions are used to determine vulnerability, or their potential of failure to mitigate primary resource outages.

- Energy and water requirements are used to help size resilience solutions within the Solution Development module.

3 Risk Approach

The TRN resilience planning process is based on a semi-quantitative risk assessment approach to evaluate energy and water risks faced by a site and identify the key risk drivers that may be candidates for mitigation through resilience solutions (Unwin et al. 2020).

The TRN methodology described in this report uses a formally structured risk model to generate replicable and defensible risk analysis results that can support decision making. This strategy allows users to develop resilience assessments that can be compared across an organization's portfolio and are designed to account for both the likelihood and consequence of a disruptive event without deemphasizing or overemphasizing either component. Because other factors besides risk are also considered for prioritization of resilience solutions (see Section 4), the TRN is a risk-informed approach to resilience planning rather than a risk-based approach. In other words, the development and prioritization of solutions developed through the TRN process is expected to be driven by risk insights, but also by other factors important to the organization.

While the TRN methodology follows a formally structured risk approach, it is designed to be used by facilities personnel, such as facilities managers or energy and water managers. To make the model straightforward for nonrisk experts, the TRN incorporates simplifying assumptions. The general principle for these assumptions is to err on the side of being conservative, that is overestimating rather than underestimating risk. In other words, the simplifying assumptions lead to estimates of larger impact or lower ability to avoid the impact rather than a smaller impact or higher ability to avoid the impact. This conservative approach makes it more likely that important risks will not be overlooked as a result of the simplified approach and is in line with the aim of the TRN, which is to use a comparison of relative risk to prioritize risks rather than to estimate their precise values. The methodology—including the required inputs and key outputs—is described below. Also described is the mathematical structure of the model, although knowledge of this structure is not required of the user.

3.1 Risk Assessment Methodology

The TRN methodology is constructed around risk scenarios. Each scenario is made up of:

- **Realized hazard or threat.** An initiating event that leads to an outage of the primary electric, natural gas, or water supply to the site. This can be a natural hazard (e.g., earthquake, hurricane), an operational failure (e.g., random equipment failure, operator error), or a deliberate act of sabotage (e.g., cyberattack, physical attack). Note that deliberate acts of sabotage are often referred to as "threats;" however, for the remainder of this report, we use the term "hazard" to represent all of the types of initiating events described above.
- **Critical load.** An energy or water load that supports a critical function at the site. If this load is unavailable due to lack of energy or water supply, the site is not able to fulfill one or more of the critical functions that enable the critical missions of the site.

A key concept for characterizing the realized hazards and critical loads is the distinction between primary and redundant energy or water supply. The primary supply is the source of energy or water that is provided from offsite during the course of regular operations (e.g., the electric grid). Operation and maintenance for the primary supply is generally outside of the site's control. The redundant supply is a backup system that can provide energy or water to critical loads when there is a disruption to the primary supply. Operation and maintenance for the redundant system is generally within the site's control.

Risk for each scenario (Figure 4) is characterized using the risk equation:

$$Risk = Hazard * Vulnerability * Consequence * Criticality\ Weight \quad \text{Equation 1}$$

where hazard is the likelihood of the loss of primary energy or water, vulnerability represents the likelihood that onsite redundant energy or water systems fail in the event of the hazard or threat, consequence is the impact that would occur if the hazard were realized and onsite redundant systems failed, and criticality weight is associated with the critical function impacted in the risk scenario. Each of these parameters is discussed in more depth below.

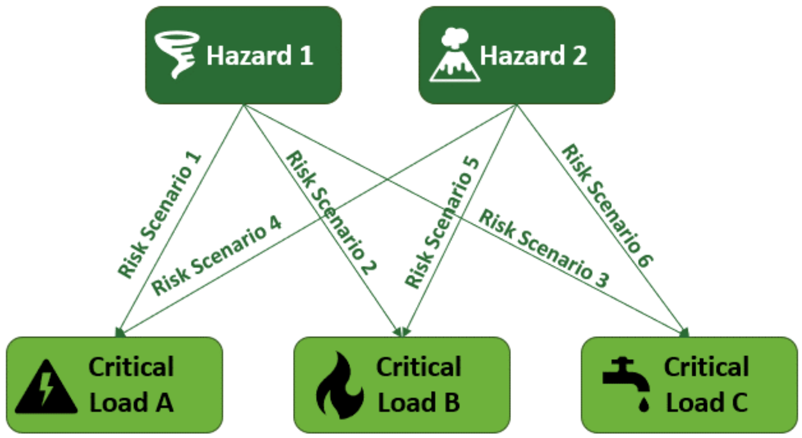


Figure 4. Risk scenarios based on unique combinations of hazards and critical loads.

The TRN model explicitly accounts for numerous factors that might impact the elements of the risk equation. These factors are collected throughout the first three modules of the TRN: Site-Level Planning, Baseline Development, and Risk Assessment. Because the objective of the TRN is to identify and prioritize major drivers of risk and solutions that can mitigate those drivers, as opposed to precisely quantifying the risk values associated with different drivers, high precision of quantitative inputs is not required.

3.1.1 Inputs

Below, each input into the risk equation is described along with a description of where the relevant data is collected in the TRN.

3.1.1.1 Hazards

In the TRN, hazards are quantified based on:

- Duration for which they would cause an outage to the primary energy or water supply
- Frequency with which the hazard is expected to recur.

Both of these factors are captured based on semi-quantitative scales. This approach is taken to allow the user to roughly quantify the hazard without undertaking a detailed hazard assessment and aligns with the simplified approach taken in the TRN. The outage duration caused by a hazard can be characterized using the following categories: 1 hour, 1 day, 1 week, 1 month, or 6 months. The frequencies with which the hazard recurs can be characterized using the following categories: almost certain (three times in 1 year), likely (once a year), anticipated (once in 10 years), unlikely (once in 100 years), or extremely unlikely (once in 1,000 years). Hazards with frequencies significantly less than once in 1,000 years are not considered in this assessment. Selection of appropriate duration and frequency categories may be based on site-specific experience and review of regional or national data on relevant hazards. The hazards selected for analysis are those to which the site is exposed.

The TRN model allows two types of hazards to be incorporated into the risk assessment: grouped hazards and dual-impact hazards. These two hazard types are discussed below.

Grouped Hazards

Grouped hazards are hazards that could disrupt energy or water supply to the site but would not impact onsite systems. Because these hazards do not impact onsite systems differently (e.g., it does not matter to the site whether power went out due to operator error or animal damage to a transmission line), grouped hazards can be aggregated (or grouped) so that only the combined frequency of the hazards needs to be estimated. The only factors differentiating one group of hazards from another are which supply type is impacted (electricity, natural gas, or water) and the resultant outage duration.

An example of a hazard that might be considered part of a grouped hazard would be corrosion of water supply infrastructure to the site. Though pipes supplying water to the site could fail, cutting off water supply, this would not impact onsite systems, such as redundant water systems. Therefore, it could be grouped with other hazards that lead to a similar water supply outage duration.

Energy and water outage likelihoods can be significantly impacted by factors like local investments in infrastructure, and therefore are likely to vary by region and site. Ideally, grouped hazard frequencies will be estimated based on the experience of the site or region. However, where site-specific information is unavailable, national averages can be used as inputs. Estimates of outage frequencies are provided in the TRN resource “Grouped Hazard Outage Frequency Values” (Table 1).

Table 1. Frequency estimates for electricity, natural gas, and water outages

	Frequency of Outage		
Outage Duration	Electricity	Natural Gas	Water
1 hour	Likely (once a year)	Unlikely (1 in 100 years)	Anticipated (1 in 10 years)
1 day	Anticipated (1 in 10 years)	Extremely unlikely (1 in 1,000 years)	Unlikely (1 in 100 years)
1 week	Unlikely (1 in 100 years)	*<< 1 in 1,000 years*	Extremely unlikely (1 in 1,000 years)
1 month	Extremely unlikely (1 in 1,000 years)	*<< 1 in 1,000 years*	*<< 1 in 1,000 years*
6 months	*<< 1 in 1,000 years*	*<< 1 in 1,000 years*	*<< 1 in 1,000 years*

For electricity, these estimates are based on recurrence intervals calculated in Ericson et al. (2022) for the contiguous United States. These recurrence intervals were calculated using the EAGLE-I dataset of customer outage rates and durations, compiled by Oak Ridge National Laboratory. Recurrence intervals were determined for seven outage duration ranges: 0–12 hours, 12–24 hours, 1–2 days, 2–3 days, 3–5 days, 5–7 days, and >1 week. To map these data onto the five outage durations modeled in the TRN, we combined ranges that included each outage duration in the TRN assessments with adjacent outage duration ranges. This resulted in comparing the TRN outage duration point estimates to the outage duration ranges from Ericson et al. (2022) as shown in Table 2. Note that this strategy of grouping outage duration ranges aligns with the intent of the approximate order-of-magnitude outage duration categories used in the TRN. Users are intended to select outage durations that approximately describe the outage durations expected for energy or water outages at their site. Therefore, it is expected that each TRN outage duration represents a range of durations.

Table 2. Outage duration mapping between durations used in the TRN and ranges reported in Ericson et al. (2022).

TRN Outage Durations	Outage Duration Ranges
1 hour	0–12 hours
1 day	12–24 hours, 1–2 days
1 week	2–3 days, 3–5 days, 5–7 days
1 month	>1 week
6 months	*No equivalent range*

For each outage duration range from Ericson et al. (2022), the associated recurrence interval was converted to an annual frequency (i.e., numbers of outage events per year). These frequencies were summed for each TRN outage duration category to obtain the annual frequency for that TRN outage duration category. The decadic logarithm was taken of each frequency estimate and rounded to the nearest whole number to obtain the order-of-magnitude annual frequency estimate for power outages shown in Table 1. These generally align with estimates based on assessments conducted by the U.S. Nuclear Regulatory Commission (NRC n.d.; Johnson and Ma 2019).

For natural gas, outage frequencies were informed by a Gas Technology Institute report that provided evidence that natural gas outages are roughly two orders of magnitude less frequent than those for electricity (Liss and Rowley 2018). As shown in Table 3., on a national basis, the electric distribution system unavailability exceeds that of natural gas by a factor of 69.

Table 3. Electric and natural gas distribution unavailability and outage rates (as reported in or derived from Liss and Rowley (2018))

Metric	Natural gas	Electric	Ratio (Electric/Natural gas)
Average unavailability (planned and unplanned)	4.30E-06	2.97E-04	69.1
Average outage rate (planned and unplanned events per customer per year)	0.00895	1.017	113.6

Unavailability refers to the fractional downtime of a supply. While this metric does not directly relate to outage frequency or duration of individual outage events, it does reveal that the annual average outage time of electricity systems is in the vicinity of two orders of magnitude greater than that for natural gas. Table 3. also reports that the average outage rate for electricity, in terms of number of events per year, exceeds that of natural gas by a factor of 113. The combination of these two pieces of evidence led us to reduce the natural gas outage frequency estimates for each given outage duration by two orders of magnitude relative to those for electricity, as reported in Table 2.

Outage frequencies for water were not readily available. Therefore, the frequencies estimated in Table 1 for water outages are based on the experience that water distribution systems are generally more robust than their electrical counterparts, so water outages are less frequent than electricity outages. To be conservative, the frequency estimates for each water outage duration are reduced by only one level relative to the estimates for the same outage duration for electricity. Note that as water infrastructure ages, failures may become more common. It is recommended that users consider the level of maintenance of the water distribution system that provides their site's water when determining the frequency values used in their TRN analysis.

Dual-Impact Hazards

By contrast, dual-impact hazards are hazards that could impact both offsite supply of energy or water as well as onsite systems. For example, an earthquake close to a site could cause damage to the transmission system, leading to disruption of electricity. Additionally, the seismic shaking could also damage onsite infrastructure, potentially preventing onsite redundant systems from functioning properly. Because these types of hazards can impact infrastructure at the site differently, they must be characterized independently. For example, the type of damage to a diesel generator associated with seismic shaking would be very different from the type of damage a diesel generator would experience if exposed to flooding. To effectively evaluate the need for site-level mitigations for these two hazards, they must be analyzed separately in the risk assessment. A key additional TRN input associated with dual-impact hazards is whether redundant systems are designed to withstand the hazard. This information feeds into the vulnerability assessment, which is described in Section 3.1.1.2.

One additional consideration for dual-impact hazards is whether the site wants to assess risk with respect to different severity levels for the same type of hazard. In the TRN model, the severity of hazards is captured in the consequence metric, in terms of the outage duration. If the user would like to consider multiple severities of the same hazard (e.g., Category 5 hurricanes as well as Category 1–4 hurricanes), the different severity levels can be entered into the model as individual hazards and labeled to identify which hazard refers to which severity level and frequency of occurrence. This would allow the user to characterize the same hazard at different severity levels with a different combination of outage duration and frequency. To simplify the assessment, it is recommended that severity levels are grouped where they are likely to have similar consequences. For example, in the case of hurricanes, the user could characterize 1) Category 1 hurricanes, 2) Category 2 hurricanes, 3) Category 3 hurricanes, 4) Category 4 hurricanes, and 5) Category 5 hurricanes separately; however, if Category 1–4 hurricanes are expected to cause ~1 week of electricity supply outage and Category 5 hurricanes are expected to cause ~1 month of electricity supply outage, the user could simplify the analysis by including only two hazards: 1) Category 1–4 hurricanes and 2) Category 5 hurricanes. This approach would significantly reduce the burden of analysis.

Identify Potential Hazards Tool

For sites that do not have access to site-specific or regional hazard assessments, or for sites that are not sure which hazards to incorporate into their risk assessment, the TRN contains a resource called the Identify Potential Hazards tool. This tool leverages data included in the Federal Emergency Management Agency's National Risk Index (NRI) tool (FEMA 2022). The NRI evaluates community exposure to 18 natural hazards at the county or census tract level. The hazard data are presented in terms of annual frequency in each county in the United States; in contrast, the TRN focuses on site-level risk assessment. Therefore, the TRN Identify Potential Hazards tool modifies the NRI dataset to calculate the likely annual frequency of a hazard at a site level. For example, the NRI provides an estimate of the frequency of tornadoes that is likely significantly higher than an individual site would expect to experience given a tornado's limited physical area of impact and the small area of a site compared to the size of the entire county. To account for the fact that the target area of impact is significantly smaller than the size of a county, the TRN Identify Potential Hazards tool refines tornado frequency by multiplying the NRI frequency by the average area of impact for tornadoes (Schaefer, Kelly, and Abbey 1985) and dividing by the area of the county (Thom 1963).

The user inputs for the Identify Potential Hazards tool are as follows:

- **Location.** The site zip code (can be auto-populated based on the address entered when setting up a TRN framework) is used to identify which county the site is in. Alternatively, the user can directly select the state and county without entering their zip code. *[Required]*
- **Exposure to flooding.** A yes or no answer to the question "Is the site in a location that has the potential to experience flooding?" This question is intended to account for situations where significant topographical variations could lead certain parts of the county to have high flood likelihood while other parts have almost no chance of experiencing coastal or riverine flooding. *[Required]*
- **Highlight hazards likely to be impacted by climate change.** The user has the option to highlight hazards that are likely to be impacted by climate change based on assessments available in the National Climate Assessment. These data are not explicitly used in the TRN risk model, but are intended to help the user determine whether to modify the outage duration and frequency estimates based on whether the hazard is likely to be impacted by climate change (Delgado and Rabinowitz 2021; Rabinowitz et al. 2022). This information can also be used to motivate sensitivity analysis (see Section 3.3) related to climate change. *[Optional]*

Based on these inputs, the Identify Potential Hazards tool displays the annual frequency of hazards likely to impact the site, with the option to have the hazards that could be impacted by climate change highlighted (Figure 5). For cold wave, drought, and heat wave, an annual frequency is not provided. In the case of drought, this is because drought is a chronic rather than acute hazard and is unlikely to cause acute energy or water supply disruptions. Instead, it is more likely to act as a stressor that makes other hazards (e.g., wildfires) more likely or more severe. In terms of water supply, drought could cause stress to the water supply system, but this is also more likely to be a chronic issue rather than an acute outage risk. In the case of cold waves and heat waves, frequencies are not included because the definitions of what constitutes these events are not consistent across the country. Instead, they are defined based on deviations from local expected temperatures. While this may have significant impacts on human experience of outdoor environmental conditions, these types of hazards are not likely to cause failures of onsite redundant systems. Therefore, though they might put stress on energy or water supplies, potentially leading to an outage in the primary supply to the site, they would not be considered dual-impact hazards for the purposes of the TRN.

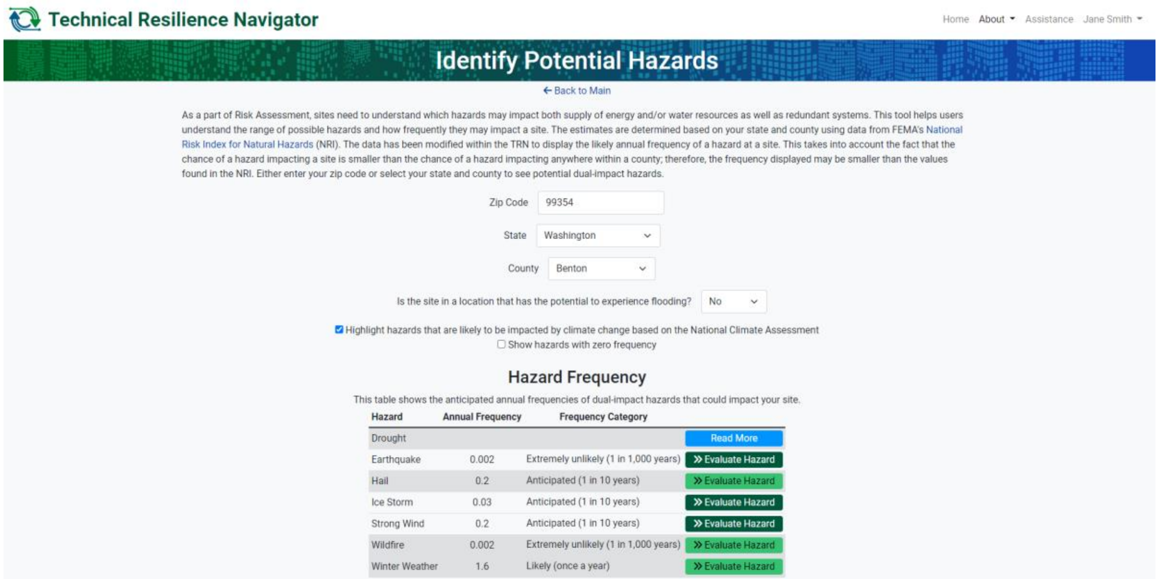


Figure 5. Example of analysis using the TRN Identify Potential Hazards tool.

3.1.1.2 Vulnerability

Vulnerability in the TRN reflects the likelihood that redundant systems (e.g., backup generators, water tanks) will fail to operate according to their capabilities in the event of an outage. In the TRN, consideration of redundant systems is confined to backup energy or water systems that supply the resource during an outage of the primary supply to the site. This is because the TRN is focused on loss of critical loads due to failure of the primary supply, and does not consider other failure modes such as failures intrinsic to the critical load itself.

Because vulnerability is directly tied to individual redundant systems, it is evaluated on a redundant system basis and then applied to each risk scenario where that redundant system supports the relevant critical load. Note that a redundant system can have multiple components that operate at different points during an outage. For example, one redundant system could be made up of an uninterruptable power supply (UPS) and a diesel generator. The UPS would support the critical loads beginning immediately upon loss of electricity supply, but only operate for a short time. This would allow enough time for the diesel generator, which can operate for a longer duration, to turn on.

The vulnerability estimate for each redundant system is generated based on user answers to a series of questions in Baseline Development Action 3 and Risk Assessment Action 2 (Table 4). Note that for the reliability category, there are multiple questions; as a conservatism, the TRN calculations require that the user answer “Yes” to all questions to achieve a lower vulnerability (X_1 = 0). If any of the questions receive a “No” answer, the TRN assigns a higher vulnerability (X_1 = 0.8) to reflect that a negative response reveals a higher likelihood of failure.

Table 4. Vulnerability questions used to evaluate vulnerability in the TRN.

Vulnerability Category	Vulnerability Question(s)	Where Information is Gathered	Quantification of Response[a]
Reliability	• Is the equipment in the redundant system part of a preventive maintenance program? If the user answers "Yes": • Are written schedules and procedures in place and followed for the preventive maintenance and testing of the equipment? • Is there documentation of performance of preventive maintenance and testing, and documentation of observations associated with these activities?	Baseline Development Action 3	If "Yes" to ALL questions: $X_1 = 0$ Otherwise: $X_1 = 0.8$
Startup configuration	Is the redundant system configured to automatically start upon disruption of the primary supply system?	Baseline Development Action 3	If "Yes": $X_2 = 0.01$ Otherwise: $X_2 = 0.1$
Startup configuration	*[If the user answers "No" to the previous question]* If manual startup of the redundant system is required, is it supported by written, up-to-date procedures, and are these procedures trained upon with documentation of completion of the training?	Baseline Development Action 3	If "Yes" for previous question: $X_3 = 0$ If "Yes" for this question: $X_3 = 0$ Otherwise: $X_3 = 0.8$
Design basis	*[Asked for each dual-impact hazard]* Select ALL redundant systems for which each component is designed and documented to withstand the realized hazard.	Risk Assessment Action 2	If the redundant system is selected for the hazard or if the hazard is a grouped hazard $X_4 = 0$ Otherwise: $X_4 = 0.8$

[a] The values selected for vulnerability quantification are intended to be typical of estimates for automated and manual redundant systems, where the analysis errs on the side of conservatism. Precision in such numbers is not required since TRN focuses on the risk-informed prioritization of scenarios rather than application of absolute risk estimates, and would anyway be impractical for the diversity of systems the TRN is intended to address. The values used are consistent with sources for hardware reliability (e.g., NREL, 2020) and human error probabilities (e.g., INL, 2005).

Based on the answers to these questions, the vulnerability associated with each redundant system is:

$$V_i = 1 - (1 - X_1)(1 - X_2)(1 - X_3)(1 - X_4) \quad \text{Equation 2}$$

where V_i represents the vulnerability associated with redundant system *I* for a given hazard and the *X* variables reflect the answers to the vulnerability questions as defined in Table 4.

In the TRN, each critical load can have up to two redundant systems associated with it (i.e., *i* = A, B). The second redundant system is considered to operate only in the event of a failure of the first redundant system (they do not operate in series). For example, in the case described above of a UPS and a diesel generator, the diesel generator starts up only after the UPS has stopped providing backup based on its expected operational parameters. Because the UPS and diesel generator operate in series, they are considered one redundant system (i.e., the diesel generator is *not* considered a second redundant system that provides backup only in the event that the UPS is unsuccessful). However, if the site additionally had a second diesel generator that operated only if the first generator failed, it could take credit for two redundant systems:

1. UPS + backup diesel generator #1
2. Diesel generator #2

In addition to being characterized based on vulnerability questions, each redundant system is characterized in terms of how long it takes to initiate and how long the system can run during an outage. These inputs are used to determine whether the redundant system is qualified for each individual risk scenario. For a redundant system to be considered qualified (Figure 6 a–c) to support critical loads for a given risk scenario, it must:

- Start up within the relevant critical load's tolerable outage duration (TOD), which is defined based on a) the amount of time over which the critical function can persist without access to its critical energy or water load, and b) the site's tolerance for the loss of the critical function, and/or
- Be able to run through the end of the outage.

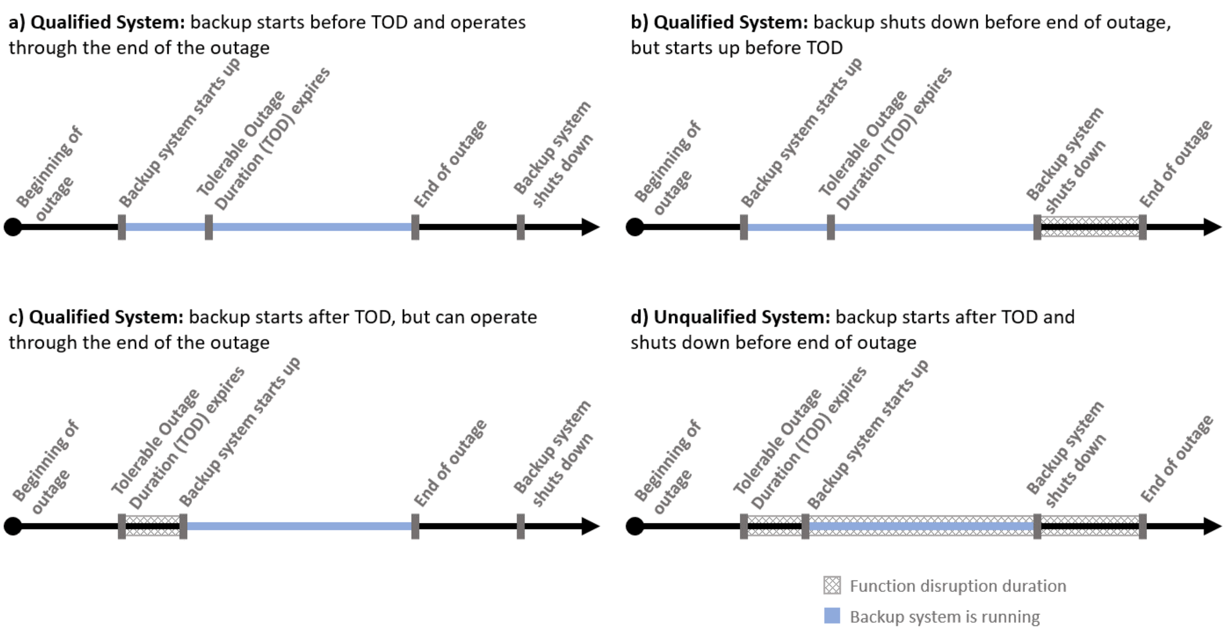


Figure 6. Timelines showing scenarios for which redundant systems would be considered qualified in a risk scenario (a–c) and under which they would be considered unqualified (d). Blue bars show the duration over which the redundant system is operating. Gray hatched bars show the duration over which the function is considered to be experiencing a disruption in the TRN methodology.

Redundant systems that cannot start within the critical load's TOD nor run through the end of the outage (Figure 6 d) are considered unqualified in the TRN methodology. These are assigned a vulnerability of 1, meaning in the event of that realized hazard, there is a 100% chance the redundant system will fail to mitigate the associated consequence.

Note that these requirements are less restrictive than those of the original TRN risk methodology, which was updated in February 2023 (Unwin et al. 2020). The original methodology did not allow users to take any credit for redundant systems that do not meet both of the qualification requirements listed above (see Appendix E – for more information about the original TRN risk methodology).

3.1.1.3 Consequence

In the TRN, consequence is quantified as the outage duration of a critical function supported by a critical energy or water load. This duration is determined for each risk scenario using two numbers: 1) the TOD of the critical function supported by the critical load, and 2) the duration of the outage (*D*).

Because the TRN is focused on whether the energy or water outage associated with each risk scenario would actually cause an intolerable interruption to the relevant critical function, the analysis also considers whether the site would be able to maintain the function by restoring it at another location that would be unaffected by the outage of the primary energy or water supply to the site being assessed in the TRN framework. This function restoration capability is characterized by:

- *F* – The time it takes for the function to be restored at another location. This duration is a direct user input in Risk Assessment Action 1 for each critical load.
- P_F – The probability that the function restoration would be successful. The value of P_F is set based the answer to “Has the site documented AND exercised the function restoration capability?” If the answer is yes, P_F = 0.9; if the answer is no, P_F = 0.1.

Risk is calculated based on the shortest outage of the critical function achievable with the existing redundant systems in place by using the lesser of:

- The expected function outage duration associated with function restoration at another location
- The expected function outage duration associated with a strategy of using redundant systems.

To simplify the model and reduce the data gathering and input burden on the user, the TRN does not consider a mixed strategy where the function is maintained both through partial backup and through function restoration at another location.

First, we consider the consequence associated with the site’s ability to duplicate the relevant critical function (C_F):

$$C_F = max\{P_F[\min(F, D) - TOD], 0\} + \max\{(1 - P_F)(D - TOD), 0\} \qquad \text{Equation 3}$$

where the first term describes the consequence, in terms of duration of intolerable function disruption, if the function restoration were to be successful, and the second term describes the consequence if the function restoration were to fail.

Next, we determine the consequence associated with usage of redundant systems to support critical loads. The consequence associated with the redundant system (C_R) depends on the scenario. In the case where the backup system can operate through the end of the outage, whether it is capable of starting up within the TOD or not (Figure 6 a and c), C_R can be set equal to C_1, where

$$C_1 = \max\{\min(K, D) - TOD, 0\} \quad \text{Equation 4}$$

where *K* is the time between the beginning of the outage and the startup of the redundant system.

In the case where the redundant system can start up within the TOD, but is unable to operate for the full duration of the outage (Figure 6 b), C_R can be set equal to C_2, where

$$C_2 = \max\{D - \max(K + J, TOD), 0\} \quad \text{Equation 5}$$

where *J* is the operating runtime of the redundant system.

3.1.1.4 Criticality Weighting

The final component of the risk equation is the criticality weighting factor. This factor, *W*, represents the relative importance of a critical function to the site's ability to perform its critical missions. It can be thought of as the measure of "how bad would it be if the site lost that function?" The criticality weighting factors are assigned to each critical function using tiers, with each tier assigned a weighting factor that is an integer greater than or equal to 1. The user can assign multiple functions to the same tier, differentiating only between groups of functions, or assign different tiers to each function. Though the user has the flexibility to assign these criticality weights as is most relevant to their site, the logic should adhere to the following guidelines:

- The most important functions are grouped into the first tier, the next most important functions fall into the second tier, and so on
- The highest weighting factor is associated with the first tier and subsequent tiers have progressively decreasing weighting factors.

The user is also encouraged to assign weighting factors to each tier that will sufficiently differentiate them, while accurately reflecting the relative importance of the functions in each tier. For example, consider a criticality framework where there are three tiers, each assigned sequential weighting factors (Tier 1, $W = 3$; Tier 2, $W = 2$; Tier 3, $W = 1$). In this case, the weighting factors are unlikely to significantly differentiate between the risk associated with the functions assigned to these different tiers. This is because the other inputs to the risk equation have much more significantly differentiated ranges (e.g., logarithmic scale for hazard frequency) which are likely to overpower the effect of the criticality weights. On the other hand, if the weighting factors were assigned logarithmically (Tier 1, $W = 100$; Tier 2, $W = 10$; Tier 3, $W = 1$), the risk results would be much more likely to reflect the relative importance of these different tiers. However, users should not assign weights that exaggerate the relative importance of each tier simply to attain greater differentiation in the final weighted risk results.

3.1.2 Risk Calculation

When calculating risk for a scenario, three potential subscenarios are considered, each with its own vulnerability and consequence driven by how many of the redundant energy or water systems fail (both, one, or neither). The risks for these three subscenarios are added to produce the overall scenario risk. So, based on previous inputs, unweighted risk (*R*, in units of hours/year) for each risk scenario can be calculated as

$$R = H * [V_A * V_B * C_F + (1 - V_A) * \min(C_F, C_{A,R}) + V_A * (1 - V_B) * \min(C_F, C_{B,R})] \quad \text{Equation 6}$$

Where *H* is the hazard frequency, V_A and V_B are equal to the vulnerabilities associated with redundant systems A and B (where system B is a backup that operates in the event that system A fails), respectively, and $C_{A,R}$ and $C_{B,R}$ are the consequence terms associated with redundant systems A and B, respectively. C_F, or the consequence associated with the site's ability to duplicate the relevant critical function is calculated as described in Equation 3 and C_R is equal to C_1 or C_2 as described in Equation 4 and Equation 5. Each term in Equation 6 represents different possible outcomes of operating redundant systems during an outage:

- $V_A * V_B * C_F$ Equation 7

  Both backup systems fail.

- $(1 - V_A) * \min(C_F, C_{A,R})$ Equation 8

  The first backup system operates successfully.

- $V_A * (1 - V_B) * \min(C_F, C_{B,R})$ Equation 9

  The first backup system fails, but the second backup system operates successfully.

We cannot know ahead of time whether the backup system(s) will operate successfully in any given outage event, so the possibility of their failure, as characterized by their vulnerability, must be considered for every risk scenario. Equation 6 is an expanded version of the risk formulation displayed in Figure 1 where each of the components described in Equation 7–Equation 9 are structured as a vulnerability multiplied by a consequence and all components are multiplied by *H* to obtain unweighted risk (*R*).

Once unweighted risk is calculated, weighted risk ($R_{weighted}$) for the risk scenario can be calculated as

$$R_{weighted} = R * W \quad \text{Equation 10}$$

Note that for weighted risk, the units are less meaningful due to inclusion of the subjective weighting factor.

3.1.3 Outputs

The outputs of the TRN risk analysis are provided in Risk Assessment Action 4, both as unweighted risk (i.e., risk calculated without the criticality weighting factor, Equation 6) and weighted risk (Equation 10). Unweighted risk is in units of hours/year and represents the probability-adjusted expected annual function outage time. Weighted risk is not reported with units because it incorporates the criticality weighting factors that are subjective assessments of the relative importance of the functions supported by each critical load (see Section 3.1.1.4).

The risk is reported in terms of total unweighted and weighted risk, summed across all risk scenarios, and is also broken down by critical load and hazard. These results can be seen in tabular or graphical format. Additionally, results can be downloaded as an Excel file for users who would like to investigate the data in another way or generate graphics that are not available on the TRN website. Finally, the TRN web tool includes a Review Risk Factors filter table. This table allows users to review their risk results, filtered by outage duration, critical load, and/or supply type (electricity, natural gas, or water). Using these outputs, users can identify their key risk drivers by asking questions such as:

- Which critical loads contribute the most to risk at the site?
- Which hazards contribute the most to risk at the site?
- Does weighted risk show a significantly different pattern than unweighted risk? If so, does this reflect that the relative importance of certain critical functions is driving risk?
- Are longer outage durations driving risk? If so, is this associated with redundant systems that are not designed to operate for sufficiently long durations?

As the results of the risk assessment are reviewed, the user can record the identified risk drivers in Risk Assessment Action 4. These risk drivers can be added to a running list of resilience gaps identified while progressing through the TRN's modules in Risk Assessment Action 5.

3.2 Example

Here, we walk through an example of how data supporting the TRN risk analysis would be entered and what the resulting outputs would be.

3.2.1 Site-Level Planning

Though the Site-Level Planning module focuses largely on steps related to establishing the team that will be involved with the resilience planning process (Action 1), collecting information and identifying data sources (Action 2), and defining institutional priorities and the scope of the resilience planning process (Action 3), it also begins the process of defining the critical missions and functions that the site must support (Action 4). In this example, we will identify one critical mission that our site supports: Data Analysis. Note that there may be other missions, but critical missions should include only those that define the reason for the site's existence. These other missions are important to the organization, but do not define the reason the site exists.

For the critical mission of Data Analysis, we can define two critical functions: 1) Data Storage and Processing and 2) IT Training. These critical functions are housed in two facilities at the site: 1) the Data Center and 2) the Training Facility. The final key piece of information that is documented in Site-Level Planning Action 4 is the criticality weighting assigned to each critical function. In this example, the resilience planning team determines, through discussions with site leadership, that the Data Storage and Processing critical function is about 10 times more critical to the site's ability to fulfill its critical mission than the IT Training function. The data recorded in Site-Level Planning Action 4 are summarized in Table 5.

Table 5. Example critical mission, critical functions, criticality weighting factors, and facilities.

Critical Mission	Critical Function	Criticality Weighting Factor	Facilities
Data Analysis	Data Storage and Processing	10	Data Center
	IT Training	1	Training Facility

While going through Site-Level Planning, the resilience planning team may notice some resilience gaps, such as the lack of necessary data. These gaps can be recorded in Site-Level Planning Action 5.

3.2.2 Baseline Development

The Baseline Development module guides users through the process of gathering technical information about their critical loads and the redundant systems that support them. These data are directly used in the risk assessment as described in Section 3.1.1. While key sources of data are identified in Action 1, the data inputs are documented in Actions 2 and 3.

Baseline Development Action 2 focuses on characterizing the critical loads that support critical functions at the site, including capturing their energy and water requirements and their TODs. Data are entered into the tool using an interactive form, seen in Figure 7. This form collects data on TOD and energy and water requirements for critical loads supporting critical functions at the site. In the figure, the critical load Cooling is open for editing. Data has already been entered and saved for the critical loads IT plug loads; Plug loads, lighting, HVAC; and Water for kitchenette and restrooms.

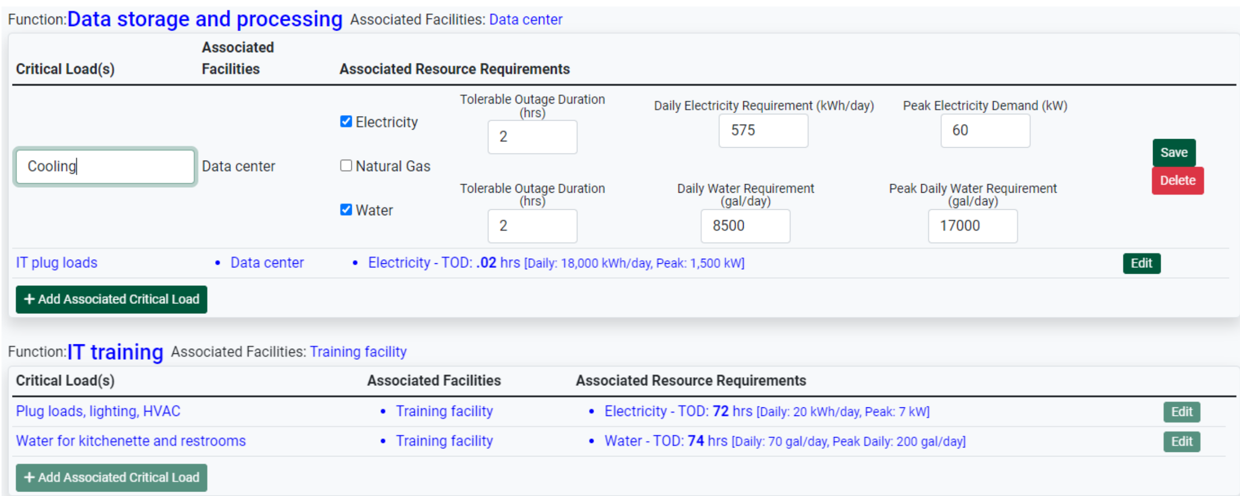


Figure 7. Example data entry form from Baseline Development Action 2.

In Baseline Development Action 3, we record answers to most of the vulnerability questions discussed in Section 3.1.1.2 (that is all questions other than those related to design basis for dual-impact hazards) as well as the time to initiate the redundant system and the redundant system runtime. The data input interface can be seen in Figure 8. Data collected here include the answers to vulnerability questions used to estimate vulnerability associated with each redundant system, startup time for the redundant system, and run time for the redundant system.

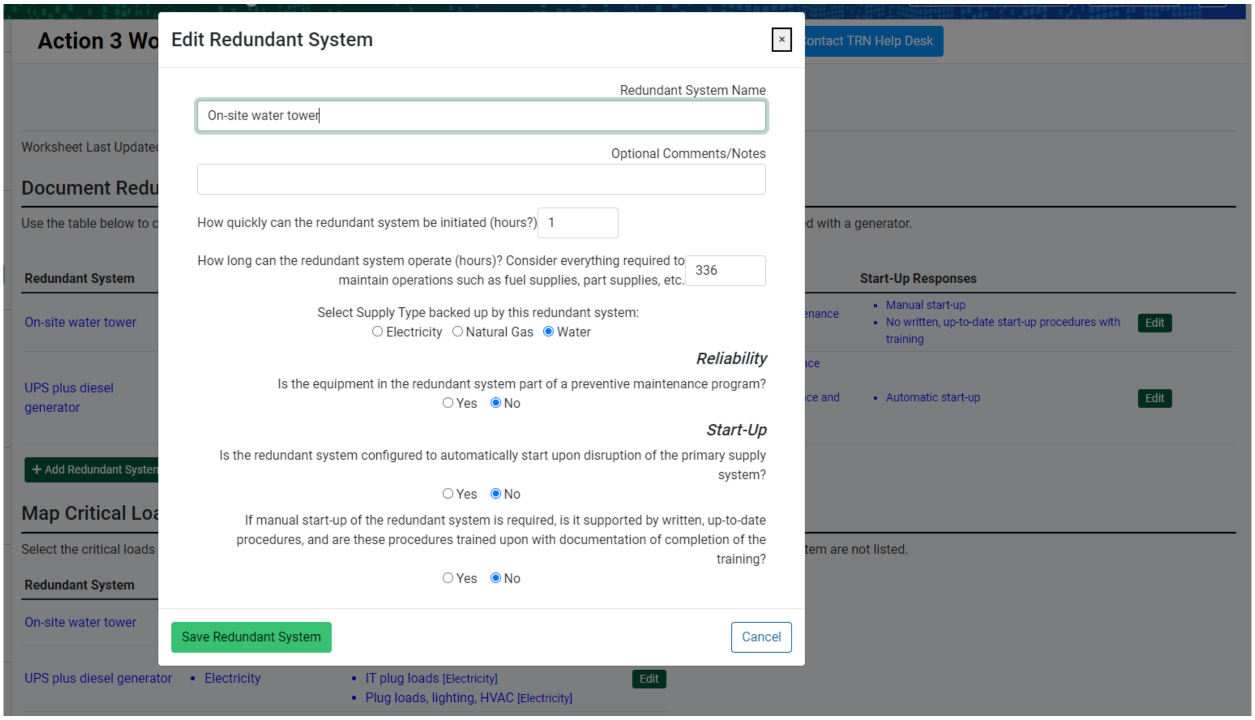


Figure 8. Example data collection for Baseline Development Action 3, as described in Table 4 and used in Equation 2.

For users that need additional guidance for estimating the run time of their redundant systems, the TRN provides two simplified runtime calculators: one for generators (Appendix C –) and one for water systems (Appendix D –).

In Baseline Development Action 3, we also assign redundant systems to the critical loads they support. This allows the TRN web tool to automatically generate risk scenarios with the appropriate vulnerabilities linked to each critical load. In this example, we assign redundant systems to critical loads as shown in Figure 9.

Redundant System	Supported Supply Type	Supported Critical Loads [load supplies required]	
On-site water tower	• Water	• Cooling [Electricity, Water] • Water for kitchenette and restrooms [Water]	Edit
UPS plus diesel generator	• Electricity	• Cooling [Electricity, Water] • IT plug loads [Electricity] • Plug loads, lighting, HVAC [Electricity]	Edit

Figure 9. Example assignment of redundant systems to critical loads.

Again, if any resilience gaps have been noted through the Baseline Development process, they can be added to the running list of resilience gaps in Baseline Development Action 4.

3.2.3 Risk Assessment

In the Risk Assessment module, the final required inputs for the TRN risk assessment are gathered and the outputs are reported. In Risk Assessment Action 1, the ability to restore a critical function without support of each critical load is documented. In our example, we identify that the Data Storage and Processing critical function can be restored at another site, but the process of transferring that function takes 48 hours. This information is documented for all critical loads serving that function (Cooling and IT plug loads). We also note that the IT Training function does not have a function restoration capability (Figure 10).

Critical Function	Critical Load	Tier	Facilities	Supply Type(s) - Redundant Systems	Capability to restore function without critical load?	
Data storage and processing	Cooling	1	• Data center	Electricity - FIRST: UPS plus diesel generator Water - FIRST: On-site water tower	Yes, 48 hrs	Edit
Data storage and processing	IT plug loads	1	• Data center	Electricity - FIRST: UPS plus diesel generator	Yes, 48 hrs	Edit
IT training	Plug loads, lighting, HVAC	2	• Training facility	Electricity - FIRST: UPS plus diesel generator	No	Edit
IT training	Water for kitchenette and restrooms	2	• Training facility	Water - FIRST: On-site water tower	No	Edit

Figure 10. Example documentation of function restoration capability for critical loads, used to calculate C_F in Equation 3.

In Risk Assessment Action 2, we document both grouped hazards and dual-impact hazards for the site. For this example, the hazards along with their associated outage durations and frequencies are shown in Table 6.

Table 6. Example hazard characterization.

Type of Hazard	Hazard Description	Outage Duration	Outage Frequency
Grouped Hazards	Electric outage	1 hour	Likely (once a year)
	Electric outage	1 day	Anticipated (1 in 10 years)
	Electric outage	1 week	Unlikely (1 in 100 years)
	Electric outage	1 month	Extremely unlikely (1 in 1,000 years)
	Water outage	1 hour	Anticipated (1 in 10 years)
	Water outage	1 day	Anticipated (1 in 10 years)
	Water outage	1 week	Unlikely (1 in 100 years)
	Water outage	1 month	Extremely unlikely (1 in 1,000 years)
Dual-impact Hazards	Earthquake, mag. 6.0+, electric outage	1 week	Unlikely (1 in 100 years)
	Earthquake, mag. 6.0+, water outage	1 week	Unlikely (1 in 100 years)
	Hurricane, electric outage	1 day	Anticipated (1 in 10 years)
	Hurricane, water outage	1 week	Unlikely (1 in 100 years)

For the dual-impact hazards, we also note that neither the UPS plus diesel generator nor the onsite water tower are designed to withstand earthquakes of magnitude 6.0 or greater nor are they designed to withstand a hurricane. Based on the collected inputs, the TRN automatically calculates the risk associated with each risk scenario and displays both unweighted and weighted risk values in Risk Assessment Action 3 (Figure 11). Reviewing the risk results at this granular risk scenario-level can provide detailed insight as to what is contributing the most risk to the site.

Critical Load	Facilities	Hazard	Supply Type	Hazard Frequency	Unweighted Risk (hrs/year)	Weighted Risk
Cooling	Data center	Grouped: 1 day	Electricity	Anticipated (1 in 10 years)	0.02	0.2
Cooling	Data center	Grouped: 1 week	Electricity	Unlikely (1 in 100 years)	0.5	4.9
Cooling	Data center	Grouped: 1 month	Electricity	Extremely unlikely (1 in 1,000 years)	0.6	6.0
Cooling	Data center	Grouped: 1 day	Water	Anticipated (1 in 10 years)	2.1	21.2
Cooling	Data center	Grouped: 1 week	Water	Unlikely (1 in 100 years)	1.5	14.8
Cooling	Data center	Grouped: 1 month	Water	Extremely unlikely (1 in 1,000 years)	0.6	6.4
Cooling	Data center	Dual-Impact: Earthquake, mag. 6.0+	Electricity	Unlikely (1 in 100 years)	1.3	13.3
Cooling	Data center	Dual-Impact: Hurricane	Electricity	Anticipated (1 in 10 years)	1.8	17.6
Cooling	Data center	Dual-Impact: Earthquake, mag. 6.0+	Water	Unlikely (1 in 100 years)	1.5	15.3
Cooling	Data center	Dual-Impact: Hurricane	Water	Unlikely (1 in 100 years)	1.5	15.3
IT plug loads	Data center	Grouped: 1 hour	Electricity	Likely (once a year)	0.01	0.1
IT plug loads	Data center	Grouped: 1 day	Electricity	Anticipated (1 in 10 years)	0.02	0.2
IT plug loads	Data center	Grouped: 1 week	Electricity	Unlikely (1 in 100 years)	0.5	4.9
IT plug loads	Data center	Grouped: 1 month	Electricity	Extremely unlikely (1 in 1,000 years)	0.6	6.0
IT plug loads	Data center	Dual-Impact: Earthquake, mag. 6.0+	Electricity	Unlikely (1 in 100 years)	1.3	13.5
IT plug loads	Data center	Dual-Impact: Hurricane	Electricity	Anticipated (1 in 10 years)	1.9	19.2
Plug loads, lighting, HVAC	Training facility	Grouped: 1 week	Electricity	Unlikely (1 in 100 years)	0.5	0.5

Figure 11. Example risk calculated for each scenario. Unweighted risk is calculated using Equation 6 and weighted risk is calculated using Equation 10.

Using the data collected up until this point, in Risk Assessment Action 4, the TRN automatically generates a report showing distribution of total risk across the critical loads (Figure 12) and hazards (Figure 13) included in this example. These graphs can be downloaded from the tool.

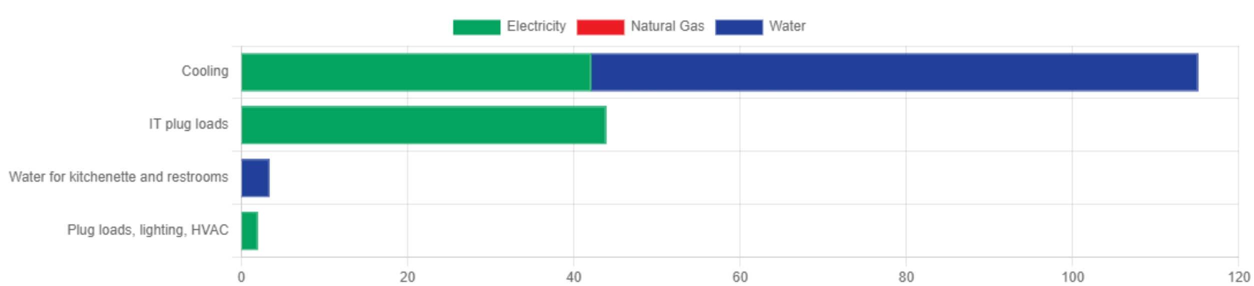


Figure 12. Example graph of weighted risk for each critical load.

Looking at the weighted risk by critical load (Figure 12), we can see the critical loads that are driving risk at the site are the Cooling and IT plug loads, both of which are associated with the Data Storage and Processing critical function. By comparison, the loads associated with the IT Training critical function contribute much less to risk (both in terms of the water and electric loads). We also see that the risk associated with electricity outages is approximately the same for the Cooling load and the IT plug loads. However, the risk associated with water outages is dominated by the Cooling load.

Note that this graph can also be generated for unweighted risk. In this example, unweighted risk exhibits less of a difference between the Data Storage and Processing and the IT Training critical loads. However, even in the unweighted risk, the Data Storage and Processing critical loads account for about three times as much risk as the IT plug loads. This analysis suggests that resilience solution development may have the largest impact on risk if focused on the Cooling and IT plug loads.

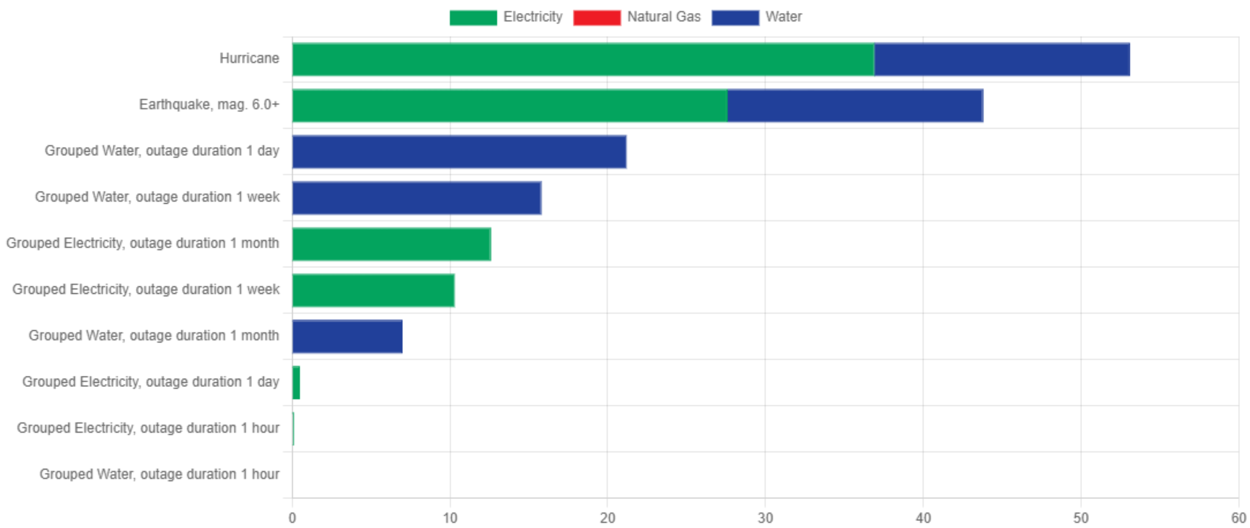
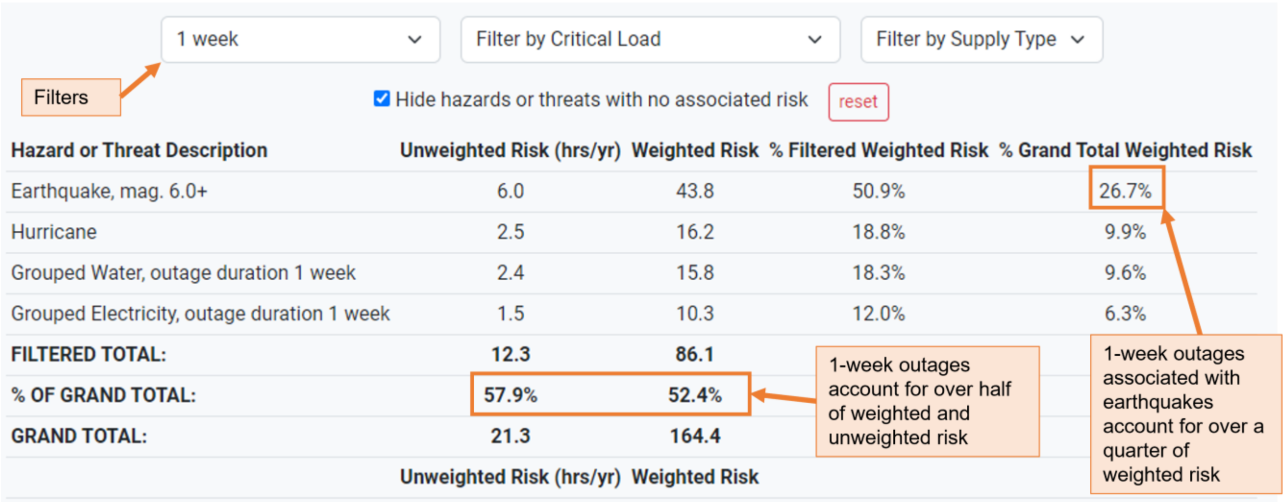


Figure 13. Example graph of weighted risk for each hazard.

A similar analysis can be performed to identify the hazards that drive risk at the site. By examining Figure 13, we can see that hurricanes, earthquakes, and water outages lasting 1 day are the top risk drivers, and that for the top two risk drivers, the supply type driving that risk is electricity.

If we consider only risk associated with water outages, we see that the major driver is outages lasting 1 day, though risk associated with outages from hurricanes, earthquakes, and lasting 1 week are all close behind. Overall, this analysis suggests that risk is driven mainly by relatively short duration (≤ 1 week) outages in electricity and water. This implies that resilience solutions should be focused on reducing vulnerability or improving performance for those durations. This could be accomplished by improving training and maintenance for redundant systems or extending backup capabilities to support critical loads for outages of durations up to 1 week. Additionally, since both hurricanes and earthquakes are risk drivers for both electricity and water, the resilience planning team may consider solutions related to enhancing the design basis of redundant systems at the site for these hazards.



Hazard or Threat Description	Unweighted Risk (hrs/yr)	Weighted Risk	% Filtered Weighted Risk	% Grand Total Weighted Risk
Earthquake, mag. 6.0+	6.0	43.8	50.9%	26.7%
Hurricane	2.5	16.2	18.8%	9.9%
Grouped Water, outage duration 1 week	2.4	15.8	18.3%	9.6%
Grouped Electricity, outage duration 1 week	1.5	10.3	12.0%	6.3%
FILTERED TOTAL:	**12.3**	**86.1**		
% OF GRAND TOTAL:	**57.9%**	**52.4%**		
GRAND TOTAL:	**21.3**	**164.4**		
	Unweighted Risk (hrs/yr)	**Weighted Risk**		

Figure 14. Example of risk results displayed using the filter table in Risk Assessment Action 4, filtered to show risk scenarios incorporating 1-week outages of all supply types.

Additional insights can be gained from analysis of the risk results using the Review Risk Factors table provided in Risk Assessment Action 4. For example, we can use this table to confirm that 1-month outages are not significant risk contributors (they account for 14.5% of unweighted risk and 12% of weighted risk) by filtering to view only risk scenarios with 1-month outage durations. By changing the filter to look at 1-week outages (Figure 14), we can see that outages lasting for one week account for over half of both weighted and unweighted risk. We can also see that 1-week outages resulting from earthquakes account for over a quarter of weighted risk at the site. This tool can also be used to filter results by critical load and/or supply type.

3.3 Sensitivity Analysis

Sensitivity analysis allows users to investigate inputs that are major drivers of the risk model and understand how changes to these inputs may impact results. The sensitivity analysis capability within the TRN web tool focuses on a few inputs to the risk analysis that are most likely to be associated with uncertainty that the user may wish to explore. These inputs were chosen based on two main drivers for uncertainty:

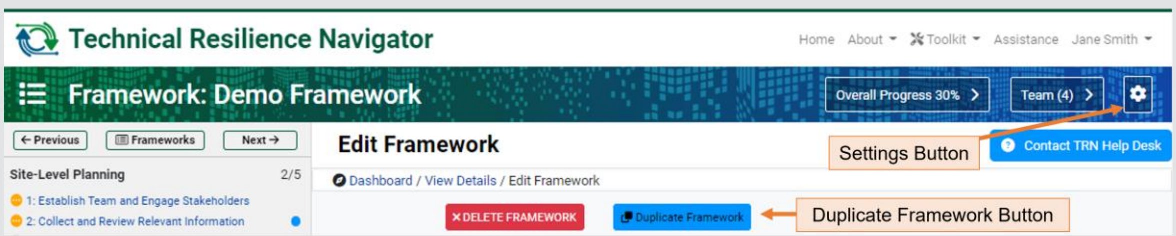
- **Inputs based on professional judgment.** For certain inputs, the value assigned may be based on a subjective determination from the resilience planning team or other stakeholders. The ability to conduct a sensitivity analysis that adjusts these inputs can help the user to understand how their decisions about assigning values may drive or have minimal impact on the risk results. Inputs that fall under this driver are:
  - Criticality Weighting Factors
  - Tolerable Outage Durations
- **Inputs that are expected to change over time.** For inputs that are likely to change as a result of future conditions, sensitivity analysis allows users to adjust these inputs to understand how the site's energy and water risk may change as a result of future conditions. One example of a future scenario that the user may want to investigate is the potential effect of climate change on hazards that could impact the site (Delgado and Rabinowitz 2021; Rabinowitz et al. 2022). Inputs that fall under this driver are:

- Grouped Hazards
- Dual-Impact Hazards

In both cases, the user can adjust inputs to generate a sensitivity case. The TRN tool then calculates the risk associated with each sensitivity case, allowing the user to see how the risk distribution shifts between the original base case and the sensitivity cases. Of particular interest is whether the adjustments in criticality weighting factors, TODs, grouped hazards, and/or dual-impact hazards result in a different set of critical loads or hazards that are driving risk. If the sensitivity cases result in the same set of risk drivers, this may give the user more confidence that the risk drivers they identified in Risk Assessment Action 4 are really the areas on which they may want to focus resilience solutions to reduce risk. If some sensitivity cases result in different critical loads or hazards rising to the top as risk drivers, the user may consider whether their initial assumptions should be adjusted or whether additional risk drivers and/or resilience gaps should be recorded. These additional drivers could then serve as the foundation for additional solutions to consider in the Solution Development module.

Framework Duplication

Though the sensitivity analysis capability allows the user to adjust only a few inputs, the TRN also provides the ability for the user to investigate the risk impacts of more extensive adjustments to the inputs. In the framework settings (to get there, click on the gear button in the framework banner), the user can click on “Duplicate Framework”. This will allow the user to make an exact copy of the framework that they can rename and use to adjust any TRN inputs of interest.



Note that the TRN does not currently have functionality to compare different frameworks with each other.

4 Solution Development and Evaluation

Following the identification of risk drivers as well as other resilience gaps that may have been recorded throughout the first three TRN modules, users begin the process of developing and evaluating resilience solutions. This process culminates in a prioritized list of resilience solutions that the user can use as a basis for determining which solutions should move forward into more in-depth project planning phases.

4.1 Developing Resilience Solutions for Prioritization

Throughout the TRN process, users document any resilience gaps that become evident as a result of stakeholder engagement, data collection, and/or risk analysis. In the Solution Development module, users brainstorm potential solutions that could be used to address the identified resilience gaps.

This process begins in Site-Level Planning Action 5, Baseline Development Action 4, and Risk Assessment Action 5 where users identify and characterize each resilience gap in more detail. Each gap is characterized in terms of its type (Technological, Operational, and/or Institutional), its resilience attributes (Redundant, Robust, Resourceful, and/or Recovery), and the critical loads and supply types that it impacts. In Solution Development Action 1, the TRN summarizes how many solutions fall under each gap type, each resilience attribute, and each supply type (electricity, natural gas, and water). This is intended to aid the user in determining whether they may have neglected identifying certain categories of resilience gaps that should be considered. For example, if the gap summary tables are as seen in Figure 15, the user may consider whether there are any additional gaps that were not captured related to the natural gas system.

Gap Types	
Technological	11
Operational	4
Institutional	3

Gap Attributes	
Redundant	9
Robust	9
Resourceful	2
Recovery	3

Gap Supply Types	
Electricity	9
Natural Gas	1
Water	8

Figure 15. Example of resilience gap characterization summary.

Once resilience gaps have been analyzed, the user can begin brainstorming solutions to address those gaps in Solution Development Action 2. The intention is for the resilience planning team to document any solution that is thought of, whether or not it is practical or feasible. There are opportunities later in the TRN process to screen solutions that will be analyzed for prioritization, but the brainstorming process is intended to capture and document all potential solutions. Even if a solution is not practical at the moment for political or economic reasons, it is possible that conditions will change in the future (e.g., the price of the technology could decrease due to market forces) and the site may want to consider it.

Solution Development Action 3 provides the opportunity to bundle solutions together into solution sets for analysis as a combined solution. It is sometimes worth analyzing groups of solutions as solution sets for a couple of reasons. First, there may be economies of scale, reducing costs associated with implementing a package of solutions together, particularly if they impact either the same facility, the same redundant system, or involve the same technology or other improvement for multiple facilities. For example, if several solutions impact the Training Facility, they may have a bigger impact and potentially achieve economies of scale if they were to be implemented as a solution set that is part of an upcoming building renovation as opposed to being implemented individually as one-off solutions. Another reason it can be useful to analyze solution sets is due to the multiplicative nature of the risk calculation. A set of solutions may provide a greater modeled risk reduction than the sum of the risk reductions for each individual solution.

Once solutions and solution sets have been developed, they are screened in Solution Prioritization Action 1. In this action, users identify go/no-go criteria that can be used to determine whether a solution should progress further for analysis. For example, one go/no-go criterion could be excessive cost. If a solution does not meet that criterion, it would be marked with a no-go designation and would not proceed to solution analysis. This approach allows users to document solutions that may not be feasible at the current time, but not use significant amounts of time investigating and characterizing those solutions for the current prioritization effort. A solution can later be marked as go, enabling it to be analyzed using the process described below if conditions change.

4.2 Solution Risk Assessment

In Solution Prioritization Action 2, users are able to evaluate each proposed resilience solution for its risk-reduction potential. For each solution, users can adjust the redundant system characterization (startup time, estimated run time, and responses to vulnerability questions) and critical load characterization (Figure 16).

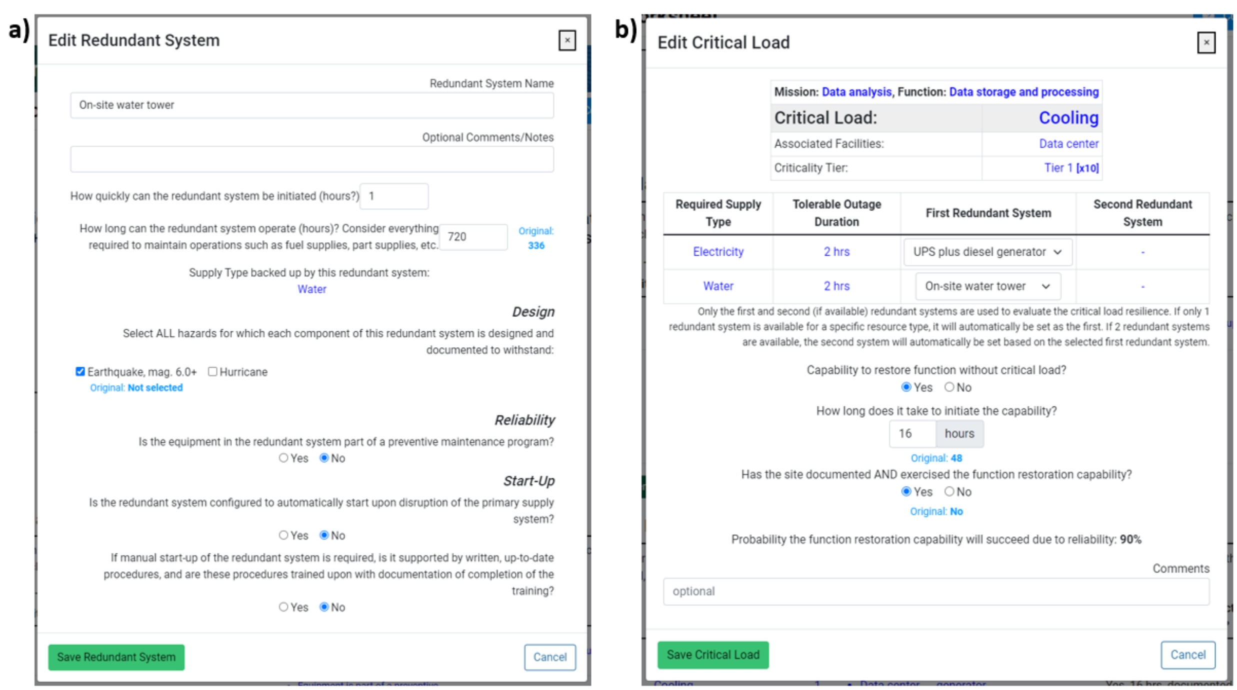


Figure 16. Examples of adjusted inputs for a resilience solution analyzed in Solution Prioritization Action 2, including a) adjustments to the redundant system characterization and b) adjustments to the ability to restore the critical functions served by the load and which redundant system(s) support the load. Note that changed parameters display the original response to the question in blue text.

Based on how each solution would change the risk inputs, as modified in the forms shown in Figure 16, the TRN web tool calculates the risk associated with the solution. To understand how effective the solution would be at reducing risk, the solution risk can be compared with the current risk (the risk calculated based on current conditions documented through the Site-Level Planning, Baseline Development, and Risk Assessment modules). This comparison is displayed as the risk-reduction efficacy, which is calculated as:

$$Risk\ reduction\ efficacy = \frac{Current\ weighted\ risk - Solution\ weighted\ risk}{Current\ weighted\ risk} \times 100\% \quad \text{Equation 11}$$

Risk-reduction efficacy is automatically calculated, based on the adjusted inputs as shown in Figure 16, and assigned to a category for use later in the Solution Prioritization module (Table 7). Each category has an associated risk-reduction efficacy score (B_R) that is used in the calculation of a solution benefit potential.

Table 7. Risk-reduction efficacy category assignment.

Calculated risk-reduction efficacy	Risk-reduction efficacy category	Risk-reduction efficacy benefit score (B_R)
< 25%	Minor	1
25% – <50%	Moderate	2
50% – <75%	Significant	3
75% – 100%	Major	4

Both the calculated risk-reduction efficacy and the category are displayed in the Solution Prioritization Action 2 summary table. An example of this output can be seen in Figure 17.

Current Weighted Risk: **164.42**

Solution Description	Supply Types Affected	Solution Weighted Risk	Risk-Reduction Efficacy	
Reduce required time to move operations to offsite data center, and train on that process.	• Electricity • Water	68.61	Significant (58%)	Update Impacts
Implement COOP plan.	• Electricity • Water	100.94	Moderate (39%)	Update Impacts
Arrange MOU/mutual aid agreement to obtain fuel resupply, extending electrical redundant system capability to 1 week.	• Electricity	151.45	Minor (8%)	Update Impacts
Implement ability to move training offsite.	• Electricity • Water	159.66	Minor (3%)	Update Impacts
Full set of electrical and water redundant system improvements (water efficiency, hazard design, robust water PM, automate water start-up, MOU) + improvement of process to move data center operations offsite.	• Electricity • Water	3.41	Major (98%)	Update Impacts
Full set of electrical and water redundant system improvements (water efficiency, hazard design, robust water PM, automate water start-up, MOU).	• Electricity • Water	14.05	Major (91%)	Update Impacts
Upgrade electrical and water redundant systems with earthquake and hurricane design.	• Electricity • Water	109.73	Moderate (33%)	Update Impacts
Add PV microgrid with batteries, capable of supporting elec. critical loads for 1 week, and 20% of site elec. loads during normal operations.	• Electricity	88.81	Moderate (46%)	Update Impacts

Figure 17. Example output showing risk-reduction efficacy of a series of resilience solutions.

4.3 Nonrisk Prioritization Criteria

Though reducing risk is a critical aspect of resilience planning, organizations must frequently balance multiple priorities when deciding where to invest money for improving energy and water systems at their sites. To address this, the TRN allows users to optionally evaluate solutions with respect to user-specified criteria other than risk. Additionally, the TRN includes one required nonrisk criterion, decarbonization potential, which is evaluated in its own action in the Solution Prioritization module. The risk and nonrisk criteria are all incorporated into the ultimate solution benefit potential.

4.3.1 Emissions Impact

While much of the TRN focuses on risk reduction to support resilience, federal agencies are also working to meet ambitious emissions reduction requirements for their facilities. To meet these requirements, it is important for resilience planning teams to understand how the energy and water resilience solutions proposed through the TRN process would impact progress toward emissions reduction.

Carbon dioxide (CO_2) emissions reduction is achieved through strategies that reduce the use of fossil fuels. In the TRN, this is modeled through two main strategies:

- Reduce energy consumption, and thus demand for fossil fuels, through approaches such as increasing energy efficiency. These types of solutions are generally associated with a reduction in scope 1 (or direct) emissions.
- Provide electricity via sources with lower CO_2 emissions, such as renewable energy resources. These types of solutions are generally associated with reductions in scope 2 (or indirect) emissions.

The emissions impact analysis takes place in Solution Prioritization Action 3, an action added to the TRN in September 2022. In this action, users evaluate whether each potential solution has the potential to provide a notable reduction in the site's energy-related CO_2 emissions (Elliott et al. 2022). The emissions impact analysis follows an approach consistent with the semi-quantitative TRN risk assessment discussed in Section 3.1, with emissions reduction for each solution falling into one of four categories: major emissions reduction, significant emissions reduction, marginal emissions reduction, and no emissions reduction. These categories are assigned based on a quantification of the CO_2 emissions reduction for each solution as a percentage of the current energy-related CO_2 emissions at the site. The analysis focuses on emissions reductions associated with the electricity and natural gas systems, in line with the focus of the rest of the TRN process. Producing emissions reduction estimates as a percentage of current site emissions allows the output of the analysis to reflect the types of decarbonization goals being set by federal agencies in their Climate Adaptation and Resilience Plans as well as Executive Orders that set decarbonization goals across the federal government.

One area in which the emissions impact analysis departs from the scope of the TRN risk assessment is that CO_2 emissions reductions reflect the *total* energy use at the site associated with electricity and natural gas rather than being limited to critical loads. Broadening the scope of the emissions reduction analysis in this way allows the user to take credit for emissions reduction benefits that extend beyond their critical loads. Again, this approach allows the emissions reduction benefit potential calculated in the TRN to be more reflective of the site's potential progress toward meeting their federal decarbonization goals, which consider emissions across the site rather than focusing only on the critical loads.

4.3.1.1 Emissions Impact Inputs

There are two general types of inputs in Solution Prioritization Action 3:

- **Solution agnostic inputs.** These characterize the current CO_2 emissions associated with the site's electricity and natural gas usage.
  - **Average emissions factor.** Associated with the site's electric grid subregion and represents the average CO_2 emissions from the electricity produced and used within that subregion. The average emissions factor is auto-populated using estimates from the Environmental Protection Agency (EPA) eGRID website (EPA 2019), but can be adjusted by the user if they have a more specific estimate that incorporates site-specific electricity sources (e.g., onsite electricity generation).
  - **Marginal emissions factor.** Associated with the site's electric grid subregion, it represents CO_2 emissions from marginal or nonbaseload plants within that subregion. These plants will ramp generation up or down in response to demand increases or decreases, respectively. The marginal emissions factor is auto-populated using estimates from the EPA eGRID website (EPA 2019), but can be adjusted by the user.
  - **Present site energy use.** The amount of electricity and natural gas that is currently used annually at the site. This is a user input.
- **Solution-specific inputs.** For each solution, these inputs characterize the CO_2 emissions associated with the site's electricity and natural gas usage in the event that the solution would be implemented.
  - **Changes to site energy use.** How would electricity and/or natural gas use change if the solution was implemented (increase or decrease)?
  - **Shift of electricity consumption.** How would the solution shift electricity consumption to another resource?
  - **Emissions factor for new electricity generation.** What is the emissions factor associated with the new electricity source? This can be as low as zero for fully renewable generation. This is a user-entered value, but the TRN provides example emissions factors of common site-level electricity generation technologies based on EPA eGRID data.

For the first two solution-specific inputs, the user can select using a drop-down as seen in Figure 18. These dropdowns allow the user to specify how much energy use (both electricity and natural gas) will change as a percentage of the current site energy use (Table 8) and how much electricity will be shifted to another source as a percentage of the electricity that would be used at the site if the solution was implemented (Table 9). This approach of using percentage ranges as opposed to direct inputs allows the user to conduct the analysis at a high level with rough estimates, rather than waiting to conduct the analysis until in-depth design efforts have been undertaken for the proposed solutions. The third input is a direct user input. However, the TRN provides estimates for technology-specific emissions factors based on analysis of eGRID plant data as a starting point.

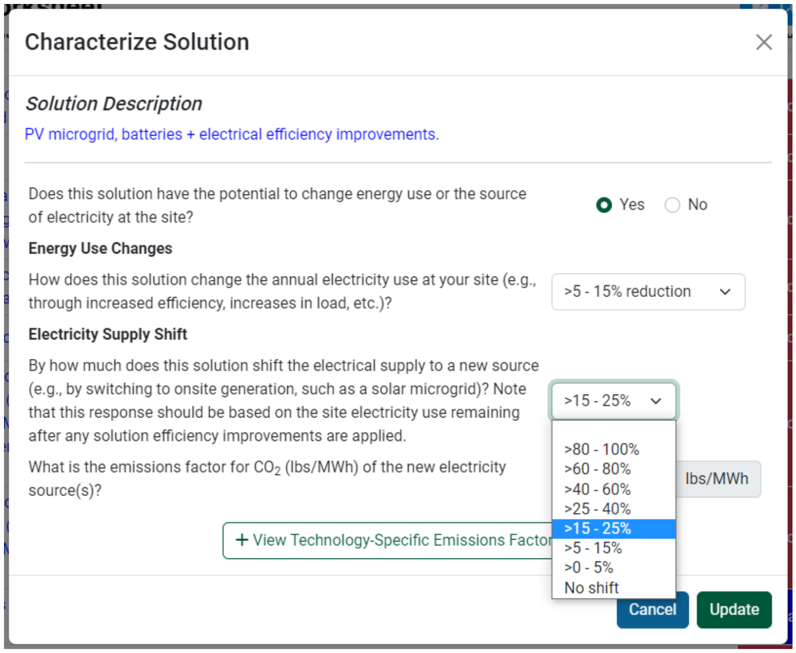


Figure 18. Example data entry form to input solution-specific data characterizing decarbonization inputs for the resilience solution "Install solar PV microgrid, batteries + electrical efficiency improvements."

For each percentage range, the number used in the calculations described in Section 4.3.1.2 are the midpoints of the range as shown in the examples in Table 8 and Table 9. Note that the dropdown options for energy use changes allow solutions to be characterized as either decreasing energy use (e.g., efficiency measures) or increasing energy use. Table 8 shows examples of the associated electricity and natural gas use changes as well as the midpoint values used in calculations. Arrows indicate whether the energy use would be reduced (down) or increased (up) by the solution.

Table 8. Energy use percent change ranges available in dropdown menu.

	Example of change ranges			
Energy use change percentage range	Electricity, using E_p= 2000 MWh/year	Electricity, midpoint	Natural gas, using N_p = 4000 MMBtu/year	Natural gas, midpoint
>80 – 100% ↓	>1600–2000 ↓	1800 ↓	>3200–4000 ↓	3600 ↓
>60 – 80% ↓	>1200–1600 ↓	1400 ↓	>2400–3200 ↓	2800 ↓
>40 – 60% ↓	>800–1200 ↓	1000 ↓	>1600–2400 ↓	2000 ↓
>25 – 40% ↓	>500–800 ↓	650 ↓	>1000–1600 ↓	1300 ↓
>15 – 25% ↓	>300–500 ↓	400 ↓	>600–1000 ↓	800 ↓
>5 – 15% ↓	>100–300 ↓	200 ↓	>200–600 ↓	400 ↓
>0 – 5% ↓	>0–100 ↓	50 ↓	>0–200 ↓	100 ↓
No change (0%)	0	0	0	0
>0 – 25% ↑	>0–500 ↑	250 ↑	>0–1000 ↑	500 ↑
>25% ↑	>500 ↑	750 ↑	>1000 ↑	1500 ↑

This is intended to capture solutions that may improve resilience but may also increase the amount of electricity or natural gas used. However, because the purpose of adding this emissions impact methodology is to allow sites to model how well their resilience solutions would help to contribute to emissions reductions, the dropdown options for energy use reductions are more granular than those for energy use increases.

Note that the energy shift input accounts only for shifts in electricity generation and does not consider changes in the source of natural gas used. Table 9 shows examples of the associated electricity shifts as well as the midpoint values used in calculations. Shifts in electricity account for solutions that shift site electricity use from the current utility (or other) electricity supply to a lower emissions source. This could include building a renewable microgrid on the site to supply some percentage of electricity use. In contrast, solutions associated with shifting natural gas supplies to a substitute lower emissions fuel are less common.

Table 9. Electricity consumption shift ranges available in the dropdown menu.

Electricity consumption shift percentage range	Example of shift ranges Electricity, using E_p= 2000 MWh/year and E_s = 400 MWh/year)	Midpoint
>80 – 100%	>1280–1600	1440
>60 – 80%	>960–1280	1120
>40 – 60%	>640–960	800
>25 – 40%	>400–640	520
>15 – 25%	>240–400	320
>5 – 15%	>80–240	160
>0 – 5%	>0–80	40
No shift (0%)	0	0

4.3.1.2 Calculation of Emissions Impact

The emissions impact calculations, as discussed above, aim to use inputs characterizing how each solution would change energy use and/or shift electricity supply to estimate the reduction of CO_2 emissions if the solution were implemented. These calculations are performed automatically by the TRN tool to display the output, both in terms of the CO_2 emissions reduction and the reduction category on a four-category scale. Below, the calculations to determine avoided emissions associated with each solution are presented for the electricity and natural gas systems.

Electricity

The tool characterizes total avoided CO_2 emissions at a site associated with the implementation of a resilience solution based on the two factors described above. The avoided emissions associated with electricity for each solution (A_E) are calculated as follows:

$$A_E = \gamma_{margingal} U_E E_p + S_E E_p (1 - U_E)(\gamma_{marginal} - \gamma_{s,E}) \quad \text{Equation 12}$$

where $\gamma_{marginal}$ is the marginal emissions factor of the site's electric utility or existing electricity supply, U_E is the change in electricity use as a fraction of its present use, E_p is the site's present annual electricity use (MWh), S_E is the amount of the site's electricity use that will be shifted from the present electricity supply mix to a lower emissions source as a fraction of its electricity use under the solution, and $\gamma_{s,E}$ is the emissions factor of the new electricity supply. U_E and S_E are the midpoints of the percentage ranges selected by the user from the dropdown menus described in Section 4.3.1.1 (in fractional form). If the user selects the >25% increase option, U_E is taken to be the midpoint between 25% and 50%, or 37.5%.

The site's present annual emissions associated with electricity (G_E) are:

$$G_E = \gamma_{avg} E_p. \quad \text{Equation 13}$$

where γ_{avg} is the average emissions factor for the site's utility or existing electricity supply.

Natural Gas

The avoided emissions associated with natural gas for each solution (A_{NG}) are calculated as follows:

$$A_{NG} = \gamma_{NG} U_{NG} N_p \quad \text{Equation 14}$$

where γ_{NG} is the CO_2 emissions factor for natural gas (116.65 lbs/MMBtu, EIA 2021), U_{NG} is the change in natural gas use as a fraction of the site's present use, and N_p is the site's present annual natural gas use (MMBtu). U_{NG} is the midpoint of the percentage range selected by the user from the dropdown menu described in Section 4.3.1.1 (in fractional form). If the user selects >25% increase, U_{NG} is assumed to be the midpoint between 25% and 50%, or 37.5%.

Note that Equation 14 is equivalent to Equation 12, aside from the fact that it does not include a term for shifting natural gas supply to a lower emissions gas supply (e.g., renewable natural gas). As discussed above, this is because solutions related to substitute gas supplies are less common and less well characterized than those associated with shifting the electricity source to a lower emissions source.

The site's present annual natural gas emissions (G_{NG}) are:

$$G_{NG} = \gamma_{NG} N_p. \quad \text{Equation 15}$$

4.3.1.3 Emissions Impact Outputs

Once the avoided and present annual emissions are calculated, the impact, in terms of a reduction in CO_2 emissions relative to current emissions, is determined using the following metric:

$$\frac{A_E + A_{NG}}{G_E + G_{NG}} * 100\%. \quad \text{Equation 16}$$

This calculated emissions impact is reported in terms of a categorical emissions reduction categories using the designations in Table 10. These categories are designed to be comparable with the four risk categories (Table 7) and are similarly assigned a benefit score, in this case an emissions reduction benefit, B_E. Because different organizations may have significantly different definitions of what qualifies as a major, significant, or marginal emissions reduction, the TRN web tool allows users to adjust the breakpoint values between each category. It is recommended that all sites within an organization's portfolio use the same breakpoint values to allow for comparisons and prioritization of projects between sites.

Table 10. Decarbonization benefit categories.

Decarbonization benefit category	Calculated emissions reduction[a]	Emissions reduction score (B_E)
Major	50 –100%	4
Significant	10 – <50%	3
Marginal	>0 – <10%	2
No emissions reduction	≤0%	1

[a] Ranges can be adjusted by the user

4.3.2 Qualitative Prioritization Criteria

In addition to the benefit associated with risk-reduction and emissions reduction potentials, sites may have other criteria they would like to use for evaluating and prioritizing resilience solutions. To allow for user flexibility in selecting the most relevant prioritization criteria for their site, the TRN allows users to specify up to five additional prioritization criteria that are relevant to their site. Such criteria could include priorities such as “meets training goals” or “improves water conservation.” Because these criteria are user-defined, the determination of how well each solution meets each criterion is also defined by the user using a fully qualitative ranking scale, shown in Table 11. Like with risk-reduction efficacy (Table 7) and emissions reduction (Table 10), qualitative prioritization criteria are assigned a benefit score, B_i, where i refers to the qualitative criterion between 3 and 7.

Table 11. Qualitative prioritization criterion benefit categories.

How well the solution meets prioritization criterion	Qualitative criterion benefit category	Qualitative criterion benefit score (B_i)
Solution does not address this criterion	Not well	1
Solution only partially addresses the criterion	Moderately well	2
Solution provides significant progress in meeting the criterion, but does not fully address	Well	3
Solution fully addresses criterion	Very well	4

4.4 Solution Benefit Potential

Quantitative and qualitative criteria are combined to generate an overall resilience solution benefit potential. First, for each criterion, users must assign a weighting factor, α, to reflect the relative importance of that criterion to the site. For example, if the resilience planning team determines that risk-reduction efficacy is 10 times more important than meeting training goals, but only twice as important as the emissions reduction potential, it could assign a weight of 10 to risk-reduction efficacy, 5 to emission reduction potential, and 1 to meeting training goals. The TRN web tool automatically converts these numerical weights to percentages that sum to 100%, which can be expressed as fractions: α_R=0.625, α_E=0.313, and α_3=0.063.

The overall solution benefit potential is calculated as a weighted average of the solution prioritization criteria, using the scores associated with the benefit categories assigned to each solution and the user-assigned criterion weights. The total solution benefit potential (B_{total}) is calculated using the following equation:

$$B_{total} = \alpha_R B_R + \alpha_E B_E + \sum_i \alpha_i B_i . \quad \text{Equation 17}$$

In the example above, let's say that for a particular solution, the risk-reduction efficacy was calculated to be 32% (moderate, B_R=2), the emissions reduction potential was calculated to be 44% (significant, B_E=3), and the rating with respect to meeting training goals was determined to be "not well" (B_3=1). In this case, using the prioritization criterion weightings specified above, the solution benefit potential would be calculated as:

$$B_{total} = 0.625 * 2 + 0.313 * 3 + 0.063 * 1 = 1.25 + 0.939 + 0.063 = 2.25 \quad \text{Equation 18}$$

Based on the calculated solution benefit potential, each solution is assigned a solution benefit potential rating, as shown in Table 12.

Table 12. Solution benefit categories.

Calculated solution benefit potential range	Solution benefit potential rating
<1.5	Low potential for benefit
1.5 to <2.5	Moderate potential for benefit
2.5 to <3.5	High potential for benefit
3.5 to 4	Very high potential for benefit

While the TRN requires both risk-reduction efficacy and emissions reduction be variables in the calculation of B_{total}, it does not set any minimum or maximum value for their weighting. This flexibility allows the resilience planning team to define the relative importance of risk reduction, emissions reduction, and other user-defined qualitative criteria that best fits their site and leadership. Without careful consideration of these weights, however, it is possible that the resilience planning team may arguably underweight insights derived from robust quantitative analysis and overweight qualitative inputs that are much less rigorously derived and defensible.

Returning to the example above, let's say the user changed weighting for their three criteria to heavily weight how well a solution meets their training goals, α_R=0.13, α_E=0.13, and α_3=0.74. In this new case, using the prioritization criterion scores specified above, the solution benefit potential would be calculated as:

$$B_{total} = 0.13 * 2 + 0.13 * 3 + 0.74 * 1 = 0.26 + 0.39 + 0.74 = 1.39 \quad \text{Equation 19}$$

This revised weighting would change the solution benefit potential from moderate to low. Analytical work conducted previously in the TRN process to understand risk-reduction efficacy and emissions reduction potential is likely being underemphasized as a result of this weighting, demonstrating a key word of warning to users. Underemphasizing the results from quantitative outputs in the final calculation of the solution benefit potential in favor of qualitative inputs results in lost insight derived from the TRN's formal risk structure.

4.5 Estimating Solution Costs

In addition to quantifying the potential benefits of each solution, it is important to quantify the cost of implementing each solution to determine which solutions are candidates for implementation. First, the resilience planning team works with relevant personnel at the site and/or within the organization to determine the basis for estimating the relative cost of the solutions. Specifically, the user selects a number of years over which to assess the cost. The relevant number of years may be based on the typical analysis period for energy and water projects or other considerations. Then, the user sets breakpoints between each cost category reflecting what the organization considers to be minimal, low, moderate, and high costs over the selected number of years (Figure 19).

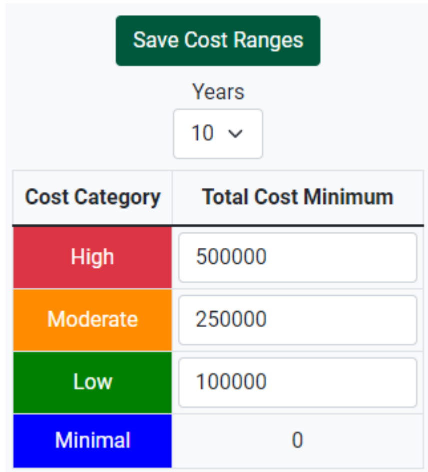


Figure 19. Example of data entry for setting cost categories in the TRN.

Once cost categories and the number of years for analysis have been set, the user can estimate the initial or upfront cost for each solution as well as the ongoing annual costs. Based on those inputs, the TRN web tool automatically calculates the total cost over the specified number of years and assigns the appropriate cost category for the solution.

4.6 Prioritizing Resilience Solutions

The ultimate output of the TRN assessment process is a prioritized list of resilience solutions. This list can be used to determine which solutions merit further consideration and development through the Roadmap to Action module. The TRN provides users the ability to sort resilience solutions based on their solution benefit potential and their cost. Users can decide to prioritize first based on benefit potential, with cost being the secondary factor (e.g., Figure 20), or prioritize based on cost first with benefit potential being the secondary factor.

Cost vs Potential	Very High Potential	High Potential	Moderate Potential	Low Potential
Minimal Cost	1st	5th	9th	13th
Low Cost	2nd	6th	10th	14th
Moderate Cost	3rd	7th	11th	15th
High Cost	4th	8th	12th	16th

Figure 20. Solution prioritization ordering scheme that prioritizes highest benefit potential first and lowest cost second.

Within each priority category (e.g., very high benefit potential and minimal cost are prioritized first in Figure 20), any ties are resolved based on the numerical value of the benefit potential and estimated cost. So, for prioritization schemes that prioritize highest benefit potential, the sort order is based on:

1. Benefit potential category
2. Cost category

In cases where there are ties:

1. Calculated benefit potential
2. Calculated cost

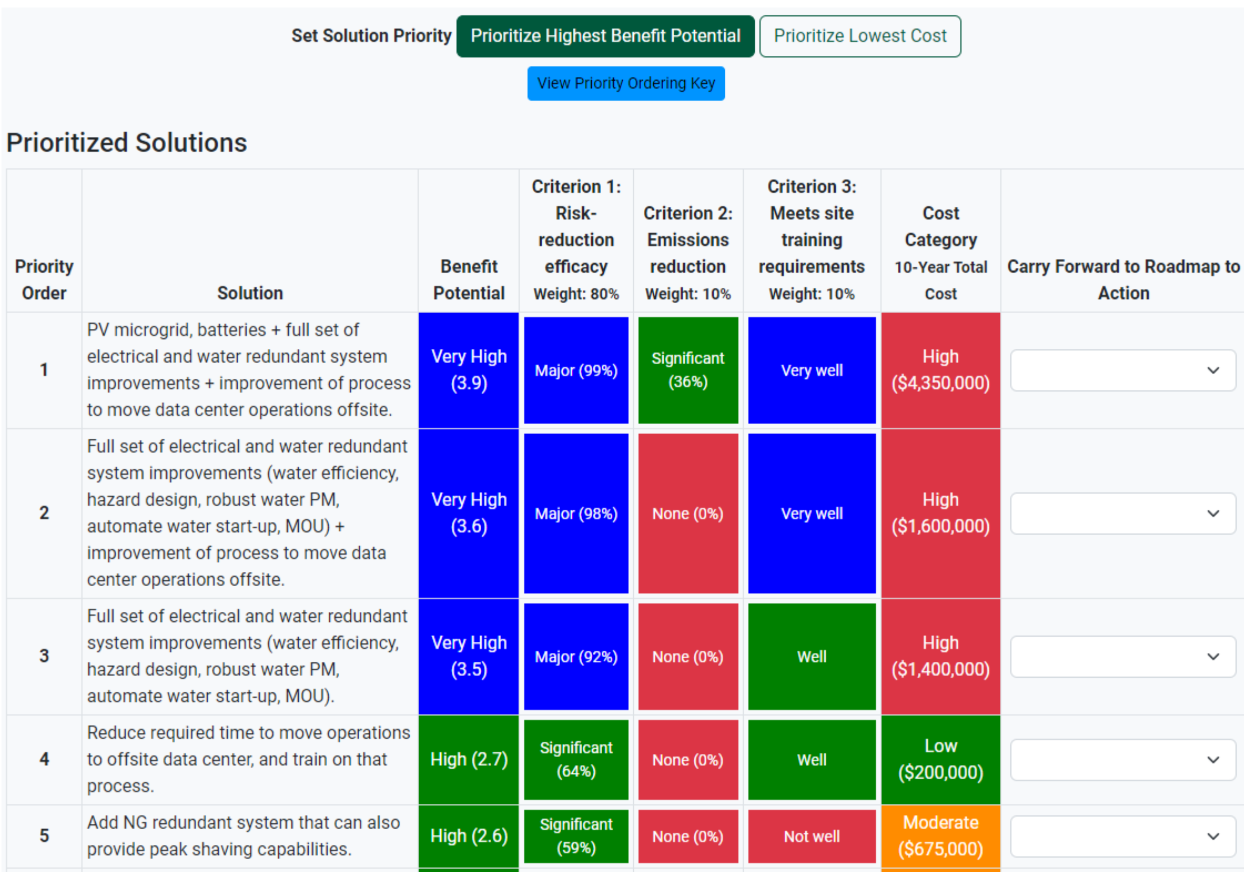
For prioritization schemes that prioritize lowest cost, the sort order is based on:

1. Cost category
2. Benefit potential category

In cases where there are ties:

1. Calculated cost
2. Calculated benefit potential

An example of the solution prioritization output can be seen in Figure 21. Notice that, while the prioritization based on benefit uses the solution benefit potential rather than the individual prioritization criteria, each criterion's score is also shown for each solution. This allows users to view how each solution addresses each individual organizational priority.



Priority Order	Solution	Benefit Potential	Criterion 1: Risk-reduction efficacy Weight: 80%	Criterion 2: Emissions reduction Weight: 10%	Criterion 3: Meets site training requirements Weight: 10%	Cost Category 10-Year Total Cost	Carry Forward to Roadmap to Action
1	PV microgrid, batteries + full set of electrical and water redundant system improvements + improvement of process to move data center operations offsite.	Very High (3.9)	Major (99%)	Significant (36%)	Very well	High ($4,350,000)	
2	Full set of electrical and water redundant system improvements (water efficiency, hazard design, robust water PM, automate water start-up, MOU) + improvement of process to move data center operations offsite.	Very High (3.6)	Major (98%)	None (0%)	Very well	High ($1,600,000)	
3	Full set of electrical and water redundant system improvements (water efficiency, hazard design, robust water PM, automate water start-up, MOU).	Very High (3.5)	Major (92%)	None (0%)	Well	High ($1,400,000)	
4	Reduce required time to move operations to offsite data center, and train on that process.	High (2.7)	Significant (64%)	None (0%)	Well	Low ($200,000)	
5	Add NG redundant system that can also provide peak shaving capabilities.	High (2.6)	Significant (59%)	None (0%)	Not well	Moderate ($675,000)	

Figure 21. Example solution prioritization output prioritized based on highest benefit potential.

5 Conclusion

The TRN resilience planning process uses a risk-informed approach to help users identify resilience gaps impacting their energy and water systems, develop solutions to address those gaps, and prioritize the solutions to identify which will move forward for further development. This process implements a formally structured risk assessment model that characterizes risk as:

$$Risk = Hazard * Vulnerability * Consequence * Criticality\ Weighting\ Factor$$

where hazard is the frequency with which a disruption to the energy or water systems occurs, vulnerability represents the likelihood that redundant systems supporting critical loads at the site will fail during an outage, consequence is the downtime of a critical function (beyond the TOD) supported by critical loads at the site during an outage, and the criticality weighting factor represents the relative importance of the critical function to fulfilling the site's critical missions. This formal structure allows the TRN to provide defensible and reproducible risk calculations, which help users identify the key drivers of risk at their site.

After identifying risk drivers, users can develop solutions that address these drivers, and then model the risk-reduction potential of each solution. Based on the risk-reduction potential, as well as additional prioritization criteria including emissions reduction potential, the TRN generates a prioritized list of resilience solutions.

The TRN methodology provides federal energy and water managers and facility managers the tools required to systematically evaluate their site's energy and water resilience and develop an enhancement plan while also making progress toward their decarbonization goals.

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Appendix A – Table of TRN Risk Analysis Inputs

Table A-1. Inputs for the TRN assessment.

Input	Type of Input	Unit/ Value	Variable	Equation Used In	Collected In [a]
		Risk Assessment			
Hazard frequency	Dropdown	/year	H	Equation 6	RA Action 2
Hazard duration	Dropdown	hours	D		RA Action 2
Vulnerability questions	Yes/No Answers	unitless	X_1, X_2, X_3, X_4	Equation 2	BD Action 3; RA Action 2
Redundant system startup time	Numerical	hours	K	Equation 4 andEquation 5	BD Action 2
Redundant system runtime	Numerical	hours	J	Equation 5	BD Action 2
Tolerable outage duration	Numerical	hours	TOD	Equation 3, Equation 4, and Equation 5	BD Action 2
Average energy or water requirement	Numerical	kWh/day, gal/day, MMBtu/month		For reference	BD Action 2
Peak electricity or water demand	Numerical	kW, gal/day		For reference	BD Action 2
Time to restore function at another site	Numerical	hours	F	Equation 3	RA Action 1
Probability that function restoration is successful	Yes/No Answer	unitless	P_F	Equation 3	RA Action 1
Criticality weighting factor	Numerical (integer)	unitless	W	Equation 1	SLP Action 4
		Emissions Impact			
Marginal emissions factor	Numerical (auto-populated)	lbs/MWh	$\gamma_{marginal}$	Equation 12	SP Action 3
Average emissions factor	Numerical (auto-populated)	lbs/MWh	γ_{avg}	Equation 13	SP Action 3
Present annual electricity use	Numerical	MWh	E_p	Equation 12, Equation 13	SP Action 3
Change in electricity use	Dropdown	%	U_E	Equation 12	SP Action 3
Shift in electricity supply	Dropdown	%	S_E	Equation 12	SP Action 3
Natural gas emissions factor	Numerical (auto-populated)	116.65 lbs/MMBtu	γ_{NG}	Equation 14, Equation 15	SP Action 3

Input	Type of Input	Unit/ Value	Variable	Equation Used In	Collected In [a]
Present annual natural gas use	Numerical	MMBtu	N_p	Equation 14, Equation 15	SP Action 3
Change in natural gas use	Dropdown	%	U_{NG}	Equation 14	SP Action 3
Breakpoints for decarbonization benefit potential ranges	Numerical (auto-populated but can be adjusted)				SP Action 3
Prioritization Criteria					
Solution prioritization criterion weighting factor	Numerical (integer)		α	Equation 17	SP Action 4
Benefit score for qualitative prioritization criteria	Dropdown		B_i	Equation 17	SP Action 4
Costs					
Number of years over which to assess solution costs	Dropdown	year			SP Action 4
Breakpoints for cost ranges	Numerical (auto-populated but can be adjusted)				SP Action 4
Upfront cost and ongoing annual costs	Numerical	$			SP Action 4

[a]Abbreviations for TRN modules as follows: SLP – Site-Level Planning; BD – Baseline Development; RA – Risk Assessment; SP – Solution Prioritization

Table A-2. Equations used in TRN analysis. Note Equations 18 and 19 are not included because they are simply examples of the calculation in Equation 17.

Equation	Description	Equation number
$Risk = Hazard * Vulnerability * Consequence * Criticality\ Weight$	Generalized risk equation	Equation 1
$V_i = 1 - (1 - X_1)(1 - X_2)(1 - X_3)(1 - X_4)$	Vulnerability calculation based on answers to vulnerability questions	Equation 2
$C_F = max\{P_F[\min(F, D) - TOD], 0\} + \max\{(1 - P_F)(D - TOD), 0\}$	Consequence associated with relocating a critical function	Equation 3
$C_1 = \max\{\min(K, D) - TOD, 0\}$	Consequence associated with running a redundant system if the redundant system can operate through the end of the outage	Equation 4
$C_2 = \max\{D - \max(K + J, TOD), 0\}$	Consequence associated with running a redundant system if the redundant system cannot operate through the end of the outage but can start within the TOD	Equation 5
$R = H * [V_A * V_B * C_F + (1 - V_A) * \min(C_F, C_{A,R}) + V_A * (1 - V_B) * \min(C_F, C_{B,R})]$	Expanded risk equation considering the three cases described in Equations 7–9	Equation 6
• $V_A * V_B * C_F$	Both backup systems fail	Equation 7
• $(1 - V_A) * \min(C_F, C_{A,R})$	The first backup system operates successfully	Equation 8
• $V_A * (1 - V_B) * \min(C_F, C_{B,R})$	The first backup system fails, but the second backup system operates successfully	Equation 9
$R_{weighted} = R * W$	Weighted risk	Equation 10
$Risk\ reduction\ efficacy = \frac{Current\ weighted\ risk - Solution\ weighted\ risk}{Current\ weighted\ risk} \times 100\%$	Risk reduction efficacy	Equation 11
$A_E = \gamma_{margingal} U_E E_p + S_E E_p (1 - U_E)(\gamma_{marginal} - \gamma_{s,E})$	Avoided CO_2 emissions associated with electricity usage	Equation 12
$G_E = \gamma_{avg} E_p.$	Present annual CO_2 emissions associated with electricity usage	Equation 13
$A_{NG} = \gamma_{NG} U_{NG} N_p$	Avoided CO_2 emissions associated with natural gas usage	Equation 14
$G_{NG} = \gamma_{NG} N_p.$	Present annual CO_2 emissions associated with natural gas usage	Equation 15
$\frac{A_e + A_{NG}}{G_E + G_{NG}} * 100\%$	Emissions reduction relative to present CO_2 emissions	Equation 16
$B_{total} = \alpha_R B_R + \alpha_E B_E + \sum_i \alpha_i B_i.$	Total solution benefit potential	Equation 17

Appendix B – Table of TRN Risk Analysis Outputs

Table B-1. Outputs of the TRN assessment

Output	Description	Unit	Reported In [a]
Unweighted risk	Probability-adjusted expected annual function outage time	hours/year	RA Action 4
Weighted risk	Probability-adjusted expected annual function disruption accounting for function criticality weights	unitless	RA Action 4
Risk-reduction efficacy	Percent risk reduction if a solution were to be implemented	%	SP Action 2
Risk-reduction efficacy benefit score	Score (1–4) associated with risk-reduction efficacy categories: minor, moderate, significant, or major	unitless	SP Action 2
Emissions reduction	Percent reduction in CO_2 emissions associated with energy use at the site if a solution were to be implemented	%	SP Action 3
Emissions reduction score	Score (1–4) associated with emissions reduction categories: no emissions reduction, marginal, significant, or major	unitless	SP Action 3
Qualitative prioritization criterion benefit score	Score (1–4) associated with qualitatively assigned benefit categories: not well, moderately well, well, very well	unitless	SP Action 4
Cost	Cost calculated based on upfront cost and ongoing annual costs over the number of years specified	$	SP Action 4
Cost category	Minimal, low, moderate, high	unitless	SP Action 4
Prioritized list of resilience solutions	List of resilience solutions prioritized based on benefit potential and cost		SP Action 5

[a]Abbreviations for TRN modules as follows: SLP – Site-Level Planning; BD – Baseline Development; RA – Risk Assessment; SP – Solution Prioritization

Appendix C – Generator Runtime Calculator

The Generator Runtime Calculator is a web-based tool (https://trn.pnnl.gov/toolkit/generator-runtime-calculator) that determines how many days a generator can support its critical loads. This information is an input for characterizing redundant systems in Baseline Development Action 3.

The tool provides two methods for calculating runtime:

- Daily consumption (kWh) is known or a reliable estimate is available
  - It is assumed that if selecting this method, the generator has sufficient capacity to meet the required demand (kW).
- Daily fuel consumption is unknown, but generator size (kW) is known
  - For this method, generator capacity is a value that can be changed by the user, but the default assumption is that the load is 25% of the generator capacity.

The methodology considers these principles in the use of the tool:

1. The analysis provides a high-level estimate of expected runtime of the backup generator during an electric outage event.
2. The analysis provides estimates only for generators operating using fossil fuels. Other types of electric redundant systems should use other resources to characterize their runtime capabilities.
3. The analysis can be performed for diesel, propane, gasoline, liquefied natural gas (LNG), and fuel oil. Natural gas is not included as a fuel type for generators in this tool. Natural gas generators are connected directly to a natural gas line and are therefore assumed to have an "infinite" runtime. This assumption holds true unless a natural gas disruption has also occurred. However, since the TRN does not consider interdependencies and treats each outage event as independent, this is beyond the scope of the TRN analysis.
4. Assumed efficiencies provided for generators are rules of thumb: 20–25% efficiency is typical and new or larger generators can be up to 40% efficient. For fuel types other than diesel, these values may vary, and it is recommended that estimates be checked with the generator manufacturer.
5. The daily load factor is defined as the percent of total generator output used to serve the load over the course of a day. For example, a 100 kW generator could produce 2,400 kWh in a day, but in practice may only produce 600 kWh.

With these principles in mind, the proposed methodology considers calculations for each of the two runtime methods. The methods differ in how they calculate the daily fuel consumption. Once this value is calculated, the methods are the same for the rest of the process.

C.1 Method 1: Finding Daily Fuel Use When Daily Consumption is Known

To find the runtime when daily consumption (kWh) or a reliable estimate is available, the daily fuel consumed by the generator in BTUs ($Fuel_{Daily}$) is calculated as:

$$Fuel_{Daily} = (Consumption_{Daily} * kWh_{Btu})/Eff \quad \text{Equation C-1}$$

where $Consumption_{Daily}$ is the known daily electricity consumption (kWh), kWh_{Btu} is a constant that converts kWh to BTU, and *Eff* is the assumed efficiency of the generator (%).

C.2 Method 2: Finding Daily Fuel Use When Generator Size is Known

To find the runtime when generator size (kW) is available, but the critical loads supported by the generator are not, the daily fuel consumed by the generator in BTUs (D_F) is calculated as:

$$Fuel_{Daily} = (Generator_{kW} * LoadFactor * 24 * kWh_{Btu})/Eff \quad \text{Equation C-2}$$

where $Generator_{kW}$ is the generator size (kW), *LoadFactor* is the generator daily load factor (%), kWh_{Btu} is a constant that converts kWh to BTU, and *Eff* is the assumed efficiency of the generator (%).

C.3 Finding Runtime from Daily Fuel Consumed

From either of the initial methods, once $Fuel_{Daily}$ is known, the gallons of fuel consumed per day ($Gallons_{Daily}$) can be calculated:

$$Gallons_{Daily} = Fuel_{Daily}/\ Content_{Btu} \quad \text{Equation C-3}$$

where $Content_{Btu}$ is a constant that provides the BTU content of fuel per gallon. This value corresponds to the fuel type the user selects. When $Gallons_{Daily}$ is known, the time the site's critical load can be met can be calculated as:

$$Critical_{Days} = Gallons_{Storage}/Gallons_{Daily} \quad \text{Equation C-4}$$

where $Critical_{Days}$ is the number of days the critical load can be met, and $Gallons_{Storage}$ is the onsite fuel storage capacity. If additional refueling is not available, $Critical_{Days}$ is the final step and can be converted from days to hours with:

$$Critical_{Hours} = Critical_{Days} * 24\ hours \quad \text{Equation C-5}$$

where $Critical_{Hours}$ is the longest duration in hours that the critical load can be met.

If offsite fuel deliveries can arrive prior to the end of the duration of $Days_{Critical}$, the tool can incorporate that refueling capability into the estimate of generator runtime. If refueling is available, the user will be asked, "If the generator is refueled, will the fuel storage dedicated to the generator be completely refueled?" If the answer is no, the user will enter the number of gallons that will be supplied. Additional days provided by a single refueling are calculated, assuming that refueling occurs with 20% fuel remaining, using one of the following two equations:

If $Gallons_{Refueled} > Gallons_{Storage} * 0.8$, then $Critical_{DaysAdditional} = (Gallons_{Storage} * 0.8)/\ Gallons_{Daily}$ — Equation C-6

If $Gallons_{Refueled} < Gallons_{Storage} * 0.8$, then $Critical_{DaysAdditional} = Gallons_{Refueled}/Gallons_{Daily}$

where $Gallons_{Refueled}$ is the number of gallons that will be supplied during refueling, and $Critical_{DaysAdditional}$ is the number of additional days the critical load can be met.

If the answer to whether the generator's storage tank is completely refueled is yes, assuming that refueling occurs with 20% fuel remaining, the additional days provided by the refueling can be calculated as:

$$Critical_{DaysAdditional} = (Gallons_{Storage} * 0.8)/Gallons_{Daily} \quad \text{Equation C-7}$$

Next, the user will be asked if the refueling availability is a recurring or one-time event. If the refueling occurs one time, the longest duration of outage (days) this redundant system can support is calculated with:

$$Critical_{DaysTotal} = Critical_{Days} + Critical_{DaysAdditional} \quad \text{Equation C-8}$$

where $Critical_{DayslTotal}$ is the longest duration that the critical load can be supported. If the user answers that refueling is recurring, the longest duration is automatically defaulted to "6 months or more." This statement assumes that recurring fuel deliveries will arrive again within $Critical_{DaysAdditional}$ of the previous fuel delivery.

Appendix D – Redundant Water System Runtime Calculator

D.1 Background and Terminology

The web-based runtime analysis tool (https://trn.pnnl.gov/toolkit/water-supply-runtime-calculator) calculates the amount of time a redundant water system can support its critical loads. This is an input in the TRN for Baseline Development Action 3. The tool can account for three types of systems:

1. Onsite storage tank(s) connected only to the primary water supply
2. Onsite or offsite secondary water source that supplies the onsite storage tank(s)
3. Onsite or offsite secondary water source that directly supplies the critical load(s).

The following definitions provide details for what is considered to be an onsite storage tank, offsite secondary supply, and onsite secondary supply for the purposes of this calculator. See Figure D-1 for more details.

- ***Onsite storage tanks.*** Could be connected to only a primary water supply (e.g., municipal or utility), which would be classified as system type 1 in the list above, or connected to a secondary, onsite or offsite water source, which would be classified as system type 2 in the list above.
- **Useable volume.** The storage capacity of the tank(s) that can be used assuming the tank is full. It is equal to the total storage volume minus the dead volume and reserved volume.
- **Dead volume.** The volume of water at the bottom of the tank that, when water reaches this level, there is not enough head (i.e., water pressure) to supply the system. This level depends on the elevation of the tank(s) and the system pressure requirement. This volume may be small, but it is important not to include it in estimates of the usable tank volume in order to receive an accurate runtime estimate.
- **Reserved volume.** Tank volume that must be reserved for emergency fire suppression requirements or similar uses and, therefore, cannot be counted toward the water available to supply critical loads at the site.
- **Empty volume.** The amount of empty volume at the top of the storage tank before it would be refilled during normal operations. Storage systems may be operated with automatic setpoints, using an automatic control rule to fill from the supply source when the water drops below a certain volume, or with a manual process by the operator. Incorporating the empty volume into the calculation is important to take into account the smallest volume of water that could be available at the time of an outage. It is usually not possible to know exactly what the water level will be at the moment of an unexpected outage, so using the greatest typical empty volume that the storage tank could have at any given time is recommended to yield a conservative result.
- ***Onsite secondary supply.*** May be a well, aquifer, or lake that is located on the site. Rainwater storage tanks are often considered secondary water sources, but for the purpose of this tool, rainwater does not qualify as it is not reliable enough to model as a consistent secondary source.
- ***Offsite secondary supply*****.** Could be a regional water tower or industrial-grade storage facility that can supply the site in the case of an outage to the primary municipal water

supply. A water source is considered secondary if it relies on separate supply infrastructure to the primary source that water for the site generally comes from.

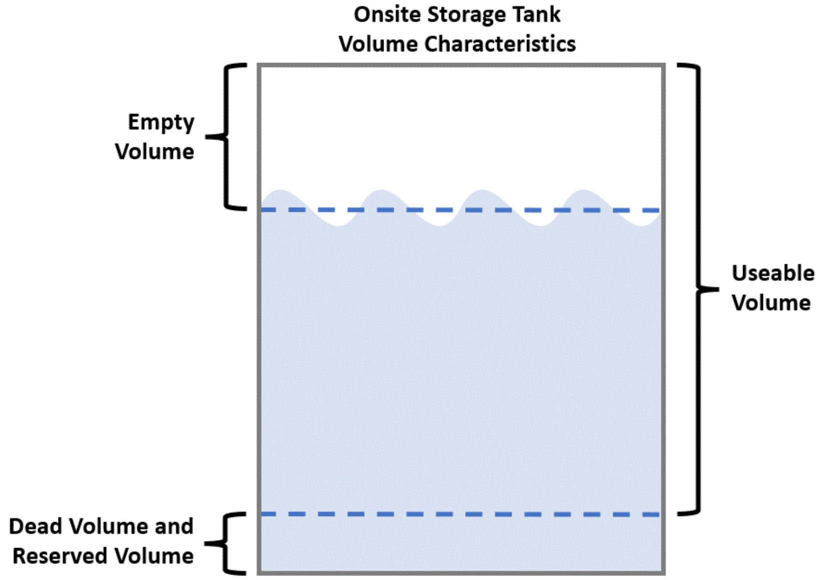

Figure D-1. Onsite storage tank and relevant terminology for the calculator.

D.2 System Qualifications

After providing the required inputs, the tool calculates an estimate of the number of days the existing redundant system(s) will be able to meet critical load requirements. The instructions for the calculator mandate the following system requirements, which were determined as critical baseline conditions for the system to qualify as a redundant water system.

- **Basic water quality.** The amount of residual disinfectant (e.g., chlorine) in the water, both in the storage tank and throughout the distribution network, should meet the criteria described in American Water Works Association Manual 20 or equivalent standard, while in regular use and during an outage. The amount of residual disinfectant will be dependent on the tank management, pressure, and network characteristics. Residual disinfectant must be maintained for potable or nonpotable water that comes into contact with humans.
- **Advanced water quality.** Beyond maintaining acceptable water quality, some critical water loads may have more stringent requirements if they are to be used for human drinking or for use cooling batteries, for example. The site must provide the ability to achieve the appropriate water quality from the redundant system that is required for the site and critical loads, such as potable or ultrapure water.
- **Secondary supply.** When fully operational, the source of a secondary water supply (onsite or offsite) is not expected to be exhausted within a reasonable timeframe (e.g., months) and it must be able to continuously provide the design flow rate over the entire duration of the outage. This includes meeting the instantaneous peak load, not just a daily or yearly average load, otherwise partial outages may occur at the critical load. It is outside the scope of this tool to be able to model the supply capacity of a water source at a given moment in time.

- **Co-location of distribution infrastructure.** An offsite secondary redundant system must not have any known co-locations or shared vulnerabilities with the primary water system. This could include shared distribution pipe infrastructure, shared reliance on a substation, or shared water source supply. These types of shared systems increase the likelihood that the redundant system is vulnerable to the same outage events as the primary system, and therefore it is not truly a redundant system.

D.3 Methodology and Calculations

Table D-1 summarizes the inputs that may be required to complete the Water Redundant System Runtime Calculator. The variable nomenclature will be used to refer to these inputs in the subsequent equations.

Table D-1. Inputs required by user for Water Redundant Runtime Calculator.

Input	Variable	Options	Description
Required for all systems			
Type of redundant water system	NA	Onsite storage tank(s) connected only to the primary water supply Onsite or offsite secondary water source that supplies onsite storage tank(s) Onsite or offsite secondary water source that directly supplies critical load(s)	Select the description that best describes the site's redundant water system from the dropdown list.
Average daily water load for the system during an outage	$load_{daily}$	Numeric entry in gallons per day	This may be larger than the critical load(s) if the redundant system is connected to a larger system including noncritical loads. The user should account for any loads that will be curtailed during an outage, such as irrigation.
Only required for onsite storage tank systems			
Usable tank volume	$vol_{useable}$	Numeric entry in gallons	This value is the storage capacity of the tank(s) that can be used during an outage. If there are multiple tanks, they should be treated as one aggregated system for this section.
Empty tank volume at any given point in time pre-outage	vol_{empty}	Numeric entry in gallons	This is the maximum amount of empty volume at the top of the storage tank before it would be refilled during normal operations.
Water loss factor for piping between storage tank and load(s)	$wlf_{storage}$	Very low (0–10%) Low (10–20%)	The percentage of water expected to be lost between the source (e.g., storage tank) and the load. This is presented in ranges because the user may not know

		Typical (20–30%) High (30–40%) Very high (40–50+%)	the exact value. The user must estimate based their knowledge of the piping system. The age of pipes will be the biggest factor (older pipes will leak more, PVC tends to be newer), followed by distance to load (longer distance means more opportunities to leak).
Only required for onsite or offsite secondary water sources			
Flow rate that can be provided by the onsite or offsite secondary water source supply	$Supply_{secondary}$	Numeric entry in gallons per minute	This information could be provided by system/pump specifications. Enter the flow rate that offsite or onsite secondary water system is designed to provide the site.
Water loss factor for piping between onsite or offsite secondary water source and onsite storage tank (if present) or load(s) (if no storage tank)	$Wlf_{secondary}$	Very low (0–10%) Low (10–20%) Typical (20–30%) High (30–40%) Very high (40–50+%)	The percentage of water expected to be lost between the source (e.g., water source) and storage tank or load. This is presented in ranges because the user may not know the exact value. The user must estimate based their knowledge of the piping system. The age of pipes will be the biggest factor (older pipes will leak more, PVC tends to be newer), followed by distance to load (longer distance means more opportunities to leak).

D.3.1 Onsite Storage Tank Calculations

The calculation for the runtime of a redundant storage tank system uses Equation D-1, which is only used in the calculator if the user selects one of the two system types that has an onsite storage tank.

$$runtime_{storage} = (vol_{useable} - vol_{empty}) * \left(1 - \frac{wlf_{storage}}{100}\right) / load_{daily}$$ Equation D-1

This equation finds the runtime of a storage tank by first calculating the difference between the usable volume and the empty volume, which is the smallest amount of water that would be expected to be in the tank during an outage (based on the level at which the tank will be refilled). This value is multiplied by one minus the water loss factor to estimate the storage volume that will be available at the load after accounting for leakage. This new value is then divided by the daily average load during an outage to obtain the total runtime (in days, which is later converted to hours for the final result) of the storage tank.

If the user selects onsite storage with a secondary water supply, then the runtime value calculated here is an intermediate value used in the relevant section below. Otherwise, if there is no secondary water supply, this is the final runtime value.

D.3.2 Secondary Supply Without Storage Calculations

In the case of a redundant system using a secondary water source with no onsite storage, it is important to use the peak load because the daily load will likely not be evenly distributed throughout the day. So, if there is no storage tank onsite, then the secondary source must meet the peak load to achieve full functionality of the system. This value is estimated using Equation D-2, which calculates the peak load in gallons per minute.

$$load_{peak} = \frac{1.5 * load_{daily}}{24\ hours * 60\ minutes}$$ Equation D-2

The peak load (measured in gallons per minute) is estimated to be 1.5 times greater than the daily average load (measured in gallons per day). The value of 1.5 was determined to be an approximate and slightly conservative value based on the experience of water infrastructure subject matter experts at PNNL. If the peak load is known, the user may overwrite this cell in the calculator; however, it is anticipated that many sites will not have this information, necessitating the approximation. In reality, if the peak load cannot be met, there would be partial outages. However, to provide a conservative risk assessment that does not overlook key energy and water risks faced by the site, the TRN only gives credit for meeting the entire critical load(s).

Once peak load has been determined, the runtime of a redundant system that has an onsite or offsite secondary supply without storage is calculated as follows:

If $supply_{secondary} * \left(1 - \frac{wlf_{secondary}}{100}\right) > load_{peak}$ Equation D-3

Then the runtime for the redundant water system ($runtime_2$) is longer than the longest outage duration modeled in the TRN.

However, if $supply_{secondary} * \left(1 - \frac{wlf_{secondary}}{100}\right) < load_{peak}$

Then the runtime for the redundant water system ($runtime_{secondary}$) is zero hours because the secondary supply is not sufficient to meet the peak load.

Equation D-3 estimates the supply volume that will be available at the load after accounting for leakage, and compares this value to the peak load (measured in gallons per minute). If the supply volume is larger than the peak load, it is assumed that the secondary source can supply the critical load for the longest outage duration modeled by the TRN (6 months or 4,500 hours) based on the definition of a secondary source for this tool. Notably, this depends on the assumption that the secondary supply can continue supplying water to the site at the specified volume for at least six months. If the value is smaller than the peak load, then it is assumed runtime is zero because the secondary source cannot meet the requirements of the critical load.

D.3.3 Secondary Supply With Storage Calculations

The calculation for the runtime of a redundant water system that has an onsite or offsite secondary supply with onsite storage uses Equation D-4. For a secondary supply with storage, the daily load is used instead of the peak load, because it is assumed that the storage tank will buffer any instantaneous increases in load. The supply of the secondary source is converted to gallons per day for this section and is represented by *supply*$_{secondary}$ - *supply*$_{daily}$ in Equation D-4 instead of *supply*$_{secondary}$.

If $(supply_{secondary} - supply_{daily}) * \left(1 - \frac{wlf_{secondary}}{100}\right) > load_{daily}$ Equation D-4

Then the runtime for the redundant water system ($runtime_{secondary} + runtime_{storage}$) is longer than the longest outage duration modeled in the TRN.

Otherwise, $(runtime_{secondary} + runtime_{storage}) = \frac{runtime_{storage}}{1-\left(1-\frac{wlf_{storage}}{100}\right)*\frac{(supply_{secondary}-supply_{daily})}{load_{daily}}}$

This equation multiplies the supply of the secondary source (measured in gallons per day) by one minus the water loss factor to estimate the supply volume that will be available at the load after accounting for leakage. This value is compared to the daily load (measured in gallons per day)—if it is larger than the daily load, then it is assumed that the secondary source can supply the critical load for the longest duration measured by the TRN (6 months or 4,500 hours) based on the definition of a secondary source for this tool.

If the secondary source cannot supply water at the rate demanded by the critical load, then the storage tank will need to supply some of the load, but it will not be able to do so indefinitely. In this case, the storage tank will become depleted as it supplies water to the load to supplement the water coming from the secondary source. However, as this is happening, the secondary water source will replenish some of the storage tank. This process (emptying and replenishing the water in the storage tank) will continue until the storage tank is completely depleted and the secondary water source does not have the capacity to fully provide the critical load alone. This process can be represented by an infinite geometric sequence, where the limit is defined by the formula $a + a*r + a*r^2 + a*r^3 + … = a / (1 – r)$, where r is a value less than one. In the context of this calculation, “a” is the runtime of the storage tank not considering the secondary source, and “r” is the percent of the critical load that can be met by the secondary source. Each time the storage tank is emptied, an exponentially smaller portion is replenished until that portion approaches zero and the runtime approaches the limit defined by the series.

Appendix E – Original Risk Methodology

The TRN risk methodology was updated in February 2023 to remove some of its inherent conservatism (that is, its tendency to produce high-side risk estimates). This was done by providing partial credit for risk reduction if a site has a redundant system that can support critical loads for part of an outage but not for the whole outage. This updated methodology is discussed in Section 3.1. Here, we provide a description of the original TRN risk methodology as a reference for users who generated and analyzed risk assessment results prior to the methodology update.

The original TRN risk methodology made a simplifying assumption that vulnerability can only be reduced in a given risk scenario by redundant systems that are capable of starting up within the critical load's TOD *and* are capable of running throughout the entire duration of the outage (Figure 6 a). This approach was taken to provide a conservative estimate of the risk associated with an energy or water outage by giving credit for redundant systems only in risk scenarios in which those redundant systems have the capability to run for the whole time that the critical function could be considered disrupted. This approach led to limitations, particularly in the context of evaluating the risk-reduction potential of resilience solutions. For example, under the original methodology, if a site has a redundant system that provides 2 hours of supply, it qualified for the 1-hour outage duration; if a solution was added that would extend this supply to 12 hours, no additional risk-reduction "credit" was given because the next duration on the discrete scale is 24 hours, making it appear to the user that there has been no risk-reduction benefit from the solution.

Based on feedback from sites that piloted the TRN resilience assessment tool, this approach led to an overly conservative assessment of the benefits associated with resilience solutions that they were evaluating. In reality, the site does benefit from an imperfect redundant system. For example, in the case of a data center, there might be a very low TOD (e.g., 0.01 hours) due to the high value and time-sensitive nature of the data analysis mission. In the original TRN model, if a backup system did not initiate prior to the TOD, the site would receive no credit for having a backup system. However, in reality, if the system started up after the TOD, it could still enable the mission, for a significant portion of the primary system outage (Figure E-1). Therefore, it would not experience the consequence of loss of power throughout the entire primary outage in the case where the redundant systems run successfully.

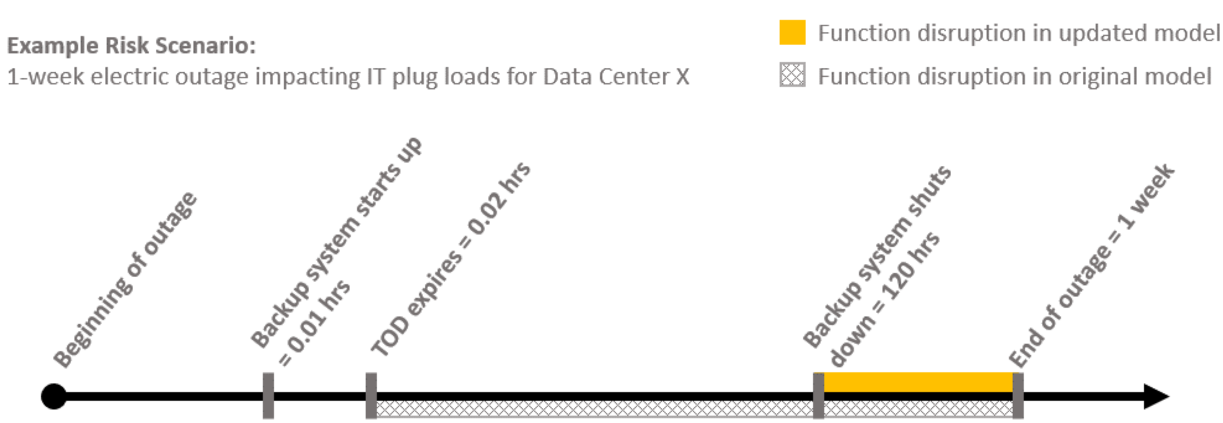

Figure E-1. Timeline showing the duration over which a critical function is considered disrupted in the updated TRN risk methodology (yellow) and the original TRN methodology (gray hatched) for an example where the redundant system cannot start within the TOD of the IT plug load but can operate through the end of the electric outage.

The math underlying the original TRN model is consistent with the updated model as discussed in Section 3.1, though the original methodology gives credit only for the case where a redundant system starts within the TOD and runs throughout the outage. Due to these conservative assumptions, the equations describing this risk reduction could be simplified such that the consequence for a given risk scenario (i.e., a unique combination of one hazard acting upon one critical load) could be expressed simply as:

$$C = \max\,(D - TOD, 0) \qquad \text{if } F > D \qquad \text{Equation E-1}$$

$$= \max[P_F(F - TOD), 0] + \max\,[(1 - P_F)(D - TOD), 0] \qquad \text{if } F \leq D$$

and the vulnerability associated with a risk scenario could be expressed as:

$$V = V_A * V_B \qquad \text{Equation E-2}$$

where V_A and V_B reflect the vulnerabilities associated with the first and second redundant systems, respectively. If there is only one redundant system in place for a critical load, $V_B = 1$. If there is no qualified redundant system in place for a critical load, the vulnerability for all risk scenarios involving that critical load is set to 1 (i.e., 100% probability that if the outage occurs, there will be no backup supply to the critical load).

Given these inputs, unweighted risk (in hours/year) could be expressed as:

$$R = H * V * C \qquad \text{Equation E-3}$$

and weighted risk (unitless) could be expressed as:

$$R_{weighted} = W * R \qquad \text{Equation E-4}$$

Though this original approach met the principle of erring toward conservatism within the TRN model, the additional complexity introduced by the updated risk methodology has allowed the TRN risk calculations to provide a more realistic account of the risk associated with each evaluated risk scenario.

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