

Decarbonization in Climate Resilience Planning

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ABSTRACT

Recent executive orders, such as Executive Order 14008, require federal agencies to address climate change by enhancing resilience and reducing emissions through decarbonization. Traditionally, federal agencies require their sites to develop preparedness plans, such as continuity of operations plans and/or more comprehensive resilience plans. When climate change is included in these plans, the focus tends to be on climate adaptation solutions, such as hardening infrastructure, rather than climate mitigation through decarbonization. However, with the ambitious emission reductions targets set by the federal government, it is essential to provide resources and tools to support energy and water managers in achieving decarbonization goals. To achieve this, there is a need for decarbonization to be incorporated into existing resilience planning processes. We discuss a method for incorporating decarbonization analysis into an existing resilience planning process to create a holistic framework that considers climate adaptation, climate mitigation, and risk reduction priorities when developing and prioritizing solutions for federal sites. Site managers and decisionmakers must be aware of potential opportunities and trade-offs in meeting energy and water performance goals, emission reductions goals, and climate adaptation goals when developing technological, operational, or institutional resilience solutions. By combining these processes, energy managers can minimize the additional level of effort to ensure that their sites are able to both withstand climate-related energy and water disruptions and contribute to climate change mitigation. A holistic approach can help federal agencies serve as a model for incorporating decarbonization strategies into site-level resilience planning for the rest of the nation.

Introduction

The United States has taken renewed actions at the domestic and international policy level to reduce greenhouse gas emissions, while also building resilience against the impacts of climate change. Executive Orders, such as E.O. 14008 *Tackling the Climate Crisis at Home and Abroad*, direct federal agencies to deploy their full capacity to reduce climate emissions, build resilience to climate impacts, protect public health, conserve natural resources and biodiversity, deliver environmental justice, and spur economic growth (86 Federal Register 7619, 2021).

Federal agencies identified specific actions they could take towards these goals in publicly available climate adaptation plans (Office of the Federal Chief Sustainability Officer 2021). Within these plans, agencies identified the need to strengthen their operations, infrastructure, and facilities to increase their resilience to the impacts of climate change, as required for successful mission operations. For example, in its Climate Adaptation and Resilience Plan, the Department of Energy (DOE) notes the need to integrate climate readiness into its facilities and infrastructure asset management program (DOE 2021). Specific strategies identified to meet this goal include reducing facility energy and water use and employing resilience-enhancing land use planning. Additionally, DOE plans to integrate climate-ready

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measures into early-stage building design, update site vulnerability assessments, and, as available, use performance contracting mechanisms to more widely implement identified energy- and water-saving measures that reduce demand and could also enhance climate resilience.

Federal facilities across all agencies also have targets for energy use and water use reductions under E.O. 14057, which mandates a 65 percent reduction of scope 1 and scope 2 emissions by 2030 relative to 2008 levels, a net-zero emissions building portfolio by 2045, and 100 percent carbon pollution-free electricity on a net annual basis by 2030, including 50 percent 24/7 carbon pollution-free electricity (86 FR 70935 2021).

These strategies reflect a dual focus of climate resilience, which encompasses both climate adaptation (preparing for the impacts of climate change) and mitigation (taking steps to reduce the emissions causing anthropogenic climate change). To enhance both adaptation and mitigation goals in energy and water planning, energy managers and facility managers at federal sites need tools and resources that balance these sometimes competing priorities. In this paper, we discuss recent work to expand an existing resilience planning process to incorporate decarbonization considerations to help federal sites meet both their adaptation and mitigation goals.

In the following sections, we describe an approach based on calculating the site-level CO₂ emissions reduction potential of each solution developed using a resilience planning process laid out in the Technical Resilience Navigator (TRN), through two decarbonization strategies, which can be applied individually or in combination¹:

- Enhancing energy efficiency to reduce energy consumption (and thus emissions), and/or
- Shifting some or all electricity use from the existing source (e.g., standard utility-provided supply) to a low- or no-emission source of electricity.

Technical Resilience Navigator Resilience Planning Process

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 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 and provide strategic energy management assistance for agencies to become resilient, efficient, sustainable, and secure. In support of that goal, the Pacific Northwest National Laboratory, in partnership with the National Renewable Energy Laboratory, supported the development of FEMP's [Technical Resilience Navigator](#). FEMP has supported uptake of this tool via technical assistance for sites using the TRN, including one-on-one engagements and a cohort of DOE sites receiving technical assistance together, and by offering live- and on-demand accredited training. Users have reported using findings to help identify key areas of risk and short-list planned resilience projects.

¹ For simplicity, the analysis focuses solely on CO₂ rather than the broader category of CO₂-equivalent (CO₂e) emissions. EPA eGRID data indicate that at the eGRID subregion level, CO₂ and CO₂e for electricity differ by at most 1.0% (https://www.epa.gov/sites/production/files/2021-02/egrid2019_summary_tables.xlsx). For natural gas, reported emissions factors tend to focus on the direct emissions of CO₂ associated with end-use combustion, and the methodology employs such a factor. Although beyond the scope of this methodology, there are upstream greenhouse gas emissions (both CO₂ and CH₄), as described in this report (Bradbury Clement and Down 2015): [Greenhouse Gas Emissions and Fuel Use within the Natural Gas Supply Chain – Sankey Diagram Methodology](#). PNNL-SA-171015

The TRN is an online resilience planning tool serving building facilities managers, business continuity planners, emergency managers and others in managing risk to critical missions from disruptions in energy and water services at the site. The tool's focus on energy and water system resilience requires an understanding of critical energy and water loads that are essential for the site to accomplish their critical mission(s) and the site's ability to sustain the functionality supported by those loads through a disruptive event. Working through the resilience planning process helps the site build a detailed understanding of plans, priorities, and baseline conditions related to energy and water systems, and the types of gaps that might expose the site to risk. The ultimate outcome of the TRN is a set of actionable solutions that address the site's most important gaps in resilience and enhance the ability to maintain mission continuity in the event of a natural hazard or malicious threat that causes a loss of energy or water.

The TRN breaks down the resilience planning process into six broad sections called modules (Figure 1): Site-Level Planning, Baseline Development, Solution Development, Solution Prioritization, and Roadmap to Action. Each module has several actions that lead users through information collection and specific analyses. Though the TRN lays out a sequential path through the resilience planning process, resilience planning is an iterative exercise, and it is expected that users may revisit actions or modules based on newly discovered information to re-evaluate key needs or outcomes.



Figure 1. Technical Resilience Navigator modules

After users have identified solutions that will improve their energy and water resilience posture, they evaluate the solutions against each other within the Solution Prioritization module to help identify which solutions best meet site-defined prioritization criteria. The TRN requires that sites consider how well each resilience solution—or set of resilience solutions—reduces site risk as a criterion for prioritizing the solutions. It also gives users the ability to add up to five additional solution prioritization criteria. Users assign a weight to each criterion based on its relative importance to site decision-making processes and qualitatively assess each solution against the additional prioritization criteria to yield a “solution benefit potential.” Examples of prioritization criteria may include how easily a solution can be implemented, alignment with organizational policies, or alignment of a solution with sustainability standards.

Given new goals for decarbonization, greenhouse gas emission targets, and energy and water-use reduction targets, federal sites need to be able to assess how well resilience solutions meet these other priorities in addition to assessing the risk impacts. Some resilience solutions, such as re-commissioning a fleet of diesel generators, may serve to reduce site risk from outages

of varying durations, but may fail to produce any benefit for a site’s greenhouse gas emissions goal. While the TRN currently allows for user-defined prioritization criteria related to decarbonization to be added, such as “Meets Decarbonization Goals,” that approach only allows users the ability to provide a qualitative evaluation of how well the resilience solution meets that goal. Given the importance of decarbonization to federal facilities, a more rigorous methodology for evaluating the decarbonization potential of each solution is beneficial, alongside the risk reduction potential, to evaluate resilience solutions within the TRN. A methodology for evaluating decarbonization potential, such as the one we describe below, provides a more robust, defensible input into the final decision-making regarding which resilience solutions should be developed into projects.

TRN Methodology for Evaluating Decarbonization Potential

Site decarbonization is achieved by reducing the use of fossil fuels, and consequently decreasing CO₂ emissions. This can be achieved through two main strategies. The first is to reduce the demand for fossil fuels through a reduction in energy demand, for example through increased efficiency. Alternatively, decarbonization can be achieved on the supply side by providing energy using renewable sources that can replace fossil fuels. Both strategies are considered in the methodology presented here.

The analysis of decarbonization potential takes place after sites have already completed the first four TRN modules (Site-Level Planning, Baseline Development, Risk Assessment, and Solution Development, Figure 1) and is used as a mandatory input for Solution Prioritization. The goal of this analysis is to determine whether a solution constitutes a notable reduction in the site’s energy-related CO₂ emissions as the metric for a solution’s “decarbonization potential”. Solutions may address both scope 1 (or direct) emissions (e.g., by replacing an HVAC system with a more energy-efficient alternative) and/or scope 2 (or indirect) emissions (e.g., by switching to on-site renewable energy generation) associated with end-use loads². The TRN uses a semi-quantitative approach for risk analysis, rather than providing highly precise quantitative risk estimates. This type of approach is carried forward in this new analysis—with decarbonization benefits categorized as “major,” “significant,” “marginal,” and “no” benefit for the purposes of solution prioritization.

The output of this analysis is a quantification of how well a solution (or set of solutions) reduces a site’s energy-related CO₂ emissions as a percentage of the site’s current CO₂ emissions associated with electricity and natural gas use. These two supply types (electricity and natural gas) align with the two energy resources already analyzed within the TRN³. The benefit of characterizing decarbonization potential relative to current site emissions is that any site, even a small one with relatively low energy use, can design solutions that would be categorized as having substantial impacts on their CO₂ emissions. Additionally, federal sites’ decarbonization goals are likely to be tied to their agency’s Climate Adaptation and Resilience Plan and/or to Executive Orders covering the whole federal government, as described above. These policies set emissions reduction targets as a function of site, agency, or federal government emissions.

2 Further information on Scope 1 and 2 emissions can be found here: <https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance>.

3 Note that sites may use other fuel supplies on their site that may emit greenhouse gases. However, these are currently beyond the scope of the TRN resilience planning process.

Therefore, information about the site-level emissions reduction will be useful for demonstrating progress towards these goals.

In this methodology, CO₂ reduction is estimated relative to *total* current site CO₂ emissions associated with electricity and natural gas use. Therefore, it is not limited to *critical* energy (or water) loads, which are the basis for the risk assessment in the TRN. The intent of this approach is to help estimate additional site-wide benefits associated with decarbonization (i.e., a reduction in CO₂ emissions), which can be considered alongside the risk reduction benefits captured through the risk analysis. This allows the solution analysis to take advantage of decarbonization benefits beyond those impacting critical loads. For example, take a solution that impacts a load that is a significant energy user (SEU), as may be identified through a process like DOE's 50001 Ready Navigator (DOE 2022). If that SEU is not a critical load that would be included in the TRN risk analysis, a decarbonization screening focused only on energy use for critical loads would neglect the significant decarbonization benefits associated with that SEU. Instead, this methodology includes that non-critical SEU for the purposes of the decarbonization screening.

Inputs for the Decarbonization Analysis

Inputs for the decarbonization analysis within the TRN fall into two categories: solution-agnostic and solution-specific inputs. Solution-agnostic inputs are required to characterize the site's baseline energy use and emissions, and the emissions changes associated with any changes in grid-provided electricity. These inputs are 1) the average and marginal emissions factors⁴ of the site's electric utility or the Environmental Protection Agency's (EPA's) eGRID subregion, and 2) the present annual site energy use, including present annual site electricity use (E_p , MWh/year) and present annual site natural gas use (N_p , MMBtu/year). Users may vary emissions factors to examine the sensitivity of their results to projected future grid changes. They may also change the emissions factors relative to their auto-populated EPA eGRID subregion emissions factors to reflect the contributions of existing on-site generation resources.

Solution-specific inputs characterize how much of a change in emissions each individual solution provides. These inputs include 1) how the solution changes the quantity of energy used (for electricity and natural gas) and 2) how the solution shifts electricity consumption from utility and/or other existing electricity supply to a low- or no-emission resource.

To quantify a solution's change in energy use, a user selects from a dropdown list of energy use reduction or increase ranges, with the displayed change in energy use calculated based on percentage ranges relative to the site's present energy use (see Table 1). As with other parts of the analysis, rough estimates are appropriate for preliminary decision-making and reduce user burden by providing input options as dropdown lists rather than through direct numerical data entry. Note that the options provided for reductions in energy use in Table 1 are more granular than those provided for increases in energy use. The purpose of incorporating this methodology into the TRN is to assess solutions that contribute to decarbonization. Therefore, while it is important to provide the ability to model resilience solutions that increase energy use, the methodology limits the options for characterizing energy increases.

⁴ Average emissions factors refer to the CO₂ emissions associated with the overall generation mix of the grid. Emissions associated with current electricity usage at a site can be characterized using average emissions factors. Marginal emissions factors refer to emissions associated with marginal or non-baseload plants that would be brought online or offline (or have their utilization ramped up or down) to respond to changes in demand.

Table 1. Energy use percent change ranges which can be selected as data input from a dropdown menu, with example calculated values and midpoint used in calculations; down arrows indicate an energy use reduction, while up arrows indicate an energy use increase

Energy use change percentage range	Example of displayed change ranges			
	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 ↑

The second solution-specific user input identifies the degree to which the solution shifts electricity consumption from the utility and/or another existing electricity supply to a low- or no-emission resource. This input focuses only on electricity because energy resources to displace fossil fuel-based electricity production are more readily available and commonly implemented, while shifting the natural gas supply to a substitute gas of reduced carbon intensity is much less common⁵. For this input, the user selects from a dropdown list of electricity shift ranges calculated based on percentage ranges relative to the site's present annual electricity use less the efficiency savings from the previous input (E_s , see Table 2). The user must also provide a CO₂ emissions factor for any new source of electricity used in the solution.

Note that this analysis requires the user to assess the potential energy use reductions and electricity usage shifts prior to entering the data into the tool. These estimates are expected to be rough at this stage of the solution development process given that significant investments into engineering designs for solutions are unlikely to be made prior to the down selection of solutions facilitated by the solution prioritization process. Indeed, the fact that precise estimates are not required is the major reason that the inputs for efficiency benefits and the shift towards electricity supply with reduced carbon intensity can be gathered using dropdown lists as shown in Tables 1 and 2.

⁵ According to a study produced by Energy Vision and Argonne National Laboratory, as of 2020, domestic production capacity of renewable natural gas was roughly 59 TBtu (<https://energy-vision.org/wp-content/uploads/2020/12/EV-Argonne-2020-RNG-Release-1.pdf>). This is roughly 1/500 of the over 30 quadrillion Btu of natural gas consumed domestically in 2020 (<https://www.eia.gov/outlooks/aeo/data/browser/#/?id=1-AEO2021&cases=ref2022&sourcekey=0>).

Table 2. Electricity consumption shift ranges which can be selected as data input from a dropdown menu, with example calculated values and midpoint used in calculations

Electricity consumption shift percentage range	Example of displayed 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

Calculation of Annual Energy Emissions and Emissions Reduction

This screening analysis involves calculating the reduction in emissions from energy use as a fraction of the site’s present annual CO₂ emissions associated with electricity and natural gas use—the two energy resources currently analyzed within the TRN. The output is displayed using a four-category scale of “major,” “significant,” “marginal,” or “no” decarbonization benefit, which is largely consistent with the other categorical scales in the TRN’s Solution Prioritization module. This final output is determined based on emissions reductions through changes to the site’s electricity use (based on changes in the quantity and the source of electricity used) and natural gas use (based on changes in the quantity of natural gas used).

Electricity

To characterize total avoided CO₂ from changes to the site’s electricity use from a resilience solution, the tool calculates the site’s electricity emissions reduction based on the solution and the site’s present annual electricity emissions. The site’s avoided electricity emissions under the solution (A_e) are:

$$A_e = F_{m,e}R_eE_p + U_eE_p(1 - R_e)(F_{m,e} - F_{s,e}) \quad (\text{Equation 1})$$

where $F_{m,e}$ is the marginal emissions factor of the site’s electric utility or existing electricity supply, R_e is the fractional change in electricity use due to efficiency measures (relative to the site’s present electricity use), E_p is the site’s present annual electricity use (MWh), U_e is the fraction of the site’s electricity use that will be shifted from the present electricity supply mix to a low or no emissions source, and $F_{s,e}$ is the emissions factor of the new electricity supply to which a portion of use will be shifted. R_e and U_e are the midpoints of the percentage range (in fractional form) of the user-selected categories (Tables 1 and 2). If the user selects “>25 percent increase,” R_e is assumed to be the midpoint between 25 percent and 50 percent, or 37.5 percent.

The site’s present annual electricity emissions (P_e) are:

$$P_e = F_{a,e}E_p. \quad (\text{Equation 2})$$

where $F_{a,e}$ is the average emissions factor of the site’s existing electricity supply or utility.

Natural Gas

To characterize total avoided CO₂ from changes to the site's natural gas use, the tool calculates the site's natural gas emissions reduction based on the solution inputs and the site's present annual natural gas emissions. The site's avoided natural gas emissions under the solution (A_{NG}) are:

$$A_{NG} = F_{NG} R_{NG} N_p \quad (\text{Equation 3})$$

where F_{NG} is the CO₂ emissions factor of natural gas (taken to be 116.65 lbs/MMBtu), R_{NG} is the fractional change in natural gas use due to efficiency measures (relative to the site's present natural gas use), and N_p is the site's present annual natural gas use (MMBtu) (EIA 2021a). R_{NG} is the midpoint of the percentage range (in fractional form) of the user-selected category (Table 1). If the user selects ">25 percent increase," R_{NG} is assumed to be the midpoint between 25 percent and 50 percent, or 37.5 percent.

Note that Equation 3 is similar to Equation 1 for electricity, but it does not include a term for the shift of a natural gas supply to a substitute gas supply (e.g., renewable natural gas). As mentioned previously, this is because shifting the natural gas supply to a substitute gas of reduced carbon intensity is less common than shifting the electricity source.

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

$$P_{NG} = F_{NG} N_p. \quad (\text{Equation 4})$$

Decarbonization Output

The final output of the analysis is a rating of "major," "significant," "marginal," or "no" decarbonization benefit (D). This is calculated based on the percentage reduction in CO₂ relative to the site's current emissions, a metric that is also reported by the tool:

$$D = \frac{A_e + A_{NG}}{P_e + P_{NG}} * 100\%. \quad (\text{Equation 5})$$

This percentage is converted to the final decarbonization benefit rating based on a scale similar to that shown in Table 3. Note that preferences for categorization of decarbonization benefits (i.e., percentage ranges for each category) may vary by site or organization and may be set by a user within the TRN.

Table 3. Decarbonization benefit categories

Decarbonization benefit category	Calculated D	Score (S_D)
Major	50+%	4
Significant	10 – <50%	3
Marginal	>0 – <10%	2
No decarbonization benefit	≤0%	1

As described above, the decarbonization benefit category is included as a prioritization criterion, along with risk reduction and other prioritization criteria. These criteria are combined into the calculation of the overall solution benefit potential in the TRN Solution Prioritization module as a weighted average of the prioritization criteria, which are used to prioritize resilience solutions. The solution benefit potential (B) is calculated using the following equation:

$$B = W_R S_R + W_D S_D + \sum_i W_i S_i. \quad (\text{Equation 6})$$

where W_R is the user-assigned weight applied to the risk reduction criterion, S_R is the numerical score (1–4) associated with the risk reduction efficacy category, W_D is the user-assigned weight applied to the decarbonization criterion, S_D is the numerical score (1–4, Table 3) associated with the decarbonization benefit category, and W_i and S_i are the weights and scores, respectively, associated with any additional prioritization criteria.

Example Decarbonization Analysis

To demonstrate the methodology described above, we examine a site that uses 2,000 MWh of electricity and no natural gas each year (Table 4). The average CO₂ emissions factor of the site's electric utility is 719.9 lbs/MWh, resulting in present annual site CO₂ emissions of 1,439,800 lbs/year using Equation 2. The marginal emissions factor of the site's electric utility is 1,124.7 lbs/MWh.

Table 4. User inputs related to current site energy usage for decarbonization example. Corresponding variables in Equations 1–4 are provided to the left of the inputs.

	Energy supply type			
	Electricity		Natural gas	
Energy use	E_p	2,000 MWh/year	N_p	0 MMBtu/year
CO ₂ emissions factor	$F_{a,e}$	719.9 lbs/MWh	F_{NG}	116.65 lbs/MMBtu
Total current emissions	P_e	1,439,800 lbs/year	P_{NG}	0 lbs/year

As part of the site's resilience efforts, it is considering a solution that would provide:

- 1) a 20 percent reduction in electricity use (in the >15 – 25 percent reduction range, Table 1), for an annual savings of 400 MWh; and
- 2) a 10 percent shift (in the >5 – 15 percent shift range, Table 2) of the remaining electricity (i.e., 10 percent of the remaining 1,600 MWh, or 160 MWh) to a zero-emission source.

These values are also reported in Table 5.

Table 5. User inputs for decarbonization example solution. Corresponding variables in Equations 1 and 3 are provided to the left of the inputs.

	Emissions reduction strategy			
	Electricity use reduction		Shift in electricity source	
Percent change	R_e	20%	U_e	10%
Avoided or shifted electricity use	$R_e E_p$	400 MWh/year	$U_e E_p (1 - R_e)$	160 MWh/year
CO ₂ emissions factor	$F_{m,e}$	1,124.7 lbs/MWh	$F_{s,e}$	0 lbs/MWh
Avoided CO ₂ emissions	$F_e R_e E_p$	449,880 lbs/year	$U_e E_p (1 - R_e) (F_e - F_{s,e})$	179,952 lbs/year

Referring to the first component of Equation 1, we calculate the avoided emissions associated with the reduction in electricity use as: 1,124.7 lbs/MWh * 0.20 * 2,000 MWh = 449,880 lbs. With the second component of Equation 1, we calculate the avoided emissions provided by the partial shift in remaining electricity use to a zero emissions source as: 0.10 * 2,000 MWh * (1 – 0.2) * (1,124.7 – 0 lbs/MWh) = 179,952 lbs. Summing the two components

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yields 629,832 lbs of CO₂ avoided, which is 43.7 percent of the site’s existing CO₂ emissions (Figure 2).

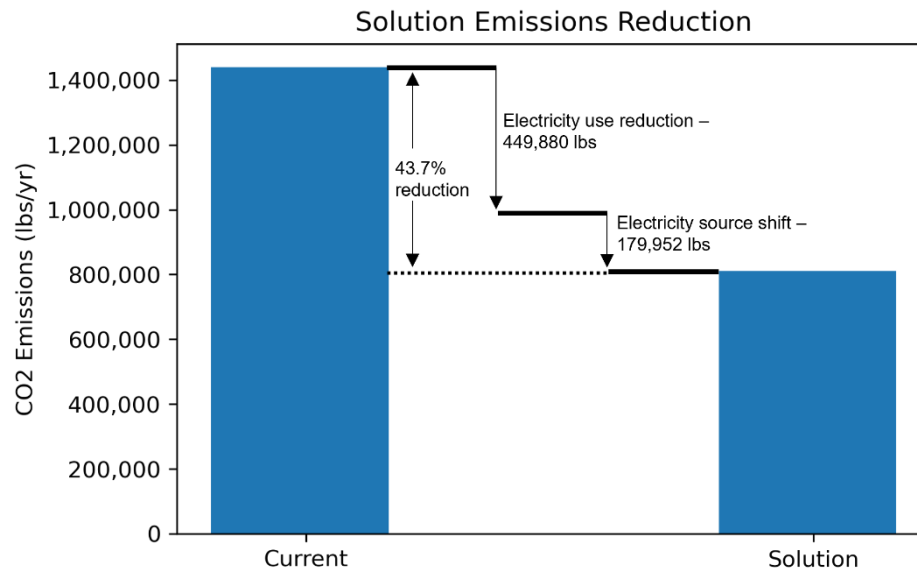


Figure 2. Current CO₂ emissions compared with projected emissions based on example solution

Based on the decarbonization benefit categories in Table 3, this solution would be classified as having a “significant” decarbonization benefit, which has a score (S_D) of 3 (Table 3). For this example, we assume that risk reduction has already been calculated for this solution to be 27 percent, which falls into the “moderate” risk reduction potential category and has a score (S_R) of 2. However, the solution is evaluated poorly (“not well,” $S_3=1$) for a third criterion of “meets site training requirements.” The site has determined that it would like to weight decarbonization and risk reduction efficacy equally ($W_R=W_D=0.4$) and weight the third criterion less ($W_3=0.2$). Using Equation 6, the solution benefit potential can be calculated as $B=0.4*2+0.4*3+0.2*1=2.2$. This solution benefit potential can then be compared to the values calculated for other solutions for the ultimate solution prioritization in the TRN.

Additional Considerations Outside the Scope of the TRN Decarbonization Methodology

As discussed above, the methodology described here takes a simplified, screening approach to evaluating the decarbonization potential of solutions. As a result, the current methodology makes several simplifying assumptions, discussed below. Future development may offer the opportunity to increase the level of detail included in the analysis.

Decarbonization of Redundant Systems

The methodology does not consider emissions reductions *during outage events* associated with switching redundant systems from higher emissions systems (e.g., a diesel generator) to lower emissions systems (e.g., an islandable renewable microgrid). These types of changes are likely to have a much smaller impact on overall site emissions than efficiency enhancements or

shifting the electricity supply for everyday operations, due to the much shorter amount of time that the redundant systems are in use during outage events.

For example, if we consider requirements to test diesel generators once a month for an hour, this results in only 12 hours per year (~0.1 percent of the year) of runtime for a diesel generator. Adding in the probability-weighted average time that a generator might run due to electricity supply outages each year is unlikely to substantially add to the annual runtime. For example, using electric outage duration and frequency data, based on Nuclear Regulatory Commission (NRC) analysis, that is provided in the TRN (Table 6), we calculate an average annual outage runtime of a diesel generator to be 5.8 hours per year (NRC 2022).

Table 6. Estimates of the frequencies of supply outages for electricity and natural gas supplies for a range of outage durations

Outage Duration	Frequency of Outage	
	Electricity ^{a, b}	Natural Gas ^c
1 hour	Likely (once a year)	Unlikely (1 in 100 years)
1 day	Anticipated (1 in 10 years)	Extremely unlikely (1 in 1,000 years)
1 week	Unlikely (1 in 100 years)	<< 1 in 1,000 years
1 month	Extremely Unlikely (1 in 1,000 years)	<< 1 in 1,000 years

^a NRC, Reactor Operational Experience Results and Databases, <https://nrcoc.inl.gov/>

^b Johnson and Ma, 2019, Analysis of Loss-of-Offsite-Power Events, https://inldigitalibrary.inl.gov/sites/sti/sti/Sort_18393.pdf

^c Liss and Rowley, 2018, Assessment of Natural Gas and Electric Distribution Service Reliability, <https://www.gti.energy/wp-content/uploads/2018/11/Assessment-of-Natural-Gas-Electric-Distribution-Service-Reliability-TopicalReport-Jul2018.pdf>

Including diesel generator operation due to both monthly testing and unexpected outages as described above yields a runtime of 17.8 hours, or 0.2 percent of the year. Using the 2,000 MWh value for annual site electricity use from the example provided in the example decarbonization analysis section above, we estimate that a diesel generator capable of supporting that entire load, and run for 0.2 percent of the year, would emit about 7,550 lbs of CO₂ per year⁶.

The annual avoided emissions in the previously described example decarbonization analysis, at over 600,000 lbs/year, exceed the annual emissions of this diesel generator by a factor of greater than 80 (Figure 3). Even if that example had assumed only a 5 percent reduction in energy use and no shift to a cleaner electricity supply, it still would have avoided over 110,000 lbs/year of CO₂—or over 14 times the emissions of the diesel generator.

⁶ Calculation details: 2,000 MWh * 17.8 hours / 8,760 hours * 1,000 kWh/MWh * 0.003412 MMBtu/kWh * 163.45 lbs CO₂/MMBtu diesel / 0.3 = 7555 lbs, where 0.3 is the assumed generator efficiency, based on typical values. The diesel emissions coefficient was sourced from the Energy Information Administration (EIA 2021b), via <https://www.eia.gov/tools/faqs/faq.php?id=73&t=11>
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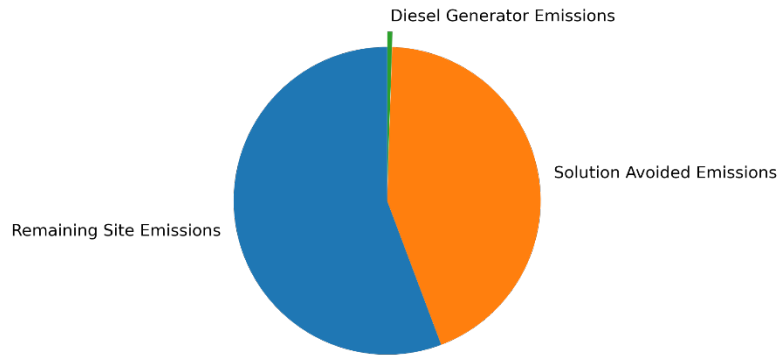


Figure 3. Contribution of emissions from running redundant diesel generator during outage events and maintenance relative to solution avoided emissions

Note that key (and more emissions-impactful) aspects of changing a redundant system from a fossil fuel-based system (e.g., diesel generator) to a renewable system (e.g., solar PV microgrid with batteries) are still captured by this model. A renewable microgrid is unlikely to be cost effective if it is only operated as a redundant system (i.e., only during outage events). Rather, the microgrid would also serve to displace some of the utility supply currently serving site electricity loads during normal operations. Such an effect would be accounted for in the supply-shifting strategy described above.

Sectors Beyond the Scope of the TRN

This decarbonization methodology is not intended to provide analysis of any efficiency-related impacts associated with sectors not analyzed in the TRN (e.g., transportation). For example, electrification of vehicle fleets is beyond the scope of this analysis. In that instance, inclusion could result in misleading results. Avoided emissions associated with reduced gasoline use would not be captured by this natural gas- and electricity-focused analysis, but additional electricity-related emissions associated with increased electricity use from vehicle charging would be, resulting in an incomplete picture. This could lead to the potentially false impression that a solution would increase emissions.

Risk Implications of Electrification

The methodology described in this paper focuses on providing insight into the decarbonization potential of solutions as an additional criterion for prioritization alongside risk reduction. The methodology, as currently described, does not fully address the risk implications associated with the implementation of strategies designed to achieve decarbonization objectives. Strategies such as electrification (e.g., switching loads from natural gas to electricity) could have the unintended consequence of increasing risk associated with energy outages due to the electric grid being typically less reliable than the natural gas supply (Table 6). This is an opportunity for future methodology development and incorporation into resilience planning frameworks, such as the TRN. As they pursue strategies, such as electrification, sites will need decision support tools to balance progress towards decarbonization with reductions in resilience, or design solutions that meet both goals.

Example of the Effect of Electrification on Risk

The potential for electrification to increase risk can be seen in the following example using the TRN risk assessment methodology⁷. The TRN's risk assessment implements a standard risk calculation:

$$\text{Risk} = \text{Hazard} * \text{Vulnerability} * \text{Consequence} \quad (\text{Equation 7})$$

where hazard is quantified using the annual frequency of outages of varying durations, vulnerability represents the likelihood that redundant systems will fail in the event of an outage, and consequence is quantified as the hours of mission outage a site faces resulting from an energy or water supply disruption.

Table 7. Critical loads included in example TRN risk assessment

Critical Function	Facility	Critical Load	Supply Type	Redundant System
Data Analysis and Processing	Data Center X	IT plug loads for Data Center X	Electricity	UPS + diesel generator ^a
		Cooling for Data Center X	Electricity, Water	UPS + diesel generator ^a , Water tank ^b
Training	Training facility	Plug loads for training room	Electricity	Diesel generator ^a
		Water for training facility	Water	Water tank ^b
		Space heating	Natural Gas	None

^a The diesel generator in this example has fuel available to support five days of electricity outage

^b The water tank in this example has water available to support 14 days of water outage

This example builds upon the risk analysis example presented in Unwin et al. (2020), which looked at a site supporting two critical functions: 1) data analysis and processing and 2) training. These functions are supported by several electric and water loads. For the current example, a natural gas space heating load is also added to demonstrate the risk impact of electrifying a natural gas system. The critical loads investigated in this example can be found in Table 7. In the current example, only outages based on national-level data are considered to simplify the analysis. Outages associated with the earthquake hazard from the original example are not included in the current analysis (Unwin et al. 2020). Therefore, outage duration and frequency data for electricity and natural gas outages used in this example are equivalent to those found in Table 6.

An electrification solution for this example could involve installing a geothermal heat pump (GHP) for the training facility. By switching the heating load from natural gas supply to electricity supply, the risk calculations associated with the heating load incorporate the frequency/outage duration pairs for electricity rather than those for natural gas (Table 6). The lower reliability of the electric grid leads to higher risk associated with the GHP solution relative

⁷ Note that the analysis presented here is not currently a straightforward output of the TRN. Future updates may build this more formally into the TRN risk assessment framework.

to the initial natural gas heating system (Figure 4). This increased risk can be partially mitigated through the application of the same backup diesel generator for the GHP that is used for the other electric loads, assuming that the generator is appropriately sized and the fuel storage is extended to still support five days of electric outage for all supported loads. However, because this redundant system is still not sufficient to fully mitigate the increased risk across all risk scenarios (i.e., five days of fuel supply is insufficient for risk scenarios that incorporate outage events of longer duration), the risk remains significantly elevated from the initial (pre-electrification) level. In this example, to achieve an electrification goal while maintaining the existing resilience posture, the site would need a redundant system that could last for the longest expected outage duration (e.g., one month) to support the space heating load (Figure 4). This demonstrates the importance of considering resilience and electrification together, such that resilience improvements can help to enable electrification and meeting decarbonization goals without significantly increasing the site's risk exposure.

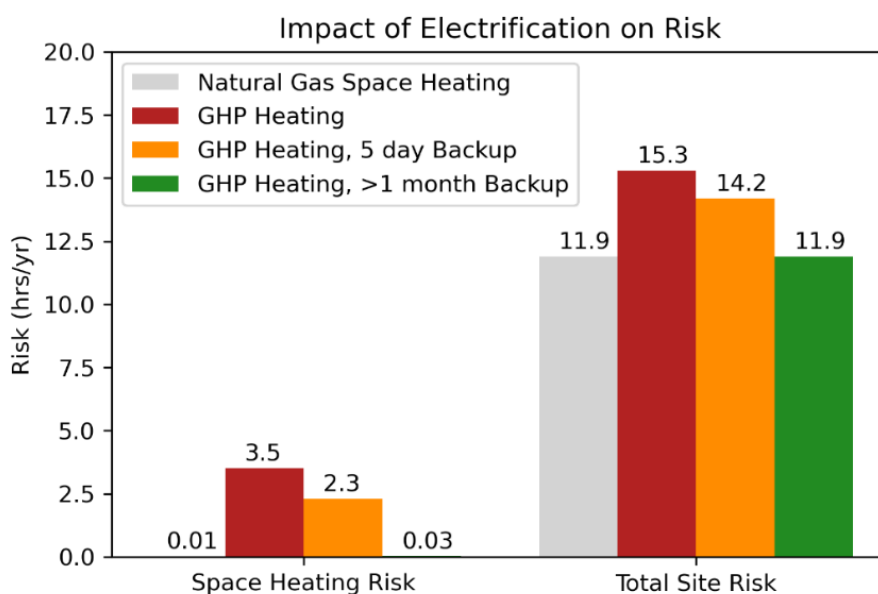


Figure 4. Risk results from four risk scenarios representing space heating powered by natural gas that is not backed up by a redundant system (grey), electrified space heating that is not backed up by a redundant system (red), electrified space heating using the five-day backup system applied to the other loads in the example (orange), and electrified space heating backed up by a redundant system that can last for at least a month (green); the risk contribution of the space heating load is shown on the left and the total site risk, including all loads at the site, is shown on the right

In the example discussed here, the long-duration backup system (at least one month) is applied only to the space heating load. A site could design a solution to provide long-duration backup electricity that is sized to support multiple loads at the site. Such a solution would have the effect of reducing energy and water risk relative to the current site risk while also enabling site decarbonization goals.

Conclusions

As federal sites are being required to pursue both decarbonization and resilience goals, federal energy managers and facility managers must find ways to balance these two sometimes competing priorities. The methodology described in this paper provides a way to incorporate a screening assessment of the decarbonization potential for solutions that have been identified through the TRN, a risk-informed resilience planning tool. This requires users to explicitly consider both risk-reduction and decarbonization in the prioritization of energy and water solutions that may be implemented at a site. The simplified methodology does not currently incorporate the potential impacts to emissions and risk associated with electrification of site critical loads. Additionally, it does not model emissions reductions associated with no longer running a fossil fuel-based redundant system (e.g., diesel generator) for standard maintenance purposes and during outage events, or emissions changes associated with fleet electrification. However, this screening analysis provides federal energy and water managers with the tools to evaluate and balance the potential risk and decarbonization impacts of energy and water solutions that they are considering. Through this multi-criterion decision-making approach, federal sites can work towards achieving both decarbonization and resilience goals.

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