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Case Study: Applying the Idaho National Laboratory Resilience Framework to St. Mary's, Alaska

March 2022

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ACRONYMS

AVEC	Alaska Village Electric Cooperative
DER	Distributed energy resource
DOE	Department of Energy
EEDS	Electric energy delivery system
INL	Idaho National Laboratory
MIRACL	Microgrid, Infrastructure Resilience, and Advanced Controls Launchpad
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
SNL	Sandia National Laboratories

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EXECUTIVE SUMMARY

This report is a case study implementing the Idaho National Laboratory (INL) resilience framework for electric energy delivery systems for the combined electrical system of St. Mary's, AK and Mt. Village, AK. In this case study, we examine the resilience benefits provided by a recently installed 900 kW turbine for the two villages. We also examine potential resilience hazards that may affect the turbine itself. The turbine was installed in 2019 to supplement the only other generation source, diesel. The villages were isolated from each other until 2020, when a new intertie line was commissioned. While both villages have their own diesel generators and fuel storage tanks, for the purposes of this analysis, we only consider the St. Mary's generators and storage, because these generators are intended to serve both villages now that the intertie is live. The Mt. Village generators will eventually be decommissioned.

For this case study, we consider resilience hazards that are most likely to affect the system based on its unique properties, namely it's geographic location in Alaska and the isolated electrical system. We study what would happen under various conditions of a fuel shortage (due to delayed diesel shipments or equipment failure) and what would happen under extreme cold snaps of various intensity and duration. The purpose of evaluating variations on each scenario is to get an overall picture of the effect of the hazard without knowing exactly where, when, or how it will strike. We also evaluate a hazard that affects the communications of the turbine in order to consider not only what risks are mitigated by the turbine, but also what new risks may be introduced.

We found that the wind turbine added resilience to the system by contributing to greater resource diversity of the system and by requiring only naturally occurring local resource (wind). The benefits we studied were directly related to the resilience goals identified by the community: reducing dependency on diesel and improving power quality. The hazard simulations showed that even when the diesel generators were made totally unavailable, the wind could still support the load intermittently. Additionally, the offset diesel from on year meant that more storage reserves were on hand for the next year, so that if a hazard delayed the delivery of diesel, there were sufficient reserves to last until a replacement could reasonably be made.

In this case study, we demonstrated the process of using the resilience framework for electric energy delivery systems to identify resilience benefits of distributed wind against hazards unique to an isolated system in Alaska. This process showed how to customize implementation of the framework to the system qualities and community goals identified. In this analysis, we considered what would happen if a hazard occurred at different times during the year. This let us extrapolate the general resilience benefits of the wind rather than analyzing only one specific instance of a hazard, which could vary widely based on the variability of the wind during that duration of the hazard or the load profile during that time of year.

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INTRODUCTION

Wind energy is one of the fastest growing sources of new energy installation in the United States, and distributed wind represents an important component of those installations. The total wind capacity in the United States was estimated at 110,809 MW at the end of the third quarter of 2020, representing over 7.3% of all installed generation capacity [1, 2]. Distributed wind is an important part of the growing wind segment, with 1,127 MW from over 83,000 turbines installed across the 50 states, Puerto Rico, the U.S. Virgin Island, and Guam from 2003 to 2018 [3]. The growing market segment and trends for rising commercial-, industrial-, and utility-use distributed wind projects motivate the need for a comprehensive understanding of the resilience of distributed wind systems. Access to reliable, resilient power systems is important in 21st century—now more than ever. While all critical infrastructure sectors have important interdependencies, the power grid is inextricably tied to the successful operation of water treatment, communications, healthcare, and many other systems, because it provides an "enabling function" across all critical infrastructure sectors [4]. Moreover, the electric grid is being increasingly tested by a combination of physical and cyber threats. Terrestrial weather events, exacerbated by climate change and extreme weather conditions, happen with greater frequency and intensity. Space events have the potential to cause widescale effects across interconnections and borders. Aging grid infrastructure is not yet adequately prepared to accommodate rapid technological changes, including variable renewable resources, transportation electrification, energy storage, and carbon-free energy standards. Cyberattacks are seen with increasing frequency against the power grid, and the attacks are becoming more sophisticated and targeted towards electric energy systems.

Traditional metrics and evaluation methods for resiliency are not sufficient to evaluate the effect that distributed wind systems will have, particularly in light of the challenges described above. While the concept of resiliency is not new, its application to the electric grid is neither standardized nor well-defined. Additionally, little to no guidance exists on how to evaluate resilience, specifically for distributed wind systems. To fill this gap, the Idaho National Laboratory (INL), as part of the multi-laboratory Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project, has developed a resilience framework for electric energy delivery systems (EEDS) [5]. The framework provides detailed steps for evaluating resiliency in the planning, operational, and future stages, and it encompasses five core functions of resilience. It allows users to evaluate the resilience of distributed wind, taking into consideration the resilience of the wind systems themselves, as well as the effect they have on the resiliency of any systems to which they are connected. Because distributed wind can operate in a variety of applications and at different scales, there is no one-size-fits-all approach for evaluating resiliency. However, this framework provides the tools and guidance for stakeholders to evaluate their current position, create resiliency goals, compare different investment options, and decide which metrics are most appropriate for their system.

In this document, the framework is applied to evaluate the resilience benefits of adding distributed wind to the St. Mary's-Mountain Village electric system.

MIRACL Reference Systems

Reference systems were defined by the MIRACL team as operational distributed-wind systems with significant data available for use in MIRACL research. The three primary MIRACL research areas of advanced controls, a proposed valuation framework, and a resilience framework will be evaluated and applied to the identified reference systems.

Required Characteristics

Reference systems were chosen based on the following required and desired characteristics [6].

1. The reference system represents a real-world system with a nonlaboratory/academic industry partner.
2. The MIRACL team has a point of contact who is interested in partnering and sharing data outlined in the technical parameters section of this report.
3. The identified reference systems cover unique MIRACL use cases.
4. The selected site either has wind turbines or could feasibly add wind turbines.

Desired Resilience Characteristics

Resilience characteristics that are desired by the MIRACL team are:

1. Defined resilience goal or understanding of potential threats to energy resilience, including climate/weather, emissions, and fuel availability.
2. Recent changes to the EEDS that might include capital investments to address system change.
3. Open to information sharing on
   - Cybersecurity policy, guidelines, and practices (e.g., detection and response)
   - Information and/or operational technology networks for power systems operation and other associated networks.

Saint Mary’s, Alaska was selected as the first MIRACL reference system based on the MIRACL team’s ability to access data and models, and their opportunity to collaborate with existing Department of Energy (DOE) and laboratory partners. The system represents an example of MIRACL Use Case 1: wind turbines in isolated grids.

St. Mary’s is a Yupik Eskimo community that maintains a fishing and subsistence lifestyle. It is a village in western Alaska, about 450 air miles west-northwest of Anchorage, located on the Yukon River with a population of 683 [7]. A road and electrical intertie connect St. Mary’s to two neighboring villages, Pitka’s Point (pop. 117) and Mountain Village (pop. 860). The connection between St. Mary’s and Pitka’s Point is older, and discussion about the St. Mary’s electrical system generally refers to the combined St. Mary’s and Pitka’s Point systems, particularly because Pitka’s Point does not have its own generation sources. The connection between St. Mary’s and Mountain Village was completed in November 2020. The electric power needs of all three communities are served by Alaska Village Electric Cooperative (AVEC), a member-owned electric cooperative.

Fuel is delivered to St. Mary’s in warmer months primarily by barge. Energy prices for these villages for electric power, gasoline, and diesel/heating fuel are among the highest in the United States. The 2019 AVEC annual report noted that the delivered cost of fuel to St. Mary’s was $2.85/gallon, which is lower than the overall AVEC average of $3.43/gallon [8].

Although the expectation was that the MIRACL team would have access to production and operation data from the St. Mary’s system through partnerships with AVEC, contractual delays have limited accessibility to real data. The MIRACL case studies will eventually be updated when real data become available; until then, models have been developed by the Sandia National Laboratories and INL teams to mimic production-level data under different conditions.

INL Resilience Framework

The INL resilience framework was developed for broad application to EEDSs so that all elements of systems that contain distributed wind can be part of the resilience evaluation. The users or audience for this framework can include any stakeholders associated with the EEDS. Not all electrical energy systems have the same stakeholders; customers, owners, and operators are generally present, but have different interests. Considering the broad electrical grid, customers, regulators, investors, utility planners, engineers, and operators each have an interest in system resilience driven by different motivating factors.

In this document, the definition of resilience for EEDS as previously identified in the INL distributed wind metrics report is used:

> *The resilience of an EEDS is described as a characteristic of the people, assets, and processes that make up the EEDS and their ability to identify, prepare for, and adapt to disruptive events (in the form of changing conditions) and recover rapidly from any disturbance to an acceptable state of operation [9].*

This definition suggests a few key considerations. Resilience is unique in the depth and breadth of factors associated with the topic. It spans an assortment of technology resources and systems, geographic factors and constraints, risk-severity levels, and diverse stakeholder perspectives. This multiplicity of factors points to the need for a framework that is applicable across various situations and scenarios and that can be effectively implemented by different stakeholders.

A three-tiered approach is developed in the resilience framework. At the top level, three stages of resilience represent different times in a system's lifecycle and different means of evaluating and executing resilience. At the intermediate level, five core functions of resilience are defined, spanning the time stages. At the lowest level, process steps are described that correspond to implementing practices for resilience in each of the core functions. This tiered breakdown is shown in Figure 1.

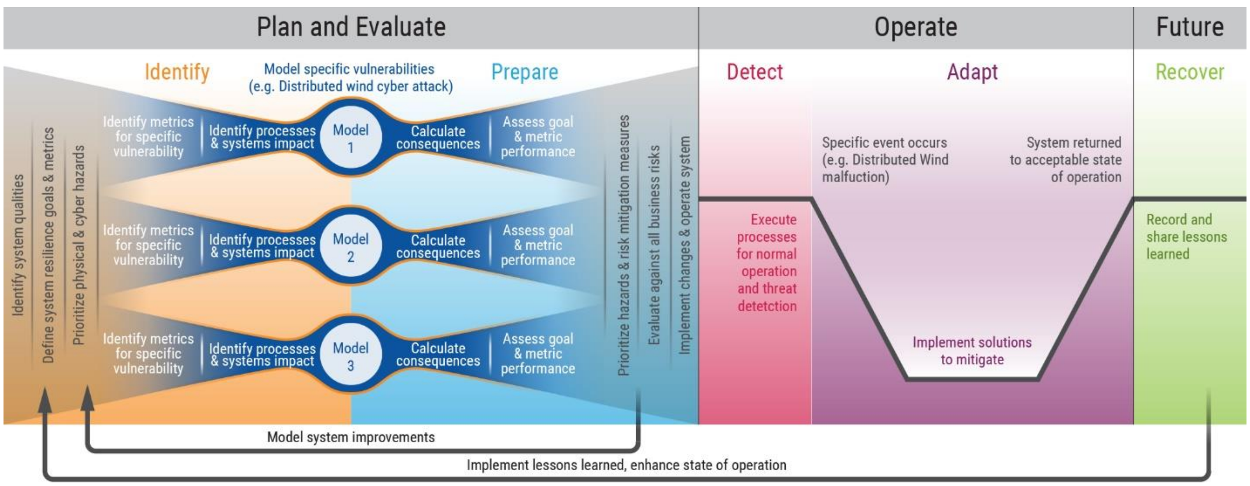

Figure 1. INL resilience framework.

The framework considers three stages of resilience to enable stakeholders to assess and improve their system's resilience throughout its lifecycle. Because considerations of time can vary based on where in the framework users find themselves, we simplify the time considerations to the planning, operational, and future stages. The planning stage uses future organizational needs and current system status to prepare for potential risks. The operational stage seeks to respond to active risks as prudently and efficiently as possible to maintain system resilience. The future stage seeks to improve on current system resilience and feeds back into the planning stage to promote continuous improvement. While all three stages are important, the planning stage (i.e., what is done in advance of the event) is critical in defining a system's resilience characteristics and in outlining how a system responds to an event. The case study presented in this document focuses on the planning stage to demonstrate how the framework can be used to add resilience planning to traditional planning efforts. In particular, it focuses on evaluating the resilience benefits of adding a distributed wind turbine.

The core functions in the framework are labeled identify, prepare, detect, adapt, and recover. These five functions stem from a rigorous analysis of definitions used across the industry, and they represent the core capabilities that a system must have to enable lifecycle resilience. While not an exact match, these core functions are partially derived from, and align with, the core functions of the National Institute of Standards and Technology (NIST) cybersecurity framework for critical infrastructure [10]. Using a structure similar to the NIST framework makes it recognizable and familiar and provides a well-established methodology. Within each core function, process steps are described that help walk stakeholders through the information gathering, evaluation, decision-making, and implementation processes they will need to ensure their resilience goals are maintained throughout the system lifecycle.

Also highlighted in the figure is the concept that a resilience framework should be cyclical in nature. Because a system's resilience is based on finite resources and time, it must continually evolve through this framework's risk management and capital investment steps at an appropriate level of scope and pace.

Stakeholders can use this framework as a key component to identify, assess, and mitigate risks associated with resilience. The framework is intended to be used alongside existing processes to determine gaps at each stage of resilience (planning, operational and future) and to develop a program for systematically prioritizing and improving resilience planning. The framework is extensible; it is applicable at global and granular scales of system resilience planning and operations. The framework is also accessible to a wide variety of interested stakeholders, such as utility practitioners, regulators, environmental constituents, or interested members of national laboratories and academia. This document helps to outline the considerations and processes associated with holistic, long-term resilience planning.

Within this document, the framework emphasizes the planning stage before applying the framework to a utility planner considering multiple investments. While extensive processes are already in place for power system planning, this framework differentiates itself from other related risk frameworks or resilience metrics by considering an all-hazards approach that complements traditional reliability analysis. The framework includes the integration of the uncertainty of cyber effects, weather events, or intentional physical damage, and it creates a process for the model-informed consideration of each hazard.

FRAMEWORK APPLICATION

This document focuses on the planning stage of the framework, the process for which is shown in Figure 2. In this document, each step is explained briefly before demonstrating its application to the St. Mary's, Mt. Village system.

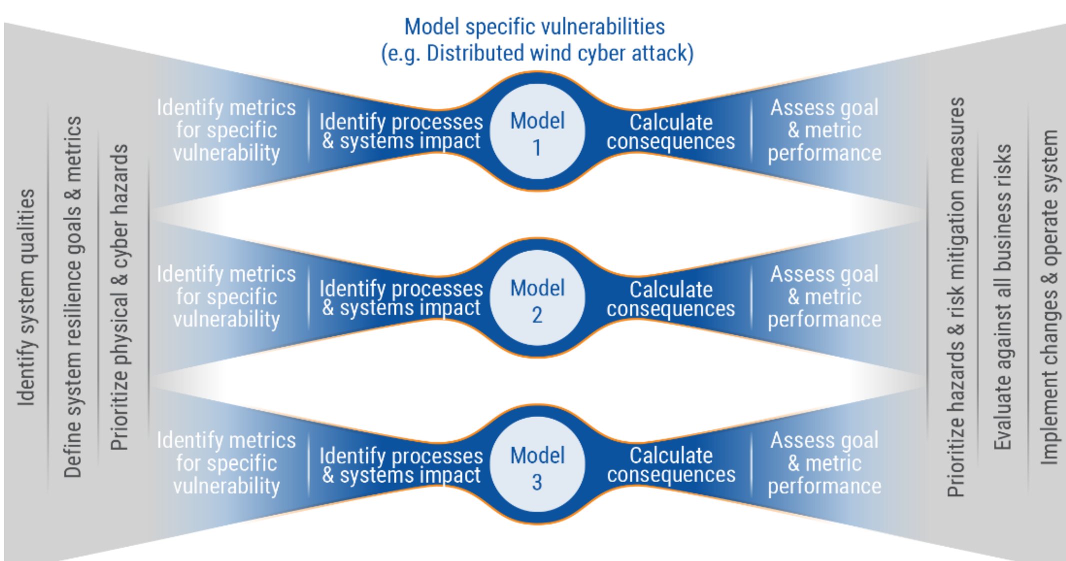

Figure 2. Nested planning bow tie.

The framework can be used for many types of resilience planning. For example, it can be used to evaluate current overall resilience or the resilience of certain subsystems. It can be used to explore existing resilience weak points and propose mitigations. It can also be used to evaluate the resilience benefits of a new investment.

We use the last application for this case study. Although the wind turbine in St. Mary's has already been installed, the resilience benefits that the turbine provided were not well defined. It was installed with the main objective to generate electric power from a renewable resource in an effort to reduce the local dependency on fuel oil as the sole source of electric power generation, which is a resilience goal on its own, but there are other ways in which the turbine can add resilience to the system, as well as scenarios of interest to analyze how resilient the wind turbine itself is against different hazards. In this case study, we analyze the operation of the St. Mary's power system both with and without the wind installed during different resilience hazards of interest. This allows us to compare the performance with wind and without wind and to quantify the resilience benefits provided by wind. Our MIRACL partners at Pacific Northwest National Laboratory (PNNL) will then take the resilience benefits and assign value to the resilience provided by wind, based on costs and costs avoided in the different scenarios.

As a planning exercise, this methodology could be used to assess or motivate the installation of a new distributed wind asset. As a post-installation exercise, this methodology can be used better understand the full value provided by a distributed wind asset and to motivate future upgrades of or expansions to the distributed wind asset.

Identify System Characteristics

A successful resilience framework begins with identifying the system. Stakeholders must know their system characteristics and qualities to define the boundaries of stakeholder roles and evaluate the consequences of certain events. The system may be defined by some combination of geographic and electric boundaries, relevant time periods, or even components. An off-grid distributed wind system might include an entire circuit. A behind-the-meter distributed wind system might only need to define the specifics of everything behind the meter but may still take into the account the status of the interconnected distribution feeder. A distribution-tied distributed wind system may need to consider a broader area. However, in each of these configurations of distributed wind systems, it will be important to note the characteristics of the turbine and the controller, including the ancillary services they can provide, the weatherization packages that are included, and the physical limitations with respect to external conditions (e.g., wind, temperature). Each system is unique; therefore, a system must be fully defined before its resilience and the relevant resilience scenarios can be uniquely defined.

The St. Mary's power system served only the St. Mary's and Pitka's Peak communities until 2019, when a 12.47 kV tie-line was installed to connect St. Mary's and Mountain Village [8]. The electrical distribution system is operated at 12.47 kV, and it largely serves residential, community, and light commercial loads. The combined maximum electrical load is approximately 1300 kW, and the minimum load is 180 kW, with annual energy usage of 3.2 GWh. In May 2019, a single Type IV, 900-kW EWT wind turbine (DW54-900HH5o) was installed at Pitka's Point and connected to St. Mary's through a roughly 4-mile, 3-phase, 12.47-kV distribution line. While it was first connected only to St. Mary's, it was sized to serve both St. Mary's and Mountain Village after the tie-line was complete. The purpose of this case study is to apply the resilience framework previously developed for EEDSs to determine the potential impact of distributed wind to resilience aspects of the overall energy system. We analyze the resilience benefits provided by the distributed wind turbine by considering resilience hazards both with and without the wind installed and comparing the performance in these scenarios. Because the turbine was sized to serve both communities, we consider their combined load.

The following is the most relevant information describing the St. Mary's, Mt. Village system.

Table 1. Technical details describing system.

<table>
<tr><th>Category</th><th colspan="4">Details</th></tr>
<tr><td rowspan="2">Resource Types</td><td colspan="4">Diesel (delivery limited to warmer months)</td></tr>
<tr><td colspan="4">Wind</td></tr>
<tr><td rowspan="3">Generation Assets</td><td colspan="4">900 kW EWT turbine (DW54-900HH5o), Type 4 generator
Cut-in wind speed: 3 m/s
Cut-out wind speed: 25 m/s 10-min average
Hub height: 50m
Ice detection, cold climate package, black blades, and power curtailment confirmed [11, 12]
See [12] for wind production efficiency curves</td></tr>
<tr><td colspan="4">St Mary’s Diesel Generation [13]:
499 kW Cummins QSX15
611 kW Caterpillar 3512
908 kW Caterpillar 3508
See [13] for generator efficiency curves</td></tr>
<tr><td colspan="4">Mt. Village Diesel Generation:
12V2000: 710 kW
QST30: 750 kW
3456: 505 kW
3412: 350 kW</td></tr>
<tr><td rowspan="3">Load [7]</td><td colspan="4">Min 150 kW (summer) [14]</td></tr>
<tr><td colspan="4">Peak 702 kW (St. Mary’s, 2019)
Peak 522 kW (Mt. Village, 2019)</td></tr>
<tr><td colspan="4">Avg. 370 kW (St. Mary’s, 2019)
Avg. 302 kW (Mt. Village, 2019)</td></tr>
<tr><td rowspan="4">Generation Production [7]</td><td></td><td>Diesel (kWh)</td><td>Wind (kWh)</td><td>Total (kWh)</td></tr>
<tr><td>St. Mary’s (incl. Pitka’s Peak)</td><td>1,891,432</td><td>1,342,374</td><td>3,233,806</td></tr>
<tr><td>Mountain Village</td><td>2,644,906</td><td></td><td>2,644,906</td></tr>
<tr><td>Total</td><td>4,536,338</td><td>1,342,374</td><td>5,878,712</td></tr>
<tr><td rowspan="3">Fuel Storage</td><td colspan="4">Existing tank farm: Capacity: 224,264 gallons (18 diesel tanks) (St. Mary’s only) [15]</td></tr>
<tr><td colspan="4">Tank farm under construction: 414,000 gallons (planned for new power plant serving St. Mary’s and Mt. Village) [16]</td></tr>
<tr><td colspan="4">2 AVEC tugs/barges: 8,000 barrel capacity (336,000 gallons) [17], and 10,000 barrel capacity (420,000 gallons) [18] [Assuming one delivery per year]</td></tr>
<tr><td rowspan="4">Power System</td><td colspan="4">Isolated distribution power system (12.47 kV)</td></tr>
<tr><td colspan="4">Central dispatch controller runs autonomously</td></tr>
<tr><td colspan="4">Tie line (25 mi) to neighboring Mountain Village [19]</td></tr>
<tr><td colspan="4">Phasor measurement units (PMUs) installed at power houses at both St. Mary’s and Mountain Village, batch data collection due to bandwidth limitations, operating since 2001</td></tr>
<tr><td></td><td colspan="4">Electric cooperative owned (AVEC)</td></tr>
</table>

Category	Details
Market Parameters	Capital and operational costs
	Rate structure unknown

Define System Resilience Goals and Metrics

There is no one-size-fits-all approach for resilience in EEDS, or even for distributed wind. Stakeholders should come together to identify what resilience means in the context of their system. Stakeholders should identify what they wish to achieve with their system before appropriate metrics and models can be determined, and before investments can be made. At this stage, the system's resilience metrics should also be identified. The metrics that are useful for evaluating resilience will depend on each individual system and the individual risk, but certain metrics will persist through all scenarios. Data availability may drive decisions about what metrics to use. However, care should be taken so that metrics selected are specific enough to enable decision making, whether for operational or planning purposes. Metrics should ideally aid in direct and indirect assessment of resilience, cover both quantitative and qualitative properties of the system, meet as many of the characteristics shown in Figure 3 as possible, and consider the entire physical and operational scope of the system, including inputs, capacity, capabilities, performance, and outcomes [9].

Figure 3: Desirable characteristics for resilience metrics.

The resilience goals for St. Mary's and Mt. Village have been derived from the St. Mary's community goals.

Resilience Goal 1: Reduce Dependency on Diesel

Prior to the wind turbine installation, the remote communities had a single source of fuel for electric energy: diesel fuel. Dependency on this single resource resulted in a higher risk associated with interrupted operations of the EEDS. Consequences from this potential risk include underserved or unserved electrical load, leading to loss of life and severe economic impact to the remote community. Hence, possible mitigations for this risk include reducing dependency on diesel fuel. Mitigations should align to carbon neutral or carbon reduction goals. This risk establishes the first resilience goal.

This resilience goal can be evaluated with the resilience metrics listed in Table 2.

Table 2. Metrics towards evaluating fuel dependency.

Indirect Metric	Source
Generation available	St. Mary's data request/ simulation
Wind generation	St. Mary's data request/ simulation
Fuel needed	St. Mary's data request/ simulation
Fuel stored/available	St. Mary's data request/ simulation

Fuel displaced (when wind is installed)	St. Mary's data request/ simulation
Load	St. Mary's data request/ simulation
Carbon emissions	St. Mary's data request/ simulation

Resilience Goal 2: Improve Power Quality

As an isolated microgrid, the system does not have interconnection to adjacent electrical systems that can provide frequency and voltage support via inertia and injection or absorption of real and reactive power. Therefore, a second resilience goal is to improve power quality. The commissioning of the intertie line between St. Mary's and Mt. Village was a step towards making the combined systems more reliable and more resilient because they can now use generators in both villages to provide backup generation as needed. In this study, we are interested in analyzing the resilience of distributed wind, so we consider the impacts to power quality both with and without the wind asset, but we consider the intertie line to be constant.

This goal can be evaluated with the resilience metrics in Table 3.

Table 3. Metrics towards evaluating power quality.

Metric	Source
Outage duration	St. Mary's data request, simulation
Load lost during outages	St. Mary's data request, simulation
Failure Rate	St. Mary's data request, simulation
Voltage level variation	St. Mary's data request
Backup capacity available	St. Mary's data request, simulation

Prioritize Physical and Cyber Hazards

Stakeholders should work together to prioritize physical and cybersecurity hazards. This can be done by considering which impacts would be most damaging to the system and, subsequently, which hazards are likely to cause them. The prioritization is used to identify what should be modeled and assessed further. After stakeholders understand the possible threats to a system, the risk of these threats should guide prioritization. Whether it is a physical or cybersecurity hazard, the following calculation is helpful in considering risk assessments.

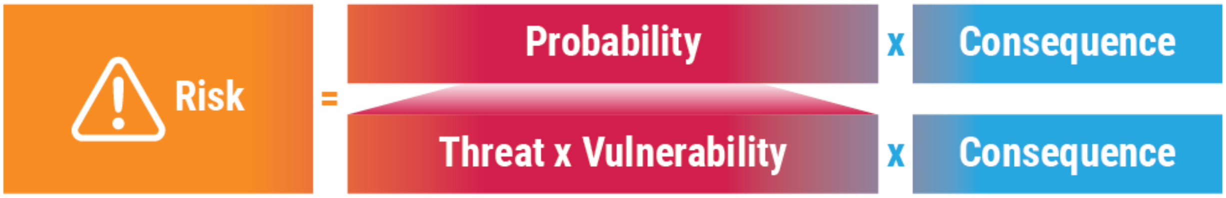

Figure 4. Risk assessment calculation.

Risk can be considered the probability (or likelihood) times the consequence (or impact). In this manner, a high-impact but unlikely event can be prioritized against a medium-impact, frequent event. The probability component includes both the threat and the vulnerability of the system to that threat. In the case of a cybersecurity hazard, threats should be evaluated within the constructs of intent and capability. For a weather-based hazard, the system may be vulnerable in different ways and in different geographic areas. Further, vulnerability may be dynamic. A system may include a defense mechanism or emergency state of operations that adjusts the system's vulnerability to various threats. The attributes of each hazard will need to be described in detail so that the consequence can be determined. Duration of the consequence should also be considered because it is a key resilience characteristic.

Fuel Shortage

The barges bringing diesel to St. Mary's are operated by AVEC and have been operated reliably for many years. However, there are still some possible scenarios where a fuel shortage could occur. We consider two fuel shortage scenarios: a forecasted fuel shortage and an immediate fuel shortage.

Forecasted fuel shortage

An unusual summer storm delays delivery of the expected fuel shipment. Due to tight scheduling constraints, the delivery is rescheduled for 6 weeks later. Then one of the following three events occurs:

- The second attempted delivery is successful.
- The second attempted delivery (planned by end of summer) is also delayed by low water on the Yukon. The villages must wait an additional three weeks for shipping barge to be available to St. Mary's with fuel.
- The second attempted delivery (planned by end of summer) is also delayed by storms, which results in an early freeze on the Yukon. The villages mut rely on air delivery of diesel via multiple shipments to last throughout the year.

While the last scenario may seem unlikely, we note that the probability is non-negligible, as a similar scenario was experienced to other remote Alaskan villages in 2012 [20]. The consequences depend heavily on the fuel reserves after the first year. If there are not sufficient reserves, the system will not tolerate many delays, and if fuel runs out, the villages will experience health and public safety consequences and economic damages. This risk can be ameliorated by ensuring that there is greater storage capacity and more reserve fuel or by using more types of energy generation, like wind, to offset diesel use.

Immediate fuel shortage

An immediate fuel shortage can occur if the access to the local diesel supply fails. This could happen via tank failures and fuel spills or pipeline ruptures that prevent the power plant from receiving fuel. We consider these two examples with the following consequences:

- A 2-day outage: A pipe ruptures. It takes two days to repair the pipe.
- A 2-week outage: A tank rupture occurs. Ensuing fires cause damage to other tanks. It takes two weeks to get a plant to deliver backup fuel to the intact tanks.

The likelihood of an immediate fuel shortage is very low. We note, too, that in order for this to be a high consequence event, the pipe rupture would have to prevent all fuel from reaching the power plant, and we assume that the Mt. Village generators are not capable of providing backup. For the tank failure scenario to cause a full halt on diesel power production, the failure would have to damage all tanks that hold the remaining fuel. This is unlikely when fuel reserves are near full capacity. However, if a tank failure occurred on the one or two remaining tanks shortly before a new shipment was expected, it is more likely that this scenario would fully halt diesel power production.

It is impossible to enumerate every possible combination of failures or the repairs or lengths of outages associated with each. We focus on high consequence scenarios in this resilience analysis so that we can analyze the worst-case outcomes and find ways to mitigate the risk of these high-consequence events.

Overall, the probability of a fuel shortage is low. However, the consequences of a fuel shortage may vary depending on whether wind is installed. If wind is not installed, a shortage of diesel fuel means that there may not be enough power to service all of the load. Given that electricity is needed for heat, failure to meet load could have significant economic and health effects. The combination of the low probability and high consequence makes it a moderate risk (Figure 5).

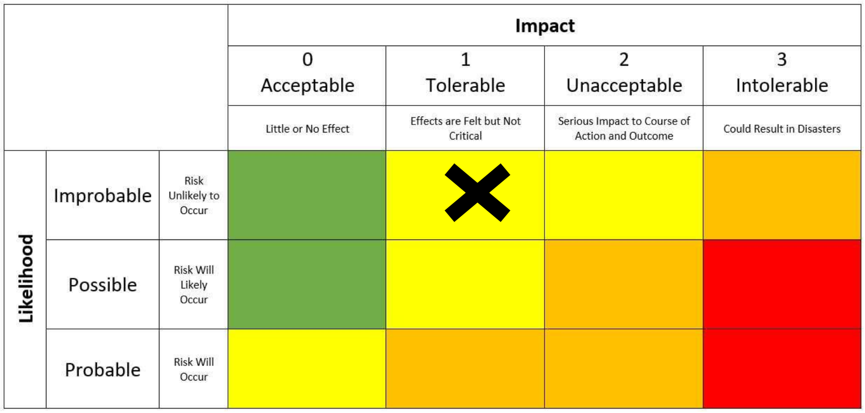

Figure 5. Preliminary risk assessment of fuel shortage without wind.

If wind is installed, a shortage of diesel fuel still means that the diesel generators would not be able to provide power. However, a 900 MW turbine has the capacity to provide for the full peak load seen in 2019. Capacity is not the same as output; the output will depend on wind speeds. The system may not always be able to meet the full demand, but it will often be able to meet most of it. The combination of the low probability and low consequence event make it a mild risk hazard (Figure 6).

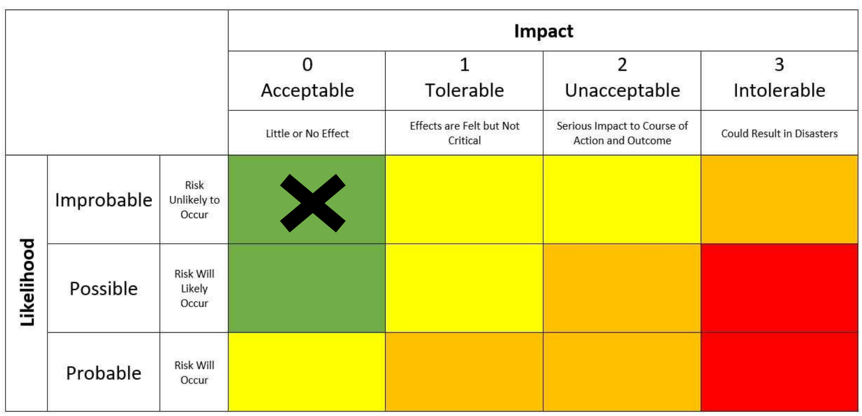

Figure 6. Preliminary risk assessment of fuel shortage with wind.

Severe Winter Weather Event

The National Weather Service defines the following winter-weather hazards for Alaska [21]:

- **Extreme cold:** Below -40°F (= -40°C).
- **Blizzard**: Sustained winds of frequent gusts to 35 mph or more and falling and/or blowing snow, reducing visibility to less than 1/4 mile.
- **Heavy snow:** Snowfall ranging from 6 in. to 1 ft in 24 hours. Criterion varies regionally across Alaska.
- **Freezing rain:** Rain that freezes on impact on surfaces such as trees, cars, and roads, forming a coat of ice.

- **Wind chill**: The temperature it "feels like" to people and animals based on the heat loss from exposed skin caused by the effects of wind and cold. Criterion varies regionally across Alaska.

- **High wind:** Sustained winds or frequent gusts exceeding 40 mph for an advisory and 60 mph for a warning.

From a power systems perspective, the St. Mary's grid is vulnerable to extreme cold, blizzards, or high winds. The extreme cold scenario would push the wind turbine out of its operating limits even with the cold weather package. A blizzard has the potential to trigger overspeed protection on the turbine, halting its power production. A high wind event has even more potential to trigger overspeed protection on the turbine.

Any decrease in temperature, particularly in the winter, is likely to drive up demand via heating needs. Any winter weather scenario analyzed needs to also consider the expected higher load.

During any of these winter hazards, diesel generators would be able to continue operating as normal. Load would have to be extremely high to exceed the diesel-generation capacity. The St. Mary's wind turbine is outfitted with a cold-weather package, which means that the turbine remains operational up to -40°C. The turbine blades are black to better absorb sunlight, causing the blades to emit heat and reduce the buildup of ice. The system is also outfitted with ice-detection sensors.

Extreme winter weather is a probable scenario, but because the wind turbine is weatherized for cold winters, is it unlikely that it will cease to operate. The consequences from this event would primarily be increased fuel use due to the higher load and potentially the wind turbine ceasing to operate at low temperatures. Unless this hazard is combined with a fuel shortage or other failure, it is expected that the system could continue to meet the full load. This event is labeled as a mild risk hazard. Just because it is a mild risk hazard does not mean it should be ignored. The comprehensive risk analysis must still be performed, and stakeholders must decide whether the business risk is acceptable or if other mitigations need to be put in place.

Figure 7. Preliminary risk assessment of severe winter-weather conditions.

Communications Outage

In this hazard, we consider a scenario in which remote communication to the wind tower are out of service. There is a fiber-optic link, attached to the distribution line poles, that provides communication between the wind turbine and the control switchgear of the St. Mary's prime power plant. Using that link, the wind turbine can then be manually or automatically controlled at both the power plant and from AVEC headquarters in Anchorage. This setup lends itself to the consideration of two scenarios: the fiber-optic link is out of service, eliminating remote access capabilities from local or AVEC operators, and the remote connection link between the St. Mary's prime power plant and AVEC headquarters is out of service, but the fiber link is still live.

In the first scenario, the probability of such an event is low. It would take a strong storm to take out the distribution line infrastructure, and even then, as long as the fiber link remained intact, it might remain operational. The biggest threat may be wildlife chewing through the line, which is unlikely. If the fiber-optic line goes down, operators will be unable to see live data from the turbine or send new commands, but the power production capability of the turbine would remain unhindered. There would be a measurable impact if an alarm occurred while the link was down, and no operator could see it. In the worst case, the turbine could shut down due to an alarm, and it would be unable to contribute to the village generation. We can consider three potential alarms that are missed during the communications outage and their associated consequences:

- **Internal trip:** A breaker in the turbine flips, and production ceases. It takes 2 days to discover the alarm and for a technician to go out to the turbine and reset it.
- **Gearbox failure:** This is one of the most common turbine failures [22]. It can take from days to months to repair a gearbox, depending on parts availability. We assume that the alarm is discovered 2 days after it is first triggered. For the sake of a simpler analysis, we assume that the wind turbine is out of commission for 2 weeks.
- **Temperature warning:** This is a low-level warning. There is no change in production due to a communications outage when this warning occurs.

			Impact			
			0 Acceptable	1 Tolerable	2 Unacceptable	3 Intolerable
			Little or No Effect	Effects are Felt but Not Critical	Serious Impact to Course of Action and Outcome	Could Result in Disasters
Likelihood	Improbable	Risk Unlikely to Occur	X			
	Possible	Risk Will Likely Occur				
	Probable	Risk Will Occur				

Figure 8. Preliminary risk assessment of downed fiber-optic link.

In the second scenario, the probability of communications going down is higher, but because AVEC is not the primary operator of the turbine, nor do they rely on live data from it, the impact is lower.

			Impact			
			0 Acceptable	1 Tolerable	2 Unacceptable	3 Intolerable
			Little or No Effect	Effects are Felt but Not Critical	Serious Impact to Course of Action and Outcome	Could Result in Disasters
Likelihood	Improbable	Risk Unlikely to Occur	✕			
	Possible	Risk Will Likely Occur				
	Probable	Risk Will Occur				

Figure 9. Preliminary risk assessment of AVEC communications failure.

Because this last risk of AVEC communications failure is so low, it is not analyzed in detail with a bow-tie assessment.

Bow-Tie Analysis of Specific Hazards

Now that stakeholders have identified and prioritized hazards, those that rank highest should be analyzed more closely. Certain hazards may be readily modeled, while others may require testing new capabilities of the system to fully understand system preparedness. The bow-tie threat analysis uses the following steps, as seen in **Error! Reference source not found.**, and each step is detailed below.

1. **Identify metrics relevant for specific hazard.** For each scenario, metrics relevant to that hazard should be identified. These metrics will supplement the system metrics that have been defined previously and provide evaluation criteria across multiple scenarios. These metrics may not be performance metrics, but rather measurements throughout the system necessary to properly understand the hazard.
2. **Identify processes and system impacted.** For the specific scenario, the relevant portions of the system should be identified. Portions of the system may include people, processes, and assets. Identifying the people, processes, and assets associated with a hazard may reveal a system vulnerability even before modeling.
3. **Model specific hazard.** Modeling the scenario may involve computer simulations, probability analyses, or test scenario procedures. Computer simulations are capable of modeling the impact of certain power system disruptions (e.g., contingency performance). Probability analyses may build on that computer simulation capability and incorporate weather and seismic activity to build survivorship models assessing asset fragility. Test scenario modeling may assess how humans, processes, technology, and infrastructure fare in a mock event.
4. **Calculate consequences.** Stakeholders should then calculate consequences of the hazard. How did the system perform against the hazard? Were the metrics identified effective in capturing those consequences? Did the system perform as expected, or were new characteristics of the system identified?
5. **Assess goal and metric performance.** Finally, for each scenario, performance should be evaluated by considering whether goals were met and metrics were within acceptable ranges. Stakeholders may ask themselves if the overall goals were met. If not, do the goals need to be adjusted to be more relevant for the system? What can be improved to meet the goal?

Figure 10. Bow-tie threat analysis.

Base Case

Before we assess the hazards, we first model the base case in order to understand the consequences of the hazards. To do this, we would ideally have at least a year's worth of raw data from the real system. However, because that is not yet available to the MIRACL team, we have used the information available about St. Mary's and Mt. Village to create our own models of the system. Details about the assumptions used to develop the models can be found in Appendix A. Assumptions are consistent with those used by the rest of the MIRACL team, although the INL team developed their own models so that the hazard scenarios could be explored in detail.

We assume that Year 1 of analysis starts on July 1 and that this is also when a barge shipment has been received. Thus, the fuel storage tanks are at full capacity. This makes it easier to analyze fuel use and diesel reserves with respect to storage capacity throughout the year and under different hazard scenarios. These synthetic data are arbitrarily assigned the year of July 1, 2007 to June 30, 2008. See the appendix for more details.

It is possible to adjust the source of the wind data to look at different potential wind production outputs. We have real wind data from the St. Mary's airport, collected at hourly intervals from 2005 to 2018. We have adjusted these data to account for hub height and added an additional correction factor to account for the change in location. The airport may be more protected from wind than is the wind turbine site, which was selected to have maximum output. We also have synthetic wind data which were generated by a HOMER model using monthly parameters for wind at the wind turbine location, again with a correction factor applied to account for the difference in wind readings and hub height. For these simulations, the airport data from 2008 were chosen as the wind source. We chose a single year, rather than the average of all years, because the average smooths out the variability of wind, but we wanted to preserve that variability. We chose the adjusted airport data rather than the synthetic data because we felt they represented the most realistic scenario, despite the measurements being collected at a location different from the turbine site.

In a base case year, wind is used to serve as much of the load as possible, and diesel generators are used to serve the remainder of the load. There is no unmet load in this base case year.

We assume that fuel storage tank farms are filled completely at the beginning of Year 1. We assume that, with wind installed, the new tank farm is used, and there is a starting capacity of 414,000 gallons. Without wind installed, we assume that the starting fuel storage capacity for the combined St. Mary's, Mt. Village system doubles the old St. Mary's fuel storage capacity of 224,264 gallons, which gives a capacity of 448,528 gallons. It is reasonable to analyze the no-wind case with higher fuel storage because it would be known that diesel was the only fuel source, so more of it would be used throughout the year (Figure 11). It is also reasonable for the fuel storage capacity to be so large for the with-wind case because the operators would want to have the capacity to run fully on diesel in the event of a problem with the wind turbine (Figure 12).

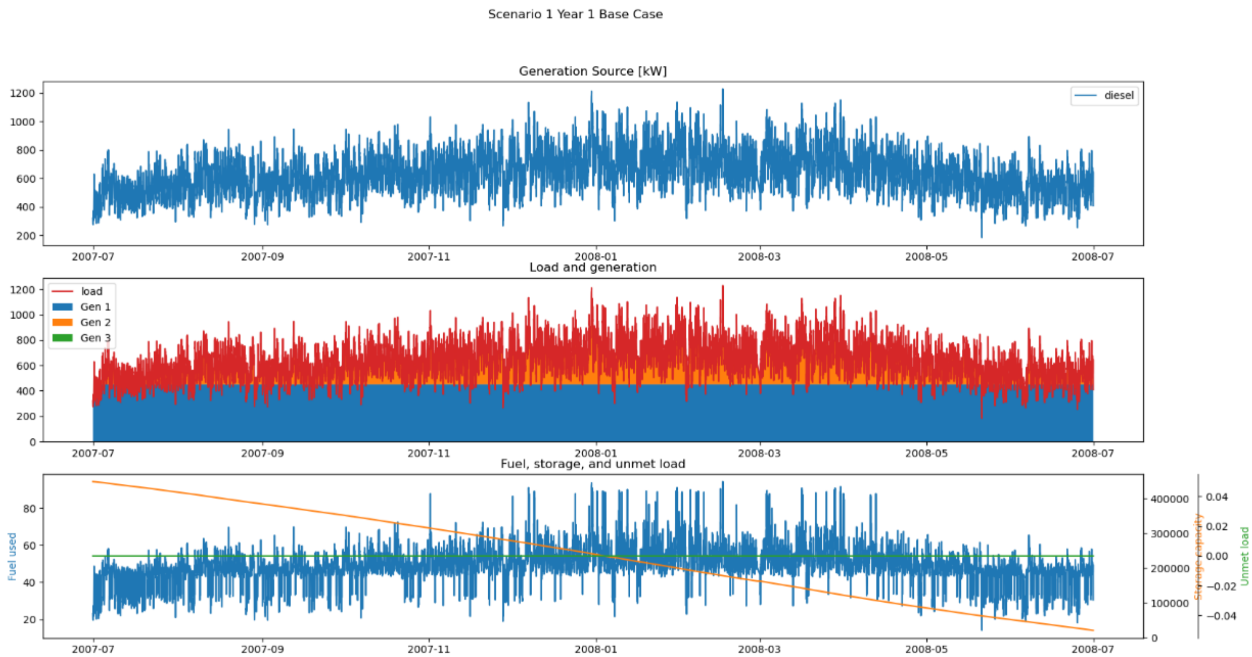

Figure 11. No wind, base-case year.

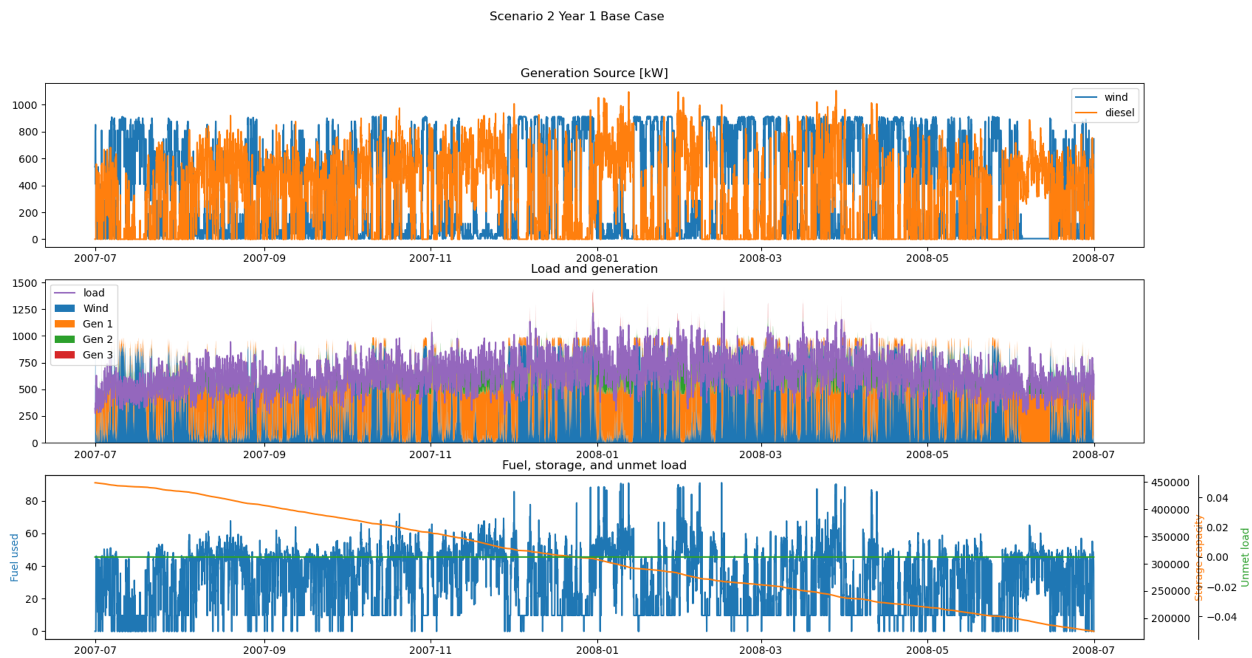

Figure 12. With wind, base-case year.

Notably in Figure 11 and Figure 12, we can see that the fuel storage capacity drops in a nearly linear format throughout the year and that there is no unmet load. Although the load and the fuel use are highly variable, they stay mostly in the same range throughout the year, with peak fuel use in the winter, which is what leads to the linear fuel reserves decrease. We can see more details of what is going on if we examine a single month.

In Figure 13, it is evident that generation exactly matches the load, as desired. In Figure 14, it is evident that, even when wind serves all of the load, some diesel generation is turned on. This is because

St. Mary's operates with 100% wind-served-load reserve capacity. In other words, if wind were suddenly to cut off, St. Mary's wants to have generators turned on with the capacity to mee the full load. When wind production exceeds load, the wind production is curtailed, and the extra power is lost. The correlation between wind production and fuel use is also evident. When wind production is high, fuel consumption is low.

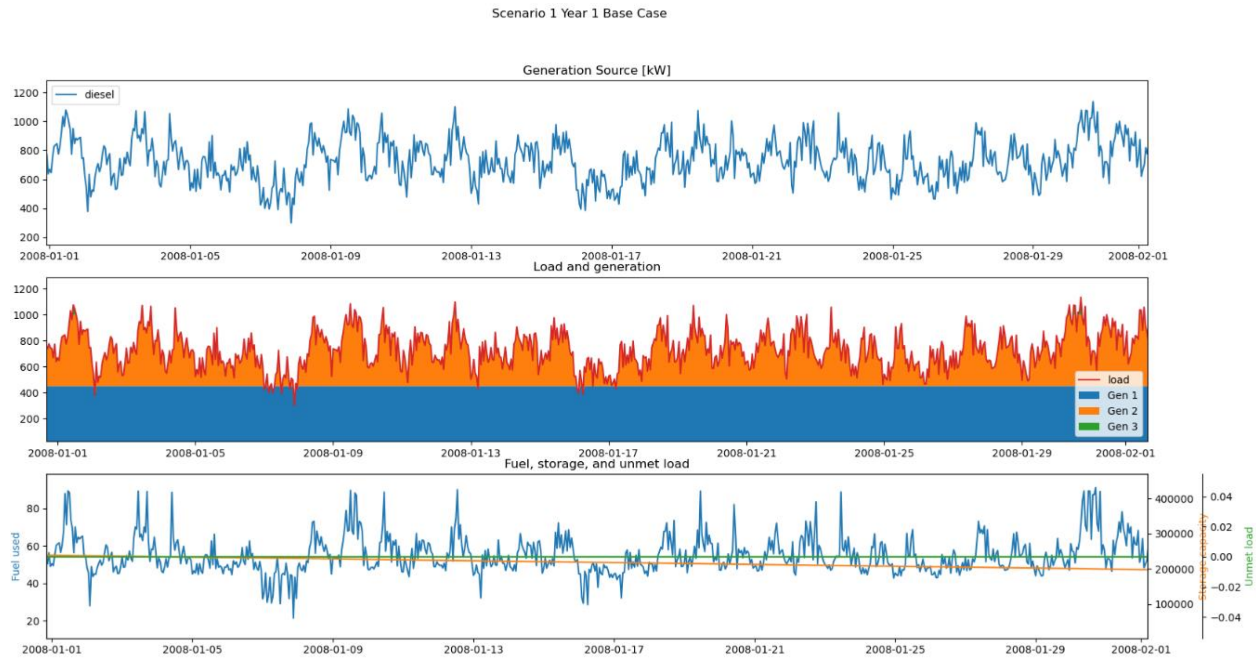

Figure 13. No wind, base case, January.

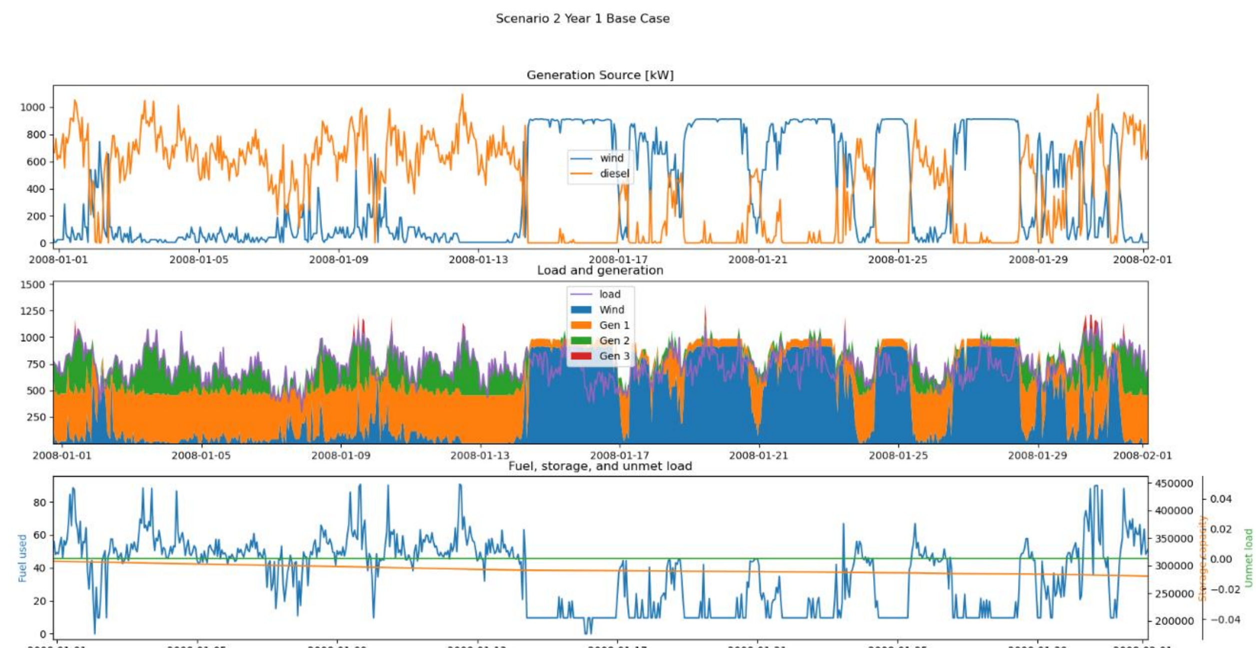

Figure 14. With wind, base case, January.

Forecasted Fuel Shortage

Identify metrics relevant for specific hazard

Beyond the basic system metrics already identified, the metrics in Table 4 are necessary to properly evaluate a forecasted fuel shortage.

Table 4. Metrics needed for forecasted fuel shortage.

Metric	Source
Load data	St. Mary’s data request / HOMER model
Wind speeds	Pitka’s Point Met Tower Wind Resource Report [23] Airport data [24]
Wind production	St. Mary’s data request / EWS Production curve [12]
Length of fuel shortage	Assumptions
Fuel available during shortage	Assumptions
Restoration plan (repairs, airlifted fuel, etc.)	Assumptions

Identify processes and the system impacted

Without the wind turbine installed, the only important metrics are the amount of fuel available, the generation production that this can serve, and the load.

With wind installed, additional metrics of importance are wind speed and production, particularly as they match variable load. Notably, there is no battery storage. Thus, although power can be curtailed if generation exceeds load, excess power cannot be stored for times when wind speeds are lower.

Model specific hazard

Using the separate starting capacities, at the end of the first year, the fuel storage tanks have 20,289 gallons remaining in the no-wind case and 190,151 gallons remaining in the with-wind case. With no extra provisions, the fuel storage remaining in the no-wind case is sufficient to last 21 days and 10 hours while continuing to serve all of the load. The fuel storage remaining in the with-wind case is sufficient to last 184 days and 18 hours, continuing to serve all the load until January 1.

In Figure 15, it can be seen that the first 3 weeks of the Year 2 are covered by the remaining fuel storage. However, after July 22, no fuel remains to serve any of the load. No alternate sources of generation are present, so all of the load is dropped. In this case, the system would not be able to operate at full capacity until the rescheduled barge delivery reached St. Mary’s. If that rescheduled barge delivery was further delayed, the St. Mary’s and Mt. Village communities would continue to be without power until a barge or an airplane could reach them.

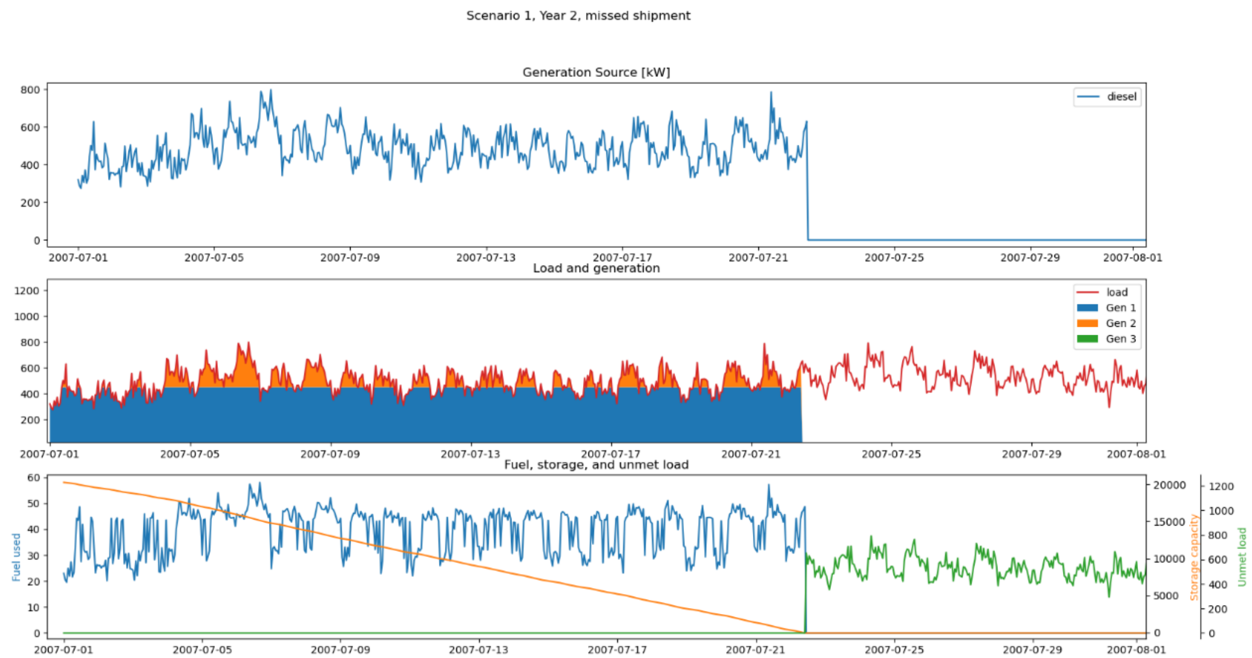

Figure 15. No wind, Year 2, missed fuel shipment.

Figure 16 shows that, with wind installed, the system can survive without a fuel shipment in Year 2 until January 1. This is because wind offsets significant diesel use in Year 1, leaving greater fuel reserves for Year 2, and wind continues to offset diesel needs in Year 2, making those fuel reserves last longer. However, one full storage tank farm worth of diesel is only sufficient to last 18 months, so additional imports of fuel, whether by delayed barge shipment at the end of the summer or by plane at some point in the fall, are needed for the system to survive the full second year.

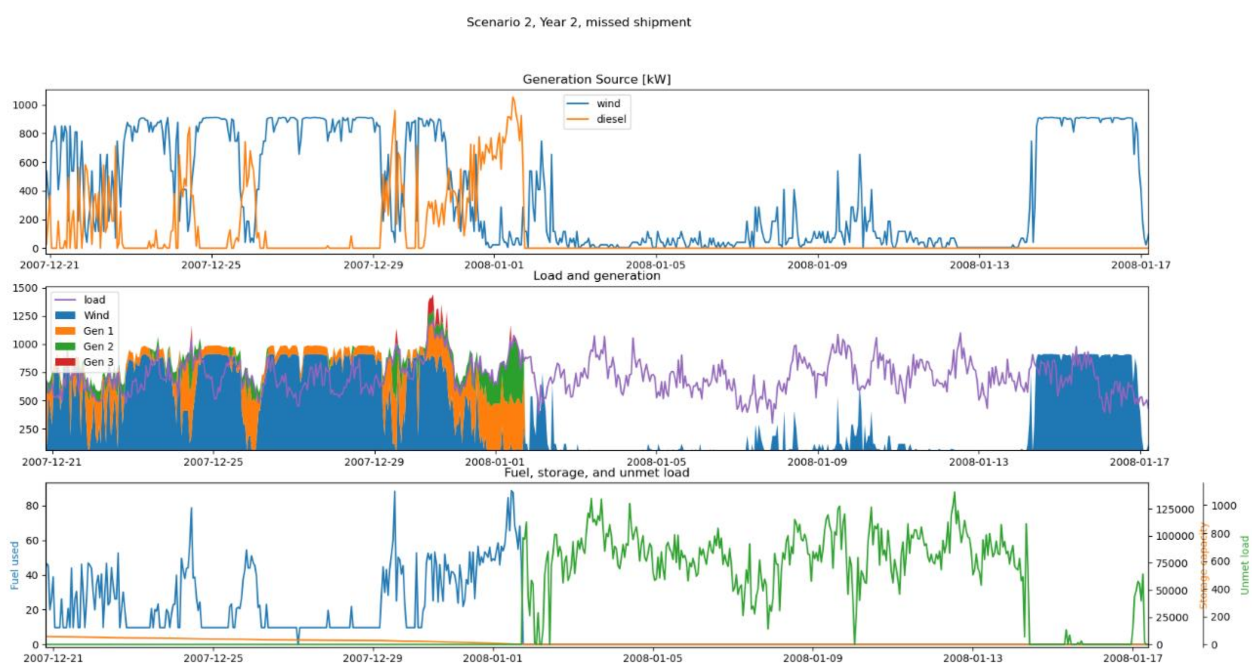

Figure 16. With wind, Year 2, missed fuel shipment.

The fraction of diesel usage that wind can offset is heavily dependent on wind production and, therefore, wind speeds. Running this analysis using different years of wind sources reveals that the system would likely survive without fuel imports until at least January, potentially into February or March, as shown in Table 5. Note, too, that if a fuel shipment was not possible in the fall, the river becomes passable again in May, so it would be necessary to fly the fuel needed until May, and then scheduling a barge shipment may be a more cost-effective way to deliver the fuel needed.

Table 5. Fuel-storage capacities as wind source changes.

Wind Source	Without Wind		With Wind	
	Storage Capacity after Year 1 [gal]	Storage Depleted in Year 2 on	Storage Capacity after Year 1 [gal]	Storage Depleted in Year 2 on
Airport 2005	20289.1	7/22 11:00	159135.8	2/10 15:00
Airport 2006	20289.1	7/22 11:00	166684.4	2/4 15:00
Airport 2007	20289.1	7/22 11:00	149916.7	1/18 10:00
Airport 2008	20289.1	7/22 11:00	141718.2	1/1 18:00
Airport 2009	20289.1	7/22 11:00	157870.1	1/29 22:00
Airport 2010	20289.1	7/22 11:00	144187.3	1/7 14:00
Airport 2011	20289.1	7/22 11:00	159726	2/18 1:00
Airport 2012	20289.1	7/22 11:00	152708.5	1/28 23:00
Airport 2013	20289.1	7/22 11:00	149002.6	1/27 9:00
Airport 2014	20289.1	7/22 11:00	162846.9	2/27 9:00
Airport 2015	20289.1	7/22 11:00	147983.1	1/21 6:00
Airport 2016	20289.1	7/22 11:00	155422.1	2/12 10:00
Airport 2017	20289.1	7/22 11:00	132224.2	1/6 20:00
Airport 2018	20289.1	7/22 11:00	173333.4	3/13 22:00
Airport Average	20289.1	7/22 11:00	171407.4	3/16 10:00
HOMER Synthetic	20289.1	7/22 11:00	162969.8	2/25 15:00

Calculate consequences

Without Wind

After first 6 weeks of delayed fuel delivery, 283,265.9 kWh are dropped. The system would need 385,124 gallons to last through the remainder of Year 2, to July 1. The system would need 321,354 gallons to last until May 1, which is approximately when fuel could be delivered the following summer.

After 9 weeks of delayed fuel delivery, 572,240 kWh are dropped. The system would need 362,217 gallons to last until July 1 or 299,030 gallons to last until May 1.

With Wind

With wind installed, the system would have sufficient fuel reserves to last through 6-week or 9-week delays on fuel delivery. There would be no load lost. However, fuel reserves would be insufficient to last for the full second year, so a delivery of fuel in Year 2 would be required. Using 2008 airport data for windspeeds would require an additional 130,486 gallons of diesel to serve 1,327,120 kWh load needed to last from the end of the reserves on January 1 to the end of Year 2 on July 1. Alternatively, an additional 87,079 gallons would be needed to last from the end of the reserves on January 1 to May 1, when an early spring barge might be able to deliver fuel.

For Both Cases

Although we identify the day fuel would run out, the total demand over that period and the total kilowatt-hours that diesel can serve do not change dramatically. Operators could potentially use demand response to cut power to everything but critical loads. Operating in this manner, running lower output for a longer period of time might change generator efficiency, so the exact number of kilowatt-hours that diesel could serve may change slightly, but the general performance would remain similar.

The simulations we performed do not dictate how the delayed shipments of fuel are received. It is still possible to receive the delayed shipment by barge, but if weather prevents that, then airplane shipments may be required.

Assess goal and metric performance

As a result of the fuel shortage hazard, villages without wind installed would be unable to meet their demand for long. They do not have sufficient tank capacity to serve the load for more than about 13 months. However, it is evident that, with the turbine installed, the villages would be able to offset their diesel usage significantly, meeting one of their resilience goals. It is also evident that with wind installed, the system would not immediately or necessarily lose load, especially if they were able to get a fuel shipment in May instead of July. If the fuel shortage were minor—for example, barges being delayed by one month—the villages might be able to ration their remaining fuel even without wind installed and rely on the maximum wind production possible. The performance against the resilience metrics identified in Section 0 are shown in Table 6 and Table 7.

We note that outage durations of 238 days and 344 days, as shown in Table 7, are highly unrealistic. If the fuel could not be delivered after 9 weeks, fuel would be flown to the location. The purpose of showing these results is to demonstrate that with wind installed, the villages could completely miss their summer shipment, survive the winter, and receive a fuel shipment by barge when the river became passable in the spring without experiencing any fuel shortage. If the villages had to wait until July 1 to receive the shipment, they might experience some fuel shortage, but that would be dependent on the wind production over the 2 years.

We note, too, that it is unrealistic to predict that, after missing the shipment in the first year (on July 1 of Year 2), the villages would be rescheduled for a delivery 6 weeks out if they knew they would likely run out of fuel before then. It is entirely possible that a delivery could be made within the first three weeks, before the fuel would run out, or at least by the fourth week, resulting in a shorter-duration outage. Although a 4-week-late delivery was not part of our original hazard-assessment parameters, it seems a more likely outcome, so we present the results from that case too.

Table 6. Fuel dependency metric evaluation for forecasted fuel shortage.

Metric	Performance without wind	Performance with wind
Generation available	**See Figure 15**	**See Figure 16**
Wind generation *All of Year 2*	0	3,241,790 kWh
Fuel needed *Diesel import needed to serve full load for all of Year 2 (On time shipment)*	428,215 gal	130,486 gal
Fuel needed *Diesel import needed to serve full load for all of Year 2 (4 weeks delayed shipment)*	400,349 gal	130,486 gal
Fuel needed *Diesel import needed to serve full load for all of Year 2 (6weeks delayed shipment)*	385,124 gal	130,486 gal
Fuel needed *Diesel import needed to serve full load for all of Year 2 (9 weeks delayed shipment)*	362,217 gal	130,486 gal
Fuel stored/available *Reserves available at end of Year 1*	20,281 gal	176,246 gal
Fuel displaced (when wind is installed) *Diesel offset by wind in Year 2*	n/a	155,934 gal
Load	Base load profile (see Appendix A: Load Modeling)	
Carbon emissions	n/a*	n/a*

* We can evaluate the carbon emissions during different fuel shortage scenarios, but we would expect a decrease in carbon emissions from a standard year if there are outages, which could be misleading. Power outages are a more severe consequence than increased carbon emissions.

Table 7. Power quality metric evaluation for forecasted fuel shortage.

Metric	Performance without wind	Performance with wind
Outage duration *With fuel delivery 4 weeks after scheduled*	6 days	None
Outage duration *With fuel delivery 6 weeks after scheduled*	20 days	None
Outage duration *With fuel delivery 9 weeks after scheduled*	41 days	None
Outage duration *With fuel delivery in May of Year 2*	238 days	None
Outage duration	344 days	55 days

With fuel delivery at the beginning of Year 3		
Load lost during outages *With fuel delivery 4 weeks after scheduled*	92,300 kWh	None
Load lost during outages *With fuel delivery 6 weeks after scheduled*	283,266 kWh	None
Load lost during outages *With fuel delivery 9 weeks after scheduled*	572,241 kWh	None
Failure Rate	n/a	n/a
Voltage level variation	Not simulated	Not simulated
Backup capacity available		

Immediate Diesel Fuel Shortage

Identify metrics relevant for specific hazard

Beyond the basic system metrics already identified, metrics presented in Table 8 are necessary to properly evaluate a forecasted fuel shortage.

Table 8. Metrics needed to evaluate immediate fuel shortage.

Metric	**Source**
Load data	St. Mary's data request / HOMER model
Wind speeds	Pitka's Point Met Tower Wind Resource Report [23] Airport data [24]
Wind production	St. Mary's data request / EWS Production curve [12]
Length of fuel shortage	Assumptions
Fuel available during shortage	Assumptions
Restoration plan (repairs, airlifted fuel, etc.)	Assumptions

Identify processes and system impacted

Without the wind turbine installed, we care only about the amount of fuel available, the generation production that this can serve, and the load.

With wind installed, we additionally care about wind speeds and wind production, particularly as it matches the variable load. Notably, there is no battery storage, so although power can be curtailed if generation exceeds load, excess power cannot be stored for times when wind speeds are lower.

Model specific hazard

In an immediate diesel shortage due to a pipe rupture or a tank failure, we assume there is no diesel production available, which means the amount of load lost is equivalent to the amount of load expected to be served by diesel. In the no-wind case, this is all of the load. In the with-wind case, this is whatever load is not served by wind production. We consider this scenario at a variety of times of the year:

Table 9 shows that over any 2 day period throughout the year, the wind will serve at least part of the load, so a diesel outage will result in more load lost if wind is not installed. We can see this graphically in Figure 17. Note that the amount of load dropped without wind installed generally increases in the winter during any two-day outage, but the amount dropped with wind installed is highly variable, which makes sense given the highly variable wind speeds. There is still a slight trend towards less load being dropped during the winter when wind is installed compared to the rest of the year. This can be accounted for by two facts. First, the load increases in the winter, so without wind available and diesel as the only generation source, the loss of diesel will result in more dropped load because the demand is higher. Second, windspeeds are generally higher in the winter, so wind production is higher in the winter, and can offset more of the load. With wind installed, the demand that diesel is required to meet is actually lower in the winter than in the summer.

Table 9. Load dropped during two day diesel outage.

Date of outage (12pm-12pm)	Load dropped without wind [kWh]	Load dropped with wind [kWh]
7/14-7/16	22355.8	2761.6
8/14-8/16	28798.0	23382.8
9/14-9/16	29034.7	12240.1
10/14-10/16	31424.9	6362.9
11/14-11/16	31038.7	29815.4
12/14-12/16	33885.7	9694.7
1/14-1/16	34218.4	13108.7
2/14-2/16	37204.1	12981.4
3/14-3/16	38863.3	21404.6
4/14-4//16	31655.6	8460.5
5/14-5/16	30958.1	11808.8
6/14-6/16	25299.8	12520.8

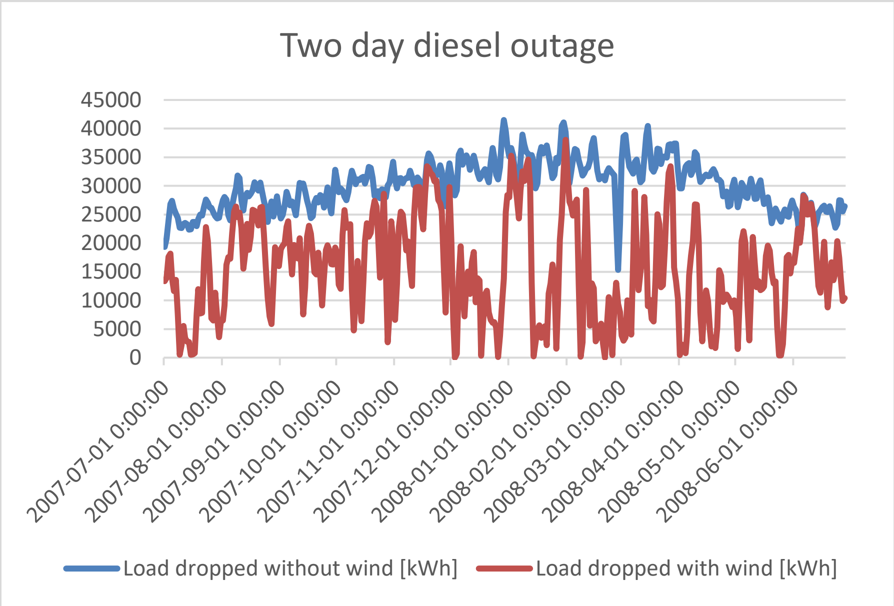

Figure 17. Load dropped during a single 2-day outage starting at any day in the year.

We also consider longer diesel outages of two weeks. Table 10 shows that more load is dropped during 2-week outages, as expected, but the trend of the with-wind case dropping less of the load than is dropped in the without-wind case remains the same. The data are visualized in Figure 18. Some variability remains, even with outages over 2-week periods, but this can again be attributed to variability in wind speeds.

Table 10. Load dropped during 2-week diesel outage.

Date of outage (12:00-12:00)	**Load dropped without wind [kWh]**	**Load dropped with wind [kWh]**
7/1-7/15	165118.5	67244.1
7/29-8/12	190965.8	113733.6
9/9-9/23	191860.3	123435.2
10/7-10/21	218984.3	114535.3
11/4-11/18	216131.5	162561.9
12/2-12/16	232916.1	75103.2
12/30-1/13	247193.9	209762.8
2/10-2/24	233197.5	64553.7
3/9-3/23	243240.2	115280.9
4/6-4/20	228524.1	89893.8
5/4-5/18	203876.6	100927.2
6/1-6/15	175453.7	157200.7

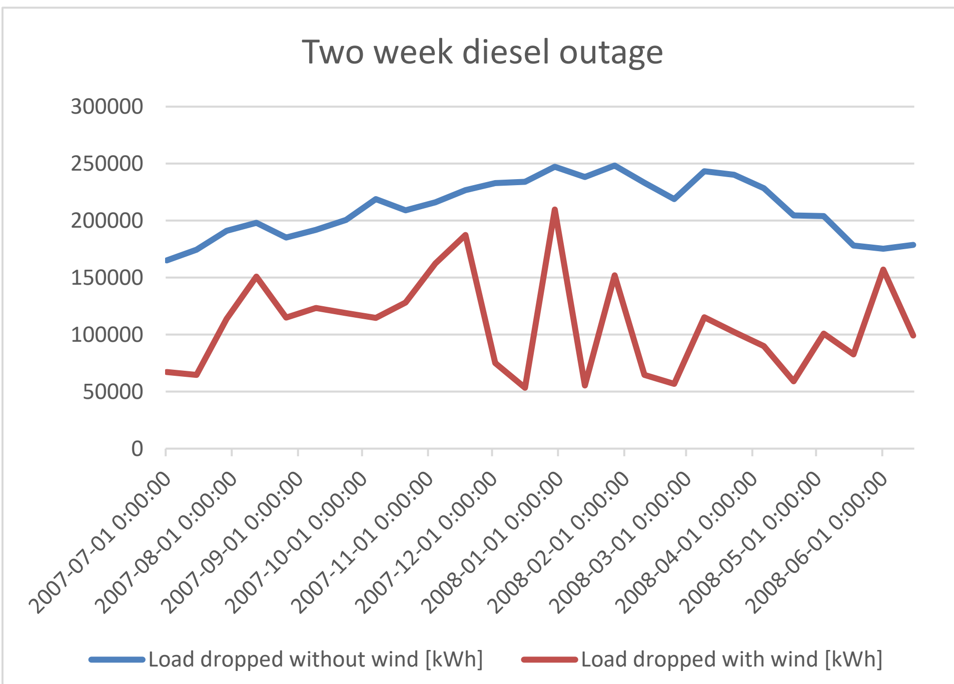

Figure 18. Load lost during 2-week diesel outage during different times of the year.

Calculate consequences

The primary consequences of an immediate diesel shortage are load lost in amounts equivalent to the load expected to be served by diesel generation during the outage period. Although the wind turbine has the capacity to serve the load throughout most of the year, the variability and average windspeeds mean that the generation from wind is not sufficient to always cover the demand.

If the immediate outage was caused by multiple tank failures, then it may be necessary to import diesel to serve the remainder of the year until the annual shipment is received. Table 11 shows the gallons of fuel needed for the remainder of the year if all existing reserves were lost in a spill or fire. We assume that the fuel could be delivered at the end of the 2-week outage period.

Table 11. Fuel needed for remainder of year.

Date of outage (12:00-12:00)	Diesel needed without wind [gal]	Diesel needed with wind [gal]
7/1-7/15	414,496	264,991
7/29-8/12	385,124	247,209
9/9-9/23	339,344	211,742
10/7-10/21	306,722	189,485
11/4-11/18	273,674	163,909
12/2-12/16	238,632	140,364
12/30-1/13	202,010	166,328
2/10-2/24	147,349	87,799
3/9-3/23	112,226	69,526
4/6-4/20	76,467	49,867
5/4-5/18	44,434	32,445
6/1-6/15	16,073	11,055

The time of year would dictate whether this diesel would need to be flown in or whether it could potentially be delivered by barge.

In this simulation, we did not consider the fuel-storage capacity of St. Mary's and Mountain Village separately. Although the future plan is for a new tank farm to store fuel for a new power plant in St. Mary's that will serve both communities, fuel storage and generation capacity exists in Mountain Village. It is entirely likely that the villages would hold some fuel reserves in the old fuel storage system at Mountain Village and keep some of their generators operational. In that case, the assumed root cause of the immediate fuel shortage, a pipe failure or a tank failure, could affect one village but likely not both. In that case, the numbers presented above represent the worst case, but it is possible that the reserves in the second village are sufficient to serve both villages. The cost associated with this hazard would then be the cost of lost fuel and repairs, but not the lost load.

Assess goal and metric performance

The performance against resilience metrics, as identified in Section 0, is shown in Table 12 and Table 13. In response to the immediate fuel shortage hazard, the villages would be unable to meet all of their demand, even with a wind turbine installed, for any extended period of time, because wind variability without battery storage will create fluctuations in generation that are unlikely to align with fluctuations in demand. Having the wind turbine installed improves the power quality metrics, although performance is not perfect. However, it is evident that with the turbine installed, the villages would be able to offset their diesel usage significantly, meeting one of their resilience goals.

Table 12. Fuel dependency metric evaluation for immediate fuel shortage.

Metric	Performance without Wind	Performance with Wind
Generation Available	See Table 9 / Table 10 for amounts [kWh] lost	See Table 9 / Table 10 for amounts [kWh] lost
Wind generation	0	Depends on time of year
Fuel needed	See Table 11	See Table 11
Fuel stored/available	n/a	n/a
Fuel displaced (when wind is installed)	n/a	See Table 11
Load	Base load profile (see Appendix A)	
Carbon emissions	n/a*	n/a*

* As in the previous scenario, we can evaluate the carbon emissions during the fuel shortage hazard, but the results may be misleading. In the without-wind case, more diesel-fed load is lost, meaning more carbon emissions were avoided than in the with-wind case. However, the loss of the larger diesel-fed load is a consequence that outweighs the benefits of saving of carbon emissions. To avoid confusion, we refrain from assigning carbon emissions numbers to these hazard scenarios.

Table 13. Power quality metric evaluation for immediate fuel shortage.

Metric	Performance without Wind	Performance with Wind
Outage duration	2 days / 2 weeks	2 days / 2 weeks
Load lost during outages	See Table 9/ Table 10	See Table 9/ Table 10
Failure rate		
Voltage-level variation	n/a	n/a
Backup capacity available		

Severe Winter Weather Event

Identify metrics relevant for specific hazard.

Table 14: Metrics needed to evaluate cold snap

Metric	Source
Temperature data	St. Mary's airport data [24]
Power performance curve of wind turbine at low temperatures	EWT or St. Mary's data request*
Load data corresponding to temperature shifts	Correlation extracted from synthetic HOMER data

* Not currently available. Assumes strict cutoff at -40°C.

Identify processes and system impacted

As with the previous scenario, the main processes we care about are the wind generation and diesel generation. We use synthetic data to estimate average correlation between temperature and load, and use this correlation to shift the synthetic load data from the HOMER model by an appropriate amount in response to the temperature changes. The load, diesel production, and wind production may all be affected by the severe winter weather.

In future work, we plan to analyze not only the impact of temperature, but the impact of blizzard-like windspeeds, which may exceed the immediate or 10-minute average wind cutoff speeds for the turbine.

Model specific hazard

We modeled different scenarios where the temperature dropped by varying amounts and for varying periods of time. The cold snaps are all centered around December 21, the beginning of winter. Although we run the hazard analysis for all temperature changes for all durations, we acknowledge that the most extreme cases, a 12-week cold snap with temperatures 20 degrees below normal, would be highly unlikely. We also note that the temperature-load correlation model (see Appendix A) loses fidelity at very low temperatures, forecasting loads that continue to rise rather than leveling off or rising linearly as temperatures drop below -35°C. However, these models are still useful, as they show the trends of different types of cold snaps. Additionally, it is useful to examine cases where the temperature drops below -40°C, since that is the point beyond which the wind turbine ceases to operate. All of the results are shown in Table 15.

Table 15. Change in fuel usage during cold snap.

Temperature Drop	Annual fuel used - regular temps (With wind) [gal]	Annual fuel used - regular temps (Without wind) [gal]	Annual fuel used, cold temps (With wind) [gal]	Annual fuel used, cold temps (Without wind) [gal]	Difference in fuel use: (With wind) [gal]	Difference in fuel use (Without wind) [gal]
1 Week						
-20	272304.8	428238.8	272586.0	428767.3	281.2	528.5
-15	272304.8	428238.8	272516.5	428626.4	211.7	387.6
-10	272304.8	428238.8	272475.5	428553.8	170.7	315.0
-5	272304.8	428238.8	272403.0	428434.9	98.2	196.1
-2	272304.8	428238.8	272339.6	428325.4	34.9	86.6
-1	272304.8	428238.8	272325.6	428283.9	20.8	45.2
2 Weeks						
-20	272304.8	428238.8	272992.8	429512.8	688.1	1274.0
-15	272304.8	428238.8	272687.9	428994.4	383.1	755.6
-10	272304.8	428238.8	272599.3	428787.2	294.5	548.4
-5	272304.8	428238.8	272481.6	428579.4	176.8	340.7
-2	272304.8	428238.8	272390.6	428390.7	85.8	152.0
-1	272304.8	428238.8	272350.2	428316.1	45.4	77.3
3 weeks						
-20	272304.8	428238.8	276312.2	431850.6	4007.4	3611.8
-15	272304.8	428238.8	273676.2	430071.0	1371.4	1832.2
-10	272304.8	428238.8	273011.8	429205.1	707.1	966.3
-5	272304.8	428238.8	272646.8	428716.1	342.0	477.4
-2	272304.8	428238.8	272429.5	428438.8	124.7	200.1
-1	272304.8	428238.8	272367.5	428340.3	62.7	101.6
4 Weeks						
-20	272304.8	428238.8	279876.9	435352.7	7572.1	7113.9
-15	272304.8	428238.8	275303.9	431763.5	2999.1	3524.7

Temperature Drop	Annual fuel used - regular temps (With wind) [gal]	Annual fuel used - regular temps (Without wind) [gal]	Annual fuel used, cold temps (With wind) [gal]	Annual fuel used, cold temps (Without wind) [gal]	Difference in fuel use: (With wind) [gal]	Difference in fuel use (Without wind) [gal]
-10	272304.8	428238.8	273642.8	429835.3	1338.0	1596.6
-5	272304.8	428238.8	272803.5	428882.6	498.7	643.8
-2	272304.8	428238.8	272489.1	428492.5	184.4	253.7
-1	272304.8	428238.8	272385.9	428362.1	81.2	123.3
6 Weeks						
-20	272304.8	428238.8	288227.9	443271.3	15923.1	15032.6
-15	272304.8	428238.8	279370.9	435753.9	7066.1	7515.1
-10	272304.8	428238.8	275258.9	431500.7	2954.1	3262.0
-5	272304.8	428238.8	273328.2	429446.7	1023.4	1207.9
-2	272304.8	428238.8	272619.8	428665.	315.0	426.2
-1	272304.8	428238.8	272467.8	428447.7	163.1	209.0
8 Weeks						
-20	272304.8	428238.8	299312.8	448529.1	27008.0	20290.3
-15	272304.8	428238.8	285440.3	441200.3	13135.5	12961.5
-10	272304.8	428238.8	277142.9	433636.0	4838.1	5397.2
-5	272304.8	428238.8	273840.7	430102.3	1535.9	1863.6
-2	272304.8	428238.8	272757.0	428864.8	452.2	626.0
-1	272304.8	428238.8	272517.9	428548.3	213.1	309.5
10 Weeks						
-20	272304.8	428238.8	303232.7	448554.5	30927.9	20315.8
-15	272304.8	428238.8	287098.1	443165.8	14793.3	14927.0
-10	272304.8	428238.8	277825.2	434555.3	5520.4	6316.6
-5	272304.8	428238.8	274125.1	430524.0	1820.3	2285.3
-2	272304.8	428238.8	272876.7	429029.5	571.9	790.7
-1	272304.8	428238.8	272542.5	428623.3	237.7	384.6
12 Weeks						
-20	272304.8	428238.8	305618.6	448570.3	33313.8	20331.5
-15	272304.8	428238.8	287839.8	444166.3	15535.0	15927.6
-10	272304.8	428238.8	278184.1	435019.0	5879.4	6780.2
-5	272304.8	428238.8	274313.1	430751.2	2008.3	2512.4
-2	272304.8	428238.8	272937.6	429132.5	632.8	893.8
-1	272304.8	428238.8	272580.7	428679.2	275.9	440.4

The changes in fuel used can be visualized according to the associated temperature drop and the number of weeks for which the cold snap occurred, as seen in Figure 19.

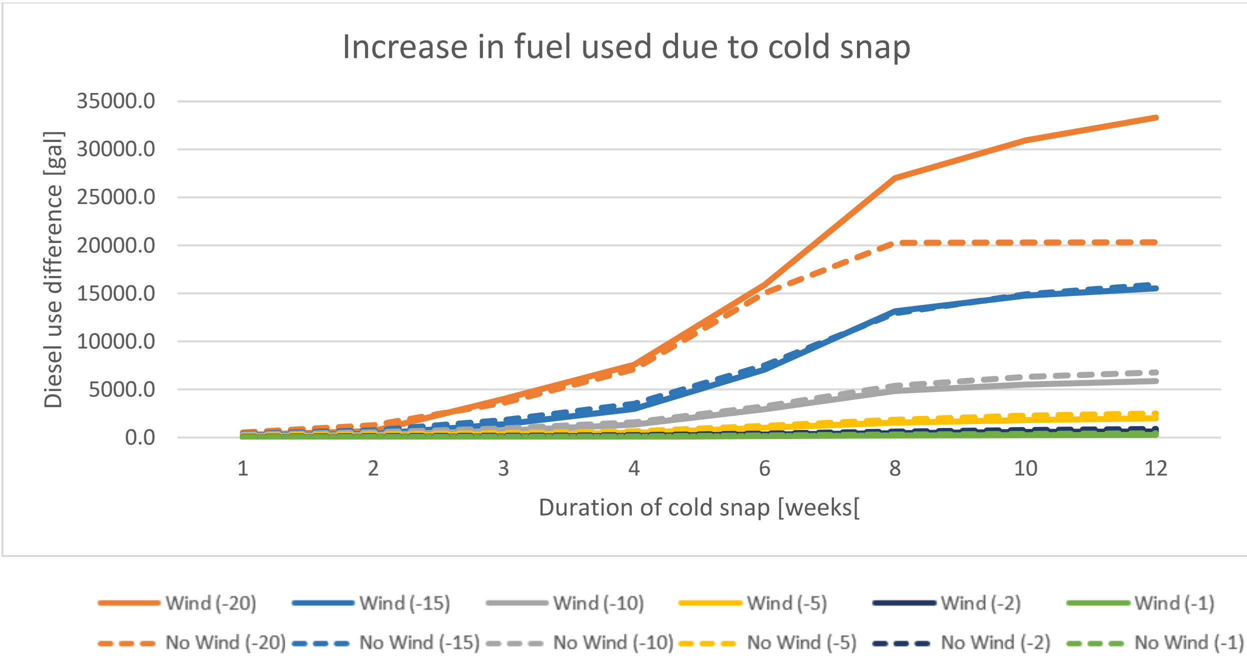

Figure 19. Change in fuel usage during severe cold snap.

Since the increase in fuel used from a normal year to a year with a cold snap is so significant for temperature drops of 20 and 15°, it is useful to zoom in on the y-axis to see what happens with smaller temperature changes too, as seen in Figure 20.

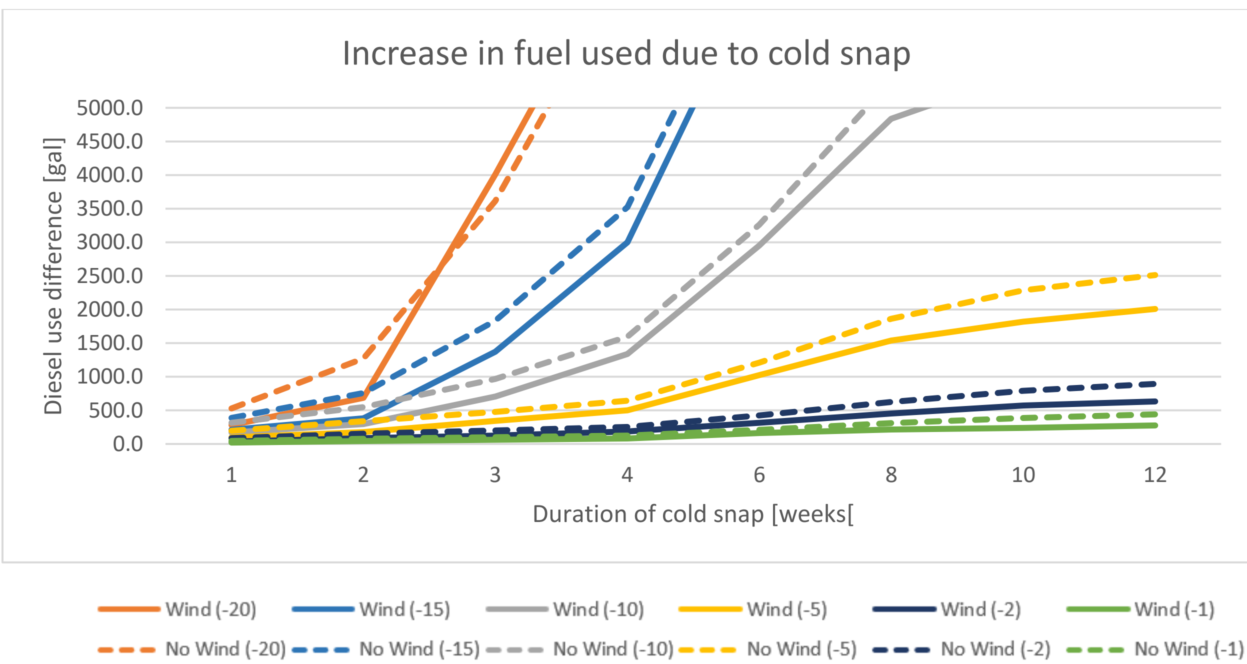

Figure 20. Change in fuel usage during moderate cold snap.

It would have been valuable to also model extreme wind scenarios corresponding to the blizzard or high-wind criteria from the National Weather Service. However, because the simulations were at the hourly level of granularity, it was difficult to model gusts of wind. We could have modeled higher hourly wind scenarios, but we would need to put reasonable limits on hourly averages for windspeeds, and if these did not meet the wind turbine cut-out speeds, this exercise would not have represented the hazard scenario well. We leave the task of more granular windspeed modeling and effects on power production to future work.

Calculate consequences

The 1- and 2-week cold snaps result in an increase in diesel use due to the increased load and potential loss of wind power, but this increased diesel use is not significant compared to the annual fuel use, even under extremely cold scenarios. Temperature changes of 2° or less result in very small changes in diesel use, even when this cold period lasts for up to 12 weeks. Larger temperature drops for longer periods of time being to result in significant changes in diesel use. In the most extreme scenarios and without wind installed, the extra fuel used is enough that an early shipment of diesel would be required as the system would not last on its existing reserves. In particular, drops in temperature of 20° for 8 weeks or more would require a shipment of diesel to arrive prior to July 1 because the extra fuel used in the cold snap exceeds the reserves that would normally be left at the end of the year. This can be seen in Table 16, which also shows that, no matter the cold-snap conditions, the with-wind case still always uses significantly less total fuel storage capacity than the without-wind case, no matter the cold-snap conditions. We note again that the temperature-load correlation model is not highly accurate for very low temperatures, so this fuel-use consequence may be exaggerated in our model for large temperature changes.

Table 16. Fuel reserves at end of year (compared to total capacity).

	Fuel reserves remaining at end of Year 1			
Temperature Drop	Regular temps (With wind) [% full capacity]	Regular temps (Without wind) [% full capacity]	Cold temps (With wind) [% full capacity]	Cold temps (Without wind) [% full capacity]
1 Week				
-20	34.23%	4.52%	34.16%	4.41%
-15	34.23%	4.52%	34.17%	4.44%
-10	34.23%	4.52%	34.18%	4.45%
-5	34.23%	4.52%	34.20%	4.48%
-2	34.23%	4.52%	34.22%	4.50%
-1	34.23%	4.52%	34.22%	4.51%
2 Weeks				
-20	34.23%	4.52%	34.06%	4.24%
-15	34.23%	4.52%	34.13%	4.36%
-10	34.23%	4.52%	34.15%	4.40%
-5	34.23%	4.52%	34.18%	4.45%
-2	34.23%	4.52%	34.21%	4.49%
-1	34.23%	4.52%	34.21%	4.51%
3 Weeks				
-20	34.23%	4.52%	33.26%	3.72%
-15	34.23%	4.52%	33.89%	4.12%
-10	34.23%	4.52%	34.06%	4.31%
-5	34.23%	4.52%	34.14%	4.42%
-2	34.23%	4.52%	34.20%	4.48%
-1	34.23%	4.52%	34.21%	4.50%

Temperature Drop	Fuel reserves remaining at end of Year 1			
	Regular temps (With wind) [% full capacity]	Regular temps (Without wind) [% full capacity]	Cold temps (With wind) [% full capacity]	Cold temps (Without wind) [% full capacity]
4 Weeks				
-20	34.23%	4.52%	32.40%	2.94%
-15	34.23%	4.52%	33.50%	3.74%
-10	34.23%	4.52%	33.90%	4.17%
-5	34.23%	4.52%	34.11%	4.38%
-2	34.23%	4.52%	34.18%	4.47%
-1	34.23%	4.52%	34.21%	4.50%
6 Weeks				
-20	34.23%	4.52%	30.38%	1.17%
-15	34.23%	4.52%	32.52%	2.85%
-10	34.23%	4.52%	33.51%	3.80%
-5	34.23%	4.52%	33.98%	4.25%
-2	34.23%	4.52%	34.15%	4.43%
-1	34.23%	4.52%	34.19%	4.48%
8 Weeks				
-20	34.23%	4.52%	27.70%	0.00%
-15	34.23%	4.52%	31.05%	1.63%
-10	34.23%	4.52%	33.06%	3.32%
-5	34.23%	4.52%	33.85%	4.11%
-2	34.23%	4.52%	34.12%	4.38%
-1	34.23%	4.52%	34.17%	4.45%
10 Weeks				
-20	34.23%	4.52%	26.76%	-0.01%
-15	34.23%	4.52%	30.65%	1.20%
-10	34.23%	4.52%	32.89%	3.12%
-5	34.23%	4.52%	33.79%	4.01%
-2	34.23%	4.52%	34.09%	4.35%
-1	34.23%	4.52%	34.17%	4.44%
12 Weeks				
-20	34.23%	4.52%	26.18%	-0.01%
-15	34.23%	4.52%	30.47%	0.97%
-10	34.23%	4.52%	32.81%	3.01%
-5	34.23%	4.52%	33.74%	3.96%
-2	34.23%	4.52%	34.07%	4.32%
-1	34.23%	4.52%	34.16%	4.43%

For large temperature drops, the without-wind case has a smaller change in fuel use than the with-wind case. This is because the wind turbine ceases to operate at temperatures below -40°C, meaning that diesel has to fulfill extra energy needs. However, for smaller temperature drops, there is a smaller change in fuel use for the with-wind case than the without-wind case; at points during the period examined, wind generation exceeded load during a normal year. With the increased load at lower temperatures, the extra load can be fully or partially served by wind production that would be curtailed in a normal year. If wind production does not exceed load during a normal year, then any excess load will have to be served fully by diesel production because all wind production is already being consumed.

Assess goal and metric performance

The system uses less fuel annually with wind installed than without wind installed during the cold-snap hazard for any severity and any duration, as seen in Table 17 measuring fuel dependency. However, we note that the wind turbine still faces a risk of shutting down at very low temperatures. As another measure of reducing fuel dependency, we show the increase in CO2 emissions due to the hazard in Table 18. It is clear that there is a larger increase in emissions without wind installed compared to when wind is installed.

There are no predicted outages, as seen in Table 19, indicating sufficient power quality is maintained during the hazard. However, we note that in the current temp-load correlation model, extreme temperature drops for long periods of time result in very high loads for long durations. If no wind is installed, these high loads are solely served by diesel, and the extra diesel generation may use a significant portion of the fuel reserves. If enough extra fuel is used during this extreme winter scenario, an early shipment of fuel may be required because the system may not have enough diesel reserves to last until year’s end, and the next regular shipment is expected on July 1.

Table 17. Fuel-dependency metric evaluation for severe winter weather.

Metric	Performance without Wind	Performance with Wind
Generation Available	Diesel generators available at full capacity	Wind production may cease for temperatures below -40°C
Wind generation	n/a	
Fuel needed	See Table 15	See Table 15
Fuel stored/available	See Table 16	See Table 16
Fuel displaced (when wind is installed)	n/a	See Table 15
Load	Adjusted load profile (see Appendix A)	
Carbon emissions	See Table 18	

Table 18. Increase in carbon emissions during hazard.

Temperature drop	-20	-15	-10	-5	-2	-1	-20	-15	-10	-5	-2	-1
Duration of outage	Change in CO_2 emissions compared to base year with wind installed [lb]						Change in CO_2 emissions compared to base year without wind installed [lb]					
1 week	5512	4149	3345	1926	683	408	10359	7598	6175	3844	1698	885
2 weeks	13486	7510	5772	3466	1682	889	24970	14810	10749	6677	2979	1516
3 weeks	78546	26879	13858	6703	2444	1229	70791	35911	18939	9356	3921	1991
4 weeks	148413	58782	26225	9775	3613	1591	139433	69084	31293	12619	4973	2417
6 weeks	312092	138495	57901	20059	6175	3196	294638	147296	63934	23675	8354	4096
8 weeks	529357	257456	94827	30104	8864	4176	397690	254045	105786	36526	12270	6066
10 weeks	606188	289949	108200	35679	11209	4659	398189	292570	123804	44791	15498	7538
12 weeks	652951	304486	115235	39363	12404	5409	398498	312180	132892	49243	17518	8632

Table 19. Power-quality metric evaluation for severe winter weather.

Metric	Performance without Wind	Performance with Wind
Outage duration	None*	None
Load lost during outages	None	None
Failure Rate	n/a	n/a
Voltage level variation	Not simulated	Not simulated
Backup capacity available		

* Possible outage if extra fuel requirement during cold snap uses so much fuel reserves that system cannot last until July 1 of following summer. It is more likely that an earlier shipment would be scheduled and that there would be no outages.

Communications Outage

Identify metrics relevant for specific hazard

Many of the potential consequences of a communications outage depend on the assumptions made about the outage and other potential alerts that happen during the communications outage. To evaluate the consequences, detailed data about the wind turbine production and assumptions about the outage scenario are needed (Table 20).

Table 20. Metrics needed to evaluate wind turbine communications outage.

Metric	Source
Load data	St. Mary’s data request / HOMER model
Wind speeds	Pitka’s Point Met Tower Wind Resource Report [23] Airport data [24]
Wind production	St. Mary’s data request / EWS Production curve [12]
Length of wind turbine communications outage	Assumptions
Restoration plan (repairs, etc.)	Assumptions

Identify processes and system impacted

In this scenario, the only system impacted directly by the hazard is the wind turbine. Processes impacted include operation of the wind turbine, response to warnings, and response to alarms. Diesel generation will also be affected because none of the load is served by wind.

Model specific hazard

If the fiber line is out of service, operators from St. Mary's and from AVEC will not be able to monitor data from the wind turbine or send commands. We assume that power curtailment is automatic, so the wind turbine can continue to operate and produce an appropriate amount of power to give to the system. The major outcome of this would be that status messages and alerts would not be visible. An agent would have to physically go to the turbine to check on it periodically. The tower is about 4 miles from the prime power plant in St. Mary's. There is a 0.3 mile access road connecting the tower to the main road. The main road and the access road are both made of gravel and dirt. This could make the turbine difficult to access, particularly during winter months.

Depending on the severity of the outage and the cost or time to repair it, the decision may be made to remove the turbine from service if it cannot be safely operated. In this case, the system loses all power production from the turbine for the duration of the outage.

The first missed alert that we consider is an internal trip, which takes 2 days to be discovered, and for a technician to reach the turbine and close the breaker. Table 21 shows a sampling of 2-day outages from each month of the year. There is a high level of variability, also demonstrated in Figure 21. Little additional fuel is used if the wind turbine is out of service for 2 days, provided that the wind during that period would have been low anyway. However, if wind speeds were high, then the loss of wind production results in more additional diesel used to serve the load.

Table 21. Fuel effects of 2-day wind-turbine outage.

Date of outage (12pm-12pm)	**Additional fuel used while wind turbine is out of service [gal]**
7/14–7/16	1295.8
8/14–8/16	266.7
9/14–9/16	897.7
10/14–10/16	1485.7
11/14–11/16	56.7
12/14–12/16	1401.8
1/14–1/16	2088.3
2/14–2/16	1355.8
3/14–3/16	986.9
4/14–4//16	1366.1
5/14–5/16	1119.3
6/14–6/16	784.8

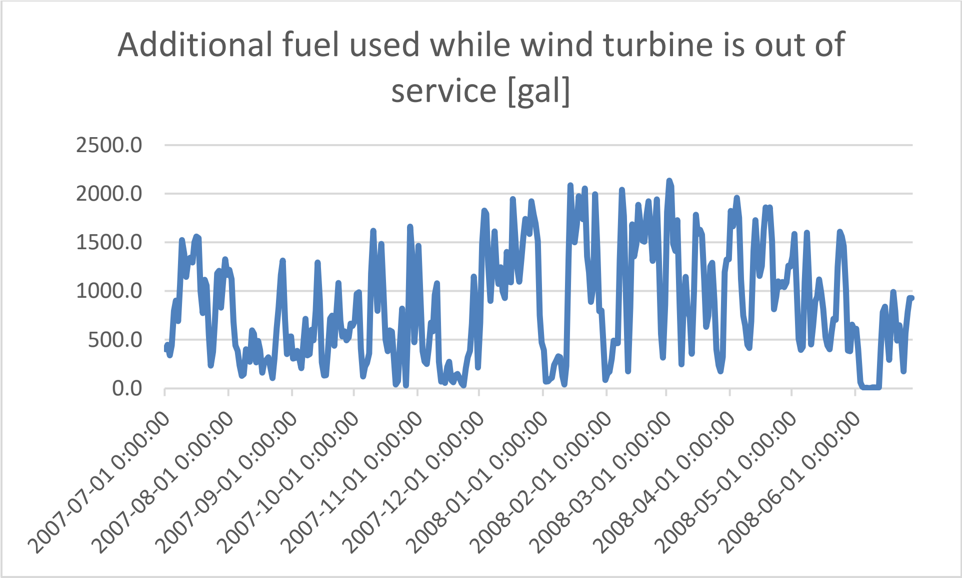

Figure 21. Two-day wind turbine repair: change in diesel used.

The second outcome we consider for the loss of wind- turbine communications is a missed gearbox failure alarm. We assume that the wind turbine is out of commission for 2 weeks, although the actual repair time is highly dependent on spare-part availability. In Table 22, a sampling of the additional diesel fuel used during a 2-week turbine outage is shown.

Table 22. Fuel effects of 2-week wind turbine outage

Date of outage (12:00-12:00)	Additional fuel used while wind turbine is out of service [gal]
7/1-7/15	6,242.7
7/29-8/12	4,589.1
9/9-9/23	3,704.7
10/7-10/21	5,784.3
11/4-11/18	2,756.9
12/2-12/16	9,265.1
12/30-1/13	1,965.7
2/10-2/24	9,880.5
3/9-3/23	7,335.1
4/6-4/20	8,079.6
5/4-5/18	5,815.3
6/1-6/15	1,130.9

Like the 2-day outage scenario, there is a high level of variability correlated with the variability in wind speeds. However, as shown in Figure 22, the largest increases in fuel used during the turbine outage would come in the winter when wind speeds are highest.

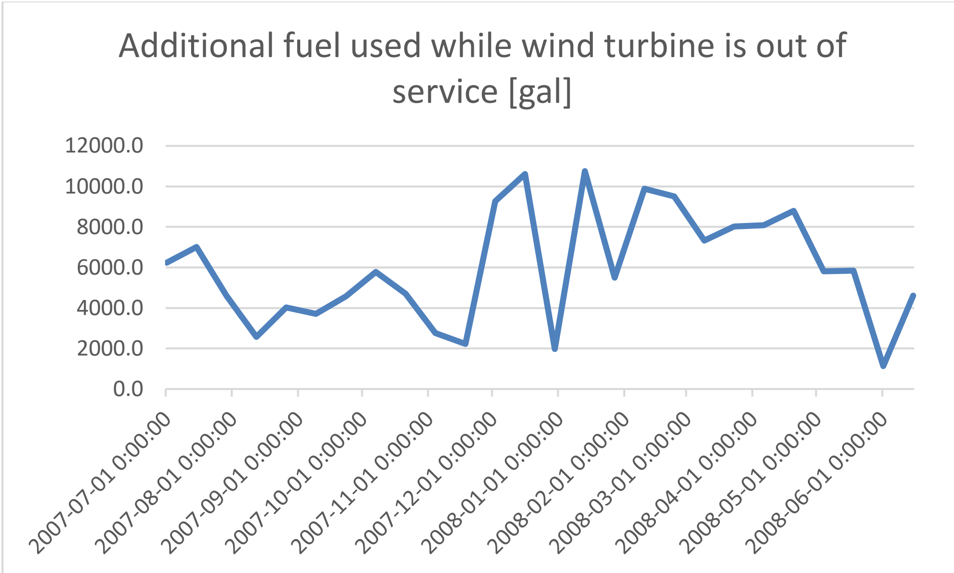

Figure 22. Two-week wind-turbine repair: change in diesel used.

Calculate consequences

In the worst case, a communications outage can lead to missed alert messages, which left untreated, can result in loss of power production from the wind turbine. However, there may be many low-level alerts that do not result in loss of power production at all, but simply make it more difficult to make operational decisions because there is a loss of visibility into live wind turbine data.

While a gearbox failure is not directly caused by a communications outage, it is possible that low-level alerts might warn operators to the status of the gearbox before total failure, and the operators may be able to take action to avoid the complete failure and, thus, the loss of wind power production. Multiple failures are required to make a communications outage a high-consequence alert, but these scenarios are worth considering.

In the event of a loss in wind production, for either a 2-day or 2-week period, there will be an increase in diesel use and an increase in CO_2 emissions during this time, as shown in the tables and figures above.

Assess goal and metric performance

During a wind turbine communications outage, there are a variety of potential outcomes and associated consequences. In the best case, the operators simply lose access to live data from the wind turbine, but it continues to provide power and curtail automatically as needed. In the worst case, a missed series of alerts and alarms can lead to physical damage of the turbine, resulting is costly repairs and lengthy outages of the wind turbine, during which time the system must rely entirely on diesel production (Table 23).

We note that the intent of this assessment was to assess the resilience benefits of distributed wind. The wind turbine communications outage hazard only applies to the scenarios where wind is installed, so we cannot compare the resilience with-wind and without-wind. Instead, the purpose of analyzing this hazard is to demonstrate that there are resilience considerations for the wind turbine itself in addition to the resilience considerations for the entire system. In the next step of the framework, mitigations for each hazard are discussed. Mitigations for the wind turbine communications outage scenario can help make turbine operation more resilient, which will enhance resilience benefits for the entire system.

Table 23. Fuel-dependency metric evaluation for communications outage.

Metric	Performance without Wind	Performance with Wind (Base)	Performance with Wind (During Hazard)
Generation Available	n/a	Wind and diesel available	Diesel only
Wind generation	n/a	Dependent on windspeeds	0 (worst case)
Fuel needed	n/a	See Table 21 and Table 22 for difference in fuel needed during hazard	
Fuel stored/available	n/a		
Fuel displaced (when wind is installed)	n/a	See Table 21 and Table 22	See Table 21 and Table 22
Load	n/a	Base load profile (see Appendix A)	
Carbon emissions (during average 2-week hazard)	321,333lbs	204,247 lbs	321,333lbs
Carbon emissions (during average 2-day hazard)	45,924 lbs	29,185 lbs	45,924 lbs

Table 24. Power-quality metric evaluation for communications outage.

Metric	Performance without Wind	Performance with Wind (Base)	Performance with Wind (During Hazard)
Outage duration	None	None	None
Load lost during outages	None	None	None
Failure Rate	n/a	n/a	?
Voltage level variation	n/a	n/a	n/a
Backup capacity available	n/a	More	Less

Prioritize Risk-Mitigation Measures

Based on the outcomes of the modeling, risk mitigation measures should be prioritized. Perhaps the system performed well against the highest priority scenario, but additional measures are needed to protect the system against the third-highest priority scenario. A single risk may have multiple mitigation options, and those options themselves may mitigate multiple risks. Risk-mitigation measures should include cost estimates and effectiveness metrics that evaluate the efficacy of a mitigation measure against a given risk.

Hazard 1, Fuel Shortage:

- Install more diesel storage; make sure tanks are full well before winter begins
- Install more wind to offset impact of fuel shortage
- Install battery storage system so overproduction of wind can be captured and returned to the system.

Hazard 2, Severe Winter Weather:

- Ensure maintenance on wind and diesel plants is kept up so that they operate to peak performance under difficult conditions.

Hazard 3, Wind Communications Outage:

- Install redundant communications lines
- Ensure roads are maintained to make access to turbine easy.

Hazard 2 had the lowest risk after all hazards were assessed. The probability of a severe winter weather event sufficiently extreme to put a wind turbine out of service is very low, and even then, diesel generators can cover the total expected load, even when it is at its peak levels. There were still negative outcomes associated with Hazard 2, including the increased diesel fuel use, but there is little that could be done to mitigate this scenario.

Hazard 3 had mild risk. The probability of a communications outage, particularly the fiber-optic line going out of service, is low, but not impossible. The consequences would likely be minimal but have the potential to be severe.

Hazard 1 was the hazard of greatest concern. Fuel shortages could have an impact on power quality and the amount of load served, even with the wind turbine installed. Analysis showed that the impact would be greater without the wind, highlighting the resilience added by the wind turbine, but there is still room for improvement on the current system. The mitigations listed above would help reduce the impact and/or likelihood of a fuel shortage, but they would all require large investments.

Evaluate Against All Business Risks

Once analysis shows how a hazard will impact the system, the system risks should be evaluated within the context of the broader business activities. Each risk and impact should be weighed against others. In the case of a limited budget, it may be that only one of these projects can move forward. Ultimately, the goal is to enable decision-makers to improve system resilience over time. Decision-makers take the prioritized resilience measures and determine what can be done with regard to other business constraints (i.e., resources, budget, feasibility).

This step is the point at which a detailed cost-effectiveness analysis may occur. There are financial tradeoffs associated with many measures that will add resiliency. By evaluating the risk of a disruptive event against all other business risks, such as economic viability, public relations, or fines if proper cybersecurity measures are not taken, stakeholders can determine how much relative risk they are willing to assume.

Hazard 1, fuel shortage, demonstrates the value of wind. Wind certainly adds resilience to the system. The displaced fuel in this scenario also offsets the significant business risk of fuel costs, particularly if that fuel must be imported via airplane during the winter. Of the mitigations proposed, we note that there are already plans in place to install more fuel storage. A new bulk fuel tank farm to store and supply power plant fuel was under construction as of March 2020. It was unclear if this would increase the supply capacity or if the previous tank farm would be decommissioned. To further mitigate this risk, we recommend strong consideration of battery system installation to create a combined wind/battery-storage system. Although it appears that the total generation of the wind turbine could almost always be fully consumed and would rarely need to be curtailed, battery storage would help maximize the efficiency of the already-installed turbine and further reduce dependency on diesel.

Hazard 2, severe winter weather, demonstrates a perceived risk that is found to be a low risk. Mitigations proposed to help would be low cost and should still be implemented.

Hazard 3, communications outage, demonstrates a hazard that has not yet been considered. The fiber-optic communication line appears to be a single point of failure that has the potential to cause significant power production losses if it fails. Mitigations to address this hazard are cost-effective and should be adopted if budget allows.

Implement Changes and Operate System

This step includes reassessing the planning stage to model system improvements, providing better understanding of new system characteristics, ensuring that the goals and metrics are still appropriate, and prioritizing any additional measures that should be implemented. The recursive quality of planning would track resilience of the system over time, but also safeguard against resilience degradation. A resilient system does not necessarily stay that way over time: risks shift, assets age, and people change.

This step also includes transitioning to the operational stage of resilience. As plans are made to improve resilience, the plans should be executed by making changes in the operational space. This should include implementation across processes, equipment, design standards, or labor resources. The transition may occur on different time scales. Some changes can be implemented immediately; others will require a longer construction or roll-out period.

CONCLUSIONS

In this case study, we step through the planning stage of the INL resilience framework in detail with the goal of demonstrating the resilience benefits to the St. Mary's, Mt. Village electric power system provided by a 900 kW distributed wind turbine. We showed that the turbine adds resilience in the form of offsetting fuel use and reducing dependency on diesel fuel by exploring two types of fuel shortage scenarios. We showed that wind was a resilience asset during winter weather hazards, particularly during cold snaps of different durations, up to a certain point. The wind turbine has limitations, including that it cannot operate below -40°C, so at temperatures below that point, the system reverted to a diesel-only system.

The case study demonstrates the resilience benefits provided by distributed wind and the limitations of those benefits. The turbine communications outage hazard is unlikely. Even if it does occur, the turbine power production could continue as normal. However, if there is a missed alarm during the communications outage, there is a potential for damage to the wind turbine that is costly and time-consuming to repair.

The process of using the framework gives stakeholder the ability to customize their resilience goals and the most relevant resilience hazards. It uses the unique assets and configurations of a particular system to evaluate performance against these hazards. The INL resilience framework emphasizes the distinctive quality of resilience and helps users explore the advantages of their own distinct system. It can be used to make planning decisions through assessment or comparison of potential investments, understanding of the most impactful hazards and appropriate mitigations, or post-installment review of new assets that go beyond generation capacity or traditional reliability metrics.

Key takeaways:

- Resilience goals, metrics, and hazards need to be customized to the system to produce the most useful outcomes. The fuel shortage and extreme cold weather scenarios saw the biggest resilience impacts. The communications failure scenario had less resilience impacts, because there was not anything about the system that made it particularly vulnerable to this threat.
- Assets that are intended to aid in resilience may still be affected by certain hazards. This was evidenced in the examination of the cold snap hazard, which was benefitted by the wind in most cases, but for the most extreme cases, the wind turbine had to shut down and ceased providing any benefit to the system.
- It is important to consider what hazards the new asset might face, i.e. what new risks are added to the system by implementing an intended mitigation. Although the wind turbine was installed to increase system resilience, there were potential hazards that could remove the turbine from service, in which case it wouldn't be able to provide any of the intended benefits.
- Joint failures will almost always increase the severity of a hazard, but they also decrease the likelihood. In the turbine communications scenario, the failure of the communications on its own did not necessarily represent a hazard to be concerned about. However, if that failure was combined with another event, such as an internal alarm that would then go unnoticed, the consequence of the hazard increased.

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Appendix A
Modeling and Simulation

Appendix A

The MIRACL team chose St. Mary’s as an isolated distributed wind system to use as one of the reference systems for our joint studies. We expected to have access to real data from the St. Mary’s system, but due to contract delays, this data were not available in time. In order to show how the processes developed work, the joint laboratory team agreed to move forward with common assumptions and synthetic data to show how new research in resilience, valuation, and advanced controls for distributed wind could be applied. This appendix details the assumptions made about the system and scenarios, and the methods of modeling data to produce synthetic, but realistic results.

A-1. SCENARIO SETUP

In all of our resilience scenarios, we consider one full year of operation. This year begins on July 1 of one calendar year and ends on June 30 of the following year. We assume that a fuel shipment is received in the summer, and that on July 1, the fuel-storage tanks are at their full capacity. This assumption allows us to evaluate 1 year of production and most easily analyze fuel-storage capacities, both over a single year and year-to-year.

The data are arbitrarily assigned the years of July 1, 2007 to June 30, 2008. These years do not correlate to any data in particular but are rather taken as an example. The data provided by HOMER were originally in the format of January 1, 2007 to December 31, 2007. In order to start the year in July to align with summer fuel shipments, the first half of the year was switched with the second half of the year. Then, to keep everything chronological, the months of January through June were reassigned to the year 2008. For analysis that considers 2 years, the year associated with the data do not change for the second year, but rather a different starting fuel-reserve value (the ending value from the first year) is provided for the calculations of fuel reserves throughout Year 2. The load and wind speed data remain identical in Year 2. While this is not the most realistic setup, the load data are a representative synthetic dataset, and the windspeed data have been adjusted to mimic the data that would be collected at a 50 m hub height at Pitka’s Point.

We use hourly data for our modeling. Over a year period, hourly data are fairly fine-grained. However, they do not capture things like immediate wind gusts, 10-minute wind maximums, voltage or frequency variations, or other qualities that would be ideal for analyzing a distributed wind system. Because much of the data are synthetic, using hourly data allows us to see general trends and compare different scenarios without worrying about sub-hour details. We would still hope that when we have access to real data, they might capture more of the sub-hour details and stability metrics.

A-2. TEMPERATURE DATA

Temperature data are extracted for the years 2005–2018 from the St. Mary’s airport (PASM) data records hosted by Iowa State University [24]. Temperature records from this source varied in sample per unit time as well as availability. Different data-extraction techniques were applied to extract hourly estimated temperatures. No correction factor is applied to account for the difference in location between the airport and the wind-turbine site. Figure A-1 shows the average hourly temperature for each month, as taken from data collected 2005–2018.

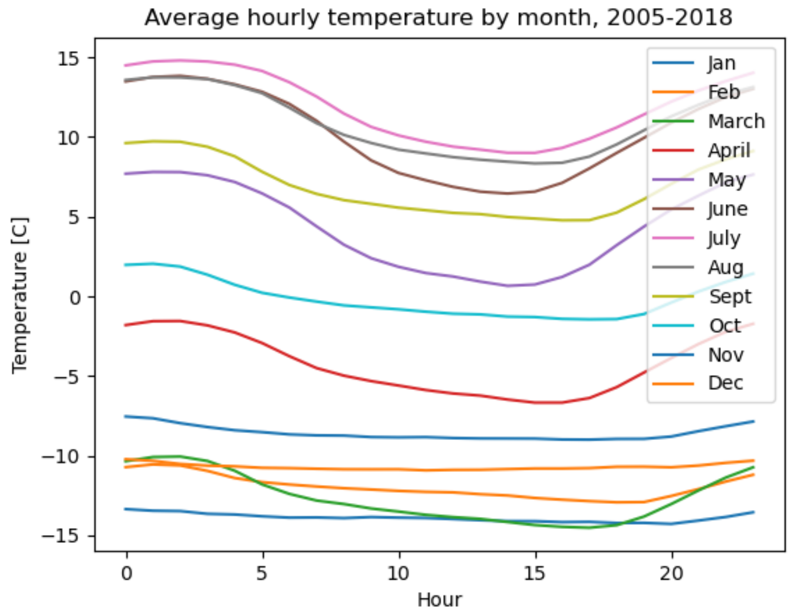

Figure A-1. Temperature data collected from PASM airport.

A-3. WINDSPEED DATA

Two sources of windspeed data are available. The first is the PASM data records hosted by Iowa State University [24]. The second is the parameters from the Pitka's Point metrological tower data synopsis, which were then used to generate synthetic wind time series in HOMER [23].

The windspeed data collected at the airport are valuable because they represent actual values recorded over many years and available at an hourly frequency, so daily and annual trends are visible. Thus, it is possible to average the data over many years. Figure A-2 shows the hourly windspeeds each month, as averaged over the 2005–2018 time period at the PASM location.

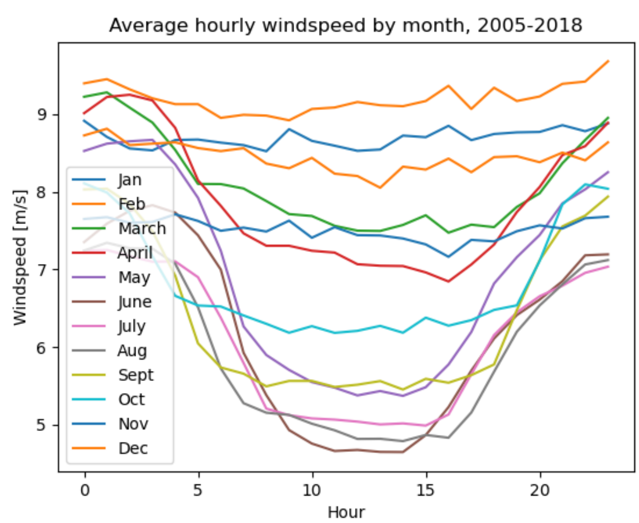

Figure A-2. Average hourly windspeed by month, raw PASM data.

The synthetic HOMER windspeed data are also valuable because they are based on the monthly averages and Weibull parameters of a wind study performed at Pitka's Point in 2012, which is where the turbine was later installed. The synthetic data also used the shear power law exponent to translate the data from the 38 m met tower data collection elevation to the 50 m hub-height elevation [23]. Figure A-3 shows the data generated by HOMER.

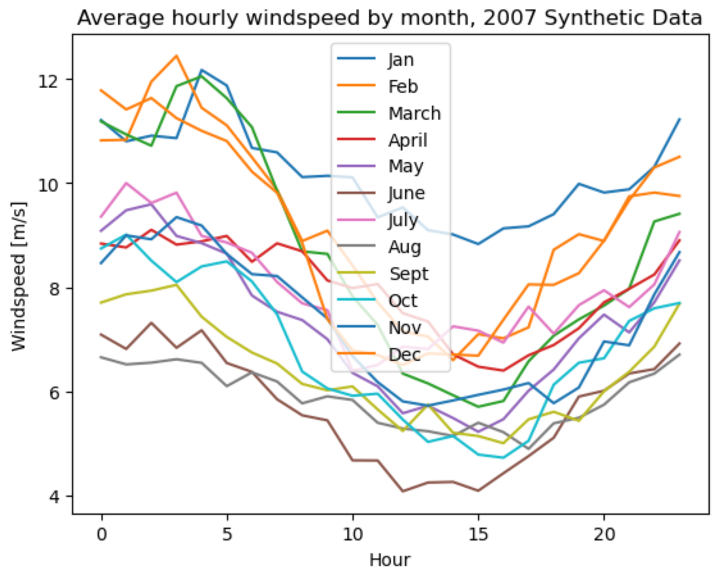

Figure A-3. Average hourly windspeed by month, synthetic data generated by HOMER.

Looking at Figure A-2 and Figure A-3, it is clear that these datasets do not align. The average synthetic windspeeds are significantly higher than the average airport windspeeds. Also, all of the months in the synthetic data follow the same daily trend—with higher windspeeds at night and lower windspeeds during the day—while the winter months in the airport data are much flatter throughout the day.

Our team decided to apply two correction factors to the airport data to make them a better substitute for data at the turbine location. First, we applied the shear power law with the assumption that the airport data were collected at an elevation of 10 m above ground level (the wind-turbine hub height was at an elevation of 50 m). Second, we applied a scaling correction factor so that the months which followed the same trend as the synthetic data had similar average values at various points in the day. Specifically, the months of April and August were taken as references, and a scaling factor of 1.2 was found to make the airport data best match the synthetic data, as well as the averages provided in the Pitka's Point wind assessment. Figure A-4 shows the corrected airport data.

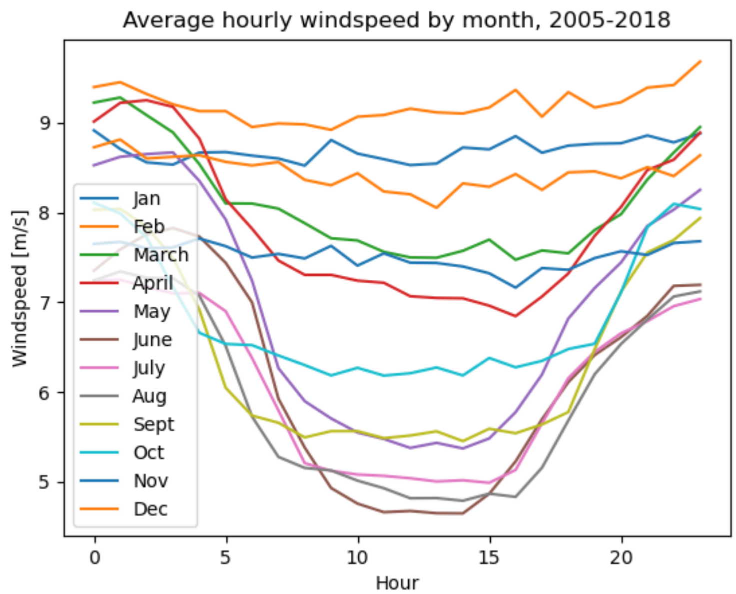

Figure A-4. Corrected airport wind data.

Like the synthetic data, the month of April has a peak of about 9 m/s and a minimum of about 7 m/s for its daily curve. Similarly, the month of August has a peak of about 7 m/s and a minimum of about 5 m/s for its daily curve. Additionally, the winter months match the averages given in the Pitka's Point report. January and February have the highest averages, 9–10 m/s, followed closely by December and March, with averages above 8 m/s.

Although no formula translates wind speed data from one location to another, and in fact, significant terrain factors may affect wind speeds and directions, even in a small region, we feel the constant scaling factor is an appropriate correction. The averages for each month align with the Pitka's Point met-tower study, and the monthly trends may be better aligned with regional trends than the synthetic data are.

Real data measured at the turbine are desired to replace this estimation, with hourly averages, maximum 2-second gusts, and max 10-minute averages.

A-4. WIND-TURBINE MODELING

The wind production curve is provided graphically by EWT, shown in Figure A-5 [12]. The Sandia National Laboratories team extracted graphical data to use in HOMER and shared this as a CSV file. The INL team then used the 46 data points provided by Sandia to fit a scaled sigmoid function to the data. The parameters found for this sigmoid function were stored and used to convert wind speed inputs into power production outputs. The function is shown in Figure A-6.

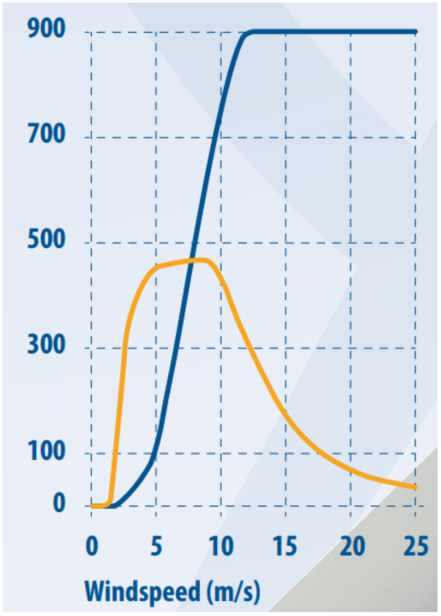

Figure A-5. Wind production curve from EWT.

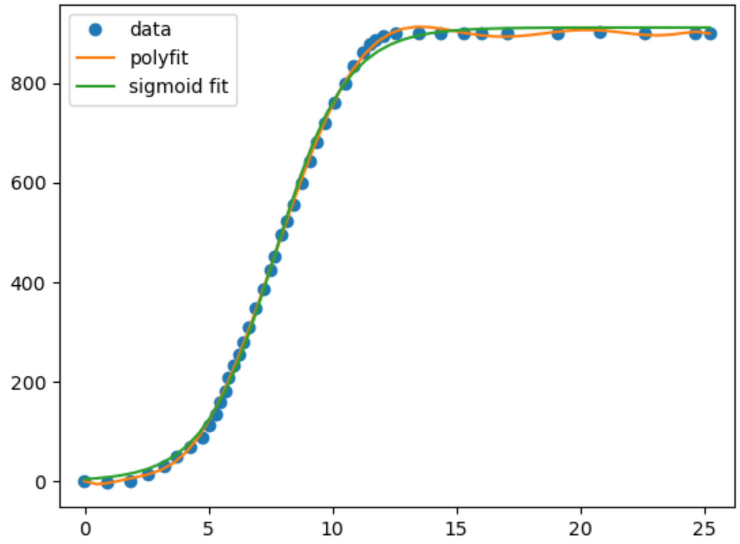

Figure A-6. Functional fit to the wind turbine production curve.

We can validate this curve by comparing the output of our model with the HOMER synthetic wind data to the wind production values reported by the HOMER model. These results are shown in Figure A-7.

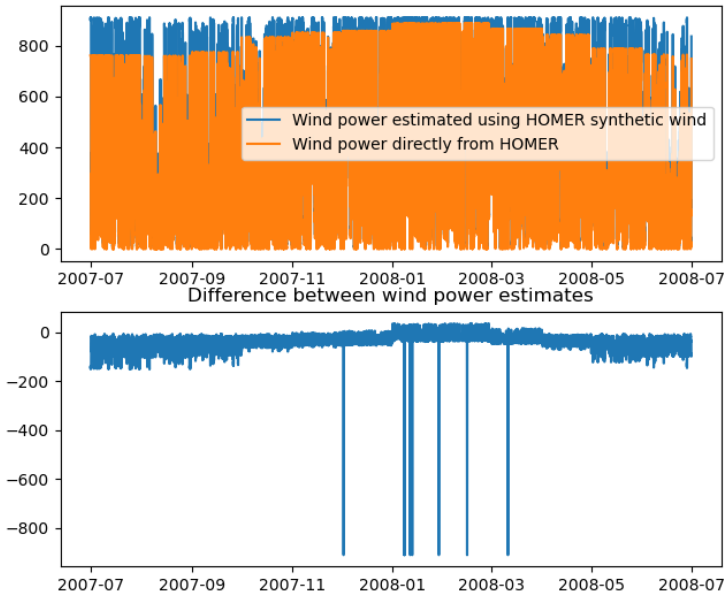

Figure A-7. Wind-production validation.

It is clear that the wind power calculations directly from HOMER are lower than those calculated by the INL model by 100–200 kW on average. We do not fully understand this difference, but because the same wind data were used for both models, the difference can be isolated to the model used for wind power production calculation, not to the source of the wind data. This difference means that in the INL model, wind production may generally be higher than in the HOMER model, resulting in less need for power production by diesel generators in the INL model, and less fuel used. Because we are working with synthetic data and estimates, we do not consider this difference to challenge the validity of the model. Note, too, that the wind power production curve is an estimate, and rather than acting exactly as the curve shown in Figure A-4, the real production data are a scatter plot that can be modeled by a trendline like that in the figure.

A-5. DIESEL GENERATION MODELING

Modeling diesel generation required two steps: the dispatch of the three generators to meet the required output and the efficiency of each generator to estimate the amount of fuel used.

Efficiency of generators was based upon the following efficiency curves for each of the sized generators. Operating points were determined upon dispatch schedule for the three gensets, and efficiency was determined based on the efficiency polynomial, which then provided fuel usage for that time interval. These parameters are shown in Figure A-8, and the resulting efficiency curves are shown in Figure A-9.

$p(x) = p_1 x^n + p_2 x^{n-1} + \ldots + p_n x + p_{n+1}$				
p1 =				
-1.9037	4.9100	-4.6803	2.0219	-0.0000
p2 =				
-1.7910	4.6648	-4.5213	1.9957	-0.0000
p3 =				
-1.9592	5.0340	-4.7884	2.0629	-0.0000

Figure A-8. Generator modeling parameters.

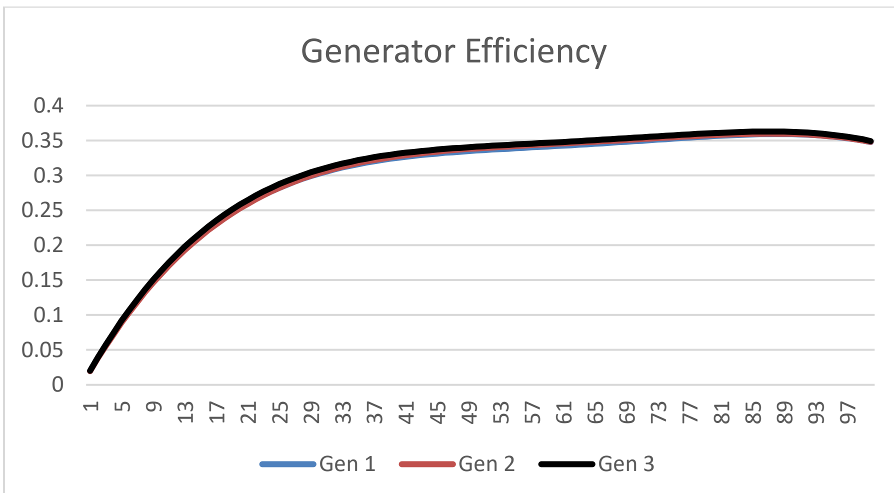

Figure A-9. Generator efficiency curves.

In our model, a very simple dispatch logic is used. The smallest generator is used to near-full capacity first. Then, the mid-sized generator is used, again to its near-full capacity. Finally, the largest generator is used. In Figure A-10, an example of a year's worth of generator dispatch is shown. The smallest generator is always on and at full capacity unless the load is less than its capacity. The largest generator is only turned on if the first two generators are operating at full capacity.

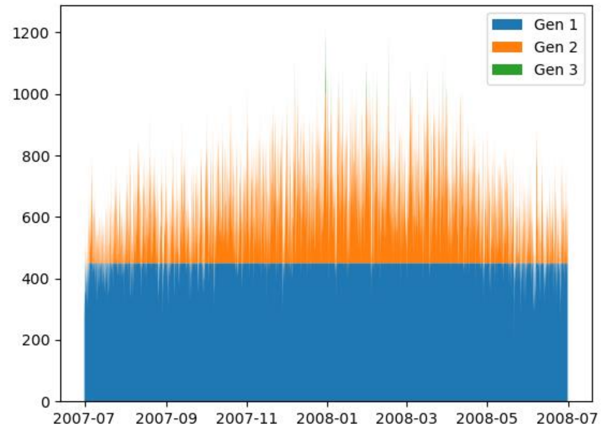

Figure A-10. Generator dispatch example.

A-5.1 Spinning Reserves

The St. Mary's system is operated with 100% spinning-reserves capacity for any load that is served by wind. In other words, the operators want to have generators turned on that have the capacity to cover the full load if the wind turbine production were to be suddenly lost. It does not mean that generation capacity has to be turned on to provide 100% reserves for load that is only served by diesel. If there are 400 kW of load, and all 400 kW are served by wind, a diesel generator with the capacity to meet that 400 kW still needs to operate should wind-turbine production be lost. The diesel generator can operate at its minimum level. The minimum operational levels for each generator are given in Table A-1.

Table A-1. Minimum generation output.

Turbine capacity	Minimum operation
500 kW	75 kW
611 kW	91.65 kW
908 kW	136.2 kW

As seen in one month's production data in Figure A-11, even when wind generation exceeds the load, a turbine is turned on at its minimum production level.

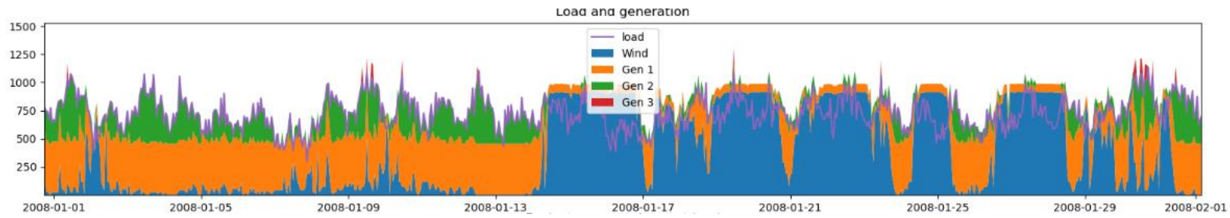

Figure A-11. Spinning reserves example.

A-5.2 Load Modeling

The loads at St. Mary's were estimated from a consultant report that was published in 2014, summarized in Table A-2. Average and peak loads from St. Mary's were estimated from prior consultant analysis [13]. The analysis was based on data provided by AVEC to the consultant from 2009 to 2011. These values were used in the HOMER analysis, but were doubled to account for the addition of Mountain Village.

Table A-2. St. Mary's load summary.

Month of 2010	Average Load (kW)	Peak Load (kW)
January	366	430
February	360	423
March	357	419
April	323	379
May	293	343
June	262	307
July	253	297
August	277	325
September	280	329
October	314	369
November	336	394
December	351	412
Annual	314	369

A-5.2.1 Load temperature dependency

As seen in Figure A-12, the model that takes temperatures as an input and gives average load as an output does a good job of approximating the HOMER synthetic load data. However, the model can only approximate averages and does not include the variability seen in the synthetic data and expected from real data. In order to use the temperature-load correlation to estimate load changes based on temperature changes, we adopt the following method. We estimate the average load each hour for a base-case year that corresponds to the HOMER synthetic-load data. We then estimate the average load based on a shifted temperature, either for the full year or for a portion of the year. We take the difference between the estimates of the average loads and add that to the HOMER synthetic-load data to generate new synthetic data.

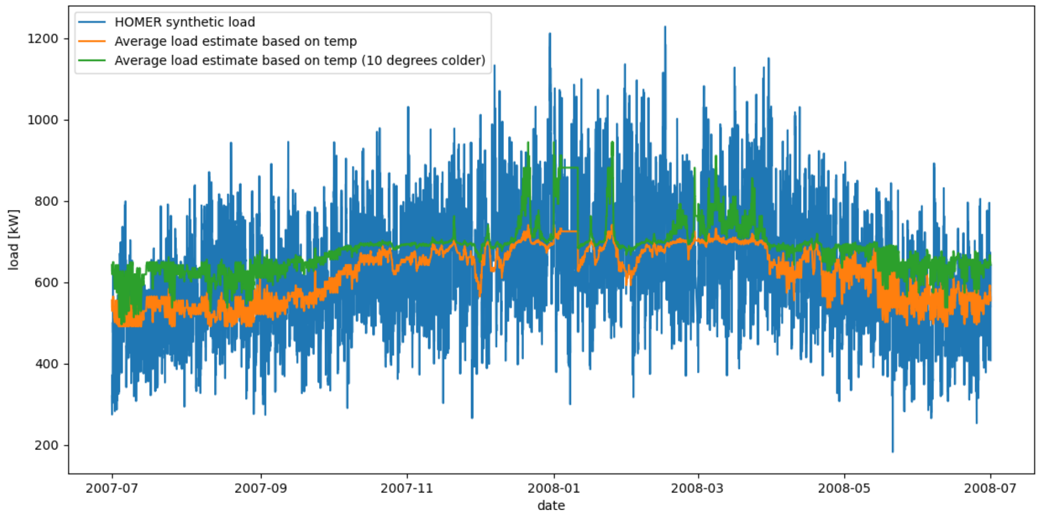

Figure A-12. Validation of average load values given temperature.

We can apply this in two ways. First, we can take the hour-by-hour difference in average load estimates and add that directly to the HOMER synthetic base load. Second, we can take the average difference between the load estimates over the whole year and add that difference to the HOMER synthetic base load. These cases are shown in Figure A-13. It is difficult to see the difference in load with all three cases laid atop one another or when they are side-by-side due to the variability of the synthetic data, therefore we also show the rolling weekly average of each case. We can see that, in both cases, the adjusted load is higher than the base load when the temperature drops by 10° for the full year, which is what we expected. Both methods of applying the load shift show no significant differences, and we opt for the hour-by-hour shift to preserve more variability.

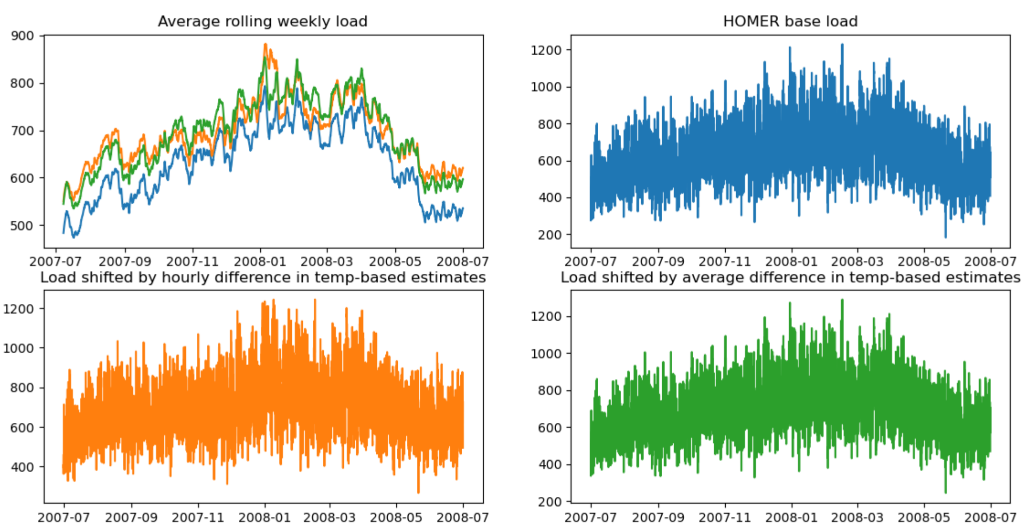

Figure A-13. Examples of shifting the load using temperature dependency.

A-5.3 Storage Capacity

We assume that fuel storage tank farms are filled completely at the beginning of Year 1. We assume that with wind installed, the new tank farm is used, and there is a starting capacity of 414,000 gallons. Without wind installed, we assume that the starting fuel storage capacity for the combined St. Mary's, Mt. Village system is double that of the old St. Mary's capacity of 224,264 gallons, which gives a capacity of approximately 450,000 gallons. It is reasonable to analyze the no-wind case with higher fuel storage because it would be known that diesel is the only fuel source, so more would be used throughout the year. It is also reasonable for the fuel storage capacity to be so large for the with-wind case because the operators want to have the capacity to run fully on diesel in the event of a problem with the wind turbine.

A-5.4 CO_2 Emissions

The conversion factor of 19.6 lb of CO_2 per gallon of gasoline was used to estimate the CO_2 emissions from the diesel generators. This conversion factor was provided by the U.S. Energy Information Administration and is taken to represent similar petroleum-fuel emissions rates [25].