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Changing the World's Energy Future

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***Abstract*—In this case study of St. Mary's Village, Alaska, we present a resilience evaluation exercise. A resilience framework is employed to identify system characteristics, relevant metrics, and resilience hazards, and to assess the performance against the hazards with and without a distributed wind turbine. The results show the resilience benefits provided by the distributed wind installation against fuel shortage hazards and cold weather hazards. The resilience benefits can be assigned monetary values, which provide insight into value streams of distributed wind that are not usually considered. For example, the single 900 kW turbine was found to prevent an average of 14,643 kWh of load from being dropped during a two-day diesel fuel shortage event, which saved the community $447,592 by preventing outages. This case study is an example of novel power system resilience analysis and builds understanding of resilience hazards in power systems.**

***Index Terms*—resilience, valuation, power system planning, distributed wind, fuel shortage, weather hazard, DER**

I. Introduction

The concept of resilience is not new, but its application to electric energy delivery systems (EEDS) is neither standardized nor well-defined [1]–[3]. In order to address growing power system challenges, including aging infrastructure, increasingly severe weather, and dependence on fossil fuels, better methods to plan for resilience are required, a need recognized by the Department of Energy (DOE) and the Federal Energy Regulatory Commission (FERC) [4], [5].

To address the need for resilience planning in the power industry, Idaho National Laboratory (INL) has developed a resilience framework for EEDS [6]. This framework is intended to help identify, assess, and mitigate risks associated with resilience hazards. An all-hazards approach is taken in the framework, giving it flexibility to address risks including terrestrial weather events exacerbated by climate change, cyber or physical attacks, space weather events, aging infrastructure, and increasing concerns about carbon emissions.

This case study uses the INL resilience framework to assess a real-world isolated power system in St. Mary's, a remote community in Alaska. This system was chosen because its isolation allows us to consider the entire system during the resilience hazards. Additionally, St. Mary's recently installed a 900 kW wind turbine, which allows us to not only evaluate the resilience of the original system, but to compare that to the resilience of the system with wind added, thereby quantifying the resilience benefits of the distributed wind installation.

The identification of resilience benefits then allows us to estimate the resilience value of the wind installation. The value of resilience is not typically captured in cost-benefit analysis of investments, nor are resilience hazards always captured in risk analysis. Resilience typically refers to high-impact low-frequency events, which can be difficult to assign likelihoods to in risk models [7]. This case study provides examples of how resilience analysis can be used in the planning, risk analysis, and operation of evolving power systems.

II. Background

A. Resilience Framework

Despite the lack of a standardized definition of resilience for EEDS, active work in the area has advanced concepts that we draw upon. Many resilience frameworks exist, but few address the full lifetime of a system and many remain abstract, making it difficult to interpret and apply concepts to real systems. Some frameworks emphasize resilience in real-time operations [8], [9]. Others emphasize methods to plan and prepare for resilience [10]–[12]. The resilience framework developed by INL uniquely covers the entire system lifecyle, and it evaluates resilience using specific steps [6]. As such, it is the chosen framework to employ in this case study.

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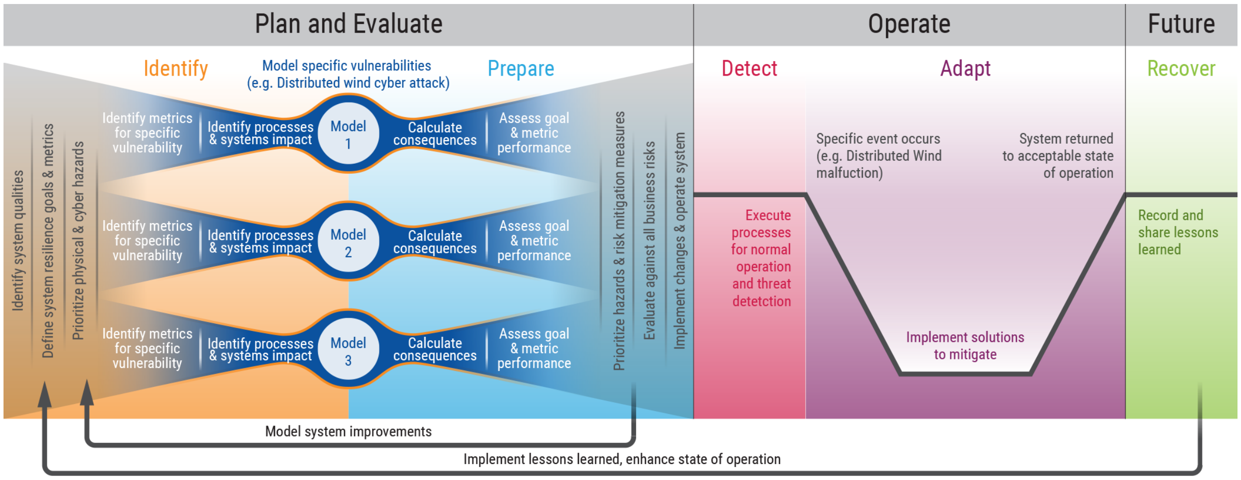

Fig. 1. INL resilience framework

The INL resilience framework is a process for model-informed consideration of resilience hazards. The framework considers three tiers, shown in Figure 1. The top tier contains three stages of resilience: *plan and evaluate*, *operate*, and *develop the future*. The intermediate tier contains five core functions: identify, prepare, detect, adapt, and recover. Finally, the lowest tier has process steps, which describe the information gathering and decision-making that stakeholders need to execute to ensure resilience goals are met.

In this case study, we focus on the planning stage, which is modeled as a nested bow-tie process, shown in Figure 1. The first steps are identifying relevant system properties, resilience goals, and metrics. Next, cyber and physical hazards can be prioritized. Each hazard is evaluated individually, using appropriate simulations. Then, metrics analysis determines the consequences of the hazard and performance against goals. The final stages include mitigation measures, which must then be evaluated against all other business risks and costs. Finally, the recommended changes should be validated and implemented in the operation of the system.

B. St. Mary's, AK

St. Mary's is a remote village in western Alaska with a population of 683 [13]. A road and electrical intertie connect St. Mary's to two neighboring villages, Pitka's Point (pop. 117) and Mountain Village (Mt. Village) (pop. 860). For the remainder of this document, reference to St. Mary's will refer to the combined system for the three villages, unless otherwise specified. St. Mary's is an electrically isolated member of the Alaska Village Electric Cooperative (AVEC).

A 900 kW wind turbine was installed in 2019. Before this, there was only a single energy source, three diesel generators, which rely on fuel shipments by barge up the Yukon river. There is no road access, and fuel is only delivered once a year. The dependence on diesel led to the primary resilience goal, to reduce fuel uncertainty and ensure sufficient reserves are present. Given the small size of the system, the second goal is to reduce the duration of short-term outages.

The information in this section serves as the foundation for the "Identify system qualities" and "Define resilience goals and metrics" steps in the resilience framework.

C. Resilience Hazards

The list of potential resilience hazards is nearly endless, but understanding the environment can help identify the most important hazards. In this study, we focus on two relevant hazards: a fuel shortage and extreme winter weather.

The barge delivery of diesel to St. Mary's is very reliable. However, a fuel shortage could occur if a tank or pipe failure limits the supply to the diesel generators. It is also possible that a fuel shortage could occur if weather or supply chain issues cause delays in the delivery, particularly if winter sets in and the river becomes impassable [14]. Although there are many ways this hazard could manifest, we consider that this scenario would lead to the diesel generators being shut down for two days while repairs are made or extra fuel is flown in.

In Alaska, intense winter conditions could have measurable effects on the system. Here, we focus on temperature. When temperatures are low, the loads will increase due to heating needs. Additionally, the turbine installed has a cold weather protection package, but still ceases to operate at $-40°$ C [15].

III. Methods

Key information about the St. Mary's system was available in consultant studies, AVEC reports, and reports of the wind turbine install [13], [16]–[19]. However, these reports lacked time-series data, which was needed to perform simulations and evaluate the resilience metrics. To simulate this data for the resilience analysis, models of multiple system components and inputs were created using data from public sources. The synthetic data covered a year-long period with hourly intervals.

A. Weather Data

The wind speed and temperature data used in simulations were collected at the St Mary's airport [20]. These data are valuable because they are real values recorded over many years. Data were collected at hourly intervals for 2005-2018. However, since these data were not collected at the wind turbine site, the regional trends and weather are reflected, but the actual wind conditions at the installation site are not. To correct for this, first the shear power exponent law was applied to account for the turbine height above ground (50m) and the anemometer height (10m). A second corrective factor was applied so that each month's average hourly data matched the trends that were seen in a wind resource analysis performed at Pitka's Point, the site of the turbine installation [19]. This data, collected from 2007-2009, provides only monthly summary data. The Pitka's Point data was collected at a height of 38m, so a shear power exponent law correction was applied before the data was compared to the trends in the airport data.

Neither the airport data nor the Pitka's Point data are sufficient on their own to perform detailed analysis. However, using the hourly data from the airport and applying corrective factors so that monthly minimum, maximum, and average wind speeds generally match those collected at Pitka's Point allows us to have representative, synthetic hourly wind data.

Although temperature data was not available at Pitka's Point, the airport data again serves as a substitute with the same regional trends. The airport is only about two miles away from the turbine site, so no corrective factors were applied.

B. Wind Turbine Model

The turbine is a 900 kW DW52 EWT turbine [1] [13]. Since the community actually installed this model, we focus on it rather than exploring various sizes or combinations of turbines, thereby examining the real resilience benefits provided to the community. The wind production curve is provided graphically by EWT [21]. 46 data points were extracted from this curve and fit to a scaled sigmoid function. This function was used to convert wind speed inputs into power production outputs. The inverter is assumed to have grid-forming capabilities, although this might require an upgrade from the existing system.

C. Diesel Generator Model

St. Mary's has three diesel generators that serve as the primary power source, with capacities of 499 kW, 611 kW, and 908 kW. Modeling the diesel generation required two steps: the three generators are dispatched to meet the required output, and fuel use is calculated using efficiency curves. We use a simple dispatch model. First, the smallest generator is used to serve unmet load up to full capacity. Then, the mid-sized generator is used as needed, and finally the largest generator. Efficiency curves were modeled as 4th-degree polynomials with different parameters for each size of generator. The combination of generator dispatch and efficiency calculations determines the amount of fuel used each hour.

We note that the St. Mary's system is operated with 100% spinning reserves capacity for any load served by wind. Diesel generators with the capacity to serve the full load must operate at least at minimum levels so that there is no interruption in service if wind production suddenly ceases. The smallest generator is used for reserves first, adding others as needed.

D. Load Model

The load data were simulated using parameters from a consultant report based on data collected from 2009-2011 [16]. Average and peak load values from the report were used to generate synthetic data in HOMER [22]. The consultant values only apply to St. Mary's Village, so the values were doubled to account for the similar loads and trends in Mt. Village.

We also estimate the change in load based on temperature. Using temperature and synthetic load data, we generated a correlation model between temperatures and average load. It performs well for approximating the average load data. However, it does not capture variability from other factors, like customer behaviors or time of day, that is seen in the HOMER data and expected from real data. To capture variability and load-temperature correlation, we adopt the following model. We estimate a load change due to temperature change by calculating the difference in average load from the load-temperature correlation model using base case and adjusted temperatures, then add this difference to the synthetic, variable load data to generate adjusted synthetic load data.

IV. Results

Before the hazards are analyzed, the base case year is simulated. Ideally, this would be done with production data. However, since this was not available, the models described in the previous section are used to simulate the system. The year of simulation begins on July 1, and we assume that this is when the barge shipment of fuel is received, which simplifies the calculations for fuel use and reserves throughout the year. The 2008 adjusted wind data is arbitrarily chosen as the year for the wind source. We chose a single year rather than an average of years to preserve the variability of real data. In each simulation, wind is used to serve as much of the load as possible, and diesel generators are dispatched to serve the remaining load and any spinning reserves needed.

A. Fuel Shortage Scenario

When a diesel fuel shortage occurs due to a pipe rupture, tank failure, delayed shipment, or a combination, no diesel generation is available. With wind serving as much of the load as it can as a grid-forming source, the load lost is equivalent to the load expected to be served by diesel. Without wind installed, this is all of the load. This scenario could happen at any time of the year, but a critical tank failure is most likely towards the end of our year of analysis. This is when fuel reserves are at their lowest, and there may not be additional full tanks to take the place of the failed tank. The case of the pipe rupture would not likely be affected by the time of year. Figure 2 shows that over any two-day period during the year, the wind can serve at least a portion of the load, so a diesel outage will result in more load lost if wind is not installed.

[1] The DW52 turbine was installed, but an error in the original HOMER analysis used the DW61 power curve, which informed later model development. This impacted wind power production values by about 7-9%, which was an acceptable margin for the purposes of this case study, especially given the variability in wind speeds and efficiency in an operational environment.

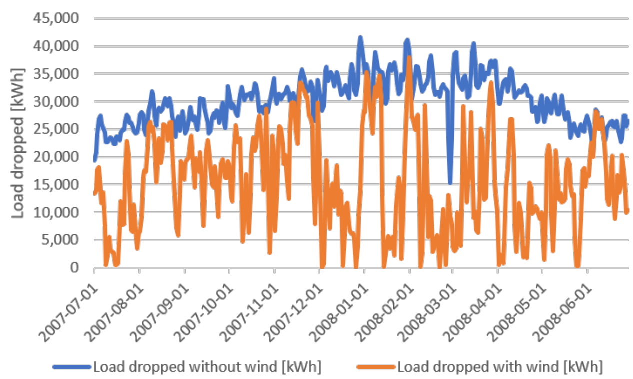

Fig. 2. Load lost during two day shutdowns of diesel generation due to fuel shortage, shown at different two day intervals throughout the year.

Resilience benefits are difficult to quantify and even more difficult to assign monetary values to given their low frequency and the unique circumstances that often create the hazard conditions. In this scenario, the resilience benefits from wind can be measured as avoided lost load. The amount of load dropped without wind is generally higher in the winter during any 2-day outage, due to the increased heat demands. The amount of load dropped with wind installed is highly variable due to wind speed variability. On average, for any 2-day shortage, the turbine prevents the loss of an extra 14,643 kWh of load compared to the same event without the turbine installed. Although wind prevents more load from being dropped, the system may still have difficulty handling the high variability and intermittent partial outages in this scenario.

The value of this resilience benefit can be estimated as the avoided customer costs of an outage and the avoided lost revenues to the utility. Due to scope and data availability, regional economic impacts and health costs during these outages were not analyzed. Estimates from other avoided-cost studies are leveraged to assign values for commercial and residential outages [23], [24]. The 24-hour outage values are extrapolated to 48 hours, and it is assumed that 60% of residential loads are low priority and 40% are high priority, according to the definitions found in [24]. Commercial customer costs were found by extrapolating outage values from [23] from 16 hours to 48 hours, and by assuming that approximately 12 small commercial and industrial customers exist in the community. We find that the two-day outage costs approximately $447,592 on average, although there is some variation depending on the time of year. The lost revenues for the utility are calculated using 2021 AVEC rates applied to the load lost and weighted by customer types, assuming that 8% of load is from small commercial and industrial customers and 92% is from residential customers. The utility lost revenues were calculated as $4,240 on average, although this value was higher in the winter and lower in the summer.

The resilience benefits and value provided by the wind turbine during the fuel shortage hazard are significant. However, the probability of such an event occurring is still low, so from a risk perspective, the expected annual benefits of the wind turbine can be calculated by multiplying the likelihood by the benefit amount.

B. Extreme Temperature Scenario

To simulate a variety of "harsh winter" conditions, we modeled scenarios with different temperature drops over several lengths of time. All cold snaps were centered around December 21. We note that the most extreme cases (e.g. a 12-week cold snap with temperatures $20°C$ below normal), are highly unlikely. We also note that the temperature-load correlation we used loses fidelity at very low temperatures. However, these models still show the general trends with different types of cold snaps, and we do want to consider the extreme cases where the temperature drops below $-40°C$, since this is the lower operating limit of the turbine.

Separate trials with temperature drops (changes compared to the base case year) of $-1°C$, $-2°C$, $-5°C$, $-10°C$, $-15°C$, and $-20°C$ were performed. Each temperature drop was considered for eight durations ranging 1 week to 12 weeks, resulting in 48 total cases. For each, the annual fuel usage was recorded for the base case year without wind, the cold year without wind, the base case year with wind, and the cold year with wind. Corresponding with-wind and without-wind years were compared across the base case and the cold year to find the difference in fuel used as a result of the cold snap. The results are shown in Figure 3.

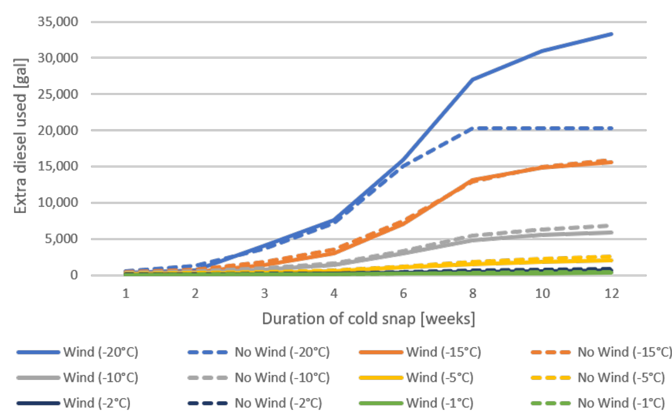

Fig. 3. Increase in annual fuel use due to extreme temperatures compared to a base year.

For most temperature differentials, the scenarios with wind result in less additional fuel being used during the cold snap than the scenarios without wind. This is because excess wind that is curtailed in a base case year can instead be used to serve the increased load during the cold snap. Without wind, all additional load must be met with diesel. This resilience benefit is not obvious, as the hazard is not directly related to either generation source or the power system infrastructure. This scenario demonstrates resilience benefits that can be overlooked, but which should be considered to properly value the addition of wind.

The resilience benefits from wind change when the temperatures drop by $20°C$ for the duration of the cold snap. There is a larger fuel increase for the with-wind cases than the without-wind cases, particularly for long duration cold snaps. This is explained by the fact that these extreme temperature changes drop the temperature below the $-40°C$ operating point of the turbine, resulting in less wind production than a normal year. In this case, the additional load due to the temperature change and also the base load must be served by diesel. This results in a larger change in annual fuel use for the with-wind case than the without-wind case. Note that while variable resources are often seen as decreasing system resilience, it is not the variability, but rather the environmental limits, that contribute to decreases in resilience for this scenario.

The 1-2 week cold snaps do not result in large increases in fuel use, even under extreme cold. Additionally, temperature drops of $2°C$ or less result in very small changes, even when they last for up to 12 weeks. In the most extreme scenarios, however, the extra fuel used is significant. In particular, without wind installed, the extreme scenarios require that extra fuel be shipped in before the end of the year, because the extra fuel used during the cold snap exceeds the reserves that would normally be left at the end of the year.

The resilience benefits of wind in this hazard analysis are measured as fuel savings during the cold snap which can be monetized by applying fuel prices for that time frame. The fuel savings during the cold snap are, on average, only slightly higher than normal years. Savings are maximized for cold snaps that drop temperatures $5 - 10°C$ below normal, as smaller temperature drops result in smaller fuel increases, and larger temperature drops push the bounds of the wind turbine's utility and availability.

V. Conclusion

In this case study of St. Mary's, AK, the resilience planning process using the INL resilience framework was followed to examine extreme weather and fuel shortage hazards. We showed that the addition of a 900 kW distributed wind turbine to the isolated system added resilience benefits during the hazards. The scenarios highlighted the obvious resilience benefits of resource diversity and less obvious benefits during environmental hazards. Dropped load and increased fuel use were highlighted as resilience metrics, which were of particular importance to the resilience goals for the system. We also assigned values to the resilience benefits, a novel process which can aid in the holistic risk analysis and investment prioritization process.

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