INL/RPT-22-67919
Revision 1

Resilience for Advanced Distributed Wind Systems

July 2022

Identifying the resilience benefits of advanced controls and hybrid systems for distributed wind

Megan Culler
Power Engineer and Researcher

Steve Bukowski
Infrastructure Security Engineer

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/RPT-22-67919
Revision 1

Resilience for Advanced Distributed Wind

Identifying the resilience benefits of advanced controls and hybrid systems for distributed wind

Megan Culler
Power Engineer / Researcher
Steve Bukowski
Infrastructure Security Engineer

July 2022

Idaho National Laboratory
Critical Infrastructure Security
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

EXECUTIVE SUMMARY

The purpose of this report is to highlight the relationship between resilience provided by distributed wind and key adaptations that can be made to distributed wind systems, namely expanding to hybrid generation sources and adding advanced controls. The resilience benefits of distributed wind can be primarily attributed to the ability to provide local generation with attributes aligning closer to electrical characteristics of thermal generation without fuel imports. In previous case study analysis of resilience benefits, modeling showed that "advanced distributed wind," meaning something beyond the turbine asset and simple safety controls, could significantly increase the resilience benefits when the system experienced a hazard.

In this report, we explore how hybrid systems and advanced controls can provide resilience benefits beyond that of simple wind and propose metrics that can be used to capture the full resilience benefits. In the advanced controls analysis, we consider a variety of control functions and show how controls enhance the benefits not just by increasing performance during the occurrence of a hazard, but also help the system better prepare for a hazard. In the hybrids analysis, we consider how adding distributed wind to other generation sources has benefits beyond energy capacity and discuss how hybrids impact various metrics in the detection, response, and recovery from a hazard.

Finally, designing and operating a system for maximum resilience is often accompanied by tradeoffs in other areas, such as maximizing profit. We present a risk analysis framework that allows users to consider how various components of risk are affected by the configuration and operation of the system. We discuss the ways in which the overall system risk is affected by hybrids and advanced controls, as well as how various operational goals may affect risk.

This document serves to provide background for future studies to consider the effects of combining advanced controls and hybrids with resilience objectives.

ACKNOWLEDGEMENTS

The Idaho National Laboratory team would like to thank contributors and sponsors for this work, which include:

- The Wind Energy Technologies Office (WETO): Patrick Gilman and Bret Barker
- Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad partners:
  - Sandia National Laboratory (SNL)
  - Pacific Northwest National Laboratory (PNNL)
  - National Renewable Energy Laboratory (NREL)

CONTENTS

ACRONYMS

DER	Distributed energy resource
DIRE	Disturbance impact resilience evaluation
DOE	Department of Energy
EEDS	Electric energy delivery systems
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
NREL	National Renewable Energy Laboratory
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
PNNL	Pacific Northwest National Laboratory
SNL	Sandia National Laboratory
WETO	Wind Energy Technologies Office

Page intentionally left blank

Resilience for Advanced Distributed Wind

1. INTRODUCTION

Under the Department of Energy (DOE) Wind Energy Technologies Office (WETO), Idaho National Laboratory (INL) has been tasked with defining the resilience benefits of distributed wind systems for the Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project. This project is a collaboration between the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL) and Pacific Northwest National Laboratory (PNNL).

1.1 MIRACL

The MIRACL project aims to address challenges in controls, communication, and hardware for grid and microgrid integration of wind energy technology with other distributed energy resources. These areas are not well-developed or standardized, so MIRACL aims to improve and validate capabilities of wind technology, which includes the use of advanced controls, validation of plug-and-play integration with other resources, and showcasing the resilience benefits of distributed wind.

The first years of the project focused on bringing technical expertise to the areas of valuation, modeling, advanced controls, and resilience. The research developed by each lab was validated in two case studies, an isolated system in Alaska and a front-of-the-meter deployment in Iowa [1].

In the final year of this project, INL is collaborating with the other labs to bring together key results from our previous work on resilience, cybersecurity and risk, distributed wind hybrid systems, and valuation of distributed wind. The purpose is to show not only how distributed wind can be used as a resilience asset, but how the use of distributed wind in hybrid systems and with advanced controls further enhances resilience beyond what any of the individual components could do alone. This research will inform a final, collaborative case study by the MIRACL team, and will help improve the operation, integration, and valuation of distributed wind in transactive environments, microgrids , and distribution system networks.

1.2 Resilience Framework

INL developed a Resilience Framework for Electric Energy Delivery Systems (EEDS) under MIRACL to plan for and evaluate resilience. In early work for the MIRACL project, INL identified that there is a "uniqueness" quality to resilience for different systems. The system characteristics, hazards that a system often faces, and goals for a system contribute to how resilience is defined and evaluated for individual EEDS. Following an extensive literature review on resilience definitions and metrics, INL defines resilience 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." *[2]*.

This definition suggests that resilience spans technology resources and systems, geographic constrains, risk tolerance, performance tolerance, and diverse stakeholder perspectives. The combination of all these contributing factors suggests the need for a framework to bring them together which can be used to plan, evaluate, and operate the system for resilience.

A three-tiered approach is developed in the resilience framework [3]. 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.

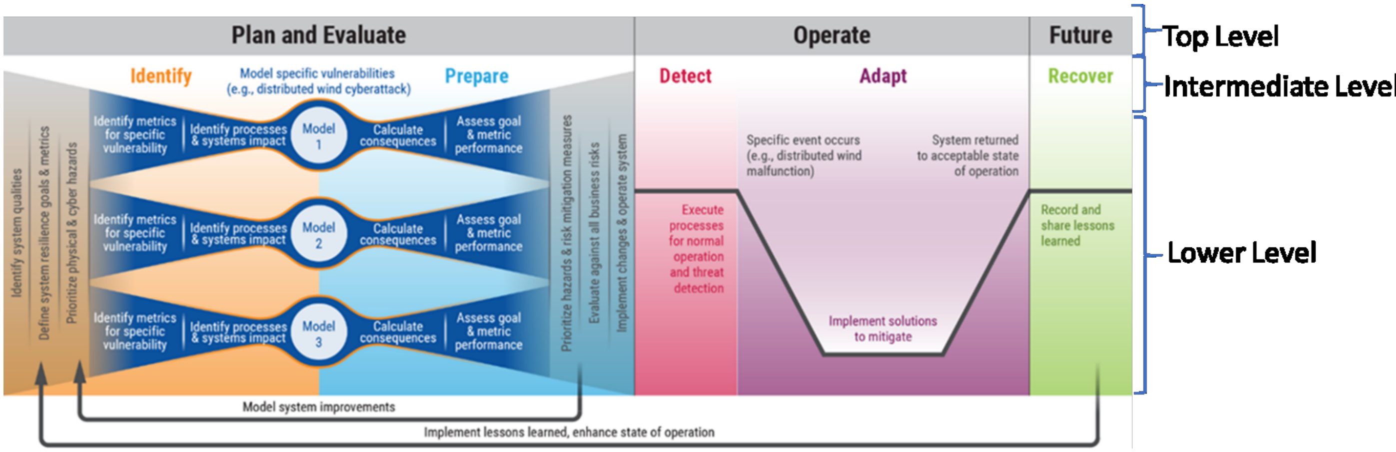

Figure 1. INL resilience framework.

1.3 Advanced Controls for Distributed Wind

SNL and NREL have jointly worked on developing advanced control abilities for distributed wind assets. The research roadmap of distributed wind control for the MIRACL project documents active and reactive control capabilities for different DERs based on a literature review and proposed application of these controls for distributed wind [4]. The NREL MIRACL team narrowed in on certain controls best suited for distributed wind in various configurations.

The controls identified as best suited for isolated deployments of distributed wind are voltage support and frequency support. Voltage support is provided via reactive power control. Frequency support is provided via active power control. Various means for accomplishing active and reactive power control are discussed thoroughly in other MIRACL reports but are not the focus of this paper [1].

NREL has also identified other ancillary services that are valuable to the power system which are or can feasibly be provided by distributed wind. These include frequency response, regulating reserves, contingency reserves (spinning, non-spinning, and replacement), ramping reserves, voltage support, black start, and energy capacity.

While not all of these ancillary services are currently required by distributed wind, the 2018 update to the Institute of Electrical and Electronics Engineers (IEEE) standard 1547, requires distributed energy resources (DERs) to be capable of providing several advanced control functions [5]. These include riding through and supporting frequency and voltage deviations.

1.4 Hybrid Systems with Distributed Wind

A hybrid energy system can be defined as one that combines multiple types of energy generation and/or storage. Distributed wind has many beneficial properties on its own, but combining wind with solar, storage, or even fuel-based generators offers several advantages over any single source system. For example, active power and reactive power support from a hybrid plant is larger than that of the individual components of the plant [6]. Hybrid systems are often necessary in order for a system to be stand-alone, and in particular, trying to power an off-grid system with a single renewable resource will likely create an unreliable and non-dispatchable system.

NREL has worked to analyze the suitability of distributed wind in hybrid deployments with solar. To do this, they studied the resource complementarity of wind and solar across the entire United States and using different time intervals and frequencies for the analysis [7]. These results are useful for understanding how wind and solar work together.

A similar effort on the suitability of wind-storage hybrids would be trivial in some ways. Because the output of the battery is dispatchable, a well-sized wind-storage system would be highly complimentary, charging the battery when wind output is high and discharging the battery when wind output is low. The sizing of the battery is what would ultimately determine the complementarity. If the battery is oversized compared to the distributed wind system, it may never be fully charged and a poor investment. If the battery is undersized, it may be fully charged quickly, still causing wind energy production to be curtailed.

Other wind-hybrid systems, like wind-diesel, are not prioritized in this report. Distributed wind has the potential to be a valuable asset in meeting clean and carbon-free energy goals. The Distributed Wind Energy Futures Study found that there is nearly 1,400 GW of distributed wind potential today [8]. However, hybrid systems with diesel or other fossil fuel generators are not as effective at promoting carbon-neutral or carbon-free goals.

1.5 Case Studies

The MIRACL team identified two existing distributed wind case studies for each lab to examine under the unique research areas. These case studies informed the research and served as proving grounds for the valuation, resilience, and advanced controls concepts developed under MIRACL [1]. We provide brief summaries here to provide context for when these case studies are referenced in the remainder of this report.

The first case study was for St. Mary's, AK, an isolated community on the Yukon river that installed a 900kW turbine in 2019. This turbine served to offset the use of the only other generation source, diesel turbines. Diesel fuel is delivered once a year by barge. The system in its current configuration, which features a new tie-line to the neighboring town of Mountain Village, serves approximately 1700 people.

The second case study was for a subsystem of Iowa Lakes, IA. The two wind plants studied each had seven 1.5 MW turbines for a total of 21 MW. Each wind plant primarily serves an ethanol plant connected at the substation level. Overproduction of wind is sold to the local generation and transmission (G&T) provided Corn Belt Power Cooperative, and the G&T provider supplies energy needs when wind is underproducing.

2. ADVANCED CONTROLS CONSIDERATIONS

This section discusses resilience considerations for various types of advanced controls feasible to use with distributed wind. In the resilience case studies performed, INL found that advanced controls enhanced the resilience benefits, particularly for the most severe hazards, which involved the failure of at least one other generation source (incoming transmission or local diesel generation) [9, 10].

In any case where the system is cut off from the bulk power system, at least one generation source needs to be grid-forming to set the frequency. In the St. Mary's example, this was the diesel generators during normal operation, but could be the grid-bridging system to allow wind production to still operate during a hazard. In the Iowa Lakes example, we assumed that either the wind inverters or the storage inverters had grid-forming capabilities. In less severe resilience hazards that don't involve the total isolation of the system, advanced controls may not be necessary to survive the event but can still add resilience. Examples of this will be discussed later in this section.

This section is not intended to be an exhaustive discussion of all advanced controls and their suitability for distributed wind. Rather, it is intended to highlight controls that have been explored under the MIRACL project and to discuss their resilience benefits in service of understanding the relationships between core research pillars of MIRACL and maximizing the utility of distributed wind systems wholistically, rather than using one pillar at a time.

2.1 Advanced Forecasting

SNL studied the impact of advanced forecasting methods on the performance and use of the wind turbines in the St. Mary's case study. The system is currently operated with spinning reserves, meaning enough diesel generators must be spun up to provide capacity to serve the full load at any time, in case the wind suddenly cuts out. However, if operators could rely on highly accurate wind forecasting, they wouldn't have to keep diesel generators spun up to provide reserve capacity and would only need to use the diesel generators when the wind generation was insufficient to meet the full load. This saves up to 28,000 gallons of diesel from being used throughout the year [1].

Offset fuel can be considered a resilience metric in its own. In the long term, reduced reliance on fuel imports supports the energy independence of the community. However, advanced forecasting directly affects the preparation of the system for a hazard. Specifically, INL analyzed the performance of the system under a fuel shortage hazard due to delayed barge deliveries of diesel fuel. Deliveries could be delayed due to storms, and the river typically becomes impassable in August, but could become impassable early if winter sets in quickly. Any extra fuel reserves available due to the advanced forecasting would be valuable in this scenario. Another example is the St. Mary's extreme winter hazard, in which, very low temperatures created a larger load due to increased heating needs. Whatever load went above the production of the wind turbine had to be served by diesel. The inclusion of Sandia's advanced forecasting to limit the fuel used as spinning reserves could help reduce the overall fuel consumed, thus providing greater fuel reserves and increased generation capacity, which is a key resilience metric.

2.2 Inverter Features

2.2.1 Grid-forming inverters

In both the Iowa Lakes and St. Mary's resilience case studies, extreme hazards required the use of grid-forming inverters in order for distributed wind to provide any resilience benefits. In the St. Mary's case, we assumed that if the diesel generation was entirely unavailable, due to fuel shortage or burst pipeline, the wind would still be able to generate power, which would only be possible if it had a grid-forming inverter. A more likely case is that diesel generation would be degraded, due to fuel rationing or failure of certain generators, and that diesel generation could still be used as a grid-forming source for the turbine to follow. In the Iowa Lakes case study, we assumed that the transmission system was lost, but that a combination of battery storage and wind could continue to serve the local ethanol plants. This again assumes that either the battery or the wind inverters could act as grid-forming to create the islanded microgrid.

In general, for distributed wind and other DER, one of the biggest reasons that it can provide resilience is because it acts as a local source of energy, so when other sources of energy or resources are cut off, the distributed wind can still produce power locally. For this power to be consumed, there needs to be at least one grid-forming source.

2.2.1.1 Automatic islanding

Beyond the ability to grid-form, inverters that are capable of performing automatic islanding can provide even greater resilience benefits. Here, we define automatic islanding as the ability to detect that the grid-forming source has been lost and automatically switch from grid-following to grid-forming mode without dropping load in the process. This capability may not be solely defined by the inverter features, as it also relies on appropriate detection and isolation of the boundaries of the island. In the language of the IEEE 1547 standard, the island should be intentional, not unintentional, feeding only loads that have been previously identified as belonging to the planned microgrid. There should be no unplanned backfeeding.

The benefits of this capability include uninterrupted service to the connected local loads, resulting in smaller or nonexistent outage durations or loads lost and improved power quality.

2.2.2 Grid-supporting features

Grid-forming features are not the only controls that can enhance resilience; voltage and frequency support can also help enhance system performance when hazards are experienced. If distributed wind inverters can help provide voltage and frequency support during smaller disturbances, then they may be able to help keep the system stable enough that the disturbance is not exacerbated into a cascading event. Not only can this support help keep the overall system more stable, it can also help keep the local voltage and frequency stable enough that the distributed wind can ride through the disturbance and not trip off. Voltage support, frequency support, and ride-through capabilities are required under the most recent revision of IEEE 1547. However, the exact support provided by the resources can be variable based on the agreement between the utility and the asset owner.

2.3 Demand Response

A final control to consider is demand response. This control is not directly associated with distributed wind, but rather with the controllability of the local loads. It is worth noting here because of the impact that intelligent management of both loads and generation sources can have on the overall resilience of a system.

Demand response to enhance resilience can be managed in a number of ways. Loads can be prioritized as “critical” or “non-critical” and separated electrically so that the non-critical loads can be shut off. General electric consumption from all loads can be reduced, such as reducing the output of a manufacturing plant to reduce its overall load.

2.4 Metrics

In INL’s literature review of resilience metrics, one key finding suggested resilience metrics could be categorized in three dimensions: resolution, type, and maturity [2]. That second dimension, type, breaks metrics down into five categories: inputs, capacities, capabilities, performance, and outcomes [11]. Performance and outcome metrics are emphasized in many combined resilience indices or examinations of the resilience trapezoid. These metrics should not be discounted, but consideration of some of the other categories can provide alternative ways to understand resilience of distributed wind systems with advanced controls.

- **Inputs:** Input metrics define what resources are available to support resilience. On their own, inputs do not provide resilience, but if they are organized to support functions or tasks they can add resilience benefits. Both advanced forecasting and demand response can affect the inputs available. Fuel displacement and generation capacity would be examples of input metrics related to these controls.

- **Capacity:** Capacity metrics refer to the ways in which inputs are organized to support resilience. Demand response is particularly relevant here, as it represents an ability to alter the system in support of resilience when a hazard occurs. Grid-forming controls are also a capacity representing an ability to island the system and continue providing service locally during a hazard.
- **Capability:** Capability metrics reflect how well capacities can serve a system when they are needed. A capability metric related to grid-forming inverters could be whether the inverter has the ability to perform automatic island detection. Measuring voltage and frequency stability of a system during a disturbance can indicate if the grid-support functions (capacities) are working as intended (capabilities).
- **Performance and Outcomes:** The resilience of advanced controls is highlighted by all of the types of resilience metrics discussed, including performance and outcomes. Grid-support controls might be able to prevent outages or dropped load (outcome) on their own, but are even more powerful when combined with grid-forming controls. Demand response may result in not all load being served, but may result in shorter outage durations, keeping critical loads served, or better power quality, which are all measures of performance.

This breakdown serves to highlight metrics which can be used to validate the resilience benefits of advanced controls for distributed wind. Since resilience is a property unique to each system and its goals and hazards, it is useful to be able to communicate justifiable metrics that explain how advanced controls are supporting resilience.

3. HYBRID SYSTEM CONSIDERATIONS

Co-locating other generation sources with distributed wind can create hybrid systems, multiplying the resilience benefits from the distributed wind. One obvious way in which this occurs is through the addition of more generation capacity, increasing the potential load that can be served by the hybrid system. This better prepares a system for a potential hazard. Another key consideration of the resilience benefits of hybrid systems is the smoothing effect that a diversity of generation sources can have. By combining distributed wind with solar, battery, or even thermal generation sources, the overall variability of the hybrid plant can be reduced. This can lead to longer durations of uninterrupted power, maximal use of renewable resources to offset energy imports or fuel use, or shorter duration interruptions.

3.1 Wind Solar Complementarity

On face value, it may seem that a wind-solar hybrid system only benefits from the increased generation capacity of the system compared to a single resource on its own, but in the right locations and sized correctly, wind and solar can act as complimentary resources. NREL measured the complementarity of wind and solar resources across the United States over each month and over a full year, analyzed at an hourly scale and a daily scale for both time periods [7]. The monthly complementarity metrics help reflect seasonal complementarity and diurnal patterns. Results showed higher complementarity for the hourly-averaged results, indicating a need to use the hourly-scale analysis to fully realize the benefits of wind and solar in hybrid plants and demonstrating that wind and solar can balance each other throughout the day. Wind tends to blow harder at night, and solar obviously produces more power during the day. Monthly analyses results revealed that there is a seasonal variability in complementarity, meaning that the complementarity of wind and solar changes throughout the year, with highest complementarity in the summer, which may be in part due to the increase in solar irradiance during summer months.

While daily or even hourly complementarity is not a guarantee of smooth power production, it does suggest a reduction in the variability of the hybrid plant output compared to a single resource by itself. As discussed above, a reduction in variability can lead to shorter outage durations and fewer interruptions of power, which both represent a more resilient system.

3.2 Storage

Storage is a powerful resource to add to distributed wind. Storage can be used to smooth hybrid plant output, and is controllable, unlike solar, making it even more useful for smoothing hybrid plant output. Although it is controllable, storage on its own has limited benefits since it has a fixed capacity. However, in combination with distributed wind, a hybrid plant can control output and have a renewable generation source not dependent on external energy imports. Storage can help ensure that continuous loads are met even while distributed wind production is underperforming and help utilize distributed wind most efficiently by absorbing power when there is wind overproduction.

Additionally, storage inverters are more likely than distributed wind inverters to have grid-forming capabilities. As discussed in Section 2.1, grid-forming controls are a key part of resilience against extreme events that cause islanding conditions. If adding storage to a distributed wind system also brings grid-forming capabilities, resilience benefits are multiplied by the ability to form and island and recharge the grid-forming source.

3.2.1 Managing storage resources for resilience

It is important to note that while storage can be an important asset for resilience, there are operational tradeoffs for managing this resource as a resilience asset. If a system wanted to achieve maximum resilience with a wind-storage system, the battery should be charged to maximum capacity and maintained at that level until a hazard is experienced, guaranteeing that the battery will be able to provide as much generation support as possible during the hazard. However, if the battery is maintained at maximum capacity, then it cannot be used to serve other functions, such as peak shaving, reducing curtailment, or performing other grid-support capabilities.

It may be economically beneficial to use the battery for purposes other than resilience. However, if the system experiences a hazard unexpectedly and the battery is not favorably dispatched, for example if it is already discharged, then resilience benefits of the system may be forfeit, which may have high costs for the system. There needs to be a risks and benefits analysis for how to operate the wind-storage system. This analysis may be dynamic. For example, operators may choose to dispatch the battery for maximum economic benefits until the area experiences a hurricane warning, and then maximally charge the battery so that it can be used for resilience in the hurricane causes transmission outages.

Even certain resilience goals may sometimes be at odds. Maintaining a battery at maximum charge gives a system the most reserve capacity in the case of a loss of generation. However, to use Volt-Var or frequency support controls, the battery often needs at least a little leeway to charge or discharge in service of these functions. It is not possible to meet the operational needs for every resilience goal at every point in time.

3.3 Metrics

In the initial assessment of resilience metrics by INL, it was clear that there are many ways to measure resilience: direct, indirect, qualitative, quantitative, operational, infrastructure, singular, combined [2]. Certain metrics, particularly certain metrics of performance, are better suited to various system components. For example, load served, number of customers served, outage duration, or number of interruptions all directly measure the performance of the system, but some may be better suited than others to reflect resilience depending on the system and its resilience goals. For hybrid systems, we find that the following metrics are well-suited for evaluating the resilience of the system:

- **Time until first outage:** Combinations of resources can smooth the overall variability of the system, leading to uninterrupted power supplied by the hybrid system for a longer period of time. This metric affects the agility of the system with reference to the distribution and impact-resilience evaluation (DIRE) curve [12].

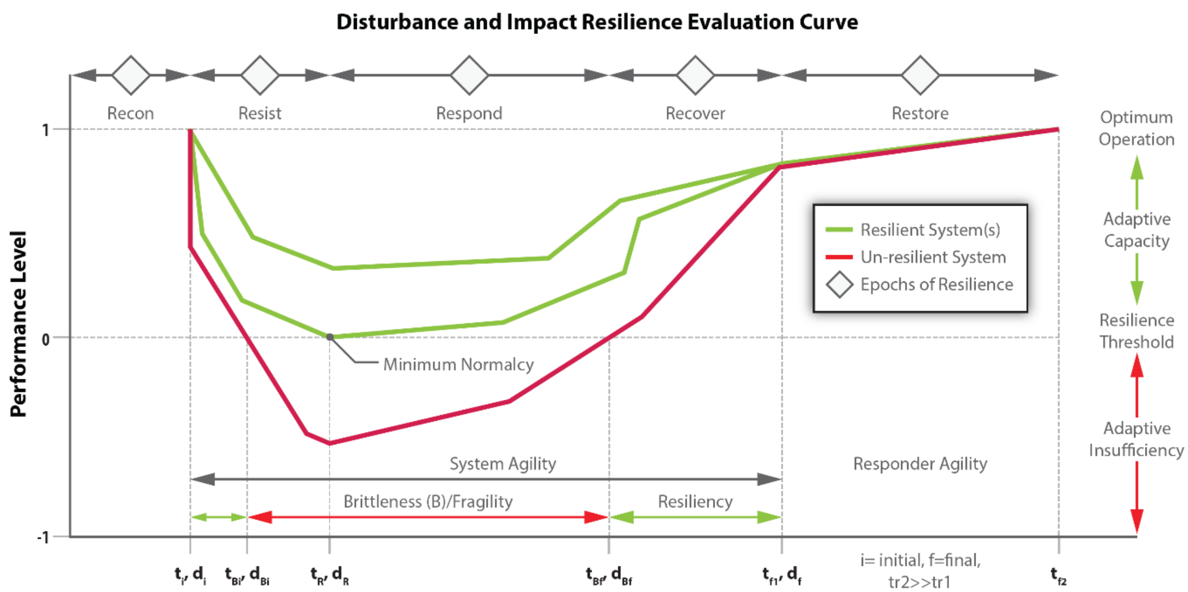

Figure 2: Disturbance and Impact Resilience Evaluation (DIRE) Curve

- **Generation capacity:** While a hybrid system doesn't necessarily mean that there is more generation capacity than if the system was built with a single resource, it often ends up this way. Pulling generation from different sources (i.e. wind, solar) can harness more energy from a single site than one resource alone. Energy storage requires a small footprint relative to other sources, but can significantly impact the capacity of the hybrid system. This metric corresponds to the steady-state adaptive capacity of the system, the sum of the apparent power capability within the system for all assets [13]. Increased apparent power capability provides an improved starting point at the beginning of a hazard, creating a greater buffer for the system before hitting the point of minimum normalcy and the resilience threshold.

- **Total load served:** Finally, performance on the DIRE curve can be measured in a number of ways. Total load served is a good, broadly-applicable metric to use for hybrid systems. Interruptions in power may still occur if a distributed wind hybrid system alone is being used to serve local load, whether a wind-solar hybrid, wind-storage hybrid, or a combination of all three resources. However, measuring total load served allows us to record the maximized use of all generated energy from all sources. This metric is best reflected in the adaptive capacity or adaptive insufficiency of the DIRE curve.

4. RISK EVALUATIONS

One of the key takeaways from the study of resilience in general, but specifically the resilience provided by distributed wind, distributed wind-hybrids, or distributed wind with advanced controls is that while there is always a way to design and operate the system for maximum resilience, this often comes at a cost. It may be an up-front investment, like an inverter with more features or sizing systems for maximum complementarity, or an ongoing cost, like trading off resilience for the most economically favorable dispatch.

The purpose of this section is to discuss a wholistic risk assessment perspective to inform the resilience mitigations that are put in place. Understanding the risk associated with a system can help inform how useful resilience mitigations, like using advanced control, hybrids, or operating plans, will be towards reducing that overall risk. The INL Resilience Framework includes a step for prioritizing resilience goals and identifying the most relevant hazards. This risk management framework was developed for MIRACL specifically around cyber incidents, but much of it can be expanded to general resilience scenarios to inform the steps of the resilience framework [14].

4.1 Framework for Risk Management

Risk is often defined by likelihood and consequence of an event happening.

$$Risk = Likelihood \ x \ Consequence$$

This relationship is often visualized as a risk matrix, like the one below.

		Consequence				
		Negligible 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
Likelihood	5 Almost certain	Moderate 5	High 10	Extreme 15	Extreme 20	Extreme 25
	4 Likely	Moderate 4	High 8	High 12	Extreme 16	Extreme 20
	3 Possible	Low 3	Moderate 6	High 9	High 12	Extreme 15
	2 Unlikely	Low 2	Moderate 4	Moderate 6	High 8	High 10
	1 Rare	Low 1	Low 2	Low 3	Moderate 4	Moderate 5

Figure 3: Risk matrix defined by likelihood and consequence

Resilience scenarios are often defined as high impact low frequency (HILF) events. The low frequency part often makes it difficult to assign actual values to assess how likely it is that a particular event will occur. Even if we have general likelihoods for events like hurricanes or floods, it is difficult to predict exactly how likely it is that a particular event with particular consequences will be. Moving away from the hazard and more towards the reliability metrics can sometimes help here. For example, most utilities will keep track of outages and failures, which can help define a general probability for a line being down, but this still doesn't directly address the challenge of predicting how the most impactful resilience scenarios might play out.

By further breaking down the "likelihood" component of risk, it becomes easier to assess the overall risk to the system.

$$Risk = Threat \ x \ Vulnerability \ x \ Consequence$$

The Likelihood component has been broken down into Threat and Vulnerability. Threat refers to the severity of the event that's occurring. This should not be confused with Consequence, which is the system's response to an event. For example, a tornado is a high Threat hazard, but if the entire system has underground lines instead of overhead lines, the Consequence will still be low.

Vulnerability refers to weaknesses or flaws in the design or implementation of a system. In relation to cybersecurity, this could refer to bugs in software or firmware or misconfiguration of firewalls. Under a broader perspective, a vulnerability could be a misconfigured relay, an undersized breaker, a worn out component, a rotted wooden pole or a number of other component level or system level flaws or weaknesses that contribute to the robustness of the system.

Finally, we can break down threat into more concrete concepts:

Threat = Intent x Capability x Opportunity

A threat may be intentional or unintentional, and intentional threats may have different objectives. Natural resilience hazards, like wind, temperatures, floods, freezing, etc., have no intent to cause damage. Considerations of resilience should not exclude intentional threats, both physical and cyber. Cyber threat actors may have a variety of objectives, from financial gain to destruction. Physical threat actors may range from vandalism up to chaos-sowing disruption [15].

Capability refers to the potential of the resilience hazard to cause damage. When discussing manmade hazards, this can refer to the time, resources, and skill an adversary has at their disposal. When discussing natural hazards, this can refer to the strength, type, and nature of the natural threat.

Opportunity refers the access a threat has to a system. A tornado in Kansas does not pose a threat to an electric system in Canada. Cyberattack opportunity can be classified by the exposed attack surface of the system. Physical attack opportunity can be thought of similarly in terms of the restrictions that are in place to guard certain access to certain locations or the general difficulty in accessing these places. For example, a remote wind system on a farm may not be well protected, but if it is difficult to get to physically, the threat of a physical attack goes down.

These breakdowns are not intended to objectively quantify all risks but are instead meant to help asset operators assess their overall risk to certain events occurring so that they can prioritize resilience mitigations and make smart investment decisions.

4.2 Risk Considerations for Advanced Distributed Wind

In the following sections, risk considerations that apply specifically to the wind-hybrid and wind-with-advanced-control scenarios are discussed. These considerations highlight the changes in risk components that are due to hybrids or advanced control, but they do not change the base risk that the system faces from the highest priority hazards.

The purpose of this section is to highlight the changes in risk, both positive and negative, that may come from implementing advanced wind systems so that the benefits of advanced wind systems can be fully maximized. The Intent and Capability components of threats are not likely to change based on the design of the system, so they are not discussed here.

4.2.1 Exposure Surfaces

Exposure surface, or opportunity, will be affected by the configuration of the distributed wind system. Typically, advanced controls will provide more capabilities, and this added complexity is likely to increase hazard exposure. There is more opportunity to maliciously or accidentally program settings wrong. The diversity of resources associated with distributed wind hybrid systems also has the potential to increase hazard exposure. There may be more interfaces to communicate with the various resource types, or even microgrid energy management systems (EMS).

While the increased complexity of these system does expose more potential interfaces and assets that can experience a hazard, note that it does not mean they are necessarily more exposed external threats.

Network protections may still be in place to limit access to interfaces, limiting exposure to cyber threats. Diversity of hybrid resources does not necessarily mean that the system is exposed to more types of hazards (i.e. weather patterns will remain the same), but it does mean that the hazards of interest may change. For example, cloudy days pose no threat to wind systems, but may lead to underperformance of solar assets, adding this hazard to risks of interest for the system.

4.2.2 Vulnerabilities

Like exposure surface, increased complexity of controls or physical assets has the potential to increase vulnerabilities. This is certainly not a guarantee, but it is reasonable to consider that as software and hardware bills-of-materials grow longer and systems become more complex, there is greater possibility for software bugs, misconfigurations, or poorly designed/manufactured components to make it in to the production system. Hybrid systems in particular should undergo rigorous testing to make sure they are configured correctly and will not behave unexpectedly in the face of a hazard.

Despite this potential increase due solely to the complexity of the system, there is also a possibility that vulnerabilities decrease. As controls become more advanced, it will be necessary to consider the use enhanced communication that might provide better protections (encryption, authentication) than traditional industrial control system (ICS) communications. The purpose of many advanced controls is to enhance the resilience and reliability of the system, so it is also reasonable that security and resilience will be considered during the development of controls.

4.2.3 Consequences

The increase in capability associated with advanced controls will also have an effect on potential consequences. If there are added capabilities meant to enhance the performance of the system if managed correctly, then it is likely that they can detract from performance if they are managed incorrectly or maliciously. Inverted Volt-Var settings and misconfigured grid-forming settings are an example of this. However, and more importantly, advanced controls have the potential to dramatically reduce consequences. In fact, that’s exactly what grid-support functions are designed to do. Grid-forming or demand response capabilities are designed in service or resilience objectives and can be put in place to protect the system against all kinds of hazards.

Hybrid systems can also reduce consequences of potential hazards through the diversification of resources. A hazard that impacts one resource may not impact another. For example, a distributed wind system may have to shut down during high gusts to avoid damage, but solar panels and batteries can supplement that lost generation, providing sufficient power for the load to remain online.

4.2.4 Combined Impact to Risk

While it is hard to say the exact change in risk without specifying details of the system and hazards it will face, it is likely that implementing hybrid systems or advanced controls will decrease the risk by mitigating the consequences of a hazard. These advanced systems may have slightly higher exposed surfaces, and the change in vulnerability may depend on the exact implementation of the system, but the known improvements in response and recovery to an event will likely offset any increase in risk. Note this is a qualitative approach, and conclusions may vary based on the priorities of the stakeholder assessing the system, but the framework still serves as a way to justify any assessments of risk.

5. Conclusion

In this report, we discussed the ways that resilience of a system with distributed wind is affected by the addition of other resources to create hybrid systems and by advanced controls. We showed that the benefits of these advanced features go beyond energy capacity and economic performance. They can significantly enhance the resilience of a system in combination with distributed wind. Examples of specific metrics that can be used to validate these resilience benefits and help justify the cost of upgrading a system are provided. We highlight not just single metrics, but how these metrics fit into all phases of resilience: prepare, detect, adapt, and recovery.

It is clear that there are resilience benefits from advanced distributed wind system, but the extent of these benefits and their place in a cost/benefit analysis may be hard to identify. To that end, the risk analysis framework can be used to explain how these upgrades will affect the overall risk of hazards to the system.

This report lays groundwork for future efforts to evaluate resilience benefits of advanced distributed wind systems. It can help ensure that appropriate metrics are used to capture the benefits of these systems in response to certain hazards, and to justify any perceived increases in risk due to the complexity of the new systems.

6. References

[1] J. Reilly, S. Barrows, M. Culler, C. Clark, J. Rane, B. Naughton, K. Mongird, A. Orrell and A. Baker, "Fiscal Year 2021 Isolated Grids and Grid-Connected Turbine Reference Systems: Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL)," National Renewable Energy Laboratory, Golden, CO, 2022.

[2] S. A. Bukowski, M. J. Culler, J. P. Gentle, J. C. Bell, C. R. Riger and E. Bukowski, "Distributed Wind Resilience Metrics for Electic Energy Delivery Systems: Comprehensive Literature Review," Idaho National Laboratory, Idaho Falls, ID, 2021.

[3] M. J. Culler, S. A. Bukowski, K. A. Hovland, S. Morash, A. F. Snyder, N. Placer and J. P. Gentle, "Resilience Framework for Electric Energy Delivery Systems," Idaho National Laboratory, Idaho Falls, ID, 2021.

[4] J. Reilly, R. Poudel, V. Krishnan, R. Preus, I. Baring-Gould, B. Anderson, B. Naughton, F. Wilches-Bernal and R. Darbali, "Distributed Wind Controls: A Research Roadmap for Microgrids, Infrastructure Resilience; and Advanced Controls Launchpad (MIRACL)," National Renewable Energy Laboratory, Golden, CO, 2021.

[5] Institute of Electrical and Electronics Engineers (IEEE), "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power SYstems Interface," IEEE, 2018.

[6] V. Gevorgian, M. Baggu and D. Ton, "Interconnection Requiremetns for Renewable Generation and Energy Storage in Island Systems: Puerto Rico Example," National Renewable Energy Laboratory, Golden, CO, Preprint. .

[7] C. E. Clark, A. Barker, J. King and J. Reilly, "Wind and Solar Hybrid Power Plants for Energy Resilience," National Renewable Energy Laboratory, Golden, CO, 2022.

[8] K. McCabe, A. Prasanna, J. Lockshin, P. Bhaskar, T. Bowen, R. Baranowski, B. Sigrin and E. Lantz, "Distributed Wind Energy Futures Study," National Renewable Energy Laboratory, Golden, CO, 2022.

[9] M. J. Culler, S. Bukowski, J. P. Gentle and C. K. Velasco, "Case Study: Applying the Idaho National Laboratory Resilience Framework to Iowa Lakes Electric Cooperative Distributed Wind Systems," Idaho National Laboratory, Idaho Falls, ID, 2022.

[10] M. J. Culler, S. Bukowski, J. P. Gentle and C. K. Velasco, "Case Study: Applying the Idaho National Laboratory Resilience Framework to St. Mary's, Alaska," Idaho National Laboratory, Idaho Falls, ID, 2022.

[11] H. H. Willis and L. Koa, "Measuring the Resilience of Electric Distribution Systems," RAND Corporation, Santa Monica, CA, 2015.

[12] K. Eshghi, B. K. Johnson and C. G. Rieger, "Power system protection and resilient metrics," in *2015 Resilience Week (RWS)*, Phyliadelphia, PA, 2015.

[13] C. G. Rieger and T. R. McJunkin, "Electricity distribution system resilient control system metrics," in *2017 Resilience Week (RWS)*, Wilmington, DE, 2017.

[14] M. J. Culler, S. Morash, B. Smith, F. Cleveland and J. Gentle, "A Cyber-Resilience Risk Management Architecture for Distributed Wind," in *2021 Resilience Week (RWS)*, Salt Lake City, UT, 2021.

[15] N. Sganga and B. Dakss, "Domestic extremists have plotted to disrupt U.S. power grid, DHS bulletin warns," CBS Nes, 26 January 2022. [Online]. Available: https://www.cbsnews.com/news/domestic-violent-extremists-plotting-disrupt-us-power-grid-dhs-bulletin-warns/.

[16] National Institute of Standards and Technology, "Framework for Improving Critical Infrastructure Cybersecurity," National Institute of Standards and Technology, 2018.