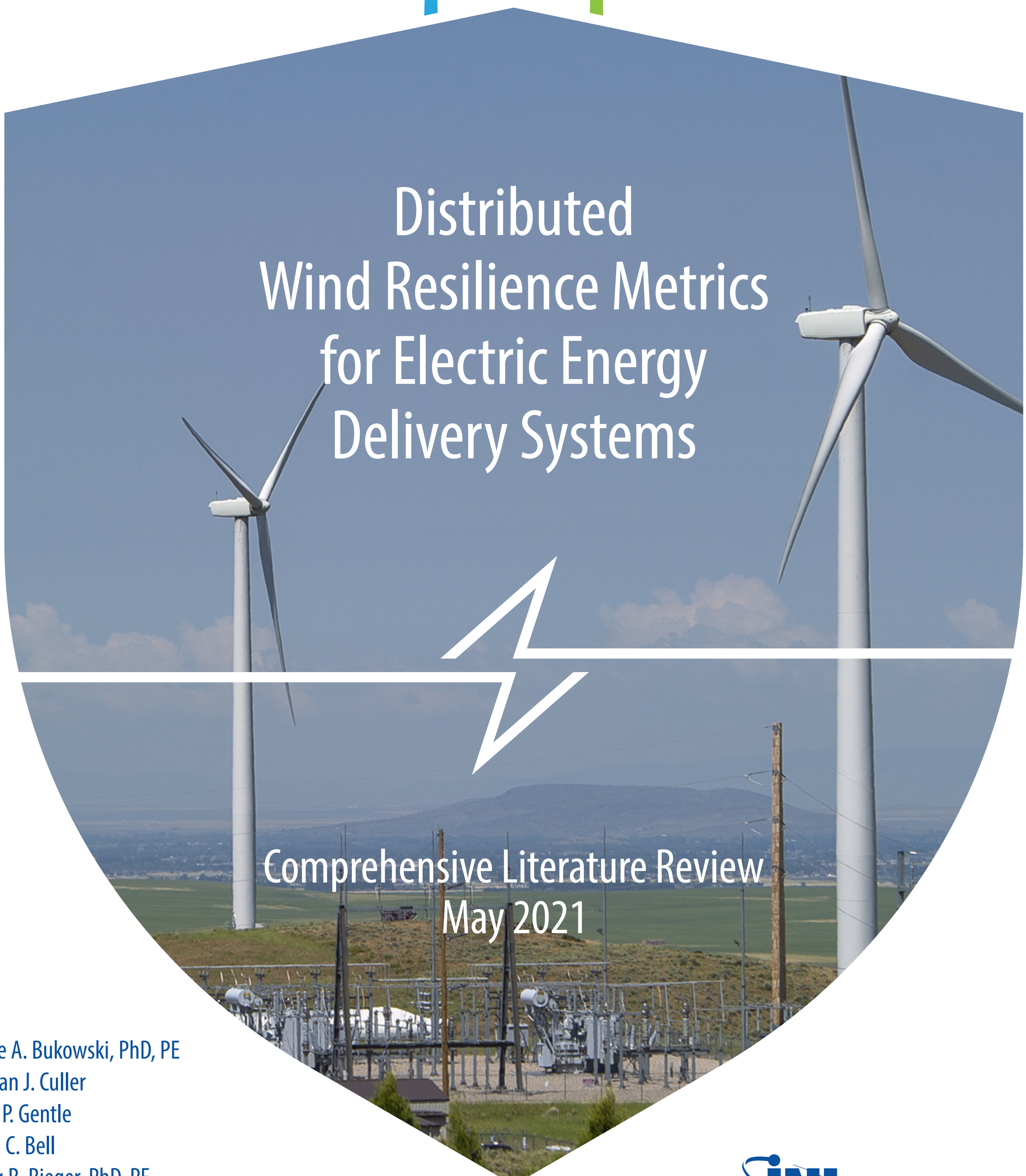

Distributed Wind Resilience Metrics for Electric Energy Delivery Systems

Comprehensive Literature Review

May 2021

Steve A. Bukowski, PhD, PE
Megan J. Culler
Jake P. Gentle
John C. Bell
Craig R. Rieger, PhD, PE
Everett Bukowski

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC
INL/EXT-21-62149

Steve A. Bukowski, PhD, PE
Researcher, Idaho National Laboratory

Megan J. Culler
Graduate Fellow, Idaho National Laboratory

Jake P. Gentle
Program Manager, Idaho National Laboratory

John C. Bell
Junior Power Engineer, Idaho National Laboratory

Craig R. Rieger, PhD, PE
Chief Control Systems Research Engineer, Idaho National Laboratory

Everett Bukowski
Undergraduate Intern, Idaho National laboratory

ACKNOWLEDGEMENTS

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

The Wind Energy Technologies Office – Patrick Gilman and Bret Barker

Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) partners:
- Sandia National Laboratory
- Pacific Northwest National Laboratory
- National Renewable Energy Laboratory

Iowa State University – Anne Kimber and Nick David

EnerNex – Brian Smith, Sean Morash

National Laboratories:
- Sandia National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest National Laboratory
- Argonne National Laboratory
- Lawrence Livermore National Laboratory
- Lawrence Berkeley National Laboratory
- National Renewable Energy Laboratory

Photo acknowledgements:
Cover – C. Morgan, INL, Idaho Falls, ID
Page iii – E. Bukowski, INL, Idaho Falls, ID

SUMMARY

While most people have a general concept of what it means to be "resilient," an examination of definitions from different sources reveals that there are key commonalities, but key differences as well. The lack of a generally accepted definition and application of resilience extends to electric energy delivery systems. Without an accepted definition, it is difficult to implement programs or processes to improve resiliency. In this paper, existing work from industry, regulatory bodies, and national laboratories to define and apply resilience to electric energy delivery systems is studied to understand the key components to define resilience and better understand associated metrics. This understanding is then applied to distributed wind for a specific example of how resilience of a system is affected by the technologies and generation sources used to support it.

A key finding is that there is no "one size fits all" process for resilience. Each system has a "distinctiveness" characteristic, which qualifies the possibility of differences in resilience due to different threats, geography, stakeholders, risk tolerance, and mitigations. The distinctiveness characteristic extends to distributed wind technologies and applications where different configurations may lend the distributed wind assets to contribute to the resilience of each system in a variety of ways.

The findings of this research demonstrate the need for a resilience framework that can be readily applied by stakeholders to improve resilience based on the specific system, threat, risk tolerance and stakeholders.

GE 1.6MW wind turbine east of Idaho Falls, ID

PREFACE

A simple examination of the hitsearch results for "resilience" on scholar.google.com covering the years 1980 to 2020 produces an interesting story. The results show a peak of hits in 2016, which represents 98 times as many hits as were found for 1980 and approximately four times as many as 2000. (Note: increased digital access to published works [via communications and personal computers] and the number of people publishing might explain the strong correlation to the increases as population and technology advanced from 1980 to 2020.) However, the number of hits fell following the peak in 2016 down to 2008 levels, representing a significant decline (Figure 1). A similar trend is seen with a more constrained search of "resilience power systems" and "resilience grid." However, when one examines the results from another simple search for "cybersecurity" with the same parameters, a normalized comparison shows that cybersecurity does not have a similar decline but rather continues to increase year after year. What might this reduction of resilience publications represent? One could infer that perhaps the resilience discussion has been solved robustly and does not necessarily command the focus in research that it had previously. An alternative line of thinking is that, given much of the work, policy will drive resilience, and differences in policy objectives from 2008 to 2016 versus those from 2016 to 2020 might explain this sharp decline. Whatever the reason for the recent decline in resilience research, the issue remains that there does not seem to be standardized definitions and metrics for resilience in the energy industry.

> **"Whatever the reason for the recent decline in resilience research, the issue remains that there does not seem to be standardized definitions and metrics for resilience in the energy industry."**

The initial goal of this research was to assess the impact of distributed wind on the resilience of an electrical system. However, when developing boundaries to this question, roadblocks prevented the development needed to proceed. These roadblocks included the lack of:

- An accepted definition of resilience and of resilience relating to an electrical energy delivery system (EEDS)
- Accepted metrics for resilience, including resilience of an EEDS
- Industry best practices relating to resilience of an EEDS
- Accepted and well-practiced approaches to examine metrics, benefits, and valuation for resilience of an EEDS.

A seemingly straightforward question about resilience and the effect of distributed wind exposed the need for a larger investigation to establish a foundation for evaluation within small EEDSs. Initial investigations into these questions revealed a much broader problem – the problem of defining resilience in general and resilience of an EEDS – that required examination before distributed wind's contribution could be addressed.

This paper aims to create a foundation to answer two questions:

1) What characteristics about distributed wind affect the resilience of the power systems they inhabit?
2) What potential metrics exist that can be adapted to measure distributed wind's impact on the resilience of an electrical energy distribution system (EEDS)?

To do this, the investigation will emphasize the current state of resilience, including its alignment with risk-management strategies, definitions, and metrics. After solidifying an understanding of resilience for EEDS, the application to distributed wind will be discussed.

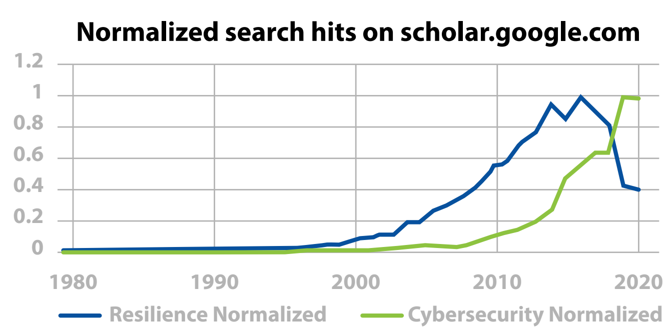

Figure 1. Normalized search hits for "resilience" and "cybersecurity" on Google Scholar.

INTRODUCTION

While reliability is a long-standing pillar of the electric energy industry, resilience has recently emerged as an equally important goal to protect against disruptive events. Historically, the focus has been on preventing disruptive events to maintain high levels of reliability. However, the community now recognizes that it is not possible to prevent all natural and manmade threats for any systems. Hence, resilience, a quality that focuses as much on the response to and recovery from disruptive events as it does preparation and prevention, is recognized as something electrical energy stakeholders need to actively consider.

The Department of Energy's (DOE's) Wind Energy Technologies Office (WETO) has funded the Microgrids, Infrastructure, Resilience, and Advanced Control Launchpad (MIRACL) project to investigate the ways that distributed wind can add resilience to energy systems, and how the distributed wind systems themselves can be resilient. To investigate this question, an understanding of what resilience of energy systems meant was required. A review of relevant literature revealed that there was not a common definition or measurement process for resilience in electrical energy delivery systems (EEDS), and in fact, there was not a common definition for resilience in general. Thus, in order to assess the impact that distributed wind technologies and applications have on the resilience of energy systems, these definitions of resilience and their application to EEDS must first be established.

ELECTRIC ENERGY DELIVERY SYSTEM (EEDS)

This document defines the term EEDSs to describe interconnected resources and assets, operational aspects, and stakeholders that ensure delivery of electrical energy. This definition covers most terms associated with the use of electricity. It is intentionally broad in order to cover traditional and new technologies, bulk power systems, transmission infrastructure, distribution systems, and even distributed and isolated systems with technologies like distributed wind in various microgrid configurations.

As seen in Figure 2, assets, operational aspects, and stakeholders are specifically called out for their importance to the EEDS. Assets represent the physical components that form an EEDS, but they are only one part of the whole EEDS picture. Operational aspects cover processes, people, and supporting resources like supply and maintenance. These can be thought of as the critical parts in motion that keep the EEDS functioning. Finally, the stakeholders represent the parties that have interests in keeping the EEDS operational and delivering a certain quality of service. These are the critical people and organizations that will make decisions about operations, policies, and planning.

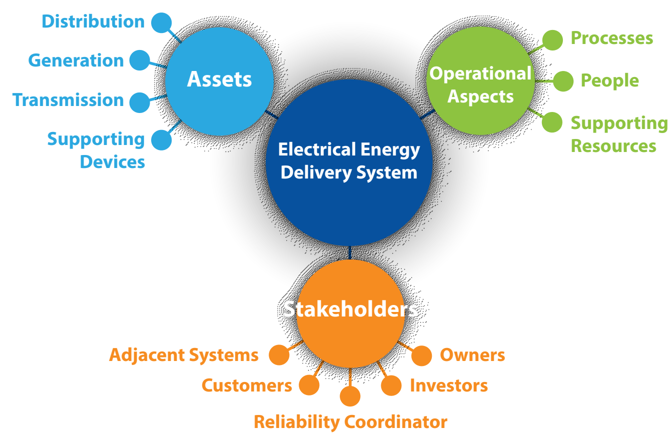

Figure 2. Components of an EEDS.

Each of the components of an EEDS will play roles in determining the resiliency of the system. It is important to see how they all work together to understand how a system's resilience can change in response to different conditions and disturbances.

DISTRIBUTED WIND

Distributed wind systems can be thought of as individual EEDSs themselves and can also be thought of as part of larger, connected EEDSs. There are assets, operational aspects, and stakeholders associated with each distributed wind system, regardless of its application or configuration. If connected to a larger system, all of the EEDS components will have to coordinate with their counterparts for the larger system to effectively evaluate, measure, and improve resilience.

DOE WETO defines distributed wind based on a wind plant's location relative to end use and power-distribution infrastructure, rather than by technology or project size.[1] Wind turbines that are installed at or near the point of end use—so that the turbine helps meet onsite energy demand or supports the operation of the existing distribution grid—are said to be in close proximity to end use; thus, they are classified as distributed wind. Wind turbines that are connected on the customer side of the meter (behind-the-meter), directly to the distribution grid, or are off-grid in a remote location are said to be distributed-wind installations (Figure 3). Distributed-wind-energy systems can be used in residential, agricultural, commercial, industrial, and community applications. They can range in size from 5 kW to multimegawatt turbines. In fact, 87.22% of new distributed-wind capacity installed in 2018 came from projects using large-scale wind turbines (greater than 1 MW in size).[2]

The DOE found that distributed wind systems could feasibly be installed on approximately 49.5 million residential, commercial, or industrial sites, or about 44% of all U.S. buildings.[3] In addition, the DOE Office of Energy Efficiency and Renewable Energy publishes an annual Distributed Wind Market Report that, in 2018, reported cumulative U.S. distributed wind capacity installed from 2003 to 2018 as 1,127 MW from over 83,000 wind turbines across all 50 states.[4] Preliminary data from 2019 puts this number at 1,145 MW from over 85,000 wind turbines.[2] This shows that there is a meaningful opportunity for distributed wind to play an increasing role in the U.S. electricity sector (Figure 3). The growing role of distributed wind creates the need to define and analyze resilience in distributed wind energy systems. Small wind (up to 100 kW) and large wind (>1000 kW) projects continue to make up the largest part of the distributed-wind market (Figure 4).[4] This means any consideration of resilience must be adaptable to a wide range of applications. Utilities make up the bulk of new large wind projects to serve local distribution grids, followed by industrial and government applications. Although utilities make up the largest share of these projects, they are not the only stakeholders of interest, so resilience definitions must consider the needs and goals of different stakeholders. An understanding of current uses, capacities, and projections for distributed wind can inform the requirements for resilience that must be established.

[1] DOE-WETO, *Distributed Wind*. Retrieved from https://www.energy.gov/eere/wind/distributed-wind, 2020.

[2] Orrell, A., D. Preziuso, S.Morris, J. Homer, 2019 Distributed Wind Data Summary, Richland, WA: Pacific Northwest National Laboratory. Retrieved from https://www.energy.gov/eere/wind/2019-wind-energy-data-technology-trends, 2020.

[3] Lantz, E., B. Sigrin, M. Gleason, R. Preus, an I. Baring-Gould,. *Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects*. Golden, CO: National Renewable Energy Laboratory, 2016.

[4] Orrell, A., D. Preziuso, S. Morris, J. Homer, and N. Foster, N. *2018 Distributed Wind Market Report*. Richland, WA: Pacific Northwest National Laboratory 2020.

Image courtesy of the Pacific Northwest National Laboratory.

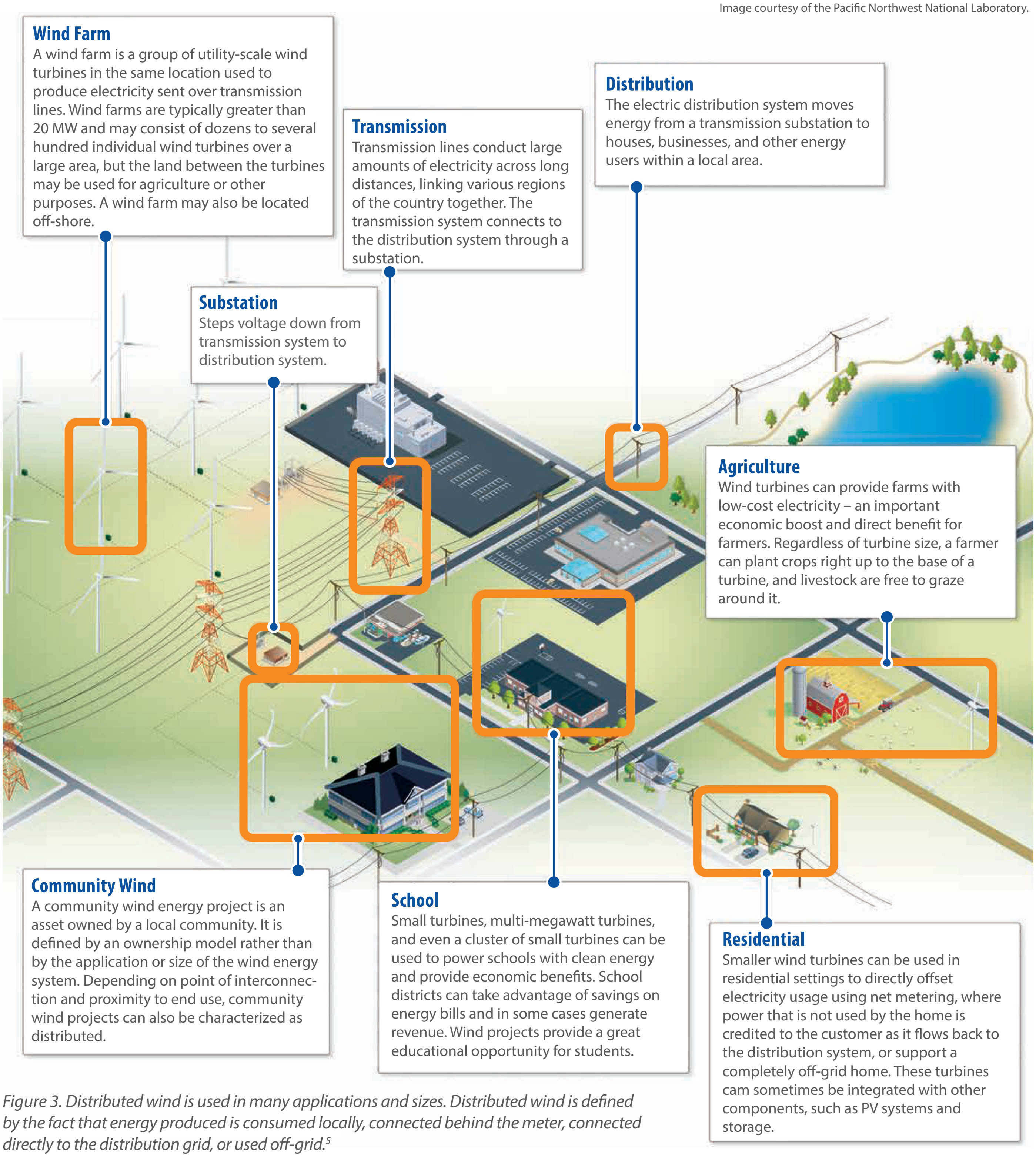

Figure 3. Distributed wind is used in many applications and sizes. Distributed wind is defined by the fact that energy produced is consumed locally, connected behind the meter, connected directly to the distribution grid, or used off-grid.[5]

[5] *Enabling Wind to Contribute to a Distributed Wind Future*, IEA Wind Task 41, retrieved from https://community.ieawind.org/task41/home

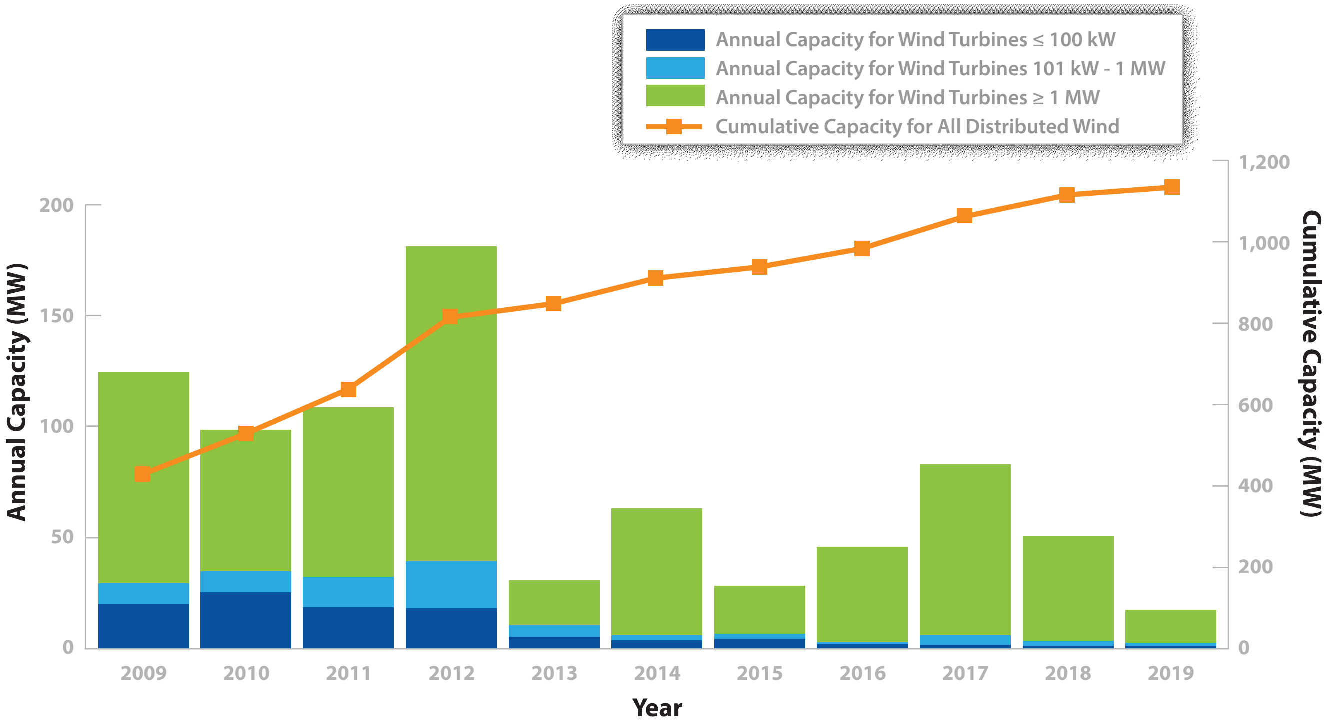

Figure 4. Annual installed and cumulative capacity of distributed wind in the U.S. from 2009 to 2019.[2]

METHODOLOGY FOR RESILIENCE

In this work, we first consider the current definitions of resilience, then the application of resilience to EEDSs, and conclude with a clear definition of resilience that can be applied to distributed wind.

As stated in the preface of this report, the initial question of this research was the impact of distributed wind on the resilience of an isolated electrical system. However, when developing boundaries to this question, roadblocks prevented the development needed to proceed. These roadblocks included the lack of:

- An accepted definition of resilience and of resilience relating to an EEDS
- Accepted metrics for resilience, including resilience of an EEDS
- Industry best practices relating to resilience of an EEDS
- Accepted and well-practiced approaches to examine metrics, benefits, and valuation for resilience of an EEDS.

These issues are reflected in two recent documents, created by the DOE and the Federal Energy Regulatory Commission (FERC). Both the DOE request for information (RFI) for guidance on enhancing resilience[6] and the FERC Notice of Proposed Rule (NOPR) on Resilience[7] (Federal Energy Regulatory Commission, 2017) in 2018 and 2019 demonstrate that resilience is not mature throughout the energy sector.

To understand the impact of distributed wind, we began by examining the existing state of the literature to understand published research and, in particular, published work around the resilience of EEDSs. Based on a lack of industry-accepted approaches, definitions, and practices surrounding resilience,

[6] Walker, Bruce J. "Codes, Standards, Specifications, and Other Guidance for Enhancing the Resilience of Electric Infrastructure Systems Against Severe Weather Events," Energy.gov. June 28, 2019. Retrieved Nov 2020, from https://www.energy.gov/sites/prod/files/2019/09/f67/DOE%20OE%20RFI%20Guidance%20for%20Resilience%20of%20Electric%20Grid%20System%20July%202019.pdf

[7] Federal Energy Regulatory Commission, Docket No. RM18-1-000. Washington D.C.: FERC, 2017.

research focused on the published work on resilience at the U.S. DOE national laboratories. After gathering the most-instrumental published works to date from each of the main national laboratories, the team worked to analyze gaps and similarities and identify and examine the differentiating characteristics of their definitions of resilience as it relates to EEDSs. This analysis formed a basis to study other challenges that have technical overlap, such as reliability and even cybersecurity. The analysis was then used to identify characteristics of resilience examined on the function, operations and assets of an EEDS.

One key finding while defining resilience for EEDS was that resiliency does not have a "one size fits all" quality. We call this characteristic "distinctiveness" of the system, which prevents a single universal measure of resilience. Based upon this distinctiveness quality we identify two categories of resilience metrics: direct metrics that can "directly" support the resilience trapezoid for a system and indirect metrics that apply to any aspects of threat, risk, and mitigation a set of stakeholders find important. Generally, direct metrics are associated with the time and ability of the system to recover to a final state, and indirect metrics apply to aspects important to the stakeholders, which eventually support the direct metrics of recovery.

Finally, the information learned about resilience for EEDS is applied to distributed wind, fulfilling the initial goal of this work. Key characteristics of distributed wind that make it a good asset to add resilience to systems are identified. Advances in technology to make the wind assets themselves even more resilient are also discussed. This work concludes with a discussion of future research that can apply the definitions and metrics for distributed wind resilience established here to create a cyclical process or framework that will aid organizations in actively evaluating and improving their system's resiliency.

It should be noted that in the middle of the literature-review process, two reports were published that provided a strong analysis and support to the foundational questions initially being asked. These reports were:

- Resilience Framework, Methods, and Metrics for the Electricity Sector, prepared by the Institute of Industrial and Electronics Engineering (IEEE) Power & Energy Society Industry Technical Support Leadership Committee Task Force[8]
- Sandia's Integrated Methodology for Energy and Infrastructure Resilience Analysis (SAND 2020-10121 report).[9]

This work builds on these reports to examine some of the foundational discussion areas related to resilience of an EEDS while providing a direction for a repeatable methodology to apply a resilience lens to an EEDS while including stakeholders, developing quantifiable metrics, and providing analysis to those metrics.

[8] IEEE Power and Energy Society Industry Technical Leadership Committee Task Force, *Resilience Framework, Methods, and Metrics for the Electric Sector*, IEEE PES., Nov 2020.

[9] Wachtel, A. M., K. A. Jones, M. J. Baca, and E. O'Neill-Carrillo, *Sandia's Integrated Methodology for Energy and Infrastructure Resilience Analysis*, Albuquerque, NM: Sandia National Laboratories, 2020.

DEFINING RESILIENCE

Before diving into resilience for EEDS, basic definitions of resilience are explored. We perform two steps:

1) Evaluate current definitions in industry and government.

2) Contextualize commonalities in existing definitions.

These steps help develop a concrete application-agnostic definition of resilience.

STEP 1: EVALUATION OF CURRENT DEFINITIONS IN INDUSTRY AND GOVERNMENT

The common understanding of resilience implies the ability of a system to return to a normal condition after the occurrence of an event which affects the original state. Resilience comes from the from Latin resiliare ("to leap or spring back; to rebound"). Hence, resilience can be applied to an unlimited range of domains and fields. We seek to define resilience in today's general uses and meaning and refine it to apply to EEDSs. As noted in many resilience documents, there has yet to be consistent acceptance of one resilience definition. One researcher stated, "the term itself (resilience) carries such a broad range of meanings that it can be difficult to validate or generalize what effective resilience means in practice."[10]

"...the term itself (resilience) carries such a broad range of meanings that it can be difficult to validate or generalize what effective resilience means in practice."[10]

"The plethora of ambiguous definitions for 'resilience' blur the path for the development of consistent resilience metrics."[11]

Another wrote, "The plethora of ambiguous definitions for 'resilience' blur the path for the development of consistent resilience metrics,"[11] and "The review of resilience definitions indicates that there is no unique insight about how to define the resilience; however, several similarities can be observed across these resilience definitions."[12]

FERC Dockets AD18-7-000 and RM18-1000 are specific to electrical-energy delivery. In them, FERC seeks a definition for resilience that is related to electricity.[13] The DOE RFI also requests clearly defined guidelines on enhancing the resilience of the electricity system.[14]

[10] Fox-Lent, C., L. Read, C. R. Allen, J. C. Arnott, E. Bellini, J. Coaffee, and M. R. Tye, "Tiered Approach to Resilience Assessment", Risk Analysis 38, 2019: 1772–1780. 10.1111/risa.12991

[11] Morash, S., and A. F. Snyder, "Toward Developing Metrics for Power Systems Resilience", Enernex, 2020.

[12] Hosseini, S., K. Barker, and J. E. Ramirez-Marquez, "A Review of Definitions and Measures of System Resilience," Reliability Engineering and System Safety 145, 2016: 47–61.

[13] FERC, Docket No. RM18-1-000. Washington D.C.: FERC, 2017.

[14] Walker, Bruce J. "Codes, Standards, Specifications, and Other Guidance for Enhancing the Resilience of Electric Infrastructure Systems Against Severe Weather Events," Energy.gov. June 28, 2019. Retrieved Nov 2020, from https://www.energy.gov/sites/prod/files/2019/09/f67/DOE%20OE%20RFI%20Guidance%20for%20Resilience%20of%20Electric%20Grid%20System%20July%202019.pdf

Despite the lack of consensus on resilience definitions, or perhaps because of it, work on resilience is broadly undertaken today, with an almost unanimous nexus for discussion around climate change and its effects on human society, infrastructure, and daily life. Thus, it is the high-impact events, with generally lower probability (though, arguably, probability is increasing) that raise the question of resilience.

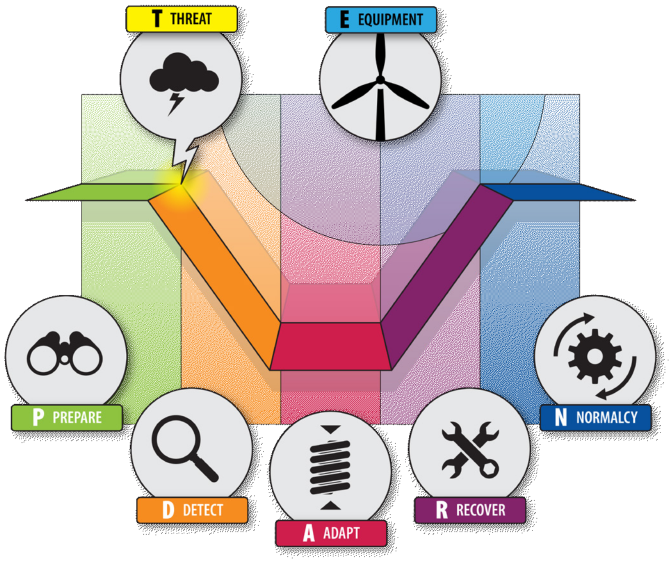

Figure 5: Key elements in resiliency definitions

Several definitions of resilience have been offered and adapted over time, and many are similar, although many definitions overlap with a number of already existing concepts such as robustness, fault-tolerance, flexibility, survivability, and agility. Many national governments have developed definitions and policies relating to resilience to attempt to move towards that capability, while industry and academia have also developed definitions that reflect resilience in different domains (environmental sciences, psychology, ecology, business, and economics).

The goal of this section is to extend the definition to resilience of EEDSs, applying the concept via a defined methodology for distributed wind in an isolated grid. The first step toward achieving this is to examine the overlap among and gaps between definitions of resilience. Note that some definitions provided are more specifically related to EEDSs by virtue of the industry, institution, or government office.

The definitions and descriptions found for resiliency are included in Table 1. The third column indicates which key themes are present in each definition. These themes are:

- P Ability to **prepare** for or anticipate a disruption
- D Ability to **detect** a disruption
- A Ability to **adapt**, whether to absorb, withstand, resist, or endure a changing condition; agility, fault-tolerance, flexibility
- R Ability to **recover**, often used with a time reference of rapidly or quickly or reasonable amount of time; survivability
- N Return to an acceptable level of **normalcy**, functioning, and/or acceptable return state.
- T The **threat**, disruption, and/or event
- E **Equipment**, operational components, and human components that can be used in multiple stages of resiliency.

As seen in Figure 5: Key elements in resiliency definitions, some of these key themes are temporally related actions (prepare, detect, adapt, recover, return to normalcy) taken by organizational actors. The threat or disruption is temporally related to these options, but externally controlled. These temporal elements bear strong resemblance to the elements of the resilience trapezoid, a resilience model used by IEEE and discussed later in the report. Finally, equipment, components, and humans are all actors that can be used across all of the other themes.

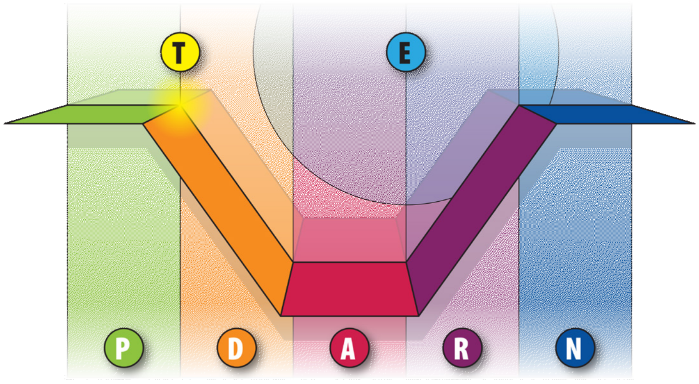

Figure 6: Reference for key elements of resilience definitions

Table 1: Definitions and descriptions of resiliency by government source. See Figure 6 for reference.

Type	Origin	Definition	P	D	A	R	N	T	E
Government	United States[a]	"ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption."	P		A	R		T	
Government	Presidential Policy Directive 21 (PPD-21)[b]	"the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions."	P		A	R		T	
Government	United Kingdom[c]	"[a]bility of the community, services, area or infrastructure to detect, prevent, and, if necessary, to withstand, handle and recover from disruptive challenges."	P	D	A	R		T	E
Government	Canada[c]	Although no single official definition is available, government agencies use roughly the same definition throughout, making only slight adaptations and specifications in different contexts. In the "Federal Policy for Emergency Management" (2009), resilience is defined as "[t]he capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure."			A		N	T	E
Industry and Regulatory	Federal Energy Regulatory Commission proposed definition[d]	"The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."	P		A	R		T	
Industry and Regulatory	Pennsylvania, Jersey, Maryland Power Pool (PJM) Interconnection suggest replacement to FERC's proposed definition[e]	"The ability to withstand or reduce the magnitude and/or duration of disruptive events, which includes the capability to identify and mitigate vulnerabilities and threats, and plan for, prepare for, absorb, adapt to, and/or recover from such an event." Note that the word "rapidly" has been omitted, while the phrase "identify and mitigate vulnerabilities and threats" has been added.	P	D	A	R		T	
Industry and Regulatory	PJM Interconnection's Working Definition[f]	"The ability to withstand or quickly recover from events that pose operational risk."				R		T	E
Industry and Regulatory	Bilal M. Ayyub[g]	"Resilience notionally means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from disturbances of the deliberate attack types, accidents, or naturally occurring threats or incidents…."	P		A	R		T	
Industry and Regulatory	Department of Energy[h]	"The ability of a power system and its components to withstand and adapt to disruptions and rapidly recover from them."			A	R		T	

Type	Origin	Definition	P	D	A	R	N	T	E
Industry and Regulatory	North American Transmission Forum (NATF)[h]	"The ability of the system and its components (i.e., both the equipment and human components) to minimize damage and improve recovery from non-routine disruptions, including high impact, low frequency (HILF) events, in a reasonable amount of time."				R		T	E
	Public Service Enterprise Group Companies (PSEG)[i]	"The ability to withstand or reduce the magnitude and/ or duration of potential highly disruptive events, whether anticipated or unanticipated." Resiliency includes the capability to identify vulnerabilities and threats that could be highly disruptive, the capability to identify practices that will increase robustness against unanticipated vulnerabilities and threats that could be highly disruptive, and the capability to prepare for, mitigate, absorb, adapt to, and/or timely recover from a highly disruptive event.	P	D	A	R		T	
	The IEEE Technical Report PES-TR65[h]	"The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."	P		A	R		T	
	National Association Regulatory Utility Commissioners (NARUC)[j]	"the ability of the system to anticipate, absorb, recover from, and adapt to disruptive events, particularly high-impact, low-frequency events"	P		A	R		T	
National	Pacific Northwest National Laboratory (PNNL)[k]	"the ability to withstand grid stress events without suffering operational compromise or to adapt to the strain so as to minimize compromise via graceful degradation. It is in large part about what does not happen to the grid or electricity consumers"			A			T	
	Sandia National Laboratory (SNL)[l]	"the ability to reduce effectively both the magnitude and duration of the deviation from targeted system performance levels" (Vugrin, Drake, Ehlen, & Camphouse, 2010)			A			T	
	Los Alamos National Laboratory (LANL)[b]	uses the Presidential Policy Directive 21 definition of resilience, "The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.	P		A	R		T	

Type	Origin	Definition	P D A R N T E
National	National Renewable Energy Laboratory (NREL)[m]	"The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions."	P A R T
National	Idaho National Laboratory (INL)[n]	"A resilient control system is one that maintains state awareness and an accepted level of operational normalcy in response to disturbances, including threats of an unexpected and malicious nature"	P D N T
National	Argonne National Laboratory (ANL)[o]	"the ability of an entity – e.g., asset, organization, community, region – to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance"	P A R T

[a] Department of Homeland Security, *DHS Risk Lexicon*, Washington D.C.: US Government, 2010.

[b] Presidential Executive Order, "Presidential Policy Directive 21: Critical Infrastructure Security and Resilience," Washington D.C.: US Government, 2013.

[c] Bara, C., and G. Bronnimann, "Risk Analysis Resilience—Trends in Policy and Research," Zurich. 2011. 10.3929/ethz-a-007334437.

[d] FERC, *18 CRF Part 35 Docket No. RM18-1-000*. October 10, 2017. Retrieved Nov 5, 2020, from https://www.govinfo.gov/content/pkg/FR-2017-10-10/pdf/2017-21396.pdf

[e] PJM Interconnection, LLC, "PJM Comments to FR DOC 2019-14547 DOE RFI Codes, Standards, Specifications, and Other Guidance for Enhancing the Resilience of Electric Infrastructure Systems Against Severe Weather Events," 2018. Retrieved Nov 22, 2020, from https://energy.gov/sites/prod/files/2019/12/f69/PJM%20Response%20to%20Grid%20RFI.pdf

[f] Monken, Jonathon, insideline.pjm.com, Dec. 2018. Retrieved Nov 2020, from https://pjm.com/-/media/committees-groups/committees/mrc/20181220/20181220-item-10-pjm-resilience-update-presentation.ashx#:~:text=PJM's%20Working%20Definition%3A%20The%20ability,events%20that%20pose%20operational%20risks.

[g] Ayyub, B. M. "Systems Resilience for Multihazard Environments: Definitions, Metrics, and Valuation for Decision Making," Risk Analysis 34, no. 2, 2013: 340–355.

[h] IEEE Power and Energy Society Industry Technical Leadership Committee Task Force, Resilience Framework, Methods, and Metrics for the Electric Sector. IEEE PES, Oct 2020.

[i] PSEG, *Motion to Intervene and Reply Comments of the PSEG Companies*. Washington D.C.: FERC, 2018.

[j] Keogh, M., and C. Cody, *Resilience in Regulated Utilities*, Washington D.C.: National Association of Regulatory Utility Commissioners, 2013.

[k] Taft, J., *Electric Grid Resilience and Reliability for Grid Architecture*. Richland, Washington: Pacific Northwest National Laboratory, 2017.

[l] Vugrin, E. D., W. E. Drake, M. A. Ehlen, and C. R. Camphouse, "A Framework for Assessing the Resilience of Infrastructure and Economic Systems," in K. Gopalakrishnan and S. Peeta (eds) *Sustainable and Resilient Critical Infrastructure Systems*, Springer, Berlin, Heidelberg, 2010: 77–116. 10.1007/978-3-642-11405-2_3.

[m] Stout, S., N. Lee, S. Cox, J, Elsworth, and J. Leisch, "Power Sector Resilience Planning Guidebook: A Self-Guided Reference for Practitioners", NREL, 2019.

[n] Rieger, C. G. *Resilient control systems Practical metrics basis for defining mission impact*, Denver: IEEE, 2014.

[o] Carson, L., G. Bassett, W. Beuhring, M. Collins, S. Folga, B. Haffenden, and R. Whitfiled,. *Resilience: Theory and Applications*. Argonne National Laboratory, 2012.

STEP 2: CONTEXTUALIZING COMMONALITIES

Within the commonality of these definitions, it is important to identify a few notable points. One can frame resilience of a system over time as the concepts of preparation and anticipation that happen before adaptation and recovery. In an ideal case, all threats have been prepared for or anticipated; however, those who operate systems would say that time and budget limit this ability. Hence, resilience should become part of the cyclical planning process. The concept of identifying threats and preparing for events raises questions of perceived risk and consequences for the system. Risks are not ubiquitous, and stakeholders of systems must individually assess risk to identify threats, disruptions, or events and their consequences that should be considered.

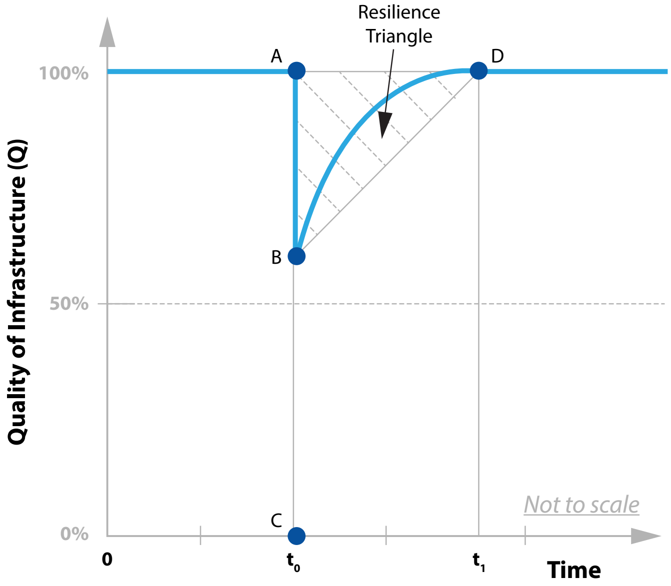

Figure 7. Resilience triangle.[15]

Resilience solutions (mitigation strategies) help dictate the rebound, adaptability, or recovery of the system to a threat.

The first three characteristics that were identified relate directly to the time axis of the "resilience triangle" shown in Figure 7. The planning, preparing, anticipating, and/or detecting happens before time t_0 at Point A. This also includes the ability to identify the threat or disturbance, which can be obvious or sometimes unknown, as in a cyberattack. The disruptions start at Point A and time t_0. Finally, the recovery is between Points A and B in the interval between t_0 to t_1. It should be noted that this first representation illustrates a return to some performance level equal to previous to the event. This is further refined in Figure 8, which addresses the time to failure (T_f) and time to recovery (T_r), along with different performance levels after recovery that are not necessarily the original performance level.

Related to this idea of recovery is the debate around inserting the word "rapidly" into definitions related to recovery. In considering the resilience of a system, a comparison of performance of resilience could include the speed of recovery. It seems logical that a stakeholder would want a recovery to be "rapid"; however, time to recovery is often dependent on many factors of the event and the system. Not until one can compare a base case against a mitigated case of the same event type can the speed of recovery actually be compared. Thus, any discussion of rapidity must consider the distinctiveness property of the system and the varying impacts of events.

The key common characteristics are also seen in the adaption of the resilience triangle to the "resilience trapezoid" in Figure 9 and Figure 10. These figures effectively identify the duration of the disturbance and time of the system to illustrate the impact of the disturbance as a performance degradation. One aspect touched on lightly by Figure 9 is the concept of preparation, which is consistent with several of the definitions provided. Thus, in Figure 10, a Phase 0 is explicitly added to include actions to prepare and detect.

[15] Ayyub, B. M. "Systems Resilience for Multihazard Environments: Defintions, Metrics, and Valuation for Decision Making," Risk Analysis 34, no. 2, 2013: 340–355.

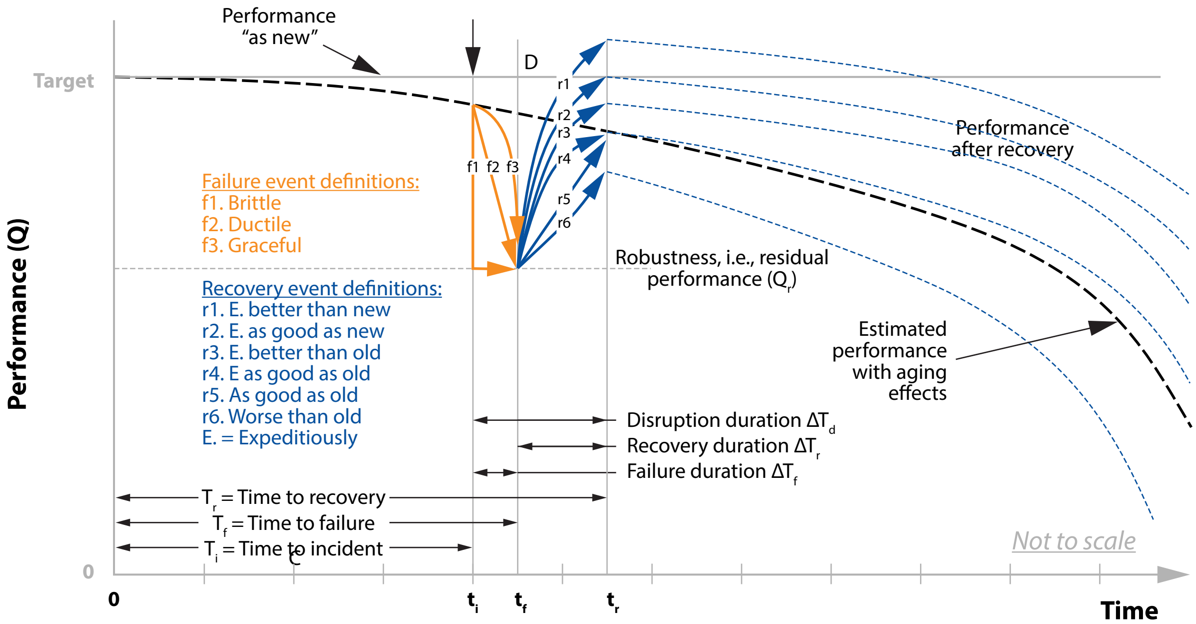

Figure 8. Refined resilience triangle.[15]

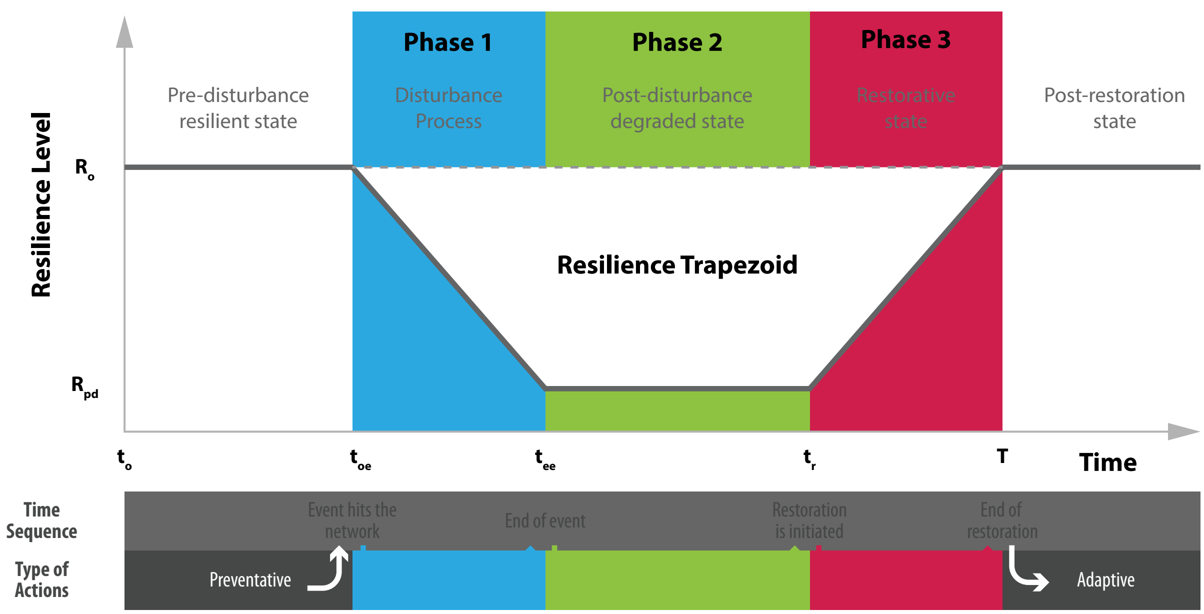

Figure 9. Resilience trapezoid.[8]

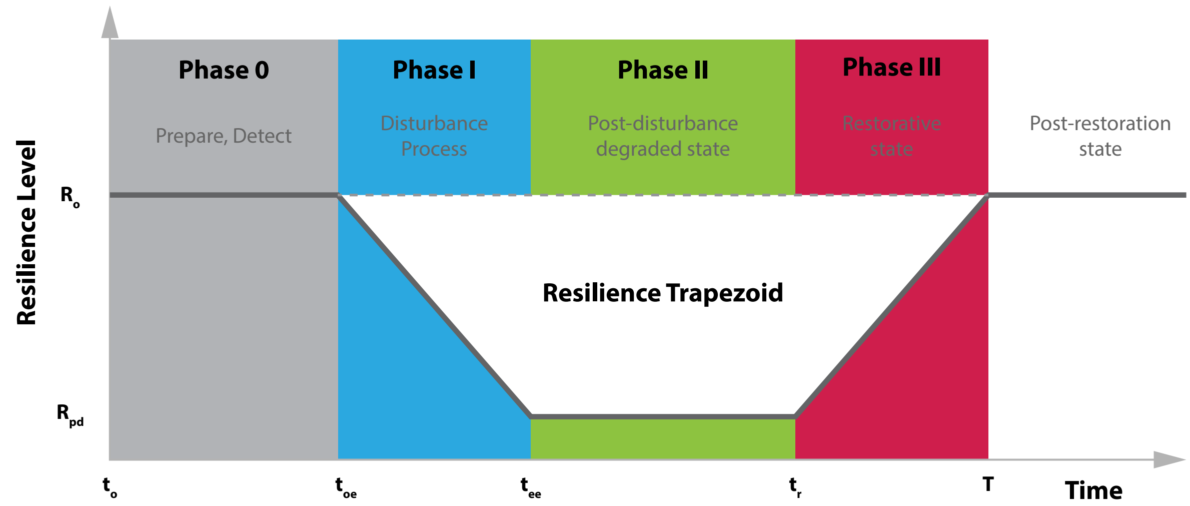

Figure 10. Resilience trapezoid, including prepare and detect phase.

The final characteristic is the concept of returning to an acceptable level of functioning. A resilient system would adapt and recover to some acceptable level of function or state of operations. Resilience does not demand that the final state return to the state prior to the disturbance after some partial or complete degradation, but it suggests a system would move to some acceptable state as seen in Figure 8, with different trajectories shown by the blue curves. For example, the effects of COVID-19 on each society will not allow a return to the societal state prior to COVID-19, nor will the people of Puerto Rico return to the state prior to hurricanes Irma and Maria. Within resilient control, "normalcy" is a term introduced to system performance: "a resilient control system is one that maintains state awareness and an accepted level of operational normalcy in response to disturbances, including threats of an unexpected and malicious nature."[16] [17]

The definition of resilience needs to reflect the physical characteristic of a system and assets or components, but also the human and operational side of that system. Hence, a resilience evaluation process can be divided into two main categories: qualitative and quantitative. The qualitative category of an evaluation process includes methods that tend to assess the resilience of a system without numerical descriptors. The quantitative category of an evaluation process focuses upon measurable quantities (metrics)[8]. Note that the focus of this paper is to identify quantitative metrics for distributed wind within an EEDS, but also to focus on the qualitative approach for decision making, risk evaluation, and best practices.

[16] Rieger, C. G. Resilient control systems Practical metrics basis for defining mission impact. Denver: IEEE, 2014.

[17] Stein, A. L. Distributed Reliability. University of Florida, Levin College of Law Research, 2015.

These characteristics show the need for a decision process or guide to help achieve identified goals of resilience—a process that can be cyclic in design and present opportunities to balance risk and consequences by the stakeholders (i.e., a resilience framework). As resilience is applicable to almost any field or domain, a resilience process becomes a tool to apply to different systems, conditions, owners, and performances. This domain-agnostic property of resilience is most likely a factor contributing to why the discussion of resilience is so confounding today. The uniqueness of stakeholders' risk tolerance, geography, events and corresponding consequences, and system demands that application of resilience and resilience planning needs a repeatable decision methodology or framework. This is an important difference between resilience and reliability, as discussed below.

"Resilience: the ability to identify, prepare for, and adapt to disturbances (disruptive events or conditions) and recover from the disturbance to an acceptable state."

With the identified characteristics above and the outline of similarities and gaps in existing definitions, the following generic definition of resilience is offered: the ability to identify, prepare for, and adapt to disturbances (disruptive events or conditions) and recover from the disturbance to an acceptable state.

"The stakeholders include any owner, operator, customer, or entity that the EEDS impacts and other systems that may impact the EEDS."

DEFINING RESILIENCE OF AN ELECTRICAL ENERGY DELIVERY SYSTEM

Defining resilience in a general sense is preliminary to a discussion that will establish a foundational definition of resilience in EEDSs. To begin this attempt at a more specific definition, from which actionable goals may be derived, we examine qualitative aspects of the electric power industry, research, and regulations to help refine and focus the determination. This process includes:

1. Examination of current industry and regulatory work related to resilience EEDSs
2. Evaluation of the current definitions and work being applied to resilience at the national-laboratory level
3. Development of an overlay of the identified characteristics of resilience examined above on the function, operations, and assets of an EEDS.

ENERGY INDUSTRY PERSPECTIVE

Step 1: Examination of Current Industry and Regulatory Work Related to Resilience in Electrical Energy Delivery Systems

It should be noted that several of the definitions provided above include definitions from electric energy delivery stakeholders, such as utilities, independent system operators (ISOs), regional transmission operators (RTOs), and regulatory bodies. Currently, the FERC mission involves pursuing three primary goals: (1) ensure just and reasonable rates, terms, and conditions; (2) promote safe, reliable, and secure infrastructure; and (3) support mission through organizational excellence.[18] Currently the term resilience is not included in the mission, but is directly related to recent rule-making efforts where there have been considerably differing responses.[5]

Along a similar line of questions, the DOE issued an RFI on resiliency in the summer of 2019 that seeks "relevant consensus based codes, specifications, and standards, state and industry best practices, and other pertinent materials to provide guidance for enhancing the physical and operational resilience of electric grid systems and their components,

[18] FERC, Homepage, Nov 5, 2020. Retrieved from https://www.ferc.gov/about/what-ferc/strategic-documents.

e.g., generation, transmission, control centers, and distribution facilities, against these events."[5] Several industry stakeholders and various other entities responded. Their responses can be seen in Table 2.

American Public Power Association's response to the DOE RFI includes discussion focusing on weather-related events and points out an important concept about resilience applied to an EEDS: "Moreover, there is no 'one-size-fits-all' approach to promoting weather-related resilience. Different states and regions face different weather-related risks, influenced by factors such as climate, geography, generation resource mix, fuel availability, and transmission and distribution topology."[19] This is a critical aspect of resilience and resilience of EEDSs. Different owners and different perspectives on risk and risk evaluation create the need for a resilience process or decision-driven framework, which should be capable of being applied to any EEDSs and its stakeholders. The stakeholders include any owner, operator, customer, or entity that the EEDS impacts and other systems that may impact the EEDS. This characteristic is a focus of the North American Energy Resilience Model, which at the highest level seeks to better inform all stakeholders of the North American energy system's interdependency between these different systems.[20]

Berkshire Hathaway Energy Company (BHE) commented that "Resilience is intrinsic in many of the activities already conducted by public utilities. The electric industry has always placed paramount importance on resilience and reliability long before regional energy markets were established." BHE concluded that "no new event has occurred to indicate a weakness in current planning processes or a problem that must be solved through mechanisms outside of the traditional manner."[21] Essentially, BHE believes the existing planning process is sufficient to address resilience, and the North American Electric Reliability Corporation (NERC) should not establish a grid-resilience standard.

The need for a resilience process is validated by an Exelon comment: "DOE should provide a forum for electric utilities to develop a flexible framework that each utility can modify as needed to assess the resilience of its system against severe weather events."[22]

Table 2: Organizational responses to the DOE request for information on resiliency

Organization	Response Summary
American Public Power Association	There is no 'one size fits all' solution to resilience, due to different risk factors based on varying climates, geographies, generation resource mixes, fuel availabilities, and transmission and distribution topologies.
BHE	Public utilities already focus on resilience, and no new event has occurred to indicate a need for a grid resilience standard.
Exelon	Achieving resiliency is a continuous process, involving constant re-assessment and re-evaluation. The DOE ought to create a flexible framework to assess resiliency that can be modified by each utility according to their specific needs.
PJM	As an RTO, PJM sees the benefit of establishing a commission process to provide verification of reasonableness of events, threats, and vulnerabilities. They are in favor of adding a planning process to assess Extreme Events for the BES.
Duke Energy	Duke Energy sees the need to address resilience, but does believe that any such cost allocation, areas with organized markets, or transmission relief programs should be included.
Electric Power Research Institute (EPRI)	EPRI directly addresses the FERC questions with definitions but identifies a few important issues: (1) Distinction between reliability and resilience where a resilience system limits discontinuity of supply. (2) Lack of consensus on events to consider. (3) Lack of resilience metrics accepted

[19] American Public Power Association (APPA), *Response of the American Public Power Association to DOE RFI on Resilience*. Washington D.C.: APPA, 2019.

[20] DOE Office of Electricity, *North American Energy Resilience Model*. Washington DC: United States Department of Energy, 2019.

[21] BHE. Comments of *Berkshire Hathaway Energy Company to FERC AD 18-7-00*, Washington, DC: BHE, 2018.

[22] Exelon, *Response to RFI Regarding Codes, Standards, Specifications, and Other Guidance for Enhancing the Resilience of Electric Infrastructure Systems Against Severe Weather Events*. Washington D.C.: Exelon, 2019.

NARUC LISTS 8 TRAITS OF RESILIENT DERS:[25]

1. **Dispatchability:** Resilient DERs can respond to a disruption at any time with little to no advance warning
2. **Islanding Capability:** Resilient DERs have the ability to island from the distribution grid and serve load during a broader outage
3. **Siting at Critical Loads/Locations:** Resilient DERs reside at critical loads or at critical points on the grid (e.g., areas of high residential density)
4. **Fuel Security:** Resilient DERs do not rely on the availability of a limited physical fuel to provide power as conventional generation
5. **Quick Ramping:** Resilient DERs are capable of changing output quickly to match rapidly changing load
6. **Grid Services:** Resilient DERs can provide voltage support, frequency response, and other grid services
7. **Decentralization:** Resilient DERs are sized and sited to support a load in the distribution system
8. **Flexibility:** Resilient DERs can be deployed quickly and cheaply (when compared to centralized generation, transmission, and/or distribution) at locations and times where resources are needed

What seems to differ in these two responses to FERC is the threats to consider, the way to evaluate whether existing planning processes can support these threats, and the means to apply policy throughout the bulk electric grid. BHE states that no new event has occurred, and Exelon continues to look for a forum to help determine events to consider. The distinguishing issue is the determination of what events should be considered under resilience. This issue seems to be directly related to the relationship with reliability.

While FERC and NERC have jurisdiction over the bulk power system and interstate sales of wholesale power, individual states' utility commissions have responsibility as economic regulators to define and quantify the benefits of resilience investments into distributed energy resources (DERs), including distributed wind, that are put into a rate base. The National Association of Regulatory Utility Commissioners (NARUC) supports efforts to quantify these benefits through studies and white papers.[23] In 2013, NARUC published Resilience in Regulated Utilities to provide a framework for utility commissions to explore regulatory issues affecting the treatment of investments in resilience.[24] More recently, NARUC published an overview of state policies, a work done in collaboration with the NREL through the Solar Energy Innovation Network.[25] From the state policies, NARUC identified eight key traits of resilient DERs, listed above.

NARUC has also identified types of regulatory processes and policies (e.g., integrated resource planning, hosting-capacity analysis, advanced rate design) that can be used to encourage resilient DERs and survey different state approaches to these processes.

NARUC examined the tools Benefit Cost Analysis (BCA), Interruption Cost Estimator (ICE) calculator, and IMPLAN. The metrics of DER resilience value explored are the contingent valuation method, defensive behavior and damage cost methods, and input-output (IO) modeling. These methods evaluate resilience based on ease of use, output scope, geographical scalability, and applicability for power interruption duration analysis.

[23] NARUC, "Center for Partnership & Innovation—Critical Infrastructure, Cybersecurity, and Resilience," undated. Retrieved Dec 12, 2020, from https://www.naruc.org/cpi-1/critical-infrastructure-cybersecurity-and-resilience/resilience/

[24] Keogh, M., and C. Cody, *Resilience in Regulated Utilities*, Washington D.C.: National Association of Regulatory Utility Commissioners, 2013.

[25] NARUC, *Advancing Electric System Resilience with Distributed Energy Resources: A Review of State Policies*, Washington D.C.: NARUC, 2020.

Beyond the importance of developing a common resilience definition and a framework for valuing resilient DERs, a significant challenge lies in quantifying these benefits because threats, DER resources (including distributed wind), and the prices of energy vary significantly by region. NARUC looked at existing tools to value resilience and application to DERs.[26] The evaluation tools examined included the Federal Emergency Management Agency's (FEMA's) BCA tool, Lawrence Berkeley National Laboratory's (LBNL's) ICE, and IMPLAN software. The results of this analysis found that the ICE calculator was scalable from the facility to the national level, but was not suitable for power-interruption duration analysis. In the evaluation of ease of use, this tool had the benefit of online availability but a challenge of resource intensity for new surveys. The ICE calculator's output scope was found to be well established on a regulatory level, but had a drawback in not considering effects from spillover. The FEMA BCA damage-cost tool also had ideal scalability, with benefits in a capability to perform power-interruption duration analysis, ease of use, and output scope. The duration capabilities of this tool benefited from accountability for relatively long-duration interruptions, but suffered from difficulties in accounting for non-linear effects that occur as a result of long-term interruptions to power. Analysis of the IMPLAN IO model showed this tool has both capabilities and limitations for each valuation metric. The tool benefits from long-term modeling disruption, regional analysis effectiveness, and commercial availability. The drawbacks of this tool are the inability of static models to capture the entirety of long-term shocks, difficulties in facility-level scaling, and a potential for economic indicators to be out of regulatory scope. After investigation of the tools, NARUC highlights several options to use in its individual analysis of the tools:

- Not considering resilience in cost-benefit analyses
- Replacing cost-benefit analysis with cost-effectiveness analysis, which does not quantify the resilience benefit
- Adopting the methods used in a previously developed case study
- Adapting some other methodology that avoids power interruptions, one not used to value resilience in DERs
- Participating in current research that seeks to determine new methods of valuing resilience.[24]

Resilience Versus Reliability

The distinction between reliability and resilience is often discussed in these terms: reliability considers low-impact, high-frequency events while resilience examines high-impact, low-frequency events. Several works examine the relationship between reliability and resilience within EEDSs. In addition, it should be noted that FERC has raised questions of defining resilience and its relationship to reliability, including:[7 10 15 27 28 29 30]

- What is resilience, how is it measured, and how is it different from reliability?
- What levels of resilience and reliability are appropriate?
- How are reliability and resilience valued, or not valued, inside RTOs/ISOs?
- Do RTO/ISO energy and/or capacity markets properly value reliability and resilience?
- What resources can address reliability and resilience, and in what ways?[6]

Reliability has been a component of most utilities and regulators within the U.S. and is frequently found in utility mission statements. In accordance with the Energy Policy Act of 2005 (EPA), Congress expanded FERC's role and jurisdiction by adding a new Section 215 pertaining to electric-grid reliability. While FERC had previously addressed electric-grid reliability in an indirect way—e.g., by allowing cost recovery of public-utility expenditures that address discrete reliability matters—the new section of the EPA tasked FERC with a direct role over an entire new field of activity.

Today, reliability is the focus of the NERC, which is tasked to ensure the reliability of the bulk power system in the U.S., Canada, and part of Mexico. NERC defines a reliable bulk-power system as one that is able to meet the electricity needs of end-use customers, even when unexpected equipment failures or other factors reduce the amount of available electricity. NERC divides reliability into two categories: Adequacy and Security.

[26] Bulkeley, M., W. Rickerson, and J. Gillis, *The Value of Resilience for Distributed Energy Resources: An Overview of Current Analytical Practices*, Washington D.C: NARUC, 2019.

[27] Clark-Ginsberg, A., *What's the Difference between Reliability and Resilience?* RAND Corp., 2017.

[28] Electric Power Research Institute (EPRI), *Power System Supply Resilience: The Need for Defintions and Metrics in Decision-Making*, EPRI, 2020.

[29] Phillips, S., *Federal Regulation for a "Resilient Electricity Grid,"* Berkeley: University of California, Berkeley, School of Law, 2019.

[30] Willis, H. H., and K. Loa, *Measuring the Resilience of Energy Distribution Systems*. Santa Monica: RAND Corporation, 2015.

RELIABILITY COMPONENTS

ADEQUACY

Having sufficient resources to provide customers with a continuous supply of electricity at the proper voltage and frequency virtually all the time. Resources refer to a combination of electricity-generation and transmission facilities and demand-response programs that reduce customer demand for electricity. Maintaining adequacy requires system operators and planners to consider scheduled and reasonably expected unscheduled outages of equipment while maintaining a constant balance between supply and demand

SECURITY

For decades, NERC and the bulk-power industry defined system security as the ability of the bulk-power system to withstand sudden unexpected disturbances, such as short circuits or unanticipated loss of system elements due to natural causes. In today's world, the security focus of NERC and the industry has expanded to include withstanding disturbances caused by manmade physical- or cyberattacks. The bulk-power system must be planned, designed, built, and operated in a manner that considers these modern threats, as well as more traditional risks to security

As represented in NERC's definition, the change in events to be considered under security relates to the issue of what type of event to examine beyond high-probability events it has traditionally studied.

Given that resilience is both a policy concern[31] and a topic of rulemaking for FERC, it is unclear exactly what resiliency (in the electric grid) means from an applied regulatory standpoint, considering the breadth of reliability and resource adequacy.[27] While many scholars, regulators, and analysts have noted that these concepts are distinguishable,[15] there is also no clear agreement on what technical problem must be solved to achieve resiliency, nor agreement as to why any such technical problem cannot be addressed within one of these existing frameworks. Thus far, resiliency hints at being a widely discussed solution to an undefined problem.[15] These questions effectively stem from the lack of definition and assumed uniform applicability to different systems, geography, and stakeholders and to differences in risk evaluation.

Two predominant camps exist on the discussion of NERC's current role in resilience. The first view is that NERC has all the regulatory tools necessary to focus on resilience. The second view is that NERC needs more policy direction to ensure resilience. Thus, defining the events to be considered is a point of contention between resilience and reliability.

An important additional issue related to the question of events is the consequence of events that have been considered previously. Reliability does not take into consideration complete system failure or catastrophic events, but rather focuses on sudden, unexpected disturbances, such as electrical faults or unanticipated loss of system elements due to natural causes. Resilience must look at broader problems that have consequences including the failure of large parts of the system and the system as a whole (Figure 11). This is echoed by the National Academies: "Resilience is not the same as reliability. While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that such outages can occur, prepares to deal with them, minimizes their impact when they occur, is able to restore service quickly, and draws lessons from the experience to improve performance in the future." [32]

[31] Presidential Executive Order, "Presidential Policy Directive 21: Critical Infrastructure Security and Resilience," Washington D.C.: US Government, 2013.

[32] National Academies of Sciences, Engineering, and Medicine, *Enhancing the Resilience of the Nation's Electricity System*, Washington D.C.: The National Academies Press (www.npa.edu), 2017. ISBN 978-0-309-46307-2. 10.17226/24836

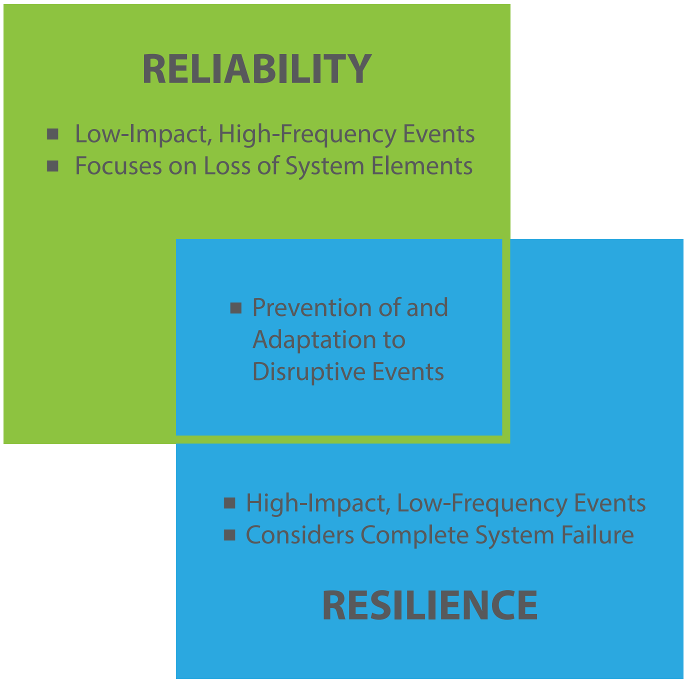

Figure 11. Comparison of reliability and resilience.

An example of this is represented in the draft integrated resource plan (IRP) proposed to the Puerto Rico Energy Bureau by the Puerto Rico Electric Power Authority. The draft IRP emphasized the concept that hurricanes will occur regularly in Puerto Rico, and the system must be designed with that constraint. The draft IRP includes a major shift in moving generation closer to load and incorporating the ability to size and harden thermal generation as a means to harden critical load, designed not only to support medical providers and first responders, but also to bring the community back to a sense of normalcy by including community centers, fuel stations, etc.[33] At the heart of the discussion is the idea that reliability cannot examine all potential threats, but has, thus far, focused first on higher-probability events with lower impact.

DIFFERENCES AND ALIGNMENT: RESILIENCE AND THE NATIONAL LABORATORIES

Step 2: Evaluation of the Current Definitions and Work Being Applied to Resilience at the National-Laboratory Level.

The next step is to discuss the work of several U.S. DOE national laboratories to determine what resilience work has already been performed. The intent is to answer the following questions for each national lab:

1. Does the lab define resilience or resiliency? If so, what are the definitions?
2. Are its definitions specific toward particular areas of resilience? If so, in what primary area?
3. Does a given lab have work relating to resilience of the grid, power systems, microgrids, energy delivery, etc.? Anything relating to electricity? If so, what does its work focus on?
4. Does the lab define or use any resilience metrics? Are metrics related to electricity systems?
5. Can the lab describe, at a high level, the direction of its resilience work?

Idaho National Laboratory

INL's work in resilience has been focused on cybersecurity, industrial control systems, and cyber-physical systems. Like many of the other labs, INL works on resilience that is focused on critical infrastructure.

INL focuses on industrial control systems via threat resilience through the Resilient Controls and Instrumentation Systems (ReCIS) distinctive signature. ReCIS includes cyber-physical degradation assessment, operational-resilience measures, and presentation of information to humans to provide root cause.[34] The ReCIS effort originated an IEEE-cosponsored International Conference on Resilient Control Systems, which has subsequently evolved to consider community and infrastructure resilience under the moniker of Resilience Week and is currently in its 13th year.[34]

[33] Puerto Rico Electric Power Authority, *Integrated Resource Plan Volume I: Supply Portfolios and Futures Analysis Draft for the Review of PREC*, San Juan: Puerto Rico Energy Commission, 2019.

[34] Idaho National Laboratory. "Resilient Control & Instrumentation Systems," undated. Retrieved Dec 12, 2020, from www.recis.inl.gov

INL's resilience research focuses on the applications to microgrids, energy storage, and other renewable energy systems to benefit resilience to critical customers. INL has applied its own metrics and design considerations to a number of new microgrids for the Department of Defense to enhance the resilience of military installations. Resilience metrics have been applied, based on controllability or time to respond, that reward these considerations. INL has also led regional resilience assessments through the Department of Homeland Security (DHS) Cybersecurity and Infrastructure Security Agency. These have different focus areas; some include power-system integration.

The largest body of work has been relative to resilience of control systems. INL has adopted a definition for resilient control systems, stating, "A resilient control system is one that maintains state awareness and an accepted level of operational normalcy in response to disturbances, including threats of an unexpected and malicious nature."[35] INL maintains the Wikipedia page for resilient control systems, and the definition is widely accepted and used by industry. INL also ties critical infrastructure to resilience, adopting the DHS definition of the "ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions."

INL has adapted the resilience triangle to reflect control and resilience.[15] INL refers to this resilience-performance chart as the disturbance and impact-resilience evaluation (DIRE) curve (Figure 12). Included in the DIRE curve are 5 R's: Recon, Resist, Respond, Recover, and Restore.[16]

INL has several projects focused on control-system resilience with power distribution and transmission as the domain of focus. There is also potential for this research to be used for the integration of microgrids with other renewables.[34] In many of these application efforts, metrics have been developed as identified below.

- Modern Distribution System:
    - *Steady-State Adaptive Capacity:* Generally described as a sum of apparent power capability within the system for all assets[36]
- Control System Metrics:
    - *Agility*. The derivative of the disturbance curve of the resilience trapezoid[37]
    - *Robustness*. A positive or negative number associated with the area between the disturbance curve and the resilience threshold, indicating either capacity or insufficiency, respectively[35]
    - *Adaptive capacity*. The ability of the system to adapt to or transform from impact and maintain minimum normalcy, considered a value between 0 and 1[35]
    - *Adaptive insufficiency*. A value between 0 and -1 that represents the inability of the system to adapt, generally indicating unacceptable operational states[38]
    - *Brittleness*. The area under the disturbance curve as intersected by the resilience threshold, representing the impact from the loss of operational normalcy.[36]

From a direct approach to the resilience trapezoid, several of these metrics represent characteristics of the resilience trapezoid of the DIRE curve, and some can be considered indirect, such as adaptive capacity and adaptive insufficiency. Recent work at INL demonstrates a migration to resilience discussion around EEDSs, with application of identified metrics.[39 40]

[35] Rieger, C. G., D. I. Gertman, and M. A. McQueen, "Resilient control systems: Next generation design research." *2009 2nd Conference on Human System Interactions*, Catania, 2009: 632–636. 10.1109/HSI.2009.5091051.

[36] Rieger, C. G., and T. R. McJunkin, "Electricity distribution system resilient control system metrics." 2017 Resilience Week, Wilmington, DE, 2017: 103–112. 10.1109/RWEEK.2017.8088656

[37] Eshghi, Kamshad, Brian K Johnson, and Craig G Rieger, "Power system protection and resilient metrics," 2015 Resilience Week, Philadelphia, PA, 2015. 10.1109/RWEEK.2015.7287448

[38] Noguera, M., B. K. Johnson, C. G. Rieger, and T. McJunkin "Enhancement of Distribution System Resilience Through the Application of Volt-Var Regulation Devices." 2020 Resilience Week (RWS-2020,. Salt Lake City, UT, 2020. 10.1109/RWS50334.2020.9241288.

[39] Phillips, T., T. McJunkin, C. Rieger, J. Gardner, and H. Mehrpouyan, "A Framework for Evaluating the REsilience Contribution of Solar PV and Battery Storage on the Grid," 2020 Resilience Week (RWS), Salt Lake City, UT, 2020.

[40] Phillips, T., V. Chalishazar, T. McJunkin, M. Maharjan, S. Alam, T. Mosier, and A. Somani, "A Metric Framework for Evaluating the Resilience Contribution of Hydropower to the Grid," 2020 Resilience Week, Salt Lake City, UT, 2020.

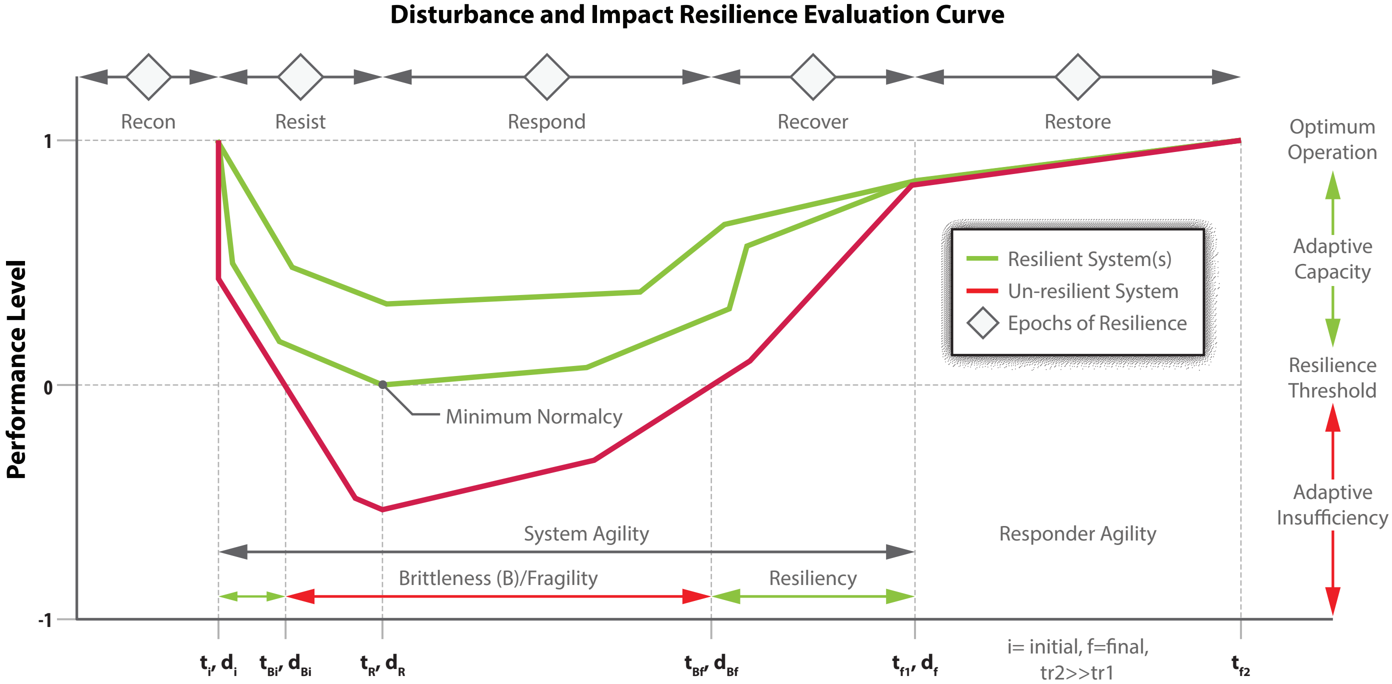

Figure 12. INL DIRE curve.

As indicated, many of the metrics applied have been specific to the situation or domain. These metrics include an easily aggregated accounting of the properties of assets available, including maximum applied power values, maximum rate of change of the application of power, energy limits, and latencies.[34 35] Additionally, metrics have been developed to measure the resilience benefit from integration of renewables' penetration[37] or reactive power controls.[36] Determination of appropriate metrics will ultimately depend on the stakeholders, resilience goals, or questions to be addressed.

Pacific Northwest National Laboratory

PNNL's work on resilience is widely applied in biology, climate change, grid architecture, and energy systems. PNNL has several definitions of resilience, including "the ability to withstand grid stress events without suffering operational compromise or to adapt to the strain so as to minimize compromise via graceful degradation. It is in large part about what does not happen to the grid or electricity consumers," and "resilience in microbial communities is best defined as the rate of recovery of a given function of interest to the researcher." PNNL's work relative to EEDSs is grid resilience work. One aspect of grid resilience noted is an "intrinsic grid characteristic comprised of stress resistance and strain compensation elements." PNNL identifies the relationship between resilience and reliability (Figure 13) in these terms: "Resilience applies to the grid under stress: how it resists losing capabilities or gracefully degrades is the essence of resilience. This explains why reliability measures are not useful for quantifying resilience. Resilience is in large part about what does **not** happen."[41]

[41] Taft, J., *Electric Grid Resilience and Reliability for Grid Architecture*. Richland, Washington: Pacific Northwest National Laboratory, 2017.

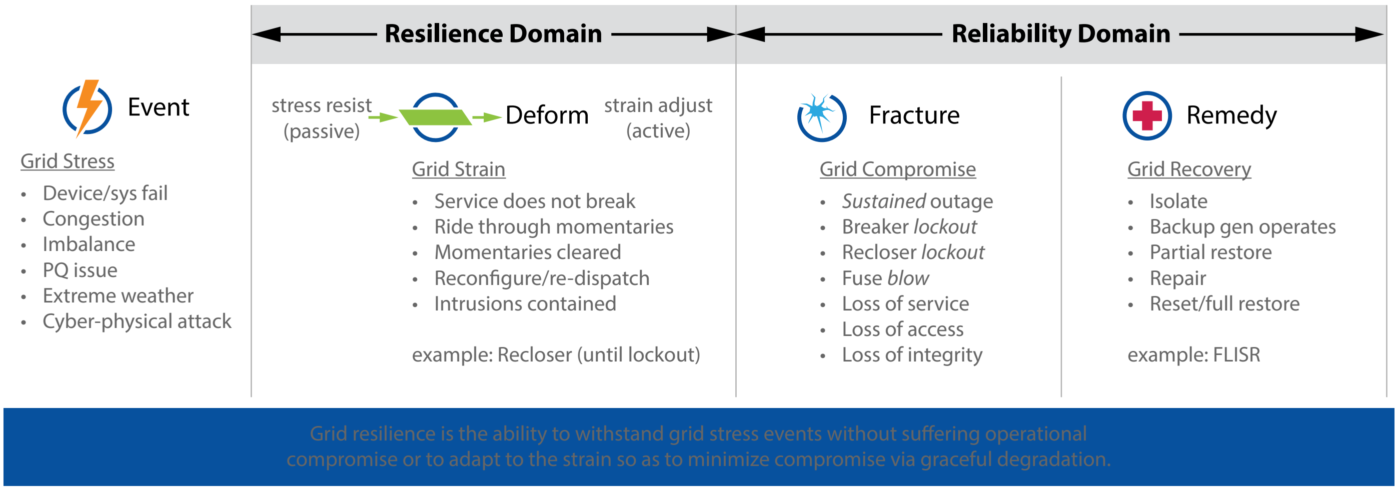

Figure 13. PNNL grid-resilience domain, adapted from [41].

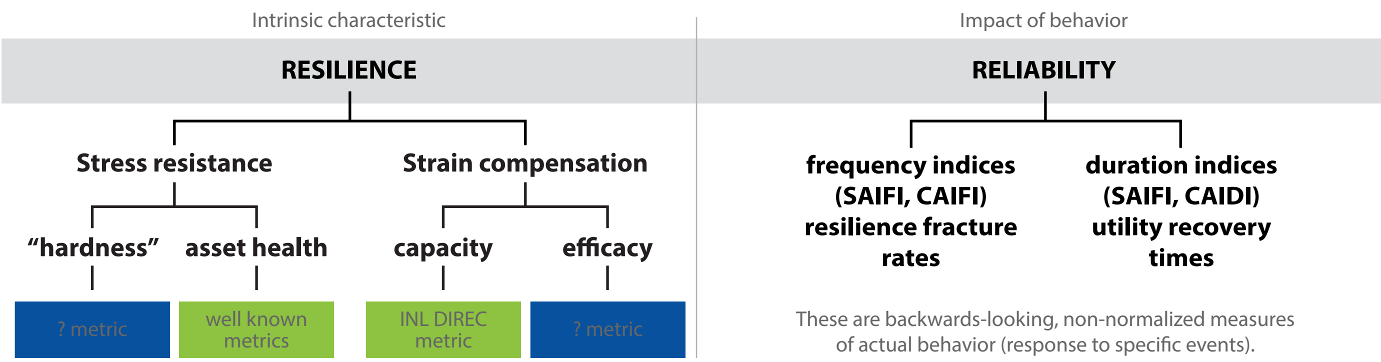

Figure 14. PNNL resilience and reliability-metric taxonomies, adapted from [41].

Work related to metrics provides a discussion on reliability versus resilience metrics, and a taxonomy is provided for both (Figure 14).

Resilience metrics are categorized under "stress resistance" or the ability to resist losing capability, and "strain compensation," or the ability to adapt actively. PNNL does reference the INL DIRE curve.

PNNL notes that there is still work needed to develop relevant metrics in areas like strain compensation and capacity, but that other areas, e.g., asset-health metrics, are better understood. Its work does include preliminary efforts for defining resilience and its relationship to reliability, and the lab has developed potential metrics, but these do not have a well-developed framework.

National Renewable Energy Laboratory

NREL directs its resilience work toward integration of renewables, microgrids, and renewable-energy hybrid systems (REHS).[42] NREL has adopted the following definition for resilience: "The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions."[43] NREL focuses on planning and integration of solutions. It has developed a Power Sector Resilience Planning Guidebook that identifies a cyclic planning process representing a methodology of implementing a resilience process (Figure 15).[44]

[42] Anderson, K., N. D. Laws, S. Marr, L. Lisell, T. Jimenez, T. Case, and D. Cutler, "Quantifying and Monetizing Renewable Energy Resilience," *Sustainability* 10, 2018: 933.

[43] NREL. *Resilience Roadmap: A Collaborative Approach to Mulit-Jurisdictional Planning*, undated. Retrieved Nov 2, 2020, from https://www.nrel.gov/resilience-planning-roadmap/.

[44] Stout, S., N. Lee, S. Cox, J, Elsworth, and J. Leisch, "Power Sector Resilience Planning Guidebook: A Self-Guided Reference for Practitioners", NREL, 2019.

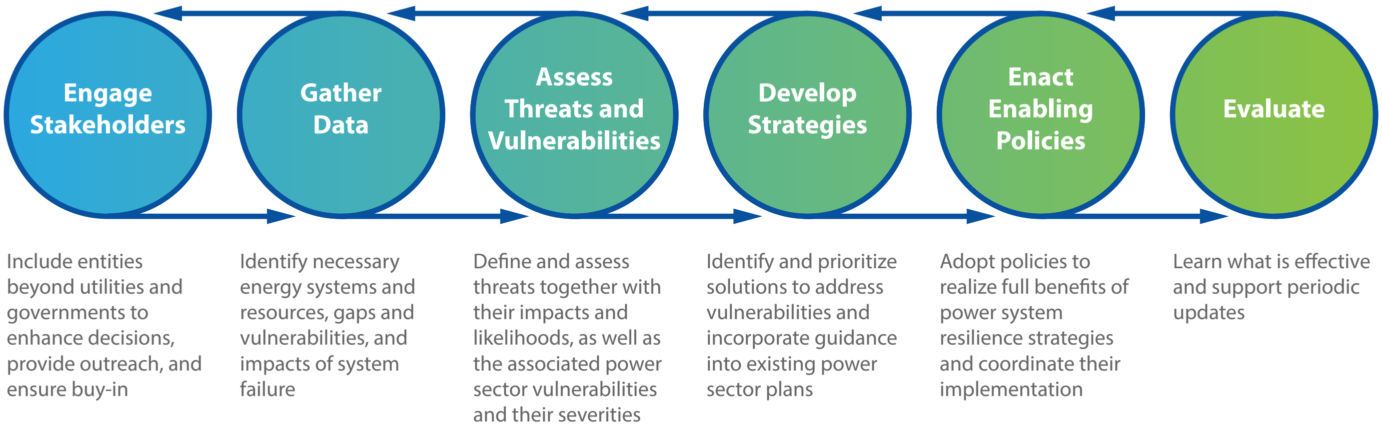

Figure 15. NREL resilience-planning process, adapted from [44].

NREL does extend the planning guide to its resilience roadmap. The roadmap attempts to define a strategic plan that outlines goals, desired outcomes, and tasks to be performed over specified time frames while also outlining the process for creating a strategic plan. The roadmap is intended for use by multiple stakeholders at the federal, state, and local government levels.

NREL explains that a "resilience metric is used to quantify the ability of an energy system to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. "[45] Additionally, NREL points out an important aspect of resilience metrics: "no one definition or metric can be applied broadly; rather, the appropriate metric depends on goals, event context, hazards, scale, and perspective."[42] However, NREL does examine a metric for evaluation of resilience from the economic side: the value of lost load (VOLL).[40] This metric is meant to provide some insight to the financial benefits of resilience as different mitigations and solutions are examined in an REHS.

Sandia National Laboratories

Sandia has several initiatives around resiliency, including economic resilience, infrastructure resilience, and energy surety, which produced a significant amount of material starting around 2000 (Figure 16). Sandia uses several definitions of resilience in their work, as well as their own definition, described as "the ability to reduce effectively both the magnitude and duration of the deviation from targeted system performance levels."[46] Sandia has developed a Resilient Energy Systems (RESs) Strategic Initiative to support a strategic vision for U.S. energy systems' resilience. Sandia has identified that a key challenge in promoting energy system resilience "lies in developing rigorous resilience analysis methodologies to quantify system performance."[7] To this end, Sandia has developed multiple frameworks to analyze resilience and applied these frameworks to inform design, investment, and decisions in various energy and interdependent systems. Sandia's frameworks provide five key steps in a methodology for resilience analysis.

1. **Scope and Goals:** defining the system, threats, and resilience goals, considering multiple stakeholders' perspectives
2. **Metrics:** defining consequence categories and selecting performance- and consequence-based resilience metrics for individual infrastructures and multi-infrastructure analysis
3. **Baseline Analysis:** modeling threats and disruptions and their component and system impacts; estimating consequences; and calculating metrics (without mitigations)
4. **Mitigations:** specifying alternative resilience mitigations, evaluating/prioritizing resilience mitigations by estimating consequences, calculating metrics with mitigations, and implementing selected resilience mitigations
5. **Improvement Analysis:** evaluating the real-world effectiveness of resilience mitigations and restarting the cycle as needed.

[45] National Renewable Energy Laboratory. (2019). Valuing Resilience in Electricity Systems. Golden: NREL.

[46] Vugrin, E. D., W. E. Drake, M. A. Ehlen, and C. R. Camphouse, "A Framework for Assessing the Resilience of Infrastructure and Economic Systems," in K. Gopalakrishnan and S. Peeta (eds) *Sustainable and Resilient Critical Infrastructure Systems*, Springer, Berlin, Heidelberg, 2010: 77–116. 10.1007/978-3-642-11405-2_3.

Figure 16: SANDIA Resilience Frameworks

Sandia proposes that resilience-analysis methodologies should enable evaluation of consequences of various disruptions and the relative effectiveness of potential mitigations. This directly supports Sandia's research and focus for establishing a robust resilience framework. Sandia has developed multiple frameworks to analyze resilience and has applied these frameworks to inform designs, investments, and decisions in various energy and interdependent systems.

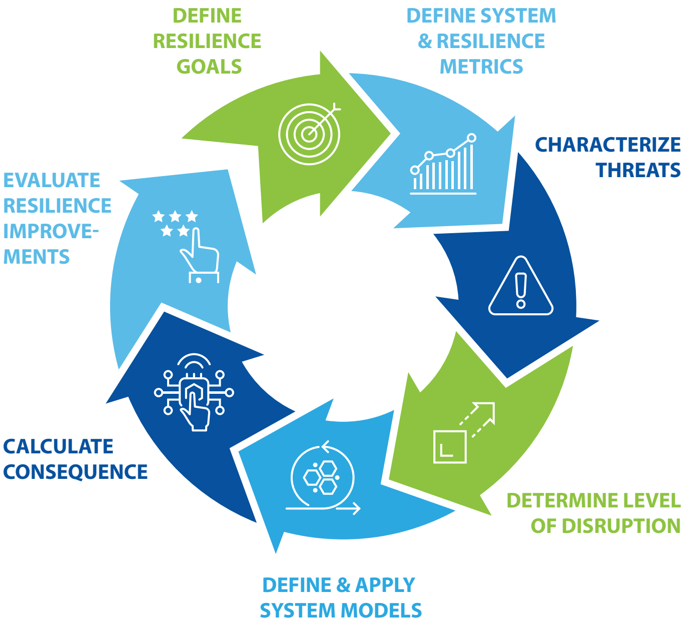

Figure 17. Sandia resilience-analysis process, adapted from [47].

These frameworks—the Infrastructure Resilience Analysis Methodology, Resilience Analysis Process (RAP), Energy Surety Design Methodology, Integrated Cyber Physical Impact Analysis, and Designing Resilient Communities Framework (Figure 17)—represent an important characteristic surrounding measuring, planning, and implementing resilience, which is the need for a framework to communicate, plan, determine risk, examine mitigations, and evaluate improvements.[47 48]

Sandia considers several applications of resilience, including cybersecurity, commercial buildings, electric and gas sectors, urban resilience, infrastructure resilience through control design, and design of distributed networks. For the electricity sector, Sandia works in electric infrastructure, bulk electricity, distribution networks, and even energy-distribution systems. They note that individual systems must have different priorities. Stakeholders must select metrics that will help them measure progress toward their specific resilience goals. This includes all considerations, from natural-disaster risks to social consequences. They have done additional work on defining system attributes that result in increased resilience, such as the number of critical spare parts in inventory. However, they have been unable to quantify the resilience benefit, only generally stating that it would improve resilience.

[47] Watson, J.-P., R. Guttromson, C. Silva-Monroy, R. Jeffers, K. Jones, J. Ellison, and L. T. Walker, *Conceptual Framework for Developing Resilience Metrics for the Electricity and Gas Sectors in the United States*, Albuquerque, NM: Sandia National Laboratories, 2015.

[48] Wachtel, A. M., K. A. Jones, M. J., Baca, E. O'Neill-Carrillo, and M. B. DeMenno, *Sandia's Integrated Methodology for Energy and Infrastructure Resilience Analysis*, Albuquerque: Sandia National Laboratories, 2020.

Los Alamos National Laboratory

LANL uses Presidential Policy Directive 21's definition of resilience, "The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."[29] This definition is in alignment with many of the commonly used definitions of resilience and represents the preparation, ability to tolerate, and recovery aspects of handling a disturbance. It also acknowledges both naturally occurring and intentionally adversarial events. LANL addresses the preparation and withstanding of naturally occurring incidents as aspects of resilience by optimizing those system improvements that will best harden the system against weather events and natural disasters, an objective chosen based on a DOE emphasis on enhancing resilience to climate change and extreme weather.[49]

LANL identifies five parts of resilience: asset hardening, system design, operations, repair scheduling, and emergency operations.[50] The bulk of its work focuses on the first two. In particular, they have a tool, the distribution resilience design tool, that allows designers to discover and prioritize the cost-effectiveness of system upgrades to minimize future outages.[51] They test possible improvements (hardening existing lines, building new lines, building new switches, building new distributed generation, or load shedding) against "damage scenarios," which are chosen as probabilistic (Gaussian) damage models for components during a storm. In related work, they propose the following metrics for measuring the impact of an electric disturbance: electric-power demand (in megawatts) not served, total population without power, total gross domestic product lost, and total number of jobs at risk.[52] These could be used in a larger resilience framework.

LANL's work does not address cybersecurity scenarios, only scenarios likely to damage components in a storm. Other gaps in its work address particular stakeholder needs or adjust priorities based on different system constraints.

Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory (LLNL) has a Cyber and Infrastructure Resilience program that includes border and physical security, civilian cybersecurity, energy infrastructure, and water security and technology. LLNL uses resilience in general terms, but does state that "the cyber and physical resilience of the transmission and distribution . . . networks must be a temporal, agile, and holistic practice that makes the electric grid less vulnerable to outages and reduces the time of service recovery."[53] LLNL's work is not extensive in the electric-resiliency area; it proposes ways that distributed resources could be used for grid resilience and compares that to the ways distributed resources are currently used.[49]

Lawrence Berkeley National Laboratory

LBNL's focus relating to resilience is on both the regulatory commission and the economics of power interruptions, which tend to be the consequence of degraded service of an EEDS. In its work, its researchers do not directly address resilience, nor seek to strictly define the term even though they acknowledge it can be used ambiguously. The only time they do define resilience, it is defined as "the ability to prevent or minimize impacts before a high-impact, low-frequency (HILF) event, the ability to respond and adapt to impacts during a HILF event, and the ability to restore functionality of electric service after a HILF event."[54]

LBNL has done significant work with utilities to understand their views on reliability. In this line of study, it found that some utilities used the term resilience often, but others rarely or never referred to resilience.[55] However, when the term is used, utilities do not separate the terms resilience and reliability clearly. LBNL emphasizes there is a similarity in literature for the definitions but notes that the unique part of resilience seems to be the ability to **prepare for** disturbances, rather than just respond in real time.[56]

[49] Ton, D. T., and W.-T. P. Wong, "A More Resilient Name: The U.S. Department of Energy Joins with Stakeholders in an R&D Plan," *IEEE Power and Energy Magazine* 13, no. 3, 2015: 26–34.

[50] Yamangil, E., R. Bent, and S. Backhaus, Designing Resilient Electrical Distribution Grids, *arXiv:1409.4477* 1, 16 Sep 2014.

[51] Nagarajan, H., E. Yamangil, R. Bent, P. V. Hentenryck, and S. Backhaus, "Optimal Resilient Transmission Grid Design," *2016 Power Systems Computation Conference (PSCC)*, 2016.

[52] Pasqualini, D., *Resilient Grid Operational Strategies*, Los Alamos, NM: Los Alamos National Lab, 2017.

[53] Arghandeh, R., M. Brown, A. D. Rosso, G. Ghatikar, E. Stewart, A. Vojdani, AND A. V. Meier, "The Local Team: Leveraging Distributed Resources to Improve Resilience," *IEEE Power and Energy Magazine*, 2014: 76–83.

[54] Elliot, R. and S. Aaronson, *Utility Investments in Resilience of Electric Systems*. Berkeley, CA: Lawrence Berkeley National Laboratory, 2019.

[55] Sanstad, A. H., Q. Zhu, B. D. Leibowicz, P. H. Larsen, and J. H., Eto, *Case Studies of the Economic Impacts of Power Interruptions and Damage to Electricity System Infrastructure from Extreme Events*, Ernest Orlando Lawrence Berkeley National Laboratory, 2020.

[56] LaCommare, K., P. Larsen, and A. J. Eto, *Evaluating Proposed Investments in Power System Reliability and Resilience: Preliminary Results from Interviews with Public Utility Commission Staff*. Lawrence Berkeley National Laboratory, 2017.

This work is foundational in establishing a valuation in risk assessments based upon cost and benefits and mitigation investment. LBNL represents several metrics relating to costs of high consequence events including:

- Avoided Customer Interruptions Costs
- Increased Transmission Costs
- Avoided Regional Economic Impacts
- Increased Distribution Costs
- Other Avoided Societal Impacts
- Increased Generation Costs
- Increased Customer Service Costs

Resilience is here also measured in terms of economic impact.

LBNL does considerable work in electricity reliability and the regulatory financial tools supporting reliability, which directly supports the approach needed to understand the cost of disruptions and benefits of investment toward mitigating solutions. Their extensive work on examining the cost of interruptions, which may play an important role in measuring resiliency, digs below traditional metrics and explores both indirect costs and costs to consumers. They have studied costs from an insurance perspective, which gives a new understanding of where the cost burden truly lies.[57] They have developed methods to estimate the costs of interruptions; here, they also loosely consider resilience, but focus on its relation to storms, natural disasters, and cybersecurity events.[58 59] They also examine the costs of interruptions to consumers[60 61] and the value of service reliability for consumers.[62] In addition to the special attention paid to consumers, LBNL highlights the economic impacts of long-duration, widespread power interruptions and investments to mitigate such interruptions.[51] This work is extended to large-scale economic modeling to estimate the indirect costs of an interruption, which works well at the regional level, but LBNL notes that further development is needed to improve a representation of resilience.[63] Putting all of this work on economic impacts of interruptions together, LBNL has developed a relevant tool for analyzing electric outages, the ICE calculator.[64] The tools they have developed could be used to help measure the impact of outages beyond traditional reliability metrics.

Overall, LBNL's work on valuation of the costs of interruptions could be very useful if built into a framework of resilience, but its current work applies more directly to traditional reliability and historical considerations of resilience (component hardening, etc.) rather than holistic definitions. LBNL finds that the costs of investments in reliability are well understood, but the benefits of such investments are difficult to monetize. Although economic effects for reliability are important, other considerations for utilities matter, including political incentives.[56] These findings are likely true for resilience as well.

Argonne National Laboratory

ANL centers the bulk of its relevant work on resilience for critical-infrastructure protection, with a few side initiatives towards power systems. They view resilience as a necessary focus in risk management and infrastructure protection.[65] ANL develops its own definition of resilience as "the ability of an entity—e.g., asset, organization, community, region—to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance" (Figure 18).[66] In developing this definition, ANL claims that the definition of resilience should be independent of the object of analysis, and the same definition should be used in all decision-making processes. They develop their definition specifically to separate resilience from protection and vulnerability.

[57] Mills, E. and R. Jones, "An Insurance Perspective on U.S. Electric Grid Disruption Costs," *The Geneva Papers on Risk and Insurance—Issues and Practice* 41, no. 4, 2016: 555–586.

[58] Sullivan, M., M. T. Collins, J. Schellenberg, and P. H. Larsen, *Estimating Power System Interruption Costs: A Guidebook for Electric Utilities*, Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory, 2018.

[59] Larsen, P. H., A. H. Sanstad, K. H. LaCommare, and J. H. Eto, *Frontiers in the Economics of Widespread Long-Duration Power Interruptions: Proceedings from an Expert Workshop*. Berkely, CA: Lawrence Berkely National Laboratory, 2019.

[60] LaCommare, K. H. and J. H. Eto, *Cost of Power Interruptions to Electricity Consumers in the United States* (U.S.), Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory, 2006.

[61] Larsen, P. H., B. Boehlert, J. H. Eto, K. Hamachi-LaCommare, J. Martinich, and L. Rennels, *Projecting Future Costs to U.S. Electric Utility Customers from Power Interruptions*, Berkeley, CA: E.O. Lawrence Berkeley National Laboratory, 2018.

[62] Sullivan, M. J., J. Schellenberg, and M. Blundell, *Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States*, Berkeley, CA: Erst Orlando Lawrence Berkeley National Laboratory, 2015.

[63] Sanstad, A. H., *Regional Economic Modeling of Electricity Supply Disruptions: A Review and Recommendations for Research*. Berkeley, CA: Ernst Orlando Lawrence Berkeley National Laboratory, 2016.

[64] *ICE Calculator*, Berkeley National Laboratory, undated. Retrieved from https://icecalculator.com/build-model?model=interruption.

[65] Petit, F. D., L. K. Eaton, R. E. Fisher, S. F. McAraw, and M. J. Collins-III, "Developing an Index to Assess the Resilience of Critical Infrastructure," *International Journal of Risk Assessment and Management* 16, 2012: 1–3.

[66] Carson, L., G. Bassett, W. Beuhring, M. Collins, S. Folga, B. Haffenden, and R. Whitfiled, *Resilience: Theory and Applications*. Argonne National Laboratory, 2012.

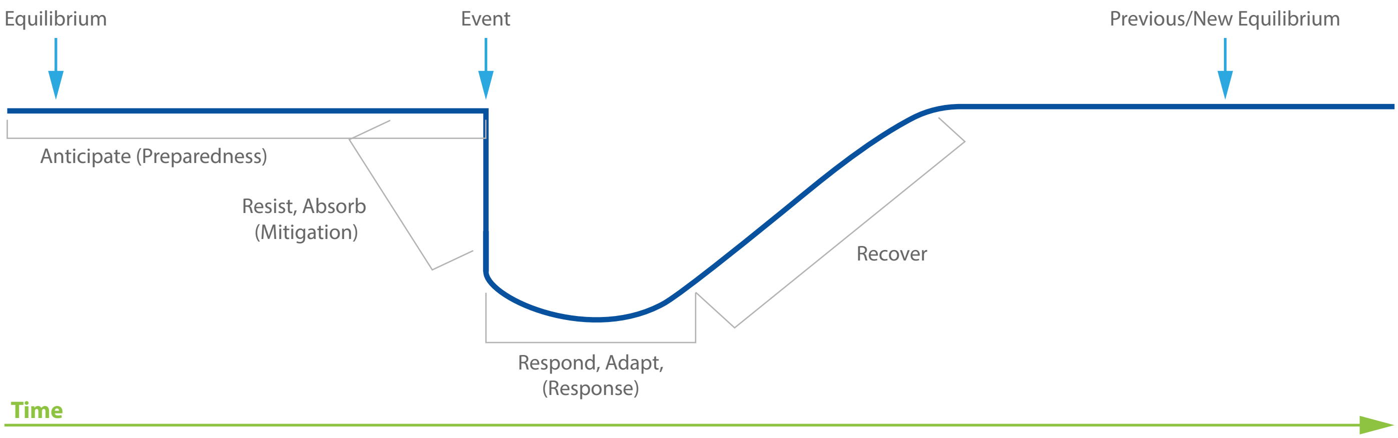

Figure 18. Components of resilience and the timing of an adverse event, according to ANL definition, adapted from [66].

ANL has developed a resilience index (RI) that uses data collected through a modified version of the DHS Enhanced Critical Infrastructure Protection (ECIP) program.[65] [66] The RI is derived from three categories: robustness, resourcefulness, and recovery.

1. Robustness refers to "the ability to maintain critical operations and functions in the face of a crisis" and is seen as protection and preparation of a system facing a specific danger
2. Resourcefulness is "the ability to skillfully prepare for, respond to, and manage a crisis or disruption as it unfolds"
3. Rapid recovery is defined as "the ability to return to and/or reconstitute normal operations as quickly and efficiently as possible after a disruption."

The RI ranges from 0 (low resilience) to 100 (high resilience).[67] [68] This measure provides no guarantees of what will cause severe consequences or failures, but is, instead, a comparative tool that can guide prioritization of limited resources. The RI is further developed into the Resilience Measurement Index (RMI), which is composed of six elements aggregated into four major (Level 1) components: preparedness, mitigation measures, response capabilities, and recovery mechanisms. This addition is intended to promote an all-hazards approach and support decision making for risk management, disaster response, and business continuity. Each component has subcategories, eventually working down four levels. Each level is given a score, which is formed by a weighted average of its sublevel components. Each component is weighted by subject-matter experts to determine its relative importance to a facility's resilience. Examples from different levels are shown in Figure 19, Figure 20, and Figure 21. All data and levels of information used for the RMI are presented on an interactive, Web-based tool called the Infrastructure Survey Tool (IST) RMI Dashboard. This can be used to provide information about a facility's resilience at a specific point in time, provide information to owner/operators about a facility's status relative to those of similar assets, and create scenarios and assess the implementation of resilience measures.

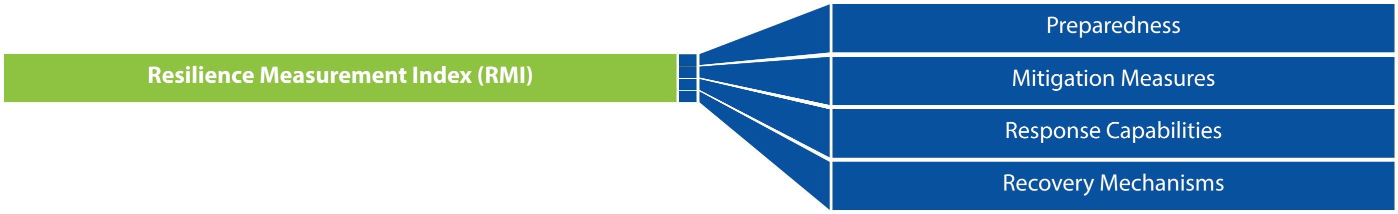

Figure 19. ANL RMI Level 1 components, adapted from [68].

[67] Fisher, R., G. Bassett, W. Buehring, M. Collins, D. Dickinson, L. Eaton, and J. Peerenboom, *Constructing a Resilience Index for the Enhanced Critical Infrastructure Protection Program*, Argonne: Argonne National Laboratory, 2010.

[68] Petit, F.D., et. al., *Resilience Measurement Index: An Indicator of Critical Infrastructure Resilience*, Argonne National Laboratory, 2013.

Major Level 1 and Level 2 Components Constituting the RMI

Level 1	Preparedness	Mitigation Measures	Response Capabilities	Recovery Mechanisms
Level 2	a. Awareness (2)* b. Planning (4) *() denotes number of subcomponents	a. Mitigating Construction (4) b. Alternate Site c. Resources Mitigation Measures	a. Onsite Capabilities (2) b. Offsite Capabilities (3) c. Incident Management and Command Center Characteristics (2)	a. Restoration Agreements (2) b. Recover Time (2)

Figure 20. ANL RMI Level 2 components, adapted from [67].

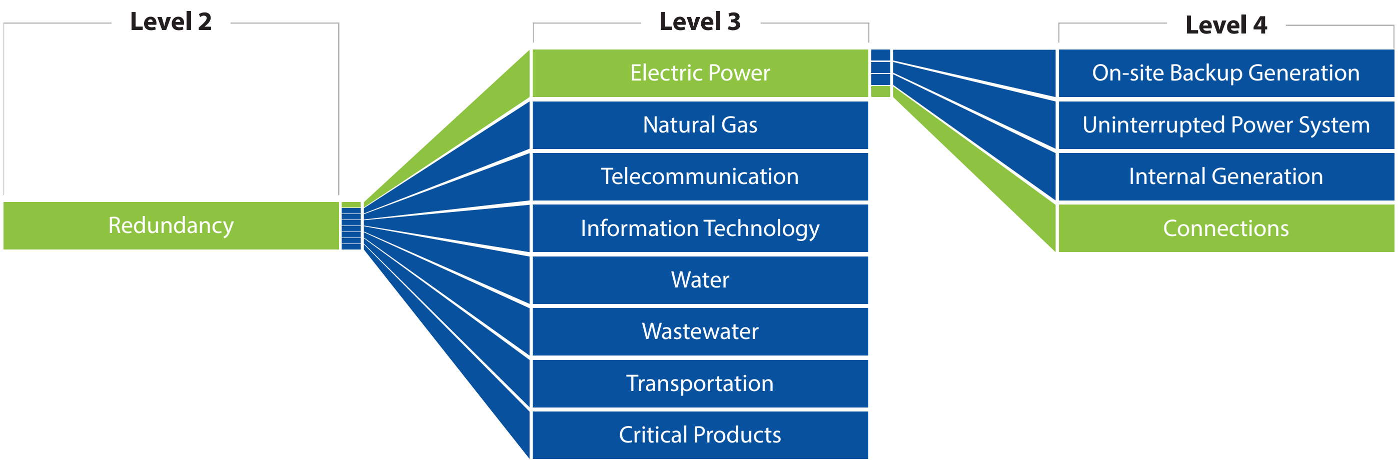

Figure 21. Example Level 3 and 4 components for electric power, adapted from [66]

In ANL's work, the RMI takes place in conjunction with the Protective Measurement Index, which assesses security, and the Criticality Measurement Index, which assesses the importance of a facility.[69] These three, together, are used to assist in the risk management of critical infrastructure, as seen in Figure 22.

Risk Management

Figure 22. DHS and ANL risk-management framework with RMI, adapted from [68].

[69] Fisher, R. and M. Norman, "Developing Measurement Indices to Enhance Protection and Resilience of Critical Infrastructure and Key Resources," *Journal of Business Continuity & Emergency Planning* 4 no. 3, 2010: 191–206.

In addition to its RMI, ANL has developed an optimization framework that is capable of modeling and prioritizing high-consequence failure points across critical infrastructure systems.[70] This framework can be applied to any infrastructure at the system level or the interdependent system-of-systems level. In this line of work, ANL claims that protecting critical infrastructure should focus on identifying and prioritizing potential failure points that would have the most-severe consequences. This can inform targeted planning and investment decisions.

With regard to energy-system applications, ANL explores an all-hazards approach to resilience. Its work discusses key electric-grid threats, hazards, and vulnerabilities, and describes resilience enhancement options.[71] ANL breaks threats into three categories: natural hazards, direct intentional threats, and other threats, hazards, and vulnerabilities. They also describe challenges and gaps in addressing resilience: predictability of storms and system responses to climate change, cost recovery and stranded investments, communication and workforce, coordination and collaboration, governance gaps, future threats and hazards, and barriers to enhancing resilience, including policy barriers, cost, uncertainty regarding dependencies and interdependencies, and uncertainty in threats and hazards. The primary research goals on behalf of utilities are to protect the system, reduce the impact of damage sustained, reduce the areas affected by damage, and improve restoration time. Historically, focus has been on component hardening against natural hazards; however, the most significant investments utilities are making toward resilience now include the installment and implementation of advanced meters and smart-grid technology.

COMMONALITIES

Step 3: Identify Characteristics of Resilience for EEDS

Each national laboratory has some level of work in resiliency that demonstrates high-level policy concern with recent high-impact weather events and cyber-physical threats and the impact these have on society and critical infrastructure. It is important to note that there are some consistent trends and areas of work that highlight consistent thought and advancement of resiliency work. One of these areas addresses a characteristic of resilience that we term the "distinctiveness" quality. This quality reflects the difficulty in applying resilience metrics broadly, the widely varied risk perception of stakeholders, the varied range of potential consequences to a system based on events, and the large set of potential mitigation strategies. This distinctiveness quality is the primary driver demonstrating the need to establish a resilience process or methodology that can be applied to any system, any set of stakeholders, and any set of events.

Another area of commonality is the discussion of resilience versus reliability within EEDSs. Each of the national labs recognizes the difficulty of aligning reliability with resilience and identifying the differences between high-probability, low-consequence and low-probability, high-consequence events. There is also recognition that resiliency expands discussion to degraded states, and this is not the case in considerations of reliability.

Finally, there is general acceptance in the national labs of the resilience trapezoid model. It has different names under different laboratories; however, there is general overall acceptance of the phases of the trapezoid and the ability to determine metrics directly related to the model describing the system performance before, during, and after disturbances.

> **"The resilience of an EEDS is described as a characteristic of the people, assets, and processes that make up the EEDS and its 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."**

DEFINING RESILIENCE OF AN ELECTRICAL ENERGY DELIVERY SYSTEM

From the industry, regulator, and national-laboratory work surrounding the resilience of critical infrastructure, the offered definition applies well to electrical-energy delivery. What is clear is the need for a process and methodology to examine threats, consequences, risks, and ultimately mitigation efforts to improve resiliency. There are close alignments to existing work in reliability of EEDSs, specifically in defining the type to threats and a divergence from reliability in examining failure

[70] Verner, D., F. Petit, and K. Kim, "Incorporating Prioritization in Critical Infrastructure Security and Resilience Programs," *Homeland Security Affairs* 13, 2017.
[71] Finster, M., J. Phillips, J., and K. Wallace, *Front-line Resilience Perspectives: The Electric Grid*. Argonne: Argonne National Laboratory, 2016.

and recovery of a system. The resilience of an EEDS is characterized by the function of the system—i.e., delivery of electrical energy. Thus, performance of the system is related to delivery of electricity, ranging from generation to load, and all devices and characteristics of that electrical system. In directly applying the previous definitions of resilience to an EEDS, we should consider a set of components that make up the EEDS including:

- Assets: generation, transmission, distribution facilities, and supporting devices
- Operational aspects: people, processes, and supporting resources
- Stakeholders: customers, load, owners, investors.

Hence, we can offer the following description of the resilience of an EEDS:

The **resilience of an EEDS** is described as a characteristic of the people, assets, and processes that make up the EEDS and its 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.

"Resilience metrics should help the measured resilience goals and overall ability and performance of the system."

RESILIENCE METRICS

Now that a definition of resilience for EEDS has been established based on a critical review of industry, national lab, and regulatory work in the area, relevant metrics to classify and measure resilience can be discussed. As stated previously, the "distinctiveness" quality of resilience makes it difficult to apply the same metrics broadly to all systems. The range of risk perception, potential consequences, and potential mitigations will all affect which metrics are most useful and most relevant for an individual system. At the end, resilience metrics should be established by the stakeholders within a resilience-framework methodology to support resilience goals and associated risks.

Resilience metrics have not yet reached a point of general acceptance or regular use within industry today—as distinct from reliability, which has generally well-accepted metrics and industry-specific uses—e.g., the System Average Interruption Duration Index and System Average Interruption Frequency Index—within the electrical-energy delivery industry. In fact, the IEEE publishes an entire book on power system reliability called the IEEE Gold Book—Power System Reliability. Resilience metrics have yet to achieve this level of acceptance and industry usage. Hence, application of resilience to planning, goals, and risk evaluation will eventually need to produce more well-accepted metrics.

Many approaches and discussions exist on resilience metrics.[7] [28] [46] [47] [72] [73] [74] [75] Our goal in this section is to describe the categories and characteristics that resilience metrics should contain. Development, tracking and refining metrics for resiliency efforts can provide feedback to future efforts and provide performance information during events. They can also be used to help categorize and prioritize investments.[35] In this section, properties of metrics are discussed first, then desirable characteristics of metrics used for resilience. Finally, examples of resilience metrics are provided, and key metrics for distributed wind applications are called out.

METRIC PROPERTIES

When categorizing metrics for resilience, two relationships can aid in the process: **direct** and **indirect** metrics. Any metric that, when analyzed, applies directly to resilience trapezoid characteristics holds a direct relationship. An indirect relationship is any metric that supports the direct metrics with an input. For example, in an EEDS, a direct resilience metric could represent the number of customers with service after the disruption, during adaption, and after recovery, while an indirect metric could be the number of dispatched trucks

[72] Ayyub, B. M. "Systems Resilience for Multihazard Environments: Defintions, Metrics, and Valuation for Decision Making," Risk Analysis 34, no. 2, 2013: 340–355.

[73] Ayyub, B. M., "Practical Resilience Metrics for Planning, Design, and Decision Making," *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems Part A Civil Engineering*, 2015.

[74] Vulgrin, E. D., "Advancing Cyber Resilience Analysis with Performance Based Metrics from Infrastructure Assessment," *International Journal of Secure Software Engineering*, Special Edition on Cybersecurity Scientific Validation, July 13, 2012.

[75] Vulgrin, E. D., M. J. Baca, M. D. Mitchell, M. D. and K. L. Stamber, "Evaluating the Effect of Resource Constraints on Resilience of Bulk Power System with an Electric Power Restoration Model," *International Journal of System of System Engineering*, 2014: 68–91.

Resilience Planning and Goal Metrics			
Direct Metrics	Customers Served	Customer-Hours of Lost Electricity Service	Fossil-Fuel Dependency
Indirect Metrics	Generators Required to Support Load	Reduced Wet Stacking—O&M	Increased Efficiency of Diesel Generator Sets

Figure 23. Metrics for resilience planning and goals.

In addition to direct and indirect properties, resilience metrics can be both **qualitative** and **quantitative**. *Quantitative metrics* are based on the quantification of system performance. Quantitative metrics are useful when evaluating certain resilience measures' effectiveness or comparing the resilience levels among different systems. Resilience is quantitatively evaluated based on the reduced magnitude and duration of deviations from the targeted during recovery. In this example the slope of recovery of the resiliency trapezoid could be impacted by this indirect metric of dispatched trucks. See Figure 23 for more examples.

A direct resilience metric could be represented by, for example, customers restored to service after an outage, as in the example of Puerto Rico after Hurricane Maria in Figure 24.[76] [77] This figure represents the percentage of customers returned to service each day after Maria. Another presentation of a direct resilience metric presented by the same researchers is customer-hours of lost electricity service (CHoLES), which presents a potential method to calculate financial losses under FEMA's Public Assistance Program and Policy Guide and disaster recovery, seen in Figure 25.[78] An indirect resilience metric in this case might be the number of transformers flooded during a storm, which can directly affect the number of customers with service.

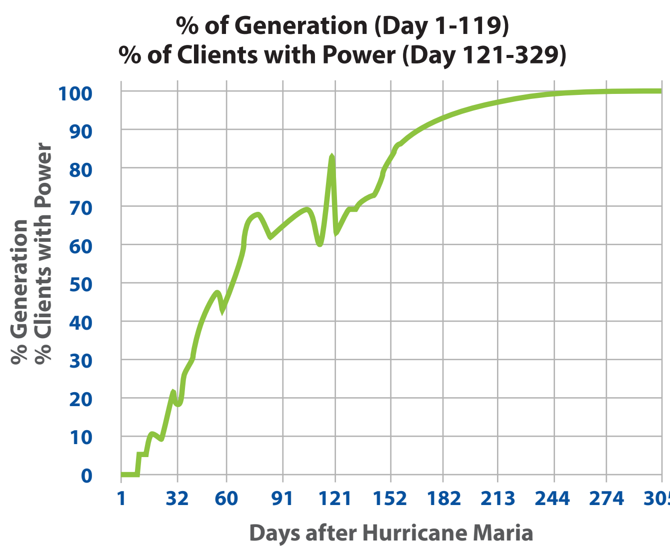

Figure 24. Percentage of customers with service, adapted from [77].

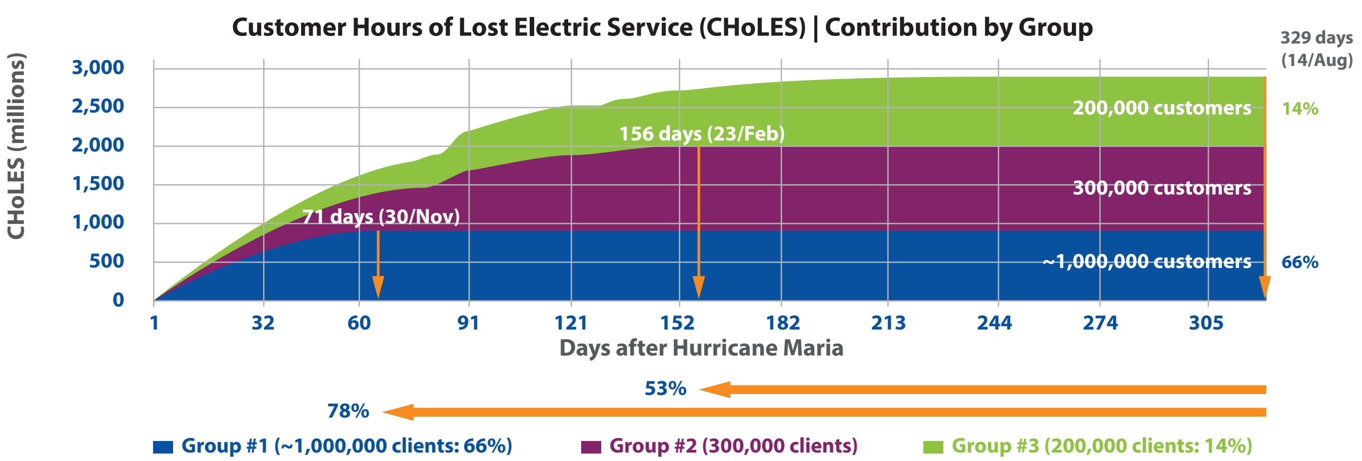

Figure 25. Customer hours of lost electric service, adapted from [77]

[76] Castro Sitiriche, M. J., *Solar for All: Jurutungo Power and CHoLES*, Solar Power Puerto Rico. San Juan, 2019.

[77] Castro-Sitiriche, M.J., Y. Cintrón-Sotomayor and J. Gómez-Torres, "The longest power blackout in history and energy poverty", Proc. 8th Int. Conf. Appropriate Technol., pp. 36-48, Nov. 2018.

[78] FEMA, *Public Assistance Program and Policy Guide*. Washington D.C.: FEMA, 2018.

or acceptable performance. Quantitative resilience metrics should be: 1) performance-related, 2) event-specific, 3) capable of considering uncertainty, and 4) useful for decision-making. They are effective for ranking different scenarios against each other, whether that is comparing different potential upgrades or comparing performance of identical systems against different disruptive events.

Qualitative metrics usually evaluate the power system's resilience alongside other interdependent systems, such as information systems, fuel supply chain, and other such infrastructures. These metrics may evaluate resilience capabilities such as preparedness, mitigation, response, and recovery (e.g., the existence of emergency plans, personnel training, repair crew availability, and other similar measures). Qualitative metrics are effective for describing scenarios and disruptive events. It may be difficult or impossible to enumerate all possible effects of different disruptive events, so qualitative metrics can help categorize disturbances or levels of impact.

Another distinction we can make is **operational** resilience metrics versus **infrastructure** resilience metrics. Operational resilience metrics determine whether operational strength and capabilities are maintained. Infrastructure resilience define whether physical and system strength is maintained.

RESILIENCE METRIC CHARACTERISTICS

Resilience metrics will represent different aspects of the system, components, and operations. They can be measured at multiple levels, from individual components to systemwide. Because of the range of applications that must be covered, there are multiple metrics needed to measure the resilience of any system, and each set of metrics identified will be unique to the resilience goals determined by stakeholders. Resilience metrics should help the measured resilience goals and overall ability and performance of the system. Additionally, resilience metrics should facilitate the appropriate measurement of improved resilience strategies, which should be founded on base cases and improved cases. Here, we identify key characteristics that should be met by the set of metrics chosen to evaluate a system. This list is heavily based on work by H. Raoufi et al.[79] and Watson et al.[47]:

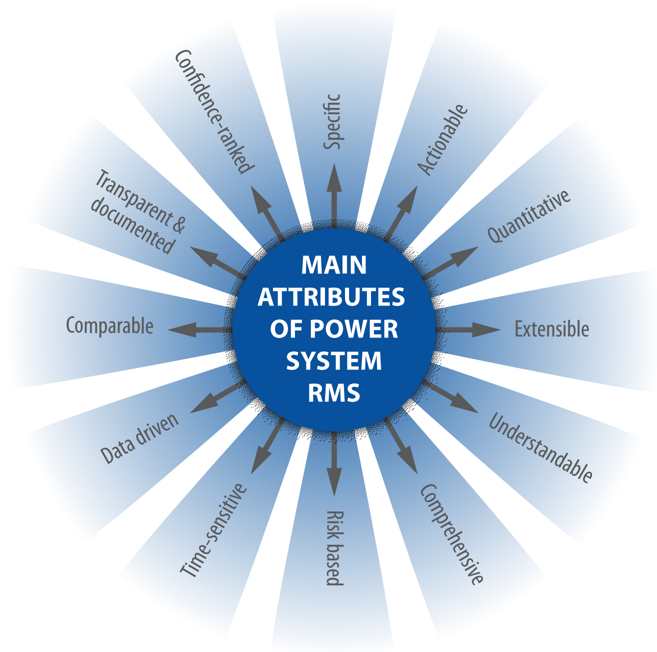

Figure 26. Desirable characteristics of resilience metrics.

1. ***Specific:*** *The metrics should align with specific resilience components in compliance with the definition.*
2. ***Actionable:*** *Metrics should be useful for decision-making. Decisions of interest include system planning, operational decisions, or policy making.*
3. ***Quantitative:*** *At least some of the metrics should be measureable or have ordinal representation in order to be useful for data analytics and to educate investment decisions.*
4. ***Extensible:*** *The metrics should be scalable to reflect different time periods, electrical landscapes, and geographical areas. The metrics should be valid across a wide range of technologies and adaptable to new technologies.*
5. ***Understandable:*** *Metrics should be readily understood by different audiences.*
6. ***Comprehensive:*** *Metrics should consider the initial state, performance at each state during a disturbance event, and the duration of each state.*

[79] Raoufi, H., V. Vahidinasab, and K. Mehran, "Power System Resilience Metrics: A Comprehensive Review of Challenges and Outlook," *Sustainability, Special Issue Energy Systems Integration: From Policy-Makers to Consumers*, 2020. 10.3390/su12229698.

7. ***Risk based:*** *The metrics should be related to particular risks that are relevant to the system. The metrics may relate to a specific disturbance or to potential consequences.*

8. ***Time-sensitive:*** *The metrics should reflect consequences that occur at different time scales, and should consider the recovery period, either directly or indirectly.*

9. ***Data driven:*** *The metrics selected should be informed by real data from the system. If data to support a certain metric is unavailable, the necessary measurement infrastructure must be added, or confidence in the metric will suffer.*

10. ***Comparable:*** *Applying the same metric across different scenarios (before and after enhancements, under different operating conditions) should provide valuable information.*

11. ***Transparent and documented:*** *Metrics should be well documented to be used or checked by others.*

12. ***Confidence-ranked:*** *The metrics should have an associated level of confidence. The uncertainty associated with a metric value will help inform decisions based upon that metric. The concept of probability is difficult to define for many HILF events, but to the extent possible, probabilistic estimations should inform the confidence in the resulting metric.*

Additional work from H. Raoufi et al. recommends that metrics should be sensitive to the spatial-temporal effects of a disturbance. For example, this can mean taking into consideration that the value of load lost is time dependent, i.e. lost load 5 minutes after an outage is different in value than 10 days of an outage.

While many metrics exist, there is no single metric or set of metrics for each purpose. Different metrics are needed to understand resilience at different levels of electrical energy delivery systems, and opportunities exist to improve metrics for each purpose. The categories and classifications for resilience metrics provide a good starting point for organizations considering how to leverage the data and metrics they already collect to evaluate resilience, and to determine gaps that they may need to fill for comprehensive resilience analysis. In the absence of standardized resilience metrics, stakeholders should identify resilience metrics that reflect these attributes and support the system's specific resilience goals.

RESILIENCE METRIC EXAMPLES

Many metrics have been proposed and used in research documents, many of which fit the characteristics described above. Figure 27 is based on work by Willis and Lao[30] and shows examples of resilience metrics categorized in three dimensions: resolution, type, and maturity. We have highlighted metrics that may be particularly useful for systems that include distributed wind. These example metrics are grouped together based on the second dimension, type, in five categories:

- Inputs: Input metrics define what is available to support resilience. In the context of energy systems, examples of inputs include budgets, equipment, spare parts, and personnel to support recovery operations. On their own, these inputs do not provide resilience unless they are organized to support functions or tasks.

- Capacities: Capacities metrics are the ways in which inputs are organized to support resilience. Examples of capacities for energy systems include response teams capable of repairing equipment, recovery plans that can be implemented following a disaster, or advanced technologies that can be used to reroute power and reconstitute portions of a grid during disruptions. Having these capacities in place is not the same thing as being able to use them, however.

- Capabilities: Capabilities metrics reflect how well capacities can serve a system when they are needed. Ultimately, capability metrics describe how proficiently tasks can be performed. Examples include the ability to detect leaks or outages, to repair damaged power lines or pipelines, or to restore power outages. Capabilities are ultimately desired because they improve system performance.

- Performance: Performance metrics describe what is produced by an engineered system. In the context of energy systems, examples of metrics include the amount of energy delivered or operating characteristics of the system, such as efficiency, reliability, fault tolerance, sustainability, or robustness.

Resilience Metrics

- Possible metric for distributed wind
- Common metric for distributed wind
- All other proposed resilience metrics

Inputs

- Energy feedstock
- Energy not supplied
- Energy storage
- Generators available
- Key replacement equipment stockpile
- Redundant power lines
- Reinforced concrete vs wood
- Siting infrastructures
- Underground, overhead, & undersea lines
- Unique encrypted passwords for utility smart distribution
- Workers employed
- Hydrophobic coating on equipment
- Distribution poles
- Number of transmission lines available
- Hierarchical levels

Capacity

- Communication/control systems
- Electrical protection and metering
- Equipment and positioning
- Flow paths, line flow limits
- Generation/load bus distribution
- Reserve/spare capacity
- Functional zones
- Substations, overhead lines, underground cables
- Hierarchical level (I, II, III)
- Operator training
- Mutual assistant agreements
- Transformers
- Tree trimming metrics

Capabilities

- Ancillary service
- Hazard rate relating function
- Line mitigation
- Load biasing
- Net-ability
- Path redundancy
- Protective and switching devices
- Viability of investments
- Adequacy
- Congestion control

Performance

- Coefficient of variation of the frequency index of sags
- Control performance
- Standard 2 violations
- Bulk electric system reliability performance indices
- Derated power
- Dropped/lost phase
- Edge resilience trajectory
- Energy efficiency/intensity
- Failure rate
- Harmonic distortions
- Overhead and underground line segments
- Peak to peak voltage
- Phase imbalance
- Protective switching devices
- Rapid voltage changes
- Resilience indices
- Survivability
- SAIDI & SAIFI
- Unscheduled generator outages
- Voltage dips
- Voltage level variations
- Voltage sags/swells
- Voltage unbalance
- Average service availability index
- Average service interruption duration index
- Customer average interruption duration index
- Customer average interruption frequency index
- Customer experiencing longest interruption durations
- Customer experiencing multiple interruptions
- Customer experiencing multiple momentary interruptions
- Customers interrupted per interrupted index
- Economy
- Fairness
- Interrupted energy assessment rate
- Load point indices per customer
- Loss of offsite power
- Minimum level of service targets
- Momentary average interruption frequency index
- Security
- Transmission losses

Outcomes

- Load loss damage index
- Annual price cap
- Annual allowed revenue
- Cost of interruption
- Impact factor on the population
- Noise
- Long distance transmission cost
- Performance based regulation regard/penalty structure
- Price of electricity
- Value of lost load

Figure 27. Potential list of metrics for distributed wind systems, adapted from [30].

- Outcomes: Performance of energy systems depends on how the systems generate the outcomes that society is seeking to achieve. Resilience of energy systems can be measured by many outcomes, such as reduced damage from disasters, increased economic activity, or reduced deaths and injuries from disasters.

While we recommend the use of many metrics to customize measurements of resiliency for a specific system, there has also been research to combine metrics into larger paradigms to evaluate resilience. Recall from the national lab review part of this document that INL has developed the DIRE curve, which formalizes the concept of adjustment capacity,[16] and ANL has performed significant work to develop their RMI metric for resilience.[67 68 69] Outside of the national labs, Smith et al. propose a single resilience that calculates the area enclosed by the trajectory through the operational state of the system during detection, mitigation, and recovery stages of a disturbance.[80] Similar work defines a resilience metric as the ratio of partial recovery to full functionality at any stage during a disturbance.[81] Clark and Zonouz describe a resilience metric that quantifies the ability of the system to recover from an attack based on the amount of control effort (cost) required to steer the system back to a stable equilibrium state.[82] These combined metrics and resilience index works can be useful to jointly use the underlying direct metrics to inform certain decisions. They may be sufficient on their own for certain texts, but it is more likely that even the combined metrics will need to be supplemented by metrics in other categories to gain full coverage of the desired resilience metric characteristics.

Not every example will apply to every system or relate to the defined resilience goals, but stakeholders can use these attributes and categories to guide their choice of direct and indirect metrics. The chosen resilience metrics should allow stakeholders to effectively measure, evaluate, and compare the resilience of their system.

[80] Smith, P. et al., "Network resilience: a systematic approach," *IEEE Communications Magazine*, vol. 49, no. 7, pp. 88-97, July 2011.

[81] Albasrawi, M. N., N. Jarus, K. A. Joshi, and S. S. Sarvestani, "Analysis of Reliability and Resilience for Smart Grids," Proceedings of the 2014 IEEE 38th Annual International Computers, Software and Applications Conference, 2014.

[82] Clark, A. and S. Zonouz, "Cyber-Physical Resilience: Definition and Assessment Metric," IEEE Transactions on Smart Grid, vol. 10, no. 99, pp. 1–1, 2017.

APPLICATION TO DISTRIBUTED WIND

After considering the broad range of work in resilience and, in particular, resilience of an EEDS, we now consider how our understanding of resilience applies to distributed wind. We identify characteristics of distributed wind that make it a good candidate for enhancing the resilience of a system and examine ways that distributed wind already applies resilience strategies.

The very nature of distributed wind lends itself to adding resilience to a system. The definition states that distributed wind may be directly connected to distribution feeders or connected behind-the-meter or off-grid, and that power produced is consumed locally. In the event of disruptive events like lost distribution or transmission lines, failure of remote power sources, or cascading failures caused by a targeted cyberattack, the local availability of wind power prepares the system to better handle the disturbance. Power output from wind turbines can fluctuate to a high degree and have large ramping rates. These factors enable wind units to supply power more quickly than traditional generation units.[83] This can aid with the rapid recovery and adaptation portion of resilience. Turbine technology has advanced to a point at which life expectancy exceeds 25 years, and maintenance and operations costs are reasonable, which further makes wind an efficient and viable source to use in planning.[84] Distributed wind can be a key part of microgrids that can, in turn, operate defensively or in islanded mode after a disaster or large contingency takes down distribution lines.[85] We can consider both static and dynamic microgrids as potential applications.[86] This can help enhance survivability and accelerate restoration through proper planning. Distributed wind can also be used for load shifting.[87]

Extensive research has studied how distributed generation, and in some cases distributed wind in particular, can be used to add resilience and aid in the recovery from a disruptive event. Distributed wind has been proposed as a backup generation source during hurricane-induced outages. In one case study, a single distributed wind unit was expected to be capable of providing backup power to 85% of customers connected to a distribution grid including the distributed-wind unit, reducing overall outages in the county by 8.5%.[88] This shows the ability of the distributed wind assets to adapt to disruptive events and maintain an acceptable state of operation for more end users. Distributed wind has also been proposed as part of the transmission-level black-start plan. In this context, distributed-wind units could be used as non-black-start units prior to load pickup.[89]

"The very nature of distributed wind lends itself to adding resilience to a system."

Additional work has studied the ways to make distributed wind more reliable, which in turn makes it a better candidate to use in preparation and adaptation for resiliency toward disruptive events. Tuned liquid column dampers have been proposed to increase turbine reliability by reducing the structural vibrations and decreasing the probability that a turbine is unavailable when it is needed. Considerations like these are important because assets (e.g., turbines), not just the overall grid, must be able to adapt to changing conditions. Renewable sources like solar and wind are exposed to the environment more than traditional thermal power sources, which could possibly lead to a decrease in resilience if plans call for distributed wind to be used during extreme

[83] Golshani, A., W. Sun, Q. Zhou, Q. P. Zheng, and Y. Hou, "Incorporating Wind Energy in Power System Restoration Planning," https://www.mdpi.com/2071-1050/12/22/9698/htm 10, no. 1, 2017: 16–28.

[84] duPont, H. G., "Wind turbine generators gain acceptance in distributed generation applications," *IEEE Power Engineering Society General Meeting*. Toronto, Ont. Canada, 2003.

[85] Jin, T., N. Mai, Y. Ding, L. Vo, and R. Dawud, "Planning for Distribution Resilience under Variable Generation: Prevention, Surviving and Recovery," *IEEE Green Technologies Conference (GreenTech)*, Austin, TX, 2018.

[86] Gilani, M. A., A. Kazemi, A., and M. Ghasemi, "Distribution system resilience enhancement by microgrid formation considering distributed energy resources," *Energy* 191, no. 15, 2020.

[87] Garba, M., M. A. Tankari, and G. Lefebvre, "Using of distributed energy ressources for microgrid resilience achieving," *IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)* San Diego, CA, 2017.

[88] Mensah, A. F., *Resilience Assessment of Electric Grids and Distributed Wind Generation under Hurricane Hazards*, Houston, TX: Rice University, 2015.

[89] Su, J., P. Dehghanian, M. Nazemi, and B. Wang, "Distributed Wind Power Resources for Enhanced Power Grid Resilience," *North American Power Symposium (NAPS)*, Wichita, KS, 2019.

events, but do not consider the ability of the turbine itself to survive the event.[90] Power-generation stations are not often included in models of damage to the grid after an event like a hurricane because they typically have high structural protection[91] Because this is not a part of traditional analysis, it is important to consider in future case studies of using distributed wind to plan for and adapt to extreme weather events. One example of how this can be done is using the resilience trapezoid to calculate resilience of a microgrid, including detailed models of wind turbines.[92]

One of the primary goals of this paper is to examine the impact of distributed wind on the resilience of an isolated electrical system. It is important to extract from the definitions and metrics discussion those metrics that can be relevant to wind and isolated electrical systems. At the highest level, direct metrics that support the characteristics of the resilience trapezoid are relevant to the system, but how they can be applied to distributed wind will be dependent on the events and systems characteristics. This aspect underscores the need for an application of a resilience framework on that system and with the stakeholders' input. In isolated EEDSs, generation tends to be fossil-fuel based and operated in coordinated dispatch in parallel with multiple genset controls. Renewable resources tend to provide a shift in approach to generation balancing and fuel transport, storage, and usage. This is one area that can be examined under a resilience lens—the availability of fuel and reduction in transport, storage, and usage for generation because fuel shortages with single-source generation can provide significant probabilistic events for resilience analysis. Additionally, renewable resources bring more than just electrical generation; the supporting power electronics of both solar and Type 4 wind turbines can provide real and reactive power support for voltage and frequency. Hence, as different events are considered under a resilience planning exercise and resilience goals are established, it is possible to apply metrics, as listed in Figure 27.

Future work should consider the resilience of distributed wind from a few different perspectives:

1. Resilience of individual distributed wind systems during disruptive events
2. Resilience of distribution systems that look to integrate more distributed wind
3. Resilience of transmission systems that contain higher penetrations of distributed wind as part of the generation profile
4. Resilience with hybrid application including inverter-based resources (IBRs) and installed conventional generation
5. Resilience of renewable generation via IBR and hydrogen production.

Different metrics may be applied, depending on the scope of the study, but any framework developed should consider these multiple tiers of resilience for distributed wind: the identification, preparation, adaptation, and recovery phases of resilience. Different stakeholders will be involved at separate tiers, and the assets and operational capabilities available will also change. This motivates the need for a flexible framework that can be adapted for these different tiers of consideration while maintaining continuity consonant with an overall understanding of resilience.

[90] Watson, E. B. and A. H. Etemadi, "Modeling Electrical Grid Resilience Under Hurricane Wind Conditions With Increased Solar and Wind Power Generation," *IEEE Transactions on Power Systems* 35, no. 2, 2020: 929–937.

[91] Winkler, A. I., L. Dueñas-Osorio, R. Stein, and D. Subramanian, "Performance assessment of topologically diverse power systems subjected to hurricane events," *Reliability Engineering & System Safety* 995, no. 4, 2010: 323–336.

[92] Yang, L., S. Fan, G. He, and Z. Wang, "Evaluation of Resilience in Grid-connected Microgrids under Extreme Disasters," *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Kota Kinabalu, Malaysia, 2018.

CONCLUSION AND NEXT STEPS

The goal of this effort was to understand clearly and define the term resilience in order to further an understanding of resilience in EEDSs. This paper emphasizes that there has been significant research work around resilience, but few industry best practices, standards, and metrics are generally accepted. This is demonstrated by the significant difference surrounding resilience within the electrical-energy delivery industry, as seen in the positions represented to FERC Docket No. RM18-1-000 with respect to reliability.[7 28] Additionally, this paper highlights two areas that separate resilience from reliability:

1. Type of events examined (high-probability, low-impact vs. low-probability, high-impact events)
2. The failure of reliability to consider system failure and resilience.

One important characteristic in resilience is the unique needs and perspectives of different systems, geographies, resources, stakeholders, perceived risks, and consequences, which we term the distinctiveness property. These needs drive the requirement to have a resilience framework or methodology that can be followed by organizations. As emphasized by the IEEE Power and Energy Society, "a comprehensive approach to developing a resilience plan must include the active involvement of diverse stakeholders." The process or methodology should be cyclic, based on finite resources and time—hence, continual evolution of the resilience framework encompassed in risk management and capital investment.

Direct and indirect metrics were defined for resilience. Direct resilience metrics provide representation of the resilience trapezoid, and indirect resilience metrics provide any role supporting these direct metrics. The IEEE Power and Energy Society notes, "Therefore, it is not possible to have simple, industry-accepted resilience metrics addressing all possible events." In other words, resilience metrics will be dependent upon resilience goals established by stakeholders for each different system, establishing a foundational principle of resilience upon which metrics are dependent specific to different systems, geography, resources, stakeholders, perceived risk, and consequences.

It is important to examine the state of resilience work within industry against the background of other fields that may be similar. Cybersecurity has many aspects similar to resilience, including the area of methodology or framework, such as the National Institute for Standards and Technology's cybersecurity framework or the cyclic process of cybersecurity risk management. Within these, evolving threats must be continually examined and assessed for risk and consequence. It is the opinion of this team that resilience will eventually mature to the present state of cybersecurity as more organizations include resilience in all planning aspects and continue to evaluate events, risks, and consequences. It is our goal to further adapt and refine a resilience framework that can be directly used by an organization to establish the resilience process for risk management and capital investment spurred by resilience goals and metrics established by stakeholders.

ACRONYMS

ANL	Argonne National Laboratory
APPA	American Public Power Association
BCA	Benefit Cost Analysis
BHE	Berkshire Hathaway Energy
CHoLES	Customer Hours of Lost Electric Service
DER	Distributed energy resources
DHS	Department of Homeland Security
DIRE	Disturbance and impact-resilience evaluation
DOE	Department of Energy
DRC	Designing Resilient Communities
ECIP	Enhanced Critical Infrastructure Protection
EEDS	Electrical energy distribution systems
EPA	Energy Policy Act of 2005
EPRI	Electric Power Research Institute
ESDM	Energy Surety Design Methodology
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
HILF	High impact, low frequency
ICE	Interruption Cost Estimator
ICPIA	Integrated Cyber Physical Impact Analysis
IEEE	Industrial and Electronics Engineering
INL	Idaho National Laboratory
IO	Input-output
IRAM	Infrastructure Resilience Analysis Methodology
IRP	Integrated Resource Plan
ISO	Independent system operator
IST	Infrastructure Survey Tool
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
NARUC	National Association Regulatory Utility Commissioners
NATF	North American Transmission Forum
NERC	National Electric Reliability Council
NOPR	Notice of Proposed Rule
NREL	National Renewable Energy Laboratory
PJM	Pennsylvania, Jersey, Maryland Power Pool
PNNL	Pacific Northwest National Laboratory
PSEG	Public Service Enterprise Group
RAP	Resilience Analysis Process
ReCIS	Resilient Controls and Instrumentation Systems
REHS	Renewable-energy hybrid system
RES	Resilient Energy Systems
RFI	Request for information
RI	Resilience Index
RMI	Resilience Measurement Index
RTO	Regional transmission operator
SNL	Sandia National Laboratories
VOLL	Value of lost load
WETO	Wind Energy Technologies Office

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

Idaho National Laboratory
Infrastructure Security
Idaho Falls, Idaho 83415

https://resilience.inl.gov/miracl/

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

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC
INL/EXT-21-62149