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Resilient Electric Grid

Defining, Measuring, and Integrating Resilience into Electricity Sector Policy and Planning

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Summary

Traditionally, electric grid planning seeks to maintain safe, reliable, efficient, and affordable service for current and future customers. As policies, expectations of the energy system, and the threat landscape evolve, additional objectives for power system planners are emerging, including decarbonization, resilience, and equity. Renewable and clean energy goals, especially in the context of deep decarbonization strategies, are changing the mix of resources on the electric grid and prompting new considerations for grid architecture. The increased frequency and severity of extreme weather events over the last two decades, coupled with cybersecurity concerns, have elevated resilience as a key system need. More recently, there has been greater focus on equity and energy justice in grid planning to ensure that disadvantaged communities are not adversely affected by grid modernization and have equal access to its benefits. In response, new thinking around multi-objective decision planning is exploring improvements in grid planning processes to better integrate approaches to meet decarbonization, resilience, and equity objectives. To provide a foundation for this work, a series of white papers was produced to summarize these emerging objectives.

This white paper presents an overview of resilience in the context of electric grid policy and planning. It provides a working definition of resilience and a synthesis of current and emerging metrics to benchmark system performance, evaluate investments, and explore tradeoffs (Section 1.0). This paper also provides a discussion of the a) policy prioritization of resilience, with examples of relevant state legislation and executive orders, b) delegation of regulatory authority and development of grid planning guidance for resilience, and c) status of utility integration of resilience into grid planning processes (Section 2.0) and associated challenges and opportunities (Section 3.0). The key findings of this paper are summarized in Table S-1.

Table S-1. Summary Takeaways

	Findings
Section 1.0 Defining and Measuring Resilience for the Electric Grid	• Although many electric sector resilience metrics exist, there is a lack of standardization in metrics and measurement methodologies across generation, transmission, and distribution system planning. • Performance-based metrics enable measurement of grid resilience and evaluation of resilience investments. There are opportunities for incremental expansion of reliability metrics to better account for grid performance during long-duration widespread outages. Populating consequence-focused performance-based metrics and to assessing tradeoffs between resilience and other emerging objectives within grid planning processes are key analytical challenges.
Section 2.0 Integrating Resilience into Electric Grid Policy and Planning	• Resilience analysis is not well institutionalized in grid planning processes. Resilience investments have tended to occur in response to major outages, and prospective analyses of grid resilience to climate change and other hazards occurring outside of traditional planning processes. • Additional regulatory guidance is required to enable more robust integration of resilience into core grid planning analyses and investment prioritizations.

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Acronyms and Abbreviations

ConEd	Consolidated Edison
DERs	Distributed Energy Resources
FERC	Federal Energy Regulatory Commission
HECO	Hawaiian Electric Companies
IRP	Integrated Resource Planning
MOD-Plan	Emerging Grid Objectives and Multi-Objective Decision Planning
MWh	Megawatt Hour
NERC	North American Electric Reliability Corporation
PBR	Performance-Based Regulation
PREPA	Puerto Rico Electric Power Authority
PUC	Public Utility Commission
PURA	Public Utilities Regulatory Authority
QUALY	Quality Adjusted Life Year
RMI	Resilience Measurement Index
SoVI	Social Vulnerability Index
VoLL	Value-of-Lost-Load

Contents

Figures

Tables

1.0 Defining and Measuring Resilience for the Electric Grid

1.1 Resilience Definition

Resilience is defined as the ability of the electricity system to "prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions," where disruptions include "deliberate attacks, accidents, or naturally occurring threats or incidents" [1, 2]. As depicted in Figure 1, resilience has a distinctive temporal and spatial scope, encompassing system performance over time (i.e., before, during, and after a disruptive event, relative to baseline system performance), where the system can be defined by grid infrastructure (e.g., generation, transmission, distribution system) or jurisdiction (e.g., city, state, nation) [3, 4]. Resilience is also inherently threat-driven, and utilities face different threats and vulnerabilities based on system characteristics [5]. For example, geographic location affects the probability of different types of natural hazards (e.g., hurricanes) and asset and infrastructure characteristics (e.g., extent of pole hardening) affect vulnerability to the impacts of natural hazards (e.g., flooding and sustained high windspeeds) [6].

Figure 1. Resilience Curve (Source: [3])

Quantifying resilience for the grid thus involves definition of the system, characterization of the threats, identification of resilience priorities, analysis of the vulnerability of grid assets and infrastructure to the specified threat, and assessment of the effects of impaired assets and infrastructure on system performance [3, 4]. Often resilience planning will focus on not only overall system performance, but also characterization of performance for priority loads—which may encompass critical facilities (e.g., hospitals, fire stations, police) and vulnerable populations—as well as the social and economic consequences of outages, as discussed in greater detail below.

Resilience planning has tended to be described as a focus on low frequency, high-impact events that result in comparatively longer and more widespread outages, however resilience can be applied to any event timescale. As technology provides more system capabilities, the ability to improve reliability during either "normal" or less frequent, longer-duration high-impact events becomes possible as we deploy resilience measures. A distinction between applying reliability metrics for "normal" events and resilience for high-impact events is arbitrary when in both cases the goal is to reduce the frequency and duration of outages under any condition. Resilience focuses on not only lessening the likelihood of outages, but also "limiting the scope and impact of outages when they do occur, restoring power rapidly afterwards, and learning from these experiences to better deal with events in the future" [5].

1.2 Resilience Metrics

Although there are a number of resilience metrics relevant to the electric power sector, in practice there is a lack of standardized resilience metrics and measurement approaches for electricity generation, transmission, and distribution systems [3, 7, 8, 9, 10, 11]. In contrast, reliability metrics are well institutionalized for both the bulk power and distribution system [5]. Bulk power system reliability metrics focus on resource adequacy and operating reliability, with probabilistic reliability indices defined by the North American Electric Reliability Corporation (NERC) and implemented by the Federal Energy Regulatory Commission (FERC) [12].[1] With respect to the distribution system, IEEE Standard 1366 defines reliability indices which are used by utilities and their regulators to assess the frequency, duration, and magnitude of sustained outages (i.e., >5 minutes) that do not exceed the "reasonable design or operational limits of a system" (i.e., major event days) [13].[2]

Resilience metrics build on reliability metrics by measuring grid performance during disruptions and the associated economic and social consequences. Discussed in more detail below, there are opportunities to both incrementally expand reliability metrics to better reflect grid performance during long-duration widespread outages as well as to adopt a more idealized set of resilience metrics that quantify the consequences of such outages.

Resilience metrics can be broadly identified as either attribute-based or performance-based, as summarized in Table 1 and Figure 2 and discussed in the following sections [3]. The National Infrastructure Advisory Council defines five resilience attributes for critical infrastructure systems, including the electric grid: absorptiveness, adaptiveness, robustness, resourcefulness, and recoverability [14].[3] Because resilience attributes are system characteristics, attribute-based resilience metrics can be measured at any time, not only during disruption conditions. Attribute-based metrics can be combined into indices and inform investment decisions via multi-criteria decision analysis [2]. For example, the Resilience Measurement Index (RMI) characterizes infrastructure resilience via metrics such as the capacity/quantity of backup generators, percentage of infrastructure hardened, presence of emergency management plans and training, and system redundancies. Similarly, the Social Vulnerability Index (SoVI) characterizes community vulnerability via metrics such as rates of flood insurance coverage, flood insecurity, employment, and home ownership [15, 16].

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[1] Examples of reliability indices for the bulk power system include: Include Loss of Load Probability (LOLP), Loss of Load Hours (LOLH), Loss of Load Events (LOLEV), Loss of Load Frequency (LOLF), Expected Unserved Energy (EUE), and Loss of Load Expectation (LOLE) [11].

[2] Example reliability indices for the distribution system include: System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI), and Customers Experiencing Multiple Interruptions (CEMIn) [10].

[3] The National Infrastructure Advisory Council defines absorptiveness as "the ability of the system to endure a disruption without significant deviation from normal operating performance," adaptiveness as "the ability of the system to adapt to a shock to normal operating conditions," robustness as "the ability to maintain critical operations and functions in the face of crisis," resourcefulness as "the ability to skillfully prepare for, respond to and manage a crisis or disruption as it unfolds", and recoverability as "the ability of the system to recover quickly—and at low cost— from potentially disruptive event" [13].

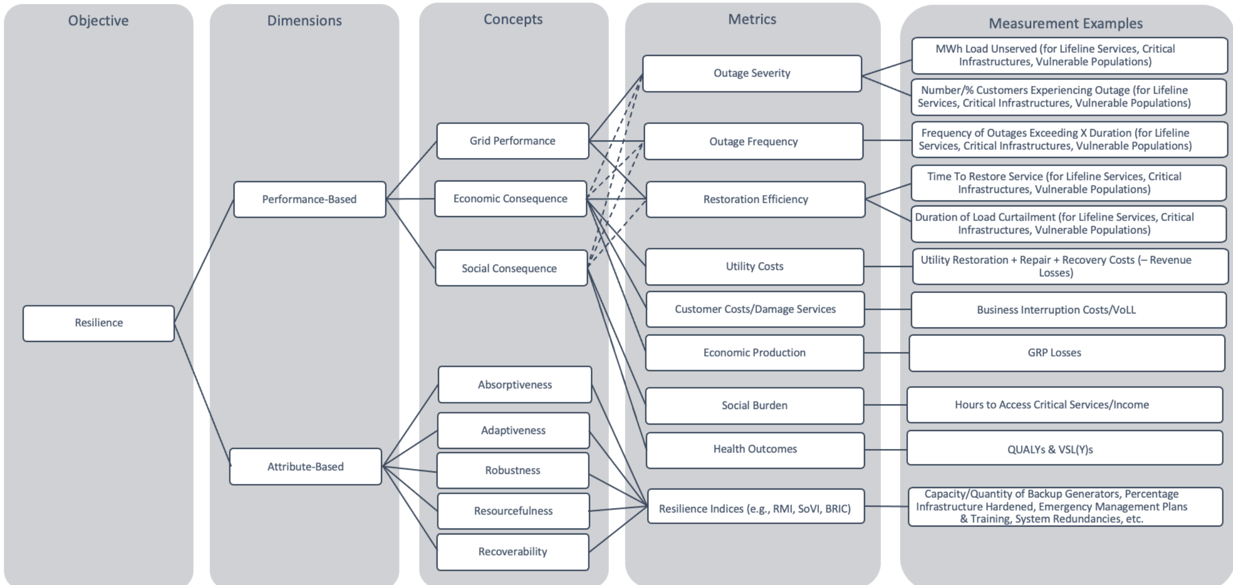

Figure 2: Resilience Objective Dimensions, Concepts, Metrics, and Measurement Examples

Performance-based metrics derive from observed or projected system performance given a disruptive event (i.e., the realization of a threat) and can be assessed at the level of individual assets, the power system, or the communities it serves. Because performance-based metrics assess performance before, during, and after (simulated or actual) disruptive events, they can be used to benchmark resilience and evaluate alternative investments to improve resilience. Specifically, performance-based metrics can guide resilience investment decisions by providing objectives against which the cost effectiveness of alternative mitigation portfolios can be assessed and thus they are well-suited for integration into electric grid planning processes [3, 4, 17, 18, 19]. As Figure 2 depicts, system resilience can be represented as a probability distribution of outages or outage consequences, where the objective against which investments are assessed could be improving average system performance (i.e., shifting the mean to the left) or mitigating the most severe outcomes (i.e., minimizing the extreme values to the right) [3, 20, 21, 22, 23].

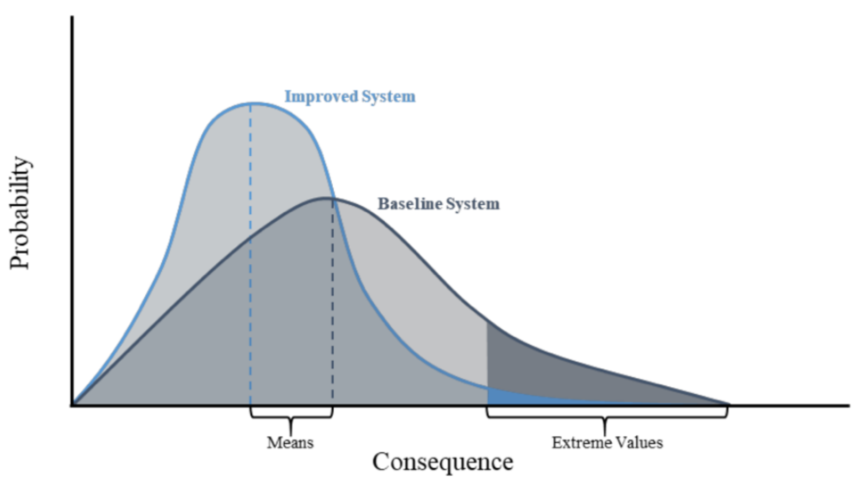

Figure 3. Improved System Resilience as Shift in Probability Distribution of Consequence (Source: [17])

As depicted in Table 1 and Figure 2, performance-based resilience metrics for the electric grid can measure performance at the asset or system level. As with reliability metrics, grid performance-based metrics generally focus on electricity service interruptions by quantifying outage severity (e.g., megawatt hour [MWh] load unserved, number or percentage of customers experiencing outage), outage frequency (e.g., frequency of outages exceeding a given duration), and restoration efficiency (e.g., time to restore service, duration of load curtailment) [3, 2, 24]. For example, two common reliability metrics System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are generally system-wide indices that measure outage characteristics across a utility territory.

For example, the Connecticut Public Utilities Regulatory Authority (PURA) identified metrics to track system performance during major storms and to retrospectively assess the performance of resilience mitigations, through such measurements as the number of customers interrupted, number of customer outages exceeding 96/126 hours, and time to restore 50%/90% of customers [25]. Individual performance metrics can also be aggregated into composite indices to quantify the degradation and restoration of grid assets or electricity services [3, 20, 21, 22]. For example, Commonwealth Edison identified several performance metrics for reliability and resilience, which included a “system visibility index” that comprises system segment visibility, communications network uptime, and integrity and utility of telemetry and control metrics [26].

Performance-based metrics can be assessed for all loads in a service territory, or for a subset of loads that are prioritized based on importance to social or economic systems (as depicted by the dashed lines in Figure 2). Resilience analysis often focuses on minimizing the frequency and severity of outages for loads serving lifeline services, [4] critical infrastructures,[5] and populations that are especially vulnerable to outages and associated consequences (e.g., due to heath conditions, lack of mobility) [14, 1, 5, 27, 9, 28]. The performance metrics identified by the Connecticut PURA can encompass all customers or can be disaggregated by commercial and industrial, critical facility, and life support customers [25]. Stakeholder engagement can support the identification of priority loads for resilience. For example, a resilience working group formed by Hawaiian Electric Companies (HECO) as an input to its integrated grid planning process identified a prioritized tiering of customers and infrastructure sectors based on importance to “national security and/or public safety and health” as well as power system recovery [28].

[4] The Federal Emergency Management Agency defines community lifelines as services that “enable the continuous operation of critical government and business functions and are essential to human health and safety or economic security,” which include: Safety and Security (law enforcement/security, fire service, search and rescue, government service, community safety), Food, Water, and Shelter (food, water, shelter, agriculture), Health and Medical (Medical Care, Public Health, Patient Movement, Medical Supply Chain, Fatality Management), Energy (Power Grid, Fuel), Communications (infrastructure, responder communications, alerts warnings and messages, finance, 911 and dispatch), Transportation (highway/roadway/motor vehicle, mass transit, railway, aviation, maritime), and Hazardous Material (facilities, HAZMAT, pollutants, contaminants) [52].

[5] Presidential Policy Directive 21 identifies 16 critical infrastructure sectors that provide “essential services that underpin American society” and for which the “incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety”: Chemical, Commercial Facilities. Communications, Critical Manufacturing, Dams, Defense Industrial Base, Emergency Services, Energy, Financial Services, Food and Agriculture, Government Facilities, Healthcare and Public Health, Information Technology, Nuclear Reactors, Materials, and Waste, Transportation Systems, and Water and Wastewater Systems [1].

Table 1. Resilience Metrics

Attribute-Based	Performance-Based		
(*absorptiveness, adaptiveness, robustness, resourcefulness, recoverability)*	Power System Performance	Economic Consequence	Social Consequence
• Resilience Measurement Index (e.g., capacity/quantity of backup generators, percentage of infrastructure hardened, emergency management plans and training, system redundancies) • Social Vulnerability Index (SoVI) and Baseline Resilience Indicators for Communities (BRIC) (e.g., flood insurance coverage, flood insecurity rate, employment rate, home ownership rate, number of Red Cross volunteers)	• Outage Severity (e.g., MWh load unserved, number/% customers experiencing outage [for lifeline services, critical infrastructures, or vulnerable populations]) • Outage Frequency (e.g., frequency of outages exceeding given duration [for lifeline services, critical infrastructures, or vulnerable populations]) • Restoration Efficiency (e.g., time to restore service, duration of load curtailment [for lifeline services, critical infrastructures, or vulnerable populations])	• Utility costs (e.g., utility restoration + repair + recovery costs [– revenue losses]) • Customer Co sts/Damage Functions (e.g., business interruption costs, value-of-lost-load [VoLL]) • Economic Production (e.g., gross regional product [GRP] losses)	• Social Burden (e.g., hours to access critical services/income) • Health Outcomes (e.g., changes in quality adjusted life years [QUALYs] and value of statistical life/life years [VSL/VSLYs])

Consequence-focused metrics translate power system performance metrics into impacts on communities [3, 24, 29, 30, 31]. Economic consequences encompass the costs associated with outages for utilities (e.g., repair, restoration, and recovery costs), the value of loss of electricity to the customers (e.g., value-of-lost-load (VoLL)), and financial loss to local economies (e.g., gross regional product losses). However, many of the adverse consequences of long-duration widespread outages are not readily monetizable. As such, metrics capturing consequences to society such as loss of life, loss of mobility, and compound effects with health are often expressed in units other than dollars, such as quality adjusted life year (QUALY), the value of health outcomes to a population.

Translating electric grid performance into social and economic consequences enables a more complete accounting of the benefits of improved resilience, but also increases the computational complexity. For example, given that the economic consequences of long-duration widespread outages are highly nonlinear, static VoLL quantification approaches measuring costs of a supply interruption are of limited applicability [32]. An emerging body of research focuses on quantification strategies for the highly variable direct, indirect, and induced economic consequences associated with long-duration, widespread outages [3, 33, 34]. With respect to social consequences, metrics focusing on the accessibility of critical services and the health outcomes can provide insight into consequences of long duration outages for vulnerable communities, but require integration of data from utilities, government agencies, and impacted communities. For example, the Designing Resilient Communities project worked with multiple stakeholders to populate the social burden metric, which measures the hours to access critical services during an outage relative to household income [4]. Spatial disaggregation of performance-based resilience metrics can also enable assessment of the distribution of (avoided) outage costs (or resilience benefits), thereby providing insight into the equity implications of alternative resilience investment strategies.

Thus, performance-based resilience metrics are particularly useful for electric grid planning processes because they can describe the performance of individual assets, the entire power system, or consequences to communities. In doing so, they can guide resilience investment decisions by providing information about how alternative investments may improve grid resilience and the implications for local economies and societies. Furthermore, these metrics can inform tradeoffs and complementarities between emerging objectives and highlight how investment strategies can change in light of equity or decarbonization considerations.

Although performance-based metrics have been explored in the literature, there is a lack of standardization in metrics and measurement methodologies in practice. Institutionalizing performance-based metrics will require investments in both metrics standardization and the development of data and modeling tools for populating these metrics. However, there are opportunities for incremental progress. Utilities and regulators could leverage outage data collected for reliability metrics but include the major event days that would otherwise be omitted to provide a more complete picture of outages. Moreover, outage data could be assessed for all customers or for a prioritized subset of customers that reflect resilience priorities (e.g., lifeline services, critical infrastructures, or vulnerable populations).

2.0 Integrating Resilience into Electric Grid Policy and Planning

2.1 Policy Prioritization of Resilience in Grid Planning

The emergence of resilience as an objective for grid planning can be attributed to several factors. First, electricity infrastructure is an enabling function upon which the operation of all other critical infrastructure sectors, and in turn the nation's economy and society, rely [1, 9, 5]. Second, the threat landscape is evolving, ranging from the increasing frequency and severity of climate change-driven natural hazards to the increasing sophistication of cyber-attacks [5, 27]. Third, there is a growing awareness that preventing all threats is fundamentally impossible and thus strategies are needed to minimize the impact of threats on the electricity system (i.e., the ability to prepare, withstand, respond, and recover) [9].

A framework for promoting and coordinating federal agency responsibilities for critical infrastructure resilience was established in Presidential Policy Directive 21 [1]. Myriad federal, state, and local government organizations, utilities, and system operators have developed resilience plans, policies, programs, and offices [35]. Resilience efforts may often cover multiple threats and sectors and several states have developed climate risk and resilience plans (threat-specific and multi-sector). Resilience is increasingly reflected in state emergency management plans (multi-threat and multi-sector) and energy assurance plans (multi-threat, sector-specific). A growing number of states and municipalities have also formed resilience offices to coordinate these activities [35]. Legislation at both the federal and state levels have sought to bolster grid resilience through funding for infrastructure hardening and grid modernization [5].

Notwithstanding this policy prioritization, the electricity system remains vulnerable to disruptions, as exemplified by winter storms in February 2021, which left millions of customers without power, in some cases for several days. This event, representing just one of $18 billion plus climate and weather events in 2021, has motivated further policy prioritization for grid resilience and underscored the relationship and tradeoffs between decarbonization, resilience, and equity issues [36]. For example, in the first quarter of 2021 alone, state legislators introduced numerous bills focused on grid resilience via the establishment of grid security commission, a critical infrastructure resiliency fund, a solar and energy storage resilience grant and loan program, and pilots focused on resilient schools and energy security and disaster resilience [37]. In 2022 state legislatures enacted over 100 bills relating to improving the physical and cyber security of their state's infrastructure.[6] Such developments underscore how the consequences of major outages have often motivated policy prioritization of grid resilience.

2.2 Development of Grid Planning Regulation and Guidance for Resilience

Public utility commissions and boards are increasingly attuned to the importance of resilience, and numerous recent state regulatory dockets have considered resilience directly or indirectly, as depicted in Table 2. However, the development of grid planning rules and guidance to enable the proactive and quantitative evaluation of system resilience and potential resilience investments within grid planning processes is relatively nascent [4, 6, 35, 38, 39].

[6] NCSL 2022 Legislative Energy Trends. https://www.ncsl.org/energy/2022-legislative-energy-trends

Table 2: Recent State Regulatory Proceedings Addressing Grid Resilience (Source: [35], adapted and updated by authors)

Jurisdiction	Proceeding (Docket)	Resilience Topic
California Public Utilities Commission	Rulemaking on Physical Security of Electrical Corporations Pursuant to Senate Bill 699 (Docket R.15-06-009)	Physical risk assessment and mitigation plans for distribution assets, with a focus on long-duration outages
	Rulemaking to Create a Consistent Regulatory Framework for the Guidance, Planning and Evaluation of Integrated Distributed Energy Resources (Docket R. 14-10-003)	DER framework, with focus on resilience value
	Application of Southern California Edison Company for approval of its Grid Safety and Resiliency Program (Docket A.18-09-002)	Funding for grid safety and resilience, including wildfire prevention and suppression activities
	Rulemaking to Implement Electric Utility Wildfire Mitigation Plans Pursuant to Senate Bill 901 (Docket R.18-10-007)	Wildfire mitigation plans, with focus on actions to ensure resilience to major events (e.g., via infrastructure hardening and modernization)
	Rulemaking Regarding Microgrids Pursuant to Senate Bill 1339 and Resiliency Strategies (Docket R. 19-09-009)	Interconnection processes, tariffs, and partnerships to support resilience projects
Connecticut Public Utilities Regulatory Authority	Investigation into Distribution System Planning of the Electric Distribution Companies (Docket 17-12-03)	Framework for advancing equitable grid modernization, including enhancing resilience via distribution system planning
	Resilience and Reliability Standards and Programs **(**Docket 17-12-03RE08)	Targets and metrics to improve the effectiveness of resilience and reliability programs and emergency response plans
Florida Public Service Commission	Review of Florida's Electric Utility Hurricane Preparedness and Restoration Actions (Docket 2017-0215-EU)	Review of utility preparedness and restoration actions to identify opportunities to improve infrastructure resilience
Hawaii Public Utilities Commission	The Hawaiian Electric Companies' Grid Modernization Strategy (Docket 2017-0226)	Grid modernization planning, with focus on resilience value of DERs
	Investigation into Establishment of a Microgrid Services Tariff Pursuant to House Bill 2110 (Docket 2018-01633)	Microgrid services tariff to increase resilience and reliability
	Investigation into Integrated Grid Planning (Docket 2018-0165)	Integrated grid planning informed by stakeholder engagement on resilience priorities
Illinois Commerce Commission	Commonwealth Edison Company Petition Concerning the Implementation of a Demonstration Distribution Microgrid (Docket 17-0331)	Microgrid proceeding with resilience benefits identified (i.e., power for critical public services) but not quantified, suggested resilience metrics that could be validated via demonstration project
	Commonwealth Edison Company Petition for the Establishment of Performance Metrics (Docket 22-0067)	Combines reliability and resilience metrics, including SAIDI, number of customers experiencing frequent and/or long-duration outages, and a system visibility index
Massachusetts Department of Public Utilities	Preparation and Response of National Grid to the October 29, 2017 Wind Storm (Docket 18-02)	Penalty for inadequate storm preparation and power restoration efforts related to 2017 windstorm
New Jersey Board of Public Utilities	Petition of Public Service Electric and Gas Company for Approval of the Second Energy Strong New Jersey Program (Docket EO18060629)	Funding for hardening and modernizing electric and gas infrastructure to enhance resilience in repose to Superstorm Sandy
	Value of Distributed Energy Resources (Case 15-E-0751)	DER valuation as part of Reforming the Energy Vision, including resilience benefits

New York Department of Public Service	Rates, Charges, Rules and Regulations of Consolidated Edison Company of New York, Inc. for Electric Service (Cases 13-E-0030/G-0031/S-0032)	Funding for storm hardening and resilience in response to Superstorm Sandy, allocation and analysis driven by Storm Hardening and Resiliency Collaborative
Puerto Rico Energy Bureau	Puerto Rico Electric Power Authority Integrated Resource Plan (Docket CEPR-AP-2018-0001)	Enhancing resilience via investments in DERs
	Regulation om Microgrid Development (Regulation 9028)	Regulation to support development of microgrids to enhance resilience
South Carolina Public Service Commission	Regarding Measures to Be Taken to Mitigate Impact of Threats to Safe and Reliable Utility Service (Docket 2021-66-A)	Requires utilities to assess extreme cold weather threats, impacts, vulnerabilities, and resilience solutions in response to 2021 winter storm
Public Utility Commission of Texas	Rulemaking to Establish Electric Weatherization Standards (Project No. 51840)	Emergency preparedness and weatherization standards in response to 2021 winter storm, and building on recommendations after 2011 winter storm
Vermont Public Utility Commission	Investigation into Electrical Power Losses and Telecommunications Resiliency (Docket 20-0141-INV)	Assessed effects of power outages on 911 services
Virginia State Corporation Commission	Petition of Dominion Energy Virginia for Approval of a Plan for Electric Distribution Grid Transformation Projects (Case PUR-2018-00100)	Grid modernization plan that includes reliability and resilience measures (e.g., intelligent grid devices, operations and automated control systems, and grid hardening)

Many public utility commissions have initiated resilience-related proceedings in response to major outages, including those resulting from wildfires, hurricanes, and winter storms (as depicted in Table 2). In particular, grid hardening requirements in response to major storms have been issued by a number of state public utility commissions over the last two decades, which have prompted utility investments in both transmission and distribution hardening and resilience planning activities [40]. Following major outages caused by Superstorm Sandy, the New Jersey Board of Public Utilities issued an order requiring electric utilities "to take specific actions to improve their preparedness in response to extreme weather events [and] provide detailed cost benefit analysis associated with a variety of utility infrastructure upgrades" [38]. The state's largest electric investor-owned utility created a storm hardening/resilience proposal called "Energy Strong," which used an asset risk model to assess outage probability and severity across grid components (e.g., transformers, disconnect switches, circuits) and prioritize upgrades based on modeled system reliability improvements [38]. This example points to the responsive nature of resilience analyses, which often occurs outside of traditional planning paradigms.

A more recent example is the response to the 2021 Texas grid failure, which shared many similarities to Texas's 2011 winter storm-driven power outage. Following the 2011 event, FERC and NERC concluded that facilities were not sufficiently weatherized, stating that the large number of units that tripped offline or could not start up during the storm "demonstrates that the generators did not adequately anticipate the full impact of the extended cold weather and high winds" [41]. The weatherization recommendations from the FERC/NERC report following the 2011 event were ultimately not implemented. However, the PUC of Texas issued weatherization standards for transmission service providers in light of the 2021 storm and called for generators to implement recommendations from a Quanta report (produced after the 2011 outage) on extreme weather preparedness [42]. In addition, recent work has presented optimization models that can identify generator winterization prioritization to increase resilience to winter storm scenarios similar to the 2021 Texas winter storm Uri [23, 43]. The catastrophic failure in Texas and severe weather conditions experienced in early 2021 also prompted the Public Service Commission of South Carolina to open a new proceeding calling for greater resiliency planning by utilities [44]. The docket requires that electric and natural gas utilities detail the steps they have taken or will take to mitigate the negative impacts of ice storms and other dangerous weather conditions to ensure safe and reliable utility service and ensure peak customer demands on the utility system can be met during extreme weather scenarios [44].

A growing number of jurisdictions have also considered resilience in the context of proceedings on distributed energy resources (DERs) [32]. DERs can be configured to support resilience by reducing the frequency and durations outages within the distribution system (where some 90% of outages originate) and by maintaining electricity for critical loads when there are disruptions in the bulk power system [45]. New York, Hawaii, and California are exploring resilient microgrid services and New Jersey, Delaware, and Florida are exploring resilience-focused distributed solar programs [32]. Resilient DERs have also been core to recovery efforts in Puerto Rico. Following the impacts of Hurricanes Irma and María, the Puerto Rico Electric Power Authority (PREPA) proposed an approach to enhance resilience via investments in eight minigrids that would span across the island, each having the generation capacity to meet its own load if the island-wide transmission system connecting the zones went offline [38, 46]. The Puerto Rico Energy Bureau reviewed the plan and issued a final order that includes creation of a new docket to consider options for increasing resilience, with two primary approaches: 1) site-specific or microgrid resilience, with on-site generation and storage; and 2) resilience provided through central generation and a hardened transmission and distribution system (the minigrid approach) [38]. Several jurisdictions have also commissioned studies, published roadmaps, or established policies/programs to support the development of DERs to enhance resilience. While resilience is often described as a benefit across these potential projects, benefits of improved resilience are generally not quantified [32].

Despite this increased consideration of the importance of resilience to extreme weather events and the potential resilience benefits of various grid modernization approaches, “consideration of and comparison of the full range of investments” to bolster resilience is lacking and that integration of resilience into investment planning processes will require further guidance from utility commissions and more robust stakeholder engagement [38]. Hawaii’s PUC has launched several proceedings to update its regulatory framework to better capture the needs of the future grid—one with increased renewable and distribution generation. The PUC has framed resilience as a key policy goal of this updated regulatory framework, noting its importance in light of the risks facing Hawaii due to its geographic isolation and exposure to natural disasters [38]. The PUC launched its Proceeding to Investigate Performance-Based Regulation (PBR) and the resulting framework will feature many interacting components, such as a multiyear rate plan, revenue decoupling, an earnings-sharing mechanism, and performance metrics (although none of these metrics address resilience).

The foundational goal of this PBR framework is to address some of the issues and disincentives inherent in traditional cost-of-service regulation and step away from companies’ potential capital bias by making their earnings largely independent of their expenditures. By expediting the transition to a more distributed and renewable grid, the proposed PBR structure could promote resilience as a secondary benefit but does not represent actionable treatment of resilience within a planning paradigm [38].

2.3 Utility Integration of Resilience into Grid Planning

In order to understand the level to which resilience is already embedded within common grid planning processes, a robustness assessment was conducted. The assessment uses a rubric scoring methodology, and considers a number of factors: a) the existing literature on the objective, associated metrics, and its role in grid planning; b) federal, state, and local policies and regulations that require or incentivize utilities to consider the objective in their planning processes; c) other market and technology drivers that have pushed planners to incorporate the objective to varying degrees; d) the (relative) assessment of traditional objectives; and e) insights from subject matter experts with experience in grid planning processes. The latter is particularly important to capture situational knowledge about the current practices and the extent to which policy prioritization of emerging objectives has led to institutionalized practices, whereby regulatory guidance or other standards provide for systematic consideration of emerging objectives in planning processes and integration into investment decisions.

Table 3 shows the level to which resilience has been integrated into traditional grid planning paradigms, with "none" indicating no translation of the objective into planning processes and "robust" indicating well-institutionalized implementation of the objective.[7] As summarized in Table 3 and demonstrated by the following integration examples, resilience has been considered in a limited capacity across resource planning processes but has received greater consideration in transmission and distribution system planning.

Table 3. Resilience Integration Robustness Assessment

Planning Paradigms	Traditional Objectives				Emerging Objectives		
	Safety	Reliability	Efficiency	Affordability	Decarbonization	**Resilience**	Equity
Integrated Resource	Connected	Robust	Robust	Robust	Robust	**Limited**	Limited
Transmission	Robust	Robust	Connected	Connected	Limited	**Connected**	None
Distribution System	Robust	Robust	Robust	Connected	Limited	**Connected**	Limited

For most integrated resource planning activities, resilience is not well integrated compared to other objectives—such as reliability and decarbonization—for which metrics and requirements are well institutionalized. Many integrated resource plans consider the ability of a utility to restore service after an extreme weather event, however, such analyses are often based on historical experience and not reflective of higher consequence threats, ranging from climate-driven shocks to cyber-attacks [5]. Reflecting the range of resilience challenges associated with both the acute and chronic impacts of climate change—everything from hydrological shifts impacting the timing,

[7] The four scores used in the rubric— "robust," "connected," "limited," and "none"—are defined as follows:

- Robust: the planning paradigm systematically integrates the objective, with institutionalized implementation guidance/practices that guide quantitative evaluation (e.g., via performance-based metrics) and directly inform investment decisions
- Connected: the planning paradigm partially integrates the objective, but in the absence of institutionalized implementation guidance/practices, evaluation is largely qualitative and only indirectly informs investment decisions
- Limited: the planning paradigm integrates ad hoc references the objective, but the objective is neither discussed in detail nor quantitatively/qualitatively evaluated and thus does not inform investment decisions
- None: the planning paradigm does not integrate the objective (and thus does not inform investment decisions), suggesting that any policy prioritization of the objective has not translated into practice.

It should be noted that the rubric evaluates how well the emerging objectives are *currently* integrated into grid planning paradigms, not the extent to which these planning paradigms are aligned to *eventually* capture these emerging objectives.

temperature, and volume of water available for thermal electric cooling and hydropower generation, to changes in the intensity of utility electric loads for heating and cooling—within integrated resource plans is in very early stages [47].

However, there are examples of utility-led climate resilience studies that have informed integrated resource planning. As part of a 2013 rate case filing in the wake of Superstorm Sandy, Consolidated Edison (ConEd) developed a multi-stakeholder group to guide analysis and allocation of $1 billion in storm hardening and grid investments, which recommended a climate change vulnerability study. The resulting study is a leading example of climate resilience planning in the electric utility sector because it includes both acute and chronic climate hazards [48, 49]. Specifically, it analyzes projected changes in temperature, humidity, precipitation, sea level, and extreme weather in ConEd's service territory over seven time periods spanning from 2020 through 2080, with results projecting a fourteenfold increase in the number of days with temperatures above 86ºF (30ºC), a 20% decrease in cold weather days, and a 25 times increase in heat wave events by 2050 [48, 49]. The study team compared anticipated climate conditions against existing asset design and operating parameters to identify vulnerabilities within the system and evaluated measures to address those vulnerabilities [49]. The findings of the climate study were then incorporated into ConEd's long-range resource planning and broader climate resilience and adaptation strategy [50].

Sophisticated climate risk analytics and stakeholder engagement are at also at the center of HECO's climate resiliency approach within its integrated grid planning process. HECO is using Jupiter Intelligence's climate modeling to analyze risks to individual assets over a 30-year time horizon [51]. Artificial-intelligence-enabled downscaled climate models with high resolution (down to three meters) will be used to prioritize geographic locations and assets that are most at risk, optimize placement of new generation sites, estimate potential renewable generation damage, and identify distribution undergrounding candidates [51]. Moreover, HECO has convened a multi-stakeholder working group to identify resilience planning criteria for Hawaii's resource, transmission, and distribution system, as well as social and economic impacts [28]. While the working group initially provided inputs into the integrated grid planning processes, regulators have highlighted how this group might also develop resilience rankings of potential investment portfolios [52].

Transmission system planners have also conducted studies addressing climate, physical, and cyber threats to resilience, which may inform planning processes. For example, in response to a FERC proceeding exploring bulk power system resilience [53], PJM Interconnection conducted a study that "stress-tested the fuel delivery systems serving generation" under extreme weather scenarios to identify "when the system begins to be impacted and to identify key drivers of reliability risk" [54]. Moreover, as part of its latest regional transmission expansion, PJM Interconnection noted it is developing a resilience metric to complement the reliability and market efficiency metrics that traditionally guide transmission planning processes [55]. Independent system operators and regional transmission organizations also routinely assess cyber and physical security of transmission infrastructure in compliance with NERC critical infrastructure protection reliability standards [56]. Utilities and system planners are also beginning to consider how changing resource mix and observability and dispatchability of assets (e.g., DERs) affect electric grid reliability and resilience, which may be accelerated by FERC's proposed rule requiring long-term scenario-based regional transmission planning that accounts for changes in resource mix and demand resulting from local, state, and federal policies, technology and commodity costs, extreme weather events, and interconnection requests/withdrawals [57].

With respect to distribution planning, hosting capacity analyses and similar high-granularity distribution system performance assessments support resilience planning by prioritizing DER projects in high-value locations on the grid and revealing areas in need of increased service quality and opportunity. While resilience has not been explicitly incorporated into hosting capacity analyses, there are opportunities to overlay the outputs of hosting capacity analysis with maps of priority loads for resilience (e.g., critical infrastructure, vulnerable populations). For example, directed by the Minnesota PUC, Xcel Energy completed a hosting capacity analysis in 2016, for which the company produced a map of the distribution system throughout its service territory with ratings of each feeder according to favorability for additional distributed energy interconnection [45]. A next step could be to combine existing analysis data with local population vulnerability indices, stakeholder engagement, and historical outage data, which would enable prioritization of high-impact infrastructure investments and needed locations for distributed energy resource installations to contribute greater resilience [45]. As described above, a number of DER-focused proceedings have focused on potential resilience benefits of DERs (e.g., dispatchability, islanding capability, siting at critical loads, fuel security, quick ramping, decentralization, flexibility, and capacity to provide ancillary services), but quantifying these benefits for resilience remains a key challenge [32, 45].

Thus, resilience analysis is not systematically integrated into planning processes, but grid planners routinely consider investments that may enhance resilience and leading utilities are conducting resilience analyses that may inform grid planning. Investments that may enhance resilience range from hardening transmission and distribution systems, to deploying distributed energy resources and microgrids, to conducting planning exercises [58]. Such investments may be considered in the context of a wide range of grid planning paradigms, where resilience is increasingly described as a goal or justification but resilience benefits (e.g., reduced outage frequency/duration, maintain service to priority loads) are seldom quantified. Investments specifically targeting resilience have tended to be in response to major outages, with more proactive analyses of grid resilience to climate change and other hazards occurring outside of traditional planning processes.

The Department of Energy's guide for electric sector resilience planning describes the importance of a risk-based approach, which includes an assessment of threats, vulnerabilities, likelihood of impacts, and thresholds for system performance, as well as a plan that identifies a set of actions to mitigate potential impacts, but only a handful of utilities have developed resilience plans consistent with this approach [59]. Moreover, tools and data are to measure the economic and social consequences of long-duration widespread outages, and thus the benefits associated with improving grid resilience, are still evolving [32].

3.0 Challenges and Opportunities

In view of this baseline condition, there are several technical challenges to incorporating resilience as a goal for future grid investments. These challenges are outlined below.

3.1 Standardization of Resilience Metrics and Development of Analytical Methods

Although many electric sector resilience metrics have been proposed, there is a lack of standardization in measurement methodologies across generation, transmission, and distribution system levels in practice. The analytical methods used populate these metrics are still under development. Performance-based metrics are particularly well-suited to integration in grid planning processes because they measure the performance of the power system during disruptions, and thus can guide investment decisions based on improvements grid resilience. A subset of performance-based metrics translates grid performance into consequences for local communities and economies. While consequence-focused performance-based metrics enable a more holistic assessment of the benefits of improved resilience, they require novel data sources and modeling approaches.

There are opportunities for incremental progress leveraging well-established reliability metrics. First, utilities and regulators could leverage outage data collected for reliability metrics but include the major event days that would otherwise be omitted to provide a more complete picture of grid performance during longer duration and more widespread outages. Connecticut's major storm reporting framework takes this approach [25]. Second, this outage data could be assessed for all customers or for a prioritized subset of customers that reflect resilience priorities (e.g., lifeline services, critical infrastructures, or vulnerable populations). Hawaii's resilience working group has engaged in a customer prioritization effort that could enable this approach [28].

3.2 Integrating Assessments of Acute and Chronic Threats and Interactions with Other Emerging Objectives

Resilience threats can be both acute (e.g., wildfire) and chronic (e.g., drought), and interact with other grid objectives such as decarbonization and equity. A key challenge is thus integrating analyses of grid performance across different timelines and assessing tradeoffs within and across emerging objectives. Recent long-duration and widespread grid outages have highlighted the linkage between resilience and equity issues: as part of the February 2021 winter storms that resulted in widespread long-duration power outages, an analysis in Texas correlating nighttime satellite imagery and demographic data concluded that "areas with a high share of minority population were more than four times as likely to suffer a blackout than predominantly white areas" [60]. Another analysis focused specifically on Houston found that power in neighborhoods with more renter-occupied properties was restored more slowly than power in neighborhoods with more owner-occupied properties, underscoring a longer term trend in "persistent disparities in economic, health, environmental, and housing outcomes for Black and/or Latinx people, renters, and residents with low incomes" [61].

Because many of these outcomes are driven by the fundamental structure of the grid, analyzing the effects of alternative resilience investments on disadvantaged or vulnerable populations is essential to evaluation and ultimately correction of performance disparities. Such analyses might also consider the effects of alternative mitigation strategies on decarbonization—and consequences for frontline communities–which will unfold over a longer time horizon.

3.3 Regulatory Mechanisms for Multi-Stakeholder Scenario-Based Planning

PUCs are increasingly attuned to the importance of resilience, yet additional regulatory guidance is likely necessary to enable more robust integration of resilience into planning processes [38]. However, regulatory strategies for resilience via multi-stakeholder scenario-based planning processes are an active area of research [4, 6, 35, 38]. For example, the Resilient Community Design Framework consists of four steps to guide resilience investment planning: (1) defining the system, threats to resilience, resilience goals, and resilience metrics; (2) assessing potential disruptions from identified threats and the effects on system performance; (3) identifying alternative technology investments, regulatory frameworks, and utility business models that may improve resilience; and (4) assessing the effects of selected mitigations on system performance and calculating resilience metrics, which can be used to co-optimize among candidate mitigation portfolios [4]. Sandia National Laboratories has worked with electric utilities, municipal governments, regulators, and stakeholders to pilot this framework in several communities [4].

Utilities and regulators have made progress in engaging a broader set of stakeholders to inform resilience assessments, particularly through multi-stakeholder working groups. Examples include ConEd's Storm Hardening and Resiliency Collaborative [50, 49], HECO's Resilience Working Group for Integrated Grid Planning [28], California Public Utilities Commission's Resilience and Microgrids Working Group [62], Duke Energy Carolina's planned Climate Risk and Resilience Working Group [63]. Stakeholders can provide critical inputs into grid planning processes for resilience, including identification and prioritization threats, tiering of critical infrastructures/services and vulnerable/disadvantaged communities, assessment of community vulnerabilities and capabilities, and articulation of the consequences and outcomes of greatest importance for metrics selection.

4.0 Conclusion

A resilient grid is able to prepare for, adapt to, withstand, and recover rapidly from disruptions, thereby mitigating the effects cyber, physical, and climate-related threats on grid performance and attendant consequences for local economies and societies. While state and federal energy policy priorities increasingly emphasize grid resilience, the translation of such policies into guidance or requirements for grid planning practices is in its early stages. Grid planners have begun exploring grid resilience to climate change and other hazards, but these analyses are often ad-hoc and occur outside of traditional planning processes. Prospective, performance-based analysis to both benchmark system resilience and bolster it via strategic investments is not institutionalized in any of the planning paradigms. Integrating resilience into grid planning paradigms necessitates the standardization of metrics and measurement strategies. While the literature, subject matter experts at national laboratories, and early policies and practices provide a rich set of candidate metrics for resilience, moving from metrics to measurement is a substantial analytical undertaking. However, there are opportunities for incremental expansion of grid planning approaches for reliability to better reflect resilience and for the development of more idealized multi-stakeholder scenario-based planning approaches.

Compared to traditional objectives—i.e., safety, reliability, efficiency, and affordability—resilience is not well integrated into grid planning paradigms, but there are opportunities for incremental and idealized expansion of grid planning to better incorporate resilience. The integration of emerging objectives—i.e., decarbonization, resilience, and equity— into grid planning necessitates the development of frameworks and methodologies to evaluate grid performance and prioritize and balance investments across traditional and emerging objectives.

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