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Observations of an Evolving Grid: Resilience and Equity Performance Metrics

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Abstract

Purpose of Review Traditionally, electric grid planning aims to maintain safe, reliable, efficient, and affordable service. As policies, societal goals, and technologies evolve, new objectives for power system planners emerge, creating a need for system performance benchmarking of these objectives.

Recent Findings With a focus on resilience and energy equity as emerging grid objectives, this review provides an overview of emerging trends in resilience and energy equity metrics, current examples of their coupling in grid planning, and observations on both metric trajectories.

Summary The simultaneous development of resilience and energy equity metrics reveals common themes relating to the scale of measurement, the use of socioeconomic inputs, a departure from utility-controlled metrics, and the need for broader stakeholder inclusion in decision-making processes. This work presents a timely discussion of the essential nature of metrics for grid planners as equity and resilience policies and goal transition from abstract objectives to accountability mechanisms and real dollar investments.

Keywords Resilience metrics · Energy equity metrics · Grid performance

Introduction

Metrics have been used by utilities and regulators for decades to track and measure electricity system performance. Metrics can help identify where the utility has met expectations or fallen short of its goals and identify system components that may warrant new or additional investment. They also tend to reflect system-wide performance, encompassing the entire utility service territory and measuring the utility's success in delivering reliable electricity with reasonable customer rates.

New objectives for power system planners are emerging in alignment with new policies, societal goals, and evolving technologies that require metrics to benchmark system performance. In particular, resilience and equity are two objectives changing the way satisfactory grid performance is viewed and measured. Discussions around grid resilience have grown in prominence in recent years, primarily as a result of the need to address challenges that arise from more frequent disruptive events [1]. Energy equity has emerged as a lens to understand how electric system benefits and burdens are distributed among different customer groups [2•]. Resilience and energy equity represent different emerging policy priorities, yet they are related in that they focus on the utility customer experience albeit with a different emphasis.

Utilities traditionally reported on reliability—the ability of the power system to withstand uncontrolled events, cascading failures, or unanticipated loss of system components, at a system level [3]. Metrics for both resilience and energy equity likely will track electricity system experiences at a more granular level, for example, at the feeder or even for households. As resilience and energy equity objectives co-evolve, it is possible to observe how the metrics share additional characteristics [4–6]. Developing metrics will be based on new information, will measure grid attributes or customer impacts that were not previously measured, and may include socioeconomic elements outside the control of the utility [7••]. Some jurisdictions have begun thinking about resilience and equity together and have issued directives that require increased transparency and customer participation [8••]. In this regard, the simultaneous

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development of resilience and energy equity metrics reveals common themes relating to the scale of measurement, the use of socioeconomic inputs, a departure from utility-controlled metrics, and the need for broader stakeholder inclusion in decision-making processes.

Background on Resilience Metrics

There is a long history of measuring reliability through metrics, but traditional reliability measures do not address system resilience—the ability of the system to prepare for, adapt to, and recover from disruptions [9]. With increased weather anomalies due to climate change, both in strength and duration, and the potential for cyber threats to the system, the ability of the electricity grid to withstand these events and to recover if impacted has become an important area of interest [10••].

In addition to traditional reliability metrics, new metrics should capture the flexibility and resilience qualities of the grid. Developing the tools and methodologies necessary to monitor system resilience will enable regulators, utilities, and the public to increase the ability to avoid and recover from electricity system disruptions. While reliability has usually been measured on a utility system-wide basis, resilience is also concerned with localized parts of the grid [4••]. Some parts of the grid may be more resilient than others; some communities may have greater access to emergency services. Accordingly, uneven resilience conditions implicate the need for equity in metric expansion. To understand how the grid serves a community during and after a disruption and to understand where on the system additional investment is needed, it is important to access data at a more granular level [5, 7], which implicates the need for finer resolution data in metric expansion as well.

Background on Equity Metrics

Energy equity recognizes that disadvantaged communities have been historically marginalized and overburdened by pollution and underinvestment in clean energy infrastructure and may lack access to energy-efficient housing or transportation electrification charging infrastructure [11]. Achieving energy equity requires intentionally designing systems, technologies, procedures, and policies for fair distribution of benefits in the energy system [12, 13]. Meeting these societal objectives requires descriptive analytics on specific populations to measure how energy system impacts are distributed.

The regulatory focus on energy equity increased in 2020, compared to previous decades [8, 14]. In the 1990s, equity issues related to access, cost, and energy burden began to receive widespread attention as an issue of climate justice and in 2013 were refined as the policy-oriented concepts of energy justice and equity [15]. The same electricity rate within the residential sector can have very different impacts depending on the individual household's ability to pay the bills [16]. Furthermore, energy technologies and regulatory programs, especially those that rely on upfront customer payments, tend to accrue to customers on the higher end of the income range, ostensibly leaving low-income customers with fewer options and fewer programmatic benefits [17, 18]. Extreme weather events, especially those caused by climate change impacts, have illuminated climate vulnerabilities in marginalized and overburdened communities. There is disproportionate risk on those that do not have the ability to anticipate, cope with, and recover from adverse events [19]. Inequities in affordability, access, and vulnerability implicate the need to consider resilience in equity metrics development. Also, like resilience, energy equity metrics will likely require granular data that recognizes the energy system impacts down to the household level. These downscaled metrics are expected to include socioeconomic factors, factors outside the control of the utility, and factors informed by the stakeholders who are locally impacted [7••].

In this paper, we discuss resilience and equity metrics for measuring grid performance, focusing on their emerging trends and future outcomes. Then, with state policies and electric utility activities, we highlight current examples of resilience and equity coupling in grid planning to demonstrate the intertwined nature of these grid objectives.

Traditional Objectives and Metrics

The electric system has traditionally focused on maintaining safe, reliable, efficient, and affordable service for its customers. The traditional, centralized system model is characterized by a small number of large generators connected to load centers by bulk transmission. Regulatory paradigms also reflect this centralized emphasis; planning and measurement have been conducted and reported to regulators at a system-wide level. As a result, established metrics reflect the traditional objectives and centralized system structure. Table 1 provides examples of traditional electricity system metrics. Established electricity system metrics are broadly understood by stakeholders and have been addressed elsewhere in great technical detail [20, 21].

The traditional attributes and metrics continue to measure important system characteristics. However, collectively, they no longer sufficiently provide the necessary information or performance incentives needed to manage the increasing complexity of the grid and the new societal expectations of the electricity system. For example, two common reliability metrics System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are, by definition, system-wide indices that measure

Table 1 Summary of traditional metrics

Performance metric category	Definition	Example
Reliability	Ability to maintain the delivery of electric power to customers in the face of routine uncertainty in operating conditions	• Reliability indices (SAIDI, SAIFI) • Resource adequacy (LOLP, LOLE)
Sustainability	Generally measuring attainment of renewable energy or energy efficiency goals	• Percentage of renewable energy delivered • MWs of energy efficiency acquired
Affordability	Ability to provide electric services at a cost that promotes universal service	• Levelized cost of electricity • Internal rate of return • Cost per kilowatt-hour

outage characteristics across an entire utility territory [9, 10]. Systemwide averages do not shed light on resilience capabilities of local components of the distribution system. Similarly, affordability has historically been measured by rates in cents per kilowatt-hour by customer classes relative to rates in other regions or compared to national averages [22]. There is very little in this generic affordability metric that actually addresses whether a household finds electricity rates affordable [6].

Measuring the grid in light of emerging objectives requires greater system awareness and significantly improved granularity. While the historical system could rely on gross measures of system performance at the distribution, generation, or transmission level, or on average rates by customer class, the evolving electricity system requires measurement of activity and performance on a sub-distribution level and even on an individual household level. This increased granularity could also be accompanied by a sociodemographic overlay to highlight disparities among communities or customers.

Emerging Resilience and Energy Equity Objectives and Metrics

Resilience

Discussions around grid resilience have grown in prominence in recent years, primarily because of the need to address climate change and cyber security-related disruptive events. Resilience can be 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" [23]. Resilience expands on reliability by considering additional elements such as preparing for, operating through, and recovering from disruptions.

Although there are a number of possible electric power sector resilience metrics proposed in the literature, in practice, there is a lack of standardized resilience metrics because of limited industry standards for grid resilience [24–27]. Translating metrics from the literature into practice is a key challenge partly because new metrics raise the need for measurement that covers connected, emerging objectives. In addition, resilience metrics often are context (location) and threat (event) specific, which makes it challenging to standardize [28]. At a high level, resilience metrics, at a minimum, consider two key characteristics [1, 4]

- Likelihood: probability that a disruption scenario may lead to decreased system performance or failure
- Consequence: the impact of system failure given a disruption scenario

Emerging Trends

Recent work from the Grid Modernization Lab Consortium[1] defined two measurement approaches that can be used together to quantify resilience of grid infrastructures: multi-criteria decision analysis (MCDA) and performance-based metrics [4••]. MCDA first screens and customizes options for resilience enhancement. It provides a baseline characterization of system attributes, such as robustness, adaptiveness, and recoverability [30] and may utilize qualitative mechanisms, like survey responses, for evaluation. A set of weighting values can be assigned that represent the relative importance of the survey responses, and a series of calculations can create numerical scores for the resilience attributes. Performance-based metrics then use the alternatives from MCDA to deepen a grid assessment with economic and regional considerations. Performance-based metrics derive from observed or projected system performance

[1] The Grid Modernization Laboratory Consortium (GMLC) was established in 2014 as a strategic partnership between DOE and the national laboratories to accelerate modernization of the nation's power grid. The portfolio of projects delivers new concepts, tools, platforms, and technologies to better measure, analyze, predict, and control the grid of the future. Resilience is a GMLC technical focus area with five activities aimed at improving the ability to identify, protect, detect, and respond to threats and hazards [29].

Table 2 Examples of resilience metrics grouped by utility perspective and community perspective, modified from resilience metrics identified in [4, 10]

Utility perspective (direct utility consequence)	Community perspective (direct community consequence)
Cumulative customer-hours of outages	Critical services without power (e.g., hospitals, fire stations, police stations)
Cumulative customer energy demand not served	Critical services without power for more than *N* hours (e.g., *N* > hours of backup fuel requirement)
Average number (or percentage) of customers experiencing an outage during a specified period	Loss of assets and perishables
Cumulative critical customer-hours of outages	Business interruption costs
Average number (or percentage) of critical loads that experience an outage	
Time to system recovery	
Cost of system recovery	
Loss of utility revenue	

before, during, and after disruptive events. A set of resilience guidelines created for Oregon Public Utility Commission used consequence categories to define performance-based resilience metrics [10••].

Consequences of resilience events, however, will vary with evaluation perspective. For instance, communities and utilities may prioritize different metrics to reflect their resilience goals (Table 2). Aspects of community resilience are linked to both grid resilience and energy equity, for example, by considering the ability of a community to use available resources to respond, withstand, and recover from disaster [31]. Thus, community resilience initiatives and metrics inherently reflect a progression to finer resolution data needs. Non-grid factors at the census-tract level, such as access to emergency services, distance to shelters, and economic impacts, are also meaningful factors to consider for community resilience metrics. There is opportunity to integrate grid resilience and community resilience goals. Several entities are creating consequence categories specifically for their local, traditionally disadvantaged groups that assess customer survivability, or the ability to withstand outages [32–34].

Reliability indices traditionally defined at the utility territory scale, like SAIDI and SAIFI which measure outage frequency and duration, can be reported for sub-systems within the larger service territory to check for disparities in infrastructure age and quality [7••]. Customer Average Interruption Duration Index (CAIDI) and Customer Average Interruption Frequency Index (CAIFI), traditionally measures of customer outage experience system-wide, can be a measure at a finer granular scale to track the experience at the community level [35].

From the utility perspective, success in new metric development will hinge on stakeholders' input and the utility's ability to welcome a more diverse set of stakeholders—from grid operators to regulators, policymakers, emergency response organizations, community organizations, customers, and others. The Industry Technical Support Leadership Committee of the IEEE Power and Energy Society also emphasized the transition to multi-stakeholder collaboration in their technical report on resilience in the electricity sector [28]. Authors defined and reviewed resilience frameworks, methods, and metrics, noting that metrics for resilience are dependent on various regional, functional, regulatory, and business factors. The value of metrics lies in their ability to be benchmarked and compared to facilitate continuous improvements. Developing metrics with diverse stakeholder groups for system-wide resilience planning across larger regions can aid regional planners in co-developing strategies with state and local planners [28].

Examples of Integration with Equity

State-level action on energy resilience is also reflecting the connection between energy system resilience and community resilience. For example, Washington's Climate Commitment Act places communities alongside infrastructure in its definition of *climate resilience*, and Oregon's Clean Energy Targets bill creates a definition of *community energy resilience* that specifically identifies the importance of critical energy facilities. Maryland's Climate Solutions Now Act (SB0528) created a Climate Catalytic Capital Fund with an aim to "optimize the economic, health, social, and environmental value of community-scale infrastructure for resilience and equity" [36]. Emerging resilience metrics also reflect equity and community considerations. For example, the social burden metric considers the individual or household level of effort, compared to ability, to reach critical services in a resilience event [37]. Microgrid siting in Puerto Rico and electric vehicle charging infrastructure siting in Texas applied this methodology to enable an equity-inclusive approach to resilience investments [25,

Table 3 Established justice tenets

Justice tenet	Scope
Distributive	Allocation of benefits and burdens in the system
Recognition	Specific recognition of who participates in the system
Procedural	System decision-making and governance
Restorative	Examination of past damages to people or the environment, and consideration of how to correct these in the future

38]. Case studies in Canada suggest that equitable resilience planning processes can also be achieved through more robust stakeholder engagement and negotiation processes [39].

Energy Equity

Energy equity is an increasingly prominent societal objective with emerging definitions and metrics. Poverty and income inequality can be associated with multiple aspects of electricity services [6, 13, 14, 40]. There are communities who have disproportionately borne the negative impacts of the electric system, such as long-duration and widespread outages and limited access to resources that mitigate the consequences of these outages [41–43]. These communities include low-income, marginalized, and/or vulnerable groups, such as communities of color, tribal communities, and rural communities, as well as those who are vulnerable to electric costs and outages. Established energy justice tenets (Table 3) call for improving the energy system in light of these community and individual circumstances [44••, 45]. For metrics, this entails a shift toward more socioeconomic assessment that goes beyond traditional measures of affordability or cost-effectiveness [7••].

Emerging Trends

Measurement strategies for equity across the economic, environmental, and social policy literature are complex and multifaceted[2]. There has been much development in energy equity measurement in recent years, including models, workbooks, toolkits, and metrics that commonly map back to the tenets of energy justice and provide approaches for varying practitioners (i.e., communities, grid planners, or regulators) and researchers [7••, 12, 47•]. Most sources emphasize the need for data at finer geography and time scales while highlighting the challenges created by data gaps and privacy concerns. Shifting to more local measurement will track more discrete consumer and vulnerability data, but mechanisms can be put in place to protect personal privacy.

States are in the process of recognizing energy equity as a goal, but only a subset have identified equity metrics. In a recent review of state energy equity policies, six states (CA, CT, IL, MA, OR, WA) were identified with metrics related to energy equity [8••]. A similar number of other states have directives to develop metrics. Also, of the 95 equity-related actions throughout all 50 states, 14 actions in six states (CA, CT, MD, MN, OR, WA) identified resilience, with 10 of these actions identifying community resilience, specifically, as an intended equity outcome. There is little consistency among the identified metrics, suggesting these are still emerging and not established or widely accepted. Further consultation with stakeholders—customers, community groups, utilities, regulators, and different levels of government—may be necessary to consolidate and operationalize energy equity metrics.

In the electricity context, equity metrics have largely focused on [6, 13, 14, 40]:

1. Affordability, reliability, and resilience of electricity
2. Availability of transition-enabling technologies, programs, and economic opportunities
3. Accessibility of electricity decision-making processes

Traditional grid metrics have a role in supporting emerging equity metrics. Traditional metrics like SAIDI and SAIFI can be downscaled to the community or distribution feeder level. Examined against a sociodemographic background, more fine-grained outage data would reflect disparities in infrastructure age and quality, resilience, and overall grid vulnerability [7••]. The current practice of calculating system-wide averages of these metrics may not capture the nuances at this finer scale [48]. Advanced metering infrastructure is an example of a technology that can advance energy equity by providing data at customer level. Many utilities already have the capability to measure customer-level outage data and report on the associated metrics, such as CEMI (customers experiencing multiple interruptions) [49•].

One energy equity metric that may be emerging with greatest prominence is energy burden, which is defined as the ratio of annual household energy expenditure to annual household income [8••]:

[2] A recent Urban Institute study synthesizes this broad literature to identify six dimensions that should inform equity measurement strategies across domains: historical legacies (i.e., "equity is measured cumulatively"), awareness of populations (i.e., "equity is measured for relevant populations"), inclusion of other voices (i.e., "equity is measured at different points in an intervention's life, starting with design and staffing"), access discrimination (i.e., "equity is measured by the ability of different groups of interest to become aware of, apply for or request, and access a service"), output differences (i.e., "equity is measured by the quality and completion of a service"), and disparate impacts (i.e., "equity is measured by disparities in the desired outcomes across groups of interest") [46].

$$Energy\ burden\ [\%] = \frac{Annual\ household\ energy\ expenditure\ [\$]}{Annual\ household\ income\ [\$]}$$

Energy burden as a metric helps visualize energy affordability [50]. A key discussion around energy burden is responsibility. As a performance metric, energy burden would ideally be under the control of the entity assigned responsibility for attaining a related target. However, utilities have limited control over both inputs to the energy burden calculation: there may be limited authority to set differentiated rates (affecting the numerator), and there is practically no control over household income (the denominator). The energy burden metric may therefore emerge first as a tracking metric—used only to inform, but not necessarily incentivize—and the transition to a performance metric may involve the collaboration of multiple entities that would share accountability in attaining energy burden targets.

The procedural aspects of energy equity are currently harder to measure, but their importance is still recognized in state action. In the review of state equity actions in the USA [8••], eight actions across seven states identified process transparency as an objective. Thirty-three actions across 18 states identified outcomes related to education and outreach or enhanced engagement. Examples include Connecticut's Equitable Energy Efficiency Proceeding [51], which identified a goal of enhancing procedural equity through new communication platforms including multilingual and more accessible materials, and Hawaii's 2022 energy equity docket, which initiated an investigation of how the Public Utilities Commission could better integrate equity considerations across its work. The process calls for input from "anyone interested" and additionally from "communities that host energy facilities, people with a high energy burden, and people that do not typically participate in Commission dockets [52]."

Examples of Integration with Resilience

The coupling of resilience and equity objectives is important for understanding the equity implications of resilience-based distribution system investment strategies. Recent grid outages, such as the Texas February 2021 winter storms, highlight the linkage between resilience and equity issues. An analysis 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" [49•]. 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" [42]. Recent work from the Pacific Northwest National Laboratory develops an iterative framework for advancing energy equity through metrics for distribution system planning [2•]. Using an equity-aware outage analysis methodology, the authors determine the impact of each line and transformer outage on the number of customers and the total load lost with tags for disadvantaged versus non-disadvantaged communities.

Conclusions

Societal objectives are expanding and evolving, and the corresponding metrics are being augmented in response to interrelated systemic changes. The objectives and metrics related to resilience and energy equity are intertwined as well; in many cases, it can be viewed as related to the well-being of an individual community. Resilience and energy equity metrics share several related attributes that enhance their interrelationship and emerge as prominent themes in the evolving grid. We discuss these attributes next.

Metrics Move from Utility Scale to Community Scale

Traditional electricity system metrics describe measurement at a national, state-wide, utility service territory or customer class scale. In years past, reliability metrics measured the number and duration of outages over the entire system and did not look at localized impacts. Similarly, measurements of customer satisfaction would look at the experience of an entire customer class regardless of location or individual circumstances [46]. Emerging metrics will have to downscale measurements so that resilience and equity can be measured at a community scale or even individual customer scale (Fig. 1). This granular approach helps to identify the location of investments to enhance outcomes [53].

Metrics Move from Solely Considering Cost or Operation Measurement to Considering Socioeconomic Factors

Typically, performance metrics are tied to specific operating or cost measurements so that performance can be objectively and accurately tracked [4••]. However, measurements based on a traditional benefit-cost analysis may have limited value in informing equity performance and decision-making. An equity metric might seek to measure the accessibility of a regulatory process to nontraditional community advocates or track energy burden that considers both electricity cost and household income. In emerging resilience metrics, combining operating or cost measurements with socioeconomic

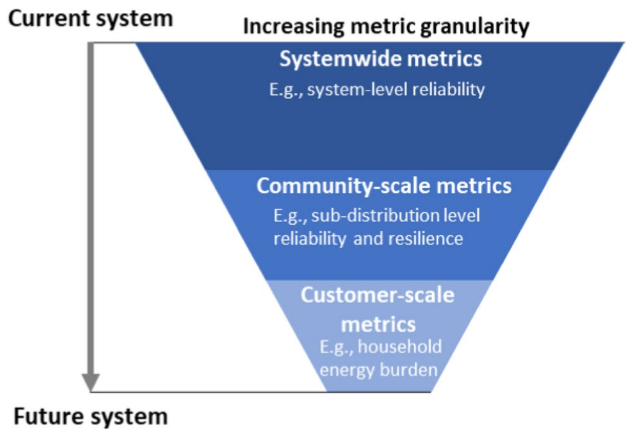

Fig. 1 Metric granularity will increase as future electric system objectives are met

factors can achieve both equity and resilience goals and assist with community resilience goals as well. For example, a resilience metric could not only measure the ability of a portion of the grid to withstand disruption but also the distance within that portion of the grid a customer might need to travel to reach shelter or medical assistance.

Metrics Move from the Utility's Control to Include Factors that Are Not Under the Utility's Control

To meet equity objectives, electricity operators should consider past harms and disparities in the electric system in order to prevent repeating them. This implies a transition from controllable operations and cost-focused metrics to consideration of uncontrollable socioeconomic factors. While this may necessarily imply that some emerging metrics are not measurable performance metrics, it also recognizes the greater societal factors that are implied from electricity service. These values may initially be represented by tracking metrics, rather than performance metrics in the traditional sense [47•].

Metric Development Moves from Traditional Stakeholder Formation to Broader Stakeholder Issues and Community Stakeholders

Regulatory proceedings can be long, can cover complicated and detailed issues, and can require specialized legal representation, particularly in contested case dockets. As a result, over many decades, regulatory proceedings have tended to attract well-resourced or dedicated advocates to the exclusion of those wishing to represent less well-funded points of view or even individual customers. As the expected outcomes of our electricity system are downscaled and increasingly include equity considerations, regulatory processes should also be downscaled, adapt to be more accessible, and include more diverse voices and the voices of the local populations.

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Compliance with Ethical Standards

Conflict of Interest Jason Eisdorfer has previously served as an adjunct professor of law at the University of Oregon School of Law and the Lewis and Clark Law School for classes unrelated to this paper. Kendall Parker, Jay Barlow, and Kamila Kazimierczuk declare that they have no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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