U.S. DEPARTMENT OF ENERGY | Office of ELECTRICITY DELIVERY & ENERGY RELIABILITY

Reliability DISPATCHES

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Electric Distribution Reliability Metrics:

What They Are and Their Role in Distribution Planning and The Evaluation of Environmental Justice

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Introduction

Tuesday, December 8, 1998, was a busy day in the reliability history of the grid. First, at 8:15 a.m., a three-phase fault at a PG&E substation in San Francisco left 500,000 customers—more than a million people—without power for most of the workday (NERC, 2001). With the city's public transit systems disabled and its roadways jammed up by darkened traffic lights, the blackout caused utter "chaos" in the streets, as Tom Brokaw reported on the *NBC News*. PG&E began working to restore the transmission system less than an hour later, but full service to all customers was not restored until around 4pm (NERC, 2001).

Later that afternoon, across the country in suburban Piscataway, New Jersey, a group of electrical engineers and power experts from the Standards Board of the Institute of Electrical and Electronics Engineers (IEEE) convened to approve the group's distribution reliability standard for the first time, as IEEE Std 1366-1998. What they titled the "IEEE Trial-Use Guide for Electric Power Distribution Reliability Indices" laid out a series of definitions and spelled out the steps needed to calculate twelve reliability indices, or metrics (later expanded to thirteen; see the Appendix) (IEEE, 1998).

The indices defined in IEEE Std 1366-1998 were not new, as many of them had been under development in some form since at least the early 1970s (Kostayl, Vismor, and Billinton, 1982; Watts et al., 2022; EPRI, 2000). However, their standardization into a widely distributed IEEE guide helped to facilitate their growing acceptance among many utilities (Brown, 2009). By 2004, SAIDI and SAIFI, the two most fundamental indices, were in use by "virtually all" utilities in the U.S. (Chowdhury and Koval, 2004), and a decade later, the EIA began requiring utilities to report both figures and CAIDI calculations annually to the Washington, DC-based federal statistical agency (Eto et al., 2019).

Whenever utility customers flip the "on" switch, they expect power to flow immediately—and for the most part, the electric distribution system in the U.S. achieves that aim. Both "the grid" at large and most utilities routinely operate without interruption more than 99.9 percent of the time (DOE, 2008; PG&E, 2023a). Such a measure of power availability alone, however, is of limited utility in evaluating reliability performance at the distribution level. To do so, utilities turn to the distribution reliability indices defined in IEEE-1366, or elsewhere, which capture the frequency and duration of system power outages at the customer meter.

While more than 40 such indices exist (EPRI, 2000), the four most common—SAIDI, SAIFI, CAIDI, and MAIFI—are easy to calculate and today are followed by nearly 80% of U.S. utilities (EIA, 2023a) (see Figure 1). Together, they are the primary window through which regulatory and industry observers alike look to assess the reliability of electric service (Eto et al., 2019).

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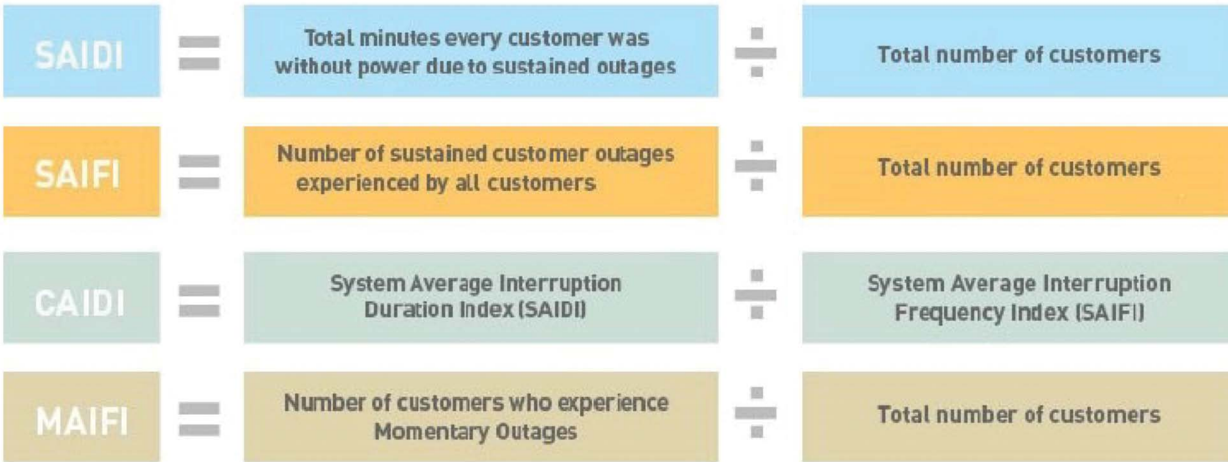

Figure 1. Simplified calculations for the primary distribution reliability indices in use today: System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Momentary Average Interruption Frequency Index (MAIFI) (Enis, 2021).

While the distribution reliability indices are useful as objective measures on the reliability of distribution systems, their importance in informing and regulating the energy transformation will likely grow. Increasingly, utility regulation is adopting Performance Incentive Mechanisms (PIMs) to incent distribution utilities to improve various aspects of the service that they provide. SAIDI, SAIFI and CAIFI are metrics commonly used to measure quality attributes in PIM programs (Joskow, 2014). As concern for environmental justice increases, new methods will need to be developed that can inform about disparities in service. As described later in the paper, the distribution reliability metrics can provide that information.

This *Dispatch* reviews how power outage data is collected, categorized, and used to calculate SAIDI, SAIFI, CAIDI, and MAIFI at the distribution level; and touches upon several areas where utility data practices vary. It concludes with a brief discussion of index attributes and how they provide insights about the overall reliability performance of the electric distribution system.

The Means for Measurement

The value to a utility in tracking distribution service failures and system performance over time is manifold. For one, doing so helps operators keep tabs on system health and identify when its condition may be improving or degrading. For those utilities equipped at the substation level with Supervisory Control and Data Acquisition (SCADA) controls—as an estimated 80 percent of U.S. public power providers are—the detailed data available to them can aid grid planners in identifying problematic circuits and in determining which specific equipment upgrades are most likely to improve reliability performance (Hyland et al., 2019; Loeff, 2022).

Unlike the Loss of Load Probability (LOLP) and other probabilistic resource adequacy planning metrics,[1] distribution reliability indices are based upon observed historical operating data.[2] Utilities capture outage event data via SCADA controls, customer call-ins, computerized system network models known as Outage Management Systems, advanced "smart" metering infrastructure, and even paper records—or more often than not, through some combination of these (Hyland et al., 2019). The "after-the-fact" nature of such a dataset makes it deterministic; it is less a *representation* of future expected reliability than a factual record of a system's historic performance. With a utility's full outage data in hand, calculating its reliability metrics becomes a simple task, at least conceptually. As Kostayl, Vismor, and Billinton explained in an influential 1982 handbook on the subject, an index can usefully describe the reliability of a distribution system as long as it can answer just two questions: "How often does the system fail?" and, "How long does it take to restore the system after a failure has occurred?"

The industry's affinity for dubbing SAIDI, SAIFI, CAIDI, and MAIFI as "distribution reliability indices" may strike some as a misnomer. Indeed, one must note that these metrics comprise *all* outages that affect a metered service point, including generation shortages and transmission outages that occur outside of utility control. This custom exists largely because it is the utilities themselves, and not

[1] See "Measuring Reliability: What is the Loss of Load Probability?," another Reliability Initiative Dispatch, published XXXX 2024.

[2] Measures such as the LOLP are forecasts of the future reliability states of the system. They are typically performed using historic data that describes generation and electric system characteristics.

generation or transmission operators, who have maximal vision into where and when outages permeate within the distribution network. Failures at the distribution level account for the majority of all power interruptions in the U.S. (many sources estimate its culpability at around 90 percent), most of which are short-lived. However, SAIDI and her "sister"[3] indices exist to capture all interruptions that de-energize a paying customer's meter, for whom—more likely than not—the reason why their home or business is darkened is rather immaterial (Eto et al., 2019).

Exploring the Indices

Some industry observers consider the System Average Interruption Duration Index, or SAIDI, to be the prime index among the four main metrics (Hyland et al., 2019). Put plainly, SAIDI calculates how long, on average, each customer in a service territory went without electric power over a set period. SAIDI is often measured in either minutes or hours and is customarily reported by calendar year. Its calculation requires that the total duration of outages be divided by the total number of customers served. SAIDI does not encompass *all* outages, however, as its definition is constrained to measure "sustained" interruptions only (i.e., those lasting longer than 5 minutes) (IEEE, 1998, 2022).

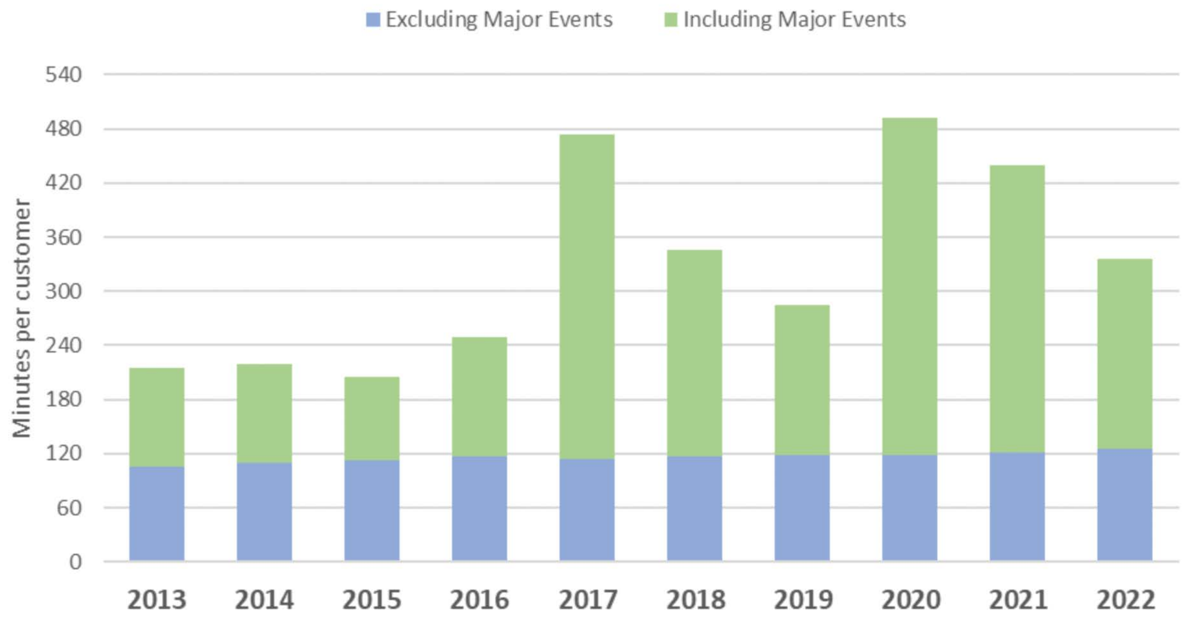

Figure 2. Average duration in minutes per customer of total annual electric power interruptions, United States, 2013–2022. Figures reflect SAIDI figures reported to EIA under "Any Method" and as "All Events," with "Major Event Days" and losses of supply included (EIA, 2023b).

The U.S. Energy Information Administration (EIA) routinely publishes reader-friendly assessments of trends in national SAIDI and SAIFI figures. In recent years, these have more than occasionally found their way—albeit alongside a barebones description of their equations—into major media headlines probing the state of the country's "Creaky" or "Increasingly Unreliable" electric grid (Blunt, 2022; Barone, 2022). If the reader is lucky, they might find a time-series chart of annual SAIDI minutes per customer accompanying the article (EIA, 2022; Barone, 2022).

SAIDI averages have also found favor by virtue of the fact that its units are somewhat intuitive. For example, between 2013 and 2022, the U.S. SAIDI average has fluctuated between a low of 205 minutes and a high of 491 minutes of interruption per year—the difference between a three-hour-plus movie, and a full eight-hour workday (see Figure 2).

SAIDI also finds common usage in reliability and resilience analyses due to its focus on sustained interruptions. Using SAIDI averages from the EIA and a third-party source of outage data (*PowerOutage.us*), one team of researchers in 2023 identified the occurrence of nearly 17,500 outages between 2018 and 2020 that lasted 8 hours or more (Do et al., 2023). Blackouts of this length can have a significant impact on societal function, public health, and at minimum,

[3] This phrase is commonly used as a convenient shorthand for SAIFI, CAIDI, and MAIFI. See Lankutis, 2014; Teixeira, 2019.

customer quality of life (Ericson et al., 2022). Finally, since IEEE Std 1366 was revised in 2003, SAIDI has been the index used for setting a statistical line between which events count as “major event days” and which are deemed “normal” interruptions. Among the 12 indices defined by the IEEE, the institute’s experts deemed SAIDI to be “the best indicator of system stresses beyond those that [a] utility’s staff [can] build and design to minimize” (Warren, 2005).

Conceptually similar to SAIDI, the **System Average Interruption Frequency Index** also considers only sustained interruptions. It is dimensionless, however, as it measures the number of sustained power interruptions that occur for the average customer over a period of time. SAIFI is analogous to SAIDI in that a higher index value denotes *lower* reliability performance; however, their scales are quite different. Between 2013 and 2022, average U.S. SAIFI has ranged from 1.20 to 1.44 outages per year. Even when averaging SAIFI figures over multiple years, outage events occur far more frequently in some sections of the U.S. than others. At the county level, portions of the Deep South, Maine, West Virginia, Kansas, and the Pacific Northwest often see outage rates more than twice the national average; the duration of customer outage-minutes follows a roughly similar geographic distribution (see Figure 3).

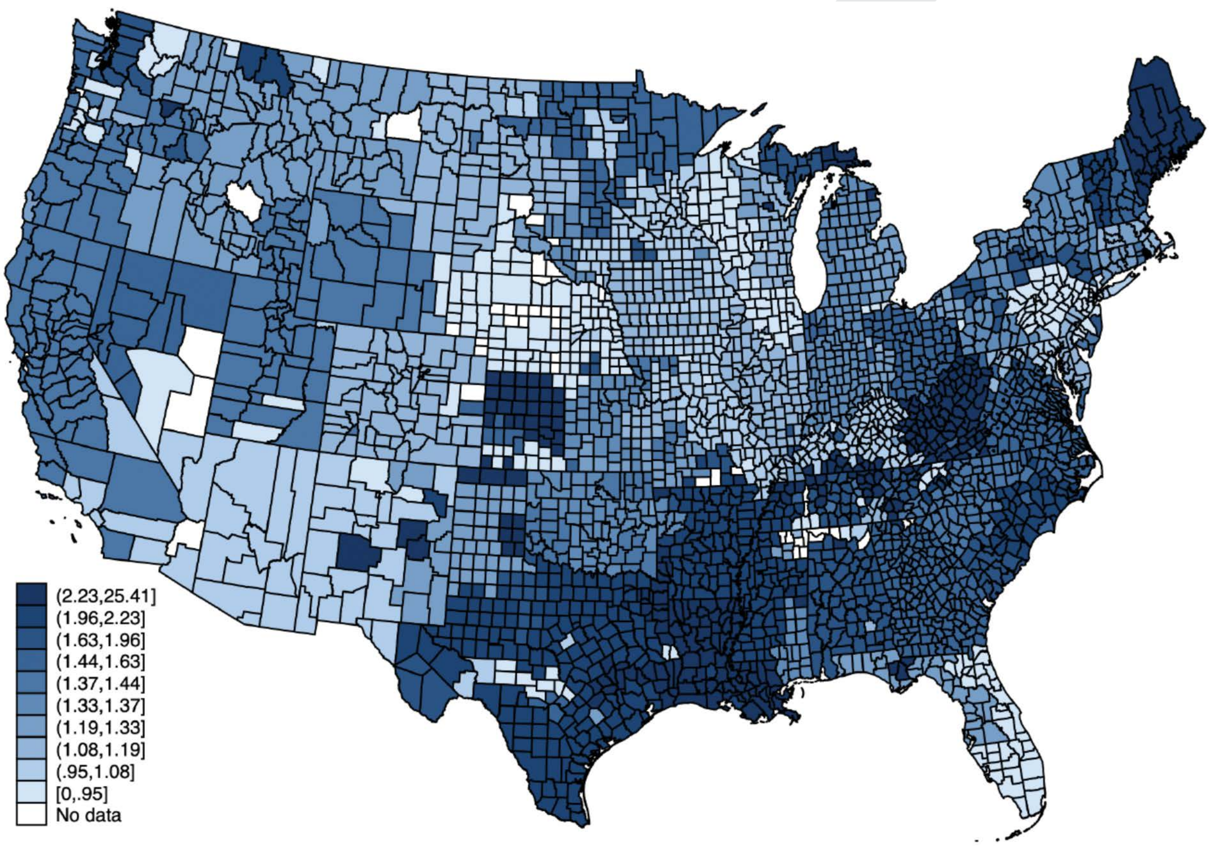

Figure 3. The average frequency of customer-averaged outage events (SAIFI), by county, 2015–2020 (Borenstein, Bushnell, and Mansur, 2023) (permission pending). A county-level map of SAIDI outage durations over the same period looks largely similar, but with higher relative customer interruption-minutes in California, Florida, Oklahoma, and Ohio.

Like SAIDI, the Customer Average Interruption Duration Index is a measure of duration, reached by dividing the total customer interruption time by the number of customer interruptions—not simply the number of customers in a service territory. CAIDI is commonly reported alongside SAIDI and SAIFI in part because it is a derivation of the two; as shown in Figure 1, its shorthand calculation is simply to divide SAIDI by SAIFI. By measuring the ratio of outage frequency to duration, CAIDI can be said to represent “the average time required to restore service,” and indeed, that is how IEEE Std 1366 defines the index (IEEE, 1998, 2022). However, as Watts et al. (2022) write in *IEEE Power & Energy Magazine*, whereas CAIDI had once been valued for more closely reflecting “customer experience” than other indices, some of that shine has since worn off. To Watts et al., and others, CAIDI is more properly seen as a “problematic” measurement with only limited utility. The value of its perceived tie to the customer’s viewpoint is tempered by the fact that in some instances, if a utility’s overall reliability performance is improving but its SAIFI figures decline at a faster rate than its SAIDI index, its CAIDI results will appear to be getting worse than before.

Finally, the **Momentary Average Interruption Frequency Index** is the primary "momentary" index in general use. Like SAIFI, MAIFI figures are dimensionless, but unlike its sister indices, MAIFI does not consider sustained interruptions. IEEE Std 1366, last revised and updated in 2022 (i.e., IEEE Std 1366-2022), defines a non-sustained or "momentary" interruption as "the brief loss of power delivery to one or more customers caused by the opening and closing operation of an interrupting device(s)" (IEEE, 2022). Importantly, when an interrupting circuit breaker or recloser functions multiple times within a five-minute event window, and is successful in restoring service, it is considered a single outage event.

Utility interest in MAIFI grew with the early proliferation of digital consumer electronics in the 1990s and 2000s. Most such devices lacked a backup power source, and so would reset after any transient outage, causing clocks to beep out a "blinking twelve" on living room VCR screens. Previously, these power blips went mostly unnoticed by customers, especially during working hours (Eto and LaCommare, 2008; Stephenson, 1999). Because MAIFI is targeted at the rapid execution of breaker/recloser actions, the sensing and collection of its data poses a different set of challenges to a utility than SAIDI or SAIFI does. Still today, many utilities do not generate adequate information to track its values (Duquesne Light Co., 2023).

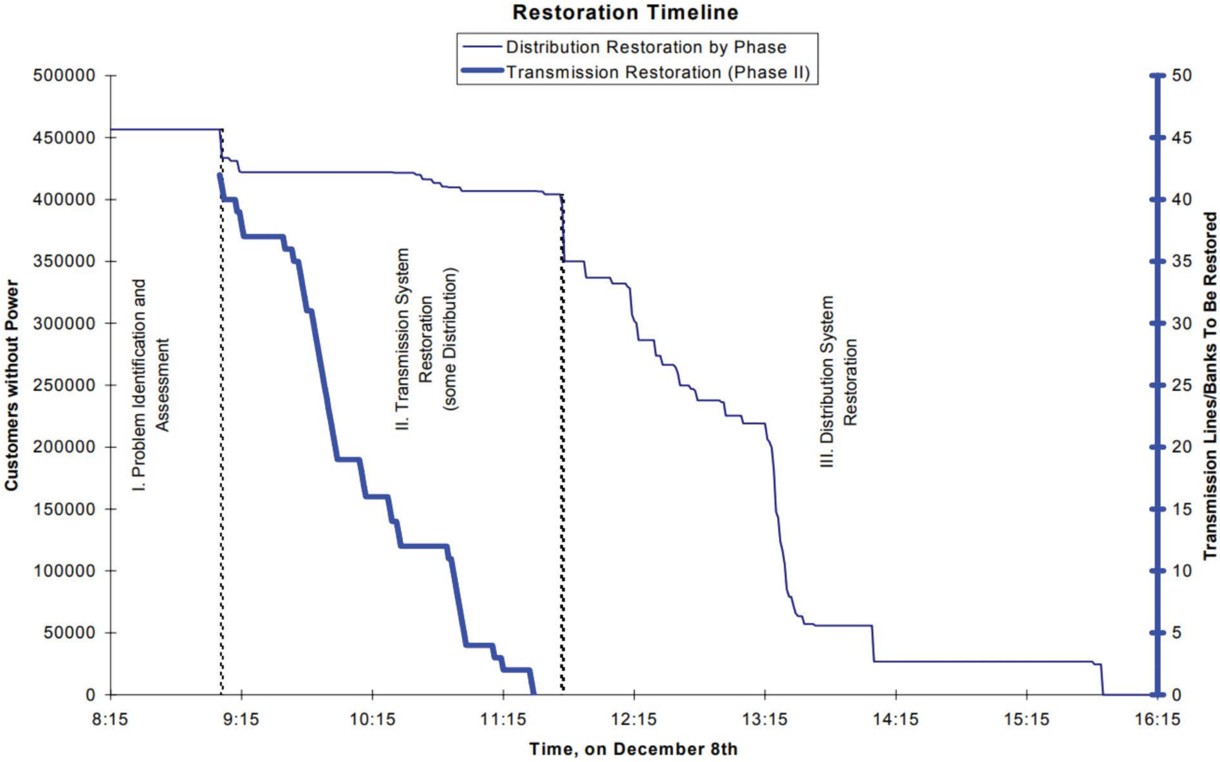

Figure 4. Restoration timeline for the December 8, 1998, PG&E power outage, as developed in 2001 by the North American Electric Reliability Council (NERC, 2001). Note: PG&E's estimate of the number of customers affected was approximately 503,000, well above the 456,000 depicted here (PG&E, 1999).

Metric Implementation Issues

Widespread adoption by utilities of SAIDI, SAIFI, and CAIDI did not necessarily translate into widespread adherence to the IEEE's protocols for calculating them. From its inception, IEEE Std 1366 has been a wholly voluntary standard, and it remains so today.[4] For a variety of reasons, many utilities opt to deviate from IEEE's guidelines. For example, of the utilities reporting SAIDI, SAIFI, and CAIDI figures for calendar year 2013, roughly 40% did so using what the EIA calls "any method," or "another standard" than IEEE Std 1366. While that figure has markedly declined since, to around 25% of utilities for 2022, a wide measure of variation among them persists. Some utilities calculate SAIDI, but not SAIFI; others report their annual SAIDI averages with major event days included, yet not also sub-divided out; yet others calculate major event days but do so according to their own criteria.

The indices' use of averaging can be both a boon and a hin-

[4] IEEE Std 1366 was last updated and approved in September 2022, as the "IEEE Guide for Electric Power Distribution Reliability Indices" (IEEE Std 1366-2022).

drance. As Kostayl, Vismor, and Billinton explained in 1982, it is through averaging against total system customers that SAIDI, SAIFI, and CAIDI "attempt to capture the *magnitude* of disturbances" (emphasis added). Yet, this same technique makes SAIDI and her sisters particularly suspect for informing a conclusion about trends in the grid's reliability, or even that of any individual utility system. Apart from pointed critiques that the averaging conducted by a distribution operator fails "to accurately capture the reliability experience for their customers" (Watts et al., 2022), averaging can also insulate the indices from reflecting specific interruptions affecting the full grid.

Moreover, the structure of SAIDI, SAIFI, CAIDI, and MAIFI does not necessarily place "blame" upon a reporting utility for an outage event caused by, say, a third-party transmission outage, or a curtailment initiated by an upstream power producer. When, in 1998, the IEEE standardized how to calculate and report SAIDI and eleven other common indices into a guidance document for the first time as IEEE Std 1366, it included a provision to account for the differences between routine, "day-to-day" system operations, and those catastrophic or extreme events that stress grid operations beyond a reasonably expected level (IEEE, 1998, 2022). The determination of such events, known as "major events," was initially left to each utility's discretion, but revisions to the standard approved in 2003 (i.e., IEEE Std 1366-2003) set in place a specific statistical means of determining which outages should be assessed separately (see Figure 2).

Separating out the most severe events is not the only way to account for outages that originate beyond the reach of utility control, however. The Pacific Gas & Electric Company (PG&E) was an early adopter in this vein. In 1997, the California Public Utilities Commission (CPUC) began requiring its utilities to submit an annual Reliability Report, to include a table cataloguing their system wide SAIDI, SAIFI, and MAIFI figures for the year. Starting in 1999, PG&E began including two supplemental tables in its report to the commission, presenting its Transmission and Distribution index performance separately (PG&E, 1999, 2023b). Since 2003, the IEEE has encouraged utilities to report their outage statistics with such "losses of supply" noted.

As one analyst has explained, even if year-over-year changes in SAIDI averages for a given entity are clearly explicable, "it's not really quite correct to say that interruptions are getting longer or shorter… I think it's very important not to therefore interpret SAIDI and SAIFI in a literal sense" (Eto, 2020). Recent inquiries have also firmly established that no less than an immense effort to collect, edit, filter, and clean murky utility-level datasets—at a minimum—would be required for any index-driven set of conclusions to even approach a level of statistical validity or significance (Larsen, et al., 2015; Eto et al., 2019).

Data Quality Issues

While the intuitive quality of SAIDI and SAIFI metrics make them apt for providing a neat picture of overall grid reliability, SAIDI averages on the state level are drawn from smaller datasets and can be prone to far broader variations. Rhode Island averaged just 54 SAIDI minutes in 2014, for example, while Louisiana—beset in 2021 by Winter Storm Uri, followed by a one-two punch from Hurricanes Ida and Nichols—tallied 4,811 minutes that year (EIA, 2023c). Similar to differences in SAIDI averages among the states, average SAIFI frequencies ran between a low of 0.608 in Nebraska during 2022, to a high of 5.123 in Maine in 2014 (EIA, 2023d). (Like Louisiana in 2021, Maine was battered in 2014 by record-breaking "mighty" storms for much of the fall (Byrne and Graham, 2014).)

Moreover, wide discrepancies in the technical capabilities and financial resources of utilities only exacerbate differences in how detailed their outage data collection and reporting can be (Shadle, 2021). PG&E's ability in 1999 to produce separate SAIDI and SAIFI tables covering its transmission and distribution systems separately is emblematic of such variation: nearly a quarter of a century later, reporting SAIDI and SAIFI figures at a level below the full system is not a universal practice (Hyland et al., 2019).[5] Additionally, whereas a not-unsubstantial number of utilities still operate without *any* SCADA-enabled, digital insight into the operation of their systems, PG&E tracks its power interruptions to a minute level of detail—it knows, for example, that on June 30, 2022, "a squirrel caused a breaker level outage on the Auberry 1101 feeder," contributing "0.007 customer-interruptions" to the SAIFI performance of PG&E's Fresno Division (PG&E, 2023b).

A Blackout, and a Guide

One final look at the power outage that PG&E experienced in December 1998 is warranted. The power outage and service restoration chart from the event (Figure 4) nicely illustrates how the vagaries of a firm's technical capabilities can impinge on how they report their reliability performance to regulators and the public. As the IEEE 1366-1998 guidance document noted, calculating indices like SAIDI may "require step-restoration tracking" in order to provide a "reliable" figure, as large power interruptions are rarely remediated all at once (IEEE, 1998). In their 1999 filing with

[5] Doing so is important to highlight which system circuits are most vulnerable to failure; this, in turn, would help resolve environmental justice-related allegations that certain communities have systematically lower levels of reliability in electric power service. See Do et al., 2023; Liévanos and Horne, 2017.

the public utilities commission for calendar year 1998, PG&E explained that its computerized outage tracking system sported an insufficient "level of detail" to capture the "step restoration" activities that returned power to customers in tranches over the blackout's eight hours (PG&E, 1999).

As a result, the utility based its SAIDI figures on an approximation, estimating that the 500,000 customers who lost power did so for either 0–1 hour, 1–5 hours, or 5–10 hours (see Table 1). Because the latter two groupings display a wide range of durations that those customers experienced (1–5, 5–10 hours), it is possible that this method resulted in an overcount of the December 8 event's total customer-minutes of lost power. If PG&E multiplied each of the three groupings by its maximum duration (e.g., 250,327 customers x 5 hours), the total falls just shy of 3,340,000 customer-minutes. If doing so by average duration (250,327 x 3 hours), the total of customer-minutes lost is approximately 2,300,000.

Outage Event Duration Summary

Outage Duration (hours)	*Number of Customers Affected*
0 to 1	49,753
1 to 5	250,327
5 to 10	203,628

Table 1. PG&E outage duration estimates by customer tranche for the December 8, 1998, blackout (PG&E, 1999).

The detailed restoration timeline depicted in Figure 4 was constructed more than a year after PG&E submitted its 1999 reliability report to the CPUC, as a result of an in-depth review of the event conducted by NERC officials in 2001. By dividing the restoration timeline into 15-minute intervals to track the progress of PG&E's step restoration, a back-of-the-envelope calculation finds the total customer-minutes lost to be far closer to 2,000,000 than the 2,300,000 derived from each group's average outage duration. The ~14 percent difference between the two is a salient reminder that even the most dutifully collected SAIDI, SAIFI, CAIDI, and MAIFI figures should be viewed and analyzed with a good measure of judgment.

The Evolving Role of Distribution Reliability Metrics in the Energy Transformation

The reliability indices discussed in this paper provide real-world data as to how well distribution systems provide service to customers. As distribution systems become more complex, these indices will grow in importance.

Utility regulation is increasingly relying on these indices to provide incentives based upon distribution reliability indices to improve service. Aggregate statistics on a utility scale are sufficient for this purpose.

There are two additional ways that the indices can facilitate the transformation of the electric distribution system. Doing so, will require more fidelity in reporting. Advanced metering will enable utilities to develop a more detailed depiction of the reliability and restoration at the circuit level. This information can facilitate planning through the identification and prioritization of circuits that require being upgraded. Detailed circuit specific reliability data can be used in conjunction with socio-economic data to evaluate whether environmental justice issues exist at the distribution level. For example, to the extent that circuits that serve disadvantaged communities have lower levels of reliability, or require longer restoration times, the issue of whether this is because of discriminatory service can be addressed.

In conclusion, distribution reliability statistics are based upon the historic operation of the utility in providing distribution service. While the industry does not evaluate these statistics on a consistent basis, they provide useful information. Continued development of techniques to improve the fidelity of these statistics can help to prioritize planning of different distribution circuits, as well as provide a tool for evaluating environmental justice.

Appendix

Definitions of the thirteen reliability indices defined in IEEE Standard 1366-2002, IEEE Guide for Electric Power Distribution Reliability Indices, September 2022 (IEEE, 2022).

Electric Power Distribution Reliability Indices (IEEE 1366-2022)		
	Sustained interruption indices (> 5 minutes)	
SAIFI	System Avg. Interruption Frequency Index	Frequency that the average customer experiences an interruption
SAIDI	System Avg. Interruption Duration Index	Total duration of interruptions for the average customer
CAIDI	Customer Avg. Interruption Duration Index	Average time required to restore service
CTAIDI	Customer Total Avg. Interruption Duration Index	Total duration of interruptions for only interrupted customers
CAIFI	Customer Avg. Interruption Frequency Index	Frequency of interruptions for only those customers interrupted
ASAI	Avg. Service Availability Index	The percent of time that the avg. customer has received power
$CEMI_n$	Customers Experiencing Multiple Interruptions	The ratio of customers experiencing a sustained interruption a set number of times (n) to all customers served
CELID	Customers Experiencing Long Interruption Durations	The ratio of customers with interruption durations over a set threshold of time to all customers served
	Load-based indices	
ASIFI	Avg. System Interruption Frequency Index	Equiv. to SAIFI, measured by kVA of load interrupted/ served
ASIDI	Avg. System Interruption Duration Index	Equiv. to SAIDI, measured by kVA of load interrupted/ served
	Other indices (momentary, <5 minutes)	
MAIFI	Momentary Avg. Interruption Frequency Index	Frequency that the avg. customer experiences a momentary interruption
$MAIFI_E$	Momentary Avg. Interruption Event Frequency Index	Equivalent to MAIFI, but excluding automatic interruptions related to recloser events (restoration of power)
$CEMSMI_n$	Customers Experiencing Multiple Sustained Interruption and Momentary Interruption Events	The ratio of customers experiencing either sustained or momentary interruptions a set number of times (n) to all customers served

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