

The climate change challenge: actions required to increase resilience of distribution grids

Executive summary

Resiliency improvement is becoming an ever more important topic for the power distribution sector.

For the purpose of this policy brief, we have used the IEEE definition of resilience: *the capability of electric power distribution systems to deliver electric energy to end-use customers by avoiding interruptions and/or recovering this capability following exposure to naturally occurring high impact low frequency events*¹.

The modernization of distribution grids – replacing ageing assets, increasing their robustness, rising meshing and redundancy levels, redesigning the networks for enhanced reliability and resiliency, fostering the digitalization of distribution grids, creating digital twins, developing artificial intelligence tools, fostering automation and deploying smartgrids, are creating new tools to enhance resiliency.

Reliability, measured through aggregate annual indices, captures only steady-state performance. These metrics were not meant to measure a system's ability to anticipate, withstand, adapt to, and recover from high-impact, low-probability events.

To foster power distribution system resilience, CIRED makes the following recommendations to public policy decision-makers, including **regulators and governmental authorities**, while recognizing the essential role of **DSOs/DNOs** in their implementation:

- **Develop a common resilience framework**, including clear definitions, metrics, and assessment methodologies for power distribution system resilience. Such a framework would enable regulators and governmental authorities to establish measurable resilience objectives, monitor performance, and benchmark progress consistently across utilities.
- **Establish a clear policy strategy for High-Impact, Low-Frequency (HILF) events**. Public authorities and regulators should define resilience objectives for extreme events and ensure that distribution utilities have access to appropriate regulatory and financial mechanisms to achieve them. This includes providing adequate funding and incentives for resilience-related investments and preparedness measures, on top of existing incentives dedicated to reliability enhancement.
- **Design regulatory frameworks that actively incentivize resilience enhancement**. Regulators should play a central role in translating resilience objectives into concrete regulatory mechanisms that guide utility behaviour, operational practices, and investment decisions. These frameworks should promote a balanced approach encompassing anticipation, resistance, adaptation, and recovery capabilities, ensuring that resilience is addressed holistically rather than through isolated measures.

¹ This definition was proposed by the IEEE Distribution Resiliency Taskforce. For this document, the authors have accepted the same understanding on the definition of Resilience.



- **Promote the development and adoption of common risk assessment and resilience quantification methodologies.** Distribution utilities should actively contribute to the creation of transparent and standardized approaches for evaluating risks and resilience performance. Such methodologies are essential for enabling consistent comparisons of network performance, assessing the effectiveness of mitigation measures, and supporting evidence-based investment decisions. DSOs/DNOs, acknowledging the importance of workforce preparedness, should also develop initiatives enhancing emergency response capabilities, while also promoting the coordination between interdependent critical infrastructure assets, and emergency services.



Distribution grid resilience: a need beyond reliability

For the purpose of this policy brief, we have used the IEEE definition of resilience: *the capability of electric power distribution systems to deliver electric energy to end-use customers by avoiding interruptions and/or recovering this capability following exposure to naturally occurring high impact low frequency events*^{2,3}. Other resiliency events, such as cybersecurity threats and other malicious actions are outside the scope of this policy brief, as they involve a different set of skills and solutions.

The importance of this topic is driven by increasing challenges of climate change, causing a rise in the frequency and severity of extreme weather events. Forest fires are a secondary climate hazard impacting the resiliency performance of several distribution systems. It is further compounded by the growing criticality of power distribution systems to modern society, as a result of the energy transition.

Distribution reliability has steadily improved across most utilities, driven by network meshing, feeder automation and remote switching (FLISR), sectionalizing, vegetation management, and selective undergrounding. Yet reliability, measured through aggregate

annual indices such as SAIDI and SAIFI⁴, captures only steady-state performance. Under IEEE 1366, the highest-impact days exceed the 2.5 β major-event-day threshold and are excluded from reported indices, so the events that matter most for resilience receive a statistical bypass: a utility can report improving SAIDI/SAIFI while its exposure to catastrophic events, with many contemporaneous faults, goes unmeasured. EIA data underscore the scale of what is removed, with major events accounting for 80% of U.S. customer outage hours in 2024⁵. By definition, these metrics were never meant to measure a system's ability to anticipate, withstand, adapt to, and recover from high-impact, low-probability events such as hurricanes, wildfires, floodings, heat waves, thunderstorms, wet snow or ice storms.

² This definition was proposed by the IEEE Distribution Resiliency Taskforce. For this document, the authors have accepted the same understanding on the definition of Resilience.

³ Also commonly referred to as high impact, low probability. The frequency of these events tends to increase due to climate change. The impact of the associated events is also characterized by its duration. Even if it is lower, it still may be meaningful due to that extended duration and by consumers increasing dependence on electricity for heating and transportation.

⁴ System Average Interruption Duration Index and System Average Interruption Frequency Index.

⁵ EIA, Electric Power Annual 2024, Oct. 2025.



Even where the definition of a major or exceptional event differs across utilities and jurisdictions, such events tend to account for a growing share of total SAIDI as baseline reliability improves and HILF likelihood and severity increase.

Weather related interruptions to the distribution network tend to be more widespread and severe than those from other causes. As the likelihood and severity of events such as flooding, heatwaves, and windstorms increase due to climate change, distribution network operators must ensure that existing and new grids are able to adapt to these changing threats. Forest fires are also likely to increase in frequency and severity due to climate change. In several countries, including the U.S.A., Belgium, Croatia, Portugal, and Slovenia, natural hazards are responsible for more than 50 percent of outages, according to the World Bank⁶.

A grid can be reliable by every traditional measure and still fail catastrophically when subjected to conditions beyond, or compounding at the edge of, its design basis. This distinction is what makes resilience not a replacement for reliability, but a necessary complement to it. Therefore, features for a fast recovery – partly or complete – are crucial for the restructuring of power grids.

At present, most resilience measures are treated as by-products of reliability improvement. Given the rising frequency and severity of High Impact Low Frequency (HILF) events, resilience must be progressively incorporated as one of the core constraints in power grid planning, rather than merely an incidental consideration for investment projects.

⁶ The World Bank, "Lifelines - The Resilient Infrastructure Opportunity", 2019, *Lifelines: The Resilient Infrastructure Opportunity*.

Why resilience, why now?

Several converging factors explain why resilience has moved to the centre of the conversation in a relatively short period of time.

Climate change is reshaping the threat landscape for distribution grids. Events once considered rare enough to fall outside design assumptions, such as Category 4 hurricanes, prolonged heat domes, and catastrophic wildfires, are now recurring within the operational lifetimes of grid assets. The frequency and severity of HILF events are projected to continue increasing, compressing what were once multi-decade return periods into intervals that challenge both planning horizons and capital recovery cycles.

The impact of these events is compounded by the nonlinear behaviour of grid assets under stress. Well-maintained electrical equipment can operate reliably for decades when kept within its designed operating conditions. However, abnormal climate conditions can push assets to their limits or, in the worst case, into dangerous operating regimes where failure rates escalate sharply. Storms may exceed the nominal wind load for overhead lines, flooding may submerge substation or underground equipment, or sustained heat waves that reduce the soil thermal transmittance and, as a consequence, its capability to dissipate the underground cables heat and/or expose transformers to prolonged overloads caused by surging air conditioning demand are all examples of conditions that may fall outside the envelope for which these assets were designed.

The relationship between stress and failure is not proportional; more significant impacts are seen at the extremes. Transformer insulation loss-of-life, for instance, rises exponentially with hot-spot temperature (IEEE C57.91), so sustained overload during a heat wave consumes asset life far faster than the same loading at moderate ambient, while mechanical stressors like wind and ice fail more abruptly past their design limit. That concentration of impact at the extremes is what makes HILF events so destructive.





Resiliency vs Flexibility

In discussions on the evolution of electric distribution systems, resilience and flexibility are often mentioned together and, in some cases, incorrectly treated as interchangeable concepts. However, they address different types of uncertainty, operate over different time horizons, and support decision-making at different system layers.

Flexibility describes the ability of the power system to adjust its operation in response to foreseeable variability in supply and demand. It primarily supports the continuous balancing of the system under normal or stressed-but-expected conditions. Typical flexibility enablers include demand response, controllable and fast-ramping generation, energy storage systems, grid automation, advanced forecasting, and sector coupling.

A fundamental distinction lies in scope and intent. Flexibility improves how the system operates within an assumed envelope of conditions. Resilience addresses what happens when that envelope is breached. The two also differ in time horizon and decision layer: flexibility operates continuously, over seconds-to-

hours dispatch and market timescales, while resilience concerns low-probability events on multi-year return periods and the prolonged restoration that follows, decided largely at the planning, investment, and regulatory layers rather than in real-time operation. Flexibility contributes to resilience, particularly during adaptation and restoration, but it is not sufficient on its own. A highly flexible system may still perform poorly during extreme events if it lacks physical robustness, redundancy, emergency preparedness, or effective restoration capabilities. Generally speaking, a distribution network that can be operated, during emergencies, in separate micro grids through dispatching of distributed generation combined with flexibility of DERs could improve substantially its resilience.

Flexibility, on the other hand, is often associated with an optimization of the utilization of the existing grid, resulting in an increase in that utilization. Operating networks closer to their thermal limit – as discussed further in Section 3 – can also have negative consequences on the asset failure behaviour.





Electrification of the energy sector increases the criticality of distribution grids

At the same time, the role of electricity within the broader energy system is expanding rapidly. Modern societies depend on energy as a critical input to virtually every economic and social function, and that final energy consumption has historically been spread across several sources, including oil products, natural gas, and electricity. This balance is now shifting. Decarbonization and energy transition policies are driving a structural increase in the share of electricity within total final energy consumption, as transportation, space heating, and industrial processes that once relied on direct combustion of fossil fuels progressively converted to electric alternatives.

This transition fundamentally changes the consequence profile of a grid outage. Electrification of end uses such as heating, cooling and transportation is a cornerstone of the energy transition and an essential pathway to achieving climate objectives through the reduction of greenhouse gas emissions. As societies increasingly rely on electricity to deliver these services, the continuity and resilience of power supply become even more critical for maintaining essential functions and societal welfare. Historically, energy services were provided by a mix of fuels and infrastructures, offering a degree of diversification during prolonged power disruptions. In an increasingly electrified energy system, many of these services become more closely linked to the performance of the electricity network. As a result, HILF events can have broader societal consequences, reinforcing the need to strengthen the resilience of power systems alongside the electrification process.

Electrification can also increase the utilization of network assets: heat-pump heating shifts cold-climate systems toward winter peaks and EV charging adds evening peaks. These evolving load patterns may bring transformers and feeders closer to their thermal limits and increase the importance of adequate planning and resilience-oriented investments. Reserves used to delay or defer grid expansion are reserves no longer available during rare events, making resilience considerations an increasingly important compo-

nent of long-term system development. The same electrification also expands the resilience toolkit, since distributed generation, storage, and islanding microgrids can sustain critical loads locally; realising that benefit requires deliberate design and absent it the dependence dominates. In this context, resilience of the electrical energy system is no longer merely a technical objective. It is a prerequisite for ensuring that the benefits of a decarbonized and increasingly electrified energy future can be delivered reliably, safely and sustainably, supporting both climate goals and the continued functioning of modern societies.

Electric power supply underpins the operation of several essential societal services, including telecommunications, water supply and treatment, wastewater management, waste disposal, and rail transport.

Electricity distribution networks are an essential infrastructure that underpins daily life and the economy. Maintaining resilient systems that include resilience to the HILF events is not an option and is necessary to maintain basic societal functions, economic productivity, and public service. As societies electrify, the consequences of failure become more severe, so resilience becomes more critical to societal welfare. This requires prioritisation of long-term, proactive, and climate-aware investment to safeguard that welfare.

The modernization of distribution grids – replacing ageing assets, increasing their robustness, rising meshing and redundancy levels, redesigning the networks for enhanced reliability and resiliency, fostering the digitalization of distribution grids, creating digital twins, developing artificial intelligence tools, fostering automation and deploying smartgrids, are creating new tools to enhance resiliency. Those tools also include microgrids, which enable the development of segments of the grid that, supported by distributed resources, are capable of operating in stand-alone configurations and, therefore, increase the resiliency within those segments.



Hard to quantify risks and to monetize the benefits of risk mitigation initiatives.

HILF events disproportionately affect vulnerable and low-income populations, amplifying existing socio-economic inequalities. This makes impacts on distribution grids a central consideration in resilience planning. Vulnerability is driven by both the exposure of certain communities or customer groups to HILF and their adaptive capacity. Electrically dependent customers (i.e., medical equipment users) may face disproportionate safety risks during extended interruptions.

Decision makers rely on economic indicators to assess the opportunity cost associated with investment projects. In the distribution grid sector, these economic indicators include the monetization of interruptions of supply, assessing the expected improvement in indicators such as SAIDI, SAIFI, or others. These indicators are well controlled for interruptions resulting from equipment failure with a stochastic nature – expected failure rates are variables known by distribution companies, based on their experience and on the very high number of similar equipment operated, or historical data. Adequate standardised metrics for the impact of HILF are not in place and under development. The IEEE Distribution Resiliency Task Force has also been developing a suite of metrics to quantify climate resilience. These metrics span operational and system resilience and are still under development too.

The Italian regulator, ARERA, developed regulatory tools promoting an increase in resiliency in distribution and transmission systems. The mechanism is based on the concept of a risk index, given by the ratio between the number of consumers benefiting from specific projects – measuring the impact or damage of an event – and the return period of the event. Each DSO is to identify risk factors relevant for its network and define resiliency-aimed projects mitigating those risks⁷.

The availability of updated meteorological time series with proper granularity together with reliable models of their effects on electrical grid infrastructures are fundamental to evaluate properly risk indexes.

Another example of an analytical tool developed to assess how a system – such as an electrical grid – maintains or recovers its functionality when hit by a disruptive event is the resilience trapezoid. It is plotted on a graph of performance vs time, defining four main phases (Anticipation, Resistance, Adaptation, Recovery)⁸.

The advent of digital twins, digital replications of assets and whole grids, empowers grid operators with a powerful tool for risk assessment. As digital twins behave like their real counterparts, evaluation of scenarios, such as HILFs, is a typical use-case. A digital twin may evaluate both the impact of an event and the impact of resilience measures. The value of such analyses is bounded by the failure models behind them: HILF conditions are precisely where stress-to-failure data is scarcest, so a twin reduces but does not remove the underlying quantification problem.

Resilience measures may include conventional approaches, such as considering conditions during a HILF event as rated conditions. It may also include smart grids, such as automating local transformer stations, or AI-supported dispatch of repair teams, both leading to a shorter outage and a higher resilience. Common for all these measures are that they involve effort and cost, especially if hardware related investments are needed. This results in significant resources spent for events which may, on a local level, never happen, and hence are difficult to justify within conventional frameworks.

Public policy decision-makers should evaluate the benefits that resiliency-enhancing investments deliver to both the system and society, and develop regulatory and legal frameworks that promote the adoption of resilience-enhancing initiatives while ensuring cost-effectiveness.

⁷ Lo Schiavo, Luca; Turconi, Carlo; Villa, Ferruccio, "Regulatory incentives for improving the resilience of electricity distribution grid in Italy", 2019, CIREN - 25th International Conference on Electricity Distribution, Madrid.

⁸ Panteli, Mathaios; Mancarella, Pierluigi, "Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies", Electric Power Systems Research, Volume 127, 2015, Pages 259-270.



Policy recommendations

A strategy to deal with HILF should be enacted by public policy decision-makers (regulators, governmental authorities), defining objectives regarding the resiliency towards HILFs and guaranteeing that DSOs/ DNOs undertake the necessary actions to address those objectives.

To effectively address service interruptions caused by high-intensity weather events, public policy should enable regulatory frameworks that actively support risk mitigation and resilience enhancement in distribution grids across all phases of an extreme event. Regulators must play a central role in translating resilience objectives into concrete mechanisms that guide utility behaviour and investment decisions, ensuring that anticipation, resistance, adaptation, and recovery capabilities are coherently addressed rather than treated in isolation.

Policy action in this area can take multiple forms. In the **anticipation phase**, regulatory frameworks may incentivise risk-informed based planning. In parallel, regulation can promote **resistance-oriented measures**, such as grid hardening, selective reinforcement, automation, microgrid development, and network configurations that enable the system to absorb disturbances by setting a minimum acceptable level of service that drives the necessary investment.

• **Regulators** can support resilience improvements on the anticipation phase by:

- Defining regulatory frameworks that incentivize risk-informed planning, climate-resilient network design, asset criticality assessments, and preventive investments aimed at reducing exposure and vulnerability. They must include clear definitions, metrics, and assessment methodologies for power distribution system resilience.
- Establish a clear policy strategy for HILF events. Public authorities and regulators should define resilience objectives for extreme events and ensure that distribution utilities have access to appropriate regulatory and financial mechanisms to achieve them. This includes providing adequate funding and incentives for resilience-related in-

vestments and preparedness measures, on top of existing incentives dedicated to reliability enhancement.

- Encouraging investments in grid hardening, targeted network reinforcement, automation, microgrids, and local energy resources by establishing minimum service-level requirements that drive the necessary resilience-related investments by establishing appropriate regulatory frameworks incentivizing resiliency enhancement;
- Promoting innovation by creating incentives for DSOs/DNOs to engage with manufacturers in the development of novel solutions and next-generation grid technologies. This can accelerate the deployment of grid components with enhanced resistance to extreme weather events, strengthen supply chain resilience, and support the adoption of advanced technologies across the power system. Novel equipment can include, as examples, overhead line components capable of withstanding strong winds and heavy wet snow loads, substations and switchgear designed to remain operational during flooding events and underground cables and joints able to maintain performance under prolonged heat waves.

Beyond anticipation and resistance, regulatory mechanisms should also explicitly recognise the importance of **adaptation during disruption**, fostering an enhanced agility from the system. In the **recovery phase**, policy frameworks should support efficient restoration and learning processes by recognising not only technical repair times, but also organisational preparedness, logistics coordination, and the effectiveness of restoration strategies.



- Regulators can support resilience improvements across with these phases by:
 - Establishing incentive mechanisms that encourage DSOs/DNOs to deploy operational flexibility, advanced network reconfiguration capabilities, and decision-support tools. These measures enable controlled performance degradation, effective service prioritization, and faster operational response during prolonged or extreme events.
 - Explicitly incorporating the societal and economic impacts of prolonged outages into regulatory frameworks and incentive schemes, particularly in increasingly electrified and electricity-dependent societies. This would help ensure that resilience investments are assessed not only on direct network costs and benefits but also on their broader value to customers, communities, and critical services.

In parallel, **distribution utilities** should actively contribute to the development of shared and standardized risk assessment and quantification methodologies covering all phases of the resilience trapezoid. Common and transparent approaches to risk evaluation are necessary to allow consistent comparison of network performance before and after the implementation of mitigation measures. Harmonised resilience metrics would support evidence-based regulatory decision-making, improve comparability across operators, and strengthen the link between resilience investments and their demonstrated benefits. DSOs/DNOs should also assess how to improve their own workforce preparedness, while developing initiatives enhancing emergency response capabilities, in coordination with interdependent critical infrastructure assets, and emergency services.

DSO/DNO and Transmission System Operator resilience improvement plans should be coordinated since they are both fundamental to provide real advantages to end-use customers.

Collaboration among utilities, regulators, research institutions, standardization bodies, and other relevant stakeholders, to share best practices, lessons learned, and resilience assessment methodologies is encouraged, to address increasingly global climate-related threats.

A key policy challenge for regulators therefore lies in defining clear, consistent, and practically applicable rules to recognise and reward resilience improvements achieved through both structural and non-structural measures across anticipation, resistance, adaptation, and recovery. Such rules should ensure coherence across distribution companies while retaining sufficient flexibility to reflect local risk exposure, network characteristics, and societal priorities—acknowledging that resilience is inherently context-dependent and that **one size does not fit all**.

