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THE RESILIENCE OF POWER DISTRIBUTION SYSTEMS

RECOMMENDATIONS FOR A NEW REGULATORY PARADIGM

AUTHORS AND COLLABORATORS

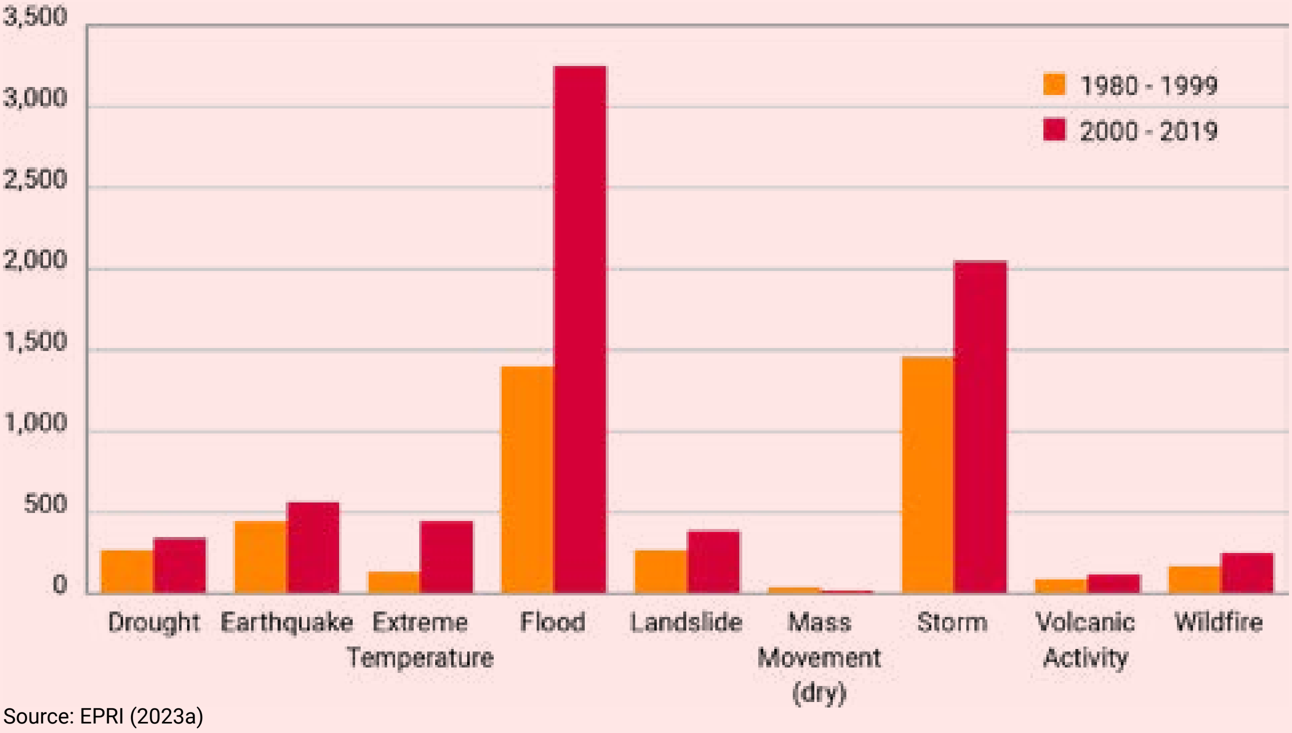
Aldo Pessanha, Viviana Vitto, Alessandra Genu Dutra Amaral, Roberto Cajamarca Gómez, Sandra Marcela Quijano López, Mena Testa, Patricio Molina, Alfredo Gallegos, Claudio Bulacio, Ernesto San Miguel, Hilario Vistolet, María José Perez Vanmorlegan, Gabriela Leoncini, Clarissa Machado, Talita Darwiche, Mariana Silva Barreto, Dimitri Barros Pereira de Oliveira, Francisco Mualim, Pablo Jofreu, Gina Pastrana, Camilo Agredo, Sergio Zambrano, Dimas Carranza, Jorge Ponce, Julio Luján.

01

INTRODUCTION

Power distribution system resilience has become a critical topic in the current context of global warming and energy transition. As our planet faces the effects of climate change, the frequency and severity of impactful events—such as hurricanes, storms, floods, snowstorms, wildfires, and heatwaves—have significantly increased. These events pose substantial challenges to electrical distribution infrastructure, especially in Latin America—a region characterized by climate vulnerability and diverse geography—where electric infrastructures were built based on environmental parameters that are now rapidly and irreversibly changing.

Figure 1. Increase in High-Impact Events Worldwide



Source: EPRI (2023a)

Simultaneously, our energy systems are decarbonizing, leading to increased electrification of end-use energy demand. As this electrification trend grows, society becomes more reliant on the electrical grid to meet basic needs. Consequently, climate-related threats demand greater resilience from our electrical infrastructure, as service failures have amplified impacts on productivity and society at large.

In this context, ensuring the resilience of distribution systems is crucial. Resilience involves not only the ability of electrical systems to withstand and recover quickly from adverse events but also their capacity to adapt and transform in response to emerging challenges.

Regulation of electrical distribution services in Latin America must evolve to address this new reality. Current regulations prioritize cost efficiency and stable coverage and access to distribution systems. However, these regulations lack flexibility to cope with increasing climate variability and environmental changes. It is essential to update policies and norms to encourage investment in resilient infrastructure, promote advanced forecasting and crisis management technologies, and establish effective coordination and response mechanisms. Clear indicators should be developed and utilized to measure network resilience and evaluate policy impact.

This document aims to foster discussion on distribution system resilience in Latin America, addressing current challenges and opportunities. It explores the impact of significant events on distribution infrastructure, provides an overview of regional resilience efforts, analyzes existing regulations and international best practices, and presents strategies for extreme event qualification, forecasting, contingency planning, crisis response, and regulatory incentives to boost investments in distribution system resilience.

02

A NEW PARADIGM: FROM RELIABILITY TO RESILIENCE

Resilience refers to a system's ability to absorb and rapidly recover from disturbances. A resilient electric grid can be defined by four fundamental properties:

Anticipation: The capacity to prevent damage caused by high-impact events.

Absorption: The ability to minimize the effects of severe events.

Recovery: The capability to restore functionality after an event.

Adaptability: The process of increasing system capacity based on learning from past events (Jufri et al., 2019).

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While the concepts of reliability and resilience differ, they are not mutually exclusive. Reliability focuses on ensuring that the system can provide electricity with a high probability of success. Resilience, on the other hand, addresses what happens when the system is under stress and may not be able to deliver that service. Resilience considers infrequent but high-impact events, while more common minor interruptions fall within the realm of quality and reliability.

Although both situations can result in service disruptions, the implications of high-impact events can be exponentially worse than those of brief interruptions. Therefore, resilience requires additional considerations beyond reliability. It encompasses broader aspects, such as the availability of critical services—whether from built infrastructure or non-traditional backup investments.

Despite this distinction, investments in resilience, particularly related to climate risks, significantly contribute to improving system quality and reliability. Thus, a resilient network is inherently reliable, but a reliably performing network is not necessarily resilient (Sinapsis, 2023).

An electric system resilient to high-impact events offers multiple benefits for electrical security. Recent studies suggest that the benefits of resilient electrical systems far outweigh the costs in most scenarios, considering the growing impacts of climate change. Investing one dollar in climate-resilient infrastructure can save six dollars. According to the World Bank, delaying resilience-building actions by ten years nearly doubles the cost (World Bank, 2019). For instance, in vulnerable countries, underground grids can significantly reduce potential damage from climate impacts and save recovery costs, even if their initial investment exceeds that of overhead grids. Resilience also facilitates the energy transition, enabling greater electrification solutions and accelerating the adoption of renewable energies, which are often sensitive to changing climates (IEA, 2021).

Shifting from a reliability paradigm to a resilience-focused one is a complex and gradual process. It requires active involvement from regulatory agents to incentivize the necessary new types of investments.

03

EFFECTS OF HIGH-IMPACT EVENTS ON DISTRIBUTION SYSTEMS

DEFINITION AND TYPOLOGY OF HIGH-IMPACT EVENTS

High-impact events, also known as extreme events, are natural or anthropogenic phenomena that, due to their intensity and extent, have the capacity to cause significant disruptions in electrical distribution systems. These events can vary in nature and duration and are commonly classified into several categories, including:

Extreme Weather Events: Hurricanes, severe storms, floods, droughts, heatwaves, and cold waves.

Geological Events: Earthquakes, tsunamis, and volcanic eruptions.

Anthropogenic Events: Acts of terrorism, cyberattacks, industrial accidents, massive technical failures, and human-caused forest fires.

HIGH-IMPACT EVENTS IN LATIN AMERICA

Latin American countries face a variety of risks from high-impact events that affect their electrical distribution systems. Common risks include earthquakes, floods, storms, hurricanes, volcanic eruptions, and landslides. The frequency and severity of these events vary by region and depend on specific geographical and climatic factors.

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ARGENTINA

Heavy rains and river flooding, especially in the coastal and Pampas regions, can affect electrical infrastructure. In summer, high temperatures may increase electricity demand and cause system overloads.

BRAZIL

Intense rainfall in regions like the Amazon, South, and Southeast (including Rio de Janeiro and São Paulo) leads to floods and landslides impacting electrical infrastructure. In the Northeast region, severe storms can damage transmission and distribution lines.

CHILE

As one of the world's most seismically active countries, Chile experiences earthquakes and tsunamis affecting coastal areas—where a significant portion of electrical infrastructure is concentrated. In the Andean region, snowstorms can disrupt power supply and hinder repairs. Central and southern Chile (where a large population resides) has seen an increase in the frequency and intensity of forest fires during summers and river flooding during winters, significantly affecting electrical infrastructure.

COLOMBIA

Intense rainfall causes landslides and floods in mountainous and coastal regions. The Caribbean coastal areas are susceptible to storms and hurricanes, while the Andean zone experiences high seismic activity.

COSTA RICA

The hurricane season in the Caribbean brings intense storms and heavy rains, causing floods—especially in the Caribbean slope and northern plains. Volcanic activity from volcanoes like Turrialba and Poás can also impact electrical infrastructure and lead to power outages.

ECUADOR

Ecuador lies in a zone of high seismic and volcanic activity, which can affect infrastructure. The rainy season can also cause floods and landslides in various regions..

GUATEMALA

Located in a seismically active region, Guatemala faces volcanic activity (such as Fuego and Pacaya) impacting electrical infrastructure. Intense rains during the hurricane season can cause floods and landslides, especially in mountainous areas.

PERU

Peru experiences frequent earthquakes that can significantly damage electrical infrastructure. During El Niño events, heavy rains—leading to floods and landslides—occur. Volcanic activity from volcanoes like Ubinas and Sabancaya can also affect electrical infrastructure.

Latin America has witnessed numerous high-impact events in recent years, putting the resilience of its electrical distribution systems to the test. Here are some notable examples:

Hurricane Maria (2017): This hurricane devastated much of the Caribbean, including Puerto Rico, causing widespread disruptions in the power supply. The complete recovery of the distribution system took several months due to extensive infrastructure damage.

Snowstorm in Santiago, Chile (2017): An unusual snowstorm in Santiago left 300,000 households without electricity.

Mexico Earthquake (2017): The magnitude 7.1 earthquake that struck Mexico City and its surroundings caused significant damage to electrical networks, leaving thousands of users with prolonged power outages.

National Blackout in Venezuela (2019): Although more complex and influenced by internal factors, the massive blackout in Venezuela left almost the entire country without electricity for several days, highlighting the fragility of the distribution system in the face of technical failures and maintenance issues.

Storms and Floods in Brazil (2023 and 2024): In 2023, a storm affected the power supply for 3.7 million people in Sao Paulo. In 2024, the worst flood in over 80 years impacted the state of Rio Grande do Sul, causing widespread landslides and the collapse of a dam, leaving over 500,000 people without electricity.

Studies conducted by the Electric Power Research Institute (EPRI) predict that due to climate change, stronger storms will increasingly disrupt the grid, especially in the Mid-Atlantic and Northeast regions. Hurricane-induced power outages are expected to rise by up to 50% (Gaffney, 2024). This underscores the need for climate risk analysis in energy planning and adaptation of infrastructure to withstand high-impact climate events.

EFFECTS ON ELECTRIC DISTRIBUTION SYSTEMS

Significant events can have detrimental consequences for electric distribution infrastructure and service continuity. While some of these effects are well-known, others remain understudied and insufficiently documented. In general terms, distribution infrastructure exhibits varying levels of vulnerability to different categories of high-impact events, as summarized below:

Table 1. Vulnerability of Distribution Assets to High-Impact Events

Type	Earthquake	Storm	Flood	Tsunami	Fire	Drought	Heatwave
Power lines	Medium	High	Low	Medium	High	Medium	Medium
Substations	High	High	High	Medium	High	Low	Medium

Source: World Bank (2019).

A study by the Electric Power Research Institute (EPRI) in 2023 identified that while each asset class has unique interactions with climate and the environment, certain common variables significantly impact individual assets:

Environment temperature: The performance of many distribution assets depends on temperature, which is affected both directly by environment temperature and indirectly by increased electrical system load caused by the same phenomenon (e.g., heating, ventilation, and air conditioning loads).

Frequency and severity of extreme events: Distribution system assets are susceptible to extreme phenomena, both directly and indirectly. For instance, distribution equipment is directly vulnerable to hurricane winds and storms.

Soil temperature and humidity: Many distribution system assets have contact with the ground—some are entirely underground, while others rely on foundations or are buried. Soil conditions, such as temperature and humidity, significantly impact corrosion and degradation rates, potentially affecting asset reliability, designs, inspection frequency, and maintenance programs over the long term.

Additionally, EPRI has highlighted the need for further research and model development to enhance understanding of the impact of environment temperature on asset load, sustained high-temperature operations' effects on long-term asset lifespan, and climate-related impacts on new technology assets and emerging materials.

Consequently, a high-impact event can have aggregated consequences on distribution systems and, consequently, on electricity service provision. The main systemic consequences include:

Physical Infrastructure Damage: Extreme events can destroy poles, transformers, transmission lines, and substations. These damages not only disrupt electricity service but also require significant investments and time for repair. For example, hurricanes can topple poles and lines, while floods can damage underground and ground-level electrical equipment.

Prolonged Service Interruptions: High-impact events can cause prolonged power outages, affecting homes, businesses, public services, critical facilities (such as hospitals and emergency systems), and electro-dependent users. Restoring service can be a slow and complex process, especially in hard-to-reach areas or severely damaged infrastructures.

Operational and Logistical Challenges: Repairing and restoring damaged electrical infrastructure requires efficient coordination of human, material, and financial resources. Post-event adverse conditions, such as blocked roads or flooded areas, can further complicate these efforts.

Long-Term Infrastructure Deterioration: Repeated high-impact events can gradually degrade electrical infrastructure, reducing its lifespan and increasing maintenance and replacement costs.

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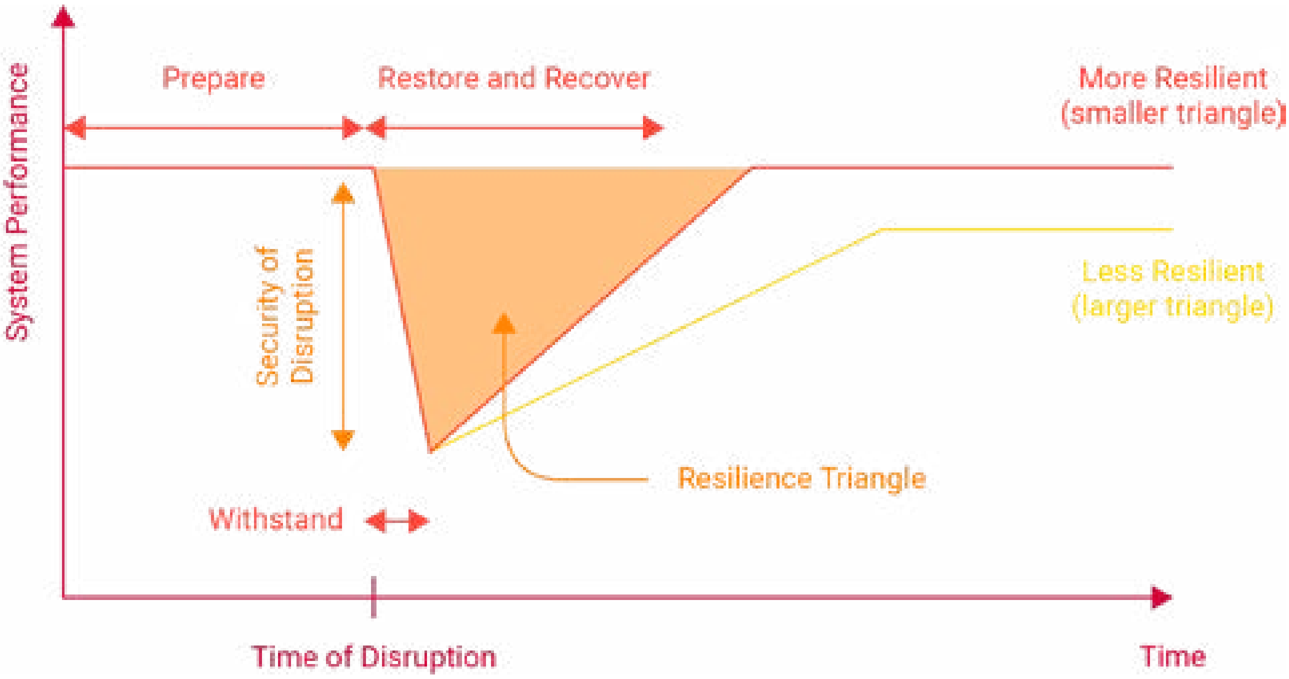
Regarding the temporal assessment of high-impact event effects, Bruneau et al. (2003) introduced the concept of the "resilience triangle." This concept illustrates the loss of system functionality due to damage and interruptions, as well as the restoration and recovery pattern over time.

Figure 2. Phases of Disruptive Events and the Resilience Triangle



Source: EPRI (2023a)

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RESILIENCE OVERVIEW IN ELECTRICAL DISTRIBUTION IN LATIN AMERICA

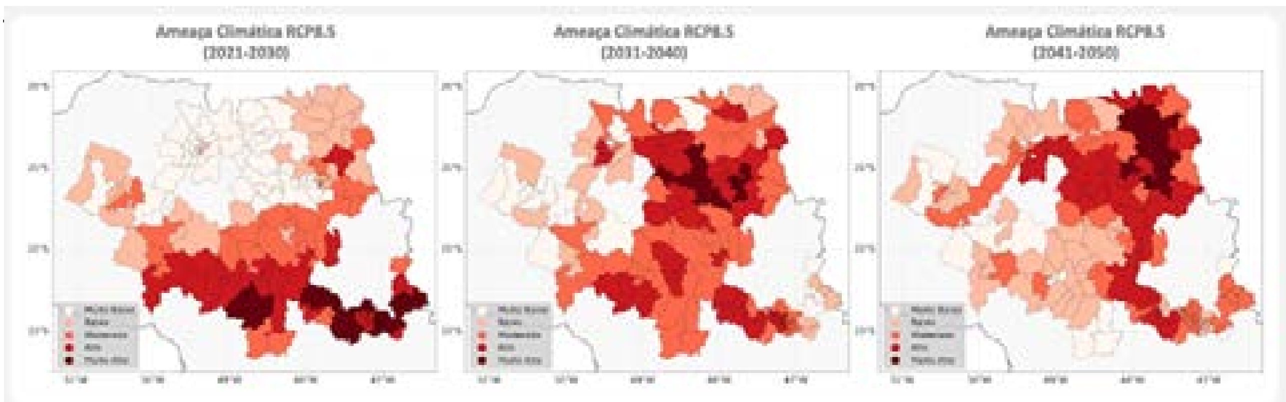
Latin America is a region characterized by its geographical, climatic, and socioeconomic diversity, which directly influences the resilience of its electrical distribution systems. In general terms, Latin American countries are just beginning to incorporate climate risk resilience as a regulatory objective. In countries like Colombia and Ecuador, which experience periodic impacts from El Niño, efforts have focused on diversifying the generation portfolio to reduce dependence on hydroelectricity and ensure supply reliability during drought periods. However, in transmission and distribution, regulatory frameworks are designed to promote cost efficiency and stable growth in coverage and access to distribution systems, leading to rigidity that doesn't adequately address the increasing climate variability and environmental changes. Resilience is currently only considered in some general policy and energy transition documents (such as those in Argentina, Chile, Colombia, and Guatemala), but concrete regulatory measures are yet to be fully implemented.

MONITORING AND ANTICIPATION MECHANISMS

Monitoring and anticipation mechanisms involve advanced technologies and proactive strategies that allow distribution companies to predict and respond rapidly to extreme events. While most countries in the region monitor weather conditions to anticipate extreme events, only a few have identified the existence of climate risk analysis systems that help distribution companies effectively plan and allocate resources.

In Latin America, most companies consult official climate forecasting services and specialized international agencies. For example, in Brazil, climate analysis tools identify regions most susceptible to extreme weather events by comparing historical data and prediction models, creating a climate threat map.[1]

Figure 3. Climate threat maps for the CPFL Paulista concession area (Brazil)



Source: Climatempo (2024).

In Colombia, some companies use databases and analytical tools to assess climate evolution, identify vulnerabilities, and plan system operations within the quality standards required by regulations, although the focus is not specifically on extreme weather events.

CONTINGENCY PLANS

Contingency plans are fundamental to ensuring a rapid and effective response to high-impact events. These plans outline actions to be taken before, during, and after an event, with the goal of minimizing impact and restoring service as quickly as possible.

In Latin America, the implementation of contingency plans for extreme weather events has been identified in countries such as Argentina, Brazil, Chile, and Peru. These plans are developed by distribution companies following guidelines set by regulatory authorities.

In Argentina, these plans are known as "Operational Emergency Plans" (POE). They are mandatory documents that each distribution company must prepare annually, based on requirements established by the National Electricity Regulatory Entity (ENRE). Key characteristics of these plans include:

Describing actions to be taken in different types of contingencies, including failures in power plants, transmission lines, substations, etc., caused by climate events, accidents, sabotage, or other unforeseen circumstances.

Establishing communication protocols among various stakeholders: distributors, system operators, major users, government authorities, and media.

Defining restoration schemes prioritized by user criticality (e.g., hospitals, essential services, critical industries).

Addressing prolonged power outages that may require rationing or other special procedures.

Additionally, distribution companies must have control centers, specialized teams, trained personnel, and logistical resources to activate the POE protocols during contingencies. This is complemented by the implementation of preventive maintenance plans to reduce the risk of failures, as well as regular drills to test procedures and coordination among different participants. The ENRE reviews, approves, or requests modifications to the plans submitted by the distribution companies before they take effect.

In Brazil, the National Electric Energy Agency (ANEEL) has implemented regulations requiring distribution companies to develop and maintain contingency plans. These plans include protocols for mobilizing teams and resources, as well as coordination with local and national authorities.

In Chile, in addition to maintaining contingency plans, annual action plans are developed for winter and high-temperature periods. These plans are reported to the Superintendency of Electricity and Fuels. Regular drills and exercises also prepare for earthquakes and other disasters.

REGULATORY DEVELOPMENTS

In Latin America, service quality regulation has not primarily focused on promoting resilient networks due to the potential impact on tariffs resulting from investments in system preparedness for extreme events. Instead, the focus has been on evaluating reliability through service quality indicators, considering the frequency and duration of interruptions caused by common faults while excluding large disruptions caused by unexpected events.

In Chile, the regulatory authority introduced the concept of "Anomalous State" and "Aggravated Anomalous State." The latter corresponds to the unavailability of 10% of distribution lines or 10% of kVA from distribution transformers within a municipality-company pair due to natural disasters. Declaring these states allows such interruptions to be excluded from supply quality indicators. Additionally, the Technical Quality of Service Standard for Distribution Systems introduced two new concepts related to disaster response. The first is emergency disconnections to prevent forest fires. The second is a new Operational Flexibility (FO) index, which distributors must report. FO measures the percentage of customers who regain service within 30 minutes, whether through load transfers, meshing, islanding operations, or the work of company brigades and resources. This index directly measures the resilience of distribution networks during supply interruptions.

In Brazil, the "Interruption in Emergency Situations" (ISE) concept have been instituted. ISE characterizes and excludes events associated with a Declaration of Emergency Situation or State of Public Calamity issued by a competent body from the calculation of service quality indicators (ANEEL, 2021).

Only after high-impact events occur, have regional authorities developed initiatives aimed at identifying measures to enhance distribution system resilience against extreme weather events. Based on evidence from extreme weather events in Brazil in 2023, ANEEL opened a public consultation, called "Tomada de Subsidios No. 002/2024," on February 2, 2024. The goal was to gather contributions to improve regulations related to increased resilience of distribution and transmission systems. Based on stakeholder input, ANEEL has prioritized normative measures to enhance the resilience of electrical systems in the 2024-2025 regulatory agenda.

In Puerto Rico, a resilience working group was formed with public authorities, electric companies, and research institutes to identify actions to withstand future storms after Hurricane Irma hit its northern coast in 2017. Among other measures, this group recommended a three-tiered approach to protect against floods and enhance distribution network resilience. The approach includes building perimeter barriers at substations, installing high-capacity pumps and backup generators, improving roofs and walls of substations to withstand strong winds, increasing the use of galvanized steel poles, and burying lines in particularly vulnerable areas (IEA, 2021).

Overall, the region requires more decisive regulatory developments to address existing weaknesses and ensure continuous and equitable investment in strengthening the infrastructure and response capacity of electrical distribution systems.

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> Latin American countries are just beginning to incorporate climate risk resilience as a regulatory objective.

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REGULATION REGARDING HIGH-IMPACT EVENTS

In power distribution regulation, the treatment of high-impact events plays a crucial role in determining responsibilities and compensations by Distribution System Operators (DSOs). These events, due to their unpredictable and often destructive nature, require special development within regulatory frameworks to protect companies from unfair penalties while incentivizing necessary investments to enhance the resilience of electrical networks.

EVENT CLASSIFICATION

For many years, transmission and distribution network operators have naturally invoked the "force majeure" legal concept when facing highly significant impact events. This concept, which is not specific to the electricity sector, applies broadly to all activities subject to external impacts. In the context of energy distribution, force majeure and unforeseeable events can justify excluding compensations that would normally be due to consumers for service interruptions. The rationale behind this is that distribution companies cannot be held responsible for events entirely beyond their control.

During the period when a high-impact event affects energy distribution, penalties for service quality non-compliance are suspended, and consumer compensations for interruptions are adjusted or eliminated. Additionally, regulators modify service quality indicators to exclude periods affected by force majeure or unforeseeable events, ensuring that companies are not penalized for circumstances beyond their control.

The abstract and cross-sector nature of force majeure has led to legal debates due to its lack of adaptation to the specificities of the electricity sector and its absence of solid, objective grounds for operator liability exemption.

In Portugal, to minimize misuse of force majeure, the Portuguese energy regulator (ERSE) established that its invocation was only applicable in cases where events "simultaneously meet the conditions of externality, unpredictability, and irresistibility in relation to good practices or applicable and mandatory technical rules." This ERSE initiative aligns with a European trend seeking to define situations where the concept of force majeure applies specifically to the electricity sector. Additionally, the term "exceptional events" has been adopted by all European regulators, albeit with variations among different countries. When evaluating exceptional events, statistical methods or other criteria, such as the number of affected consumers or the duration of interruptions, can be used.

As an illustrative example, since 2014, the ERSE considers events exceptional if they exhibit the following characteristics:

Low probability of occurrence or of their consequences.

Significant degradation of the quality of service provided.

It is economically unreasonable for DSO and retailers to avoid all consequences.

The event and its consequences are not attributable to DSO or retailers.

The Portuguese energy regulator (ERSE) introduced the concept of an "Incident of High Impact," defining it as any incident that, regardless of its cause, results in one or more interruptions leading to a non-supply or distribution of more than 50 megawatt-hours (MWh). All high-impact incidents must be documented in a report submitted to the ERSE, following a methodology defined in the regulations.

It's essential to emphasize that the classification of an Incident of High Impact alone does not automatically exempt DSOs from compensation responsibilities. Such exemption occurs only when the evaluation process concludes that the event and its consequences are not attributable to the network operators.

In other European countries, distributors need only provide documentary evidence based on predefined meteorological parameters. Waiting for an external body to declare an event as high impact is not necessary. However, the European Network of Transmission System Operators for Electricity (ENTSO-E) establishes guidelines for qualifying high-impact events, categorizing them based on severity and frequency. This classification enables companies to better manage risks and develop specific contingency plans.

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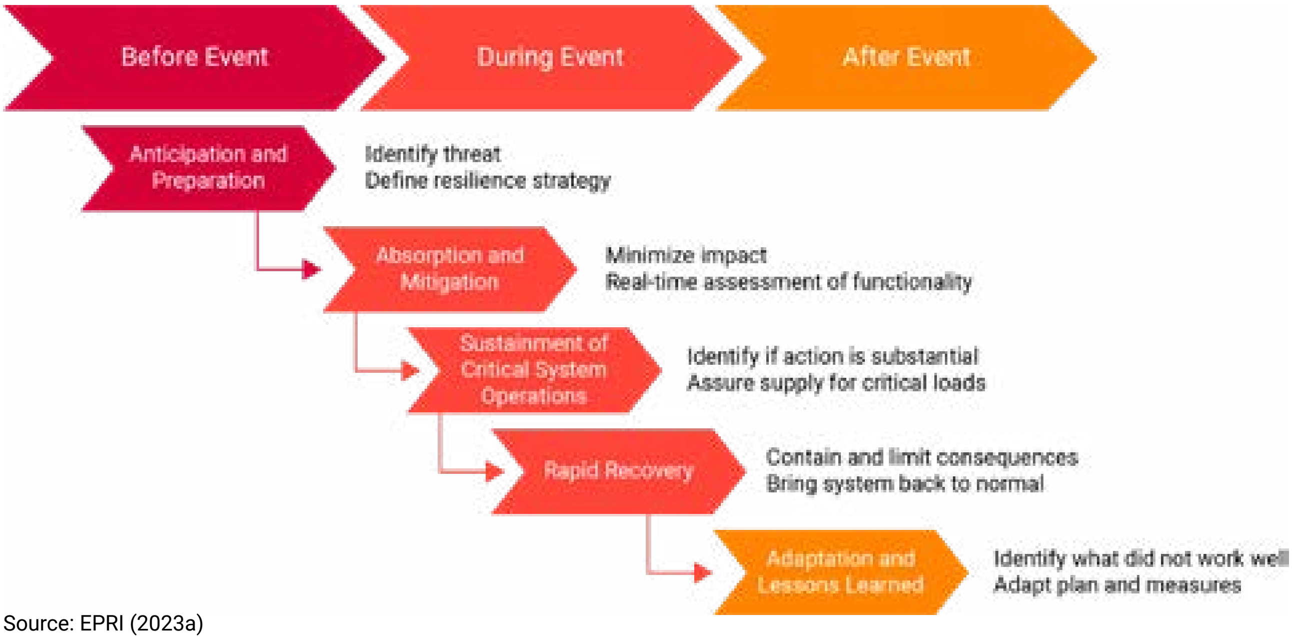
In power distribution regulation, the treatment of high-impact events plays a crucial role.

DSO RESPONSIBILITIES

The occurrence of high-impact events imposes critical responsibilities on power distribution companies to ensure service continuity, minimize damage, and protect consumers. These obligations span from pre-event preparation to immediate response, post-event recovery, and regulatory compliance.

Figure 4. Responsibilities of DSOs during a High-Impact Event



Source: EPRI (2023a)

Before the Event: Preparation and Planning

Conduct risk assessments, identify and map vulnerable areas in the distribution network susceptible to high-impact events, and evaluate potential consequences on infrastructure, operations, and users.

Develop and maintain up-to-date contingency plans that outline procedures for emergency response, define specific protocols for different event types, and ensure awareness among all staff.

Train personnel in executing contingency plans and emergency response, and conduct regular drills to assess plan effectiveness and make necessary adjustments.

During the Event: Immediate Response

Activate contingency plans as soon as a high-impact event is detected, mobilizing necessary human, technical, and material resources for response.

Conduct rapid and accurate inspections of affected infrastructure to identify damages and prioritize repairs. Implement containment measures to prevent additional harm and protect critical facilities.

Inform regulatory authorities, emergency agencies, and consumers about the event, its implications, and the measures being taken.

Monitor and operate the network to enable load transfers through meshing, islanding operations, and emergency generator activation, aiming to supply emergency electricity to priority or critical loads.

Perform urgent repairs to restore electrical supply as quickly as possible, utilizing backup systems to minimize service interruptions.

After the Event: Recovery and Rehabilitation

Address more complex repairs that couldn't be completed during the immediate response phase. Reevaluate repaired infrastructure to ensure compliance with safety and operational standards.

Prepare a detailed incident report, including the event's cause, damages incurred, response effectiveness, lessons learned, and improvement opportunities.

Provide comprehensive reports to regulatory authorities, documenting that the event qualified as force majeure or fortuitous case and was indeed the cause of service interruption. Describe the measures taken to mitigate event effects and restore service promptly.

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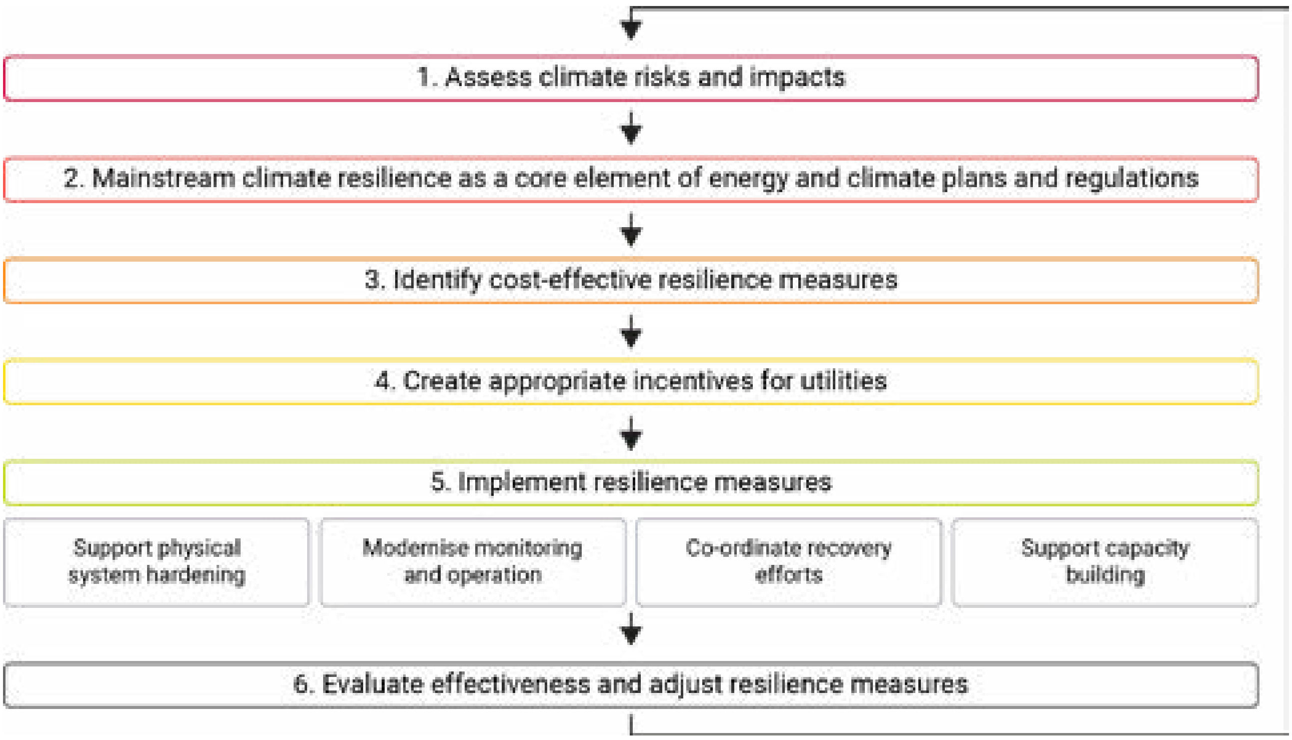
06

REGULATION FOR DISTRIBUTION SYSTEM RESILIENCE

Investments in resilience face certain barriers stemming from market failures, which can be mitigated through public policy and regulation. The benefits of investing in greater resilience often materialize only after years or even decades, while the capital cost of implementation is incurred immediately. Secondly, when high-impact events disrupt electricity supply and cause significant societal harm, operators are typically expected to bear only a fraction of the total social cost. Thirdly, monopolistic market conditions and lack of competition in some countries discourage providers from investing in resilience measures for distribution systems (IEA, 2021).

Policy makers and regulators play a crucial role in promoting resilient electrical systems by assessing climate-related risks and impacts, making resilience a central element in energy plans, identifying cost-effective measures, creating appropriate incentives for distribution companies, and evaluating their effectiveness. The following diagram illustrates this process:

Figure 5. Sequential Scheme of Measures for Resilience



Source: IEA (2021)

To achieve this, regulatory authorities must implement best practices that holistically promote resilience. These practices include action plans, resilience index calculation methodologies, regulatory signals for investment remuneration, and adoption of new technologies and emerging solutions. This section provides a comprehensive framework for enhancing the resilience of electrical distribution systems.

DEFINITION OF RESILIENCE MEASUREMENT INDICATORS

Parameters for distribution network resilience should not remain confined to typical quality-of-service indicators due to the extreme and atypical nature of climate-related phenomena. Instead, they should consider a broader set of criteria, including wind speed, temperature levels, and rainfall indices. Therefore, it is essential to define a methodology for calculating network resilience indicators to guide actions toward achieving the desired level of resilience. These indicators can be categorized as follows:

Recovery Indicators: Measure the time required to fully restore network functionality after an event.

Robustness Indicators: Evaluate the network's ability to maintain service during high-impact events.

Adaptability Indicators: Assess the network's capacity to adapt and improve in response to adverse events.

According to a study by EPRI (2023), resilience metrics should possess the following attributes: verifiability, ease of interpretation, objectivity, accessibility, comparability, clear definition, and linkage to performance areas. The study suggests several examples of metrics for resilience evaluation:

Power Service for All Customers

Cumulative customer interruption hours (hours).

Unserved load (kWh).

Average number or percentage of customers experiencing outages.

Electric Service for Critical Customers

Critical customer interruption hours (hours).

Average number or percentage of critical customers experiencing outages.

Critical services without power.

Critical services without power for more than N hours.

Restoration Metrics

Recovery time.

Percentage of customers regaining electrical service within a specified time.

INVESTMENT PLANS FOR IMPROVING RESILIENCE

According to a study conducted for the Inter-American Development Bank (IADB) in 2021, actions related to improving network resilience can be categorized into three main areas:

Network Reinforcement: Traditional approaches involve replacing utility poles, burying assets, and developing flood defenses.

System Flexibility Enhancement: This includes investments in redundancy, network reconfiguration, distributed energy resources (DERs), microgrids, and customer participation to mitigate the impact of extreme events. Demand response programs play a crucial role here.

Intensified Restoration: Allocating additional resources to minimize downtime during system restoration.

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These actions can be integrated into detailed investment plans aimed at enhancing resilience. Investments may focus on reducing the magnitude of event impact (physical infrastructure resilience) or minimizing system recovery time (operational resilience) (IADB, 2021). Below is a summary of the main technologies used.

Table 2. Types of Resilience Investments

Infrastructure Resilience	Operational Resilience
Vegetation management	Mobile equipment for provisional supply restoration
Selective undergrounding of lines	Repair team management
Replacement of components with superior design and construction standards	Monitoring and communication systems
	Microgrids and distributed energy resources (DER)
	Protection and control schemes
	Forecasting systems
	Mutual assistance agreements

Source: Own elaboration based on IDB (2021).

To implement these plans effectively, distribution companies should present them to regulators and incorporate them into their tariff review processes. Explicit compensation signals should be defined in advance for distributors investing in projects and solutions to enhance system resilience. Bonuses could be awarded to companies surpassing predefined resilience thresholds.

RECOGNIZING MUTUAL ASSISTANCE MECHANISMS

Additionally, recognizing mutual assistance mechanisms is crucial. Not only should each agent define contingency plans for extreme events, but these plans should also be integrated through Mutual Assistance Groups. These groups coordinate actions among nearby distribution companies, facilitating resource exchange. Clear indicators should be established for companies providing and receiving assistance, along with corresponding implications for consumers.

In the event that mutual assistance is activated, any additional costs incurred by the distributor should be compensated through tariff mechanisms. Ensuring tariff recognition even when the event intensity deviates from initial expectations is essential for maintaining system resilience.

07

INTERNATIONAL BEST PRACTICES FOR RESILIENCE REGULATION

The resilience of power distribution systems is an increasingly prioritized goal in the regulation of some developed countries to address the challenges posed by high-impact events. This section explores successful international cases in Europe and the United States, highlighting risk assessment, forecasting mechanisms, contingency plans, event classification, response mechanisms, regulatory incentives, resilience indicators, and technological innovations that can offer valuable lessons for Latin American countries.

RISK ASSESSMENT AND MITIGATION

Several countries have introduced guidelines for climate risk and impact assessments. For example, the United States government has developed a guide for vulnerability assessments related to climate change as the initial step in climate resilience planning for the electricity sector. The US Climate Resilience Toolkit provides tools to explore climate hazards and evaluate vulnerability and risks. These assessments can aid in further developing climate resilience strategies and plans, allowing countries to identify evidence-based effective measures.

In the European Union, general requirements for climate adaptation assessments are established for member states. However, the depth and coverage of assessments vary among countries. Countries such as Estonia, Finland, France, Germany, Italy, Portugal, Sweden, and the Netherlands have conducted impact, vulnerability, and climate change risk assessments in their electrical systems. Others, like Slovenia, Malta, and Bulgaria, have not yet completed such assessments. While this method of evaluating energy systems tends to focus on electricity as a key component, the specific areas of focus differ significantly, ranging from resource availability for electricity generation to electricity demand.

These initiatives can be complemented by the creation of specific disaster response funds, improved governance in emergency declarations, broad societal discussions on defining high-impact events and the best ways to prevent and combat them, mutual aid protocols among distributors for mobilizing additional teams and resources during extreme events, and integrated climate change plans with joint governance involving distributors, regulators, and national, state, and municipal governments.

Additionally, comprehensive risk assessments must be accompanied by mitigation measures, such as preventive tree pruning near power distribution lines, considering resilience criteria for electrical infrastructure in urban planning, and community awareness to avoid behaviors that increase risk. A recent example of such measures is Law 20.081 of 2019, enacted in the state of Paraná (Brazil), which establishes limits for planting exotic and native trees near electricity distribution lines and networks.

Finally, effective risk management requires coordination among government authorities, electric distribution companies, and emergency response agencies (firefighters and civil defense). Given recent cases and evidence that extreme weather events will become more frequent, improving processes and governance in the collaboration between these entities is essential.

FORECASTING AND ANTICIPATION MECHANISMS

The European Early Warning System, used in several European countries, combines meteorological, geological, and technical data to anticipate high-impact events and coordinate rapid responses. Additionally, countries like Germany and the United Kingdom have integrated smart grid technologies with advanced weather prediction systems. These systems allow for the anticipation of extreme weather events and preparation of appropriate responses.

In Italy, companies use tools like Weather Alerting to make forecasts and calculate the impact of weather conditions on network infrastructure. The output provides a risk level indicating the probability of an emergency occurring on the network within the next 72 hours. This application also allows monitoring of specific wind, rain, and temperature information on an hourly basis for a specific area. The forecast quality depends on the availability of private and public meteorological stations. The Resilience Index (IRI) incorporates the probability of event occurrence before and after measurement (in this case, by multiplying the projection by the number of affected customers).

In the United States, the National Energy Forecasting and Analysis Center uses big data and predictive analytics to anticipate high-impact events on the power grid. Tools like Geographic Information Systems (GIS) help map risks and plan responses. Additionally, the Department of Energy (DOE) funds research to develop advanced predictive models that anticipate infrastructure failures due to natural or cyber events.

CONTINGENCY PLANS AND CRISIS MANAGEMENT

The United Kingdom has developed detailed contingency plans that include specific protocols for different types of events, from storms to cyberattacks. These plans are regularly reviewed and updated.

France has implemented a resilience strategy that includes infrastructure modernization, regular crisis simulations, and the creation of command centers to manage emergencies.

In Italy, distribution companies define implementation plans in case of emergencies, although it is not a regulatory requirement.

In the United States, the Federal Emergency Management Agency (FEMA) collaborates with electric companies to develop robust contingency plans. These plans focus on interagency coordination and rapid resource mobilization. Specifically, California, prone to wildfires and earthquakes, has developed an advanced crisis management system that includes controlled deactivation of the power grid to prevent fires and rapid service restoration.

In the southeastern United States and the Gulf of Mexico, annual training is conducted in preparation for hurricane season (DOE, 2010). For example, Florida Power & Light tests its contingency plan through simulations related to locating outages, damage assessment, communication with customers and employees, and initiating service restoration. In this context, there is a strong emphasis on improving storm impact recording systems for plan updates and adoption of new resilience measures (BID, 2021).

Contingency plans must include specific indications of when emergency protocols should be activated and anticipate clear and effective communication strategies to keep the population informed about risks and preventive measures.

RESPONSE MECHANISMS AND COORDINATION

Within the European Union, cross-border cooperation in electric crisis management is promoted. Member countries share resources and technology to jointly address high-impact events. Additionally, countries like Germany and the Netherlands have implemented real-time communication platforms that allow authorities and energy companies to efficiently coordinate responses.

In the case of Italy and Spain (Barcelona and the Balearic Islands), there is mandatory operational interaction between the electricity distribution company and other entities, such as fire departments and medical units, to expedite power grid recovery. This is achieved through an automatically activated crisis committee. The committee coordinates all responsible agencies, including the municipality, civil authority, fire department, police, water and gas companies, and civil protection. To trigger alarms, the State Meteorological Agency (AEMET) uses indicators with associated thresholds. For example, winds must exceed 96 km/h with intervals of 10 minutes or less. Once an extreme weather prevention alarm is activated (e.g., for a cyclone or tropical storm), the authority is obligated to mobilize all relevant agencies. The processes and responsibilities of each organization are well-documented.

In the United States, there is a long tradition of mutual assistance among electric companies in response to severe weather events. Recently, this has been standardized through mutual assistance programs by the Edison Electric Institute (EEI), which operate regionally and on a voluntary basis. These agreements are managed by seven Regional Mutual Assistance Groups (RMAGs). When a company needs assistance, it submits a request through the regional group, which assesses personnel and equipment needs for each case. There is a resource allocation program (RAMP UP) that allows RMAG leaders to activate an event online. Through an algorithm, the tool enables the requesting company to access resources from neighboring companies.

In this American model, the receiving utility must provide logistical support such as accommodation, food, and fuel. They must also have all necessary spare parts available (which can also be obtained through agreements) and the capability to efficiently deploy teams to affected regions (EPRI, 2013).

Additionally, a National Response Event (NRE) framework has been defined to expand assistance at the national level. In these cases, the CEO or designated person from an affected company can declare an NRE, reserved for the most significant events. To test response capabilities, hurricane, earthquake, and ice storm simulations are conducted, involving government entities such as the Department of Energy, the Department of Homeland Security, and the Federal Emergency Management Agency (FEMA).

Distribution companies operating in Florida, a state highly impacted by extreme weather events—especially hurricanes—also utilize coordination schemes through Emergency Operation Centers (EOCs), which function as hubs. For instance, Florida Power & Light (FPL) establishes a Critical Information Team that manages Request for Action (RFA) and Request for Information (RFI) processes, interacting with police, fire departments, and EOCs.

In Japan, the Disaster Cooperation Plan aims for rapid and flexible recovery from high-impact events, leveraging examples of cooperation between power transmission and distribution companies. The plan includes provisions such as mutual support among operators, coordination during normal times for preparation against extreme events based on lessons learned from previous natural disasters, division of the country into areas, development of mutual support manuals for distribution restoration, creation of a list of essential facilities, cooperation with telecommunications companies, self-defense forces, and local governments, and joint training of transmission and distribution company teams (BID, 2021).

In Brazil, due to the floods that occurred in the state of Rio Grande do Sul between late April and early May 2024, other distribution groups were mobilized for the first time, in addition to those directly involved in the tragedy. Companies like Enel and Light sent teams and materials to assist Equatorial and CPFL groups in crisis management.

REGULATORY INCENTIVES FOR RESILIENCE INVESTMENTS

In Italy, since 2019, Distribution System Operators (DSOs) are required to annually publish and update investment plans for extreme events, with a three-year horizon, classified into three categories:

Snow/Ice on cables (medium-voltage overhead lines)

Heatwaves (medium-voltage underground cables in urban areas)

Storms/Falling trees (medium-voltage overhead lines)

In this context, in 2023, the regulatory authority defined initial provisions for bonus mechanisms as incentives for distribution network interventions in anticipation of extreme events (ARERA Deliberation No. 617/2023). These incentives encourage investments with higher benefit-cost ratios, such as expanding underground networks (or converting overhead to underground). Specifically, the resilience investment plan is based on the following criteria:

Results-based reward mechanism.

Approval by the regulator based on the DSO's prior request.

Reward = 2 years of gross benefit with a cap + RAB (similar to typical CAPEX).

Cap = 13% of the minimum between expected investment cost and actual investment cost.

Eligible interventions for reward are limited based on the total CAPEX presented in investment plans (up to 15% of the total 2024 investment for projects starting from that year).

For investments made between 2025-2027, an annual report is required before March of the following year.

Similar incentives exist in the United Kingdom, where the Office of Gas and Electricity Markets (OFGEM) implemented the RIIO model (Revenues = incentives + innovation + outcomes) starting in 2010. Under this model, tariff revenues are determined through incentives to provide innovation and products to consumers. Regarding system resilience, companies can obtain resources as part of the tariff agreement. These resources can be used to cover flood protections, black start activation, physical security for critical infrastructure, and protection of overhead lines through tree removal (OFGEM, 2018).

In Germany, the government offers subsidies and tax benefits to electric companies investing in resilience technologies, such as smart grids and energy storage systems.

In the United States, the Department of Energy provides funding and grants for projects aimed at improving the resilience of the power grid, incentivizing the adoption of advanced technologies. Additionally, the Federal Energy Regulatory Commission (FERC) implements regulations that allow companies to recover costs associated with resilience investments through tariffs.

INDICATORS FOR MEASURING RESILIENCE

In Italy, grid resilience is measured in terms of the benefit from reducing the number of disconnected users (delta IRI). Furthermore, bonuses for investments in networks anticipating extreme events are defined based on performance in the following categories:

B1 - Expected reduction in interruptions for end customers due to increased network resilience under extraordinary conditions.

B2 - Costs avoided by emergency actions after interruptions caused by extraordinary events.

B3 - Expected reduction in interruptions for end customers under normal conditions.

B4 - Costs avoided by emergency actions after interruptions due to ordinary events.

B5 - Reduction in renewable generation losses due to interruptions.

B6 - Expected reduction in severe voltage drops.

B7 - Extraordinary post-failure maintenance costs avoided as a result of intervention.

B8 - Expected ongoing operation and maintenance cost savings (e.g., avoided preventive maintenance and tree trimming).

B9 - In the case of interventions to interconnect previously isolated network segments, the expected reduction in electricity generation costs and other costs due to energy vector substitution.

B10 - Reduction (or, with a negative sign, increase) in CO2 emissions due to the expected variation in network losses.

France and Spain are also advancing in the development of evaluation systems that combine technical performance metrics, responsiveness, and grid redundancy to assess the resilience of distribution systems. In the United States, the DOE has developed tools that allow companies to evaluate their resilience using a combination of historical data, simulations, and predictive analysis.

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> The resilience of power distribution systems is an increasingly prioritized goal in the regulation of some developed countries to address the challenges posed by high-impact events.

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CONCLUSIONS AND REGULATORY IMPROVEMENTS

Extreme events occurring more frequently highlight the need to give greater importance to the concept of Power Systems Resilience, with a risk-based approach to assess potential impacts and prioritize investments. Proactive and informed investment to better withstand and recover from high-impact events, rather than reactive repairs during crises, can result in lower overall costs in the long term (EPRI, 2023).

In Latin America, regulatory frameworks are designed to promote cost efficiency and stable growth in coverage and access to distribution systems. However, these frameworks often fail to address the increasing climate variability and environmental challenges. Resilience is only considered in some general policy and energy transition documents, which have not yet translated into regulatory measures. Therefore, it is essential to incorporate resilience concepts into distribution networks at the level of public policy and subsequent regulatory development. This can encourage investment in infrastructure, promote the adoption of advanced forecasting and crisis management technologies, and establish effective coordination and response mechanisms. The process could consider the following elements:

Engage sector experts to develop guidelines for quantifying the social impact of power outages attributable to High-Impact Events, including economic, safety, and health effects.

Develop guidelines based on risk assessment methods and vulnerabilities of electrical systems to climate change. Prioritize evidence-based strategies for risk mitigation in distribution, such as preventive tree pruning and incorporating resilience criteria into urban planning. Collaboration among government authorities, utility companies, and emergency response agencies is crucial.

Establish guidelines for classifying High-Impact Events based on severity and frequency, defining the responsibilities of DSOs in risk management and contingency planning.

Create detailed contingency plans for high-impact events, agreed upon by system coordinators and distribution companies. These plans should enable critical situation alerts and effective management to restore normalcy. Specific protocols for different types of events (from storms to cyberattacks) should be periodically updated, accompanied by clear and efficient communication actions, and overseen by a coordinator.

Implement regulatory signals for forecasting and early warning mechanisms, combining meteorological, geological, and technical data to anticipate infrastructure failures attributed to high-impact events and coordinate rapid responses..

Establish mutual assistance mechanisms that coordinate actions among nearby distribution companies and other entities such as civil authorities, fire departments, police, and medical units. These mechanisms should have pre-assigned responsibilities, equipment and spare parts availability, mechanisms to determine travel costs, food, and accommodation for deployed teams, and tariff recognition guarantees in case of distributor mobilization. Regulatory and supervisory authorities should participate in designing these mechanisms, establishing indicators for companies that provide and receive resources, as well as repercussions for respective consumers.

Develop indicators and methodologies for evaluating the resilience of distribution systems, separate from those related to service quality indicators, given the extreme and atypical nature of high-impact events. These criteria should include recovery, robustness, and adaptability.

Promote the development of investment plans to enhance operational resilience levels and infrastructure. These plans should include investments in technologies and solutions related to network reinforcements, increased system flexibility, and intensified restoration. Distributors would present these plans to the Regulator and incorporate them into their tariff review processes.

Explicit regulatory incentives for ex-ante tariff remuneration to distributors for investments relevant to system recovery from high-impact events. Examples of such investments include automatic fault diagnosis systems, immediate response infrastructure for operational events, protection management centers, mobile generators, mobile storage systems, communication systems, auxiliary services, critical spare parts, and accessories. These incentives can take the form of tariff bonuses based on performance in the proposed resilience indicators.

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