Position Paper
Climate Resilience Metrics for Electricity Grids

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Introduction

It is widely acknowledged that different metrics are required to quantify the reliability of a network to ensure interventions improve the performance of the network or asset. Traditionally, metrics such as CML (SAIDI) or CI (SAIFI) have worked well, and for the most part continue to provide good indication of network performance. However, the environment for electrical utilities is ever changing, assets are aging, network usage is changing to address climate change, and climate change is increasing the frequency and magnitude of once considered high impact low frequency (HILF) events.

Resilience is concerned with severe and rare events, which cannot be modelled by the reliability metric of expected average impact of frequent events. Resilience metrics must therefore be introduced along with traditional reliability metrics to capture the necessity to control longer term (>40 years) impact such as those HILF presented by climate change.

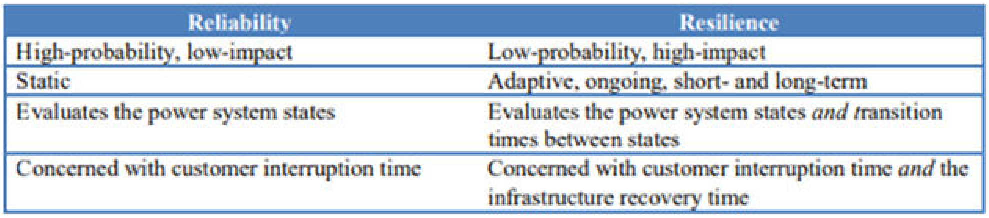
This paper explores reliability and resilience and how resilience metrics can provide the basis to measure networks improvements in a changing climate environment.

1. Reliability versus Resilience

Panteli and Mancarella, 2015, identified that “a reliable and well-designed power system should be capable of minimizing the amount of power disruption and of recovering very quickly from a blackout. On the other hand, a disaster, which usually includes a blackout, refers to severe and rapidly changing circumstances possibly never before experienced.

A disaster can cause the incapacitation of several and often large parts of a power grid, which may last for a long period depending on the extent of the disaster. Hence, a power infrastructure that can maintain high levels of performance under any condition should be reliable to the most “common” blackouts, but also resilient to much less frequent disasters.” (1).

Table 1 provides some of the main variations between reliability and resilience in the context of an electrical network. A resilient network will be designed and managed taking onto account the longer-term impact of a major event from the pre-event state to the system state following full recovery.



Reliability	Resilience
High-probability, low-impact	Low-probability, high-impact
Static	Adaptive, ongoing, short- and long-term
Evaluates the power system states	Evaluates the power system states *and* transition times between states
Concerned with customer interruption time	Concerned with customer interruption time *and* the infrastructure recovery time

Table 1. Reliability versus Resilience [1]

An event state transition can be represented by a conceptual resilience curve to define and quantify power system resilience. **Figure 1** shows the level of resilience as a time-dependent function with respect to disaster event.

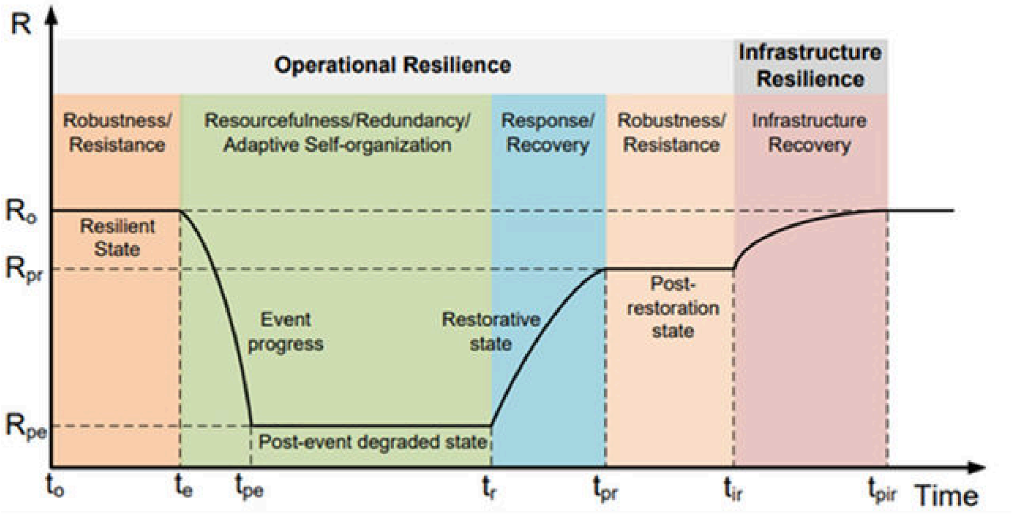


Figure 1. Conceptual resilience curve associated to an event [1]

- Before the event occurs, a power system must be robust and resistant to withstand the initial shock.
- A well-designed and operated power system should demonstrate sufficient resilience (indicated here with R_o, where R is a suitable metric associated to the resilience level of the system – see also further below) to cope with any type of events. The capability of preventive operational flexibility is highly critical here, as it provides the operators with the assets to configure the system in a resilient state.

- Following the event, the system enters the post-event degraded state, where the resilience of the system is significantly compromised (R_{pe}). The resourcefulness, redundancy and adaptive self-organization are key resilience features at this stage of the event, as they provide the corrective operational flexibility necessary to adapt to and deal with the evolving conditions (that are possibly never experienced before). This helps minimize the impact of the event and the resilience degradation (i.e., $R_o - R_{pe}$) before the restoration procedure is initiated at t_r.

- The system then enters the restorative state, where it should demonstrate the restorative capacity necessary for enabling the fast response and recovery to a resilient state as quickly as possible.

- Once the restoration is completed, the system enters the post-restoration state. The post-restoration resilience level R_{pr} may or may not be as high as the pre-event resilience level R_o, i.e. $R_{pr} < R_o$.

- In particular, while the system may have recovered from the point of view of fully returning to its pre-event operational state (thus showing a certain degree of operational resilience), the infrastructure may take longer to fully recover (infrastructure resilience), i.e. $(t_{pir} - t_{ir}) > (t_{pr} - t_r)$. This would depend on the severity of the event, as well as on the resilience features that the power system will demonstrate before, during and after the external shock [1].

2. Climate Resilience Metrics

It is widely acknowledged that different metrics are required to quantify reliability and resilience. The traditional and widely used reliability metrics, such as Expected Energy Not Served (EENS) and Loss of Load Expectation (LOLE) are not considered appropriate for measuring resilience. The traditional reliability metrics focus on the average event; on the contrary, resilience is concerned with severe and rare events, which cannot be modelled by the expected average impact of frequent events [4]. Until now, there have been no standard resilience metrics, nor are there standard methods to evaluate them. Although several resilience metrics have been proposed, it is still an ongoing discussion on how to establish a standardised set of resilience metrics, especially when there is an opportunity of using flexibility resources to support grid resilience [5].

Resilience introduces four attributes and determinants for a resilient system:

Robustness, i.e., “the ability of systems, system elements, and other units of analysis to withstand disaster forces without significant degradation or loss of performance”
Redundancy, i.e. “the extent to which systems, system elements, or other units are substitutable, that is, capable of satisfying functional requirements, if significant degradation or loss of functionality occurs”
Resourcefulness, i.e. “the ability to diagnose and prioritise problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological, and human resources”
Rapidity, i.e. “the capacity to restore functionality in a timely way, containing losses and avoiding disruptions”

E.DSO has identified a suite of climate resilience metrics for network operators and managers to measure the resilience of their network based on the resilience features of redundancy, robustness, reliability, and response and recovery. These resilience metrics have been categorised as either leading metrics (resilience-oriented planning or a measure of the network/asset pre-event state) or lagging metrics (event impact or a measure of the network/asset during or post event state). The table also identifies E.DSO’s top 4 climate resilience metrics for each resilience feature, with **Appendix A** to **Appendix D** providing the full list of 71 resilience metrics.

	Resilience Feature	Pre-Event/ Resilience Oriented Planning/ Leading Metric	Reason / Weather Case
1	Robustness	% of overhead line network which has undergone vegetation management to the required DSO standard	Wildfire, windstorms
2		% of sites resilient to flash flooding out of total identified vulnerable to flash flooding	Flooding
3		% of assets with climate adaptation considered for high wind speed/flooding, lightning withstand protection, design temperature, etc.)	High wind speed, flooding, lightning, heatwaves
4		% of the power grid located in high wildfire risk areas	Wildfires
5		% of Underground network with newer cable joints (non-transition)	Heatwaves
6	Redundancy	% of circuits with n-1 for MV outlets (or most resilient variant for redundancy)	Overall
7		% of HV primary substation transformers that have spare capacity for overloading	Various hazards
8	Reliability	% remote control urban MV/LV substation	Various hazards
9	Response and Recovery	% of MV circuits under FLISR (ADMS) control	Various hazards
10		% of network with automated self-healing (reclosing) devices installed	Wind, lightning, vegetation

Table 2. E.DSO Climate Resilience Metrics

3. Recommendations

To combat climate change and the associated risks, E.DSO recommends that the following next steps are taken. This will enable each DSO to make a substantial and data-based case to their regulators on the need to reinforce their electricity networks to combat climate change.

- The results of these leading metrics are shared among member DSOs for comparison purposes during 2024.
- The climate adaptation metrics proposed are used by DSOs to support and justify appropriate work delivery programmes with their regulators.

Using these climate adaptation metrics will lead to a robust and consistent approach by all grid operators to the climate challenge that we are experiencing. This will help all of us focus on ways to increase the grid resilience and minimise the impact to our customers.

References

1. Panteli and Mancarella, 2015: The Grid: Stronger, Bigger, Smarter? Presenting a Conceptual Framework of Power System Resilience, IEEE
2. US National Infrastructure Advisory Council, 2010: A Framework for Establishing Critical Infrastructure Resilience Goals
3. Energy Research Partnership, 2018: Resilience of the UK Electricity System
4. Flexibility For Resilience - Publications Office Of The Eu (Europa.Eu)

Appendix A. Resilience Metrics – Robustness

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	Emergency Response	Restoration	
		Leading Metric*		Lagging Metric	
1	Robustness*	% of overhead line network which has undergone vegetation management (KPI). Because vegetation evolves quickly perhaps it is worth including different timeframes: In the last 1 year – In the last 3 years – In the last 5 years			Wildfires/storm (within standard)
2	Robustness*	No. of sites resilient to flooding - Sites where work has been done to increase their resilience to flooding (KPI)			Flooding
3	Robustness*	% of assets with known adaptive capacity (designed for quantitative return period values of high wind speed/flooding, lightning withstand protection, design temperature, etc.)			High wind speed/flooding, lightning
4	Robustness*	% of the power grid located in high wildfire risk areas			Wildfires
5	Robustness*	% users (i.e. LV domestic, LV non-domestic, MV users) with overloaded profiles			Heatwaves
6	Robustness*	% total length of overhead lines in forest clearing/total length of overhead lines		% outages/customers calls (social resilience - how well communities cope with outage	Commercial forestry

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	Emergency Response	Restoration	
		Leading Metric*		Lagging Metric	
7	Robustness*	Characteristics of MV cable (e.g. % of network less than 20 years old, % of XLPE insulation, % underground cable)			Heatwaves
8	Robustness*	MV feeder geolocation (e.g. % overhead line installed at lower altitude, % overhead line far forest areas)			Tree falls and ice formation
9	Robustness*	MV feeder failure rate between MV/LV substations			Heatwaves
10	Robustness*	Total length of overhead network resilient to flooding (km). No. of composite poles introduced in floodplains. Suitable materials could be different from composite. Equipment and fuses moved			Flooding
11	Robustness*	% MV/LV substation not buried			Flooding
12	Robustness*	% of fire detection sensors deployed in high-risk zones			Wildfires
13	Robustness*	% MV/LV substations with waterproof characteristics			Flooding

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	Emergency Response	Restoration	
		Leading Metric*		Lagging Metric	
14	Robustness*	% users (i.e. LV domestic, LV non-domestic, MV users) with overloaded profiles		% of fault during heatwaves period	Heatwaves
15	Robustness*	Length of overhead network undergrounded			Storm/windstorm
16	Robustness*	% MV homogeneous joints and quantities			Heatwaves
17	Robustness*	MV/LV substation geolocation and electrical topology			Tree falls and ice formation
18	Robustness*	% overhead lines/underground cable lines		% No. of lines with 0 outages/No. of lines with repeated outages	
19	Robustness*	% users (i.e. LV domestic, LV non-domestic, MV users) with overloaded profiles		No. of fires in a given timeframe per km OHL	
20	Robustness*	% total length of overhead lines in forest clearing/total length of overhead lines		No. of short interruptions (let's say time duration less than 3 min.)/No. of overhead lines in forested areas	
21		Total length of overhead conductor resilient to clearance violations (km). This is a legal requirement with predetermined timescales for resolution. Results will always be small but could be highly dynamic as work programmes must be very fast to respond to the requirements			Wildfires/wind

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	Emergency Response	Restoration	
		Leading Metric*		Lagging Metric	
22	Robustness*	% MV/LV substation installed outside critical areas			Flooding
23	Robustness*	Total length of underground network resilient to flooding (km). e.g. Raised Substations or LV Minipillars in flood plains			Flooding
24	Robustness*	MV feeder failure rate between MV/LV substations	No. of pre-emptive outages/CMLs created for network, personnel or environmental protection		Heatwaves
25	Robustness*	Characteristics of MV cable (e.g. % of helicord insulation, % underground cable)			Tree falls and ice formation
26	Robustness*	% of faults in MV/LV substation caused by flooding			Flooding
27	Robustness*	No. of sites resilient to flooding - Sites where work has been done to increase their resilience to flooding (KPI?)		No. of sites flooded in a given timeframe per total volume of sites	
28	Robustness*	% of network/assets less than 10 years old (or age before first inspection required by policy)			Older assets
29	Robustness*	% of OHL support structures adapted for birdlife protection		CML caused by birdlife incidents	Birdlife protection

Appendix B. Resilience Metrics – Redundancy

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	**Emergency Response**	**Restoration**	
		Leading Metric*		**Lagging Metric**	
1	Redundancy	% of n-1 outlets (or most resilient variant for redundancy)		CML (weather-related fault) per outlet	Overall
2	Redundancy	% of critical assets with dual communication channels. Note: Critical assets should be defined			Various hazards
3	Redundancy	% of HV/MV primary substation that can back feeding a specific portion of the grid			Various hazards
4	Redundancy	% of MV backup power lines used to back feeding a specific portion of the grid			Various hazards
5	Redundancy	% of critical assets with dual power feeds			
6	Redundancy	% No. of substations with two or more feeder lines		% outages/customers calls (social resilience - how well communities cope with outage	
7	Redundancy			avg. time spent for repair / avg. field crews number	

Appendix C. Resilience Metrics – Reliability

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	Emergency Response	Restoration	
		Leading Metric*		Lagging Metric	
1	Reliability	% remote control MV/LV secondary substation			
2	Reliability	% of critical assets with dual communication channels. Note: Critical assets should be defined			
3	Reliability			% avg. wind gusts (it could be also temperature, snowfall etc.)/outages	Wind (or temperature/ snowfall)
4	Reliability	% MV/LV secondary substations installed out of private areas			Various hazards
5	Reliability	On the % of network with inspections completed (by Area/Substation/Circuit) (Reliability), it might be more interesting to calculate the same indicators not by Area/Substation/Circuit but by type of asset (substation, line, transformation centres) For example, in the case of strong winds, such as the Spanish case, the line type area is the most affected			
6	Reliability	% of network with inspections complete (per Area/Substation/Circuit)			
7	Reliability	% of network with inspections complete (per Area/Substation/Circuit)		% assets inspected in the last x years which have failed during HILP event	

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	Emergency Response	Restoration	
		Leading Metric*		Lagging Metric	
8	Reliability	% of network with maintenance complete (per Area/Substation/Circuit)			
9	Reliability	% of network at Low (good condition) Health Index Score			
10	Reliability	% of network at Low (good condition) Health Index Score		Average Health Index score of assets failed during HILP event and replacement costs	
11	Reliability	% of Area/Substation/Circuit new devices with lightning protection			Lightning
12	Reliability	% network automation			Various hazards
13	Reliability	Characteristics of MV cable (e.g. % of XLPE insulation, % underground cable)			Various hazards
14	Reliability	% thermal-magnetic switch in MV/LV substations			Various hazards
15	Reliability	% staff available during fault and for recovery operation			Various hazards

Appendix D. Resilience Metrics – Response and Recovery

	Resilience Feature	**Pre-Event**	**During Event**	**Post Event**	**Weather Case**
		Resilience Oriented Planning	**Emergency Response**	**Restoration**	
		Leading Metric*		**Lagging Metric**	
1	Response and Recovery	% of lines under Fault location, isolation, and service restoration (FLISR) control			
2	Response and Recovery	% of automated reclosing devices			
3	Response and Recovery	% of response staff available		Restoration costs	
4	Response and Recovery	% of circuits/outlets with automated reclosing devices			
5	Response and Recovery	% of SCADA connected substations			
6	Response and Recovery	No. of spares available per asset category			
7	Response and Recovery	No. of Contingency Drills for weather-related incidents or cyberattacks			Weather related/ cyberattacks
8	Response and Recovery	% of monitoring in primary and secondary substations		No. of website accesses seeking information	

	Resilience Feature	Pre-Event	During Event	Post Event	Weather Case
		Resilience Oriented Planning	Emergency Response	Restoration	
		Leading Metric*		Lagging Metric	
9	Response and Recovery			(Load – lost load)/lost load	
10	Response and Recovery	% of monitoring in primary and secondary substations			
11	Response and Recovery	% of response staff available			
12	Response and Recovery	% of response staff available		Duration of weather-related fault per circuit/substation	
13	Response and Recovery	% of switching equipment that are telecontrolled		% of successful telecontrol operations & CML due to communication failures	
14	Response and Recovery	% of monitoring in primary and secondary substations			
15	Response and Recovery	% of monitoring in primary and secondary substations		No. of calls received and addressed on the telephone support platform	
16	Response and Recovery	% of monitoring in primary and secondary substations		No. of calls received and addressed in the Control Room	