Adaptive Resilience Metrics Framework for Distribution System

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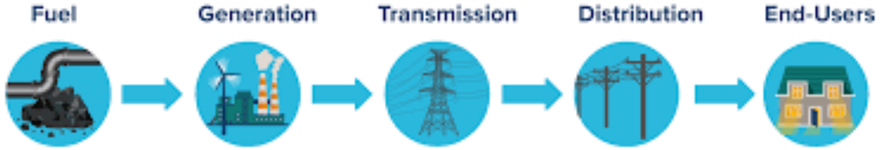
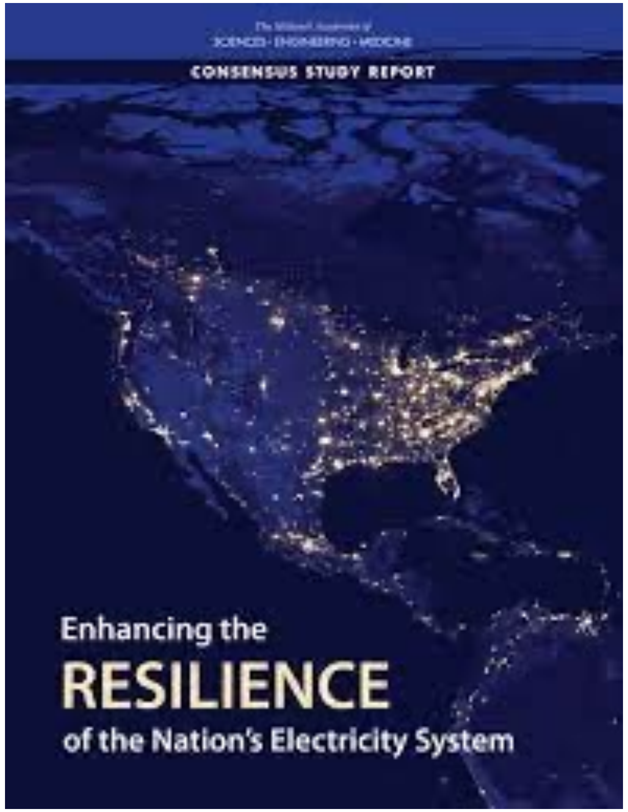
IEEE PESGM 2023 Panel on Distribution Grid Resilience: Metrics and Integration into Planning/Operation



Defining Resilience


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
Enhancing the
RESILIENCE
of the Nation's Electricity System

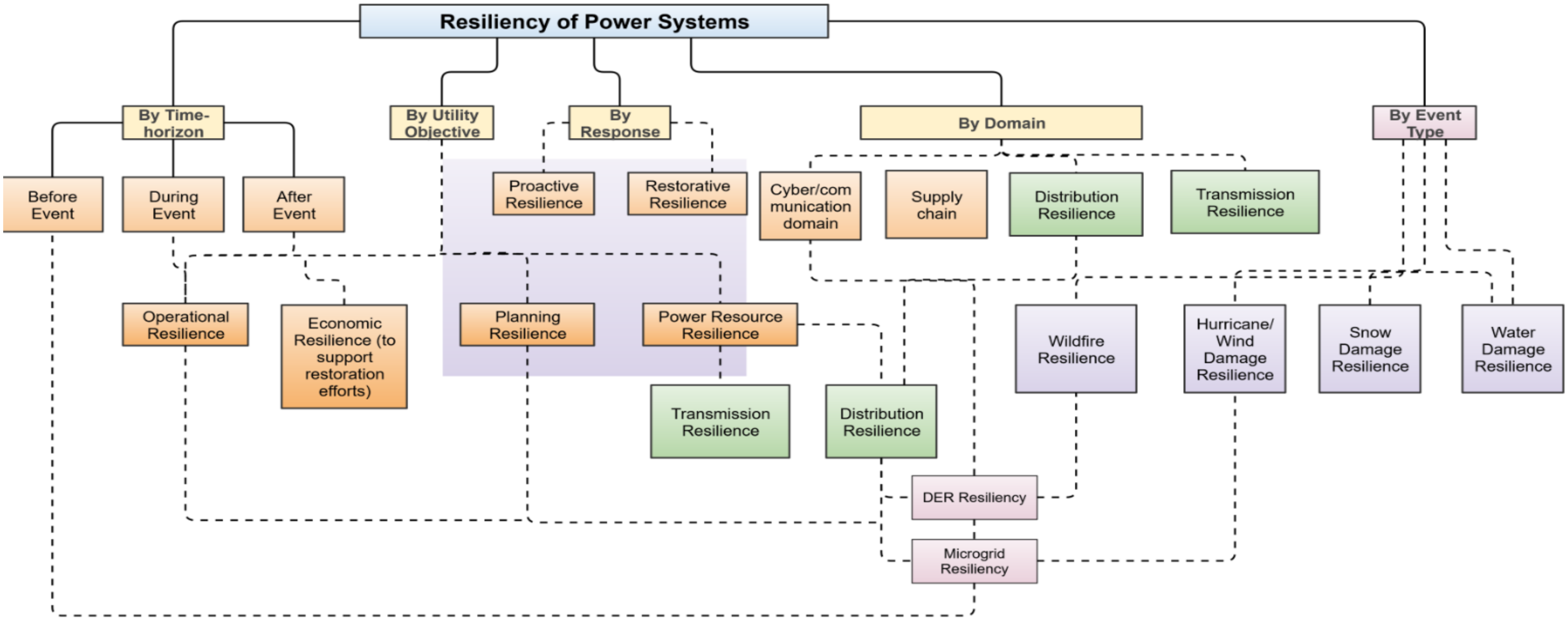
Multiple definitions exist.
Focus on critical loads for distribution grids.
"Resilience – Ability of the system to supply its critical loads, even in the presence of multiple contingencies".

FERC: The ability to withstand and reduce the magnitude and/or duration of disruptive events, which include the capacity to anticipate, absorb, adapt to, and/or rapidly recover from such an event.

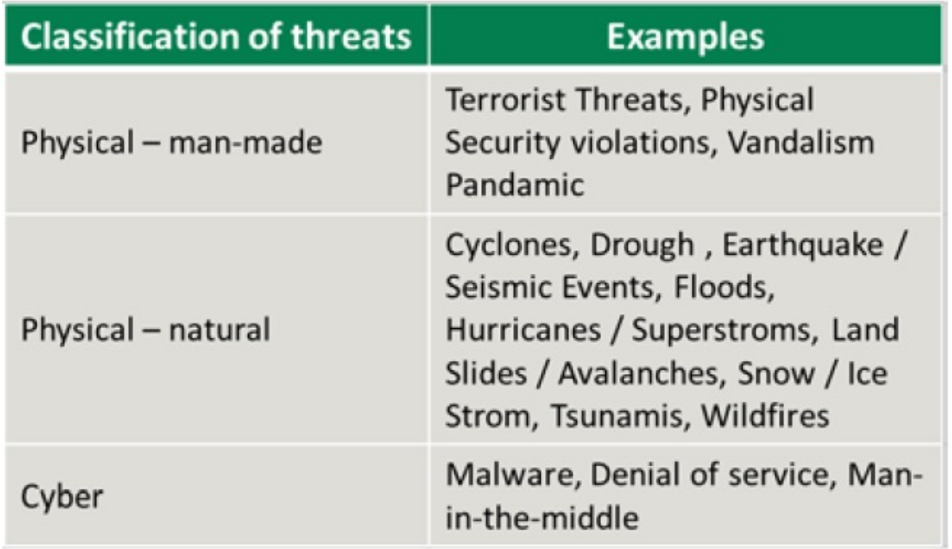
IEEE PES PSDP definition and metric for resilience WG, PES T&D Distribution System Resiliency, PSOPE tools for resilience, AMPS Resilience Metrics and Evaluation Methods and CIGRE WG 4.47 and 2.25

G. Kandaperumal*, A.K. Srivastava, "Resilience of the Electric Distribution Systems: Concepts, Classification, Assessment, Challenges, and Research Needs", IET Cyber-Physical Systems: Theory & Applications, 2019

Taxonomy of Resiliency



Event Specific Technical Challenges



Classification of threats	Examples
Physical – man-made	Terrorist Threats, Physical Security violations, Vandalism Pandamic
Physical – natural	Cyclones, Drough , Earthquake / Seismic Events, Floods, Hurricanes / Superstroms, Land Slides / Avalanches, Snow / Ice Strom, Tsunamis, Wildfires
Cyber	Malware, Denial of service, Man-in-the-middle

Operational environment and different events -- There is no silver bullet

One metric may not work for all events, data sets and scenarios

Flood: Elevating substation, flood hardened control room

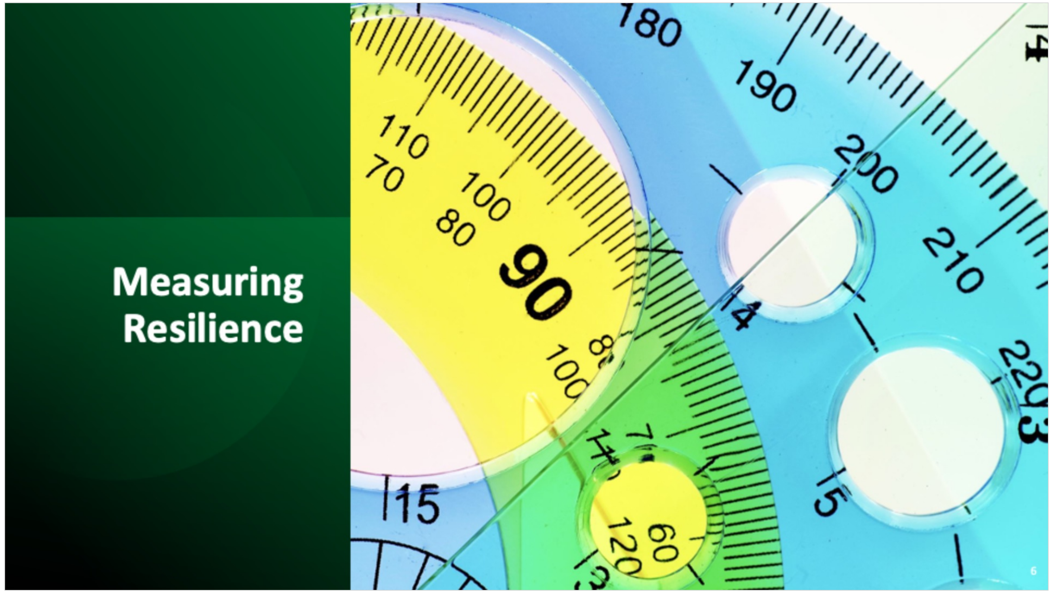
Tsunami: Isolate to be impacted generators apriori to minimize restoration time

Avalanche: Deploy crew sufficiently in advance to ensure their safety

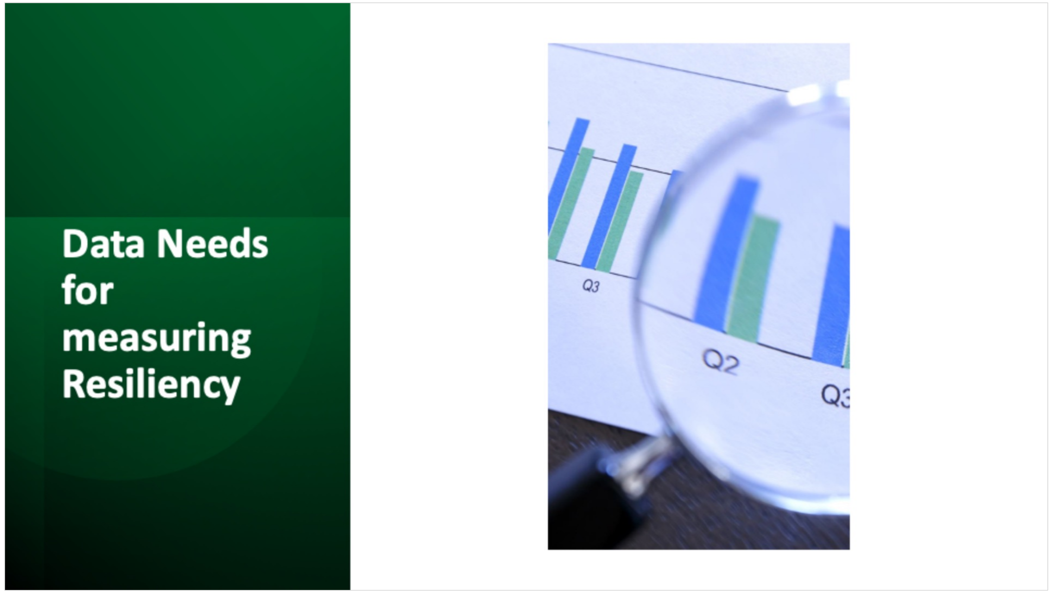
Wildfire: Vegetation management, power lines burial to minimize the probability of fire induced by power lines

Storm: Strengthening poles with guy wires, power lines burial

Cyber-events: Distributed approaches, reduced reliance on communication network



Measuring Resilience

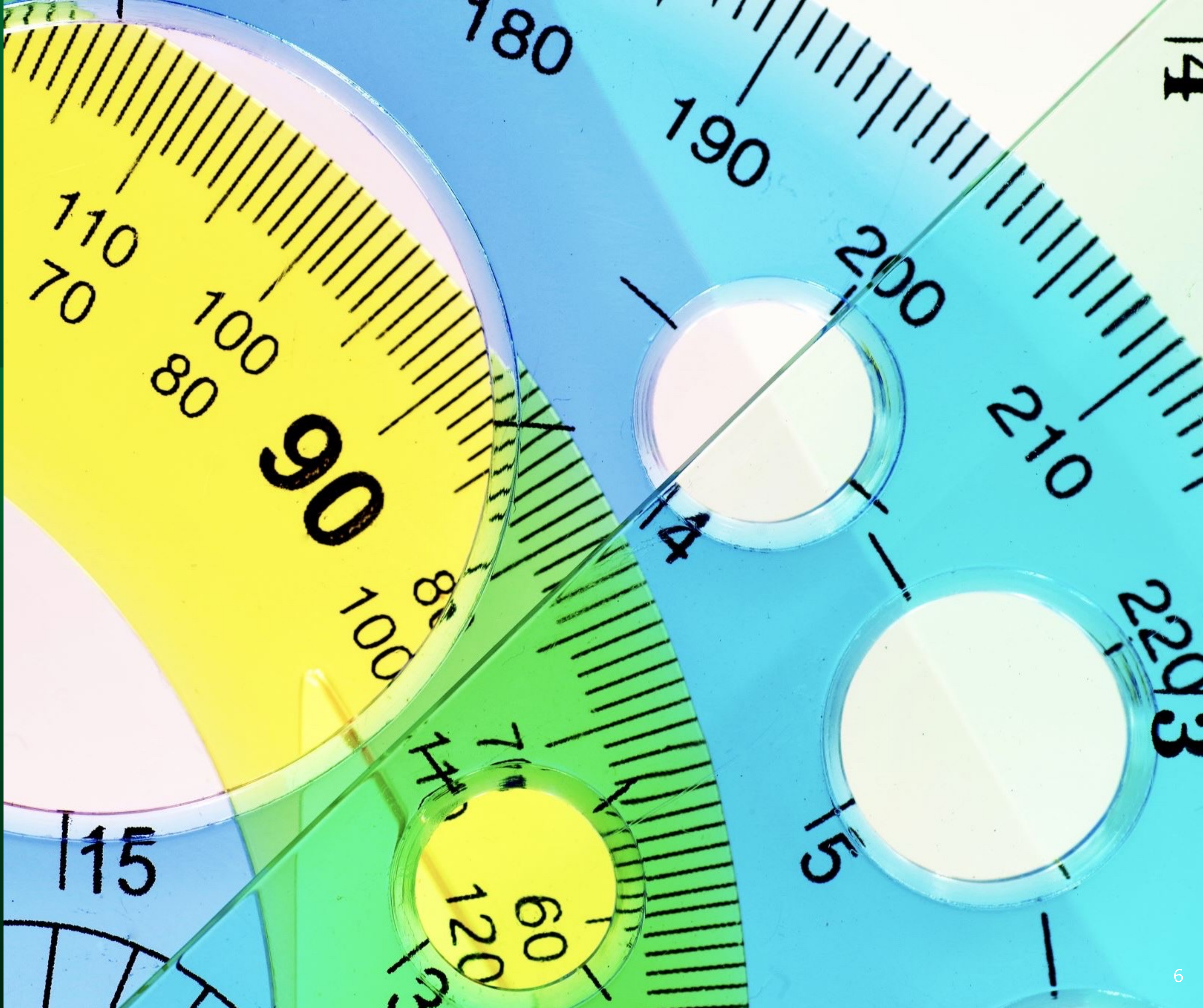


Data Needs for measuring Resiliency

Adaptive Framework for resiliency Metric

Summary

Measuring Resilience



Resilience Metrics

- Overall resilience metric considered [1]
- **Infrastructure** for design, hardening, and capital improvement planning
- **Operational** for response and restoration evaluation and planning
- Extracted resilience metrics from previous threats data in distribution utilities[2]
  - Resilience curve (t) = Outage time (t)- restoration process(t)
      - Restore and event durations, outage and restore rates,
  - A cumulative number of customers out

- M.Konya and J. Lauletta “Defining Grid Resilience”
- PES TF Report “Methods for Analysis and Quantification of Power System Resilience” May 2023

Super Storm Sandy Study by SNL

- Outage Magnitude(customer-days w/o power)

- Recovery Costs($)
  - Repair and recovery costs bore by the utility

$$\sum_{t=1}^{10} c_{labor}(t) + c_{materials}(t) + c_{parts}(t),$$

- Community Impact
  - critical assets w/o power for 48+hrs

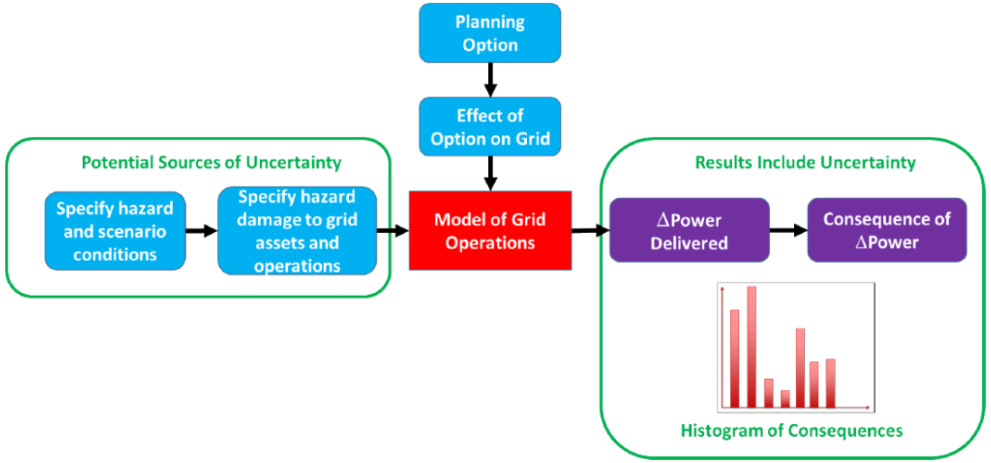

Planning Option
Effect of Option on Grid
Potential Sources of Uncertainty
Specify hazard and scenario conditions
Specify hazard damage to grid assets and operations
Model of Grid Operations
Results Include Uncertainty
ΔPower Delivered
Consequence of ΔPower
Histogram of Consequences

Fig. Calculation of Grid Resilience Metrics: inclusion of uncertainty

3. E. Vugrin, A.Castillo, C. Monroy" Resilience Metrics for the Electric Power System: A Performance-Based Approach" Feb 2017.

Hurricane[3] (Florida Power and Light)

Resilience metric considered

- Number of customers affected
- Infrastructure damage
- Restoration time
- Threat impact

Methods to improve

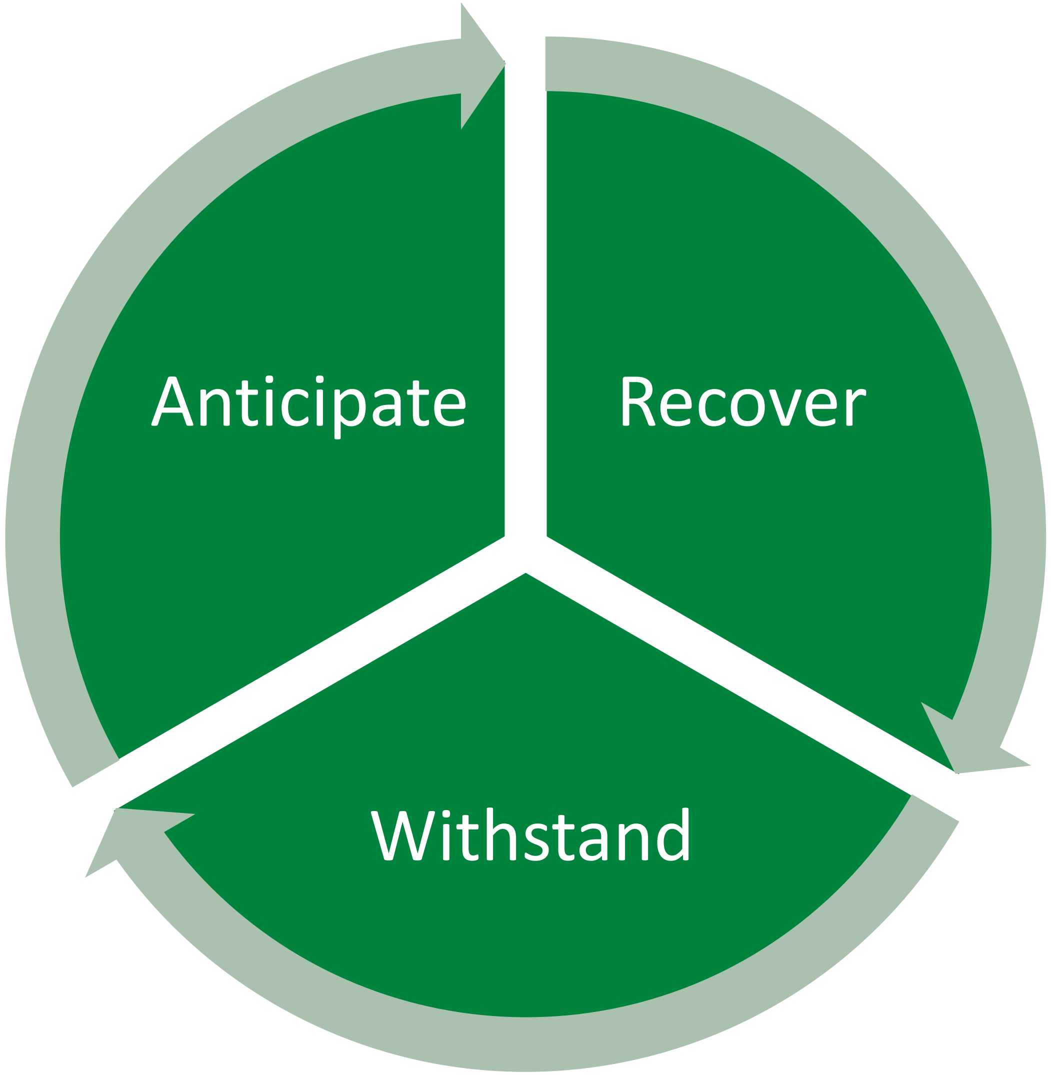
- Hardening
- Pole inspections
- Vegetation management
- Underground conversions

Storm Event (ComEd)

- First, understanding the storms types such as high, medium and low severe
- Metric-1: Number of customers without power
    - Reducing the number of customers lost within few hours
- Metric-2: Grid infrastructure

[3] W. Monzon " How FPL is building a more resilient grid" Florida Power & Light Company, May 2022.

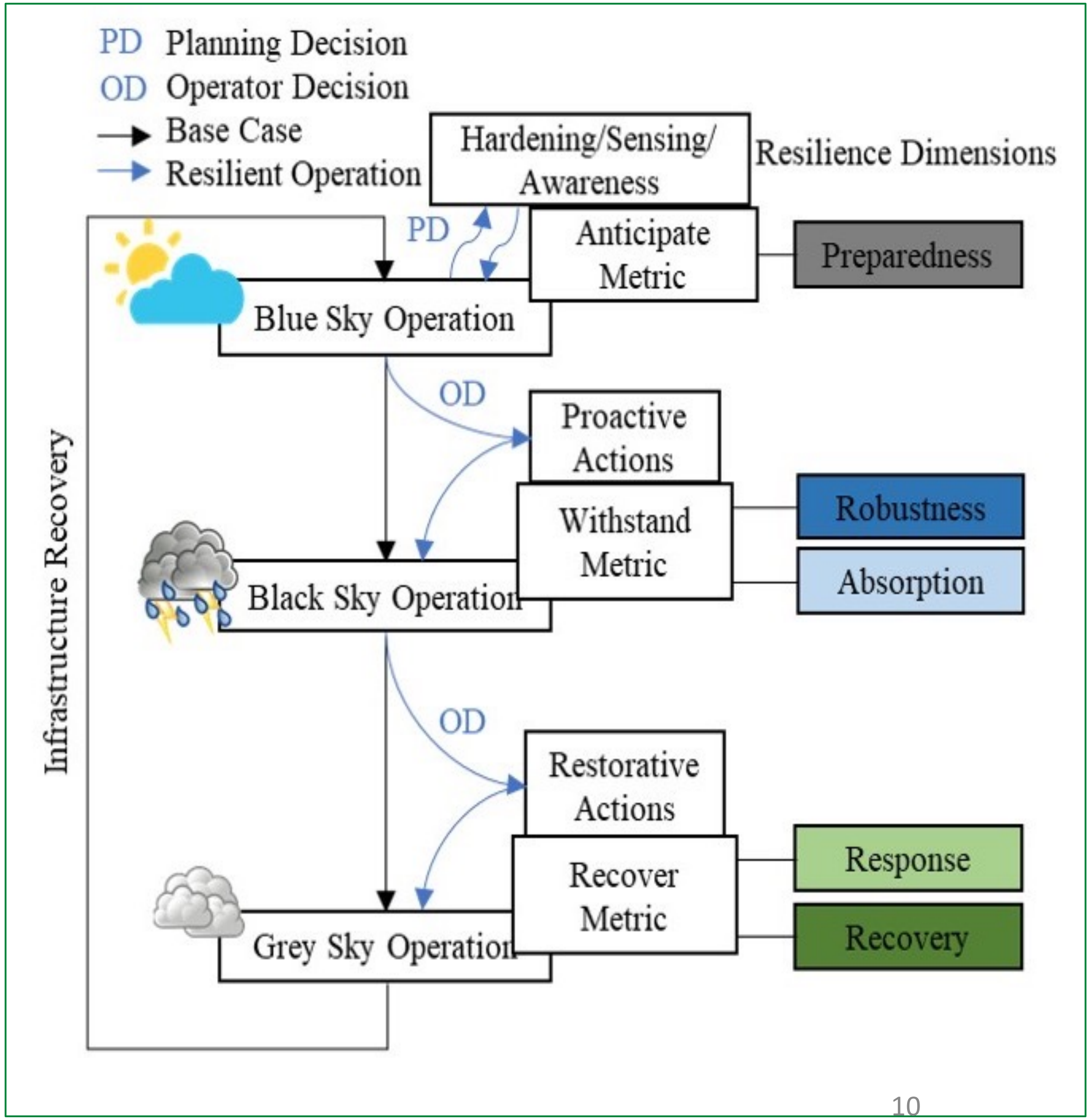
Multi-temporal Multidimensional Resilience Measure



Anticipate

Recover

Withstand



PD Planning Decision

OD Operator Decision

→ Base Case

→ Resilient Operation

Hardening/Sensing/ Awareness

Resilience Dimensions

Infrastructure Recovery

PD

Blue Sky Operation

Anticipate Metric

Preparedness

OD

Proactive Actions

Withstand Metric

Robustness

Absorption

Black Sky Operation

OD

Restorative Actions

Recover Metric

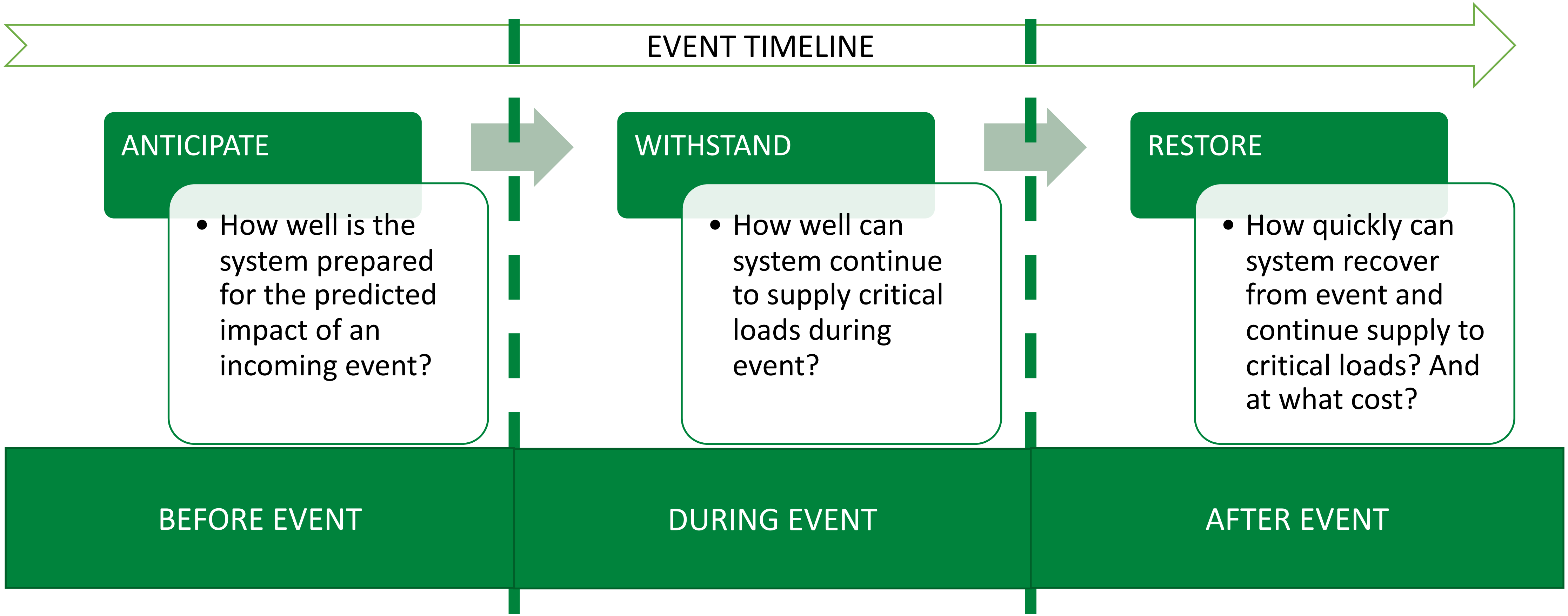
Response

Recovery

Grey Sky Operation

AWR Resilience Framework for RT-RMS

$R = f(A,W,R)$



EVENT TIMELINE

ANTICIPATE

- How well is the system prepared for the predicted impact of an incoming event?

WITHSTAND

- How well can system continue to supply critical loads during event?

RESTORE

- How quickly can system recover from event and continue supply to critical loads? And at what cost?

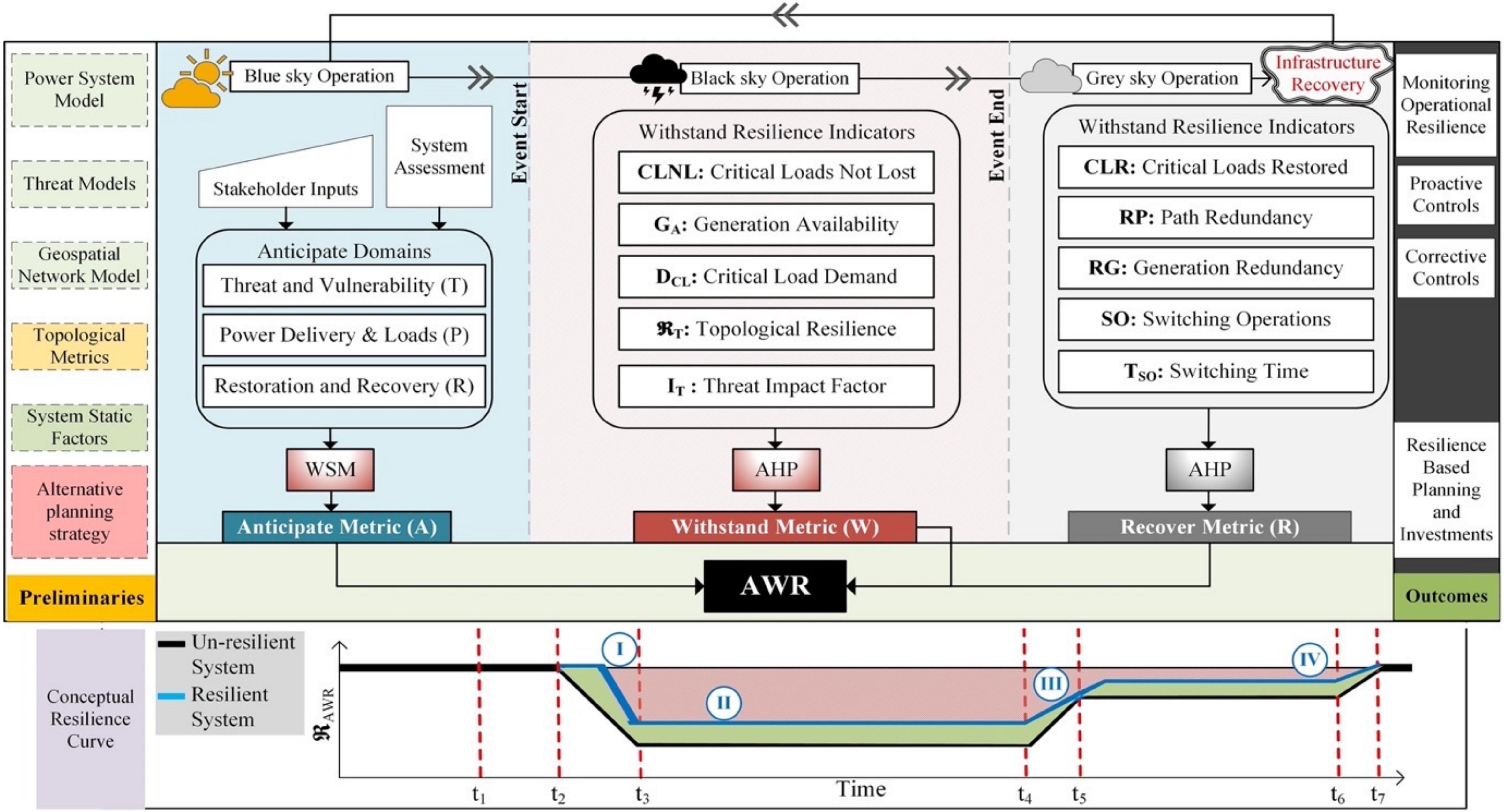
BEFORE EVENT

DURING EVENT

AFTER EVENT

Based on determining all the system factors impacting system ability to provide energy to the critical loads and integrating all the factors for AWR

Multi-temporal Multidimensional Resilience Measure



Preliminaries

Power System Model

Threat Models

Geospatial Network Model

Topological Metrics

System Static Factors

Alternative planning strategy

Blue sky Operation

Stakeholder Inputs

System Assessment

Anticipate Domains

Threat and Vulnerability (T)

Power Delivery & Loads (P)

Restoration and Recovery (R)

WSM

Anticipate Metric (A)

Event Start

Black sky Operation

Withstand Resilience Indicators

CLNL: Critical Loads Not Lost

G_A: Generation Availability

D_{CL}: Critical Load Demand

$\mathfrak{R}_T$: Topological Resilience

I_T : Threat Impact Factor

AHP

Withstand Metric (W)

Event End

Grey sky Operation

Infrastructure Recovery

Withstand Resilience Indicators

CLR: Critical Loads Restored

RP: Path Redundancy

RG: Generation Redundancy

SO: Switching Operations

T_{SO}: Switching Time

AHP

Recover Metric (R)

AWR

Outcomes

Monitoring Operational Resilience

Proactive Controls

Corrective Controls

Resilience Based Planning and Investments

Conceptual Resilience Curve

Un-resilient System

Resilient System

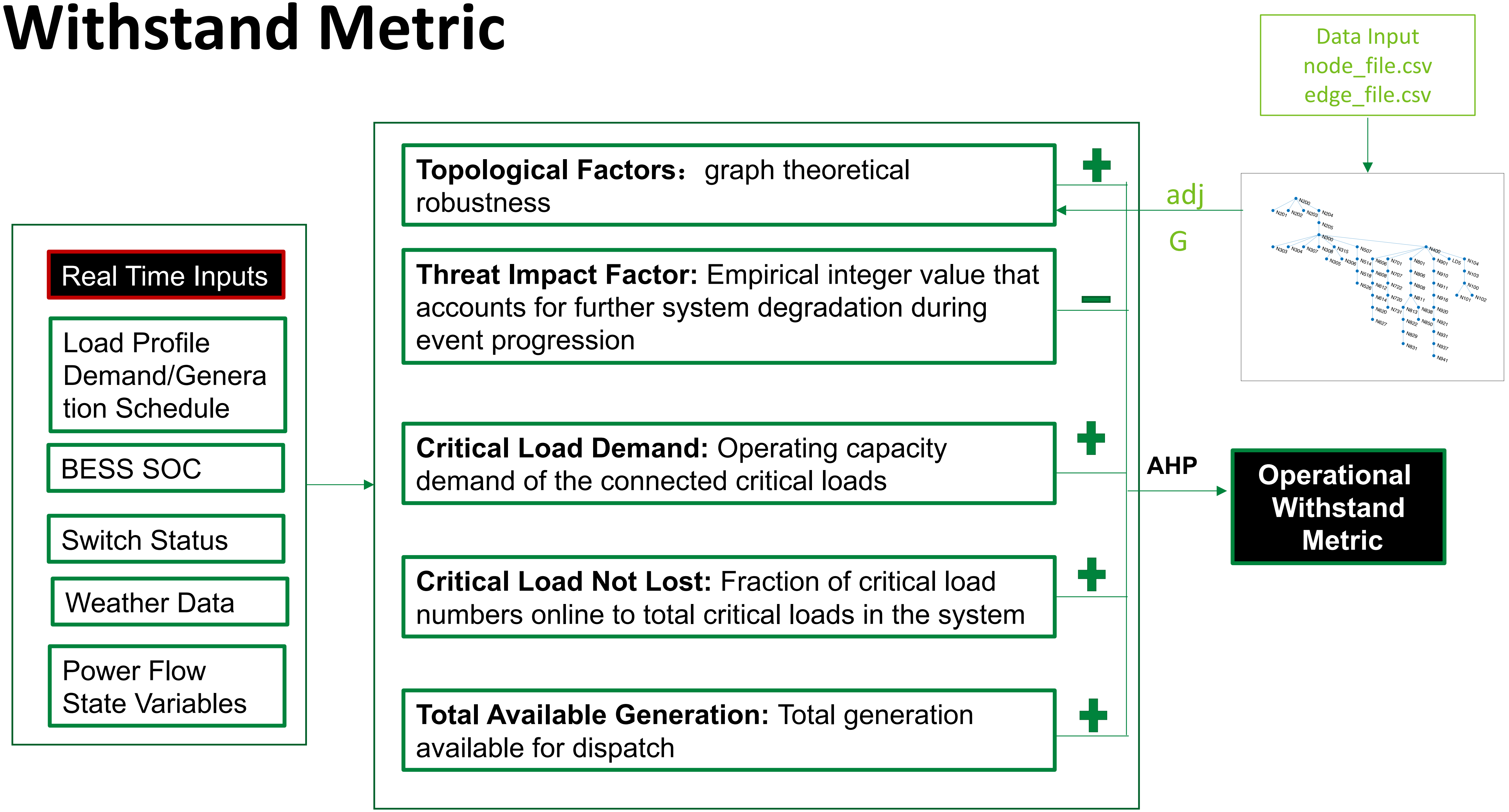
Anticipate Metric

ID	Threat and Vulnerability domain	Power Delivery and Loads domain	Restoration and Recovery Domain	Cyber and Communication Domain	
1	Have threats for the system identified?	Are critical loads identified?	Energy storage installed	Backup Communication Installed?	Critical Cyber assets identified
2	Impact of threat analyzed and documented?	Percentage of High Priority critical loads that have local backup generation	Automatic Restoration plan in place	Access to communication to crew and state agencies? Message center, Emergency Radio System	Multi-user clearance for critical cyber assets
3	Is emergency response curated for each threat?	Percentage of Medium Priority critical loads that have local backup generation	Has a restoration plan drill conducted in the last year?	Backup of all electronic data in case of loss of internet service	Firewall audit performed in the last week
4	Average warning time before threat	Average runtime of backup generation	Is repair teams on standby to be deployed	Cyber threats identified	Digital asset inventory
5	Accuracy of warning for each threat	Fault prevention plan in place?	Cross training of crew for handling all multiple equipment repairs	CEC Staff undergone cybersecurity practices training	Average time for cyber black start
6	Has drill conducted for threats in the last year?	Has vegetation management performed in the last year?	Staging site selected for triage,storm trailers, mobile restoration command center	Access control review	Anti-virus Installed
7	Anticipated maximum hours of outage for threats	Is complete asset inventory available	PPE and tools for restoration crew	Employee password authentication	Content Management System Installed
8		Is there a routine inspection plan available for system assets	Fuel inspection. Does fuel storage have polishers installed?	Virtual Private Network credential review	IP Rules for access control
9		Average black start restoration time	Mutual assistance program with neighboring cooperatives	Static IP configuration for CEC servers and network connected equipment	Are there a backup control center?
10		Average downtime of each generator due to threat		Third party access control	Are there data backup and archiving plans for critical data?

Inspired by CDC Public Health Emergency Preparedness and Response

Anticipate Metric

Withstand Metric



Data Input
node_file.csv
edge_file.csv

Real Time Inputs

Load Profile Demand/Generation Schedule

BESS SOC

Switch Status

Weather Data

Power Flow State Variables

Topological Factors: graph theoretical robustness +

Threat Impact Factor: Empirical integer value that accounts for further system degradation during event progression −

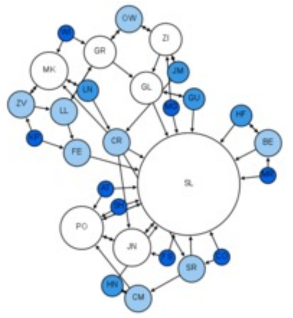
Critical Load Demand: Operating capacity demand of the connected critical loads +

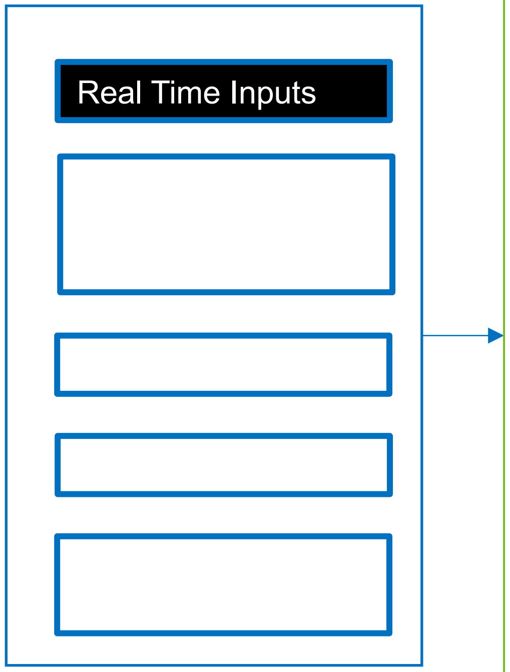
Critical Load Not Lost: Fraction of critical load numbers online to total critical loads in the system +

Total Available Generation: Total generation available for dispatch +

Operational Withstand Metric

Recovery Metric





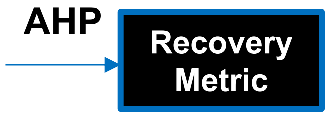
- ➢ **Topological Factors(+1):** graph theoretical robustness, mainly focus on critical loads restoration capability
- ➢ **Critical load outage cluster to redundant path ratio(-1) :**

$$\frac{\sum_{i=1}^{N} CriticalLoad_i}{\sum_{i=1}^{N} Redundant\ path_i}, i = outage\ cluster$$

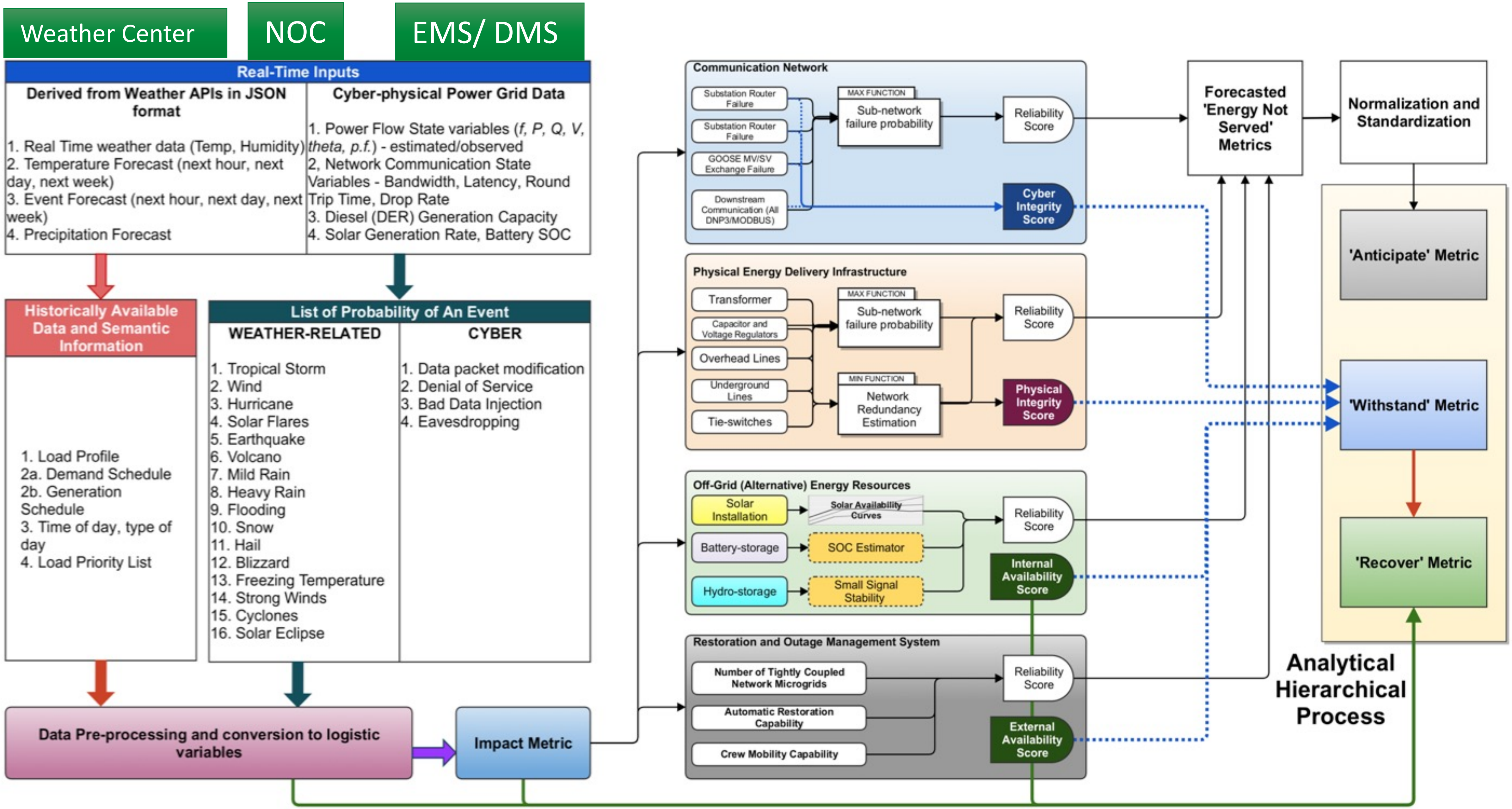
  - total capacity of critical loads to be restored/number of redundant path
  - number of redundant path : backup lines, DERs, black-start sources
- ➢ **Energy storage margin(+1):** Status of Charge of Battery
- ➢ **Power Balance Margin Ratio (-1):**

$$\frac{\sum_{i=1}^{N} Load_i}{\sum_{i=1}^{N} ReservePower_i}, i = outage\ cluster$$

  - loads to be recovered/reserve power capacity
  - reserve power capacity : spinning and non-spinning capacity of generators; DERs
- ➢ **Load shedding flexibility(+1):**
- Load capacity that can be shed or reduced.
- ➢ **Energy loss(-1):**
- Accumulated energy lost.



Measuring Resiliency using AWR



Weather Center

NOC

EMS/ DMS

Real-Time Inputs

Derived from Weather APIs in JSON format

1. Real Time weather data (Temp, Humidity)
2. Temperature Forecast (next hour, next day, next week)
3. Event Forecast (next hour, next day, next week)
4. Precipitation Forecast

Cyber-physical Power Grid Data

1. Power Flow State variables (*f, P, Q, V, theta, p.f.*) - estimated/observed
2, Network Communication State Variables - Bandwidth, Latency, Round Trip Time, Drop Rate
3. Diesel (DER) Generation Capacity
4. Solar Generation Rate, Battery SOC

Historically Available Data and Semantic Information

1. Load Profile
2a. Demand Schedule
2b. Generation Schedule
3. Time of day, type of day
4. Load Priority List

List of Probability of An Event

WEATHER-RELATED

1. Tropical Storm
2. Wind
3. Hurricane
4. Solar Flares
5. Earthquake
6. Volcano
7. Mild Rain
8. Heavy Rain
9. Flooding
10. Snow
11. Hail
12. Blizzard
13. Freezing Temperature
14. Strong Winds
15. Cyclones
16. Solar Eclipse

CYBER

1. Data packet modification
2. Denial of Service
3. Bad Data Injection
4. Eavesdropping

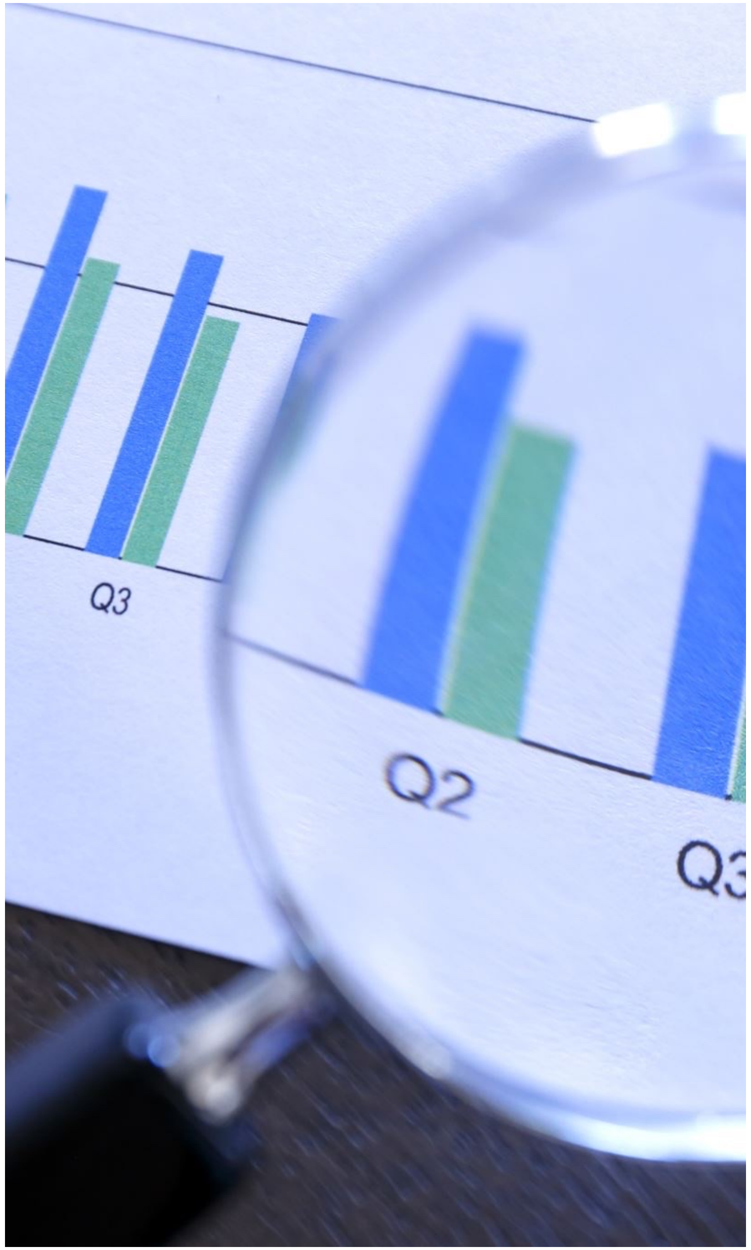
Data Pre-processing and conversion to logistic variables

Impact Metric

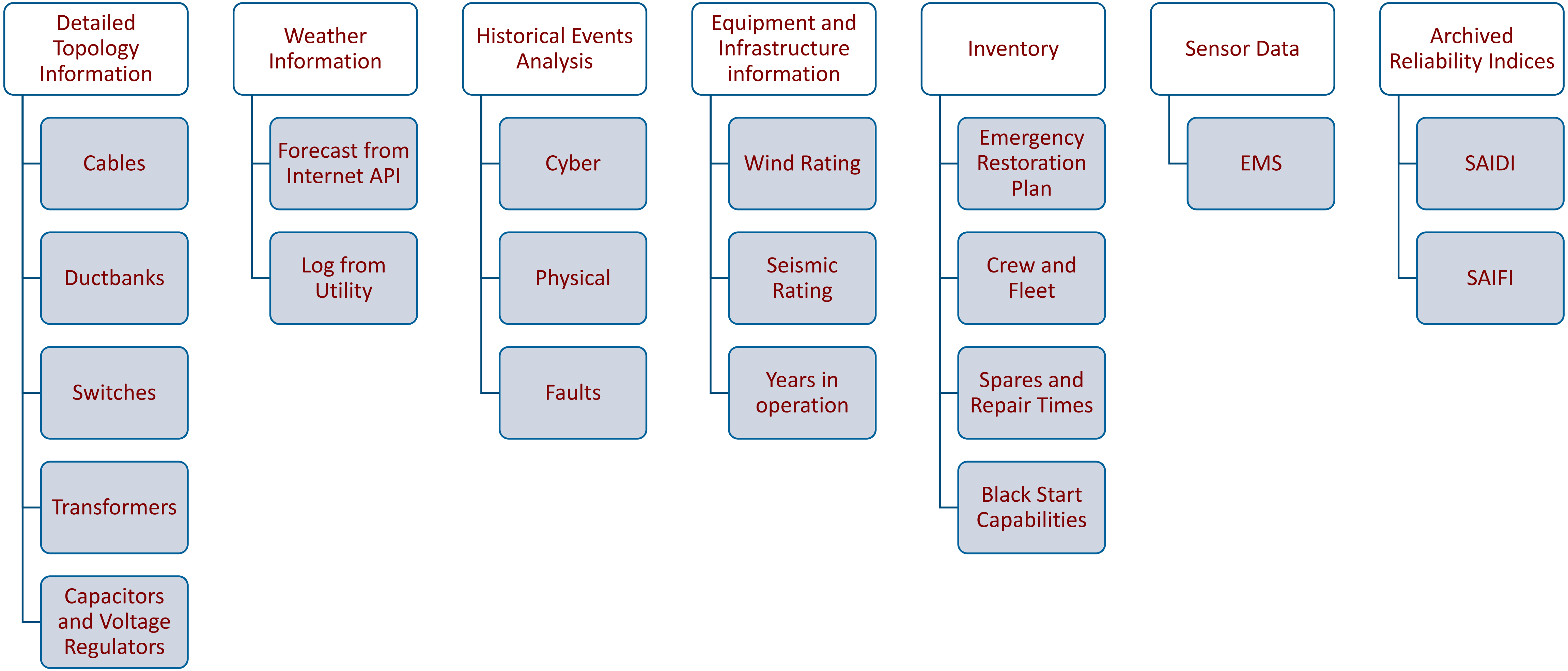
Communication Network
Substation Router Failure
Substation Router Failure
GOOSE MV/SV Exchange Failure
Downstream Communication (All DNP3/MODBUS)
MAX FUNCTION
Sub-network failure probability
Reliability Score
Cyber Integrity Score
Physical Energy Delivery Infrastructure
Transformer
Capacitor and Voltage Regulators
Overhead Lines
Underground Lines
Tie-switches
MAX FUNCTION
Sub-network failure probability
MIN FUNCTION
Network Redundancy Estimation
Reliability Score
Physical Integrity Score
Off-Grid (Alternative) Energy Resources
Solar Installation
Solar Availability Curves
Battery-storage
SOC Estimator
Hydro-storage
Small Signal Stability
Reliability Score
Internal Availability Score
Restoration and Outage Management System
Number of Tightly Coupled Network Microgrids
Automatic Restoration Capability
Crew Mobility Capability
Reliability Score
External Availability Score
Forecasted 'Energy Not Served' Metrics
Normalization and Standardization
'Anticipate' Metric
'Withstand' Metric
'Recover' Metric
Operational Resilience Metric

Analytical Hierarchical Process

Data Needs for measuring Resiliency



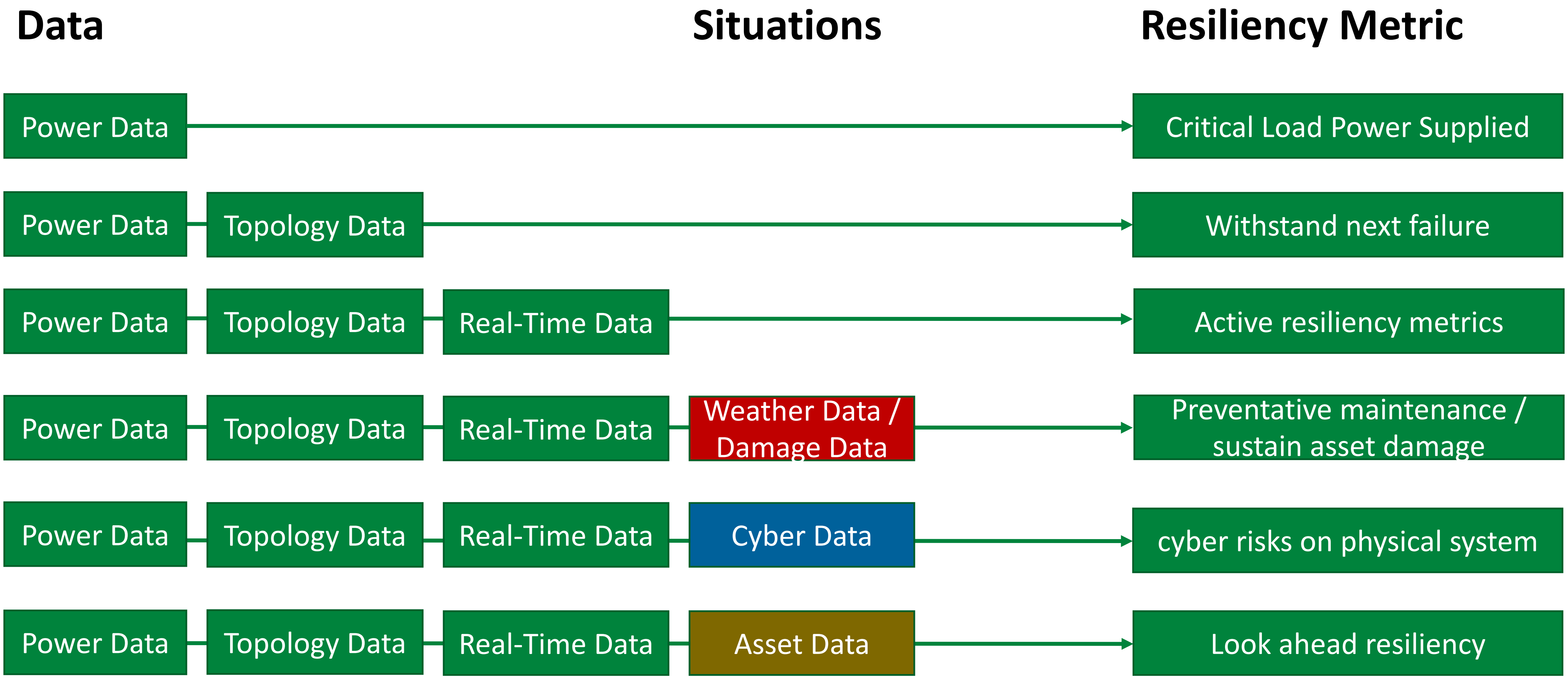
Data Required for Resiliency Metric Computation



- Detailed Topology Information
  - Cables
  - Ductbanks
  - Switches
  - Transformers
  - Capacitors and Voltage Regulators
- Weather Information
  - Forecast from Internet API
  - Log from Utility
- Historical Events Analysis
  - Cyber
  - Physical
  - Faults
- Equipment and Infrastructure information
  - Wind Rating
  - Seismic Rating
  - Years in operation
- Inventory
  - Emergency Restoration Plan
  - Crew and Fleet
  - Spares and Repair Times
  - Black Start Capabilities
- Sensor Data
  - EMS
- Archived Reliability Indices
  - SAIDI
  - SAIFI

Adaptive Framework for resiliency Metric

Adaptive Framework for Calculating Resiliency with Changing Data and Use-cases



Data			Situations	Resiliency Metric
Power Data				Critical Load Power Supplied
Power Data	Topology Data			Withstand next failure
Power Data	Topology Data	Real-Time Data		Active resiliency metrics
Power Data	Topology Data	Real-Time Data	Weather Data / Damage Data	Preventative maintenance / sustain asset damage
Power Data	Topology Data	Real-Time Data	Cyber Data	cyber risks on physical system
Power Data	Topology Data	Real-Time Data	Asset Data	Look ahead resiliency

Adaptive Framework for Using Resiliency Metric with Changing Time-frame and Use-cases

Before Event

1. Validation of nominal functions (Active monitoring)
2. Calculate system strength to withstand next event
3. Preparing for planned maintenance

During Event

1. Continuity of supply to critical loads

After Event

1. Robustness against subsequent events
2. Recognize and utilize assets to mitigate the events
3. Cost and continuity of supplying critical loads
4. Plan quick system recovery

Power System Planning

1. Check resiliency against future events
2. Check resiliency against planned/outstanding maintenance
3. Recalculate resiliency as new assets are added
4. Develop restoration plans

Power System Operation

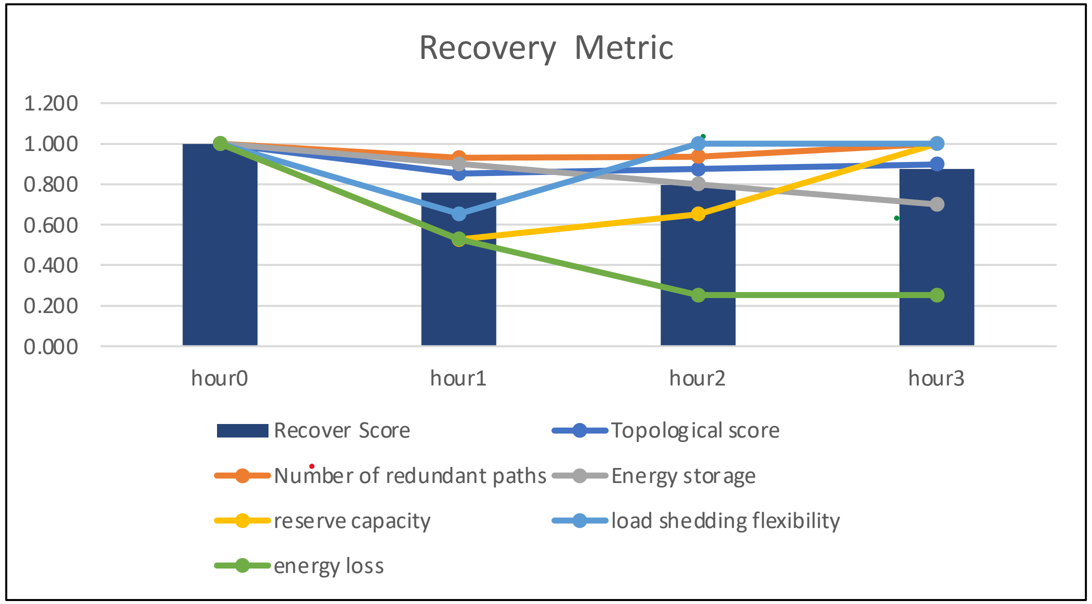
1. Active cyber-physical resiliency monitoring
2. Resiliency recalculation during/after events
3. Resiliency recalculation under planned outages
4. Anticipate outage times and impacts after events
5. Calculate recovery and restoration times

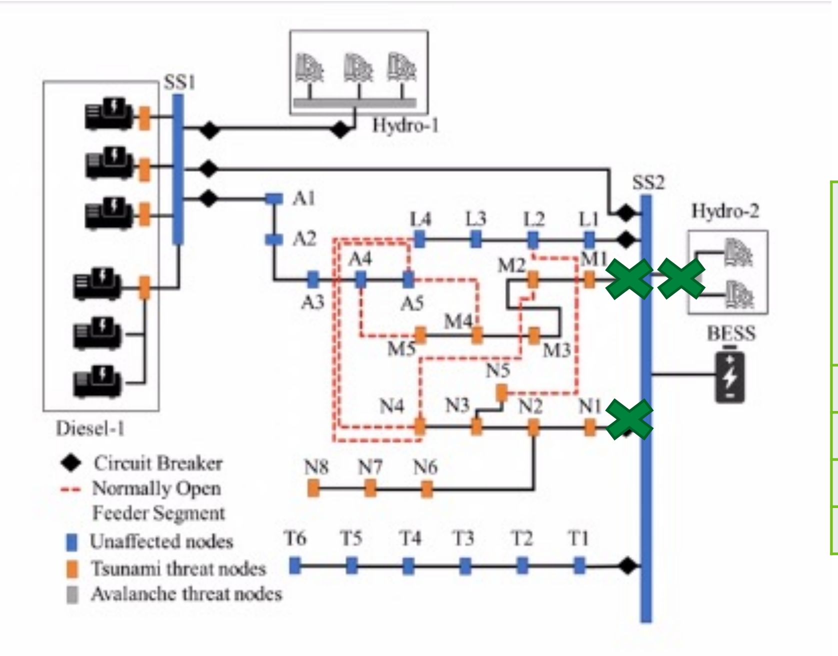
Example of using Recovery from AWR Metric

Scenario

- **T1**: loss of feeder 1+ feeder 2+ G1
- **T2**: Feeder 1 is recovered
- **T3**: Feeder 2 is recovered

*Suppose switches operate at the beginning of an hour





	Topo	Path redundancy	Energy storage	Power margin ratio	load shedding flexibility	energy loss	Recover score
Base case	1.000	1.000	1.000	1.000	1.000	1.000	1.000
hour1	0.852	0.930	0.900	0.527	0.654	0.528	0.760
hour2	0.875	0.937	0.800	0.652	1.000	0.253	0.797
hour3	0.898	1.000	0.700	1.000	1.000	0.253	0.875

Summary

Summary

- The definition of resilience – depends upon our vantage point, or what we are investigating.
- **Resilience is different from Reliability.** High Reliability does not ensure high resilience, but high resilience ensures high reliability.
- Usually resilience depends on multiple factors and Multi-criteria Decision Making (MCDM) approaches work well to define and quantify resiliency.
- Adaptive resilience framework is needed to adjust with data availability, event type, time frame and scenarios

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