Enabling the Resilient Electric Grid

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PSERC

PSERC Webinar
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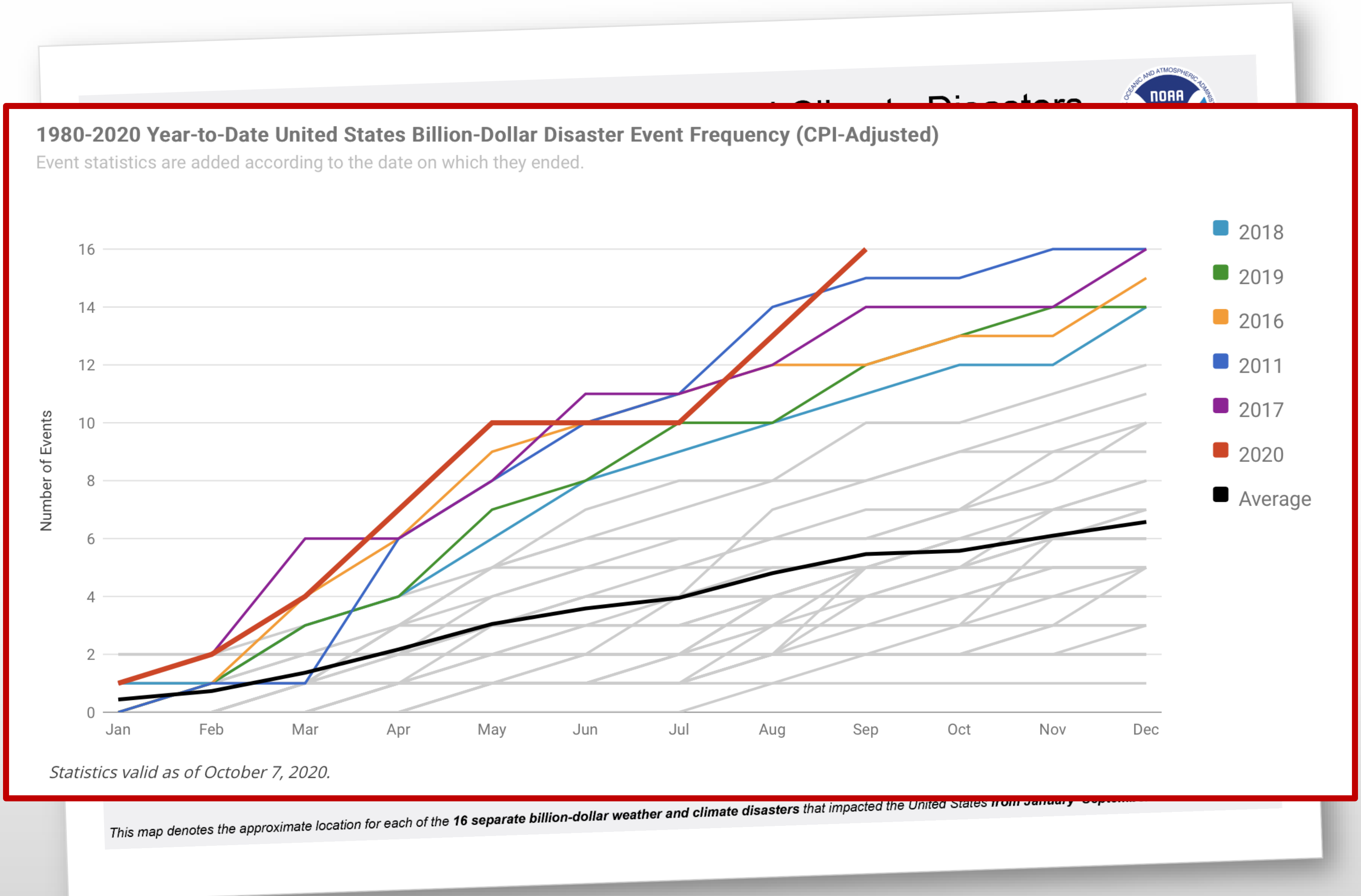
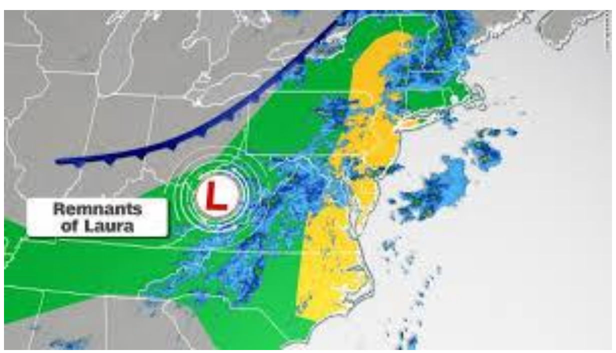

1980-2020 Year-to-Date United States Billion-Dollar Disaster Event Frequency (CPI-Adjusted)
Event statistics are added according to the date on which they ended.
Number of Events
0
2
4
6
8
10
12
14
16
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2018
2019
2016
2011
2017
2020
Average
Statistics valid as of October 7, 2020.
This map denotes the approximate location for each of the 16 separate billion-dollar weather and climate disasters that impacted the United States



EYE ON THE STORM

Hurricane Zeta's high winds cause second largest U.S. power outage of 2020

Three deaths are blamed on the storm, which made landfall Wednesday in southeastern Louisiana as a Category 2 hurricane with 110 mph winds.

By Jeff Masters, Ph.D. | Thursday, October 29, 2020

Power Outages in California as Winds Boost Fire Danger

October 26, 2020

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Tropical Storm Isaias has caused the second-largest power outage in Con Edison history, affecting 210,000 customers

Thousands without power for fourth day in eastern Washington, North Idaho

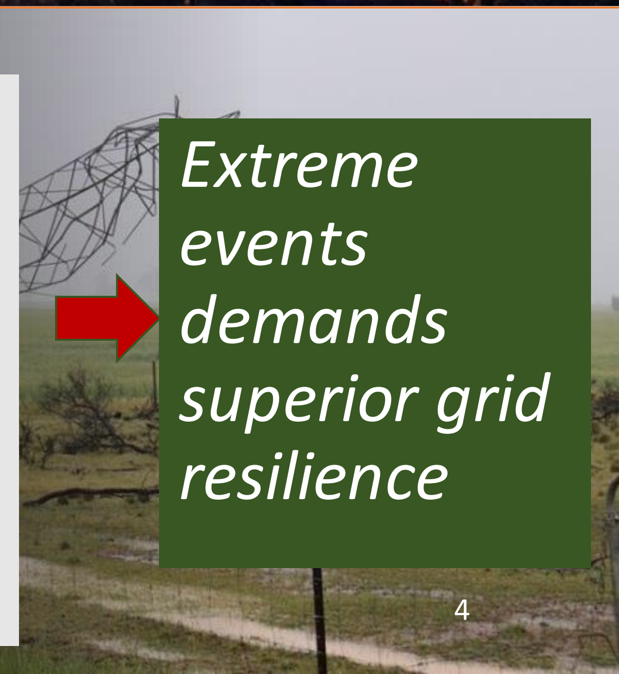
More than 50,000 were without power on Monday after high winds knocked down power lines throughout eastern Washington and North Idaho

The electrical distribution network is reliable but not resilient

Increase in extreme weather events

Aging infrastructure

Changing grid with DERs and Edge Devices



Extreme events demands superior grid resilience

What is Resilience?

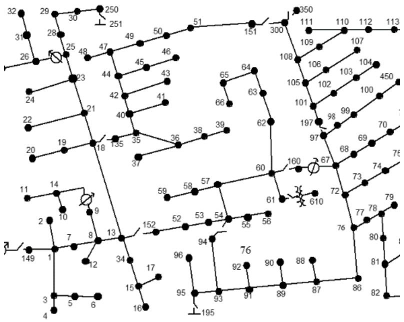
- Multiple definitions exist.
- Focus on critical loads for distribution grids.
- "Resilience – Ability of the system to supply its critical loads, even in the presence of multiple contingencies".

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.

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

Monitoring and Enabling Resilience

Distribution Network



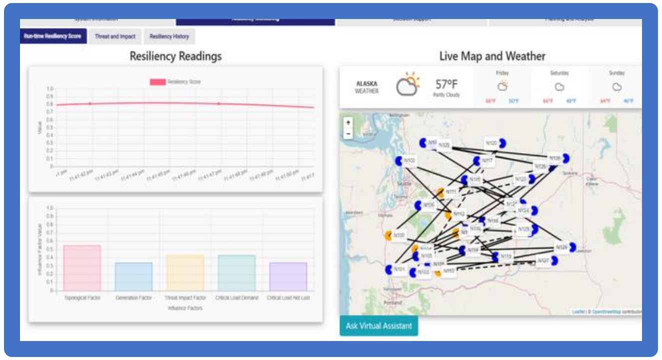
Advanced Sensors

Distributed Control

Microgrids

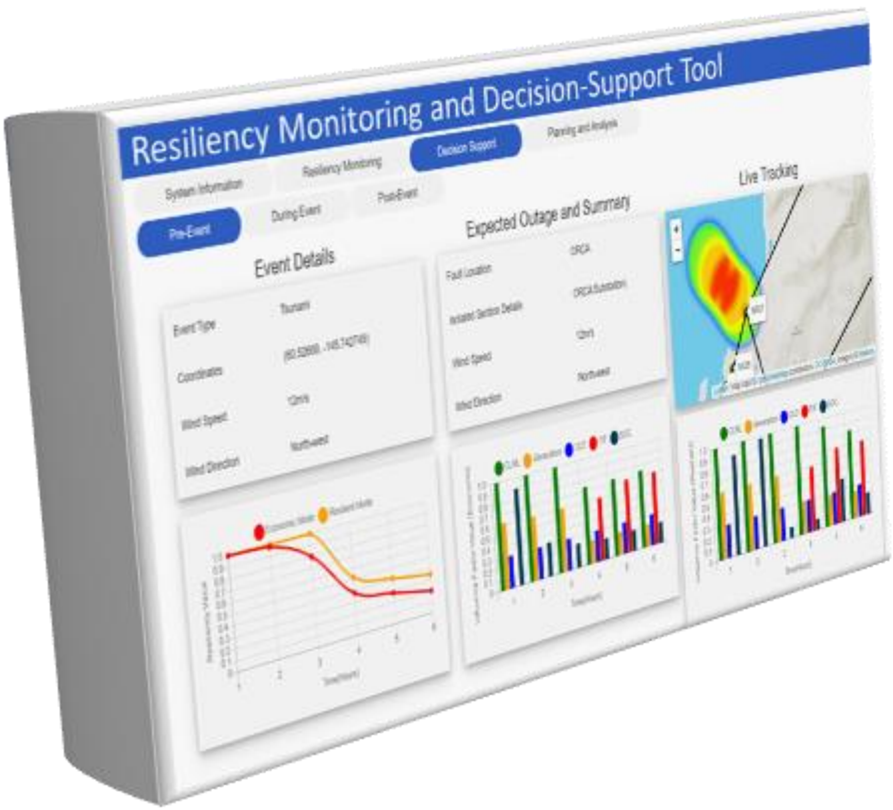
Mobile Generators

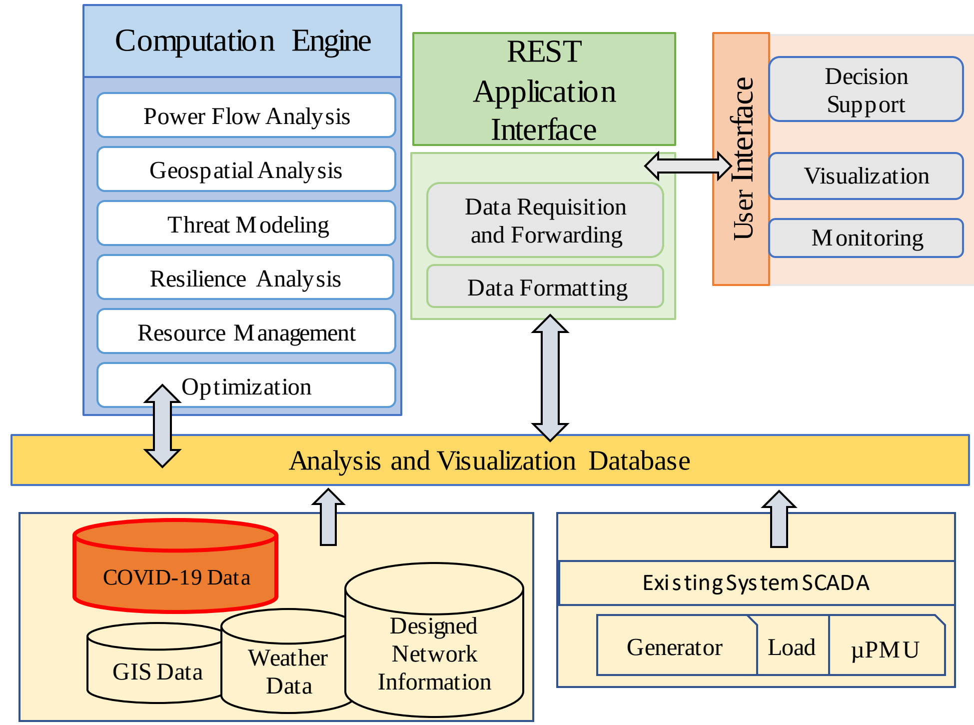
Control Center



Real-Time Resilience Management System (RT-RMS)

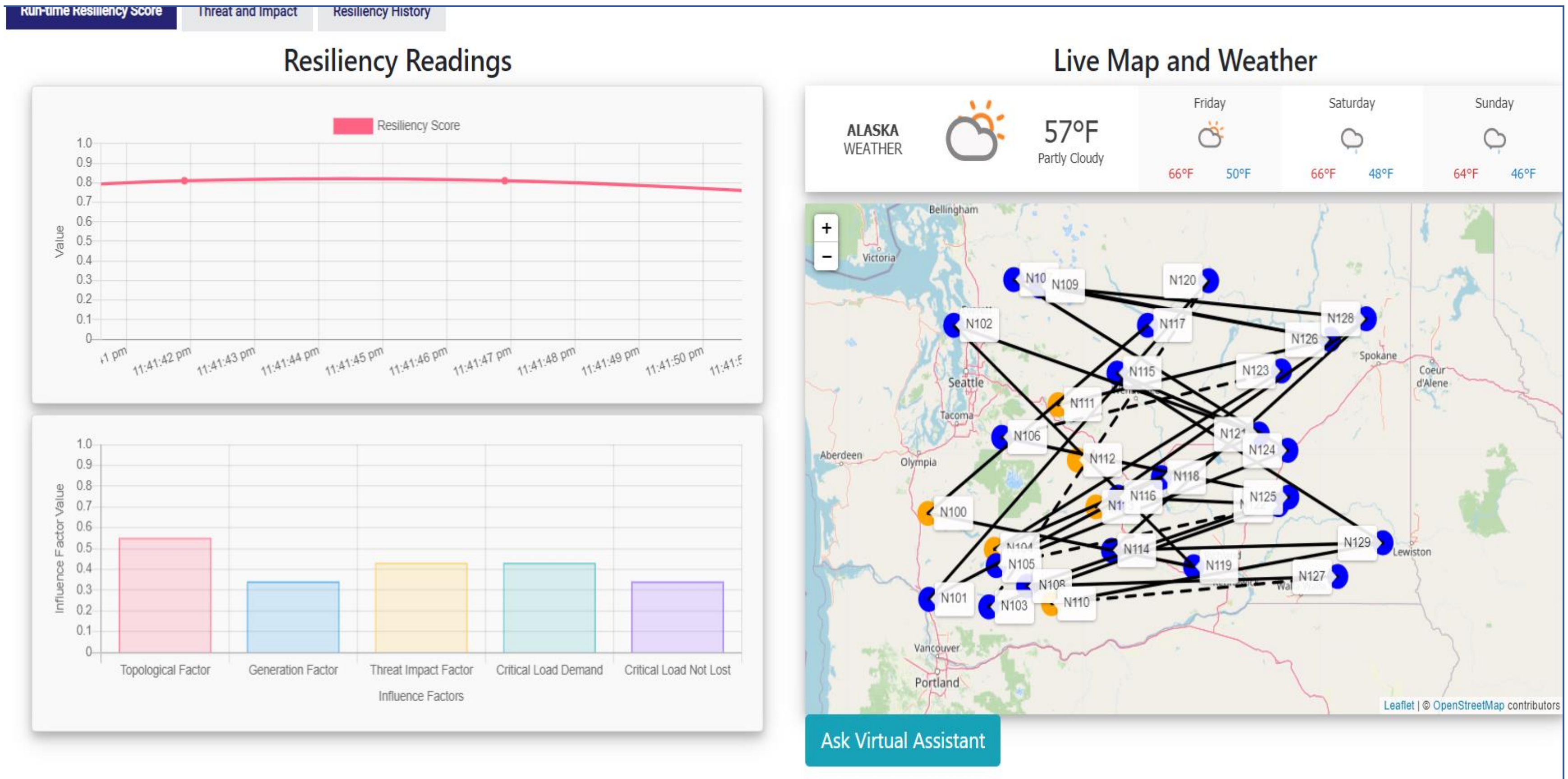
RT-RMS





Resilience Analysis Tool – Functional Block Diagram

Monitoring Resilience



Multi-temporal Multidimensional Resilience Framework

EVENT TIMELINE

R = f(A,W,R)

ANTICIPATE

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

BEFORE EVENT

WITHSTAND

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

DURING EVENT

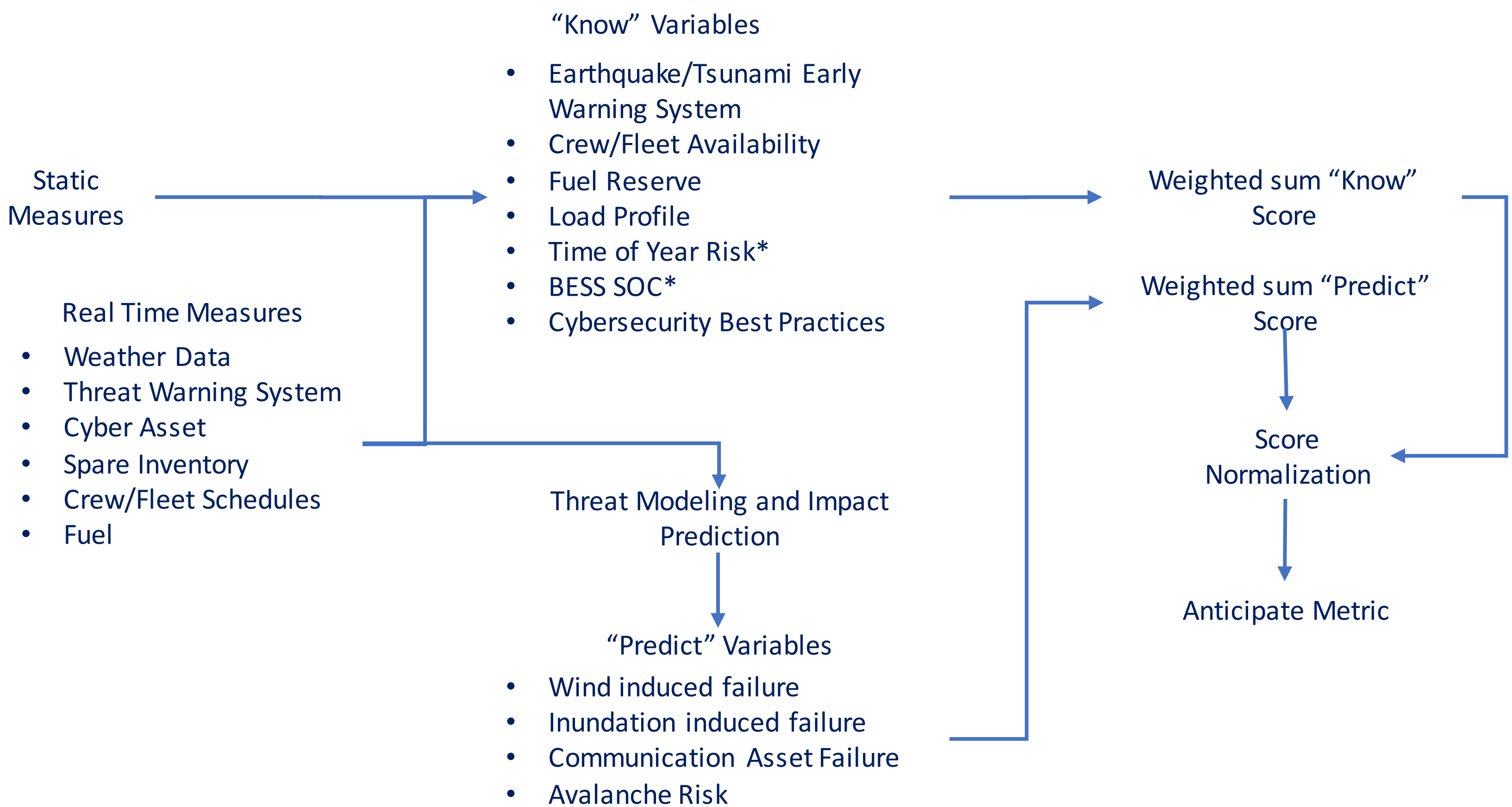
RESTORE

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

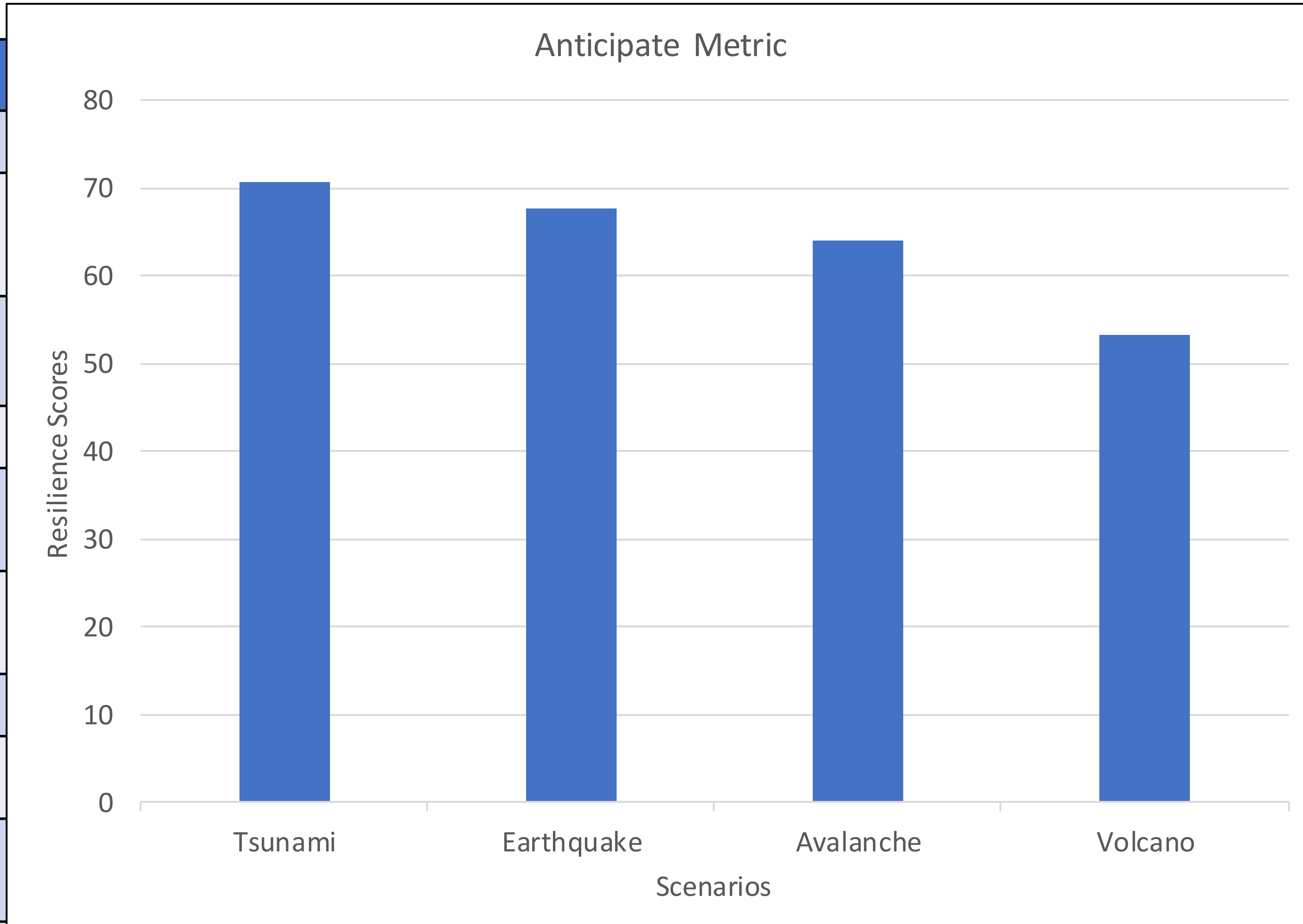
AFTER EVENT

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

Anticipate Metric



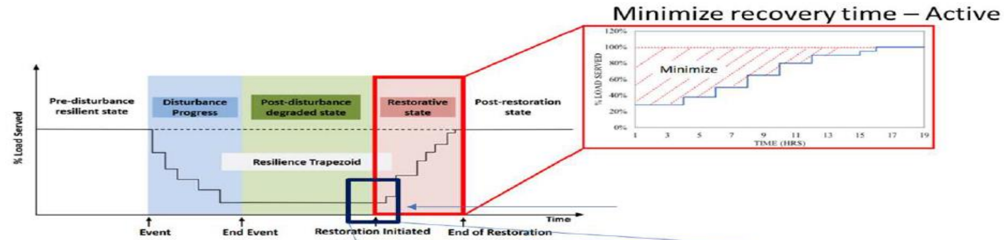
Anticipate Metric



ID					
1					ets
2					e for ets
3					med in
4					ory
5					ber
6					ed
7					ent
8					ntrol
9					ntrol
10		Average downtime of each generator due to threat		Third party access control	Are there data backup and archiving plans for critical data?

Withstand Metric

Recover Metric



Passive Recover Resilience:

- Decrease loads lost – from withstand
- Increase capabilities for recover

Real Time Measures

- Automated Switches
- AMI
- Cyber Asset
- Spare Inventory
- Fuel

'Know' variables

- Grid Topology
- Load Not Lost
- Fuel Reserve
- Water Head Level
- BESS SOC*

Recovery Schemes

Topological factors

- Topological resiliency score
- Available generation
- Critical Load not lost
- Critical path redundancy
- Critical Load Fraction

Operational factors

- Number of Switching operations
- Switching time
- Load Curtailment

Economical factors

- Repair time
- Repair lost

Recovery Capability

Weighted sum "Topological" factors

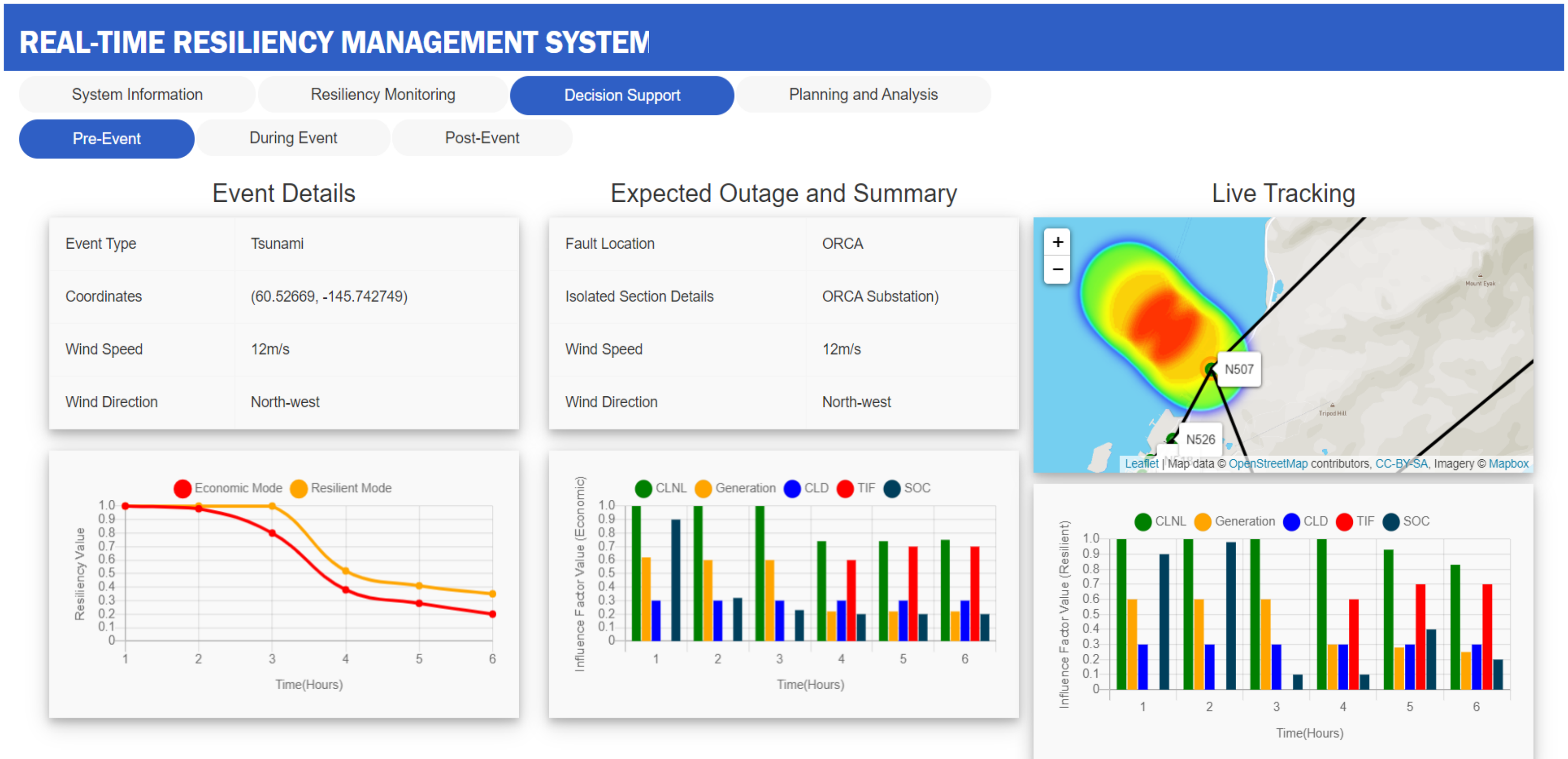
Recovery Efficacy

Weighted sum "Operational factors" and "Economical factors"

Score Normalization

Recover Metric

RT-RMS Tool: Decision Support



Enabling Resiliency

Long term Planning:

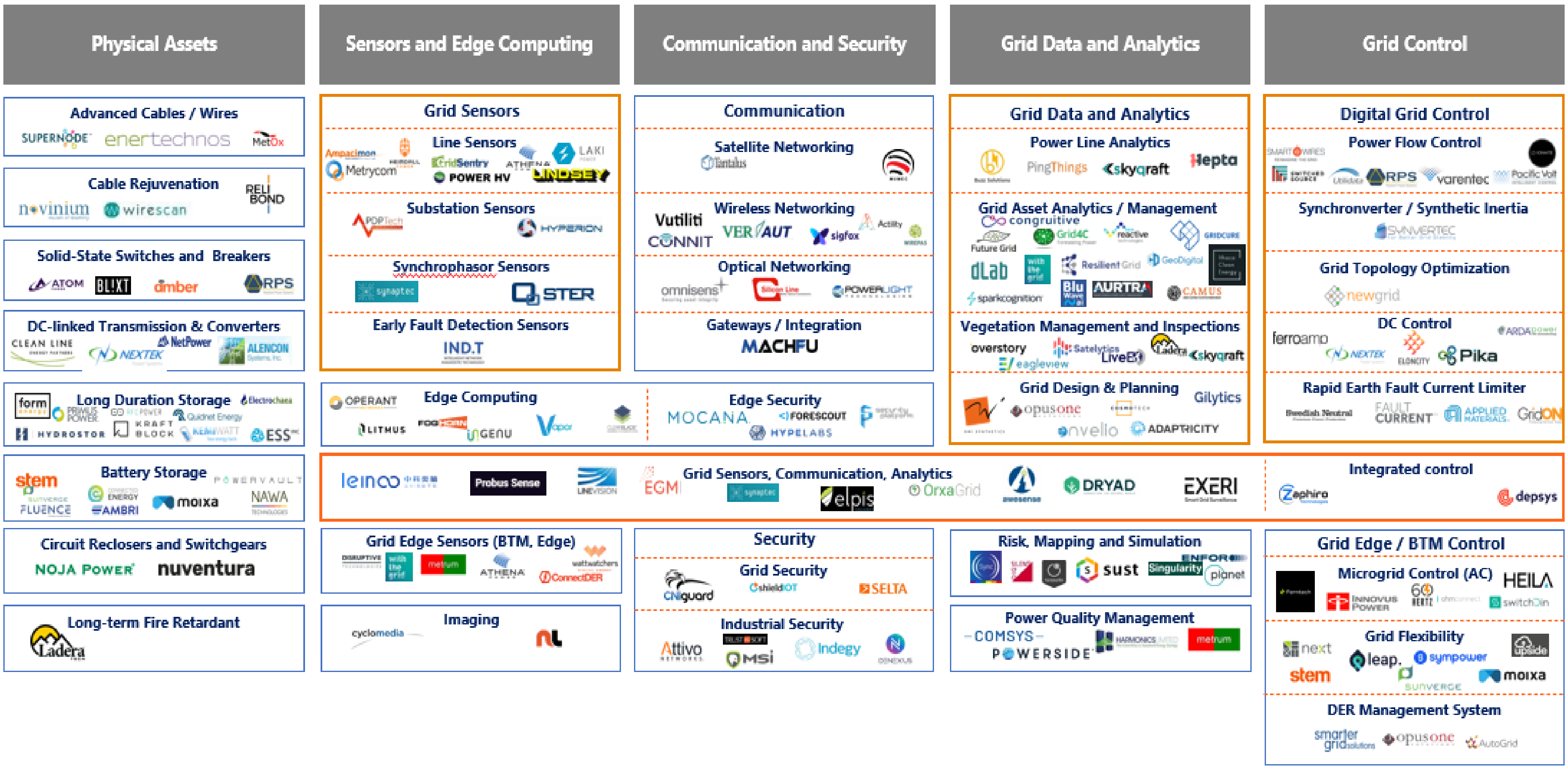
- Grid Hardening (underground cable)
- Vegetation Management and Outage Prediction
- Sensor Deployment
- Upgrade Poles and Infrastructure
- Backup/ mobile generators, Storage and Automatic Switches
- Distributed Optimization/ Control at Edge

Medium Term Proactive Control

- Damage/ outage estimation
- Transmission Network Segmentation
- Distribution Automation (Switching, Sectionalization), and Islanding
- Temporary Microgrids
- Deployment of Moving Generators
- Backup Power Support to individual critical facilities

Post Event Corrective Control

- Mobile Generators
- Restoration using sensor information, trouble call system, weather information, loads
- Distribution automation and DERs Coordination
- Microgrid with changing boundary
- Networked microgrid
- Crews and Logistics deployment



Source: Cleantech.com

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

Flood: Elevating substation, flood hardened control room

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

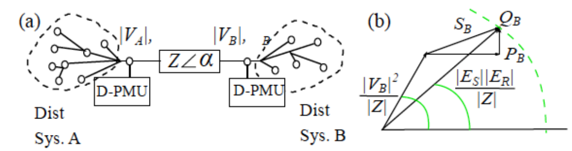
Avalanche: Deploy crew sufficiently in advance to ensure their safety

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

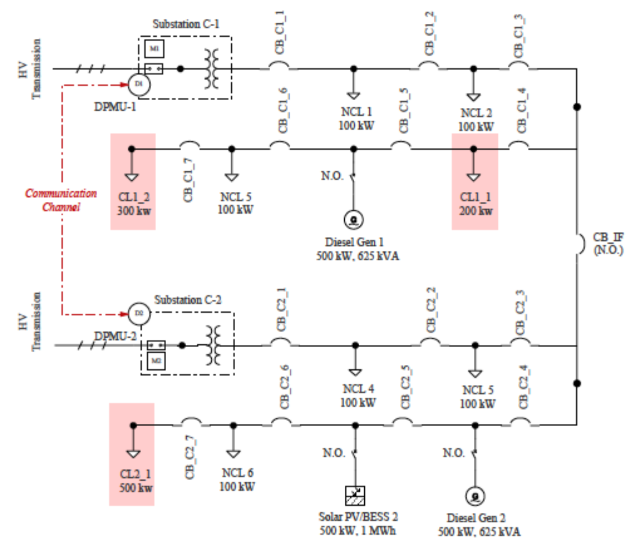
Cyber-events: Distributed approaches, reduced reliance on communication network

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



Use Case 1: Data-driven Distribution System Reconfiguration using D-PMU

- D-PMUs can help us proactive reconfiguration of the system
- Based on the measurement we can deploy pre-event reconfiguration with controlled islanding and using shift-and-shed of loads
- *Minimize impact of expected outage by pre-event shift-and-shed of loads*



Algorithms: Distribution System Reconfiguration using D-PMU

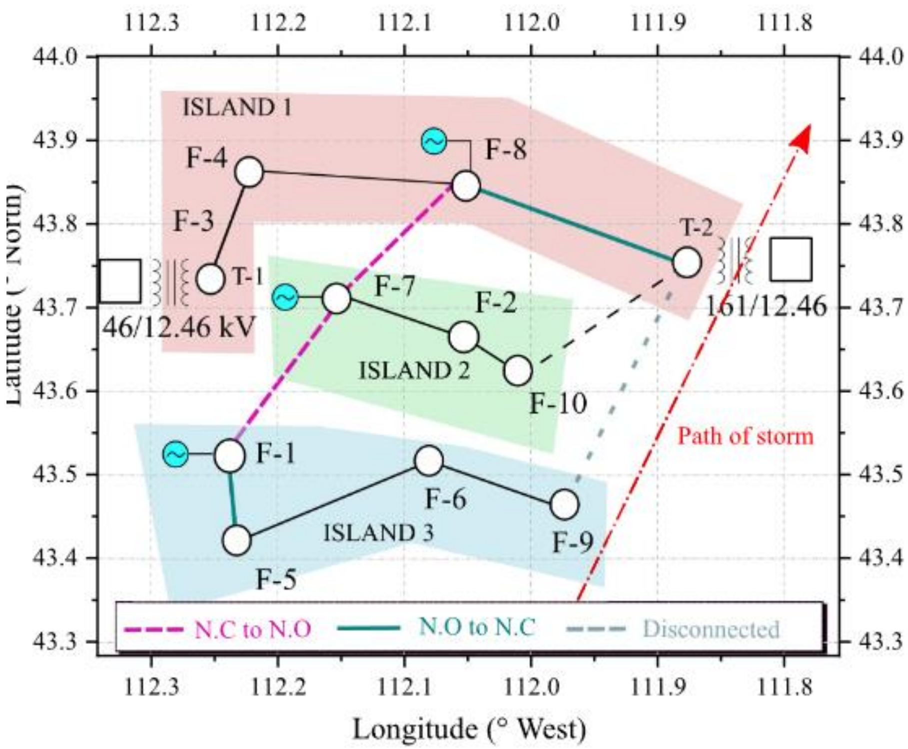
Algorithm 1: Resilient Shift-and-Shed Proactive Control Algorithm Using D-PMU Data.

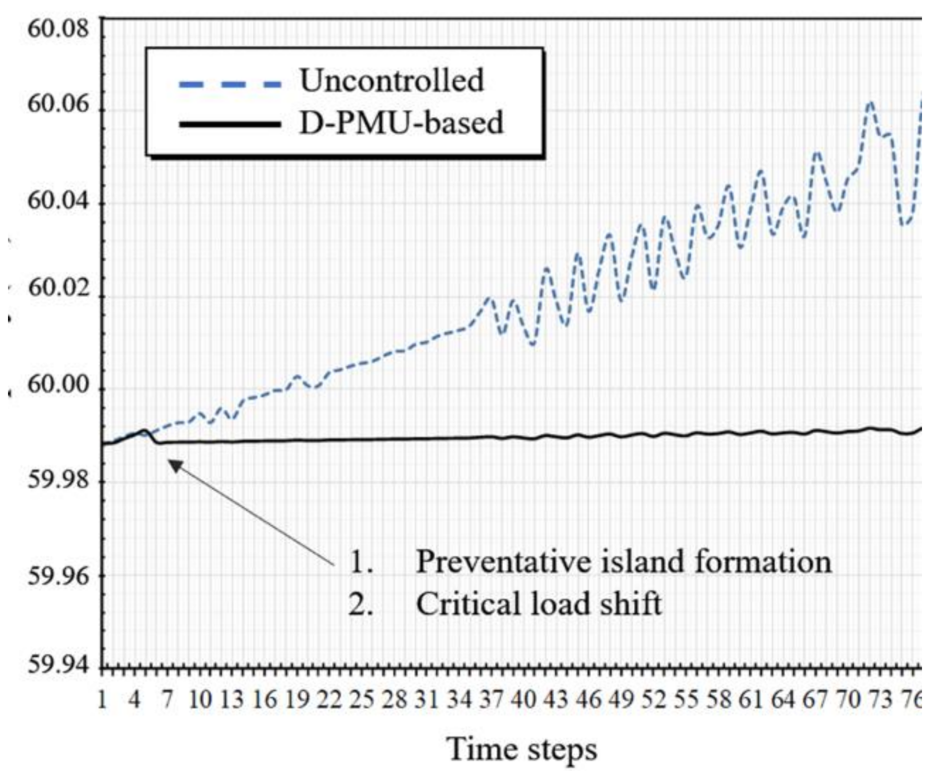
Input: $F_i = [|V_i|, \theta_i, P_i, Q_i]$, for $i = 1 \ldots n_s$, δ_{ij} (Eq. 15)
Output: Breaker status switching sequence
Phasor aggregation at DMS
1: Data filtration
2: Initialize array P_ij containing line flow data
3: **for** $i = 1$ to n_s **do**
4: Compute line flows between nodes i and j ($j \neq i$) (Eq. 13)
5: Compute $\frac{\Delta\delta_i}{\Delta t}$ (Eq. 14)
6: **if** ($\frac{\Delta\delta_i}{\Delta t} \geq \delta_{threshold}$) **then**
7: Append i to F^{risk}
8: Change CLOSED switch to OPEN at bus i
9: Change N.O. switch to CLOSED, between buses i and j
10: **if** $\delta_{ij^{new}} < \delta_{ij^{prev}}$ and $\delta_{ij^{new}} \to 0$ **then**
11: Continue
12: **else**
13: Return to Line 4
14: **end if**
15: **else**
16: Append i to F^{normal}
17: **end if**
18: **end for**
19: **return** F^{risk}, F^{normal}, δ_i, P_ij

Algorithm 2: Resiliency-Driven Reconfiguration.

Input: Feeder at risk of being islanded due to storm, f_j^{normal}, δ_{t-1}
Output: R_i, Switch-on, switch status
1: Determine load transfer required
2: Predict δ_t (Eq. 15)
3: Choose the feeder edge with lowest line-flow (from Algorithm 1)
4: Compute $\frac{\Delta\delta_i}{\Delta t}$ (Eq. 14)
5: **if** $\frac{\Delta\delta_i}{\Delta t} \leq \delta_{threshold}$ **then**
6: Compute switching sequence, available paths $(p(i,j))$ using M.S.T.
7: **if** $n(p(i,j)) > 1$ **then**
8: Determine R_i for each p
9: Sort all R_i by magnitude
10: Check for power flow convergence
11: **if** convergence is true **then**
12: **return** Switching sequence (i.e. path) that yielded highest R_i
13: **else if** convergence is false **then**
14: Choose next highest R_i path
15: Go to Line 10
16: **else**
17: Shed non-critical load
18: **end if**
19: **else**
20: Check for power flow convergence of only path p
21: **if** convergence is true **then**
22: **return** Switching sequence of path p
23: **else**
24: Shed non-critical load
25: **end if**
26: **end if**
27: **else**
28: Shed non-critical load
29: **end if**
30: Repeat iteration until all critical loads are restored

Distribution System Reconfiguration using D-PMU





Distribution System Reconfiguration using D-PMU

Resiliency Indices Comparison: Networked Microgrids

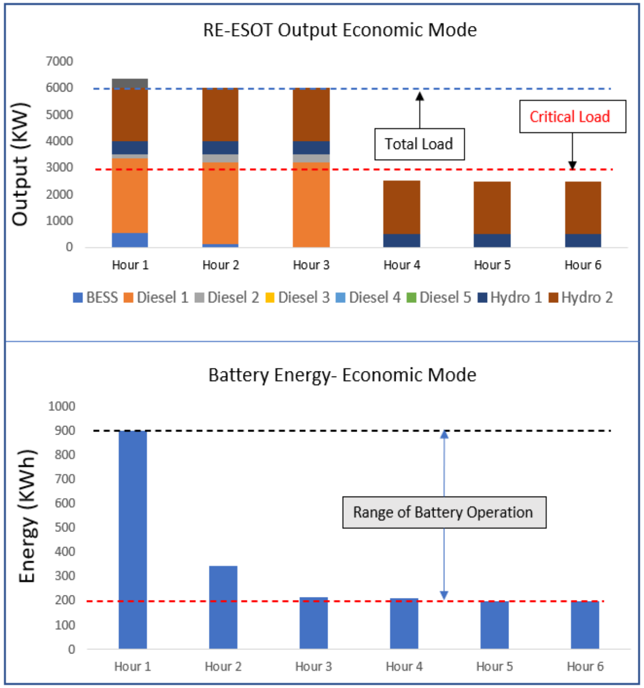
Resiliency Resource	Algorithm 1 and 2 used	Loss (kW)	Critical Load Loss (kW)	Resiliency [26]	Resiliency (AHP-based)
DG 1	No	1200	500	0.00083	0.16725
DG 1	Yes	1200	500	0.00083	0.20000
DG 2	No	1300	1000	0.00077	0.12500
DG 2	Yes	1100	500	0.00091	0.22500
DG 1, DG 2	No	1100	500	0.00091	0.27250
DG 1, DG 2	Yes	800	500	0.00125	0.32650
DG 1, DG 2, Solar	No	1100	500	0.00091	0.27250
DG 1, DG 2, Solar	Yes	400	0	0.00250	0.42125

Feeder Specific Resiliency Metrics

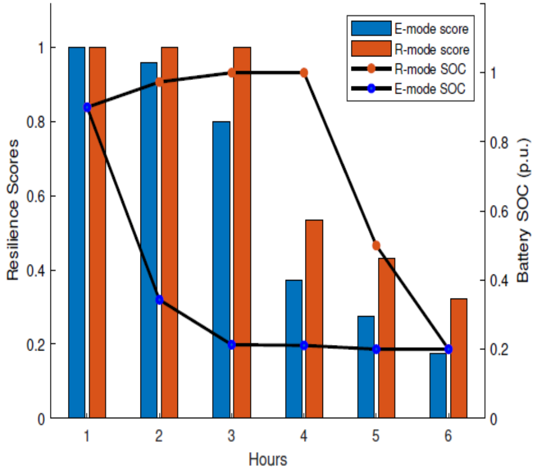
Feeder	Summer	Winter	Before Event	Without D-PMU	With D-PMU
F-1	0.78031	0.73216	0.85462	0.17819	0.58191
F-2	0.58021	0.52973	0.65232	0	0.38985
F-3	0.57223	0.56973	0.64823	0	0.26541
F-4	0.52387	0.54813	0.56648	0.19871	0.38911
F-5	0.58083	0.52364	0.60247	0	0.28192
F-6	0.46337	0.53368	0.53912	0	0.11837
F-7	0.81293	0.66107	0.72651	0.09321	0.48912
F-8	0.76938	0.68912	0.81034	0.00212	0.8103
F-9	0.64931	0.64236	0.62566	0	0.16839
F-10	0.57223	0.56981	0.64237	0	0.16892

Proactive Control for Economic and Resilient Operation with BESS

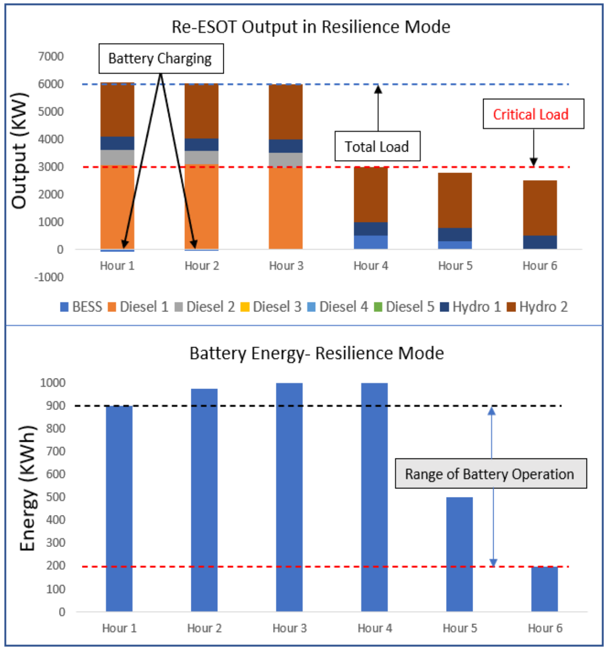
Economic mode of operation



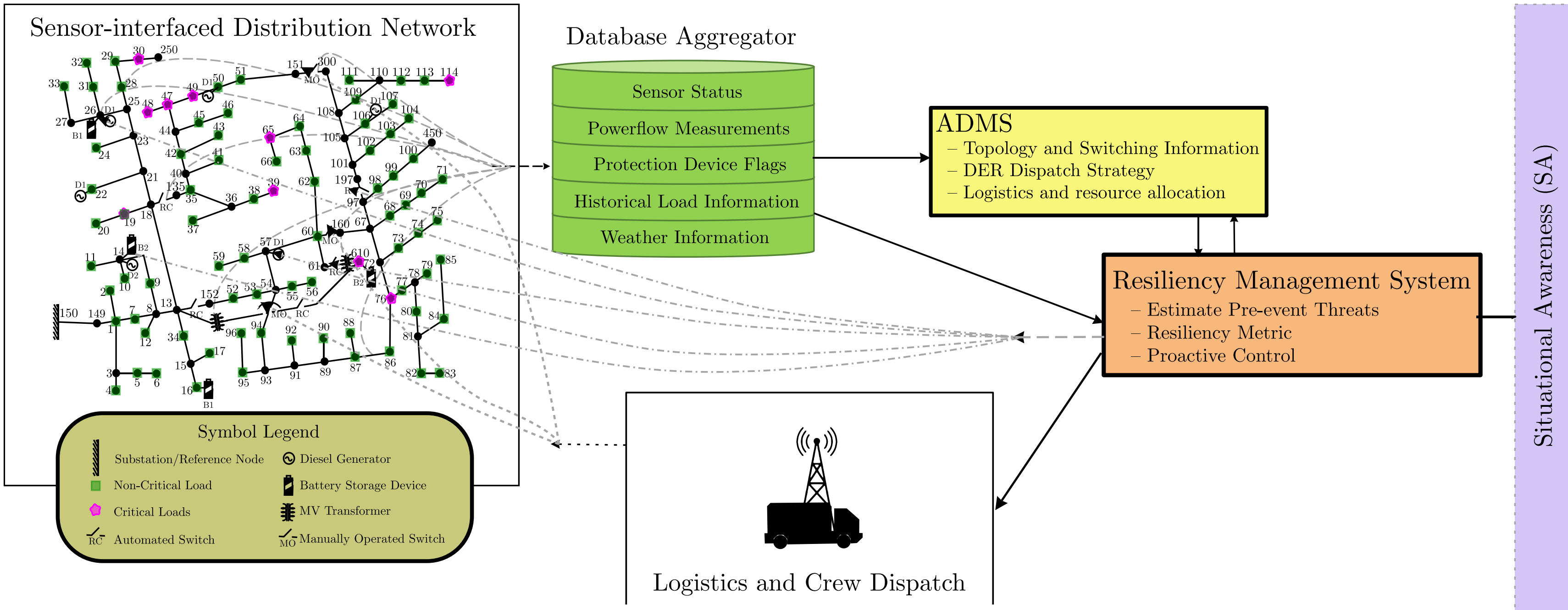
Resilience analysis of RE-ESOT operations



Resilient mode of operation



1. Pandey, Shikhar, Srivastava, Anurag K., Srivastava, Sanjeev, Mohanpurkar, Manish U., Kandaperumal, Gowtham, and Hovsapian, Rob. "Optimal Operation for Resilient and Economic Modes in an Islanded Alaskan Grid:" Preprint. IEEE PES GM 2020, Montreal, Canada August 2–6, 2020



$$\max \sum_{\forall t \in T} \sum_{\forall i \in B} k_i^{CL} \alpha_i^t (2 - \lambda_i) P_i^{CL,t} + k_i^{NCL} \beta_i^t (2 - \lambda_i) P_i^{NCL,t}$$

Use Case II: Two Stage Proactive Control

- Outage of energized lines and energized generators due to expected events will cause more impact compared to unenergized lines and generators
- *Not all* available switches available at the disposal of the operator are *remotely operable*
- When the forecast is certain, and disaster cannot be avoided, switching operations are important for resiliency improvement
- Two stage includes manually operated switch followed by automatic switches

Two Stage Proactive Control

Degenerated Radiality Constraints

$$
\begin{aligned}
&z_{i,j} \in \{0,1\}; \quad \forall i,j \in B\\
&z_{i,j} + z_{j,i} = x_{i,j} + y_{i,j}; \quad \forall i,j \in B\\
&z_{i,f} = 0; \quad \forall f \in B^F\\
&\sum_{\forall j:(i,j)\in W} z_{j,i} \le 1; \quad \forall i \in B
\end{aligned}
$$

Radiality Enforcement in a Microgrid

$$
(1 - z_{i,j})(W_i - W_j - 1) = 0; \quad \forall i,j \in B
$$

Isolation of to be Faulted Part

$$
\begin{aligned}
&\lambda_i \in \{1,2\}; \quad \forall i \in B\\
&(\lambda_i - \lambda_j)(x_{i,j} + y_{i,j}) = 0; \quad \forall (i,j) \in W\\
&\left(1 - \sum_{\forall j:(i,j)\in W} z_{j,i}\right)(2 - \lambda_i) = 0; \quad \forall i \in B \setminus B^F
\end{aligned}
$$

Healthy Subsystems including Microgrids

$$
\begin{aligned}
&\psi_{i,j} \in \{0,1\}; \quad \forall (i,j) \in W\\
&\psi_{i,j} \le z_{i,j}; \quad \forall (i,j) \in W\\
&z_{i,j}(\lambda_i + \lambda_j - 3) \le (1 - \psi_{i,j}) - \epsilon\psi_{i,j}; \quad \forall (i,j) \in W\\
&z_{i,j}(\lambda_i + \lambda_j - 3) \ge -\psi_{i,j}; \quad \forall (i,j) \in W
\end{aligned}
$$

Local generators capability limits

$$
\begin{aligned}
&\left(P_i^{DG,t}\right)^2 + \left(Q_i^{DG,t}\right)^2 \le (2-\lambda_i)\Phi_i^{DG,t}\left(S_i^{DG}\right)^2; \forall i \in B, \forall t \in T\\
&(2-\lambda_i)\Phi_i^{DG,t}\underline{P_i^{DG}} \le P_i^{DG,t} \le (2-\lambda_i)\Phi_i^{DG,t}\overline{P_i^{DG}}; \forall i \in B, \forall t \in T\\
&(2-\lambda_i)\Phi_i^{DG,t}\underline{Q_i^{DG}} \le Q_i^{DG,t} \le (2-\lambda_i)\Phi_i^{DG,t}\overline{Q_i^{DG}}; \forall i \in B, \forall t \in T
\end{aligned}
$$

Nodal Flow Balance

$$
\begin{aligned}
&P_i^t = \alpha_i^t(2-\lambda_i)P_i^{CL,t} + \beta_i^t(2-\lambda_i)P_i^{NCL,t} - \sum_{\forall DG} P_i^{DG,t} - P_i^{F,t}; \quad \forall i \in B, \forall t \in T\\
&Q_i^t = \alpha_i^t(2-\lambda_i)Q_i^{CL,t} + \beta_i^t(2-\lambda_i)Q_i^{NCL,t} - \sum_{\forall DG} Q_i^{DG,t} - Q_i^{F,t}; \quad \forall i \in B, \forall t \in T
\end{aligned}
$$

Line Flow Balance

$$
\begin{aligned}
&-S_{i,j}^L\psi_{i,j} \le p_{i,j}^t \le S_{i,j}^L\psi_{i,j}; \quad \forall (i,j) \in W, \forall t \in T\\
&-S_{i,j}^L\psi_{i,j} \le q_{i,j}^t \le S_{i,j}^L\psi_{i,j}; \quad \forall (i,j) \in W, \forall t \in T\\
&\sum_{\forall j:(i,j)\in W} p_{j,i}^t - p_{i,j}^t = P_i^t; \quad \forall i \in B, \forall t \in T\\
&\sum_{\forall j:(i,j)\in W} q_{j,i}^t - q_{i,j}^t = Q_i^t; \quad \forall i \in B, \forall t \in T\\
&\left(p_{i,j}^t\right)^2 + (q_{i,j})^2 \le \left(S_{i,j}^L\right)^2; \quad \forall (i,j) \in W, \forall t \in T
\end{aligned}
$$

Power Flow Equations and Voltage Limits

$$
\begin{aligned}
&v_i^t \le v_j^t + 2\left(r_{i,j}p_{i,j}^t + x_{i,j}q_{i,j}^t\right) + M(1-\psi_{i,j}); \forall (i,j) \in W, \forall t \in T\\
&v_i^t \ge v_j^t + 2\left(r_{i,j}p_{i,j}^t + x_{i,j}q_{i,j}^t\right) - M(1-\psi_{i,j}); \forall (i,j) \in W, \forall t \in T\\
&-M(\lambda_i - 1) + \underline{v_i} \le v_i^t \le \overline{v_i} + M(\lambda_i - 1); \forall i \in B, \forall t \in T\\
&v_i^t = v^{ref}; \quad \forall i \in B^F, \forall t \in T
\end{aligned}
$$

Two Stage Proactive Control

$$
\begin{aligned}
z_{i,j} &\geq \psi^*_{i,j}; \quad \forall (i,j) \in W \\
\lambda_i &\leq \lambda^*_i; \quad \forall i \in B \\
\alpha^t_i &= \alpha^{t,*}_i + (\lambda^*_i - 1)\hat{\alpha}^t_i; \quad \forall i \in B \\
\beta^t_i &= \beta^{t,*}_i + (\lambda^*_i - 1)\hat{\beta}^t_i; \quad \forall i \in B \\
P^{DG,t}_i &= P^{DG,t,*}_i + (\lambda^*_i - 1)\hat{P}^{DG,t}_i; \quad \forall i \in B \\
P^{BSD,t}_i &= P^{BSD,t,*}_i + (\lambda^*_i - 1)\hat{P}^{BSD,t}_i; \quad \forall i \in B \\
Q^{DG,t}_i &= Q^{DG,t,*}_i + (\lambda^*_i - 1)\hat{Q}^{DG,t}_i; \quad \forall i \in B \\
Q^{BSD,t}_i &= Q^{BSD,t,*}_i + (\lambda^*_i - 1)\hat{Q}^{BSD,t}_i; \quad \forall i \in B \\
p^t_{i,j} &= \psi^*_{i,j} p^{t,*}_{i,j} + (1 - \psi^*_{i,j})\hat{p}^t_{i,j}; \quad \forall (i,j) \in W, \forall t \in T \\
q^t_{i,j} &= \psi^*_{i,j} q^{t,*}_{i,j} + (1 - \psi^*_{i,j})\hat{q}^t_{i,j}; \quad \forall (i,j) \in W, \forall t \in T
\end{aligned}
$$

Limit operation and set point generation for healthy part

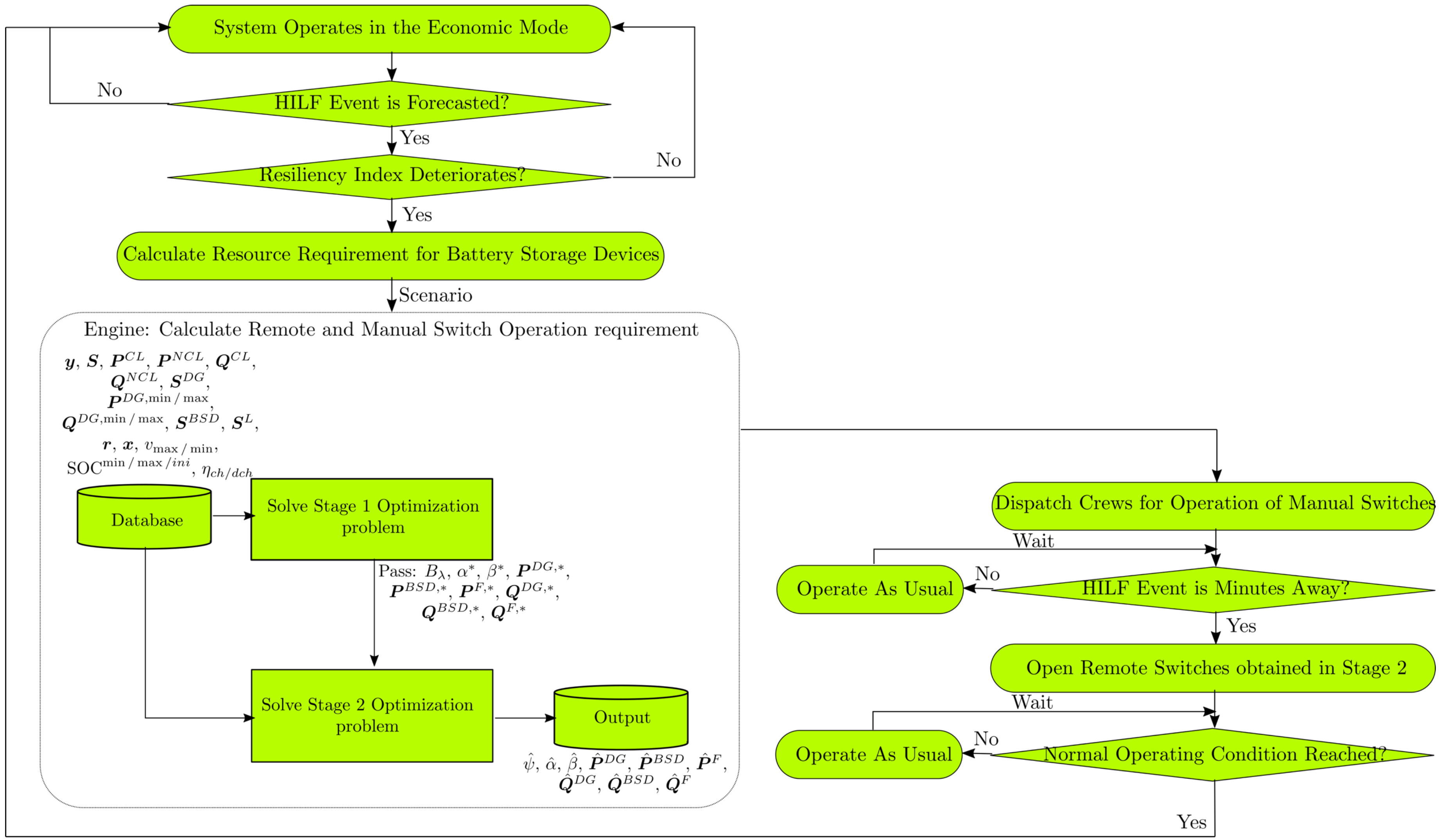
$$
\begin{aligned}
z_{i,j} + z_{j,i} &= \hat{x}_{i,j} + \hat{y}_{i,j}; \quad \forall i,j \in B \\
(\lambda_i - \lambda_j)\,(\hat{x}_{i,j} + \hat{y}_{i,j}) &= 0; \quad \forall (i,j) \in W
\end{aligned}
$$

Limit switching operations

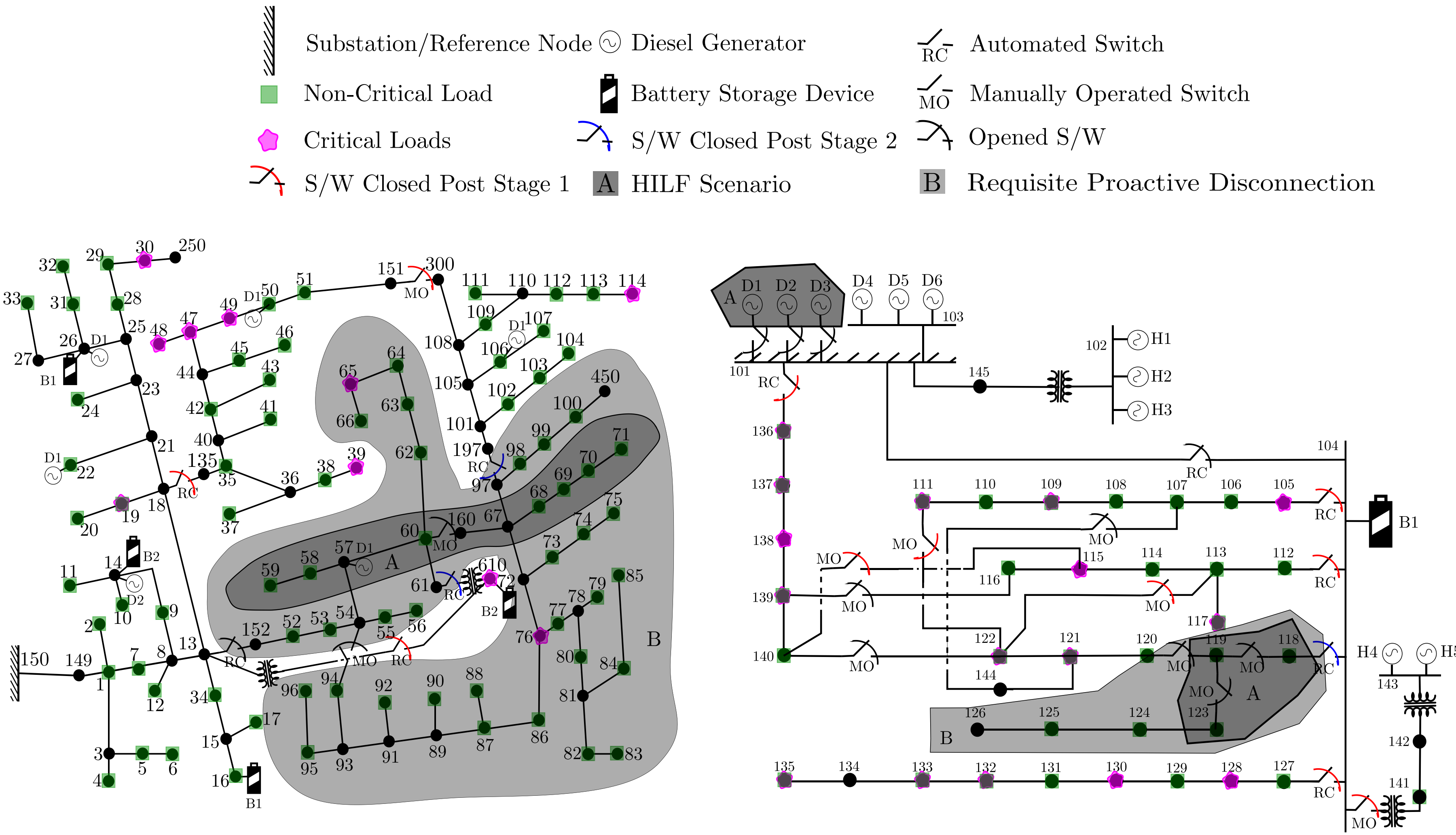
+

Constraints of Stage 1

Two Stage Proactive Control Algorithm

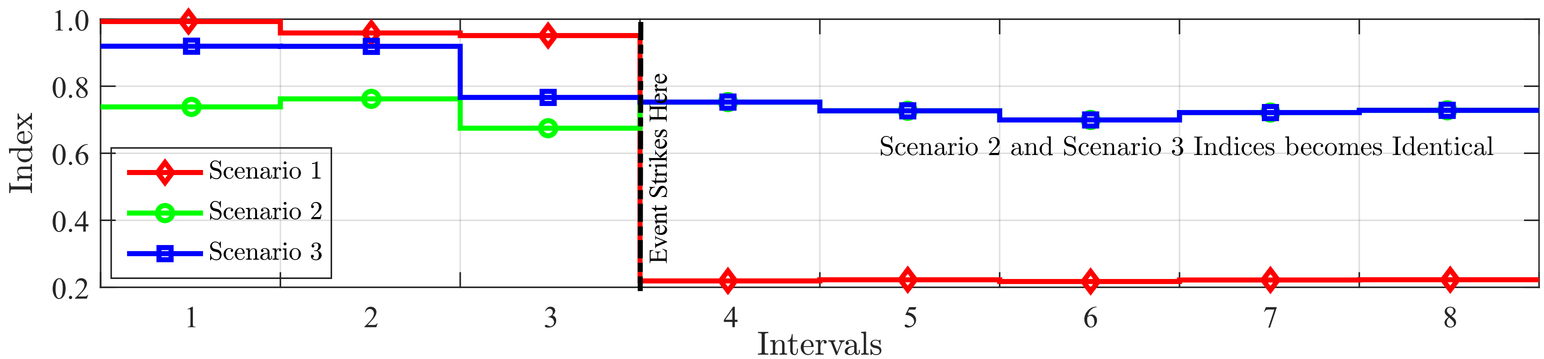


Two Stage Proactive Control: IEEE 123-Bus and 45-node CEC System

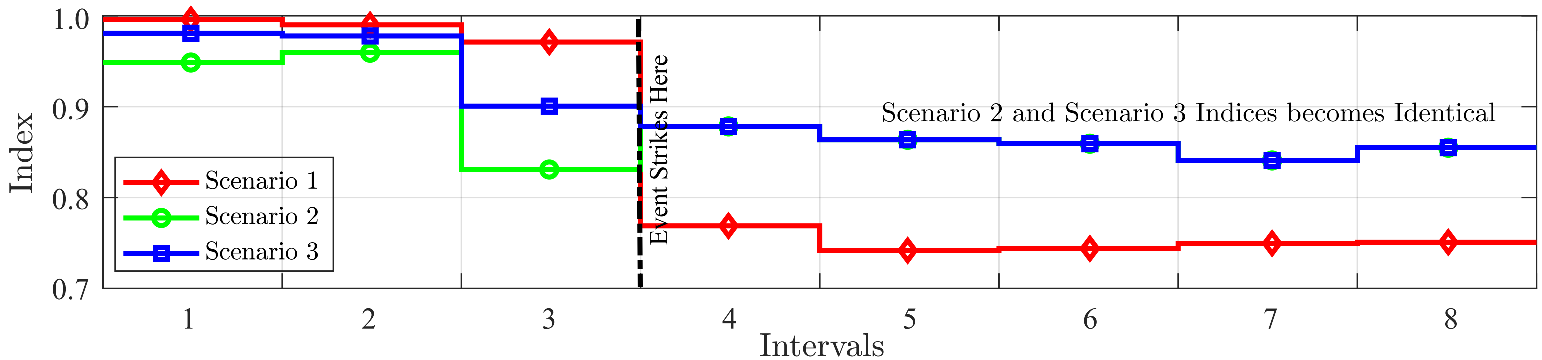


Solution with IEEE 123-bus System

Solution with CEC System



(a) Resiliency Indices for Modified IEEE 123-Node System



(b) Resiliency Indices for Isolated 45-Node System

Two-Stage Proactive Control: Results

- Scenario 1: Disaster strikes upon the network without prior preparation
- Scenario 2: Network is proactively reconfigured, but, to be outaged part removed apriori
- Scenario 3: Outaged part is operated through remote switches, only minutes before

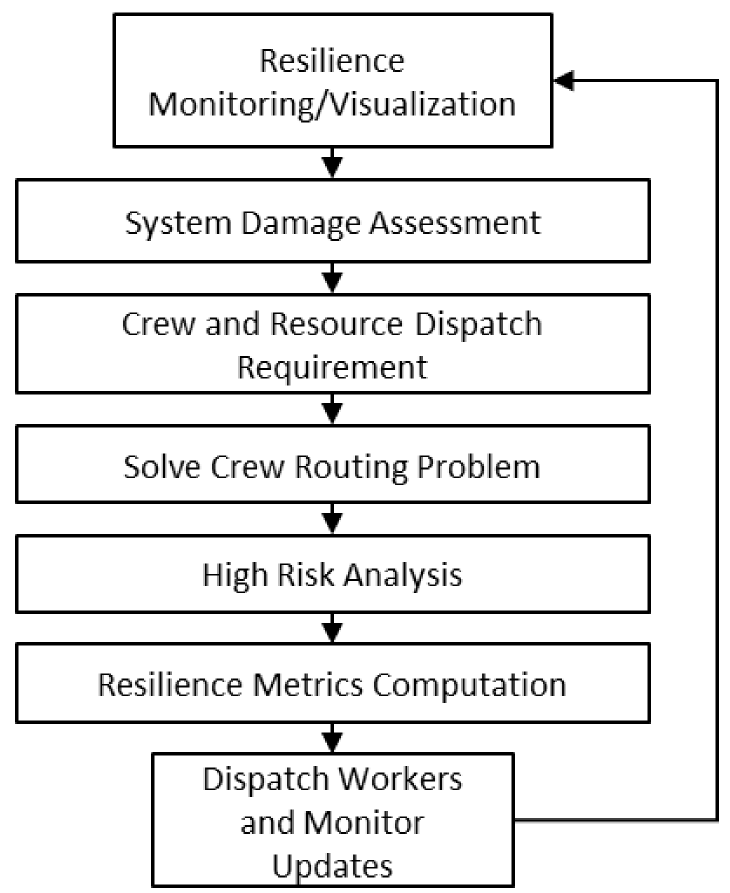
USE CASE III: CREW SAFETY DURING SYSTEM RESTORATION EFFORTS


Image source: OSHA

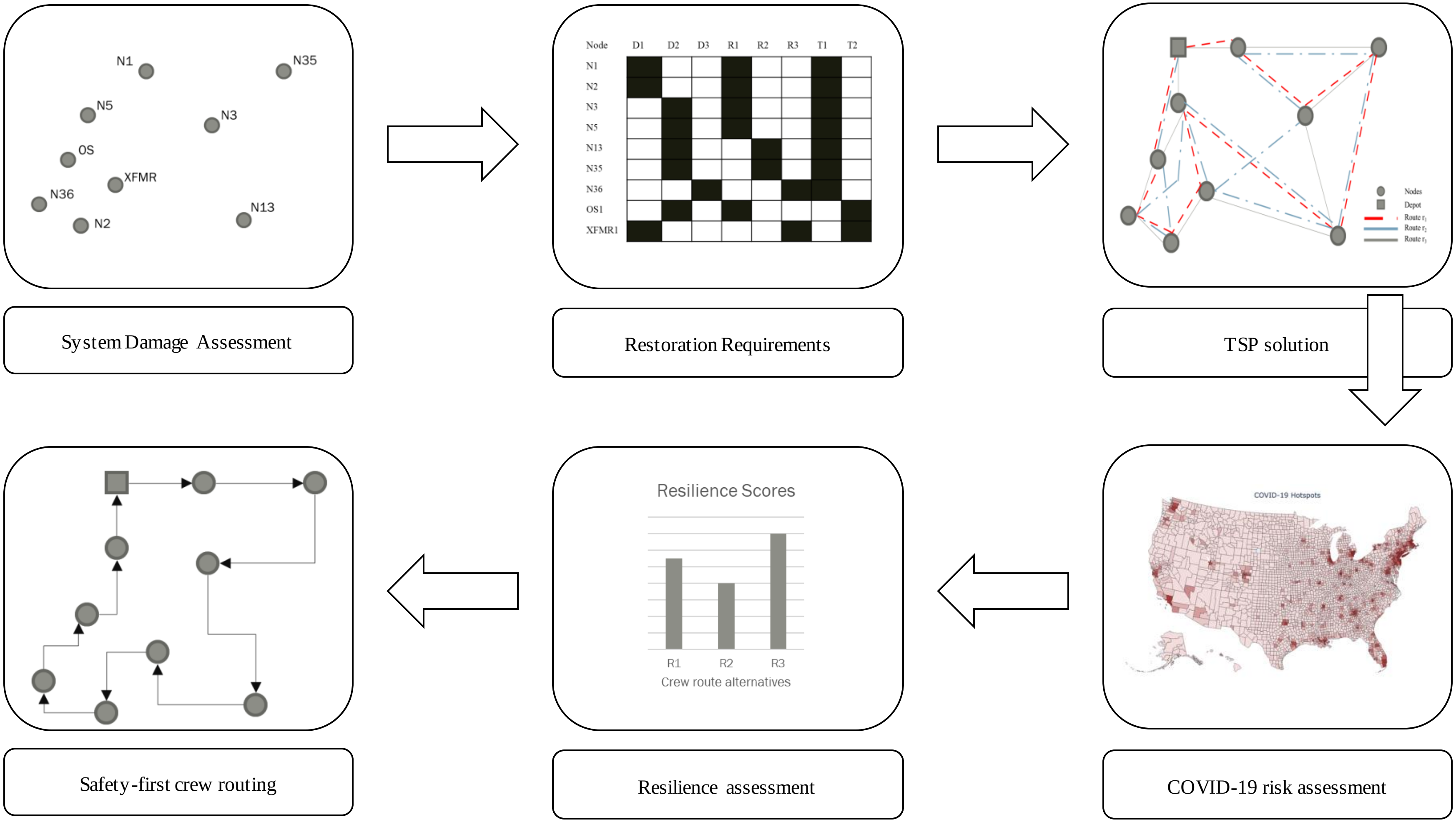
COVID-19 hotspots present safety concerns to utility workers

SAFETY FIRST CREW ROUTING ALGORITHM

- System assessment provides restoration requirements
- Crew Routing – Solves for shortest round trip based on restoration requirements, distance and proximity to covid-19 hotspots
- Solutions are subject to resiliency analysis for best solution

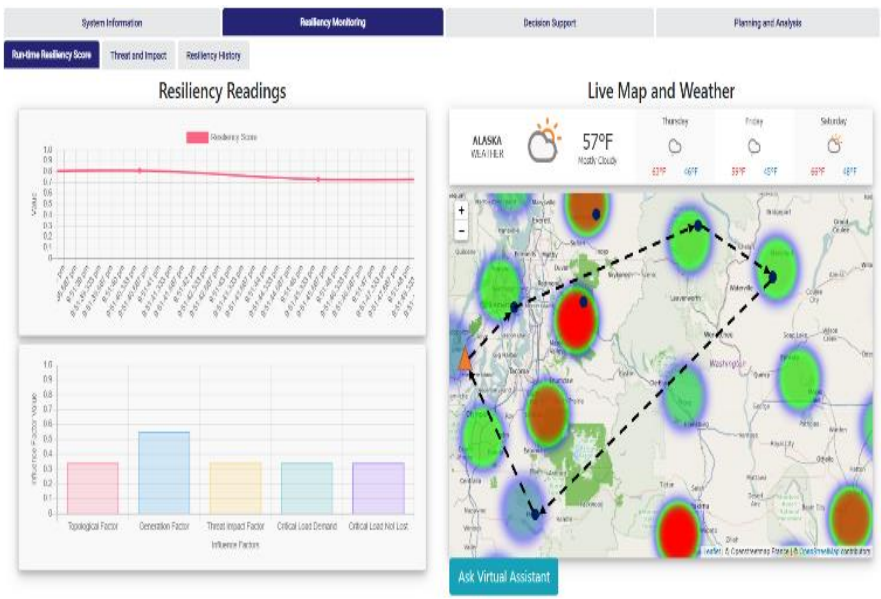


SAFETY FIRST CREW ROUTING ALGORITHM

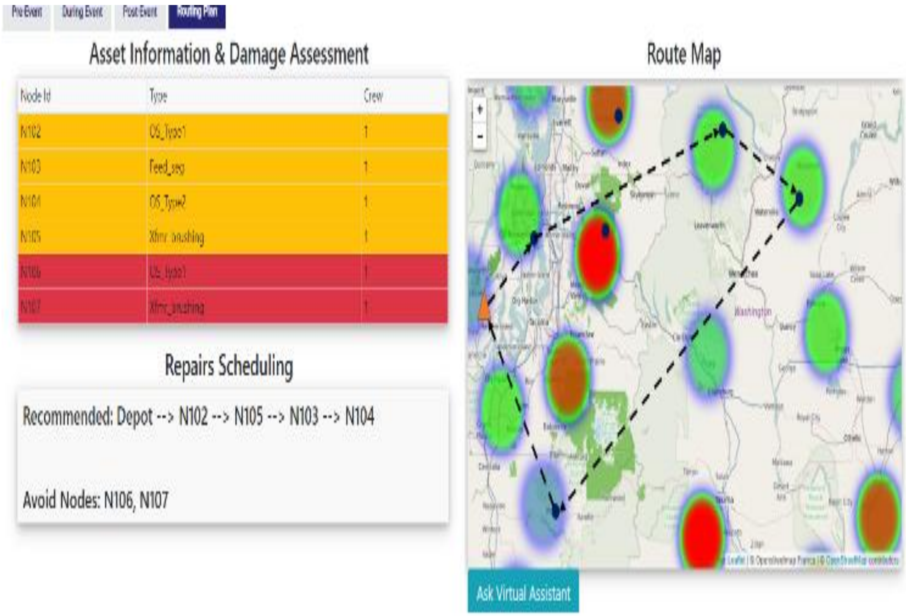


SAFETY FIRST CREW ROUTING ALGORITHM: RESULTS

- Screen capture of RT-RMS showing the live resilience metrics computation along with the live map showing asset status and COVID-19 zones

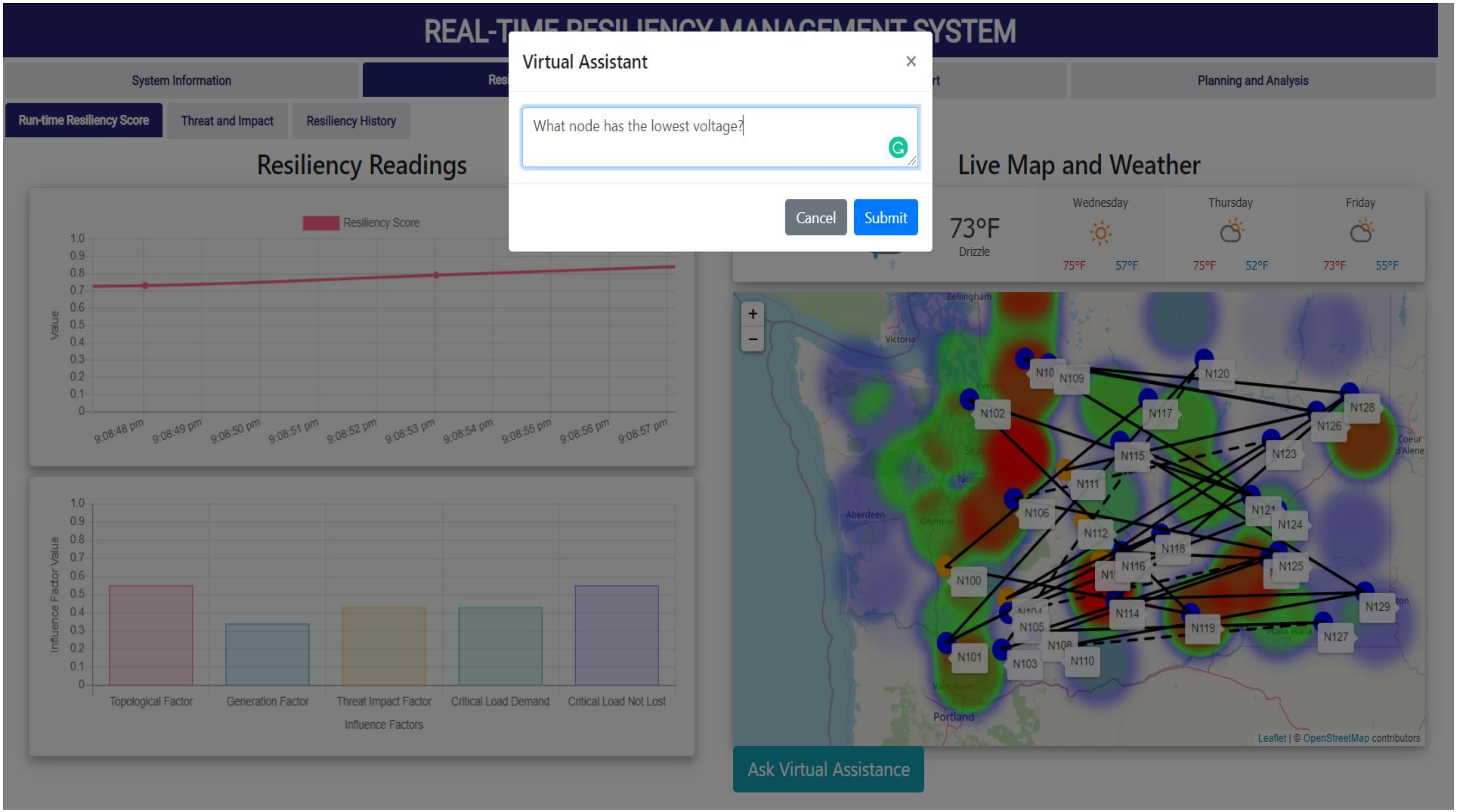


- Screen capture of RT-RMS showing the asset information with repair instructions, scheduling with no-go zones, and the routing on the map with safety first algorithm

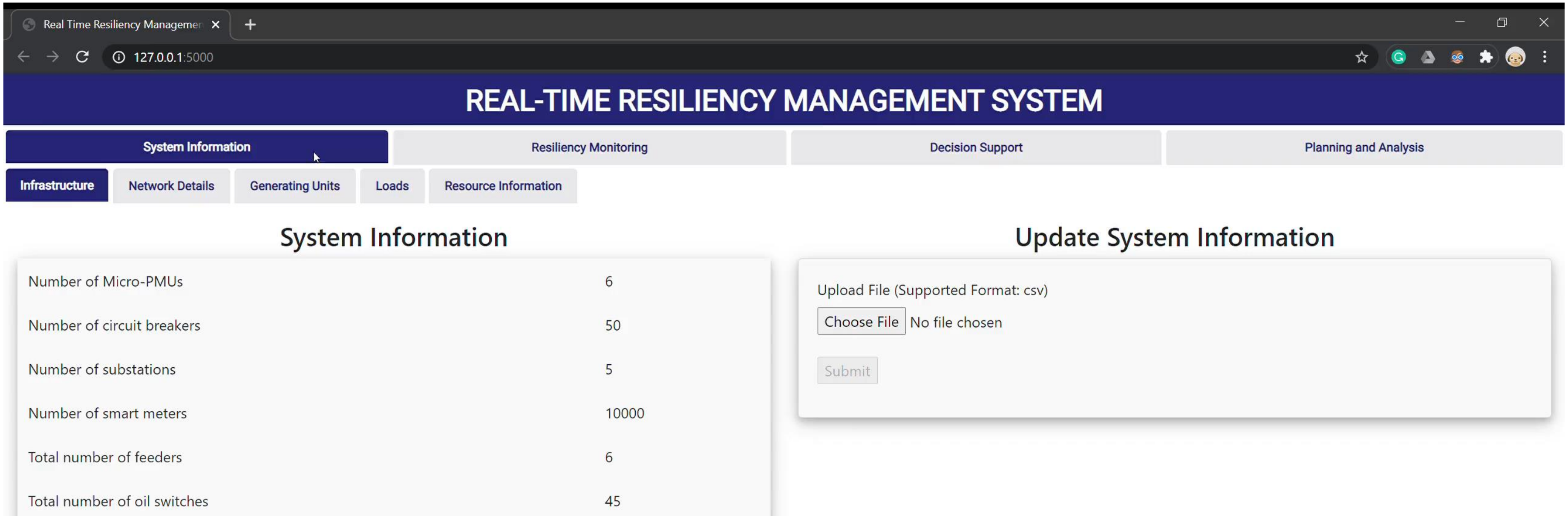


COVID-19 data for Washington State is obtained from John Hopkins Coronavirus dataset

RT-RMS: Virtual Assistant



RT-RMS Tool Video Tour



Summary

Resiliency is the ability of the system to supply critical loads

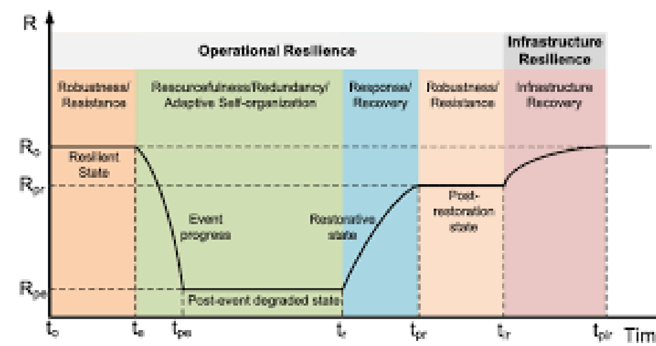
Resiliency depends on system characteristics, including network, resources, and control

Resiliency is improved through coordinated planning, proactive and corrective control

Specific threat and operating scenarios need to be considered to decide the best possible measure

Proactive optimal control problem need to be suitably linearized to improve computational tractability

Coordinated operation of manual switches and repairs ensures safety of operational crews



Thank You

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