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Resilience Webinar 1: Basics of power system resilience, its evaluation and applications

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U.S. DEPARTMENT OF ENERGY BATTELLE

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U.S. Department of State
Bureau of Energy Resources
Power Sector Program

Project background

- The U.S. Department of State, Bureau of Energy Resources, Power Sector Program (PSP), provides technical and regulatory support to the Central American regional electricity market.
- Under the PSP, Pacific Northwest National Laboratory delivers technical and analytic support to Ente Operador Regional (EOR, the Central American regional system operator).

Resilience Webinar 1 – May 12th
List of Presentations and Topics Covered

1. Introduction
   - Threat Landscape for Central America and some specific events → Motivation
   - Power System Resilience Definition and Conceptual Understanding → Resilience is broader than Reliability
   - Comparison of metrics used to evaluate/standardize reliability and resilience

2. Causes and Modeling of Grid Failure Using Earthquake Analysis Case-Study
   - What? – Performance Based Earthquake Engineering (PBEE) Method
   - How? – Detailed modeling of the 4 steps of PBEE method
   - Why? – Understanding the consequences on multiple fronts

3. Control system resilience
   - Control center
   - RAS and Protection
   - Communications

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Why is resilience important in Central America?

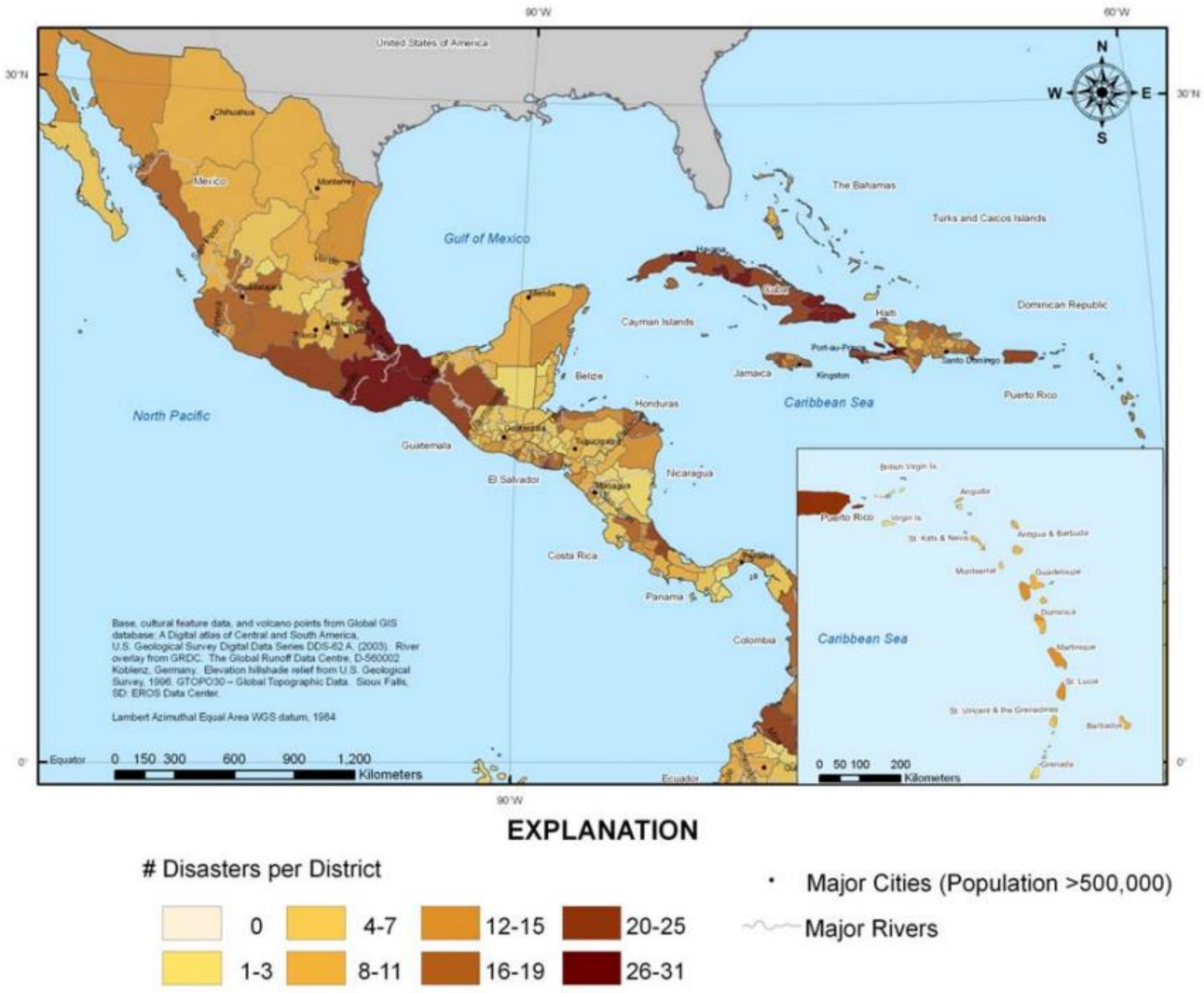

Figure 10. Natural disaster occurrences in Central America and the Caribbean by first administrative level boundary, 1900–2007.

Source: USGS, Mapping Vulnerability to Disasters in Latin America and the Caribbean, 1900–2007
https://pubs.usgs.gov/of/2008/1294/ofr2008-1294.pdf

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CATEGORY 5 HURRICANES PATHS*

	FELIX	IRMA	MARIA	DORIAN**
Disaster Subtype	Hurricane	Hurricane	Hurricane	Hurricane
Date	August 31 - September 5, 2007	August 30 - September 12, 2017	September 16 – 30, 2017	August 24 - September 10, 2019
Areas Affected	El Salvador, Guatemala, Honduras, Mexico, Nicaragua	Anguilla, Antigua and Barbuda, Bahamas (The), Barbados, Cuba, Dominican Republic (The), Haiti, Puerto Rico, Saint Barthélemy, Saint Kitts and Nevis, Saint Martin (French Part), Sint Maarten (Dutch Part), Turks and Caicos Islands (The), Virgin Island (British), Virgin Island (U.S.)	Dominica, Dominican Republic (The), Guadeloupe, Haiti, Martinique, Puerto Rico, Virgin Island (British), Virgin Island (U.S.)	Lesser Antilles, Puerto Rico, The Bahamas
Wind Speed	170 mph (274 km/h)	180 mph (290 km/h)	170 mph (274 km/h)	220 mph (354 km/h)
Deaths	189	47	143	67
People Affected	245K	10M	927K	29.5K

Ref. – Source – OCHA United Nations.
https://reliefweb.int/report/world/natural-disasters-latin-america-and-caribbean-2000-2019

Latin America and the Caribbean (LAC)

is the **second most disaster-prone region in the world**

152 million

affected by **1,205 disasters** (2000-2019)*

548 FLOODS

- Floods are the most common disaster in the region.
- Brazil ranks among the **top 15 countries in the world with the greatest population exposed to river flood risk.**
- On 12 occasions since 2000, floods in the region have caused more than **US$1 billion dollars** in total damages.

330 STORMS

- An average of **17 hurricanes per year and 14 Category 5 hurricanes** (2000-2019).
- The 2017 hurricane season is the **third worst on record** in terms of number of disasters and countries affected as well as the magnitude of damage.
- In 2019, Hurricane Dorian became the **strongest Atlantic hurricane** on record to directly impact a landmass.

75 EARTHQUAKES

- 25 per cent of earthquakes magnitude 8.0 or higher **have occurred in South America**
- Since 2000, there have been **20 magnitude-7.0 or greater earthquakes** in the region
- The 2010 Haiti earthquake ranks among the top **10 deadliest earthquakes in human history.**

74 DROUGHTS

- Drought is the disaster which affects the highest number of people in the region.
- Crop yield reductions of 50-75 per cent in central and eastern Guatemala, southern Honduras, eastern El Salvador and parts of Nicaragua.
- In these countries (known as the Dry Corridor), **8 out of 10 households** in the communities most affected by drought resort to crisis coping mechanisms.

66 LANDSLIDES

50 EXTREME TEMPERATURE

38 VOLCANIC EVENTS

24 WILDFIRES

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Central American Threat Landscape (1900-1988)

Code for disasters: VO – volcano, EQ – earthquake, LS – landslide, FL – flood, DR – drought, HU – hurricane, nd – no data.

Country (year records started)	Events	People killed	People affected	Damage U.S. $1000
MIDDLE AMERICA				
Antigua (1950)				
DR	1	nd	75 000	nd
HU	3	4	nd	1 000
Barbados (1955)				
HU	1	57	nd	nd
FL	1	3	200	500
Belize (1931)				
FL	1	nd	17 000	nd
HU	5	1 796	76 000	82 500
Costa Rica (1963)				
VO	4	104	87 391	5 000
EQ	2	22	4 038	200
LS	1	1	5 000	nd
FL	5	41	25 330	34 000
DR	1	nd	nd	nd
Cuba (1926)				
EQ	1	1	nd	nd
FL	2	22	18 000	60 000
HU	10	4 392	737 891	621 000
Dominica (1963)				
HU	3	42	80 000	49 250
Dominician Republic (1930)				
FL	2	52	151 000	nd
DR	1	nd	240 000	5 000
HU	5	3 884	1 213 000	279 700
El Salvador (1951)				
EQ	4	2 245	620 582	1 065 000
FL	1	500	50 000	280 000
HU	1	2	4 600	1 600
Guadeloupe (1928)				
VO	1	nd	75 000	nd
HU	4	39	20 000	70 000
Guatemala (1902)				
VO	3	1 000	6 500	nd
EQ	3	23 000	3 764 000	1 000 000
FL	3	709	27 500	2 500
DR	1	nd	73 000	nd
HU	1	269	10 200	15 000
Guyana (1964)				
FL	1	nd	21 000	200
Haiti (1909)				
EQ	1	6	nd	20 000
FL	6	739	178 000	959
DR	4	nd	1 270 217	1 000
HU	7	10 198	728 110	250 000

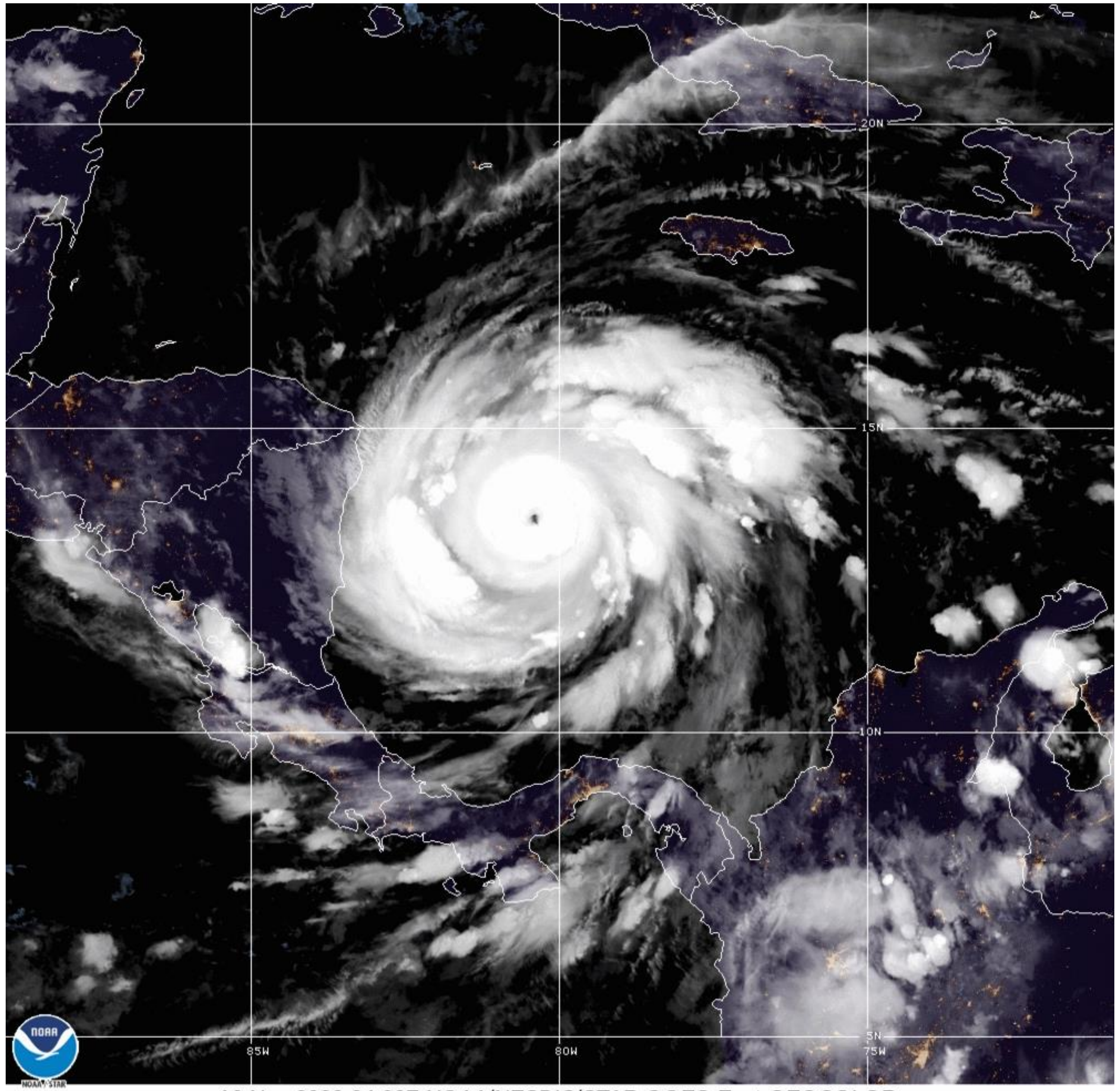
Code for disasters: VO – volcano, EQ – earthquake, LS – landslide, FL – flood, DR – drought, HU – hurricane, nd – no data.

Country (year records started)	Events	People killed	People affected	Damage U.S. $1000
Honduras (1965)				
FL	4	131	96 000	114 500
DR	2	nd	400 000	7 000
HU	3	8 000	610 000	560 000
Jamaica (1903)				
EQ	1	1 200	90 000	nd
FL	7	440	240 000	76 000
DR	1	nd	100 000	500
HU	10	537	50 000	138 725
Martinique (1902)				
VO	1	29 000	nd	nd
HU	5	70	26 000	71 000
Mexico (1909)				
VO	2	100	28 000	nd
EQ	12	9 617	117 500	4 033 000
LS	2	68	nd	nd
FL	14	2 373	450 345	132 800
HU	12	3 336	626 000	378 000
DR	1	nd	nd	nd
Nicaragua (1931)				
VO	1	nd	3 000	2 000
EQ	3	11 000	402 000	847 000
FL	5	87	131 300	357 500
HU	1	35	2 800	380
Panama (1964)				
FL	8	97	56 245	91 400
St Lucia (1960)				
HU	3	19	70 000	91 455
St Vincent (1902)				
VO	3	1 567	22 000	nd
FL	1	nd	142	nd
HU	3	122	20 000	21 600

Ref. – 1) Stillwell, H. Daniel. "Natural hazards and disasters in Latin America." Natural Hazards 6, no. 2 (1992): 131-159.

Hurricanes Iota and Eta

- Hurricanes Eta (category 4) and Iota (category 5) caused floods, landfall, infrastructure loses, etc. 25 km apart and 2 weeks apart(*)
- Iota
  - 160,233 homes without power in Nicaragua(**)
  - 357,000 homes without power in Honduras, with 80,000 homes with longer recovery times due to flooding(***)
  - Flooding affected substations in Honduras
  - Land slide in Panama affected two important 230 kV transmission lines



16 Nov 2020 04:00Z NOAA/NESDIS/STAR GOES-East GEOCOLOR

Source: NOAA

(*) NOAA, https://www.nhc.noaa.gov/archive/2020/al31/al312020.update.11170347.shtml
(**) ENATREL, https://www.enatrel.gob.ni/sector-electrico-brinda-informacion-sobre-afectaciones-del-huracan-iota/
(***) La Tribuna, https://www.latribuna.hn/2020/11/18/iota-desconecto-el-servicio-electrico-a-357-mil-hogares/

Preventive Actions Taken Before Hurricane Eta/Iota

- In Honduras, controlled water discharge in *El Cajon* hydro power plant to prepare the reservoir for arrival of hurricane Iota.

- OS/OMs in the EOR region prepared the transmission system operation to withstand the extreme weather conditions:
  - Limiting the power transfer between Costa Rica and Nicaragua.
  - Increasing AGC margins according to foreseen required needs.
  - Re-schedule programed maintenance.
    - ✓ Near 52 suspended and reprogrammed maintenances in the EOR region.
    - ✓ 21 of them occurring during the week Nov 16th – 22nd were re-scheduled.
    - ✓ Most of them re-programmed in the following weeks. Panama and Honduras took months.

Hydroelectric Francisco Morazán – El Cajon.

- Comayagua River (*Sulaco, Humuya, and Yure affluents*)
- 5,700,000,000 m^3
- Interannual regulation

https://www.youtube.com/watch?v=x6lEzbRxcJU&ab_channel=jeovanycastro
https://www.youtube.com/watch?v=V-SGwwTMBGI&ab_channel=Teleceiba

- Operational alert status declared:
  - ✓ From Sunday Nov 3rd, 10:00 hrs. (Eta) – Released Thu Nov 6th, 17:00 hrs.
  - ✓ From Sunday Nov 15th, 17:00 hrs. (Iota) – Released Thu Nov 19th, 9:00 hrs.

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Consequences and Recovery Actions

Eta affected towers of the line 230-20A Guasquitas – Cañazas from ETESA – Panamá. Towers 8, 25, 36, 37, 46, 75, 82 and 136. Maintenance required.

- Most of the events occurred at distribution system (DS) level.
  - DS lines tripped and some of them were opened by the DSO to avoid problems.

- Additional problems due to landslides affecting 230 kV transmission lines in Panama.

- https://twitter.com/Etesatransmite/status/1325128986960289793/photo/1
- https://ensegundos.com.pa/2020/11/15/etesa-aclara-situacion-sobre-torre-de-alta-tension-afectada-por-lluvias/

Consequences and Recovery Actions

- Floods in industrial region San Pedro Sula – Honduras due to continuous storms and rivers overflowing in the north region.
  - Substation floods in SPS substation.
  - One transmission line out of service.
  - Eight still energized during substation flood.

https://youtu.be/QX2J4dzQNPQ

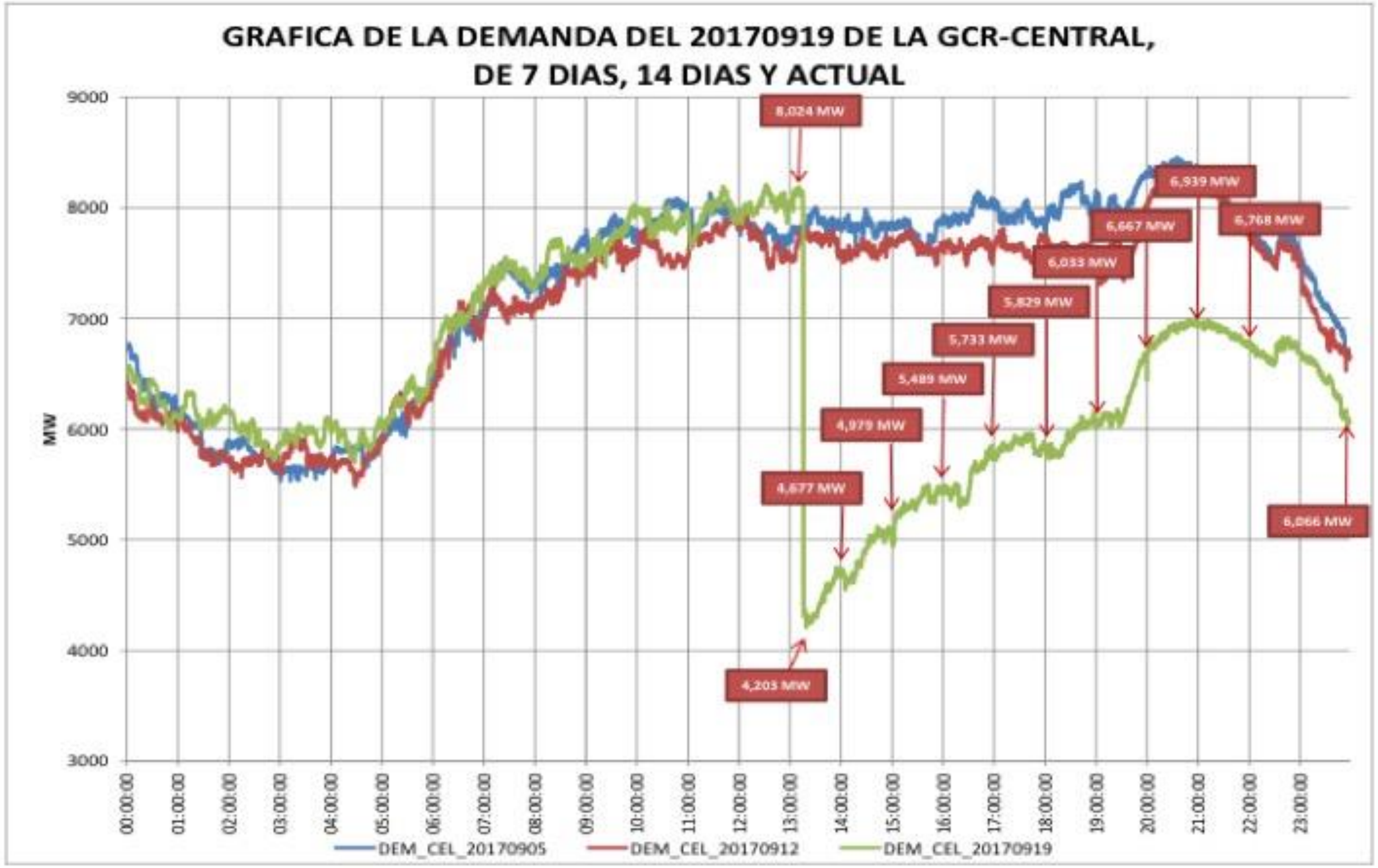
https://tiempo.hn/subestacion-electrica-eta-inundada-en-sps/

	Affected population	Relocated population	Population in Shelters	Observations
Eta	~3 mill	~180 thousand	~86 thousand	~19k houses affected. 13 and 19 bridges destroyed/affected. ~360k houses with no electricity service.
Iota	~0.7 mill	~185 thousand	~87 thousand	

Data from: *"Organización Panamericana de la Salud OPS – Huracanes Eta e Iota". Reporte 19, Nov 21, 2020.*
https://www.paho.org/es/respuesta-huracanes-eta-iota

2017 Earthquake in Mexico

- 7.1 magnitude earthquake occurred at 1:14pm on September 19th, 2017; with epicenter about 55 km south of Puebla
- Approximately 10,000 MW affected load (*)
- Infrastructure out of service (*)
  - Generation: 19 generating units for 1,185 MW
  - Transmission: 17 substations; 79 transmission lines (400, 230, 115, and 85 kV); 3 static var compensators; 64 transformers
  - Distribution: 634 distribution circuits
- Almost all load recovered by next day at 5pm (**)



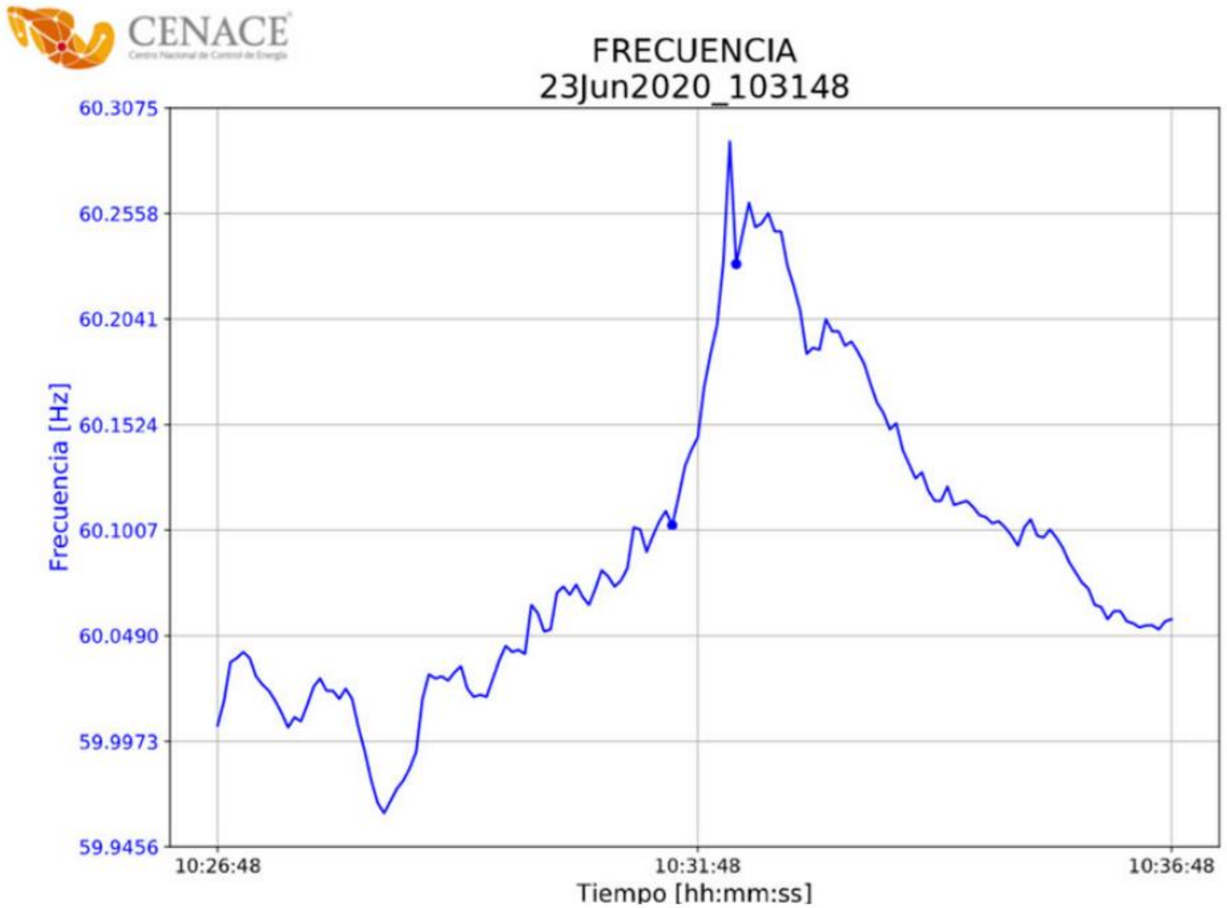
Load in one of affected areas compared with two previous days

(*) Reliability report 2016-2017: https://www.gob.mx/cms/uploads/attachment/file/317909/Reporte_de_confiabilidad_de_Electricidad_.pdf

Figure extracted from: (**) Gobierno de México: https://www.gob.mx/cenace/prensa/informacion-sobre-los-efectos-en-el-sistema-electrico-nacional-causados-por-el-sismo-de-7-1-grados-richter-en-el-centro-del-pais?idiom=es

2020 Oaxaca, Mexico earthquake

- June 23, 2020, at 10:29, 7.4 magnitude earthquake, 12 km southeast of Crucecita, Oaxaca
- Infrastructure out of service
  - Load lost 2,269 MW
  - Generation outage 412 MW
  - Frequency increased from 60.01 to 60.29 Hz
  - 1 substation
  - 16 transmission lines (230 and 115 kV)
  - 6 transformers
- No permanent damage

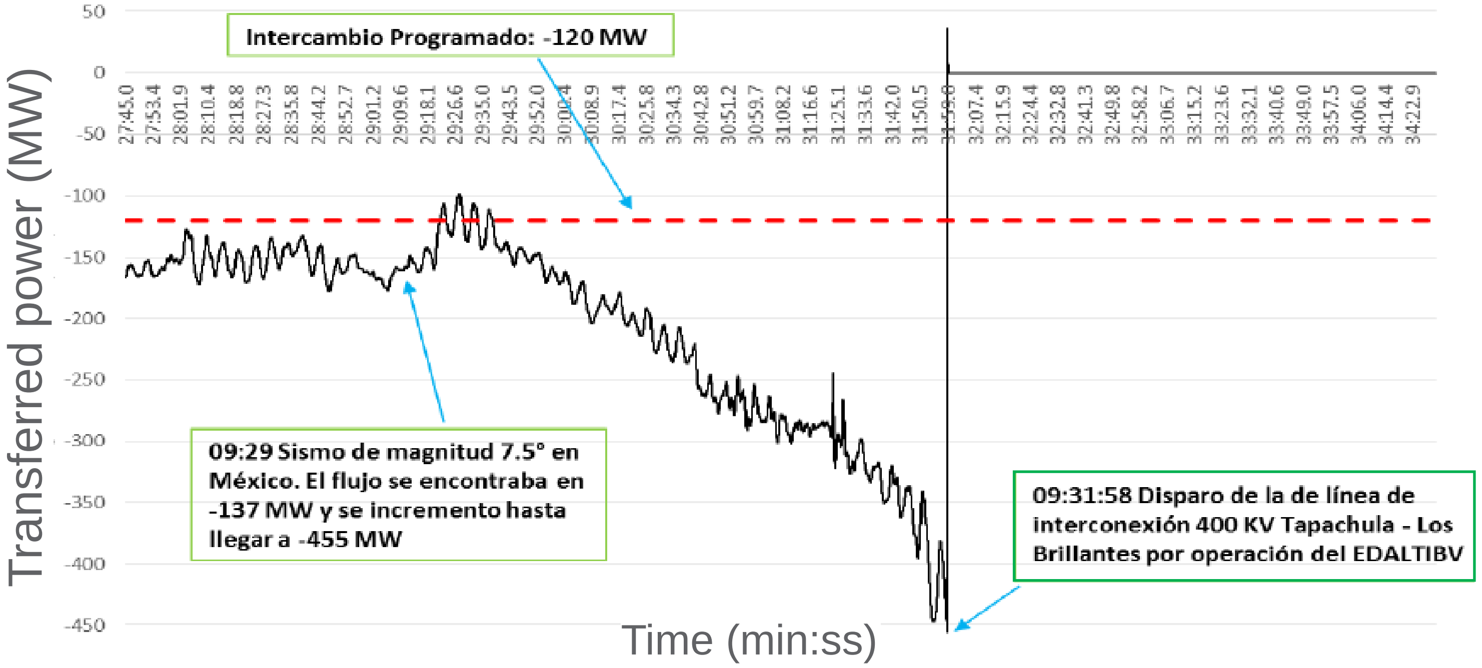


https://www.cenace.gob.mx/Docs/Transparencia/InformesGestion/12-Informe%20de%20Autoevaluaci%C3%B3n%20de%20la%20Gesti%C3%B3n%20Primer%20Semestre%20de%202020.pdf

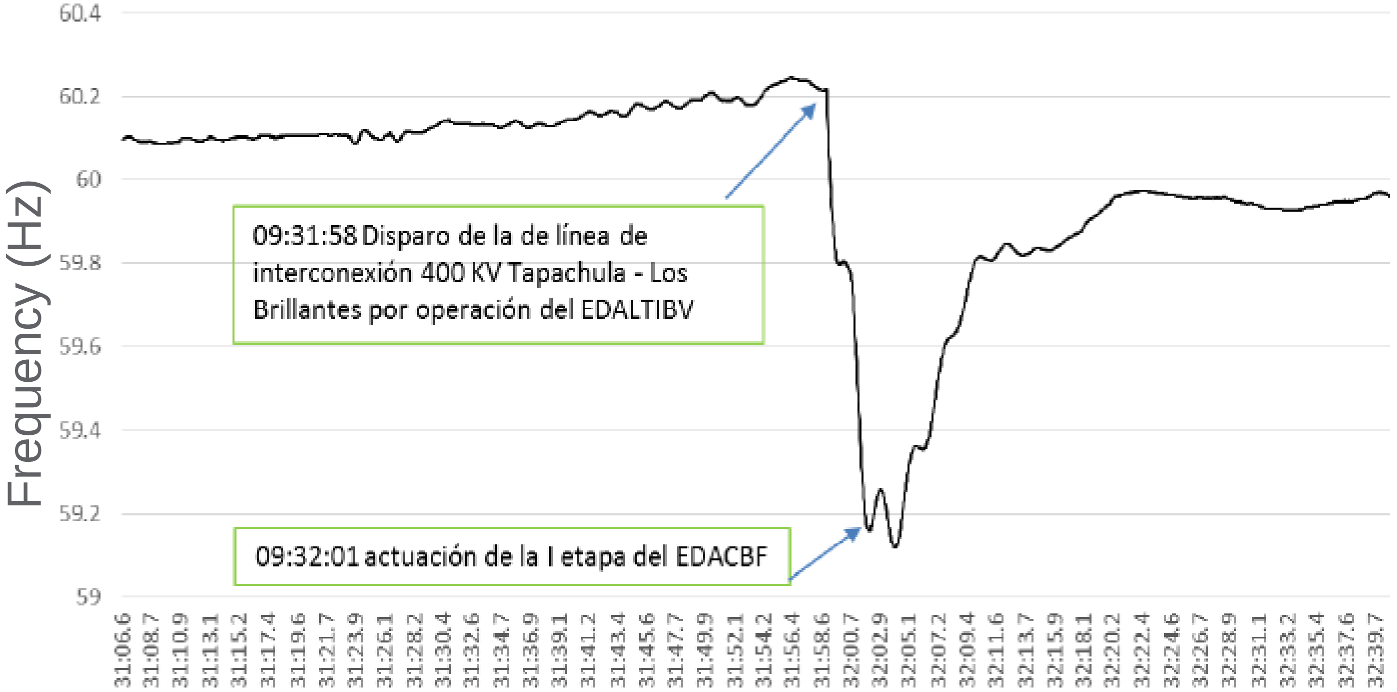
Effect of Mexico Earthquake in Central America

Evolution of the power transfer previous/during/after event

Transferred power Mexico – Guatemala(*)



Frequency measured in Guatemala (PMU Moyuta)(*)



- Programmed power transfer of 120 MW.
- 9:29 a.m. Registered earthquake in Mexico. At this point, power transfer was in 137 MW.
- Load tripping in South Crucecita, Oaxaca in Mexico (2,269 MW of load lost, and generation outage of 412 MW).

- Power transfer increased up to 455 MW before RAS tripping.
- Central American system accelerated; frequency increased over 60.2 Hz.
- 9:31:58 a.m. Registered tripping of the EDALTIBV RAS.
- Frequency drops beyond 59.2 Hz.
- Load shedding stages starts.

(*) Informe final de evento ocurrido en el sistema eléctrico regional (SER) - El 23 de junio de 2020 a las 09:32 horas.

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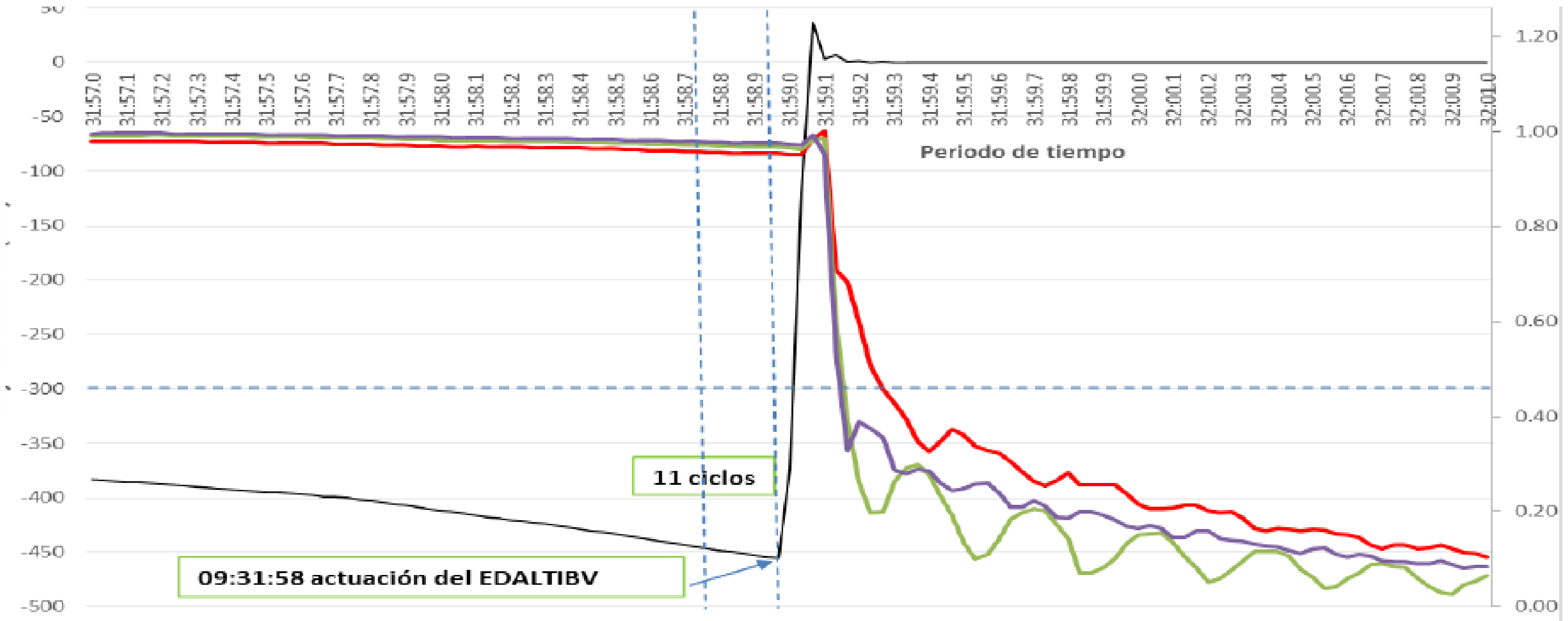

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Resilience Definitions

U.S. President's National Infrastructure Advisory Council (NIAC)

"The ability to reduce the magnitude and/or duration of disruptive events; the effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event."

North American Electric Reliability Corporation (NERC) –

Reliability Issues Steering committee Report on Resilience (2018) built its definition based on the NIAC framework and breaks down resilience into four outcomes focused abilities:

- "***Robustness*** – the ability to absorb shocks and continue operating
- ***Resourcefulness*** – the ability to detect and manage a crisis as it unfolds
- ***Rapid recovery*** – the ability to get services back as quickly as possible in a coordinated and controlled manner and taking into consideration the extent of the damage
- ***Adaptability*** – the ability to incorporate lessons learned from past events to improve resilience."

Ref. – 1) NIAC (National Infrastructure Advisory Council). 2010. A Framework for Establishing Critical Infrastructure Resilience Goals: Final Report and Recommendations by the Council. https://www.dhs.gov/xlibrary/assets/niac/niac-a-framework-for-establishing-critical-infrastructureresilience-goals-2010-10-19.pdf.
2) NERC. Reliability Issues Steering Committee Report on Resilience; Technical Report; North American Electric Reliability Corporation: Atlanta, GA, USA, 2018

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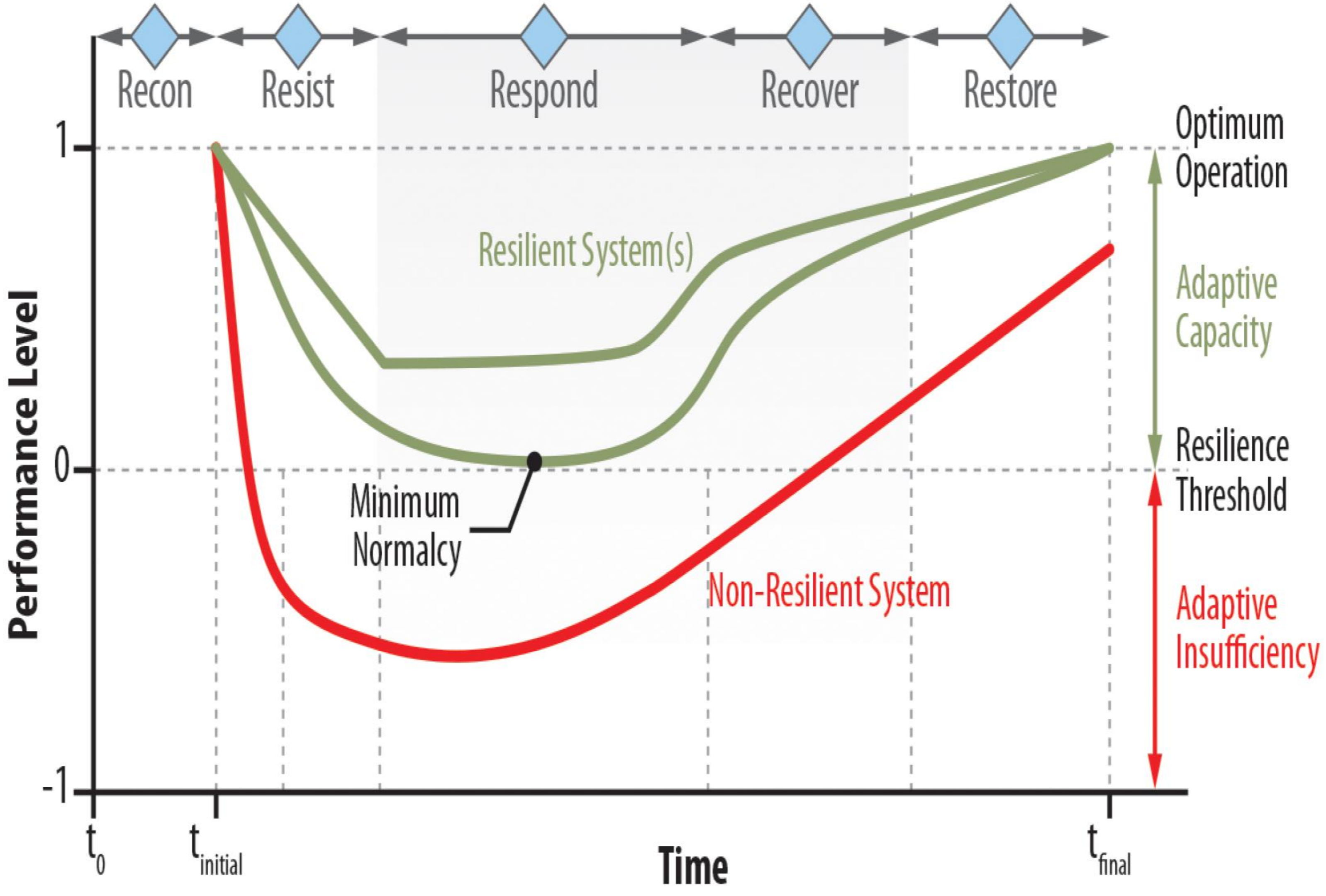
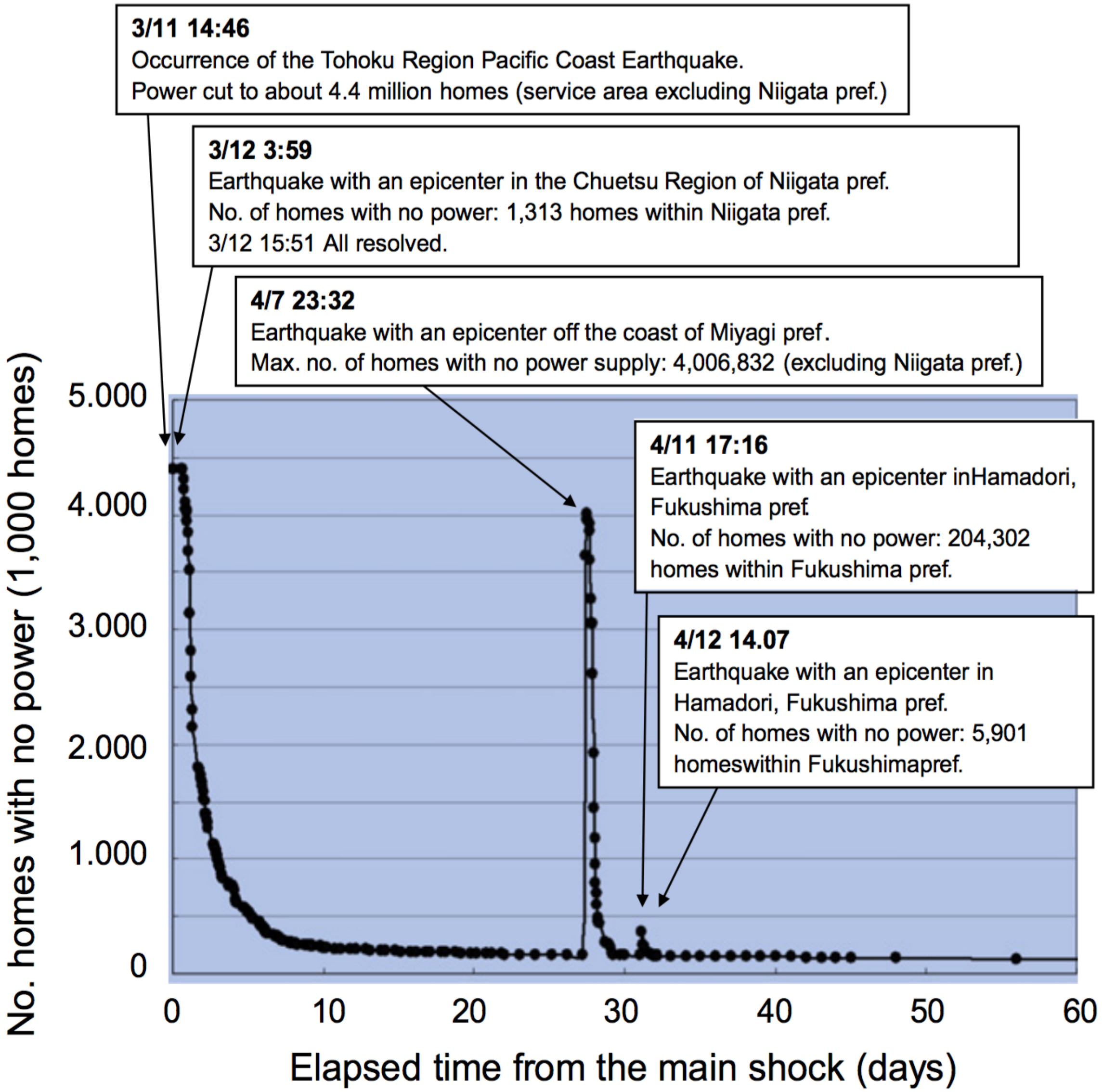
Resilience Curves

5Rs Framework



Real World Example



Ref. – 1) T. Phillips et al., "A Metric Framework for Evaluating the Resilience Contribution of Hydropower to the Grid," 2020 Resilience Week (RWS), 2020, pp. 78-85, doi: 10.1109/RWS50334.2020.9241249.
2) Kazama, M. and Noda, T., 2012. Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage). Soils and Foundations, 52(5), pp.780-792.

Resilience and Reliability are Different

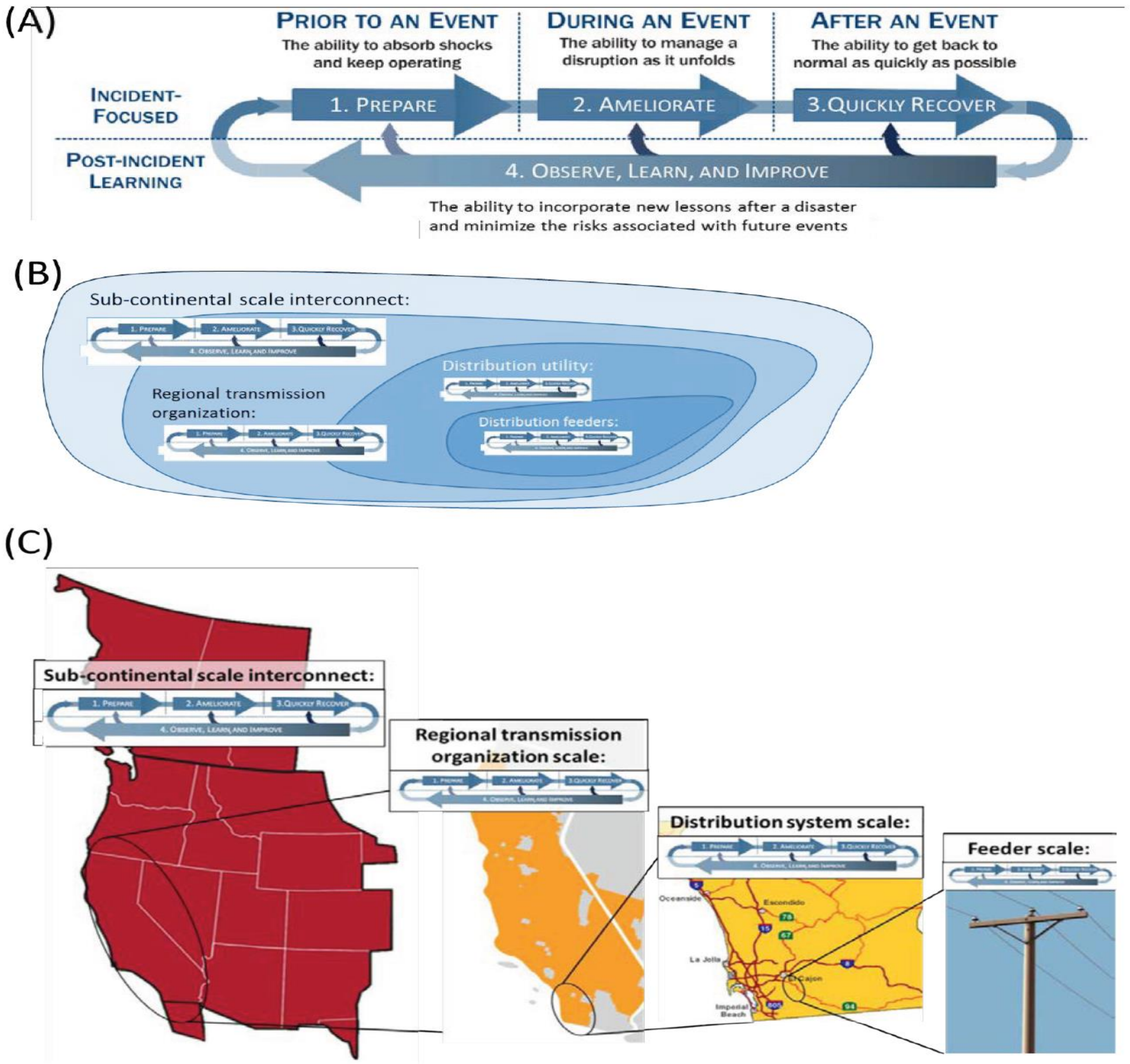
Reliability[2]

NERC is the federally approved organization responsible for developing reliability standards for the bulk power system and it defines reliability in terms of two core concepts:

1. ***Adequacy*** – The ability of the electricity system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.

2. ***Operating reliability*** – The ability of the bulk power system to withstand sudden disturbances, such as electric short circuits or the unanticipated loss of system elements from credible contingencies, while avoiding uncontrolled cascading blackouts or damage to equipment.

Resilience[1]



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2) NERC. Reliability Issues Steering Committee Report on Resilience; Technical Report; North American Electric Reliability Corporation: Atlanta, GA, USA, 2018

Key Differences – Reliability / Resilience

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

Ref. – M. Panteli and P. Mancarella, "The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience," in IEEE Power and Energy Magazine, vol. 13, no. 3, pp. 58-66, May-June 2015, doi: 10.1109/MPE.2015.2397334.

Metrics Used to Evaluate Reliability and to Evaluate/Standardize Resilience

Common Indexes used in T&D

Transmission (NERC)

- **ALR1-3** Planning Reserve Margin
- **ALR1-4** BPS Transmission Related Events Resulting in Loss of Load
- **ALR4-1** Automatic AC Transmission Outages Caused by Protection System Equipment-Related Mis-operations
- **ALR6-1** Transmission Constraint Mitigation
- **ALR1-5** System Voltage Performance
- **ALR1-12** Interconnection Frequency Response
- **ALR2-3** Activation of Under Frequency Load Shedding
- **ALR6-11** Automatic AC Transmission Outages Initiated by Failed Protection System Equipment
- **ALR6-12** Automatic AC Transmission Outages Initiated by Human Error
- **ALR6-13** Automatic AC Transmission Outages Initiated by Failed AC Substation Equipment
- **ALR6-14** Automatic AC Transmission Outages Initiated by Failed AC Circuit Equipment
- **ALR6-15** Element Availability Percentage (APC)

Distribution

- **SAIFI**: System Average Interruption Frequency Index (Sustained Interruptions) - interruptions per customer.
- **SAIDI**: System Average Interruption Duration Index. (minutes)
- **CAIDI**: Customer Average Interruption Duration Index. The resulting unit is minutes.
- **CAIFI**: Customer Average Interruption Frequency Index
- **MAIFI**: Momentary Average Interruption Frequency Index.

Ref. – https://www.nerc.com/comm/PC/Pages/Performance%20Analysis%20Subcommittee%20(PAS)/Approved-Metrics.aspx

Direct Category

Electrical Service

- Cumulative customer-hours of outages.
- Cumulative customer energy demand not served.
- Average number (or percentage) of customers experience an outage during a specified time period.

Critical Electrical Service

- Cumulative critical customer-hours of outages.
- Critical customer energy demand not served.
- Average number (or percentage) of critical loads that experience an outage.

Restoration

- Time to recovery.
- Cost of recovery.

Monetary

- Loss of utility revenue.
- Cost of grid damages (e.g., repair or replace lines, transformers).
- Cost of recovery.
- Avoided outage cost

Indirect Category

Community function

- Critical services without power (e.g., hospitals, fire stations, police stations).
- Critical services without power for more than N hours (e.g., N> hours or backup fuel requirement).

Ref. – National Academies of Sciences, Engineering, and Medicine. Enhancing the resilience of the nation's electricity system. National Academies Press, 2017.

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Causes and Modeling of Grid Failures Using Earthquake Analysis Case-Study

Vishvas Chalishazar

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

U.S. DEPARTMENT OF STATE

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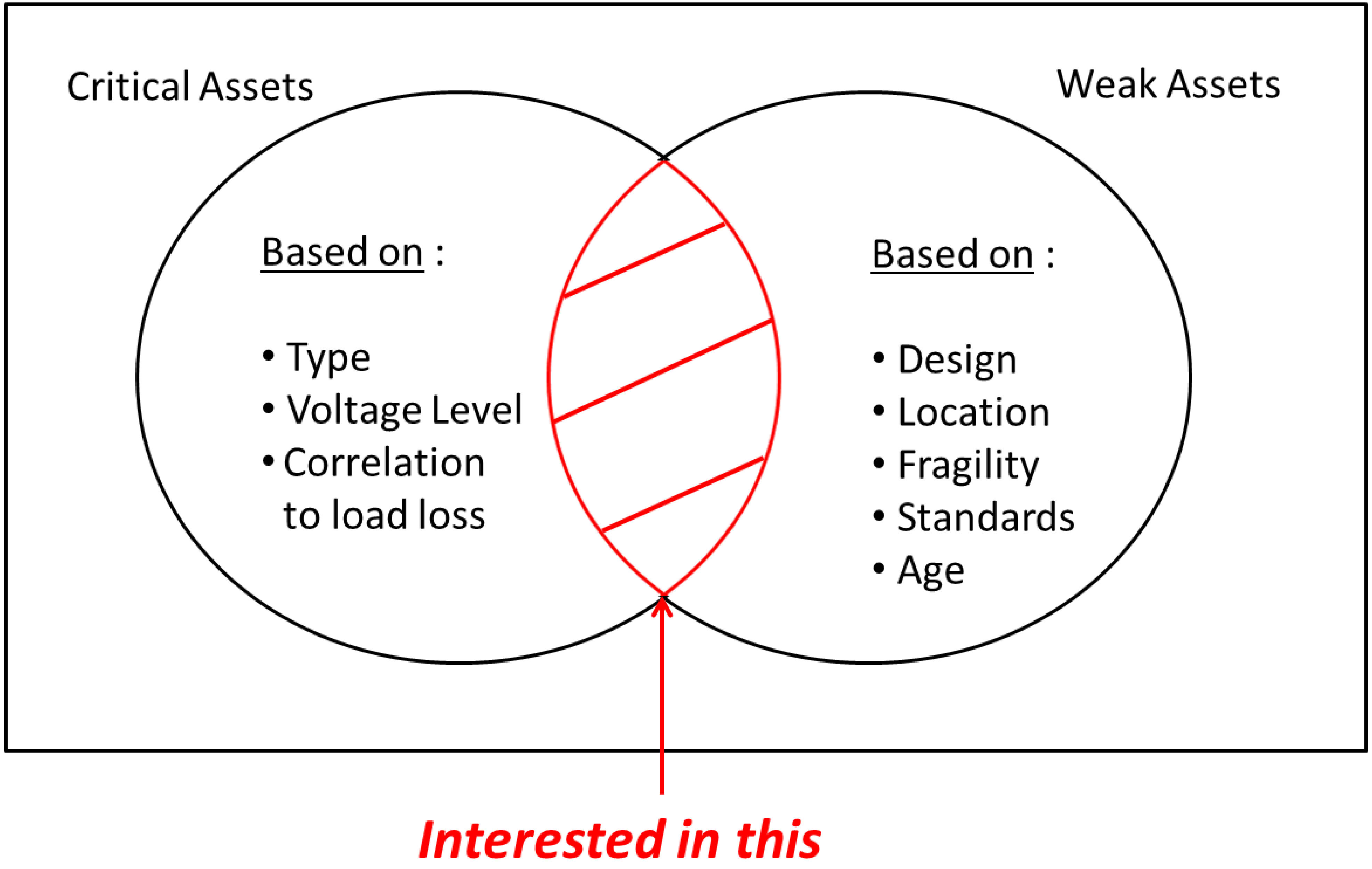
Causes and modeling of Grid Failure

- Case Study – Earthquake Analysis
  - What? – Performance Based Earthquake Engineering (PBEE) Method
  - How? – Detailed modeling of the 4 steps of PBEE method
    1. Hazard Analysis
    2. Structural Response Analysis
    3. Damage Analysis
    4. Loss Analysis
  - Why? – Understanding the consequences on 3 fronts
    1. Loss of Load and/or Unserved Energy
    2. Economic Consequences caused by unserved energy
    3. Targeted Upgrades and positive impacts

In a Nutshell



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Causes and modeling of Grid Failure

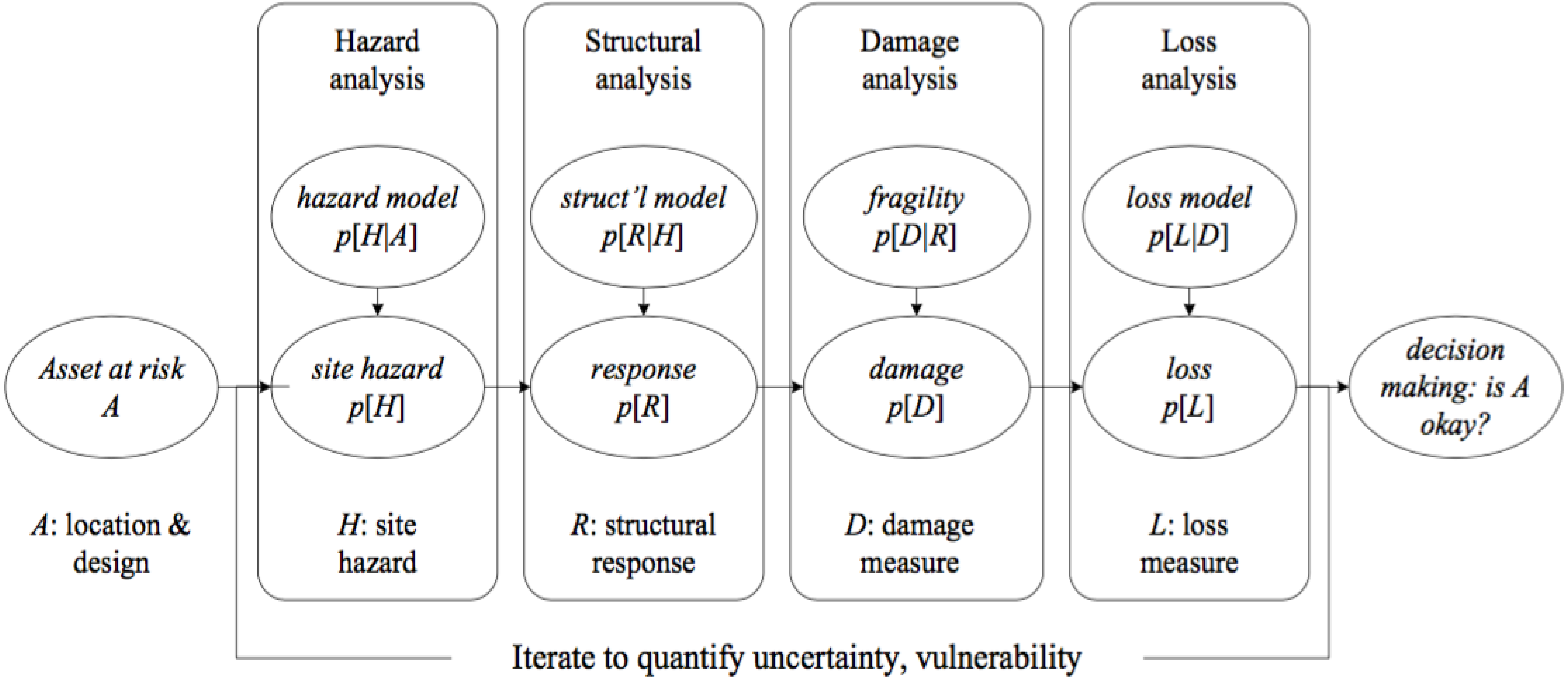
What ?

What do we do?

How ?

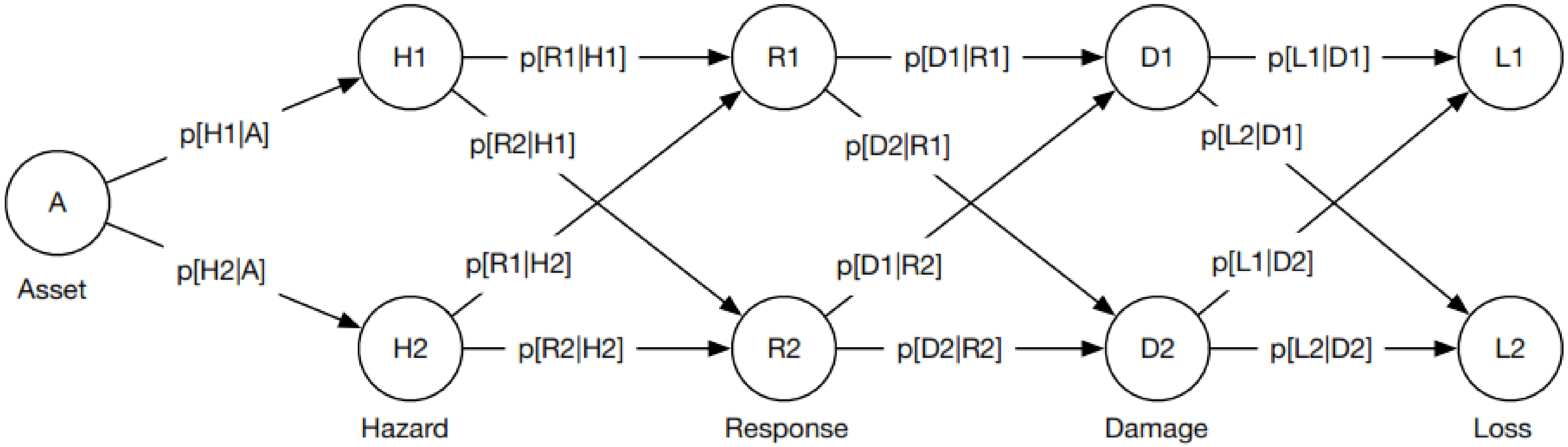
Why ?

Performance Based Earthquake Engineering



Ref: Porter, Keith. "Beginners Guide to Fragility, Vulnerability, and Risk." Encyclopedia of Earthquake Engineering (2015): 235-260

Performance Based Earthquake Engineering



The probability of an asset being in the Loss State 1 (L1) and Loss State 2 (L2) is calculated using the matrix multiplication as shown here.

$$\begin{pmatrix} P[L1] & P[L2] \end{pmatrix} = \begin{pmatrix} P[H1|A] & P[H2|A] \end{pmatrix} * \begin{pmatrix} P[R1|H1] & P[R2|H1] \\ P[R1|H2] & P[R2|H2] \end{pmatrix} * \begin{pmatrix} P[D1|R1] & P[D2|R1] \\ P[D1|R2] & P[D2|R2] \end{pmatrix} * \begin{pmatrix} P[L1|D1] & P[L2|D1] \\ P[L1|D2] & P[L2|D2] \end{pmatrix}$$

Ref: Johnson, Brandon, Vishvas Chalishazar, Eduardo Cotilla-Sanchez, and Ted KA Brekken. "A Monte Carlo Methodology for Earthquake Impact Analysis on the Electrical Grid." Electric Power Systems Research 184 (2020): 106332.

Causes and modeling of Grid Failure

What ?

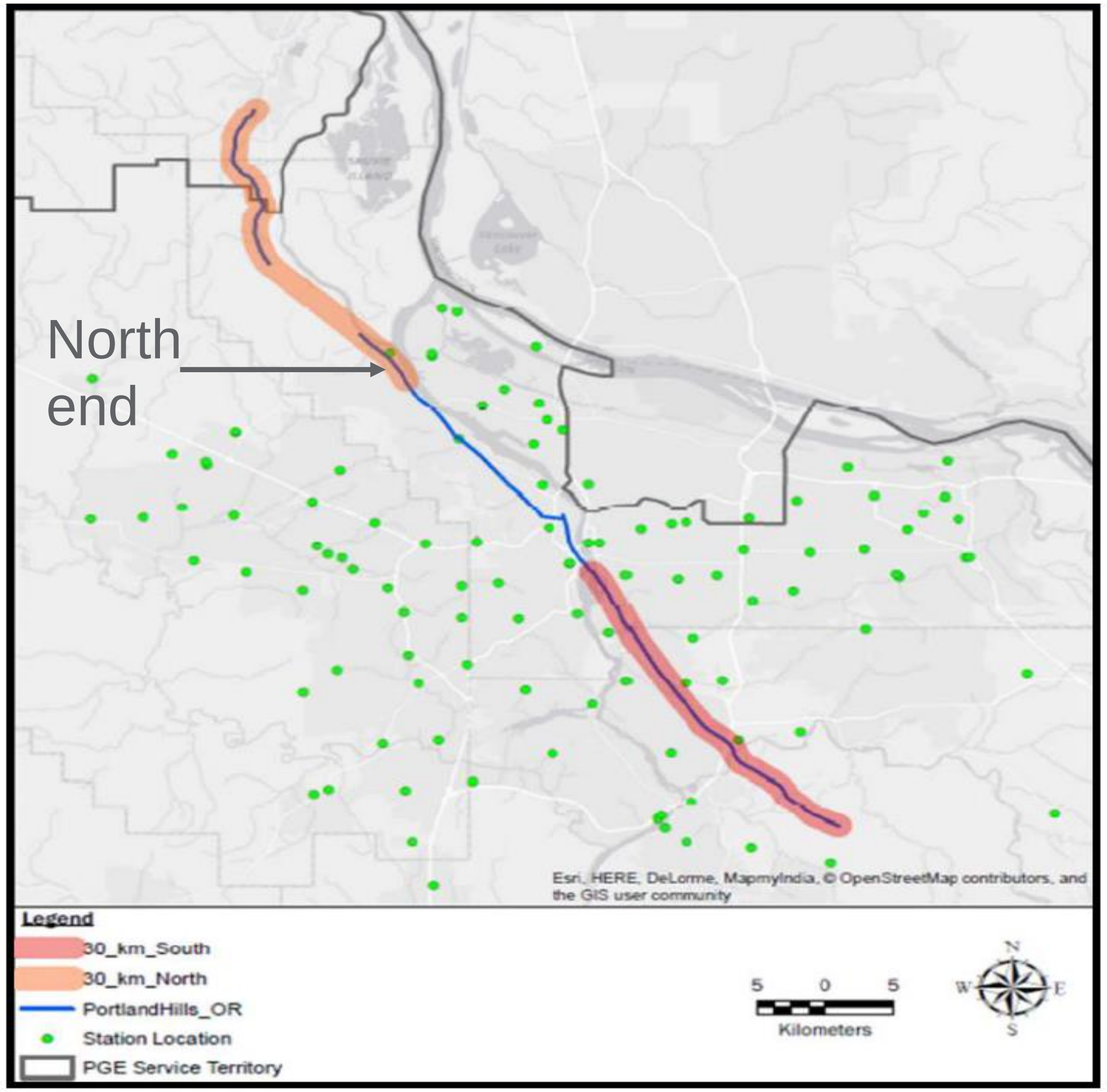
How ?

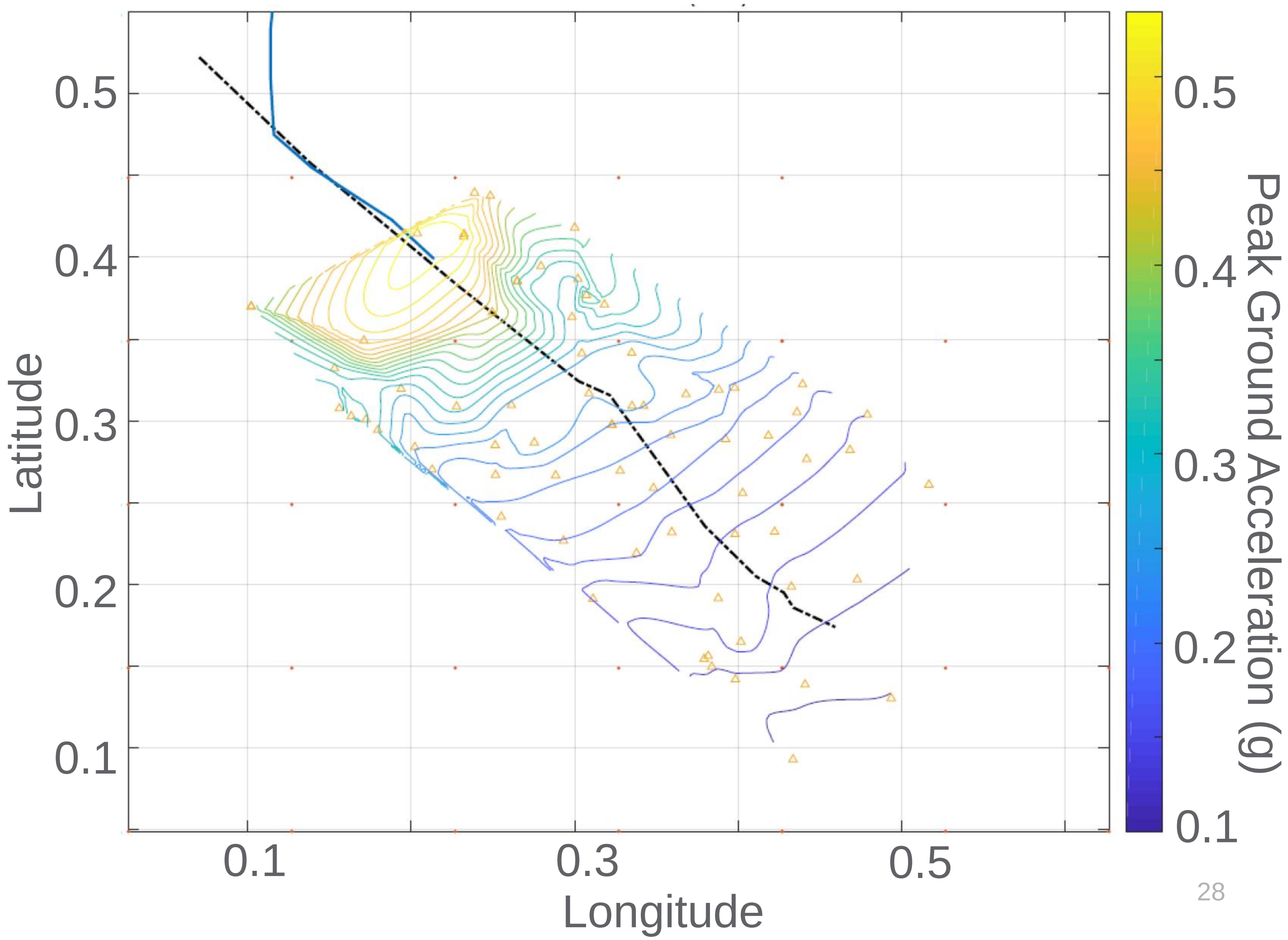
How do we do it?

Why ?

Structural Response Analysis

M = 6.8 Fault Location





Ref: Chalishazar, Vishvas H. et. al. 2020. "Connecting Risk and Resilience for a Power System Using the Portland Hills Fault Case Study" Processes 8, no. 10: 1200. https://doi.org/10.3390/pr8101200

Damage Analysis – Fragility Curves

Substations

71 substations were expected to be affected by a M6.8 Earthquake

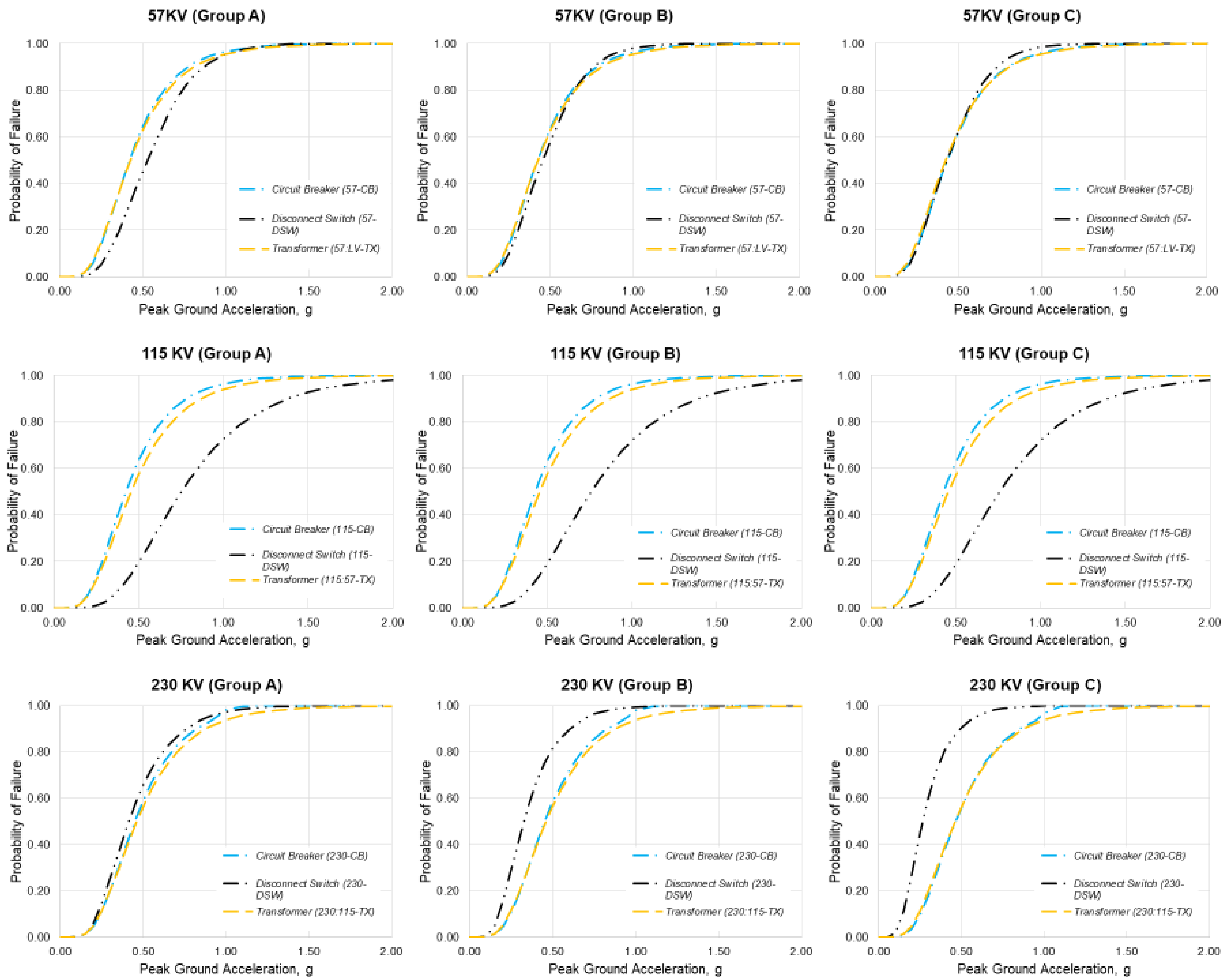
Voltage Levels

3 voltage levels were picked

- 57kV
- 115kV
- 230kV

Asset Type (Roughly 500 assets in total)

- Circuit Breakers
- D/S Switches
- Transformers

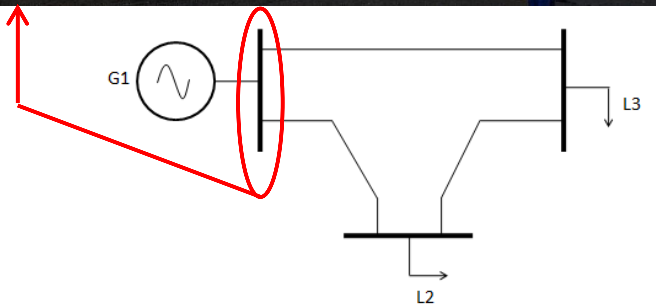


Note: Fragility Curves plot **the probability that some undesirable event occurs** (typically that an asset — a facility or a component — reaches or exceeds some clearly defined limit) **as a function of some measure of environmental excitation** (typically a measure of acceleration, deformation, or force in an earthquake, hurricane, or other extreme loading condition) [1]

Ref: 1) Porter, Keith. "Beginners Guide to Fragility, Vulnerability, and Risk." Encyclopedia of Earthquake Engineering (2015): 235-260
2) Chalishazar, Vishvas H. et. al. 2020. "Connecting Risk and Resilience for a Power System Using the Portland Hills Fault Case Study" Processes 8, no. 10: 1200. https://doi.org/10.3390/pr8101200

Loss Analysis

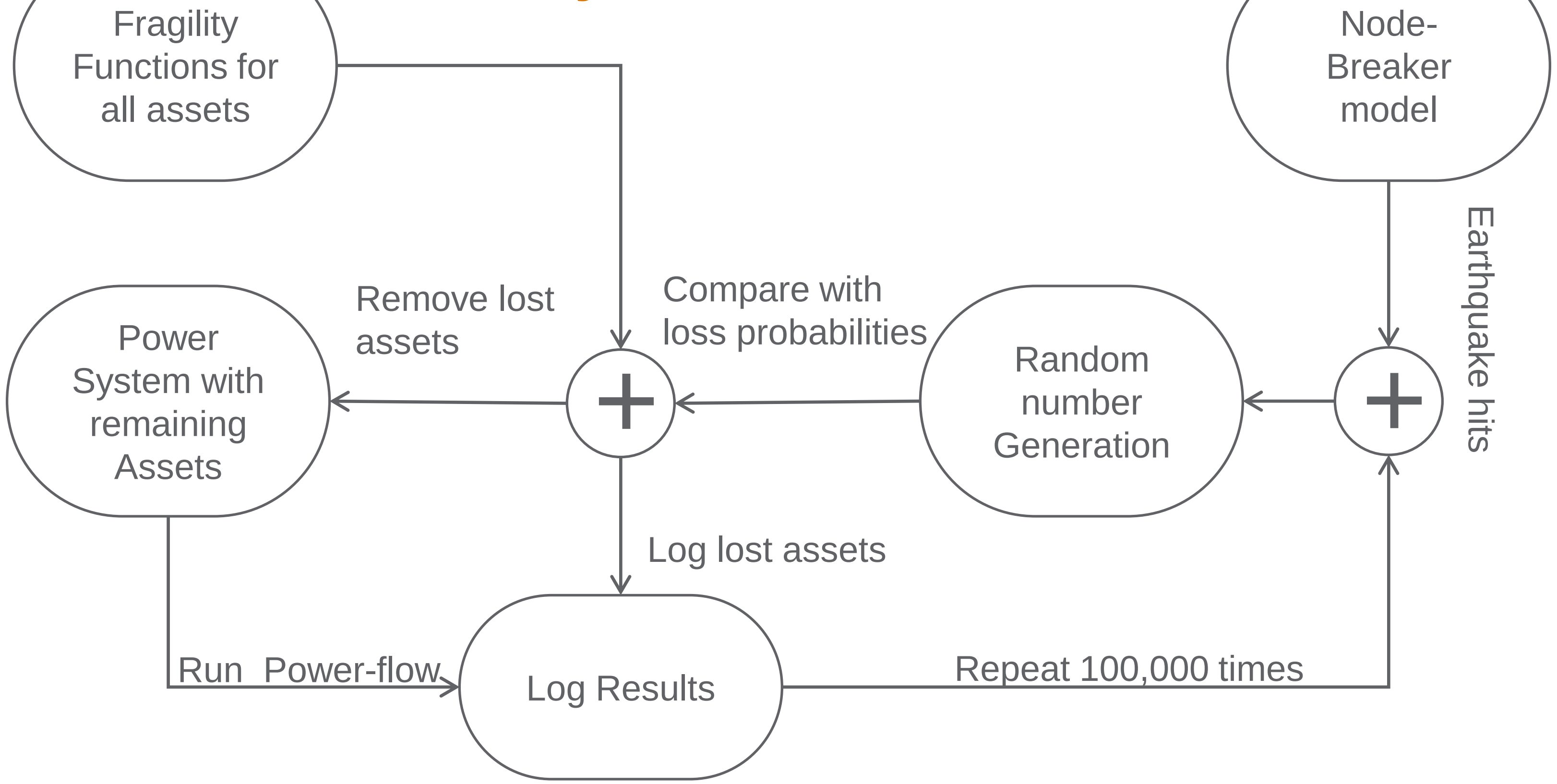
VS.

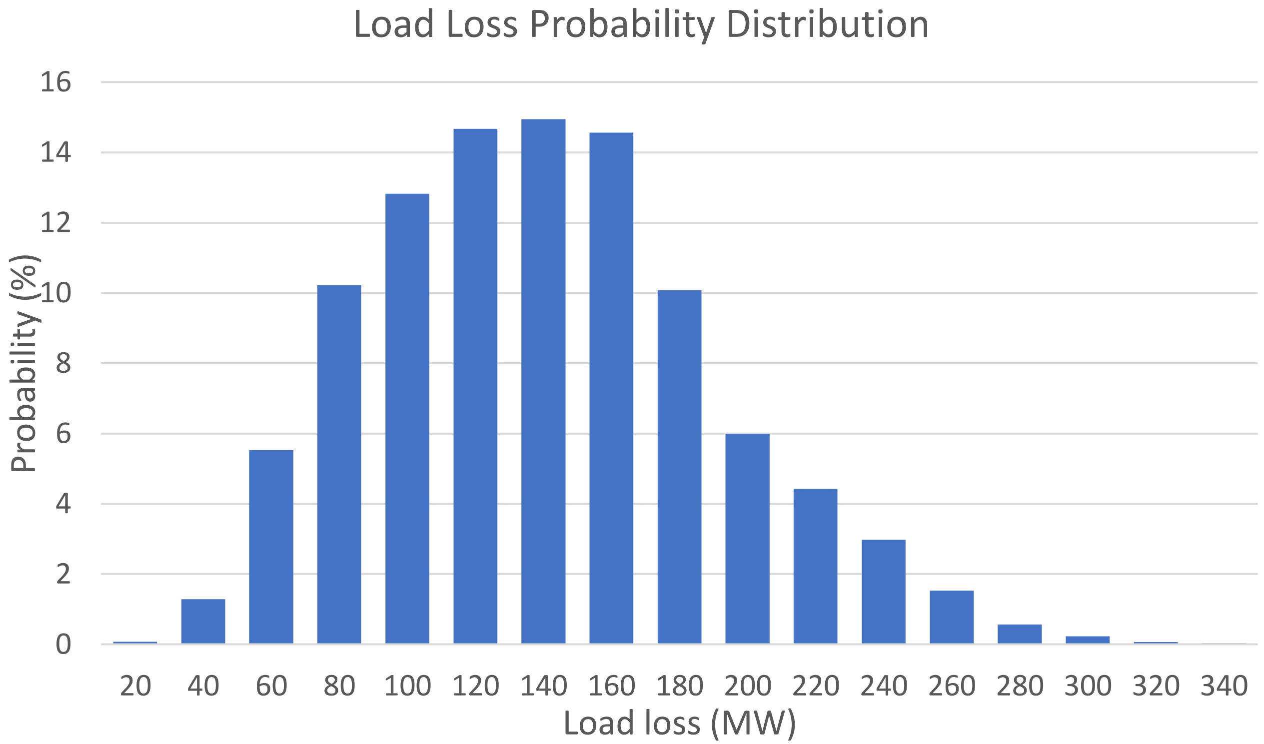


- Individual or a set of bus in the one-line diagram of the system represents a whole substation
- We should use the Node-breaker model of the power system instead traditional bus-branch model for seismic resilience
- Because there is no good way to translate individual component fragilities to the whole substation

Ref: Chalishazar, Vishvas H. et. al. 2020. "Connecting Risk and Resilience for a Power System Using the Portland Hills Fault Case Study" Processes 8, no. 10: 1200. https://doi.org/10.3390/pr8101200

Analysis Flow Chart





Causes and modeling of Grid Failure

What ?

How ?

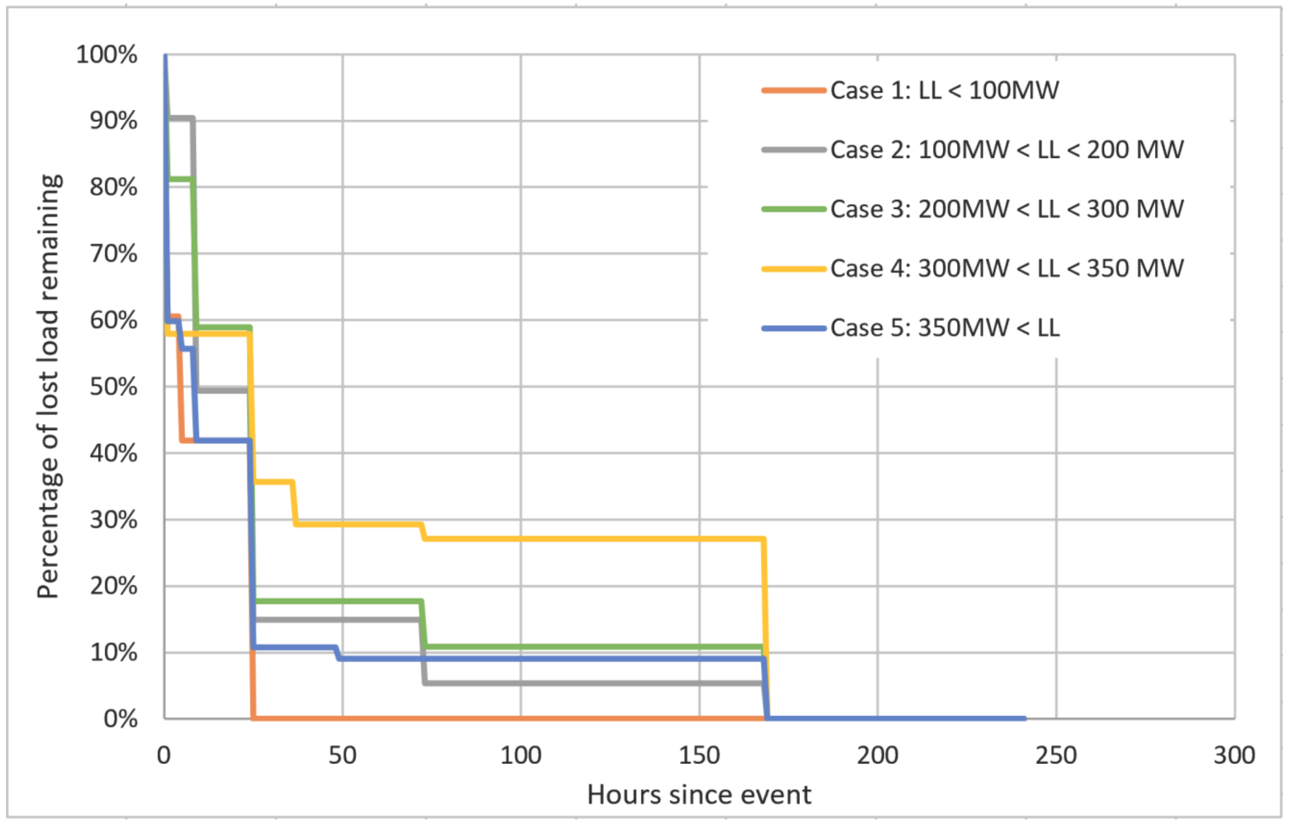
Why ?

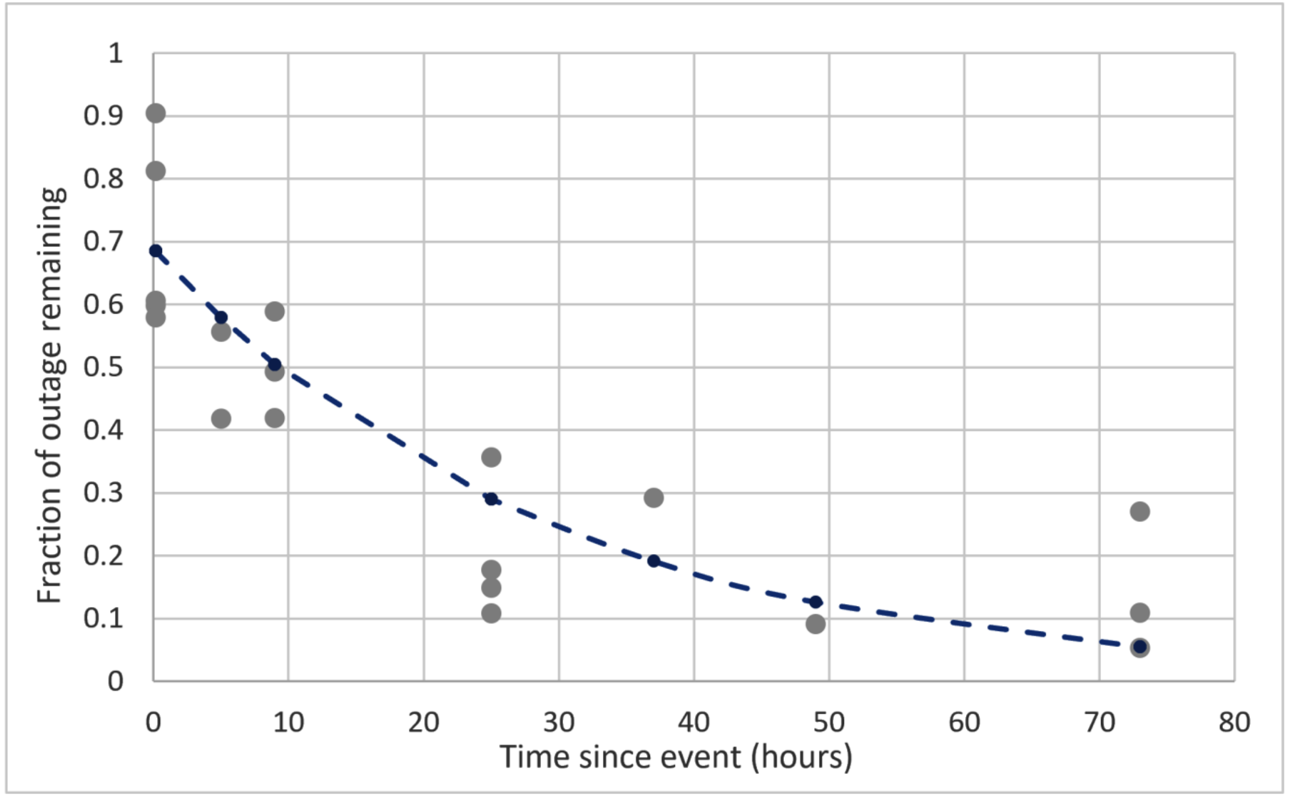
Why should we do it?

Amount of Unserved Energy

Restoration:

- Loads restored immediately due to automatic switching.
- Loads restored in hours due to manual switching and simple fixes.
- Loads that would require days to restore due to the need for temporary construction.
- Loads that would require a week or more to restore due to the need for new equipment or major reconstruction.





Ref: Chalishazar, Vishvas H. et. al. 2020. "Connecting Risk and Resilience for a Power System Using the Portland Hills Fault Case Study" Processes 8, no. 10: 1200. https://doi.org/10.3390/pr8101200

Economic Consequences

Economic Risk Assessment Strategy

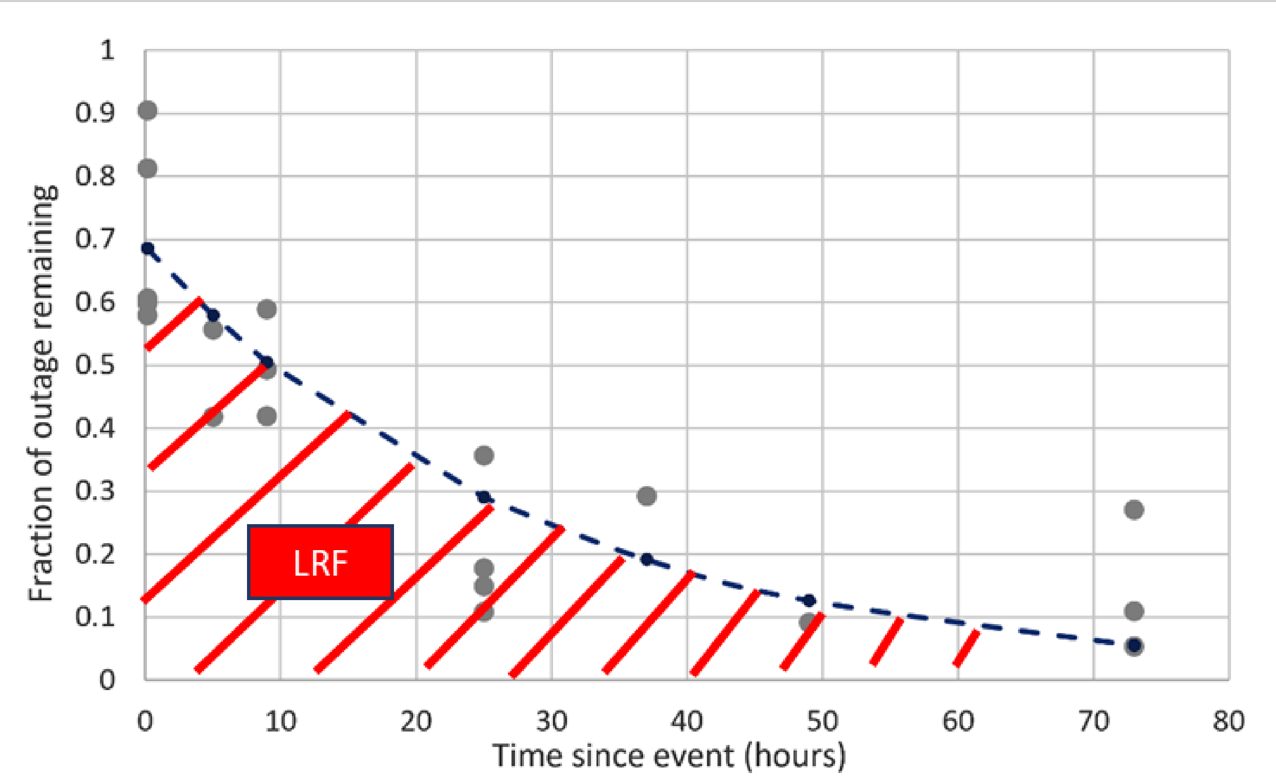
Two types of cost

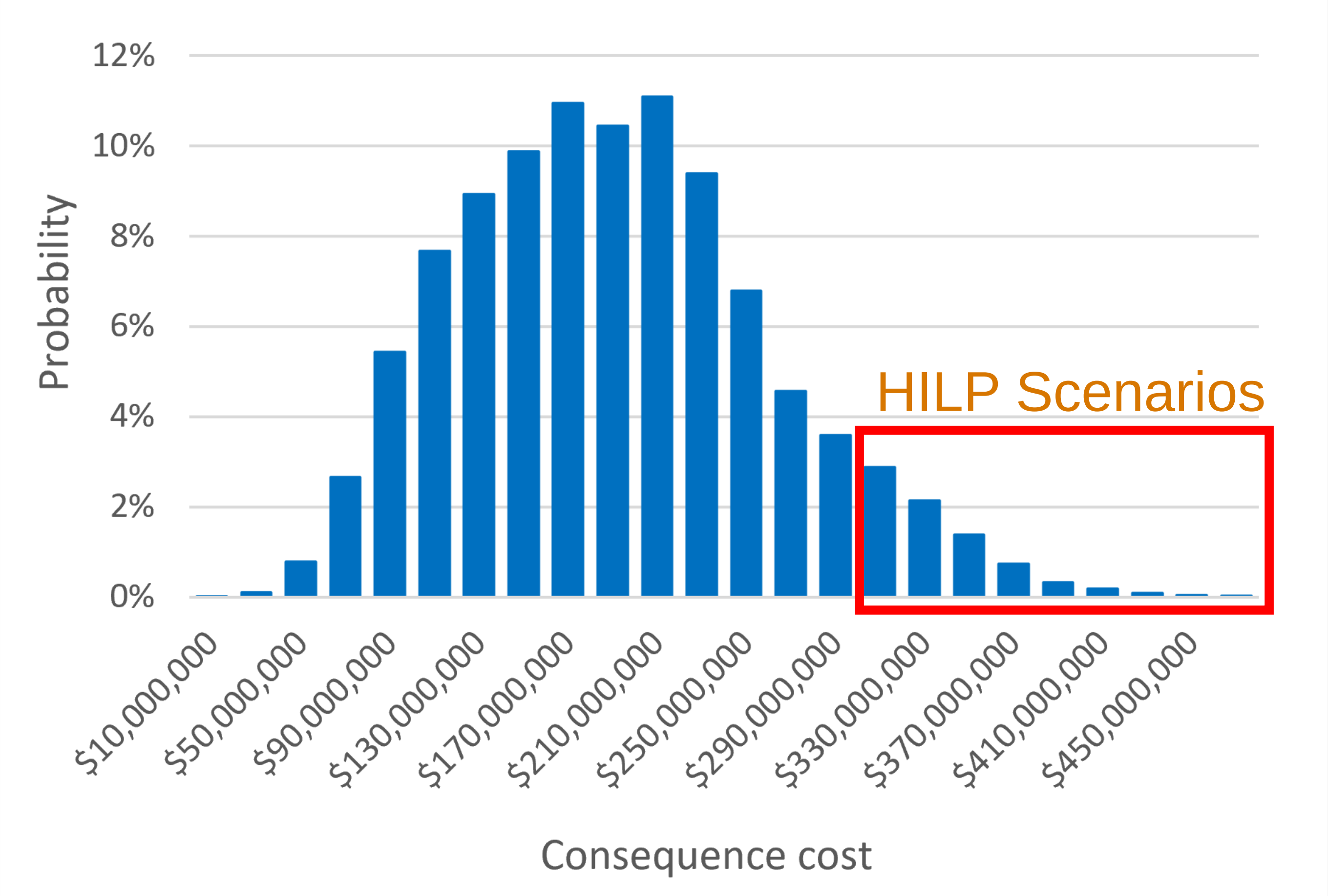
1. Initial outage cost ($/kW)
2. Outage duration cost ($/kWh)
   - Take representative cases across the load loss probability distribution
   - Use these cases to calculate outage duration
   - Use the outage duration data to plot a general out duration model

For example, a scenario with an initial outage of 20MW and Load Recovery Factor (LRF) value of 19.7 hrs. would have

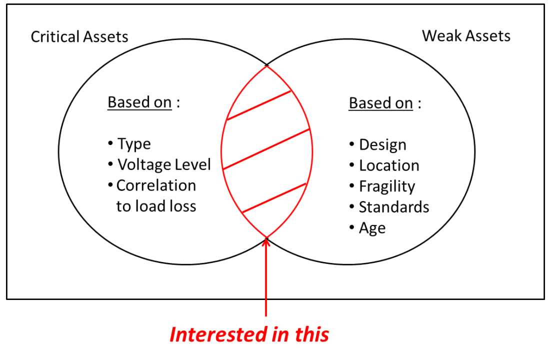
- **An initial outage cost based on 20 MW of customer interruptions and**
- **An outage duration cost based on (20 x 19.7) MWh of energy not served**

Ref: Chalishazar, Vishvas H. et. al. 2020. "Connecting Risk and Resilience for a Power System Using the Portland Hills Fault Case Study" Processes 8, no. 10: 1200. https://doi.org/10.3390/pr8101200

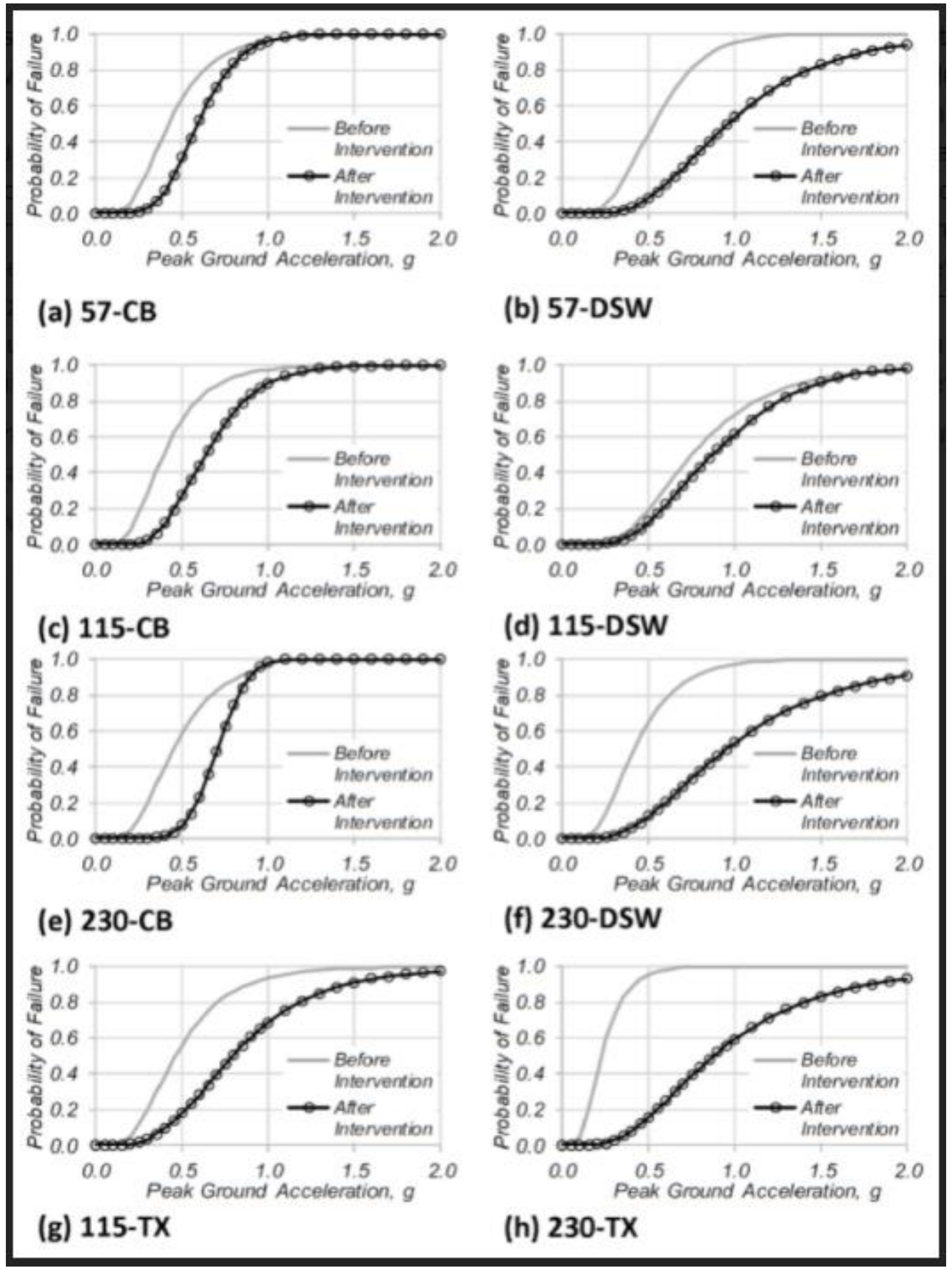


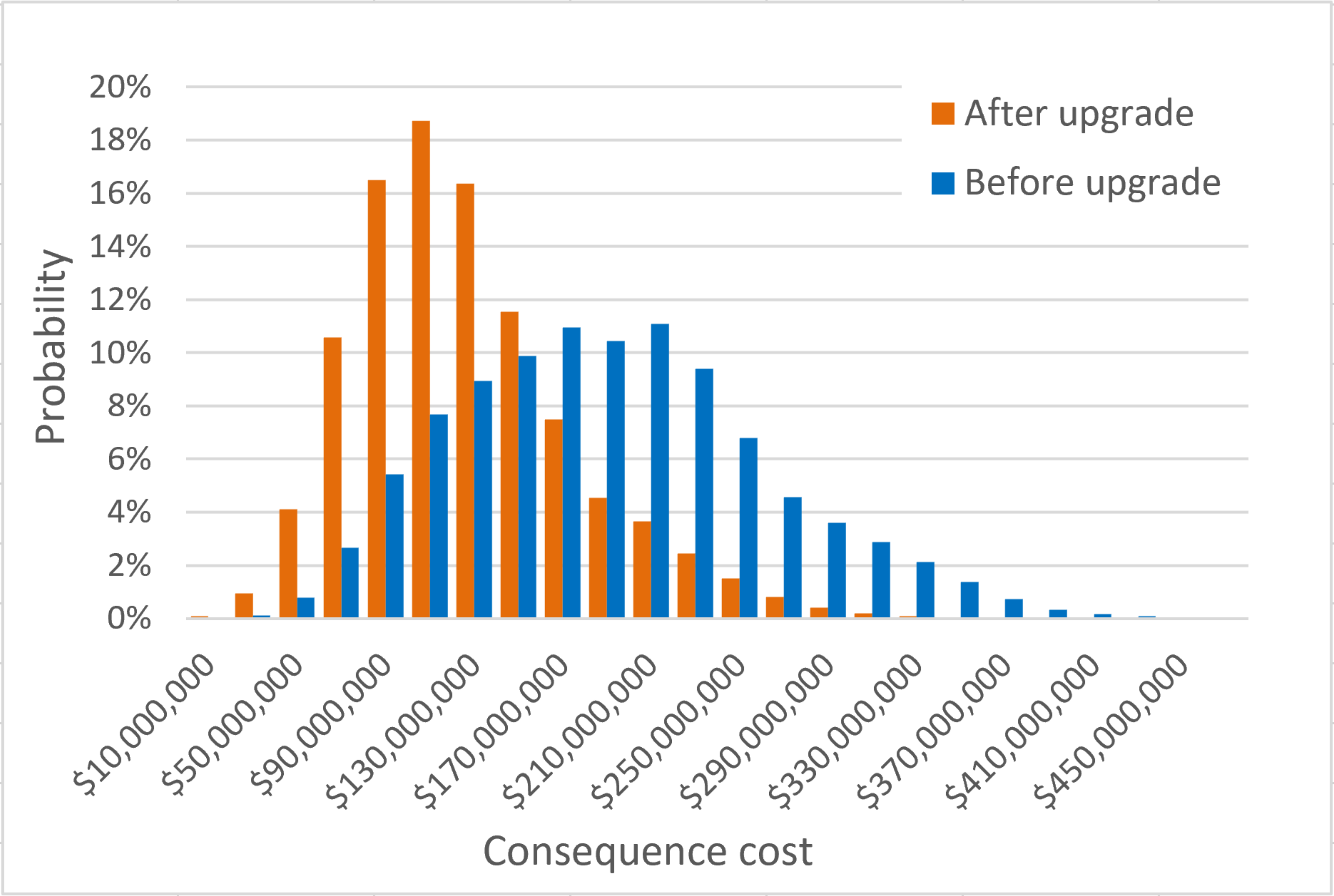


Targeted Upgrades and Positive Impacts



Based on the assets that caused high load loss, a list of 8 substations that would benefit the most from a seismic upgrade was developed





Ref: Chalishazar, Vishvas H. et. al. 2020. "Connecting Risk and Resilience for a Power System Using the Portland Hills Fault Case Study" Processes 8, no. 10: 1200. https://doi.org/10.3390/pr8101200

Pacific Northwest NATIONAL LABORATORY

Control System Resilience

Scott Mix

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U.S. DEPARTMENT OF STATE

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Power Sector Program

Control System Resilience

- Control Centers
  - No single point of failure
    - ✓ Hardware
    - ✓ Software
    - ✓ Power
    - ✓ Communications (whenever possible)
    - ✓ Automatic recovery from “soft failures” – program aborts, bad data, etc.
  - Redundant control systems
    - ✓ Recovery from hardware failures
    - ✓ Checkpoint data and analysis results – slight delay to minimize propagation of corrupted data
    - ✓ Failover/failback procedures
    - ✓ Physical isolation for servers in data center – minimize fire, flood damage
    - ✓ Difficult to recover from control room disasters

Control System Resilience

- Control Centers
  - Backup / alternate control centers
    - ✓ Independent of primary control center and location
    - ✓ Can recover from any loss at primary control center – including complete facility disaster
    - ✓ Warm or Hot recommended for backup; Parallel Operations recommended for alternate – cost and performance trade offs
    - ✓ Backup control center may have single or redundant systems
    - ✓ Checkpoint data and analysis results – same considerations on slight delay
    - ✓ Failover/failback procedures
    - ✓ Independent communications (i.e., telemetry cannot be routed through primary control center)
  - Test all changes prior to implementing them in production system
  - Additional information available in *Continuity of Operations Options for the Central American Regional Operator* report (*)

(*) S Mix, M Elizondo, A Somani, E Barrett, L Miller, U Agrawal, "Continuity of Operations Options for the Central American Regional Operator," PNNL Technical Report, PNNL-27621, October 2020

Control System Resilience

- Protection Systems and Remedial Action Schemes
  - Protection Systems
    - ✓ Primary and backup systems (relays) for key facilities or locations
    - ✓ Primary and backup should be different manufacturer or technology – eliminate common mode failures
    - ✓ Redundant data sources for primary and backup – instrument transformers (CT, PT)
    - ✓ Multiple overlapping protection zones for all locations
    - ✓ Consideration for failures – CT/PT, relay, breaker, communications, battery
    - ✓ Communications needed for line distance protection system coordination – autonomous operations when communication fails
  - RAS
    - ✓ No single point of failure
    - ✓ Considerations for failures (same as for protection systems)
    - ✓ Redundant processing (same as for control center)
    - ✓ Resilient communications
    - ✓ Resilient data sources
  - Systems need to be tested and maintained – including backup processing

Control System Resilience

- Communications
  - Resilient communications:
    - ✓ Multiple communications paths
    - ✓ Diverse physical routing
    - ✓ Multiple communication carriers (if possible)
  - Resilient communications between primary and backup control centers
  - Resilient communications between OS/OM control centers and EOR control centers
  - Resilient Communications for RAS
    - ✓ Especially if RAS functions are centralized
  - Both communication paths should be used routinely (if possible), but provisioned so that a single path can carry the entire communications load
    - ✓ Constant testing to ensure communications will be available.
  - PMU data can backup RTU telemetry