Resilience Under Uncertain Load Growth and Cascading Risks

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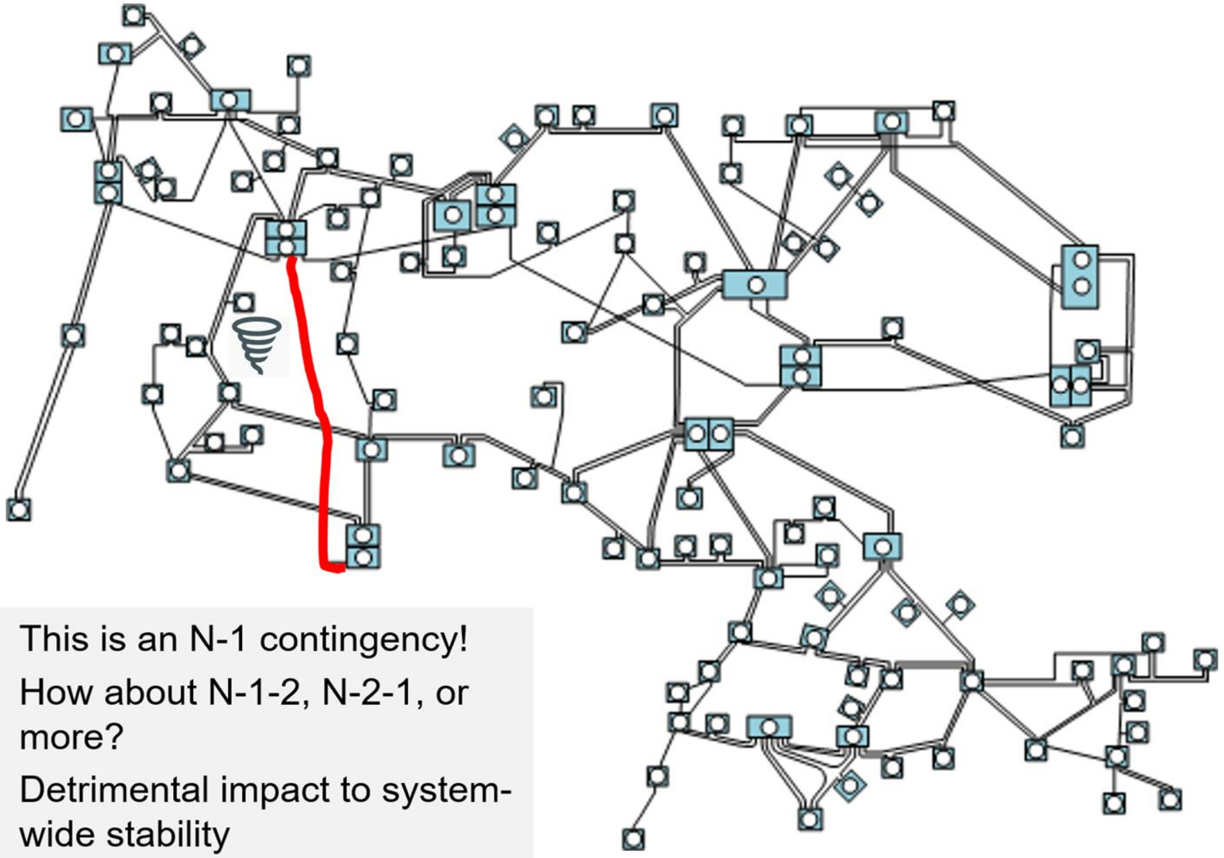
My Belief of Resilience

1. Cup half full vs. half empty
2. Adversarial attitude
3. Be flexible, persistent, open-minded — Never give up
4. Synergistic approach
5. Sustainability of business/finance
6. Readiness for the worst
7. Live happily
8. **Growth strategically**

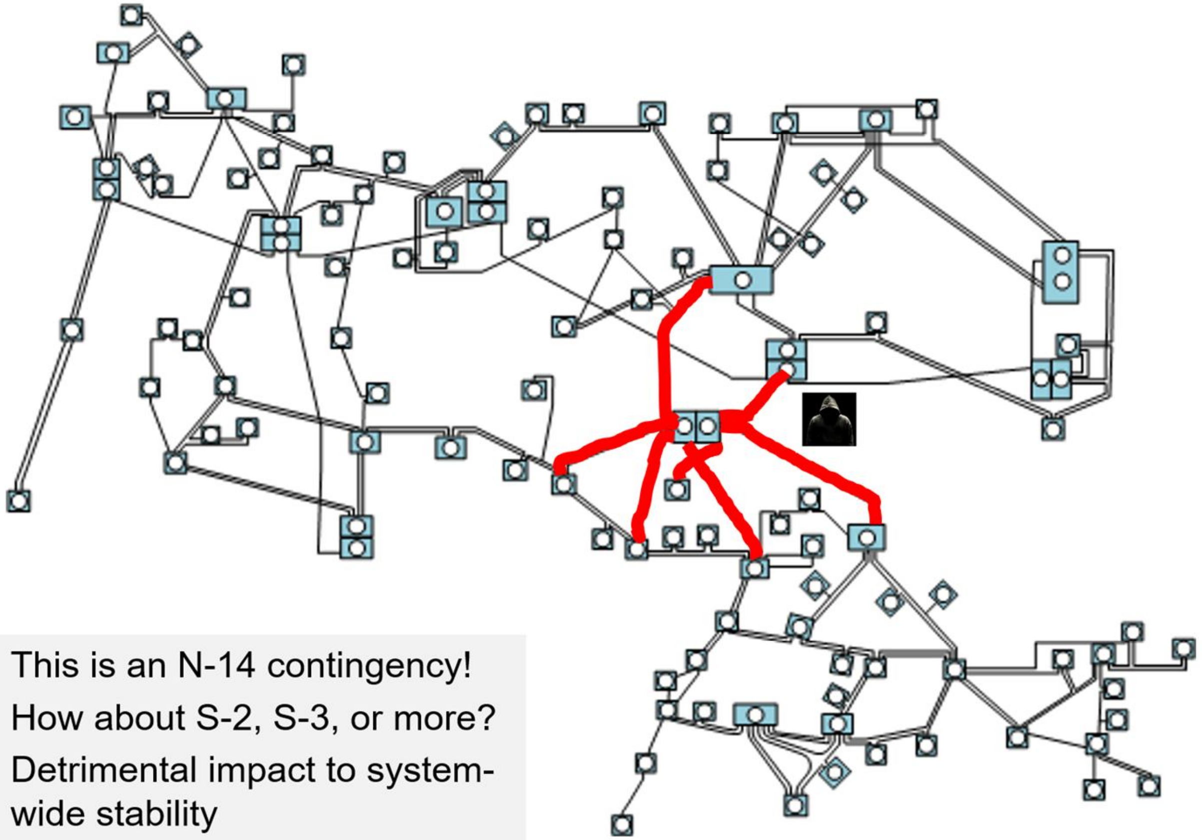
Contingency Analysis

N-1 Contingency



- ❑ This is an N-1 contingency!
- ❑ How about N-1-2, N-2-1, or more?
- ❑ Detrimental impact to system-wide stability

S-k Contingency



- ❑ This is an N-14 contingency!
- ❑ How about S-2, S-3, or more?
- ❑ Detrimental impact to system-wide stability

- Initial events, cascading outages
- Poor coordination led indecision of remedial actions
- Blackout/brownout occurs

Change of Reality

- On top of population growth
  - New EV charging stations
  - New data centers
  - Domestic manufacturing
- Intermittency of renewable energy
- Unprecedented bottleneck shift from time to time
- Congestion increases

Growth → transmission circuit expansion

It is very hard to plan for rare event occurrences in a business case.

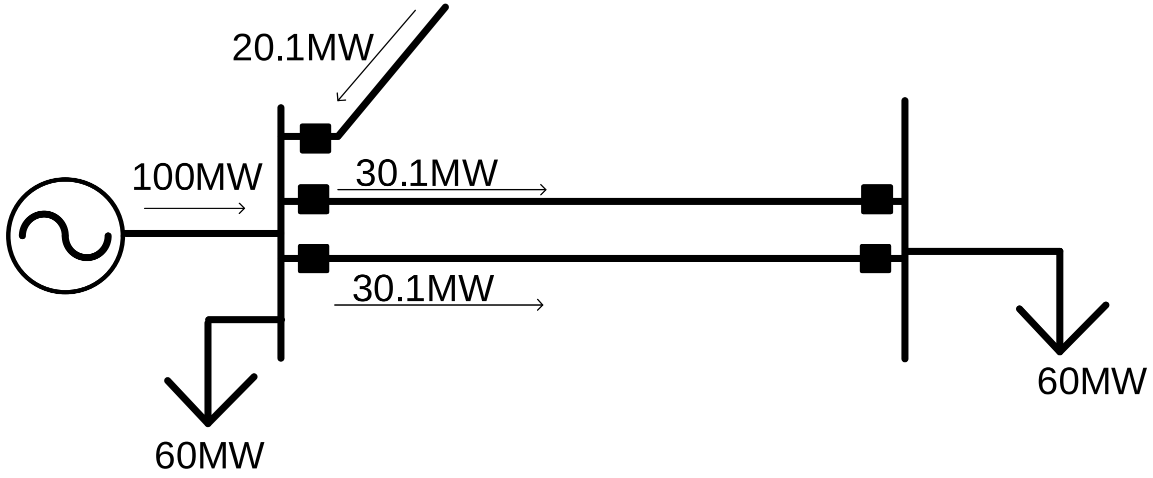
High Cost and Long Lead Times

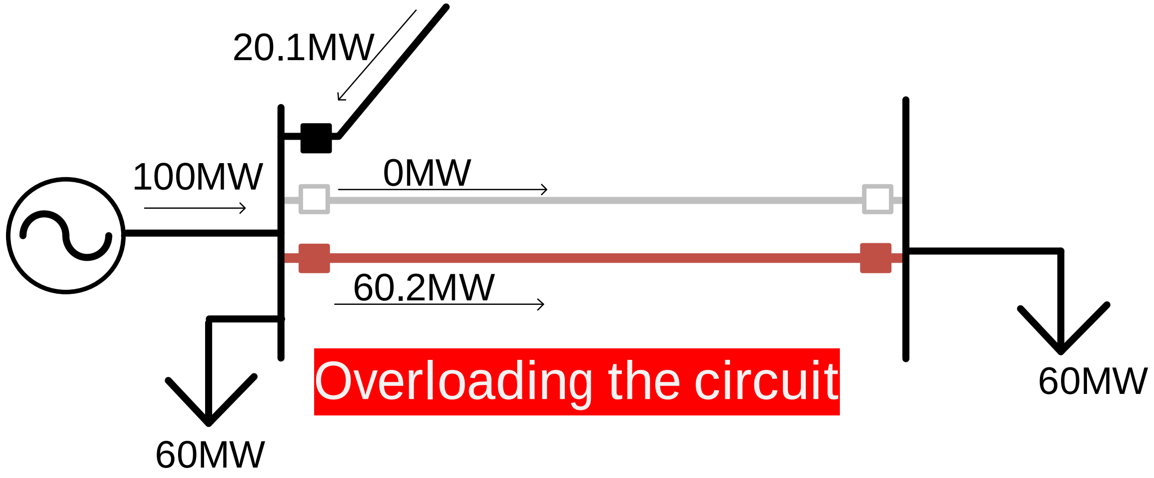
Natural Catastrophe

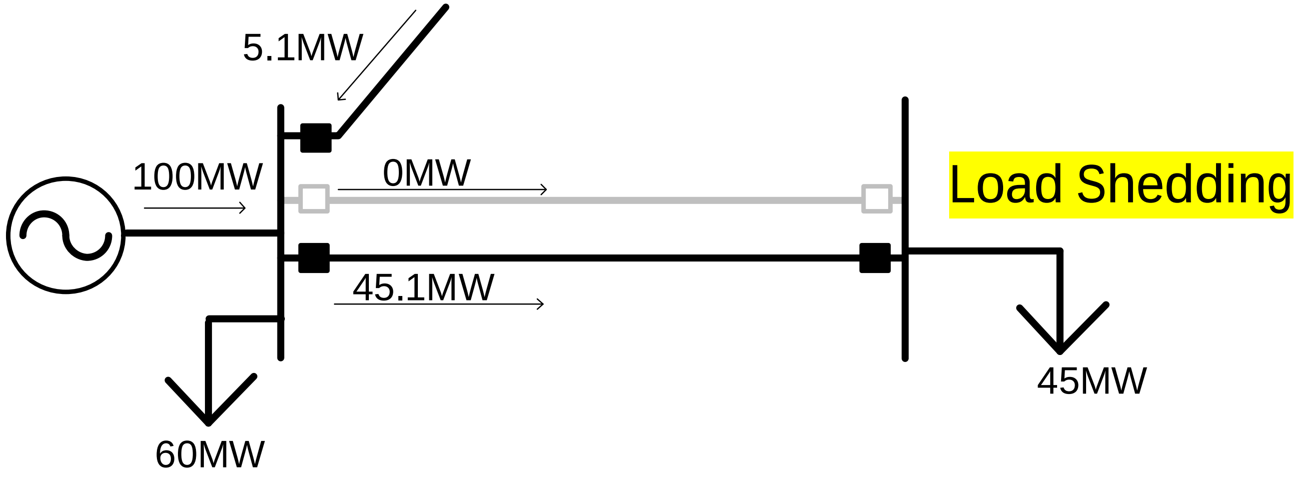
Congestion Just Moves Elsewhere

Uncertain Future Demand and Generation Patterns

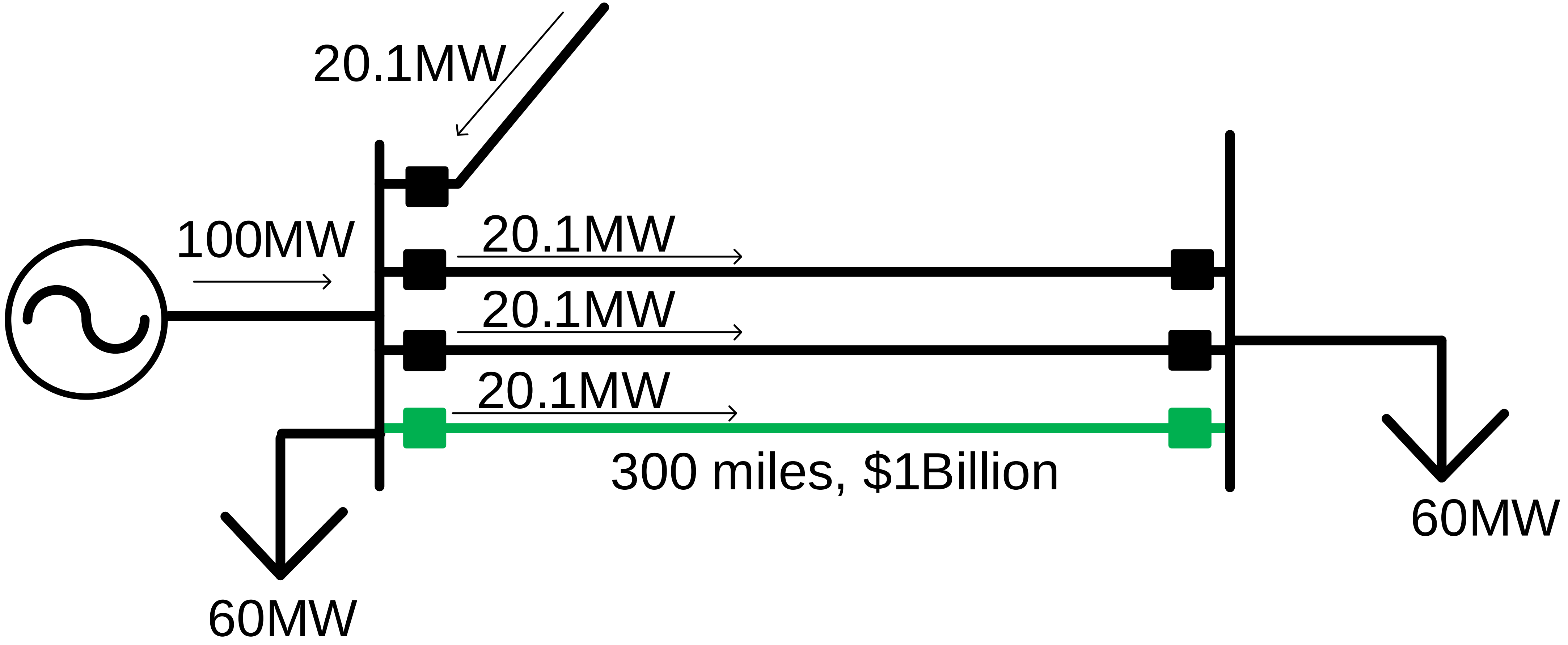
N-1Contingency View and Load Shedding







Merchant Transmission Project



Merchant Transmission Projects vs. Resilience

- Merchant Transmission Projects (MTPs) are market-driven solutions
- Objective is to optimize cost recovery under uncertain energy availability.
- Revenue Sources include transmission service charges and Financial Transmission Rights (FTRs)
- Commercial Viability hinges on fully subscribing the MTP's transmission capacity

No guaranteed investment recovery

It can take up to 10 years due to permitting, supply chain delays, and labor shortages.

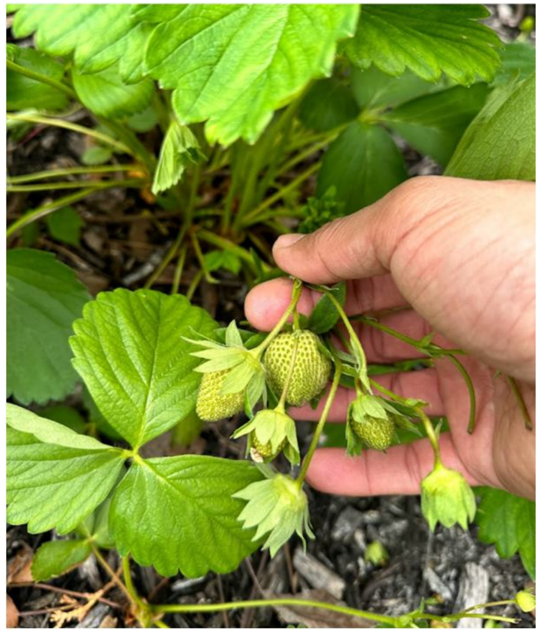
New load growth may significantly outpace transmission expansion, yet total generation remains inadequate.

Shedding load may not be necessary if we have a local generation to supply majority of it

Growth (expansion and addition) cannot be simply to brute force investment at every local – not sustainable!

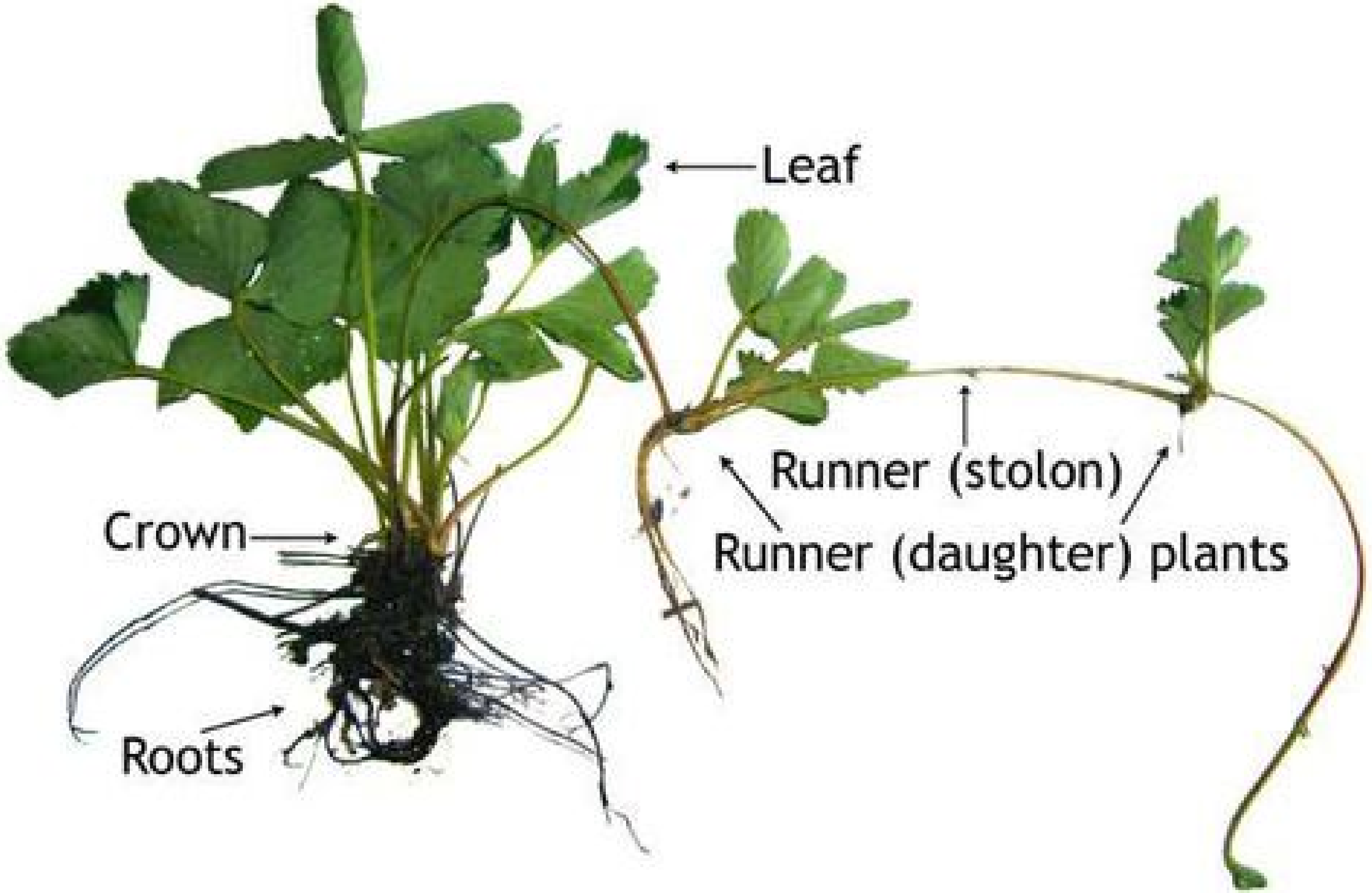
What if there is something we could turn something into generation from a load?

Our Love of Seasonal Fruit - **Strawberries**

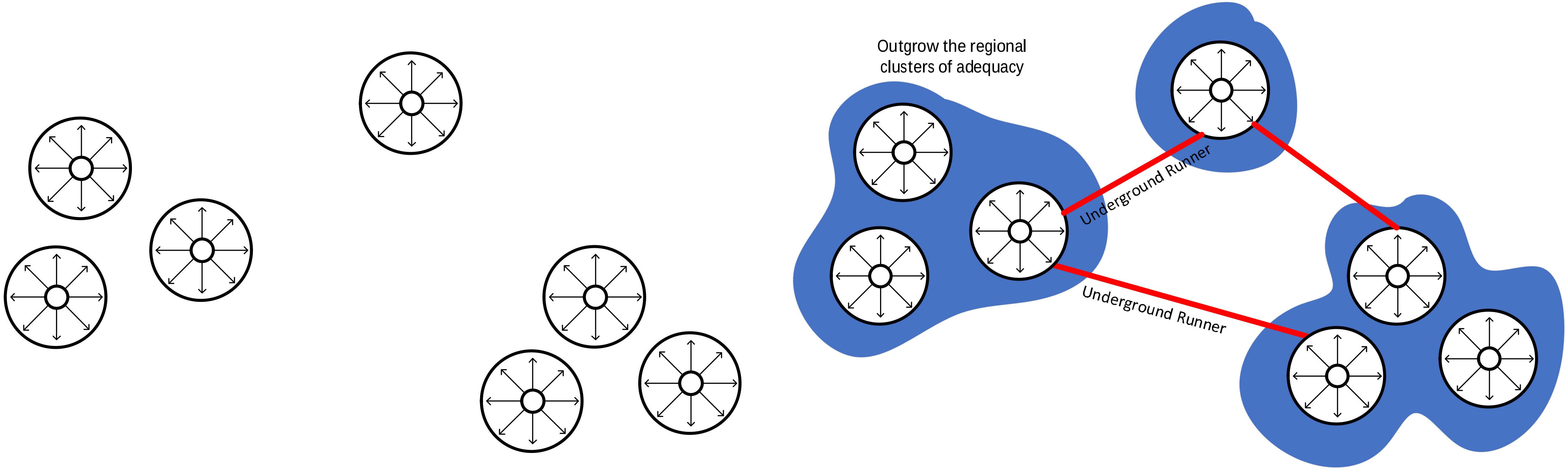


Case Study of Genomic-Informed Breeding Strategies for Strawberries

- ❑ Topological space and properties of a biological survivability system
- ❑ Crown and runner daughter plants
- ❑ The “edges” are the runners
- ❑ Established the autonomy as the runner plants grow bigger by rooting locally



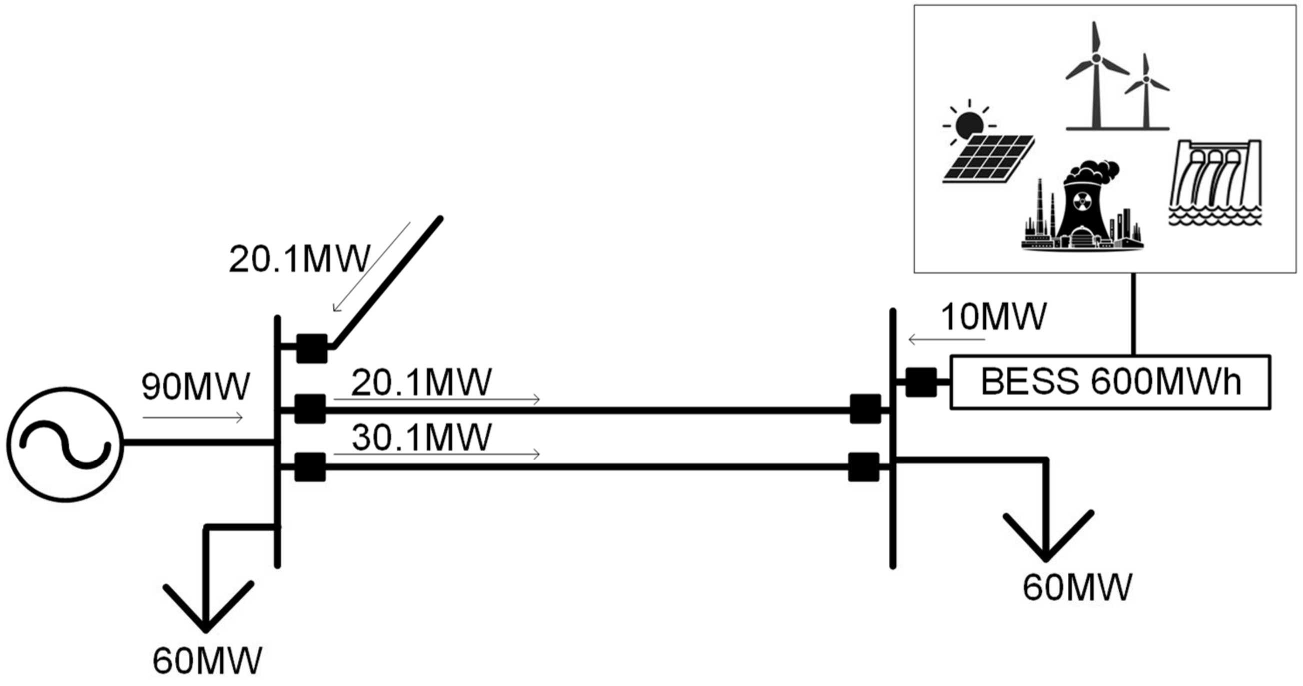
Considering Clustered Adequacy for Restoration Efforts Based on strawberry-runner paradigm

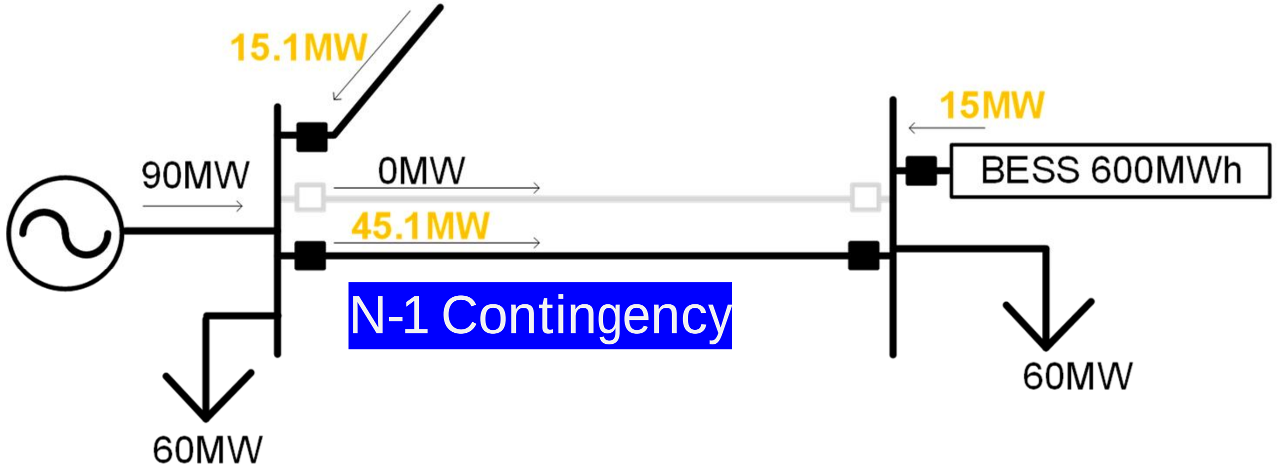


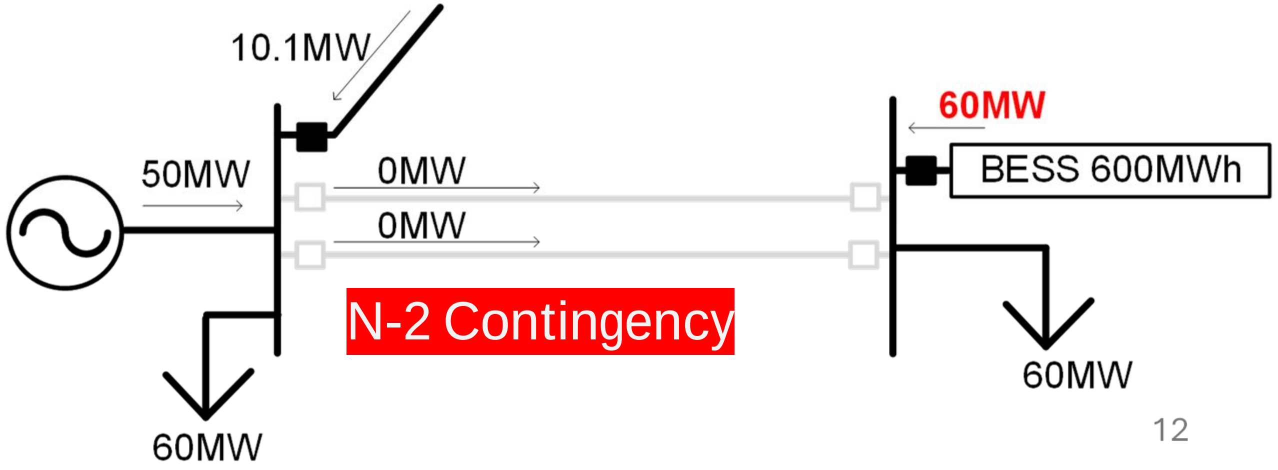
Slow expansion of underground system

BESS Investment

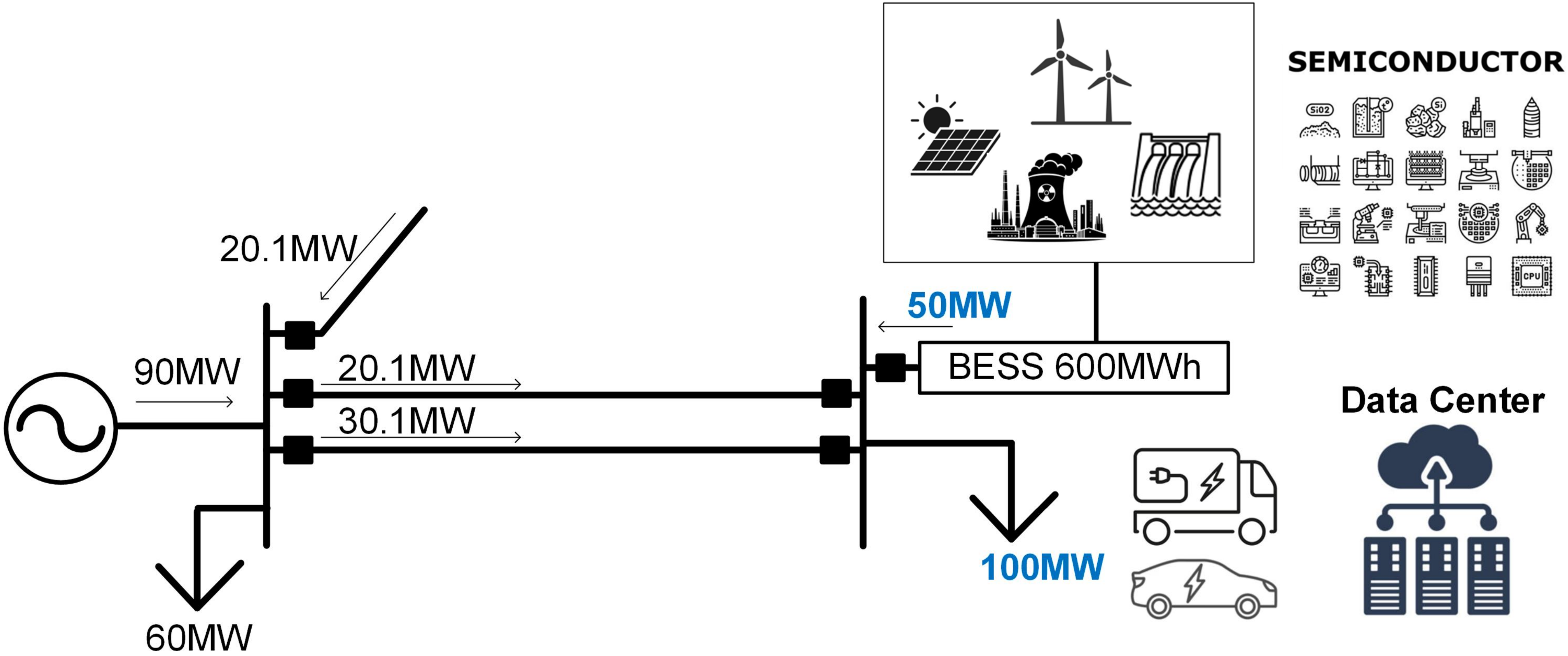
- **Equipment:** $160,044,660
- **Installation:** $34,650,000
- **Total:** Approximately **$194,694,660**
- Could take up to 1 year to complete







Flexibility of New Load Growth



Sequence of Events about Blackouts

The **Northeast Blackout of November 9, 1965**, was triggered at 5:16 PM when a **230-kV transmission line to Ontario tripped** due to an incorrectly set relay, causing cascading failures in the power grid. The sudden **redistribution of power** overloaded remaining lines, leading to instability as **generators at Beck and Niagara lost synchronization**. Within **seconds**, key transmission lines between **New York and New England tripped**, severing tie lines and causing additional generator failures. This resulted in the **East Coast Interconnect splitting into 4 sections**, leaving **30 million people without power** across the northeastern U.S. and parts of Canada.

The **Northeast Blackout of July 13, 1977**, began when **lightning strikes** knocked out multiple **345-kV transmission lines**, isolating the **Indian Point No. 3 Nuclear Plant** and reducing grid stability. Further strikes and overloading led to the sagging of **Line 92 from Niagara**, cutting off **1,202 MW of power**. A series of **equipment malfunctions and operator errors** ultimately **isolated the Consolidated Edison (Con Ed) system** from the Eastern Interconnect. At the time of separation, Con Ed faced a **1,680 MW power deficit**, prompting automatic **load shedding** of **2,230.6 MW**. However, rapid **voltage surges** caused by underground transmission lines **tripped the Ravenswood No. 3 Generator**, which produced **844 MW**, leading to a **total system collapse**. As a result, **9 million people lost power** in New York City.

The **Western Electric Coordinating Council (WECC) Blackout of July 2, 1996**, began at **2:24 PM** when the **Jim Bridger-Kimport 345-kV line tripped due to sag**, followed by a **relay failure** that also tripped the parallel **Jim Bridger-Goshen line**. Two **generators at Jim Bridger were disconnected**, and while the system initially handled the event, a **faulty relay caused further destabilization**. The **Mill Creek-Antelope 230-kV line** tripped due to another relay failure, leading to **rapid voltage collapse** in **Boise, Idaho**, and along the **California-Oregon Intertie (COI)**. As voltages fell, **four more 230-kV lines between Boise and Brownlee substation tripped**, followed by the **automatic disconnection of the COI** at substations in **southern Oregon**, severing **4,000 MW of power flow**. Within **8 seconds**, the WECC grid split into **five asynchronous islands**, cutting power to **2 million people** across the western U.S.

The **August 10, 1996 WECC blackout** began at **15:48 p.m.** when the **Keeler-Allston 500-kV line contacted a tree** due to **inadequate right-of-way maintenance**, forcing additional lines out of service and **removing hundreds of MVAR**. **Overloads and low voltage conditions** caused further line trips, and **generators at McNary Powerhouse tripped**, leading to **system-wide oscillations**. As the **system became unstable**, **0.224 Hz oscillations spread**, and **shunt capacitor banks** were switched in, but the disturbances were **not damped**. By **15:48:51 p.m.**, oscillations reached **1000 MW and 60 kV peak-to-peak**, triggering **PDCI Remedial Action Schemes (RAS)**. Despite corrective measures, the **WFCC system split into four asynchronous islands**, causing a **major blackout that affected 7.5 million people**.

The **Eastern Interconnection Blackout of August 14, 2003**, began at **1:07 PM** when **FirstEnergy (FE) turned off their state estimator for troubleshooting**. Shortly after, a **generation unit at Eastlake 5 tripped**, followed by a **345-kV line (Stuart-Atlanta) going offline due to tree contact**. System monitoring failures escalated the situation as **FE's control room lost alarm functions**, and by **3:05 PM**, multiple **345-kV lines tripped**, overloading the **138-kV system** and causing voltage collapse. At **4:05 PM**, the loss of 138-kV lines **overloaded the Sammis-Star line**, triggering further failures. By **4:08 PM**, **major 345-kV lines in Ohio tripped**, causing **power swings through New York, Ontario, and Michigan**. As disturbances spread, transmission lines and generators **failed across the region**, leading to a **widespread blackout by 4:13 PM**. The event **knocked 265 power plants offline**, leaving **50 million people without power** across the **Northeastern U.S. and parts of Canada**.

The **Texas Blackout of March 4-5, 2025**, was triggered by a **severe storm system** with **hurricane-force winds (85+ mph)** and an **EF1 tornado** in Irving, TX, causing widespread power disruptions. By **March 4 at 8:30 PM**, wind energy output had declined **18% compared to February 2024**, increasing reliance on fossil fuel generation. At **4:31 AM on March 5**, ERCOT reported a **sudden loss of 795 MW of generation**, causing grid frequency to drop to **59.902 Hz**, while **total load was 41,502 MW**. Voltage instability and transmission failures escalated the crisis, leading to further **interruptions of 4,000 MW of power flow**. By morning, over **400,000 customers lost power** across **Dallas-Fort Worth and North Texas**, with restoration efforts slowed by **severe infrastructure damage and hazardous conditions**. The blackout underscored **Texas' grid vulnerabilities**, highlighting risks from **extreme weather, aging infrastructure, and transmission limitations**.

Summary of Blackouts

1kW = 1 customer. 1MW = 1000 customers.
10,000MW = 10,000,000 customers

Date	Location	Load Interrupted
Tuesday, November 9, 1965	Northeast	20,000 MW
Wednesday, July 13, 1977	New York	6,000 MW
Wednesday, December 22, 1982	West Coast	12,350 MW
Monday, January 17, 1994	California	7,500 MW
Wednesday, December 14, 1994	Wyoming, Idaho	9,336 MW
Tuesday, July 2, 1996	Wyoming, Idaho, other	11,743 MW
Saturday, August 10, 1996	Western Interconnection	30,489 MW
Thursday, June 25, 1998	Midwest	950 MW
Thursday, August 14, 2003	Northeast	61,800 MW
Thursday, September 8, 2011	Southwest (CA, AZ, Baja MX)	~5,000 MW
Monday, October 29, 2012	Eastern U.S. (Hurricane Sandy)	~15,000 MW
Tuesday, October 1, 2019	California (Planned Shutoffs)	~3,000 MW
Friday, August 14, 2020	California (Rolling Blackouts)	~4,000 MW
Sunday, February 14, 2021	Texas Power Crisis	30,000 MW
Friday, December 27, 2024	Puerto Rico	~1,800 MW
Sunday, January 19, 2025	California (Preventive Shutoffs)	~2,500 MW
Tuesday, March 4, 2025	Texas Interconnection	4,000 MW

Split

Cascaded Outage Mess

1. **Disturbance Triggers** – A fault or outage (e.g., tree contact, lightning strike, or relay error) initiates trouble.
2. **System Instability** – Frequency and voltage become unsteady as equipment fails faster than operators can respond.
3. **Grid Splits** – The system “islands” into separate zones, each struggling to balance its own load and generation.
4. **Cascade Begins** – Power reroutes onto remaining lines, causing overloads and additional trips.
5. **Widespread Blackout** – Major sections (or all) of the grid shut down, leaving millions without power.

Automatic Load Shedding

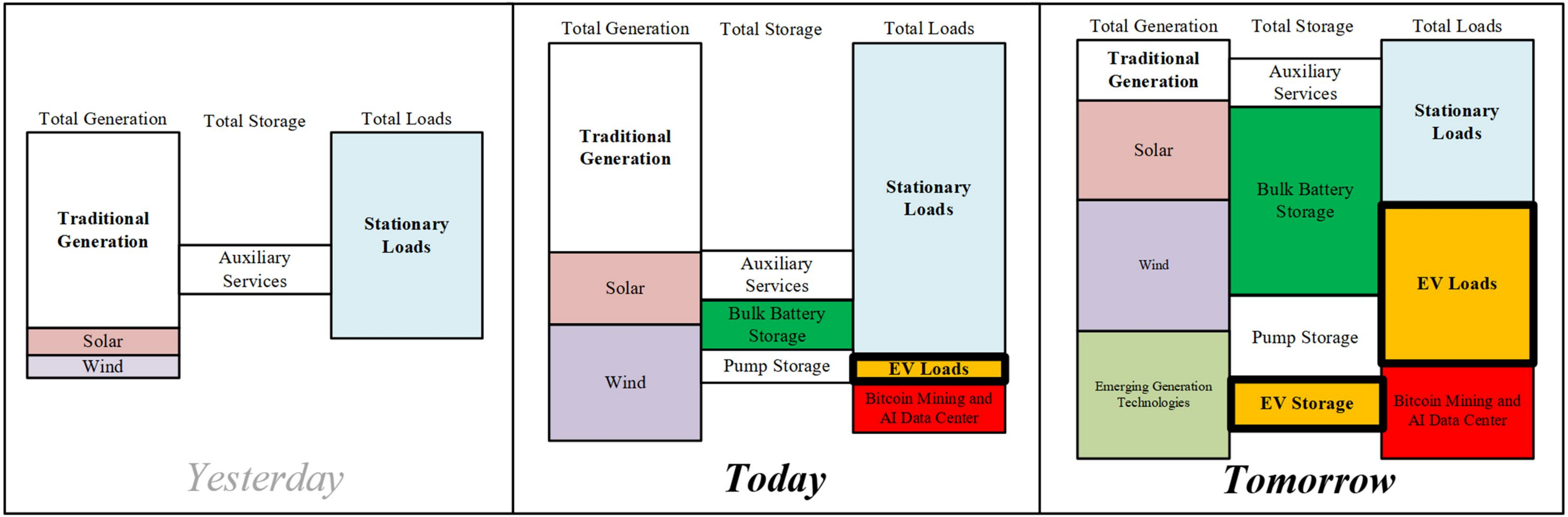
- Under Voltage
- Under Frequency
- Rate of Frequency Decrease
- Remedial Action Scheme

August 10, 1996 (Western Interconnection, 30,489 MW): On this date, a cascading failure knocked out power across the western United States, but subsequent studies showed that dropping just 0.4% of the total system load—about a 30-minute outage—could have prevented the widespread blackout.

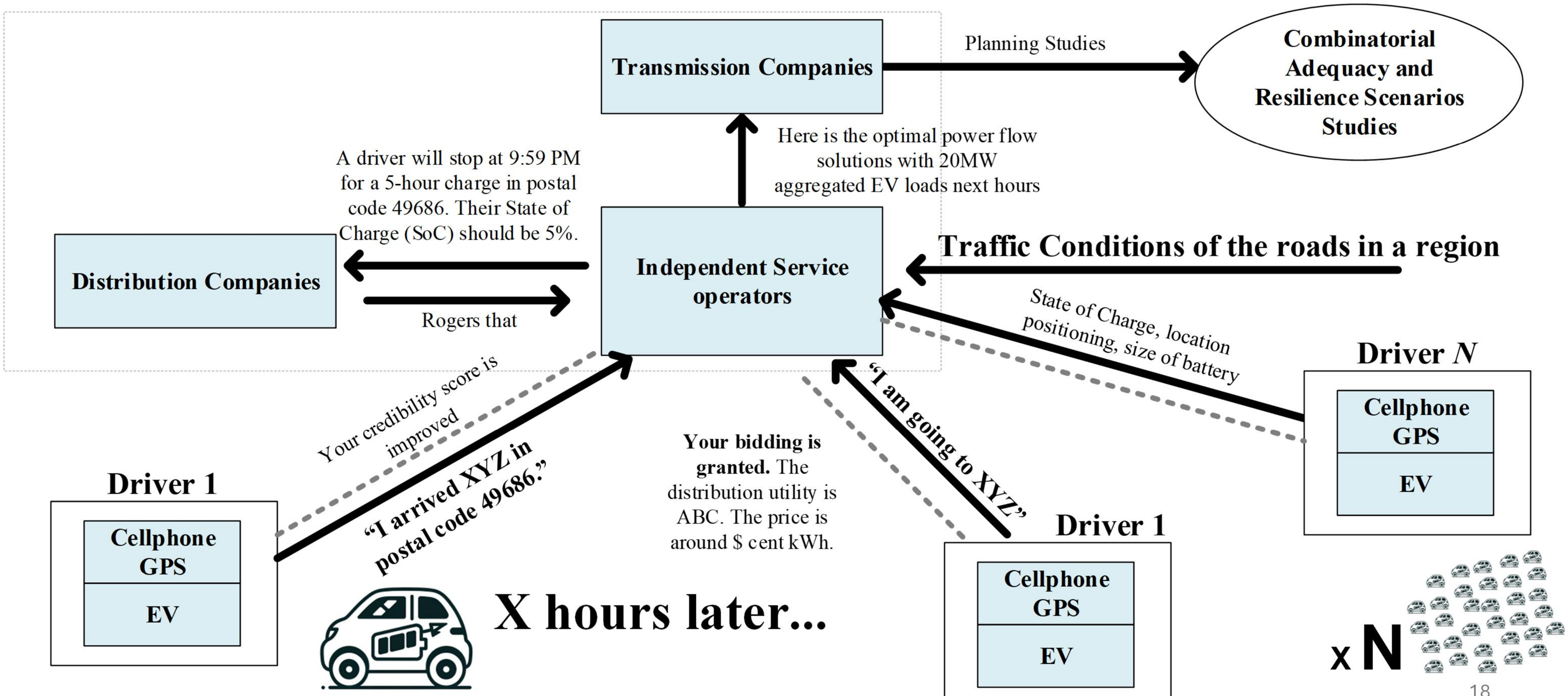
August 14, 2003 (Northeast, 61,800 MW): On this date, a major cascading outage affected the northeastern U.S. and parts of Canada, and the Final NERC Report indicated that shedding 1,500 to 2,500 MW of load in the Cleveland–Akron area *before* the critical Sammis–Star line failed would likely have prevented the massive chain reaction that ensued.

A chain of initiating events triggered cascading outages, and coordination barriers prolonged the decision-making process for remedial measures, ultimately leading to a widespread blackout or brownout.

Balancing Perspective in Adequacy Language



System-Wide Coordination of Vehicular Charging



Cyber-Informed Systems Engineering

- Revisit contingency analysis to extend extreme attack impacts
- What could constitute a great “vital measure” rather than a brain surgery
- Understand the “physics” of cybersecurity technology and “behaviors” of electronic threats
- Connect with grid investment and overlap the grid growth establishment
- Present dollars and metrics demonstrated improvements from the hypothetical scenarios
- Leverage our existing power engineering tools

Cyber-Physical Team Synergy

TEXAS A&M UNIVERSITY

Kate Davis, Associate Professor

Operational Awareness of Cyber-Physical Control Systems and Analytics

Michigan Technological University 1885

Chee-Wooi Ten, Professor

Extreme Contingencies and Cyber-Informed System Planning

COLORADO SCHOOL OF MINES

Alexandra M. Newman, Professor

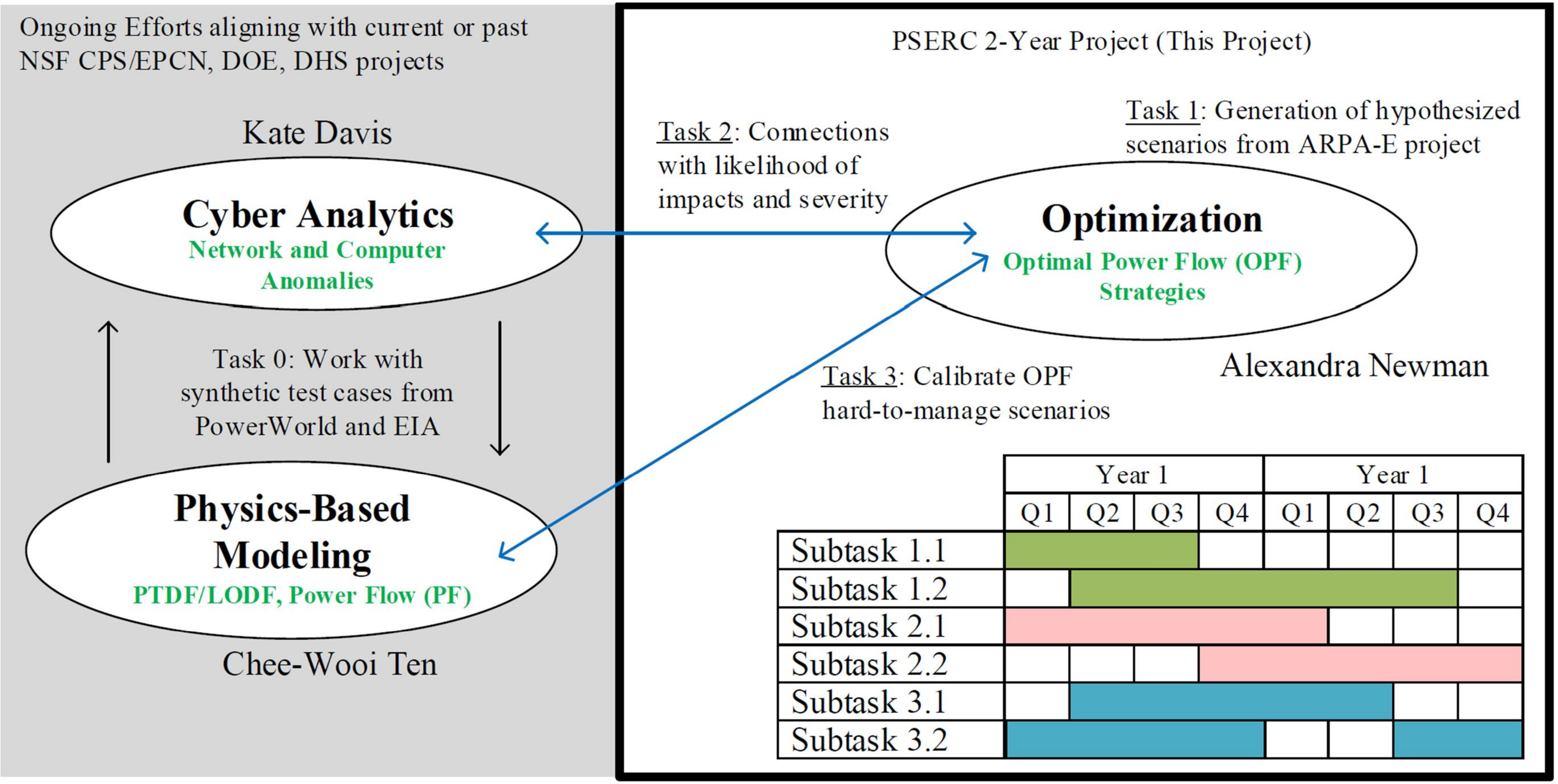
System Optimization Strategies and Validation

PSERC S-112 Project start in Fall 2025: Structural Risk Screening and Strategic Vulnerability Assessment in High-Caliber Optimal Power Flow Under High-Impact Low-Frequency Grid Events

Feedback from Industry Members

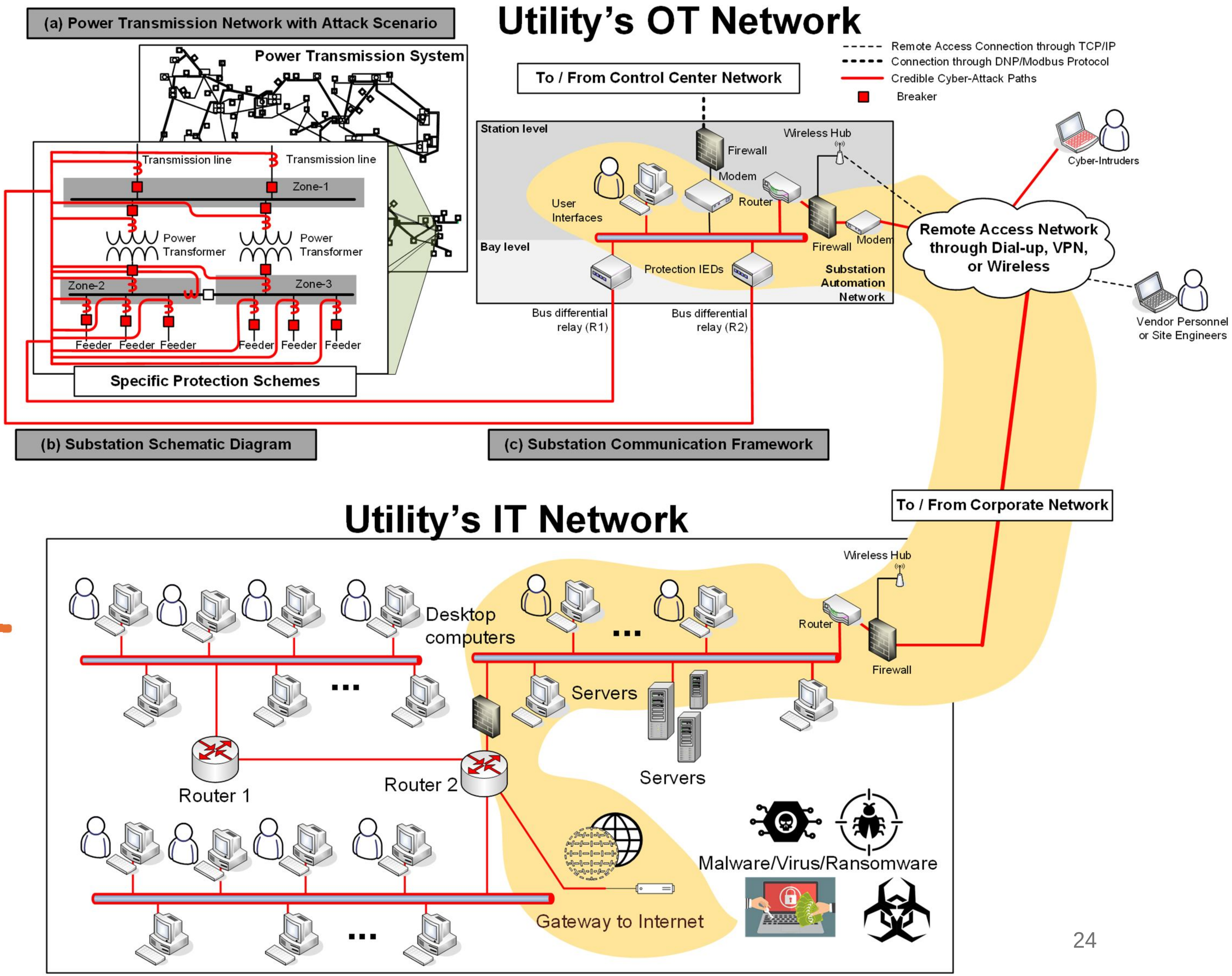
- **Broad and Ambitious Scope:** The proposal is ambitious, raising concerns about its integration with existing NSF, DOE, and DHS projects. While it considers the potential of honeynets for modeling and risk mitigation, challenges such as legal, ethical, and scalability issues remain unclear.
- **Strengthening Cyber-Physical Risk Analysis**: Key aspects, such as estimating probabilities of events and specifying the time horizon for analysis (long-term, operational, or real-time), are unclear.
- **Cyber may be medium priority, but resilience with renewable is high**: While valuable, the proposal is not a top priority for industry stakeholders but extensive contingency for resilience framework is highly desirable.
- **Connecting PTDF/LODF, PF, OPF Framework**: The relationship between OPF, risk assessment, and optimization objectives needs more detail, including inputs, outputs, and integration within the optimization process.

Proposed Tasks of Cyber-Informed Planning Framework



NERC CIP History and Milestones

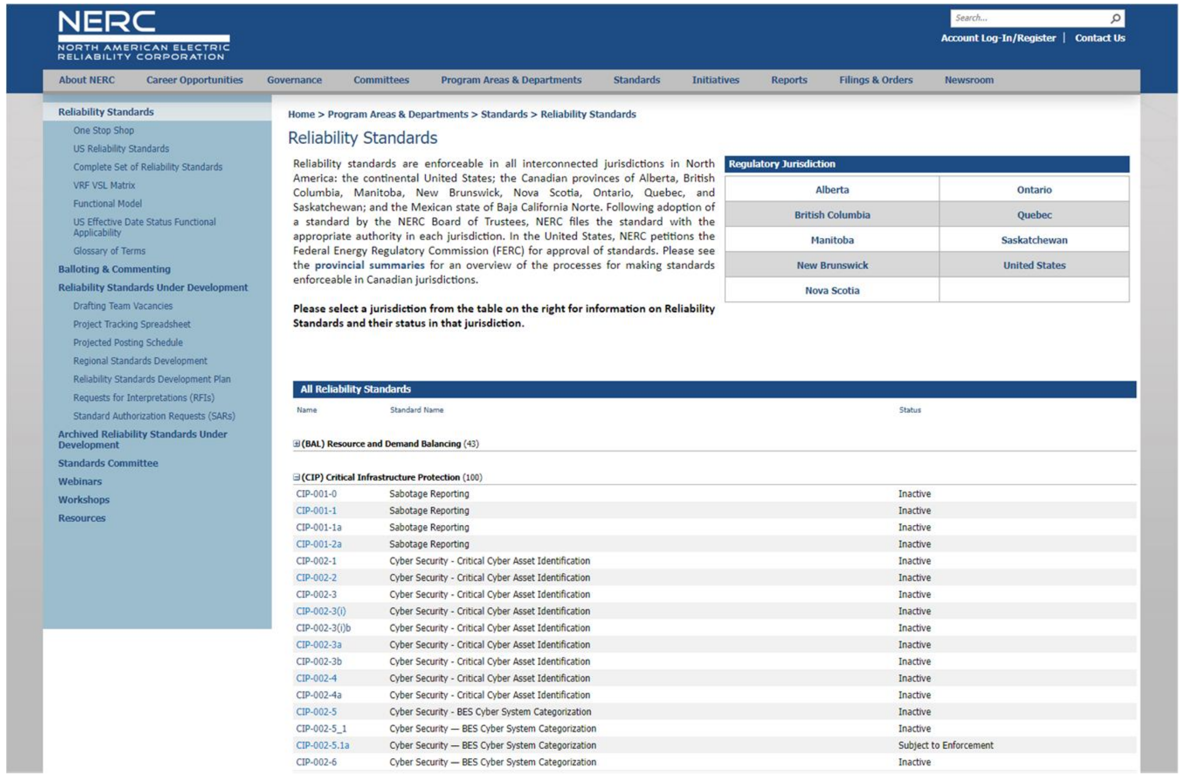
Year	NERC CIP Milestone	NIST Equivalent Milestone
2005	NERC designated as ERO under the U.S. Energy Policy Act.	Introduction of NIST SP 800-53 (Initial Release), setting cybersecurity control baselines for federal information systems.
2008	Initial CIP standards (CIP-002 to CIP-009) become mandatory and enforceable under FERC approval.	NIST SP 800-53 Revision 2, introducing asset identification, access control, and incident response baselines.
2010–2014	Transition to CIP Version 3 with improved clarity and compliance requirements.	Expansion of NIST Cybersecurity Framework (CSF) concepts, emphasizing risk-based categorization of systems.
2016	CIP Version 5 adopted with stricter cybersecurity controls.	NIST SP 800-53 Revision 4, with enhanced requirements for encryption, remote access, and supply chain management.
2018	Development of CIP-013 to address supply chain cybersecurity risks.	NIST SP 800-161 (Supply Chain Risk Management), focusing on third-party risks and vendor assurance.
2020–Present	Ongoing revisions (CIP-010, CIP-012) address emerging threats like cloud computing and DERs.	NIST SP 800-53 Revision 5 and NIST CSF updates, addressing real-time data protection and emerging technologies.
2023	Introduction of Cyber-Informed Transmission Planning Framework (CITPF).	NIST SP 800-82 (Industrial Control Systems Security) updates, aligning operational and cybersecurity planning.



OT & IT Interconnectivity

Most OT attacks start from IT networks

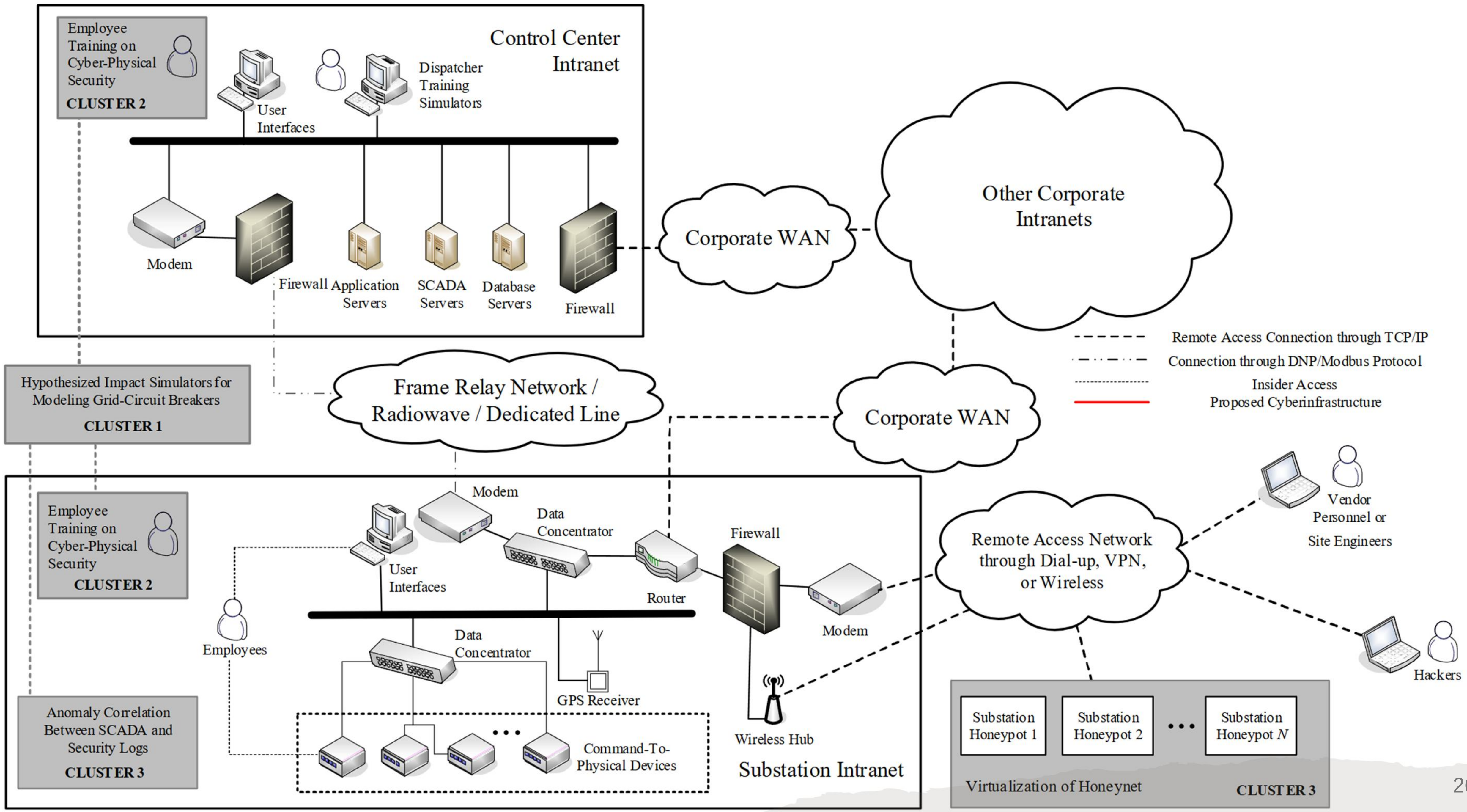
NERC CIP Comparison with Evolving Technologies and Clusters



- ❑ Went through multiple versions since 2006 (CIP 002-009 with CIP001 as physical security)
- ❑ Many terms have been *retired*, *modified*, or *newly proposed* definition, e.g., Electronic Access Control or Monitoring Systems (EACMS) / Electronic Access Point (EAP) / External Routable Connectivity (ERC), Inherent Risk Assessment (IRA) or Interval Control Evaluation (ICE)…
- ❑ The intent of this process is *continuous reporting* and *documentation* from <u>approved baseline</u>
- ❑ Accounting of cyber asset and awareness of incidents and policy improvements
- ❑ What to look for. Not so much on how exactly *qualitatively* and *quantitatively*.

Security Enhancement	**CIP-002**	CIP-003	CIP-004	CIP-005	CIP-006	CIP-007	CIP-008	CIP-009	CIP-010	CIP-011	**CIP-012**	CIP-013	CIP-014	Total Count
Advanced Threat Detection and Response	**0**	0.25	0	0.25	0.25	0.5	1	0.25	1	0	**0**	0	0	3.5
Zero Trust Architecture	**0**	1	0	1	0	1	0	0	0	0	**0**	0	0	3
Quantum-Resistant Encryption	**0**	0	0	1	0	0.5	0	0	0	1	**0**	0	0	2.5
Continuous Vulnerability Scanning and Penetration Testing	**0**	0	0	0	0	0	0	0	1	0	**0**	0	0	1
Automated Response and Orchestration (SOAR)	**0**	0	0	0	0	0.5	1	0	0	0	**0**	0	0	1.5
Red Team/Blue Team Exercises	**0**	0	0	0	0	0.5	1	1	0	0	**0**	0	0	2.5
Supply Chain Security Management	**0**	0	0	0	0	0	0	0	0	0	**0**	1	0	1
Cluster 1 - System Categorization and Controls	**1**	1	0.25	0.25					0.5					3
Cluster 2 - Personnel and Training			1	0.5					0.25					1.75
Cluster 3 - Electronic and Physical Security	**			1	1	0.5					**1**	0.25	0.25	4
Cluster 4 - System and Configuration Management	**			0.5		1			1	0.5		0.25	0.25	3.5
Cluster 5 - Incident and Recovery Management							1	1	0.5			0.25	0.25	3
Cluster 6 - Information and Communication Security						0.5				1	**0.5**	0.25	0.25	2.5
Cluster 7 - Supply Chain Security	**			0.5					0.25			1	1	2.75

Control center and substation framework with consideration for newly adopted cyberinfrastructure



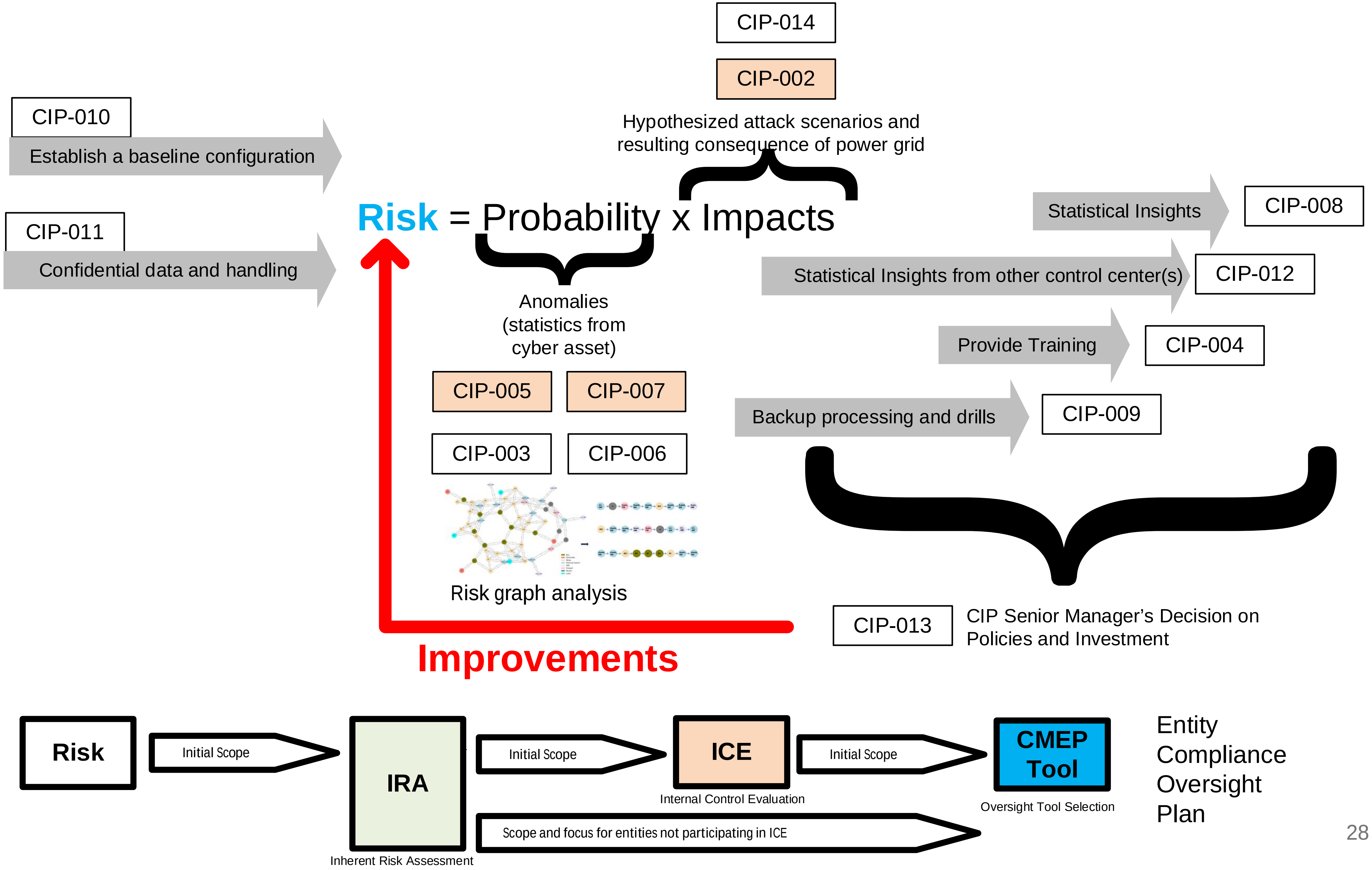
Risk-Based Assessment

Hypothesized attack scenarios and resulting consequence

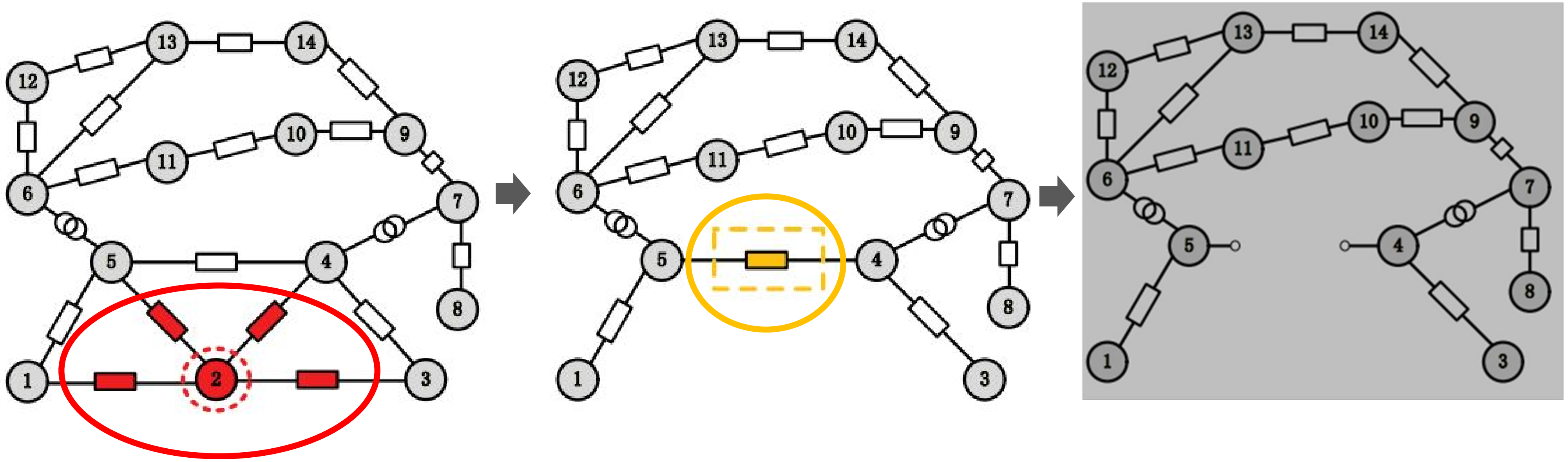
$$\textbf{Risk} = \underbrace{\text{Probability}}_{\text{Anomalies (statistics from cyber asset)}} \times \overbrace{\text{Impacts}}^{\text{Hypothesized attack scenarios and resulting consequence}}$$

Anomalies (statistics from cyber asset)

Risk-Based Assessment and Relation to NERC CIP



Modeling the Disruptive Switching and Cascading Effects



(a) Initial topology of a substation under attack *G*(*V*,*E*)

(b) Overloaded line incurred from the switching attack G'(V',E')

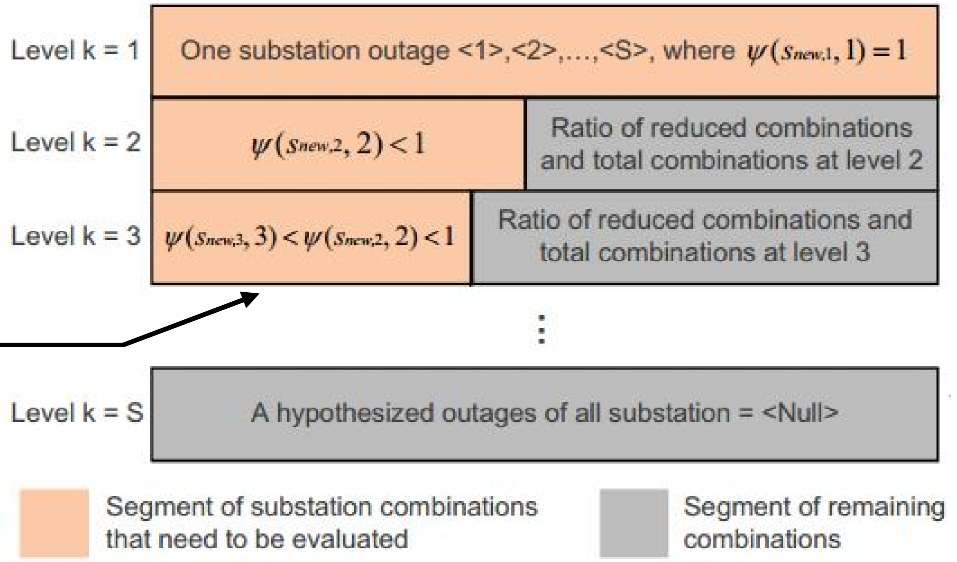
(c) Cascading line outage under the same attack scenario G''(V',E'')

$$\underbrace{G(V,E)}_{\text{(a) Original } G} \xrightarrow[\text{cyberattack}]{\text{Switching}} \underbrace{V'(G') = V(G) \setminus V_k \subset S_{sub}}_{\text{(b) Hypothesized substations outages}} \xrightarrow[\text{overloading}]{\text{Potential}} \underbrace{E'(G'') = E(G') \setminus E_k \subset \mathcal{L}}_{\text{(c) Overloading outages}}$$

Zhiyuan Yang, Chee-Wooi Ten, and Andrew Ginter, "Extended Enumeration of Hypothesized Substations Outages Incorporating Implications of Overloading," To appear in IEEE Transactions on Smart Grid. <10.1109/TSG.2017.2728792>

Enumeration Model

Enumeration from k = 1 to S' with decreasing ratio $\Psi(.)$



$$\psi(s_{new,k}, k) = \begin{cases} \dfrac{s_{new,1}}{\mathbf{C}_1^S} = 1.0, & k = 1 \\ \dfrac{s_{new,2}}{\mathbf{C}_2^S} < 1.0, & k = 2 \\ \dfrac{s_{new,k}}{\mathbf{C}_k^S} < \dfrac{s_{new,k-1}}{\mathbf{C}_{k-1}^S} < 1.0, & k \geq 3 \end{cases}$$

$$s_{new,k} = \left(\mathbf{C}_k^S - \chi\right)$$

where χ is the total reduction number that was extracted from the last level $\mathbf{SS}_{failed}(k-1)$

At level k:

$$\mathbf{SS}_{failed}(k) = \mathbf{PF}_{failed}\big(G'(k)\big) \bigcup \mathbf{PF}_{failed}\big(G''(k)\big)$$

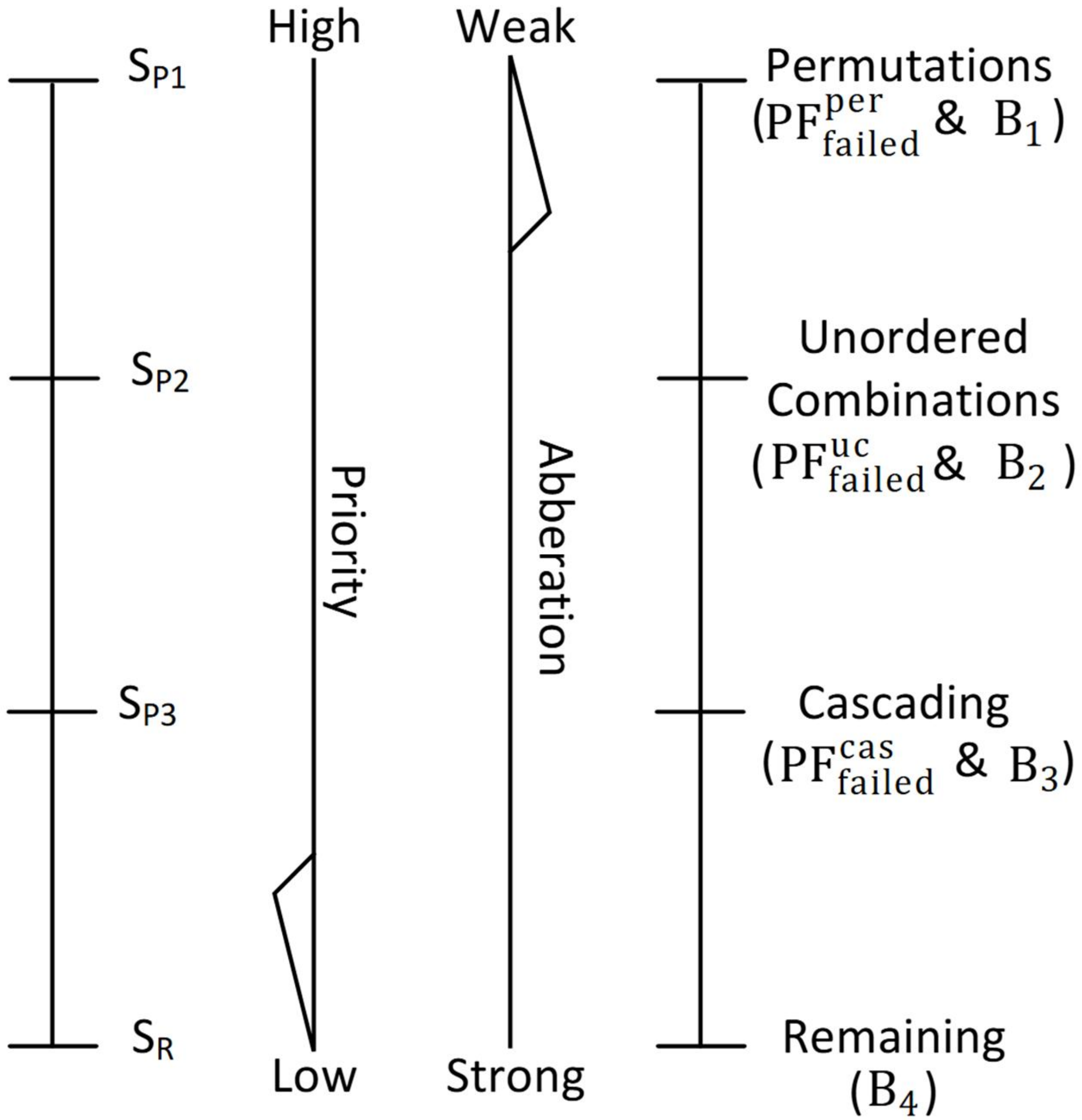
⋮

Summarize,

$$ss_{failed} = \mathbf{SS}_{failed}(1) \cup \mathbf{SS}_{failed}(2) \cup \cdots \mathbf{SS}_{failed}(S')$$

Where, $\mathbf{PF}_{failed}(\cdot) \in [0,1]$ indicates either a converged or diverged outcome, respectively.

Stage Priority Versus Introduced Aberrant Behavior



- The diagram describes the relation to stage designation and aberrant behavior within a power system.
- The use of B_1, B_2, B_3, B_4 allows for a subset of substations within the system to be assigned to the respective stage.
- The PF^{per}_{failed}, PF^{uc}_{failed}, PF^{cas}_{failed} indicates how the substations are selected through diverged power flow under conditions of ordered substation removal (PF^{per}_{failed}), unordered substation removal (PF^{uc}_{failed}), and cascading (PF^{cas}_{failed}).

Definition of Stages

Stage Selection: Utilizes a priority framework of three stages with an additional stage accounting for remaining substations.

Stage 1–Priority 1, $\mathbf{S_{P1}}$, (ordered removal, one at a time): Use 'permutation' (remove a single substation at a time, run power flow, remove additional substations as needed) up to a desired k level.

Stage 2–Priority 2, $\mathbf{S_{P2}}$, (unordered combination removal): Exclude any substation in the priority 1 stage. Next start at the S-2 level and remove 'unordered combinations' up to a desired k level.

Stage 3–Priority 3, $\mathbf{S_{P3}}$, (cascading included): Exclude all substations included in priority 1 and 2 stages. Start at the S-1 level and remove unordered combinations. Also remove any overloaded lines caused due to cascading.

Stage 4–Remaining, $\mathbf{S_R}$, (low/no priority): All remaining substations excluding priority 1, priority 2, and priority 3 stage substations are included.

Strategies

Strategy 1: Power Flow Validation: Uses power flow for determining substation cases assigned to batches based on its convergence

Strategy 2: Optimal Power Flow Validation: Uses optimal power flow for determining substation cases assigned to batches based on its convergence

Strategy 3: With Cascading Effects: Impose overloads line upon contingency analysis where this would be removed if a certain threshold exceeds.

Defining the Priorities of Strategy 1

Terms:

$L_1, L_2, L_3,$ and L_4: Listings of substation combinations (permutations, unordered combinations, unordered combinations with cascading effects, and remaining elements) to be evaluated for batch consideration

$\mathrm{PF}_{\text{failed}}^{\text{per}}, \mathrm{PF}_{\text{failed}}^{\text{uc}},$ and $\mathrm{PF}_{\text{failed}}^{\text{cas}}$: Used to evaluate the listings through divergence in power flow for their respective priority levels

Stage Priority 1 Definitions

$$\mathrm{L}_1 = \bigcup_{n=1}^{k} \{(x_1, x_2, \ldots, x_n) \mid x_i \in S, x_1 \neq x_2 \neq \ldots \neq x_n\} \forall k = 1 \cdots k_1$$

$$\mathrm{PF}_{\text{failed}}^{\text{per}} = \mathbb{I}\left(\exists \ell \in L_1 \mid \mathrm{PowerFlow}(\ell) = \mathrm{Diverged}\right)$$

Stage Priority 2 Definitions

$$\mathrm{L}_2 = \bigcup_{n=2}^{k} \{\{x_1, x_2, \ldots, x_n\} \mid x_i \in S, x_1 \neq x_2 \neq \ldots \neq x_n\} \forall k_1 \cdots k_{m_1}$$

$$\mathrm{PF}_{\text{failed}}^{\text{uc}} = \mathbb{I}\left(\exists \ell \in L_2 \mid \mathrm{PowerFlow}(\ell) = \mathrm{Diverged}\right)$$

Stage Priority 3 Definitions

$$\mathrm{L}_3 = \bigcup_{n=1}^{k} \{\{x_1, x_2, \ldots, x_n\} \mid x_i \in S, x_1 \neq x_2 \neq \ldots \neq x_n\} \forall k_{m_1} \cdots k_{m_2}$$

$$\mathrm{PF}_{\text{failed}}^{\text{uc}} = \mathbb{I}\left(\exists \ell \in L_3 \mid \mathrm{PowerFlow}(\ell + \ell^{\text{over}}) = \mathrm{Diverged}\right)$$

Stage Remaining Definitions

$$\mathrm{L}_4 = S \setminus (L_1 \cup L_2 \cup L_3) \forall k_{m_2} \cdots k_n$$

Batch Definition for Strategy 1

Notation: Determine if a substation x from the set $\mathcal{S}$ belongs in the batch subset based on the following criteria: 1) Impact Factor Threshold, 2) Power Flow Convergence.

$$B_1 = \{\ell \in L_1 \mid \mathcal{I}(x) > \tau_1, \mathrm{PF}^{\mathrm{per}}_{\mathrm{failed}} = 1\} \forall 1 \cdots k_1$$
$$B_2 = \{\ell \in L_2 \setminus B_1 \mid \mathcal{I}(x) > \tau_2, \mathrm{PF}^{\mathrm{uc}}_{\mathrm{failed}} = 1\} \forall k_1 \cdots k_{m_1}$$
$$B_3 = \{\ell \in L_3 \setminus (B_1 \cup B_2) \mid \mathcal{I}(x) > \tau_3, \mathrm{PF}^{\mathrm{cas}}_{\mathrm{failed}} = 1\} \forall k_{m_2} \cdots k_{m_2}$$
$$B_4 = \{L_4 \cup \mathcal{S} \setminus (B_1 \cup B_2 \cup B_3)\} \forall k_{m_2} \cdots k_n$$

Additional Parameters (Batch Definition):

ℓ: elements of the list L_k belonging to batch B_k

$\mathcal{I}$: Impact factor related to each batch B_k

τ_k: threshold for impact factor at a level k

Defining the Priorities of Strategy

Terms:

$L_1, L_2, L_3,$ and L_4: Listings of substation combinations (permutations, unordered combinations, unordered combinations with cascading effects, and remaining elements) to be evaluated for batch consideration

$\mathrm{OPF}^{\mathrm{per}}_{\mathrm{failed}}, \mathrm{OPF}^{\mathrm{uc}}_{\mathrm{failed}},$ and $\mathrm{OPF}^{\mathrm{cas}}_{\mathrm{failed}}$: Used to evaluate the listings through divergence in optimal power flow for their respective priority levels

Stage Priority 1 Definitions

$$\mathrm{L}_1 = \bigcup_{n=1}^{k} \{(x_1, x_2, \ldots, x_n) \mid x_i \in S, x_1 \neq x_2 \neq \ldots \neq x_n\} \forall k = 1 \cdots k_1$$

$$\mathrm{OPF}^{\mathrm{per}}_{\mathrm{failed}} = \mathbb{I}\left(\exists \ell \in L_1 \mid \mathrm{OptimalPowerFlow}(\ell) = \mathrm{Diverged}\right)$$

Stage Priority 2 Definitions

$$\mathrm{L}_2 = \bigcup_{n=2}^{k} \{\{x_1, x_2, \ldots, x_n\} \mid x_i \in S, x_1 \neq x_2 \neq \ldots \neq x_n\} \forall k_1 \cdots k_{m_1}$$

$$\mathrm{OPF}^{\mathrm{uc}}_{\mathrm{failed}} = \mathbb{I}\left(\exists \ell \in L_2 \mid \mathrm{OptimalPowerFlow}(\ell) = \mathrm{Diverged}\right)$$

Stage Priority 3 Definitions

$$\mathrm{L}_3 = \bigcup_{n=1}^{k} \{\{x_1, x_2, \ldots, x_n\} \mid x_i \in S, x_1 \neq x_2 \neq \ldots \neq x_n\} \forall k_{m_1} \cdots k_{m_2}$$

$$\mathrm{OPF}^{\mathrm{uc}}_{\mathrm{failed}} = \mathbb{I}\left(\exists \ell \in L_3 \mid \mathrm{OptimalPowerFlow}(\ell + \ell^{\mathrm{over}}) = \mathrm{Diverged}\right)$$

Stage Remaining Definitions

$$\mathrm{L}_4 = S \setminus (L_1 \cup L_2 \cup L_3) \forall k_{m_2} \cdots k_n$$

Batch Definition for Strategy 2

Notation: Determine if a substation x from the set $\mathcal{S}$ belongs in the batch subset based on the following criteria: 1) Impact Factor Threshold, 2) Optimal Power Flow Convergence.

$$
\begin{aligned}
B_1 &= \{\ell \in L_1 \mid \mathcal{I}(x) > \tau_1, \mathrm{OPF}^{\mathrm{per}}_{\mathrm{failed}} = 1\} \forall 1 \cdots k_1 \\
B_2 &= \{\ell \in L_2 \setminus B_1 \mid \mathcal{I}(x) > \tau_2, \mathrm{OPF}^{\mathrm{uc}}_{\mathrm{failed}} = 1\} \forall k_1 \cdots k_{m_1} \\
B_3 &= \{\ell \in L_3 \setminus (B_1 \cup B_2) \mid \mathcal{I}(x) > \tau_3, \mathrm{OPF}^{\mathrm{cas}}_{\mathrm{failed}} = 1\} \forall k_{m_2} \cdots k_{m_2} \\
B_4 &= \{L_4 \cup \mathcal{S} \setminus (B_1 \cup B_2 \cup B_3)\} \forall k_{m_2} \cdots k_n
\end{aligned}
$$

Additional Parameters (Batch Definition):

ℓ: elements of the list L_k belonging to batch B_k

$\mathcal{I}$: Impact factor related to each batch B_k

τ_k: threshold for impact factor at a level k

Cyberinfrastructure Investment Strategies

Objective: Minimize total investment costs across stages (maximum of j). There can be j priority stages and one remaining stage.

$$
\min \quad \underbrace{C_{\text{fix}}^{\text{inv}} \cdot T_{\text{horz}}^{\text{inv}} + \sum_{\substack{s_1 \in B_1 \\ \forall k=1\cdots k_1}} \left(\mathbb{E}\left[C_{\text{base},pr_1}^{\text{inv}} \cdot (1 + r_{\text{inf},pr_1})^t \right] + \frac{\alpha_1}{B_{1,\text{size}}} \cdot \ln x_{s_1,pt} + \mathbb{E}\left[C_{\text{lab},pr_1}^{\text{inv}} \cdot (1 + r_{\text{lab},pr_1})^t \right] \cdot x_{s_1,at} \right)}_{\text{Stage 1 Priority } S_{P1}}
$$

$$
\underbrace{+ \sum_{i=2}^{j} \sum_{\substack{s_i \in B_i \\ \forall k_1 \cdots k_m}} p_i \left(\mathbb{E}\left[C_{\text{base},pr_i}^{\text{inv}} \cdot (1 + r_{\text{inf},pr_i})^t \right] + \frac{\alpha_i}{B_{i,\text{size}}} \cdot \ln x_{s_i,pt} + \mathbb{E}\left[C_{\text{lab},pr_i}^{\text{inv}} \cdot (1 + r_{\text{lab},pr_i})^t \right] \cdot x_{s_i,at} \right)}_{\text{Stage 2 through } j \text{ Priority } S_{P2} \text{ through } S_{Pj}}
$$

$$
\underbrace{+ \sum_{\substack{s_R \in B_R \\ \forall k_m \cdots k_n}} p_R \left(\mathbb{E}\left[C_{\text{base},pr_R}^{\text{inv}} \right] \cdot x_{s_R,pt} + \mathbb{E}\left[C_{\text{lab},pr_R}^{\text{inv}} \cdot (1 + r_{\text{lab},pr_R})^t \right] \cdot x_{s_R,at} \right)}_{\text{Stage Remaining } S_R}
$$

Additional Parameters (Constraints):

l_{ji}: Labor costs.

$B_{\text{inv}}^{\text{cyb}}$: Cyberinfrastructure investment budget.

β : Scaling factor for required for minimum budget to use.

α: Scaling factor for maximum amount to spend on labor.

η_k: Scaling factor for maximum amount to spend per batch based on k level.

Constraints:

1. **Total Budget:** Investment not to exceed total budget:

$$\sum_{j=1}^{B_k} \sum_{i=1}^{S_k} C(x_{ji}) + \sum_{j=1}^{B_k} \sum_{i=1}^{S_k} l_{ji} \cdot x_{ji} \leq B_{\text{inv}}^{\text{cyb}}$$

2. **Substation Investment:** Maximum investment per substation:

$$C(x_{ji}) + l_{ji} \cdot x_{ji} \leq \frac{B_{\text{inv}}^{\text{cyb}}}{S_T} \quad \forall ji \in \mathcal{S}$$

3. **Minimum Investment:** Smallest amount of budget that must be used:

$$\sum_{j=1}^{B_k} \sum_{i=1}^{S_k} C(x_{ji}) + \sum_{j=1}^{B_k} \sum_{i=1}^{S_k} l_{ji} \cdot x_{ji} \geq \beta \cdot B_{\text{inv}}^{\text{cyb}}$$

4. **Labor Costs:** Maximum budget allocated to labor:

$$\sum_{j=1}^{B_k} \sum_{i=1}^{S_T} l_{ji} \cdot x_{ji} \leq \alpha \cdot B_{\text{inv}}^{\text{cyb}}$$

5. **Batch Priority:** Prioritize investment in earlier batches

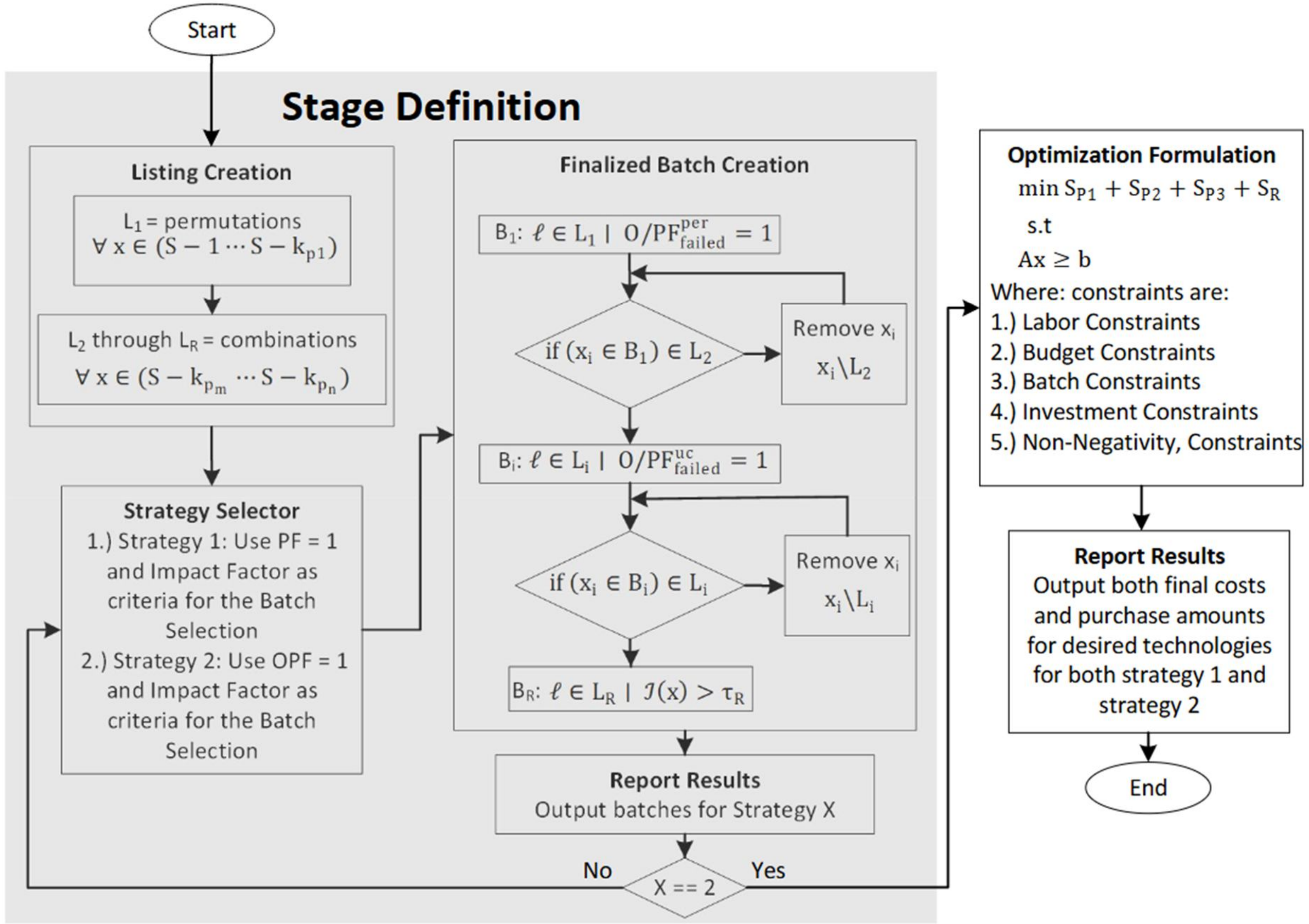
$$\alpha_k \cdot \sum_{j=1}^{B_{k-1}} \sum_{i=1}^{S_{k-1}} C(x_{ji}) > \sum_{j=1}^{B_k} \sum_{i=1}^{S_k} C(x_{ji})$$

6. **Maximum Batch Investment**: Maximum amount of investment per batch

$$\sum_{j=1}^{B_k} \sum_{i=1}^{S_k} C(x_{ji}) \leq \eta_k \cdot B_{\text{inv}}^{\text{cyb}}$$

7. **Non-negativity**: make sure decision variables are not negative

Flowchart for Detailed Algorithm



Simulated Statistics With Strategies 1 & 2

			Strategy 1a: PF Validation						Strategy 2a: OPF Validation					
IEEE Case Number	S-k Level	Total Cases	Removed Cases	Filtered Cases	PF Failures Count	% Failed	List Creation Time (s)	Total Time (s)	Removed Cases	Filtered Cases	OPF Failures Count	% Failed	List Creation Time (s)	Total Time (s)
30-Bus	S-1	30	-	30	5	16.67	0.001	0.812	-	30	12	40.00	0.017	4.959
	S-2	435	135	300	20	6.67	0.002	8.267	282	153	4	2.61	0.015	7.449
	S-3	4,060	2,166	1,894	14	0.74	0.043	70.682	3,304	756	-	-	0.027	45.785
	S-4	27,405	18,847	8,558	33	0.39	0.355	61.204	24,766	2,639	15	0.57	0.203	23.403
	S-5	142,506	114,633	27,873	11	0.04	3.383	98.552	135,888	6,618	29	0.44	0.587	74.704
	S-6	593,775	525,471	68,304	3	0.00	29.487	224.765	581,379	12,396	29	0.23	2.576	92.057
	S-7	2,035,800	-	-	-	-	-	-	2,018,122	17,678	17	0.10	6.745	121.420
	S-8	5,852,925	-	-	-	-	-	-	5,833,585	19,340	8	0.04	15.808	130.360
	S-9	14,307,150	-	-	-	-	-	-	14,290,876	16,274	1	0.01	27.595	101.204
39-Bus	S-1	39	-	39	21	53.85	0.000	1.041	-	39	21	53.85	0.009	1.539
	S-2	741	588	153	4	2.61	0.005	7.793	588	153	12	7.84	0.011	9.121
	S-3	9,139	8,383	756	0	-	0.056	5.901	8,493	646	37	5.73	0.063	8.306
	S-4	82,251	79,612	2,639	15	0.57	0.369	19.148	80,608	1,643	28	1.70	0.459	20.583
	S-5	575,757	569,139	6,618	29	0.44	2.272	47.322	573,041	2,716	49	1.80	2.366	34.230
	S-6	3,262,623	3,250,227	12,396	29	0.23	11.052	86.264	3,259,954	2,669	62	2.32	10.669	34.410
	S-7	15,380,937	15,363,259	17,678	17	0.10	43.269	119.914	15,379,552	1,385	24	1.73	43.993	21.061
	S-8	61,523,748	61,504,408	19,340	8	0.04	159.177	133.011	61,523,411	337	2	0.59	153.111	22.402
	S-9	211,915,132	-	-	-	-	-	-	211,915,094	38	-	-	507.172	3.171

			Strategy 1a: PF Validation w/ BESS						Strategy 2a: OPF Validation w/ BESS					
IEEE Case Number	S-k Level	Total Cases	Removed Cases	Filtered Cases	PF Failures Count	% Failed	List Creation Time (s)	Total Time (s)	Removed Cases	Filtered Cases	OPF Failures Count	% Failed	List Creation Time (s)	Total Time (s)
30-Bus	S-1	30	-	30	5	16.67	0.010	2.287	-	30	11	36.67	0.01	4.87
	S-2	435	135	300	20	6.67	0.024	9.059	264	171	9	5.26	0.01	12.35
	S-3	4,060	2,166	1,894	11	0.58	0.049	37.679	3,226	834	2	0.24	0.03	17.69
	S-4	27,405	18,809	8,596	25	0.29	0.320	58.952	24,503	2,902	5	0.17	0.10	33.90
	S-5	142,506	114,322	28,184	9	0.03	2.680	98.556	135,235	7,271	9	0.12	0.40	102.93
	S-6	593,775	524,188	69,587	3	0.00	33.398	244.247	-	-	-	-	-	-
39-Bus	S-1	39	-	39	12	30.77	0.005	2.577	-	39	21	53.85	0.00	3.18
	S-2	741	390	351	9	2.56	0.010	9.917	588	153	41	26.80	0.01	13.82
	S-3	9,139	6,432	2,707	61	2.25	0.055	16.185	8,746	393	19	4.83	0.05	34.52
	S-4	82,251	68,335	13,916	121	0.87	1.198	69.258	81,499	752	38	5.05	0.30	16.42
	S-5	575,757	524,741	51,016	782	1.53	22.055	170.451	574,994	763	26	3.41	1.57	10.19
	S-6	3,262,623	3,133,258	129,365	791	0.61	221.416	438.832	-	-	-	-	-	-
	S-7	15,380,937	15,150,687	230,250	171	0.07	705.051	754.228	-	-	-	-	-	-
	S-8	61,523,748	61,239,102	284,646	12	0.00	1358.915	930.318	-	-	-	-	-	-

Simulated Statistics With Strategies 1 & 2 + 3

			Strategy 1b: PF Validation Cascaded							Strategy 2b: OPF Validation Cascaded					
IEEE Case Number	S-k Level	Total Cases	Removed Cases	Filtered Cases	Total Branches Removed	PF Failures Count	% Failed	List Creation Time (s)	Total Time (s)	Removed Cases	Filtered Cases	OPF Failures Count	% Failed	List Creation Time (s)	Total Time (s)
30-Bus	S-1	30	-	30	4	7	23.3333	0.000184	1.207986	-	30	12	40.0000	0.004264	2.301727
	S-2	435	182	253	14	18	7.1146	0.001557	8.843257	282	153	1	0.6536	0.007174	12.71901
	S-3	4,060	2,609	1,451	81	27	1.8608	0.027817	25.84217	3,304	756	1	0.1323	0.018164	17.26352
	S-4	27,405	21,641	5,764	333	68	1.1797	0.261546	30.13834	24,789	2,616	6	0.2294	0.083044	31.30202
	S-5	142,506	126,510	15,996	609	34	0.2126	1.902736	80.56126	-	-	-	-	-	-
	S-6	593,775	561,054	32,721	1,059	28	0.0856	10.05601	116.3948	-	-	-	-	-	-
	S-7	2,035,800	1,985,314	50,486	1,314	4	0.0079	28.6009	178.5137	-	-	-	-	-	-
	S-8	5,852,925	5,792,858	60,067	1,195	0	-	48.20385	205.4204	-	-	-	-	-	-
	S-9	14,307,150	14,251,291	55,859	731	1	0.0018	57.19189	194.9	-	-	-	-	-	-
39-Bus	S-1	39	-	39	13	20	51.2821	0.000275	1.615513	-	39	21	53.8462	0.003375	2.321113
	S-2	741	570	171	93	45	26.3158	0.00483	7.318884	588	153	14	9.1503	0.006367	12.23011
	S-3	9,139	8,752	387	49	27	6.9767	0.053477	11.67725	8,521	618	28	4.5307	0.042147	7.86019
	S-4	82,251	81,732	519	12	5	0.9634	0.299553	51.48556	80,724	1,527	62	4.0602	0.302523	18.87962
	S-5	575,757	-	-	-	-	-	-	-	573,593	2,164	55	2.5416	1.731779	26.557
	S-6	3,262,623	-	-	-	-	-	-	-	3,260,849	1,774	18	1.0147	7.375296	19.73755
	S-7	15,380,937	-	-	-	-	-	-	-	15,380,100	837	4	0.4779	29.21853	9.747902
	S-8	61,523,748	-	-	-	-	-	-	-	-	-	-	-	-	-
	S-9	211,915,132	-	-	-	-	-	-	-	-	-	-	-	-	-

Simulated Statistics for A Larger Test System

Invesment Data

Strategy 1a: PF Validation Data / Strategy 1a: Critical Substations

IEEE Case Number	S-k Level	Total Cases	Removed Cases	Filtered Cases	PF Failures Count	%Failed	List Creation Time (s)	Total Time (s)	Unique Cases per S-k Level *(first appearance in a particular S-k Level)*	Unique Cases Across All Levels *(first appearance)*	Improvement Factor (%reduced)	Improvement Number
118-Bus	S-1	118	5	113	7	6.19	0.0020	1.5832	12, 68, 71, 85, 86, 100, 110	12, 68, 71, 85, 86, 100, 110	22.22	2
	S-2	6903	1338	5565	83	1.49	0.0847	77.4183	10, 11, 15, 17, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 38, 40, 42, 43, 44, 45, 46, 47, 49, 50, 51, 52, 53, 54, 56, 57, 59, 61, 62, 64, 65, 66, 69, 70, 72, 75, 76, 77, 78, 79, 80, 81, 82, 83, 89, 90, 91, 92, 94, 96, 101, 103, 105, 106, 108, 109, 114, 115, 118	10, 11, 15, 17, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 38, 40, 42, 43, 44, 45, 46, 47, 49, 50, 51, 52, 53, 54, 56, 57, 59, 61, 62, 64, 65, 66, 69, 70, 72, 75, 76, 77, 78, 79, 80, 81, 82, 83, 89, 90, 91, 92, 94, 96, 101, 103, 105, 106, 108, 109, 114, 115, 118	16	12
	S-3	266916	82394	184522	162	0.09	121.7167	514.0960	10, 11, 13, 14, 15, 16, 17, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 37, 38,	13, 14, 16, 33, 48, 58, 60, 63, 67, 98, 99, 102, 104, 111	0	0
										Total Reduction (All Levels)	24.49	24

***Fixed: 2, 3, 5, 8, 9 Substations**	**5 Substations Fixed**

Invesment Data

Strategy 2a: OPF Validation Data / Strategy 2a: Critical Substations

IEEE Case Number	S-k Level	Total Cases	Removed Cases	Filtered Cases	PF Failures Count	%Failed	List Creation Time (s)	Total Time (s)	Unique Cases per S-k Level *(first appearance in a particular S-k Level)*	Unique Cases Across All Levels *(first appearance)*	Improvement Factor (%reduced)	Improvement Number
118-Bus	S-1	118	5	113	56	49.56	0.0258	6.4957	1, 4, 6, 10, 12, 15, 18, 19, 24, 25, 26, 27, 31, 32, 34, 36, 40, 42, 46, 49, 54, 55, 56, 59, 61, 62, 65, 66, 68, 69, 70, 71, 72, 73, 74, 76, 77, 80, 85, 86, 87, 89, 90, 91, 92, 99, 100, 103, 104, 105, 107, 110, 111, 112, 113, 116	1, 4, 6, 10, 12, 15, 18, 19, 24, 25, 26, 27, 31, 32, 34, 36, 40, 42, 46, 49, 54, 55, 56, 59, 61, 62, 65, 66, 68, 69, 70, 71, 72, 73, 74, 76, 77, 80, 85, 86, 87, 89, 90, 91, 92, 99, 100, 103, 104, 105, 107, 110, 111, 112, 113, 116	3.45	2
	S-2	6903	5307	1596	6	0.38	0.1731	29.1039	20, 21, 22, 23, 43, 45, 51, 53, 94, 96	20, 21, 22, 23, 43, 45, 51, 53, 94, 96	33.33	5
	S-3	266916	237984	28932	2	0.01	5.2872	381.5602	45, 47, 48, 82, 94, 97	47, 48, 82, 97	80.00	16
										Total Reduction (All Levels)	24.73	23

***Fixed: 2, 3, 5, 8, 9 Substations**	**5 Substations Fixed**

Thank you for considering!

Together, we will advance the cybersecurity and resilience of electric utilities