



Distribution System Operator with Resiliency Integration and Stakeholder Evaluation (DSO-RISE)

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Monish Mukherjee, Shiva Poudel, Min Gyung Yu, Manisha Maharjan, Trevor Hardy, Sadie Bender, Hayden Reeve



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Collaboration from Grad School and Beyond



A Framework to Quantify the Value of Operational Resilience for Electric Power Distribution Systems

Manish Mukherjee, Steve Paudyal, Anamika Debroy, and Arpan Bose
School of Electrical Engineering and Computer Science

Distributed Generator Sizing for Joint Optimization of Resilience and Voltage Regulation

Manish Mukherjee, Steve Paudyal, Anamika Debroy, and Arpan Bose

Optimal Positioning of Mobile Emergency Resources for Resilient Restoration

Steve Paudyal, Manish Mukherjee, and Anamika Debroy
School of Electrical Engineering and Computer Science
Pullman, WA 99164

Abstract—Resilience to the high impact events that can occur in power distribution systems is a critical factor for power grid operators. This paper presents a framework to quantify the value of operational resilience in power distribution systems. The framework is based on the concept of resilience, which is defined as the ability of a system to absorb disturbances and maintain its essential functions. The framework is based on the concept of resilience, which is defined as the ability of a system to absorb disturbances and maintain its essential functions. The framework is based on the concept of resilience, which is defined as the ability of a system to absorb disturbances and maintain its essential functions.

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DSO-RISE Study

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Passionate Mission-Driven Team



Min Gyung Yu



Manisha Maharjan



Shiva Poudel



Monish Mukherjee



Sadie Bender



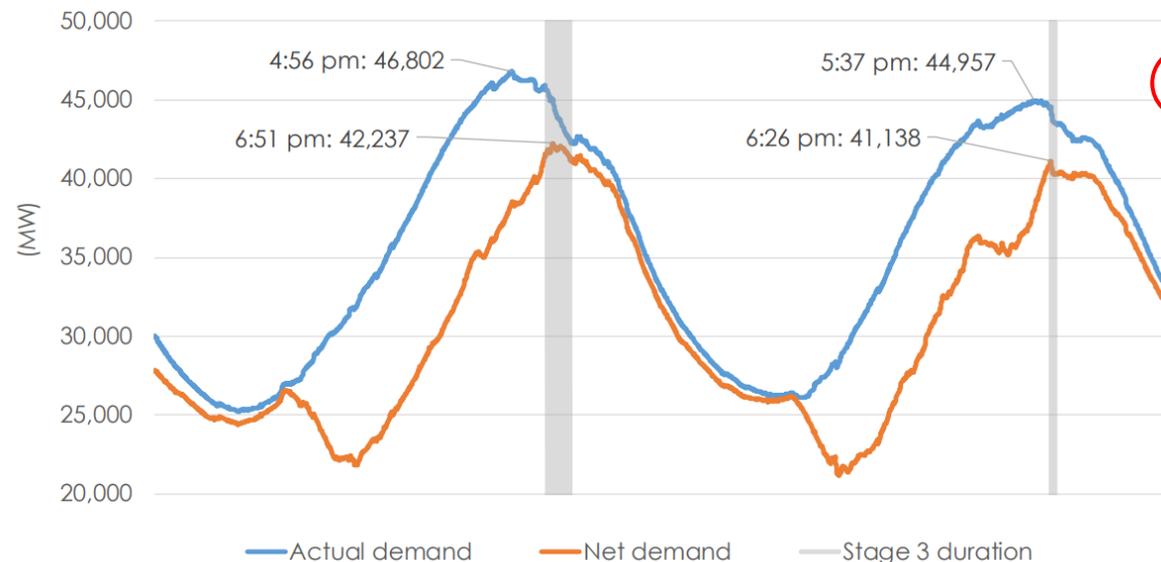
Trevor Hardy



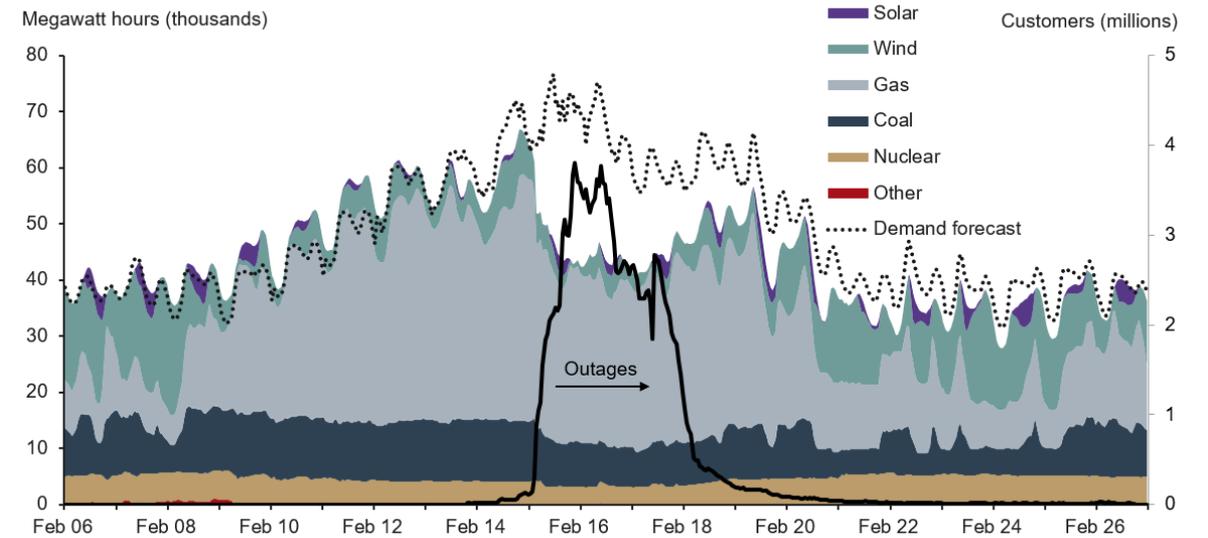
Hayden Reeve

Extreme Events – Extreme Outages

- Extreme weather events, many of which are climate-change related, are occurring with increasing frequency and intensity and causing catastrophic outages.
- One of the major modern-day concerns of utilities is dealing with such extreme outages and consequently, its repercussions on the lives of people in society and social aspects



ERCOT Electricity Generation by Source, Demand and Outages During Texas Deep Freeze



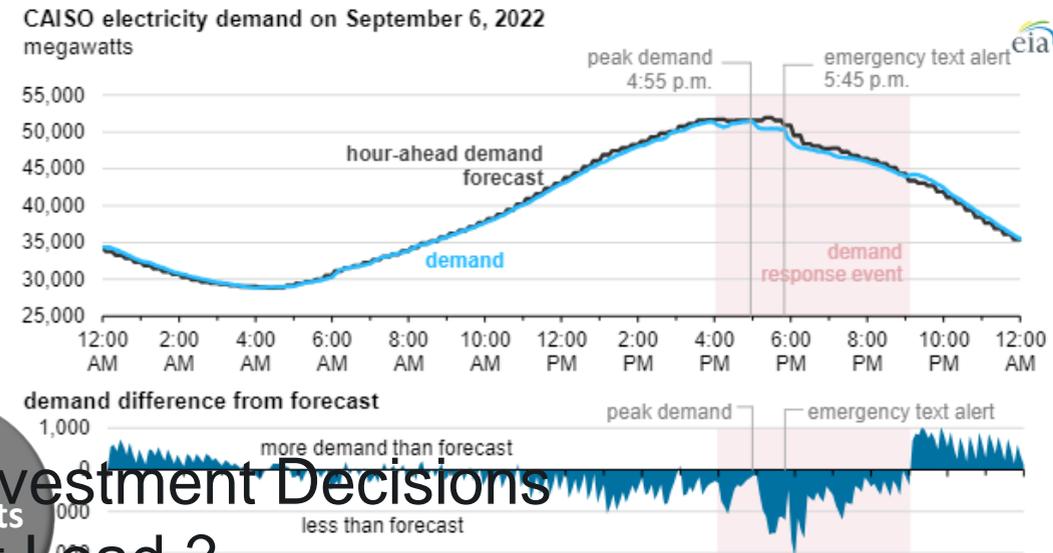
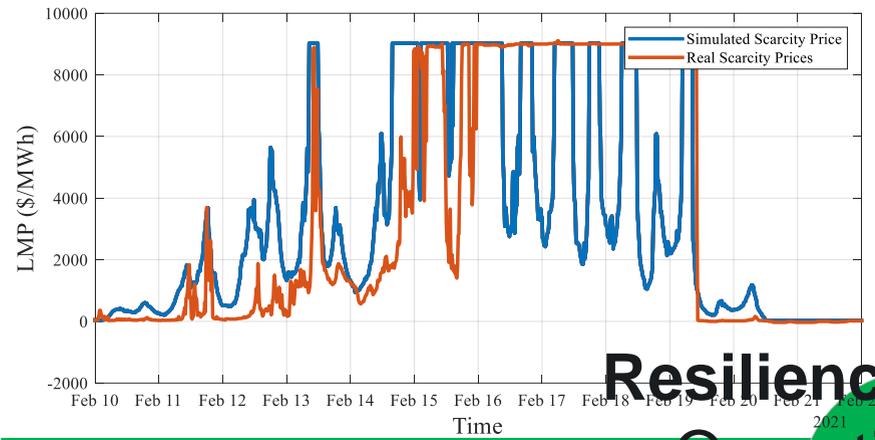
“How devastating was 2021's deadly Texas freeze, exactly?”

https://en.wikipedia.org/wiki/2021_Texas_power_crisis

Mid-august 2020 Heat Storm

On August 14, the **Stage 3 Emergency** was declared at **6:38 p.m.**, right before the net demand peak at 6:51 p.m. Similarly, on August 15, the **Stage 3 Emergency** was called at **6:28 p.m.**, just after the net demand peak at 6:26 p.m.

State of the Art Mechanisms



Resilience Valuation

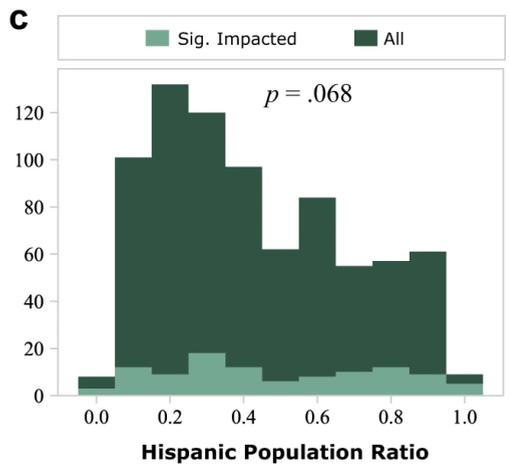
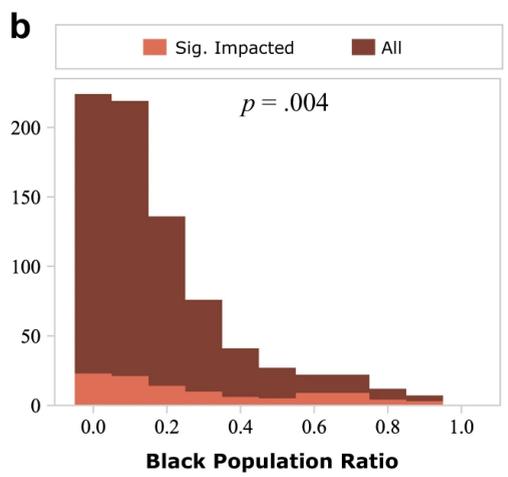
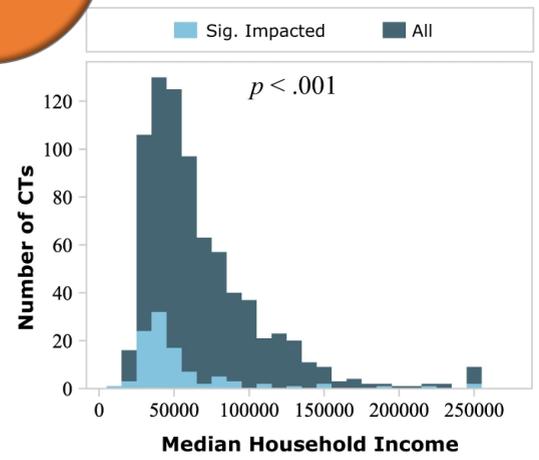
- Exposes customers to extremely high prices.
- Only customers who can afford such prices to be cleared by the market
- Operational Metrics to Investment Decisions
- What is the Value of Lost Load?
- Does it capture the regional variations along with the associated energy & nonenergy impacts?
- Situational awareness to customers
- No guarantees to avoid widespread outages

Transactive

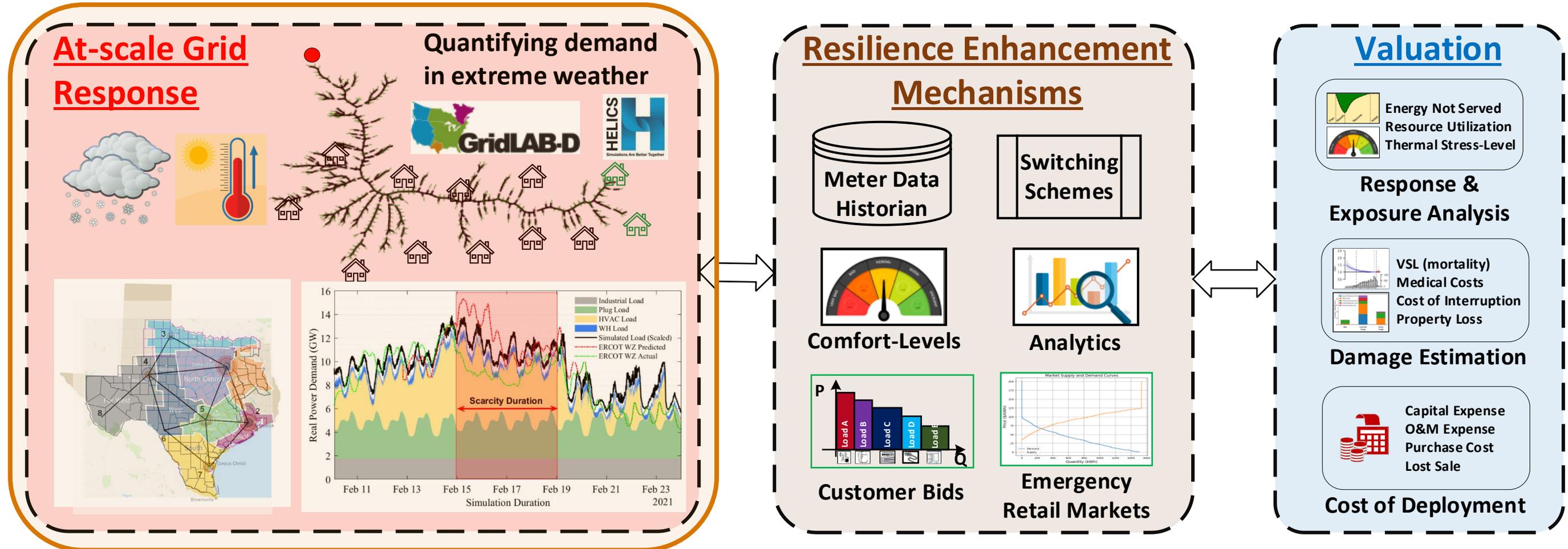
Text Alerts

Controlled Outage

- Existence of inequality in the management and implementation of the power outage – significant disparity in the extent and duration of power outages experienced by low-income and minority groups
- Lower-priority customers have high-priority loads (i.e., heating/cooling, telecom., etc) that should also be serviced (if at all possible).



Capabilities Developed in DSO-RISE Study





Regional Distribution Grid Response Models

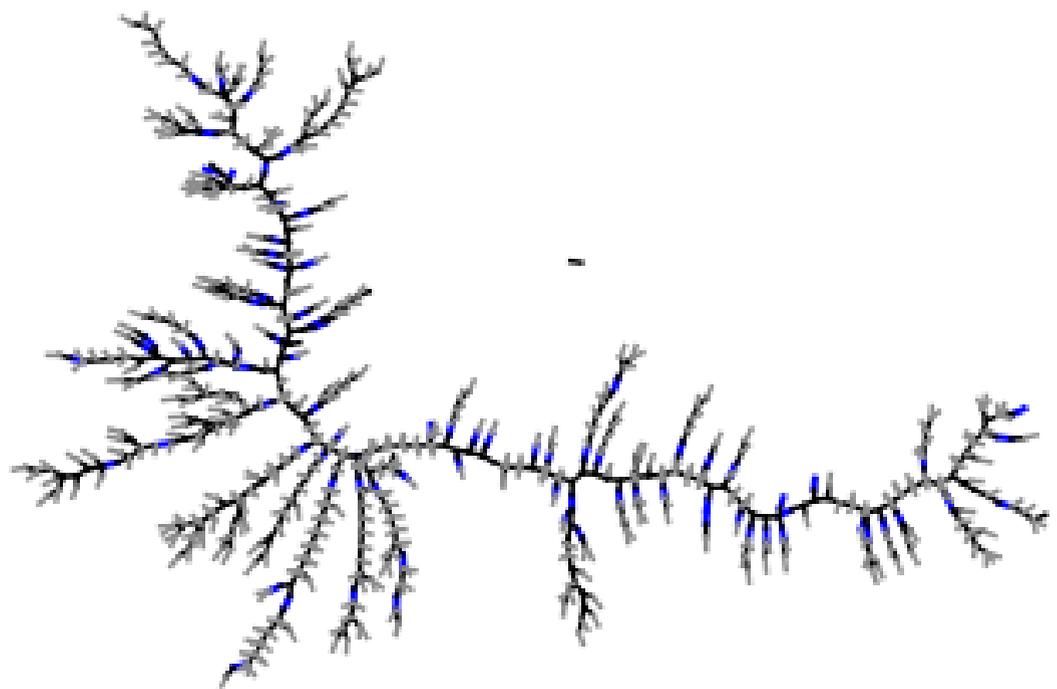
Modeling and simulation platform to
reflect realistic grid response during
extreme weather conditions



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Population Approach- Taxonomy Feeders



Backbone Circuit (Texas Specific Prototypical North American Feeders)

Circuit representation with backbone infrastructure (e.g., topology, rated equipment loading, power conversion elements, and delivery elements)

Population

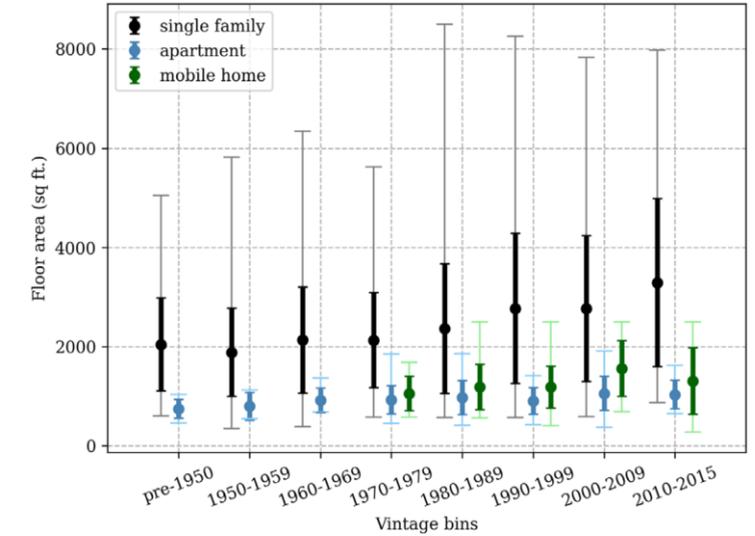
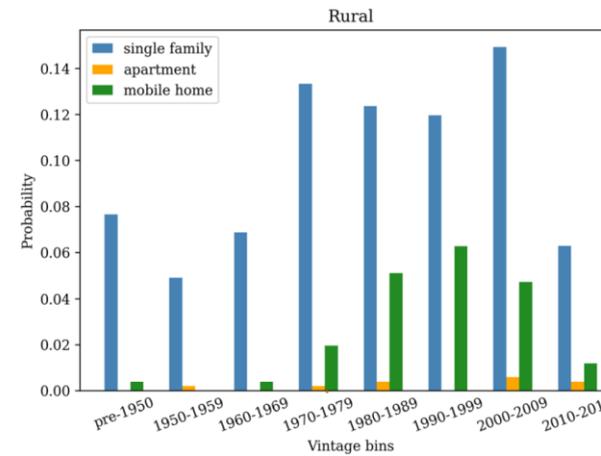
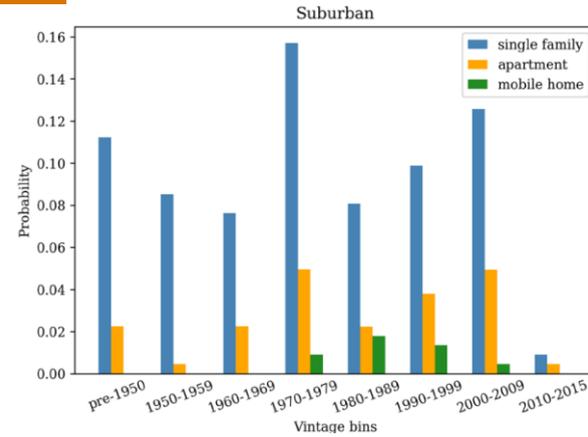
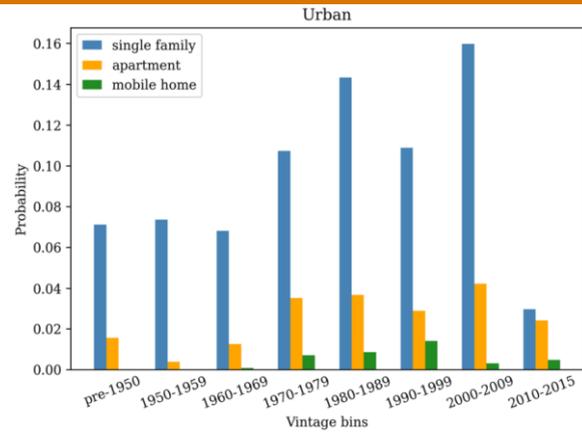


Populated Feeder with Representative RCI customer Mix and DERs

Modelling residential & commercial customers (with physics-driven device models) based on key regional characteristics from the EIA's RECS & CBECS data-sets

Population Approach – EIA’s Residential Energy Consumption Survey (RECS) for Texas

Building Types and Vintage



Building Form Factor

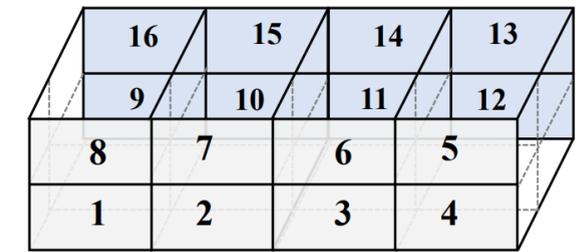
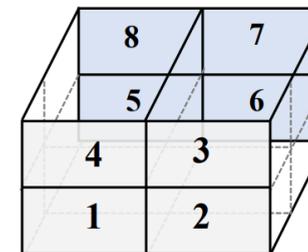
Probability of story level

Story level	Urban	Suburban	Rural
Single Story	0.62	0.80	0.75
Double Story	0.38	0.20	0.25

Key Characteristics for Residential Customers

Statistical parameters used for aspect ratio for each building type

Aspect Ratio	min	max	mean	std
Single family	1	2	1.5	0.5
Apartments	1.2	1.8	1.5	0.1
Manufactured homes single wide	4.5	5	5.5	0.1
Manufactured homes double wide	1.8	2.5	2.2	0.2



Schematics of apartment complexes

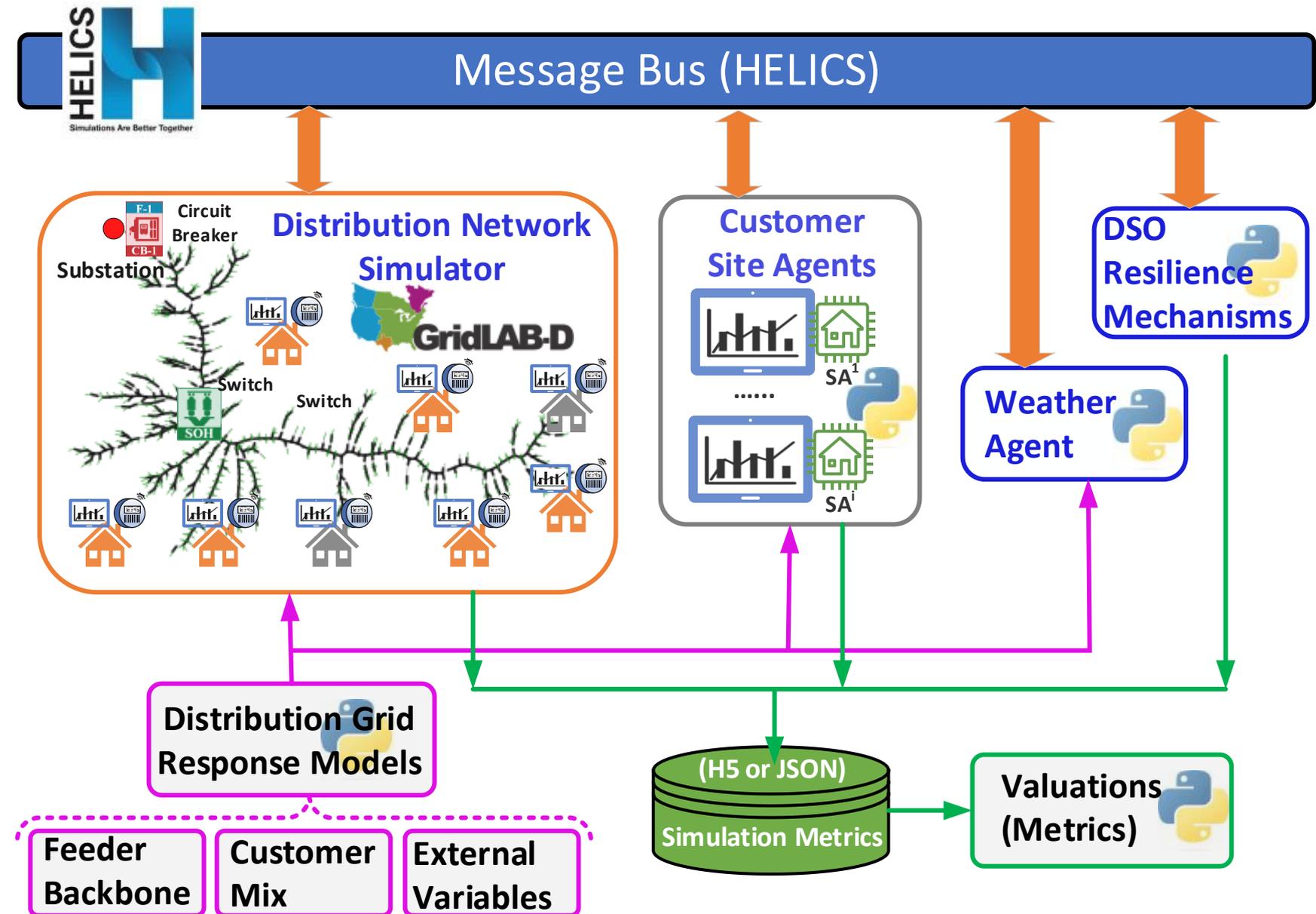
Distribution System Physics – GridLAB-D

- Three-phase unbalanced power flow
- Thermodynamic model of residential structure with HVAC system and thermostat.
 - Resistive (Heating)
 - Heat pump (Heating)
 - Gas (Heating)
 - Air Conditioning (Cooling)
- Thermodynamic model of water heater with vanilla controller



Co-Simulation Framework

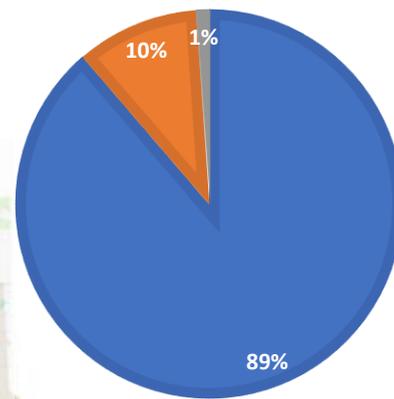
- **Distribution Network:**
 - Simulated using GridLAB-D.
 - Customer resources are modeled using different end-user loads and appliances such as WH and HVAC systems.
- **Weather agent**
 - Provides the simulator with real-time weather data like region-specific temperature, wind, and irradiance data.
- **DSO Agent**
 - Implemented using Python
 - Enables implementing and evaluating resilience enhancement mechanisms
- **Site Agents (SA)**
 - Customer-specific information to DSOs (ex. consumption, bids, Discomfort)



Scale of Regional Grid Response Model

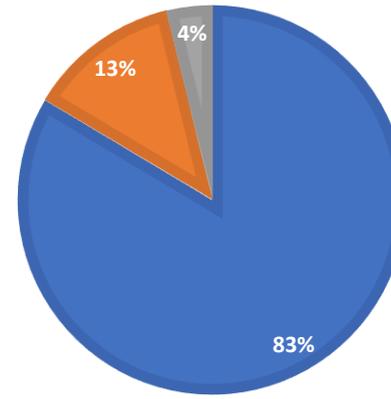
DSO 1 NORTH CENTRAL WZ

■ Residential ■ Commercial ■ Industrial



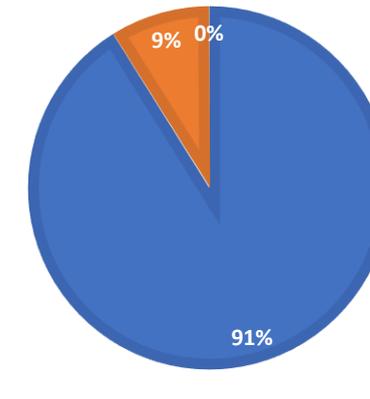
DSO 2 COAST WZ

■ Residential ■ Commercial ■ Industrial



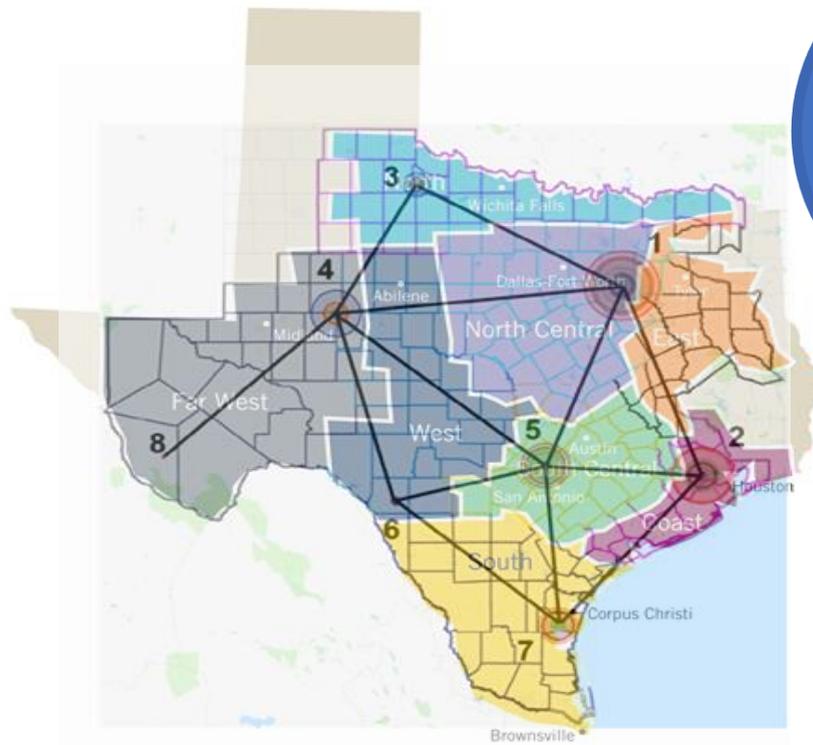
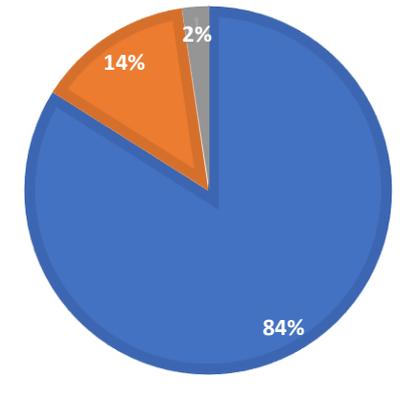
DSO 5 SOUTH CENTRAL WZ

■ Residential ■ Commercial ■ Industrial



DSO 8 FAR WEST WZ

■ Residential ■ Commercial ■ Industrial

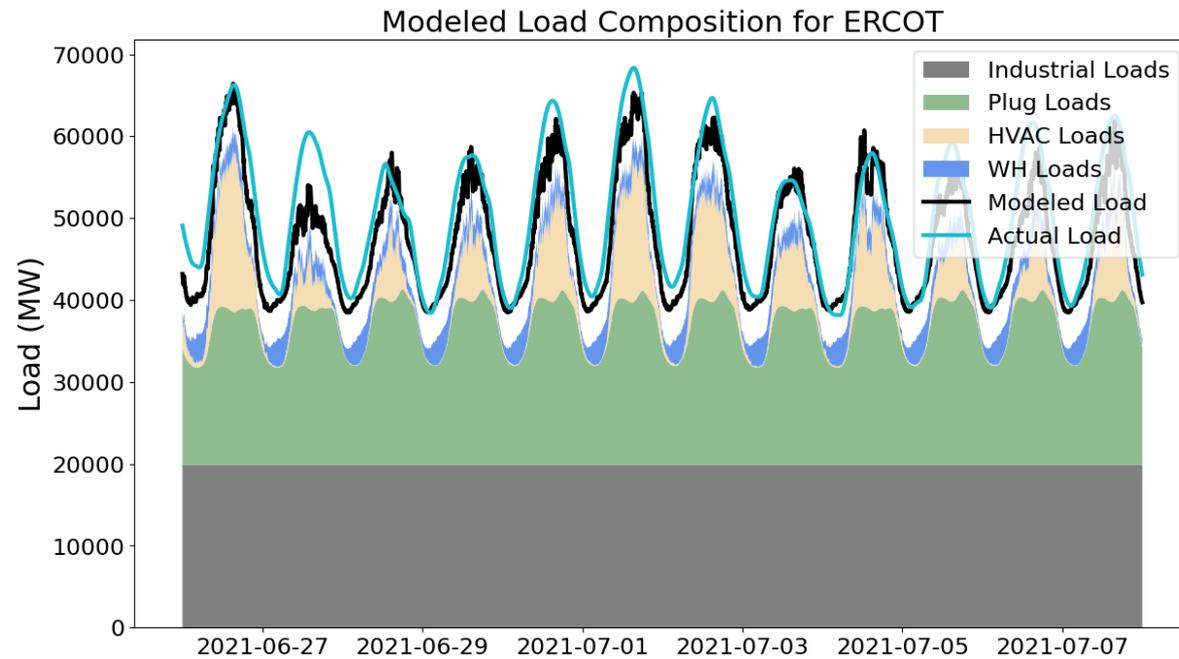


8-Node Model of ERCOT region

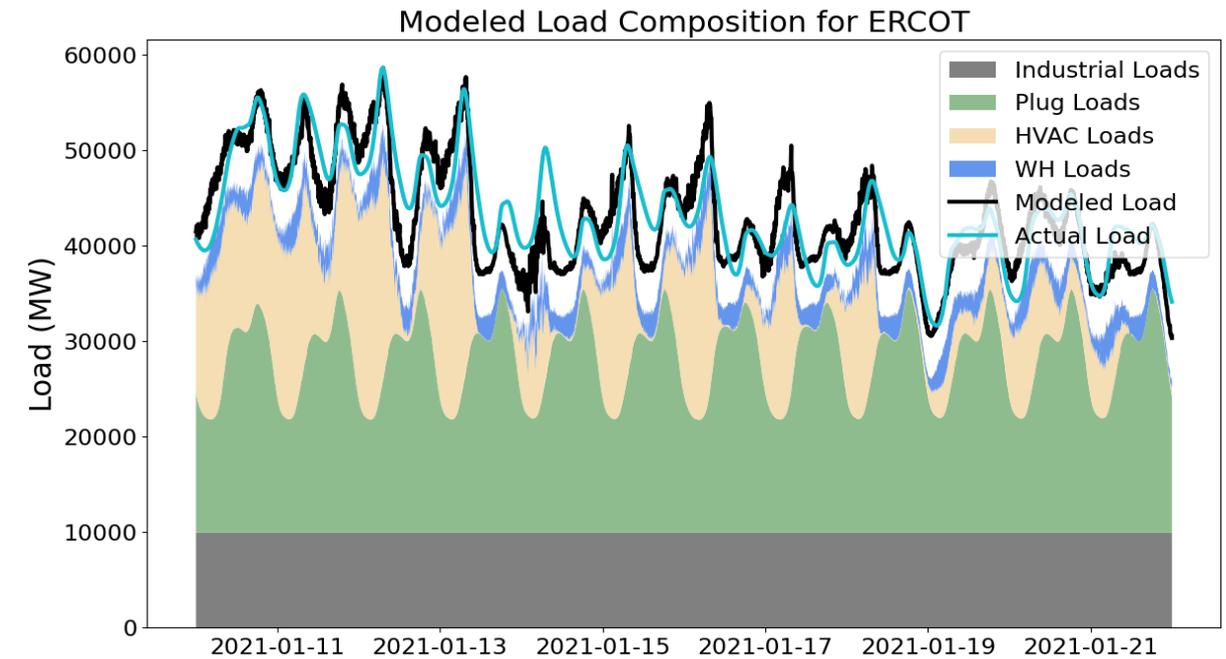
Region (Utility Type)	Modeled Feeders	Modeled Area	RES CNT	COMM CNT	Actual Customers	Scaling Factor
Region 1 (Urban)	R4-12.47-1 R4-12.47-2	Dallas, TX	893	71	3,843,475	3816.95
Region 2 (Urban)	R5-12.47-1 R5-12.47-2	Houston, TX	1,308	148	3,680,144	2351.17
Region 3 (Rural)	R5-12.47-5	Lamar, TX	1,539	56	103,821	58.14
Region 4 (Rural)	R5-12.47-5	Midland, TX	1,539	56	869,220	479.44
Region 5 (Urban)	R5-12.47-1 R5-12.47-2	Hays, TX	1,308	127	2,004,277	1395.95
Region 6 (Urban)	R4-12.47-1 R5-12.47-1	Val Verde, TX	1,525	142	118,242	67.95
Region 7 (Suburban)	R5-12.47-5	Nueces, TX	1,539	56	1,540,344	895.00
Region 8 (Rural)	R5-12.47-5	Presidio, TX	1,539	56	43,175	23.55
Total	12 Feeders		11,190	715	12,202,698	1136.02

Example Load Profiles

ERCOT Load (BAU-Summer)



ERCOT Load (BAU- Winter)



Statistical comparison of simulated load with actual ERCOT load.

	Actual (Winters)	Modeled (Winter)	Actual (Summer)	Modeled (Summer)
R ² (-)	0.73		0.91	
Mean (GW)	41.79	41.67	51.55	48.88
Median (GW)	41.04	40.71	51.21	47.53
Max (GW)	58.61	58.61	70.23	73.15
Min (GW)	31.60	29.12	38.16	38.48

Trend-wise accurate system-wide load shapes and end-load contributions

Electrification and Renewable Scenarios

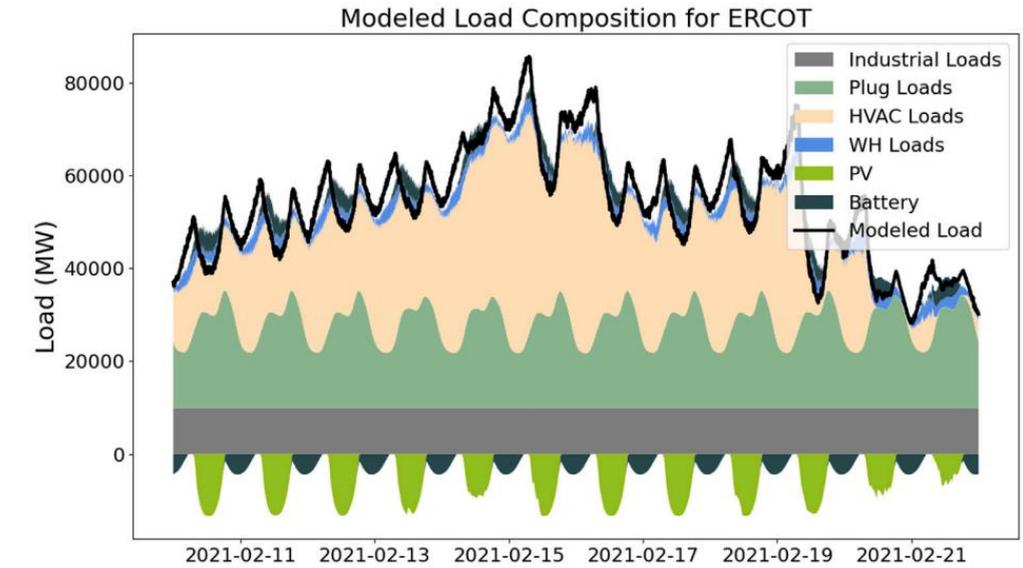
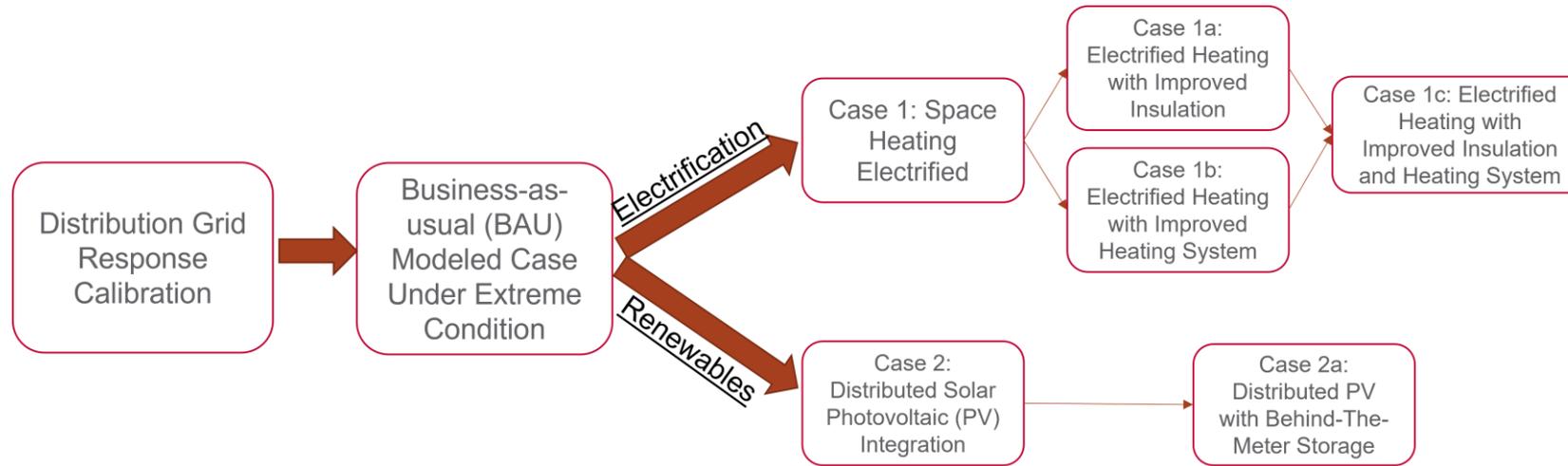
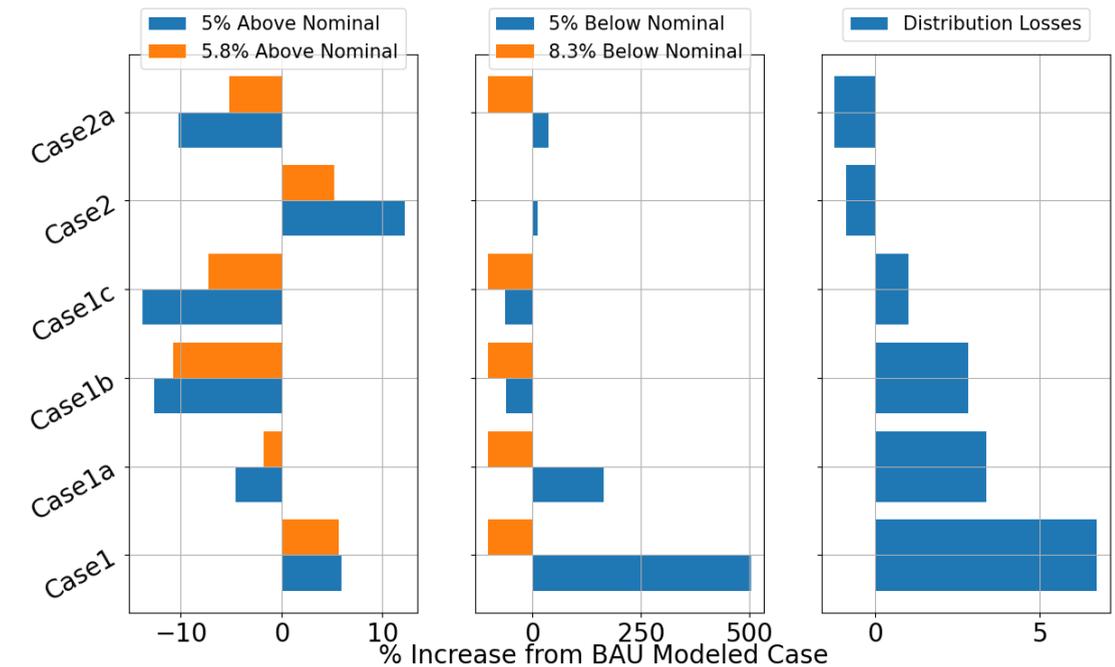
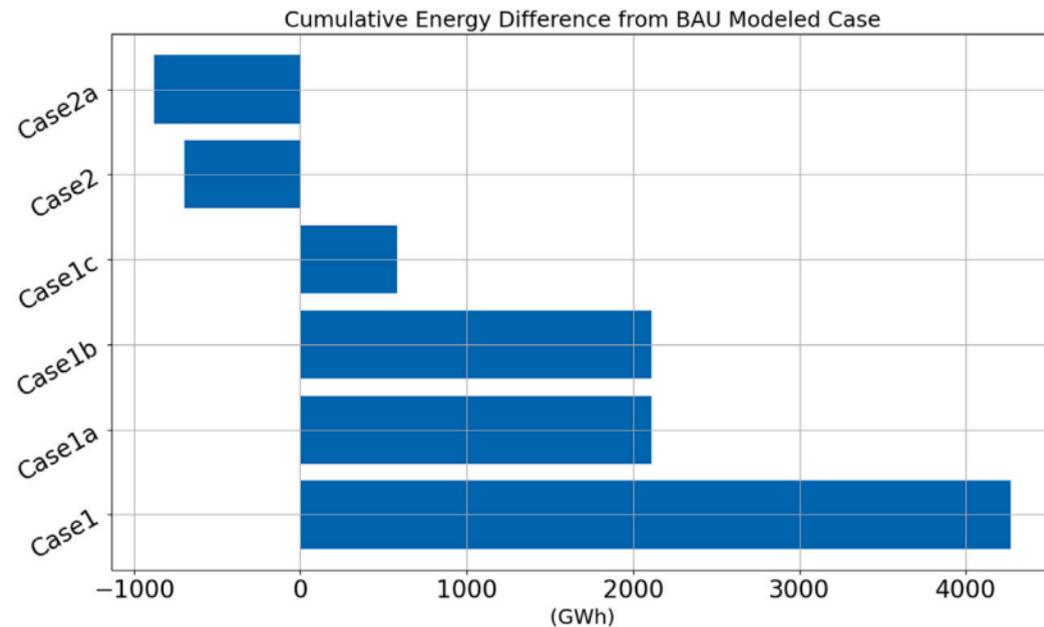


Fig. Modeled cases for Electrification and Renewable Integration Scenarios



Grid Response during Winter Storm URI – (WZ Level)

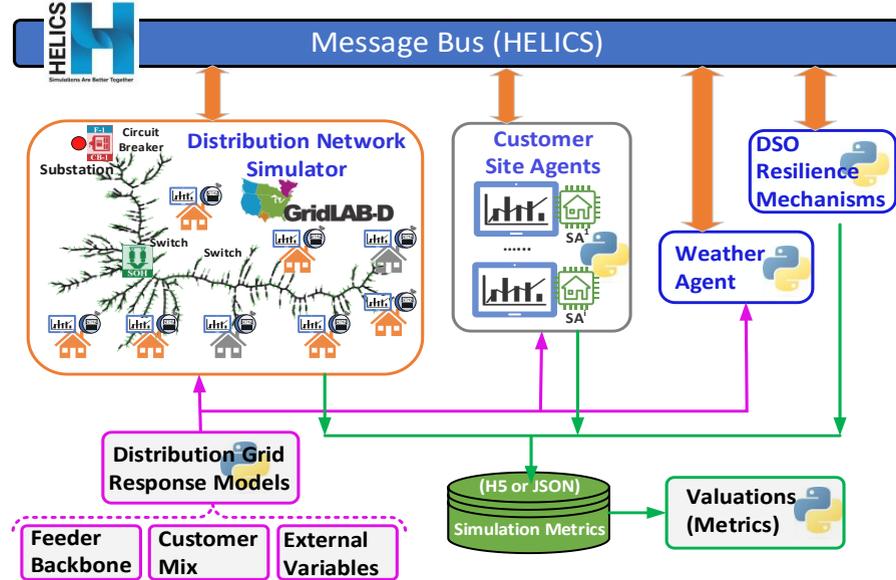


Fig. Co-Simulation Framework

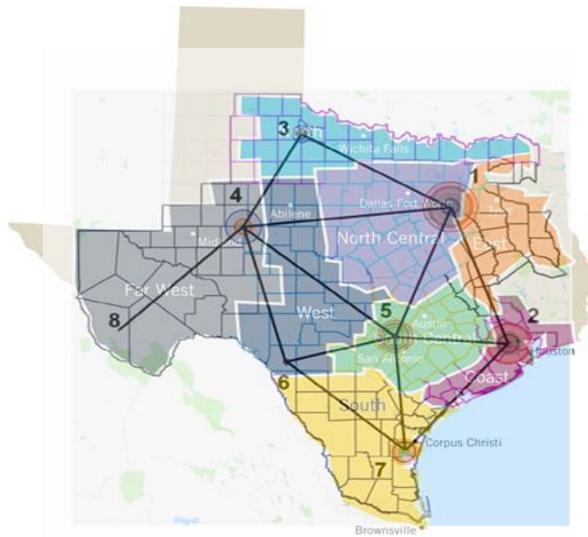
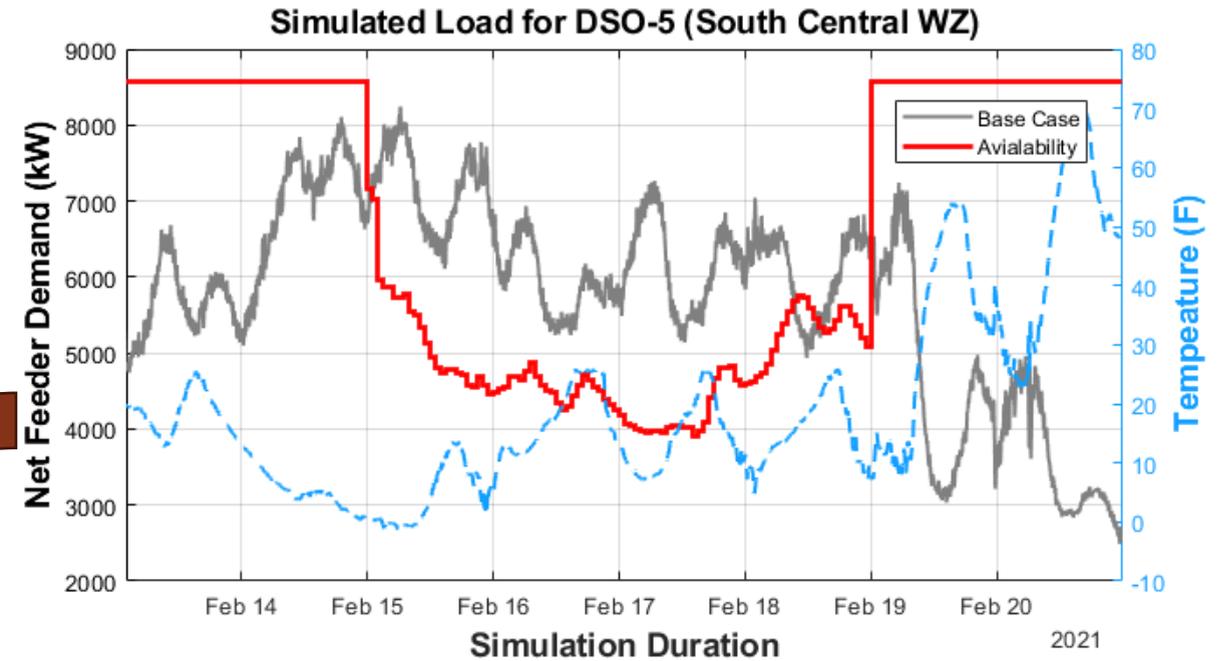
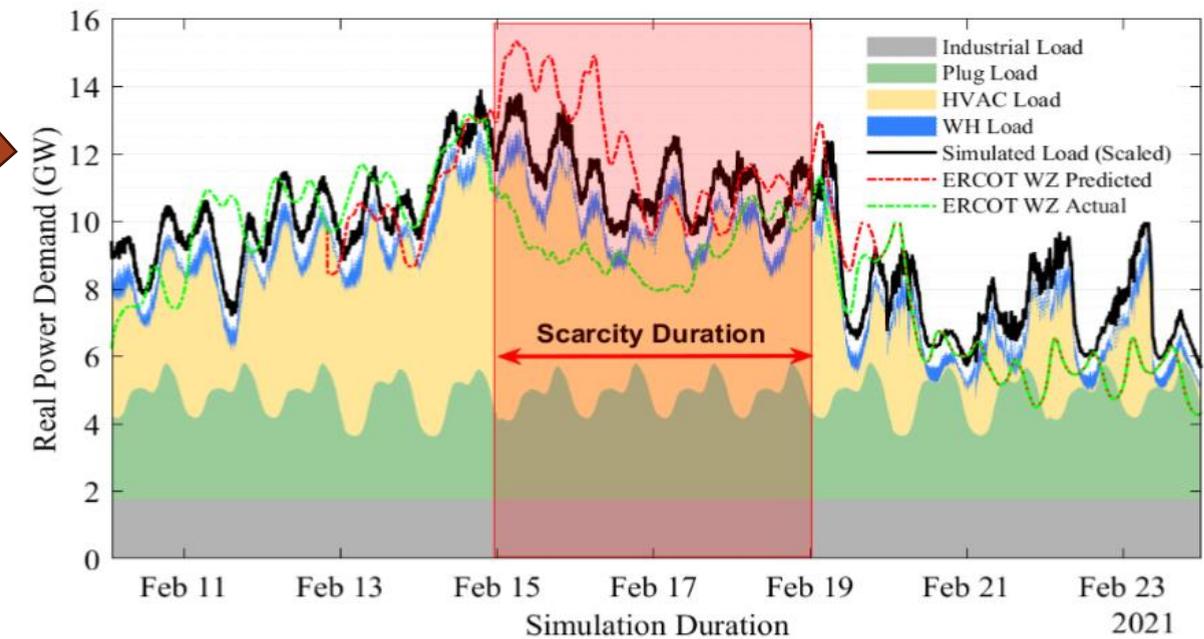


Fig. 8-Node Model of ERCOT region



Scaled



Grid Response during URI – (ERCOT-Level)

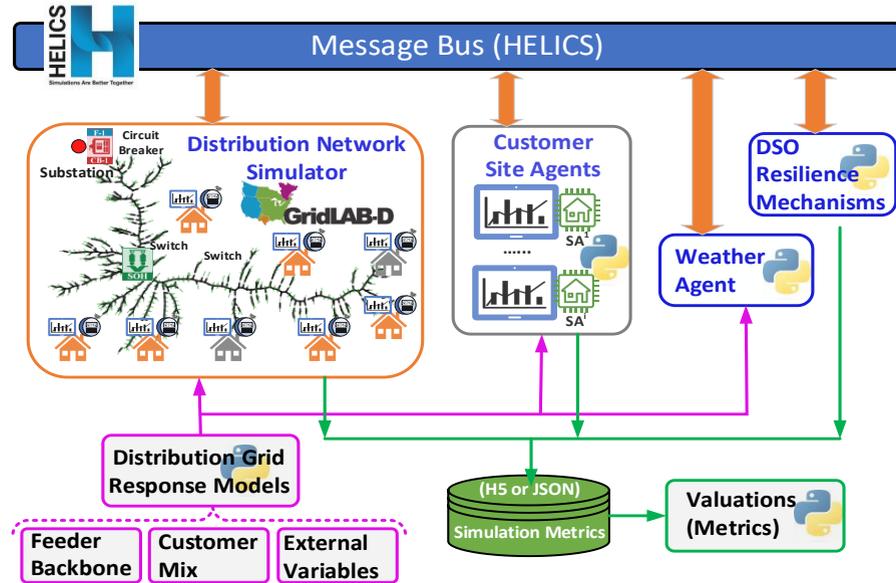


Fig. Co-Simulation Framework

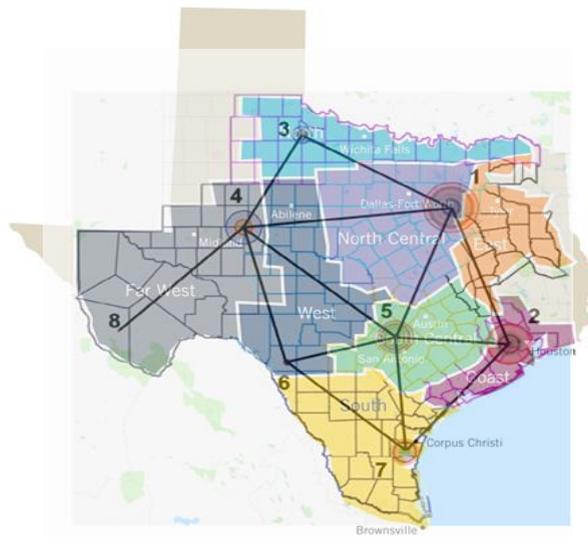
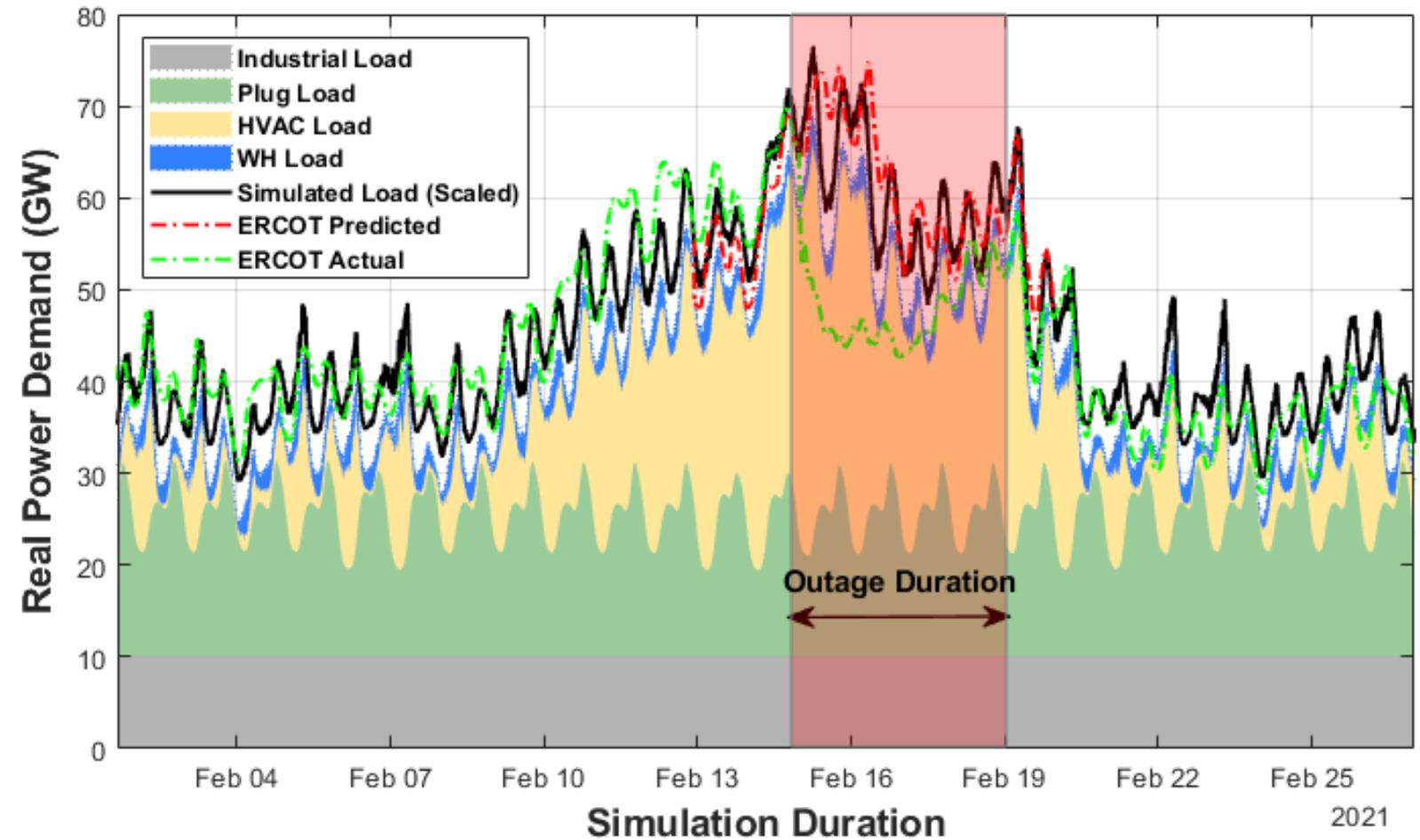


Fig. 8-Node Model of ERCOT region



Base Case and Controlled Outage

- **Base Case**

- Normal operational state in which all connected loads are served
- Heatwaves & cold snap strain the power grid

- **Controlled Outage (CO)**

- Selectively disconnect the distribution feeders as a method of reducing load
- Avoid feeders with critical loads

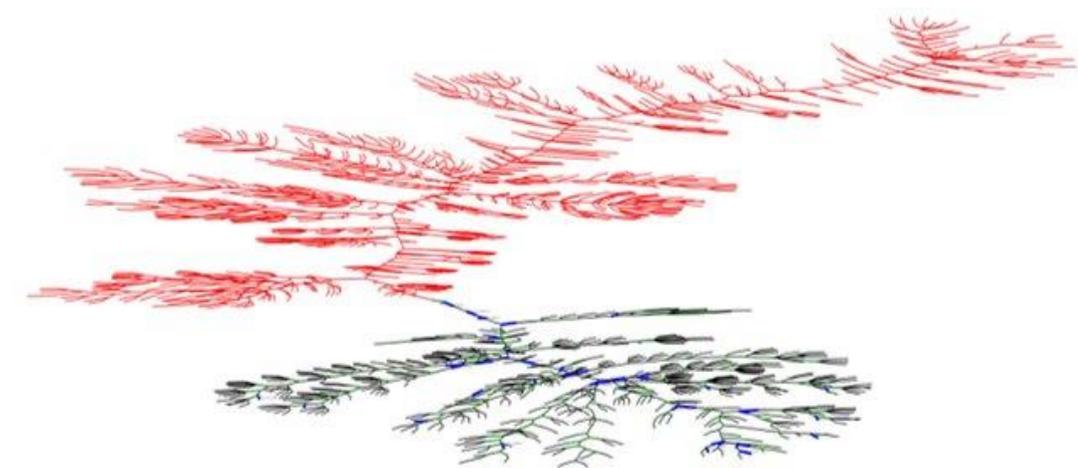
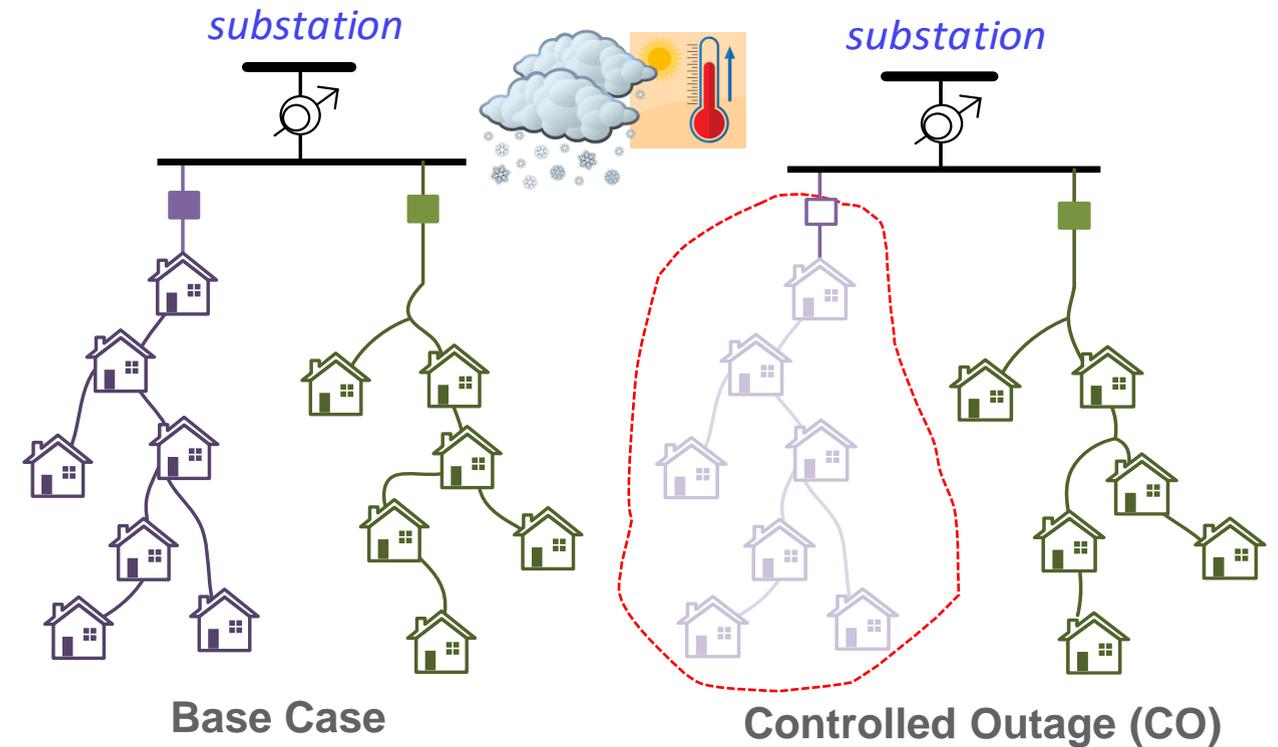
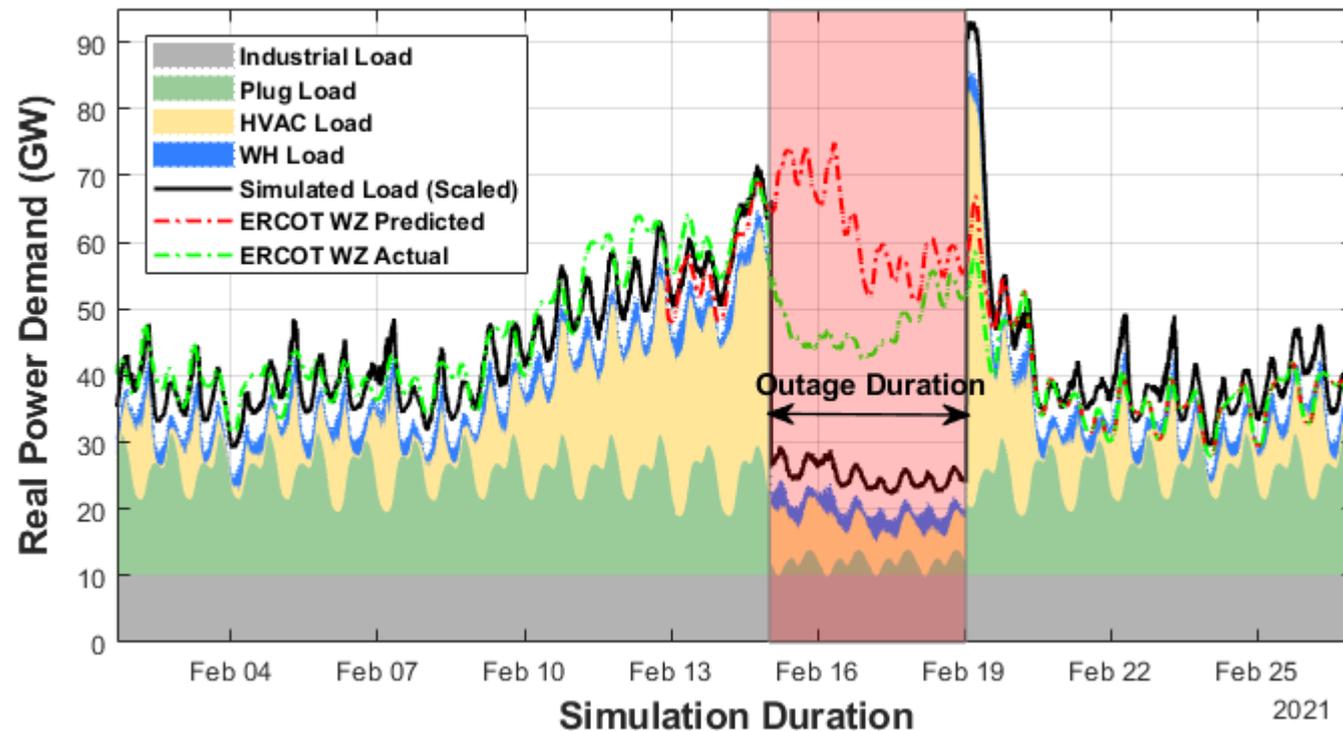
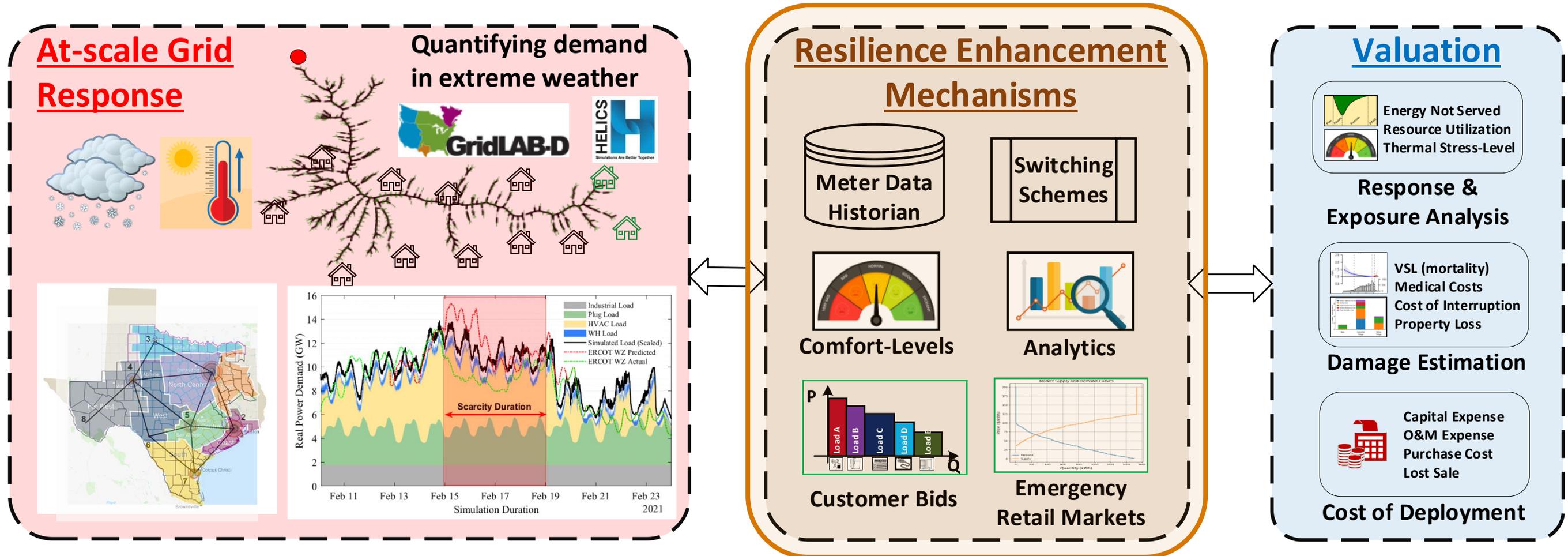


Fig. Sample Feeder Layout for Controlled Outage

Capabilities Developed in DSO-RISE Study





Resilience Enhancement Mechanisms

Mechanism that (1) systematically disconnects different areas or neighborhoods and (2) offers allocation to all customers and encourages customer participation.

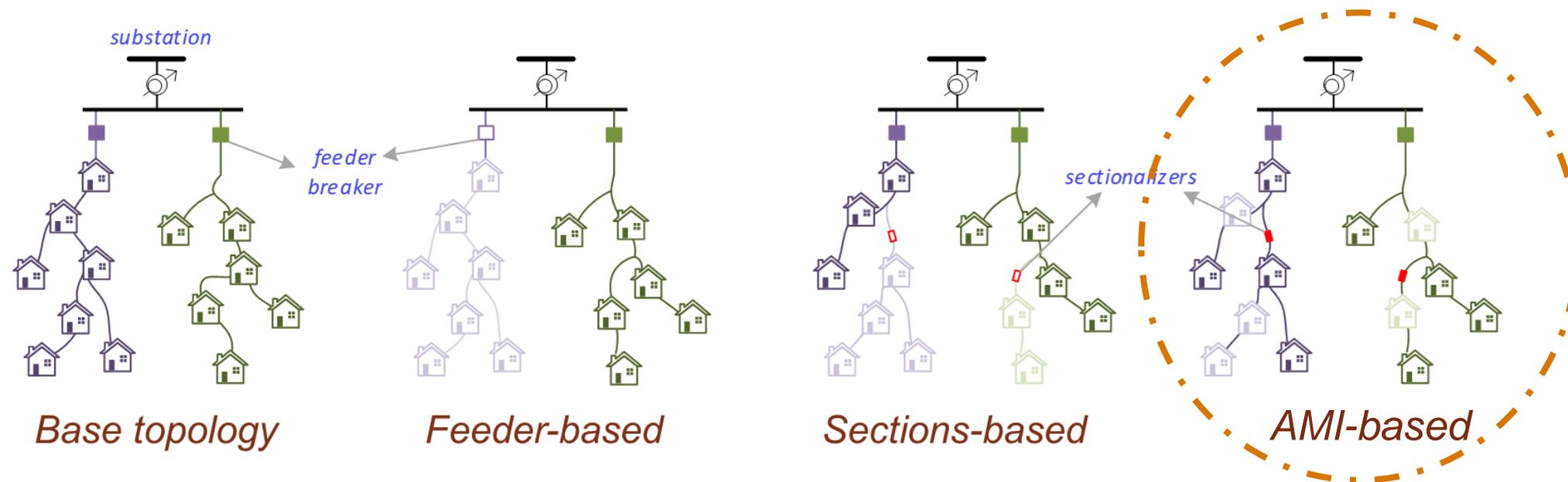


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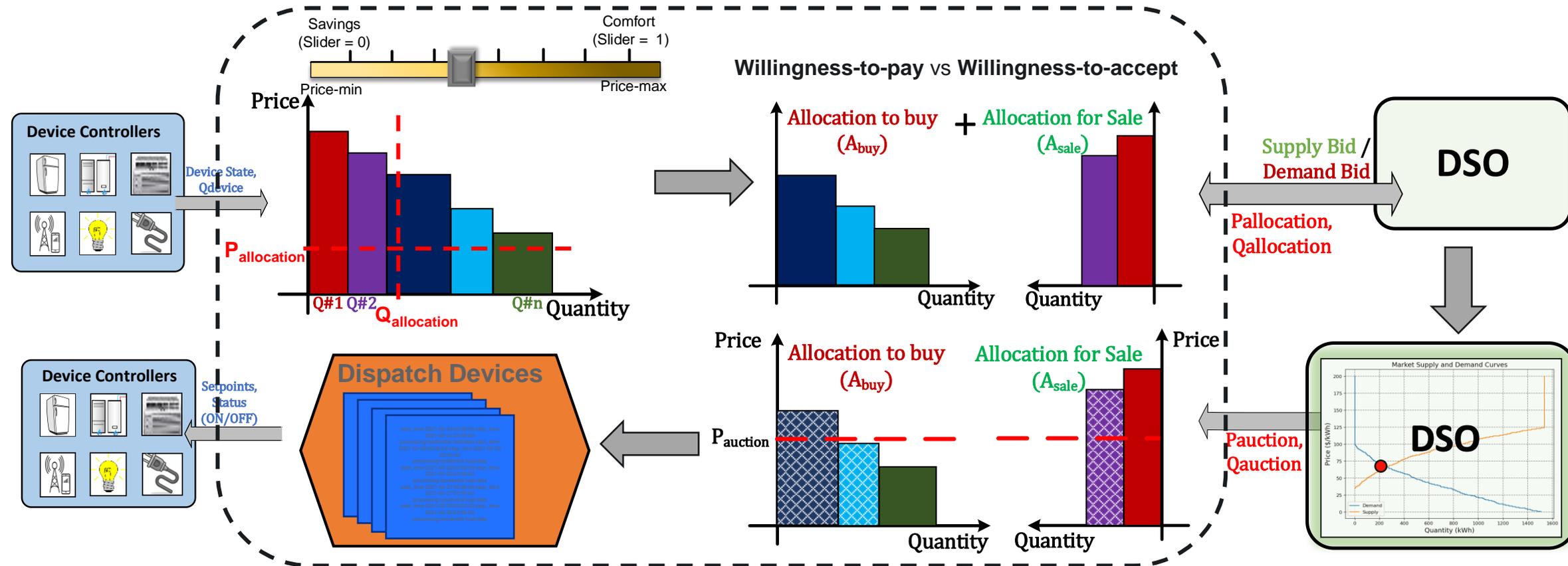


Outage Management Strategies

- Systematically cutting off electricity supply to different areas or groups of customers for short periods
- Sharing the available electricity among all its customers.
- Implement and compare performances of several load shedding mechanisms
 - Exercising the distribution system automation equipment to minimize outages*
 - ✓ Feeder-based, Sections-based, Advanced Metering Infrastructure (AMI)-based

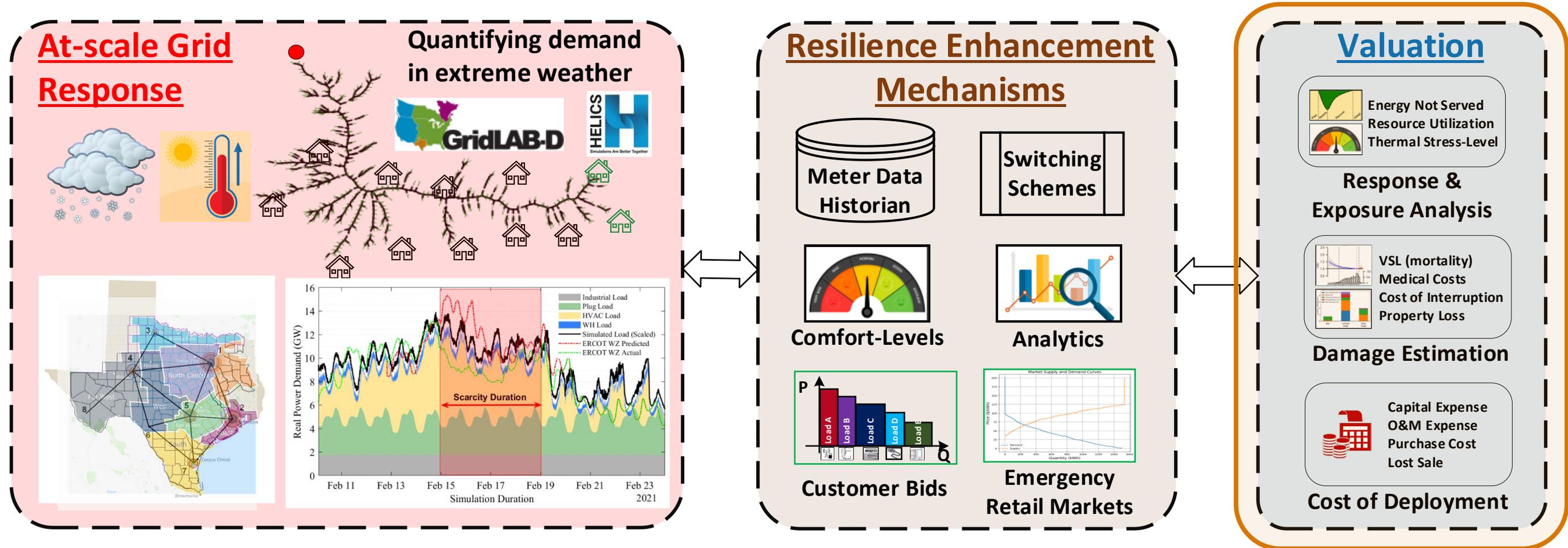


TE-Alloc Mechanism



- Novel approach with ability to provide increased amenity (load operation) to all customers; while using more of available energy
- Allocation trading customers have ability to trade portions/total of allocation
- Site-agents co-ordinate between customer's end-user devices and DSO
- Willingness-to-pay for extra allocation; form demand curve with priority of their load
- High-priority loads are in supply curve (A_{sale}) at price greater than allocation price
- Low-priority loads are in demand curve (A_{buy}) for purchase at cheaper price

Capabilities Developed in DSO-RISE Study





Resilience Valuation Framework

Methodology for calculating cost of outages as a combination of value of statistical life, productivity decrease, interruption cost and infrastructure degradation.

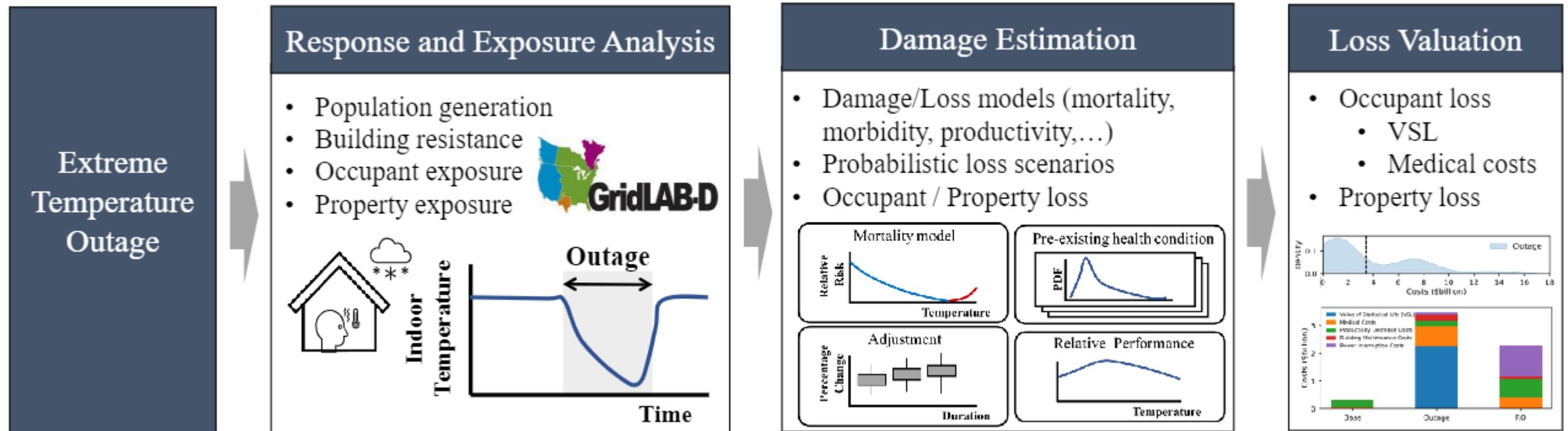


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Valuation of Customer-Oriented Impact

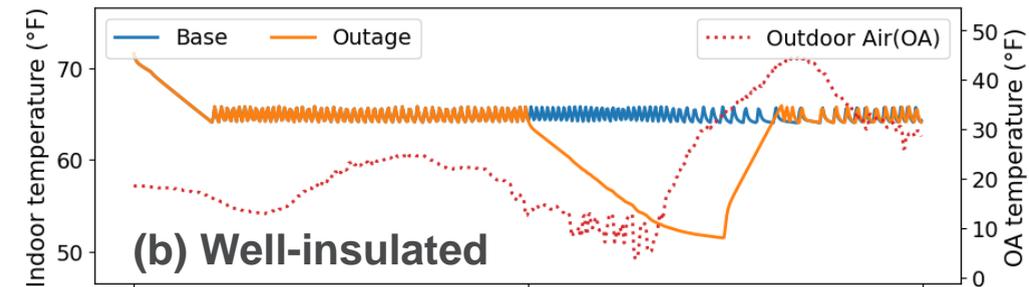
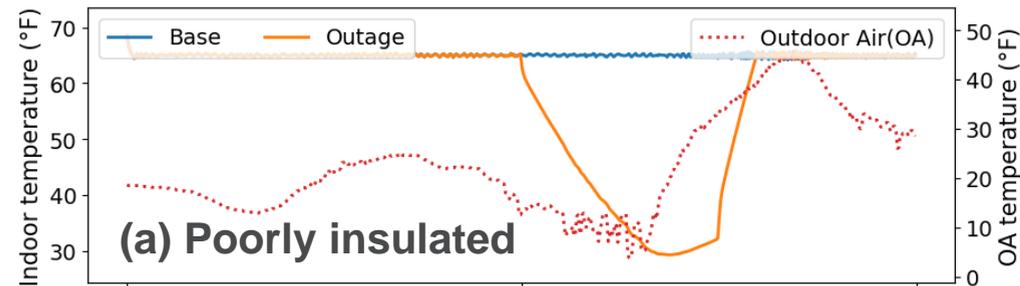
- Both economic and non-energy impacts caused by extreme temperature outages.
- Analyze risk exposure of buildings and population to severe temperature.
- Motto: “Strengthening Resilience Through Customer-Centric Impact Valuation”



Overall procedure for estimating the related damages and losses

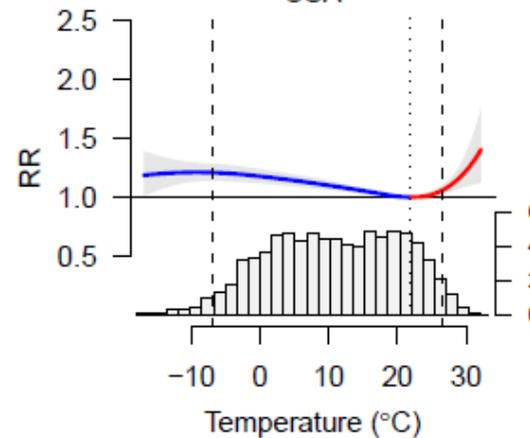
Damage Function Model to Temperature

- Based on the indoor air temperature of each building

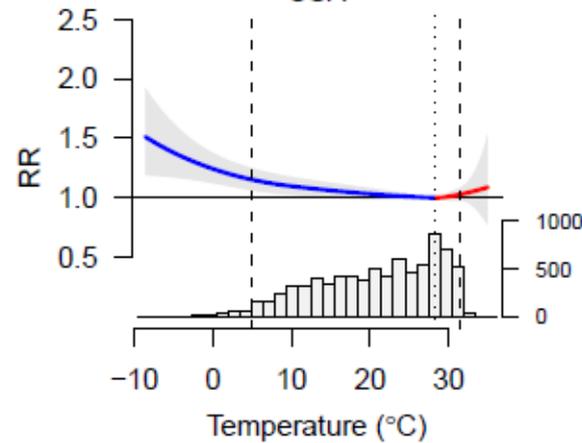


Relative Risk of Mortality

Boston, MA
USA

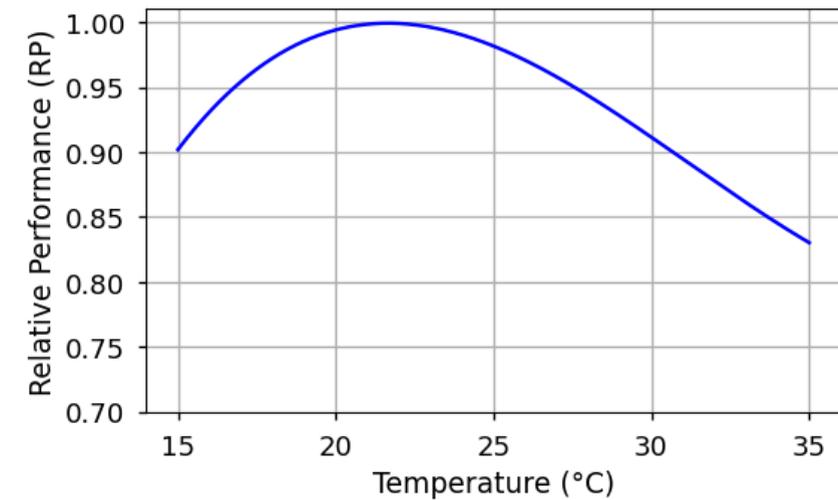


Austin, TX
USA



A. Gasparri, Y. Guo, M. Hashizume, P. L. Kinney, E. P. Petkova, E. Lavigne, A. Zanobetti, J. D. Schwartz, A. Tobias, M. Leone, S. Tong, Y. Honda, H. Kim, B. G. Armstrong, Temporal variation in heat-mortality associations: A multicountry study, *Environmental health perspectives* 123 (11) (2015) 1200–1207.

Productivity

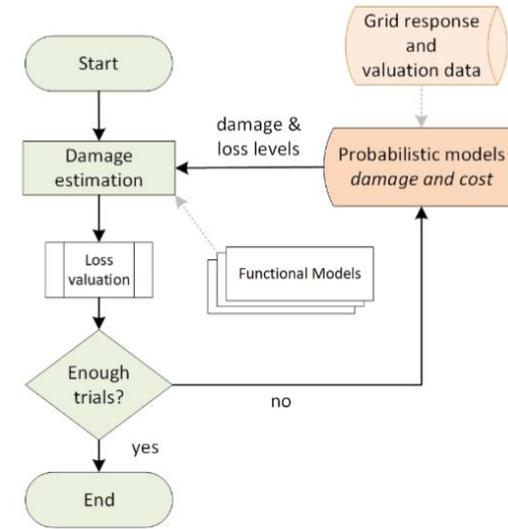
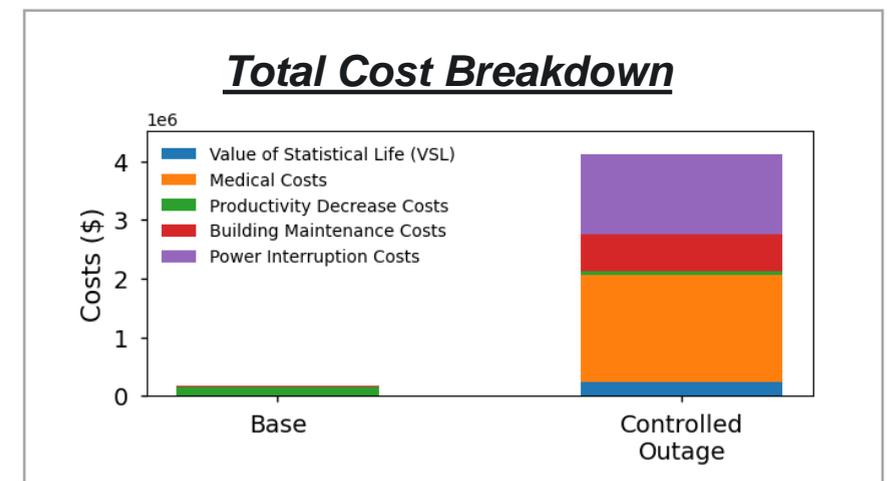
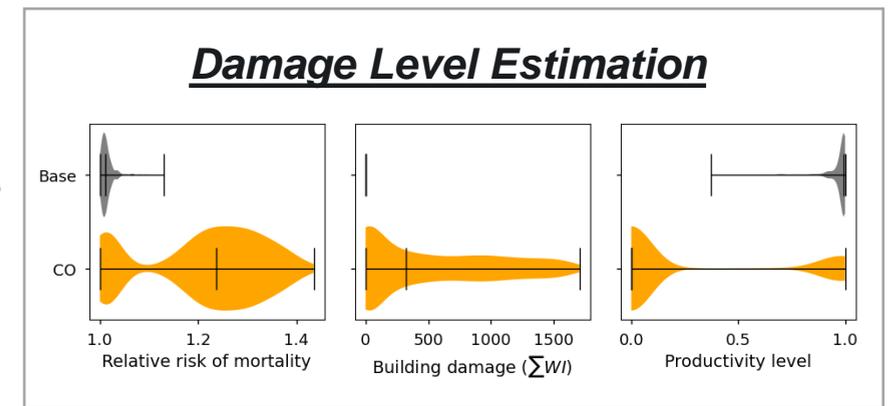
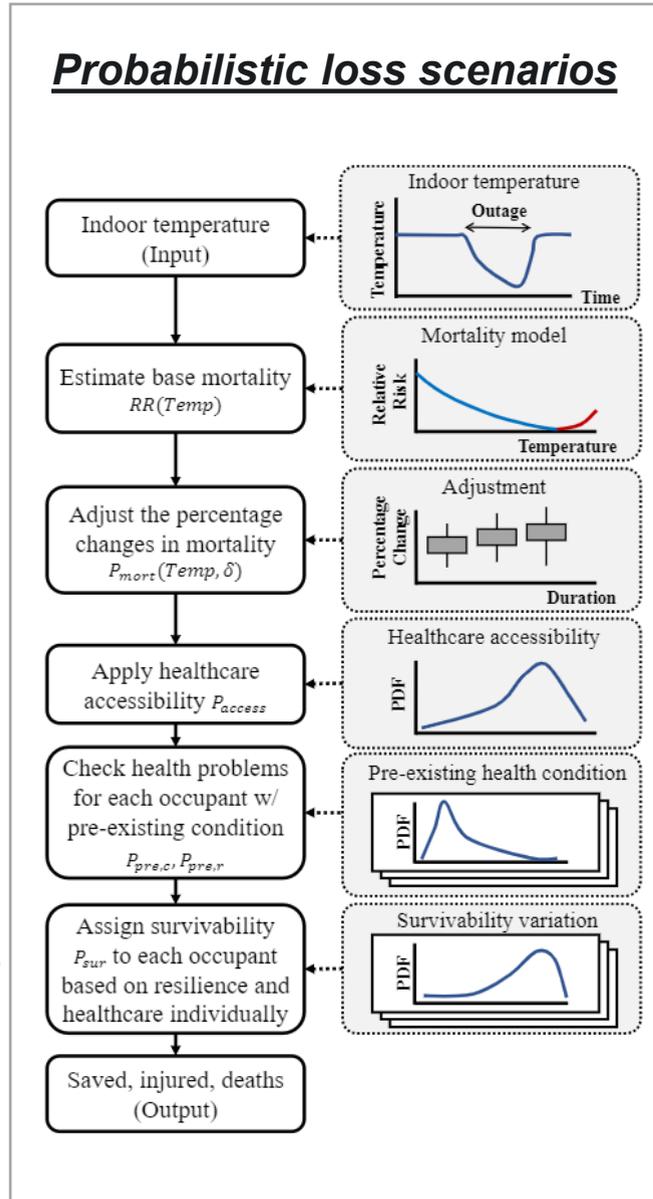
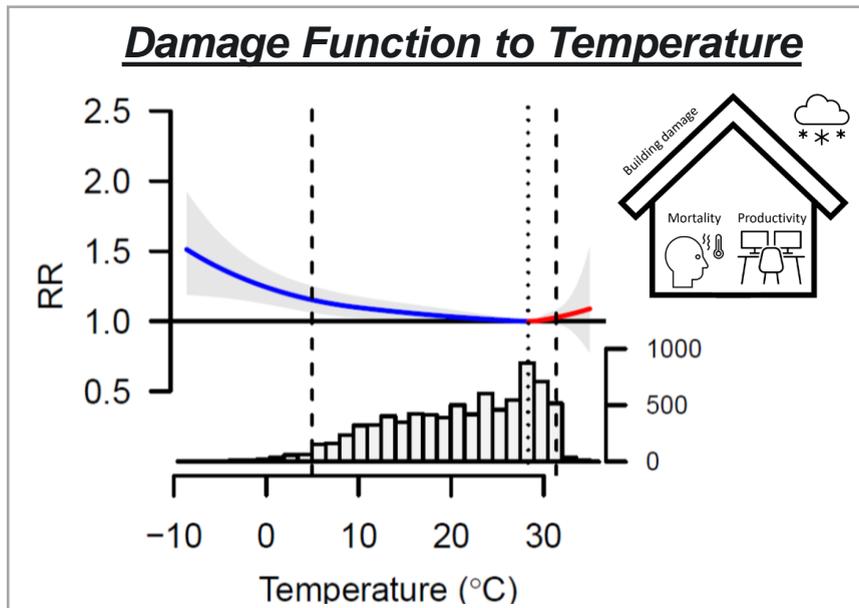
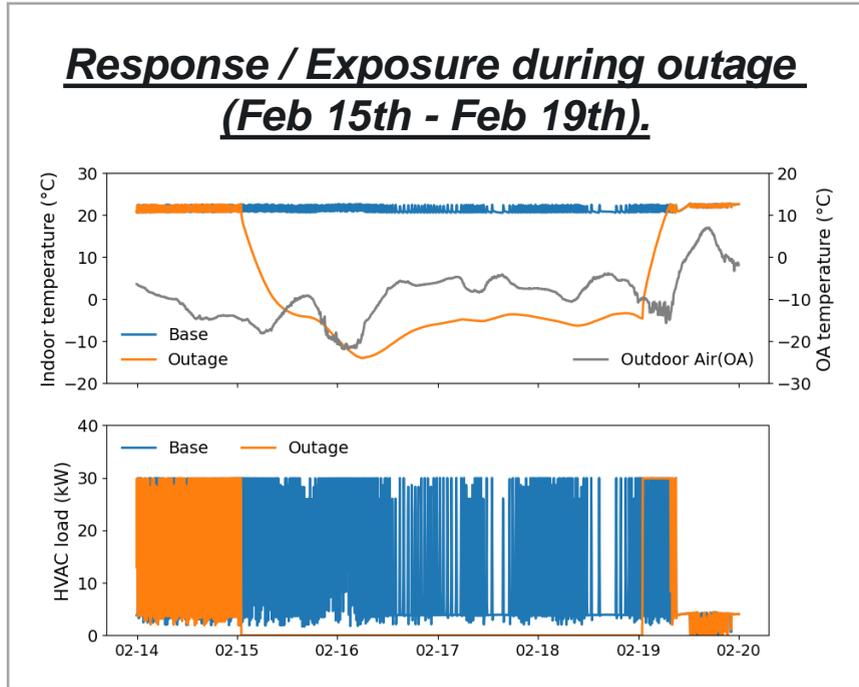


O. Seppänen, W. J. Fisk, Q. Lei, Room temperature and productivity in office work, in: *Healthy Buildings 2006 Conference*, Vol. 1, 2006. 38

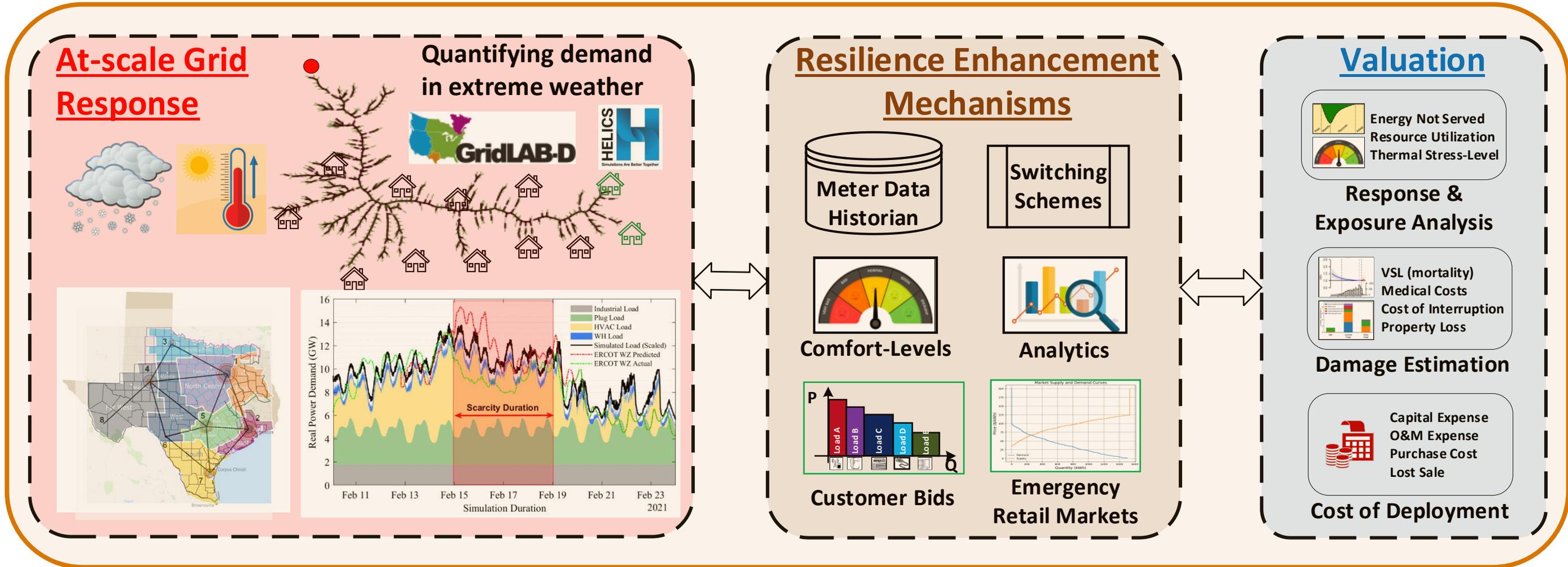
Property Damage

$$WI_t = (T_L - T_t)(RH_t - RH_L)[(T_t < T_L, RH_t > RH_L)]$$

Example of Estimating Losses Associated with Customer Non-Energy Impact



Capabilities Developed DSO-RISE Study





ERCOT-LEVEL Integrated Assessment

Techno-Economic Analysis at the
ERCOT regional Scale.



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



Grid Response during URI – (ERCOT-Level)

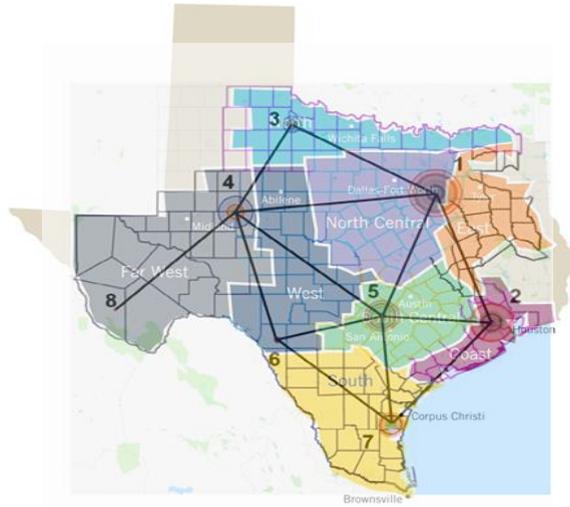
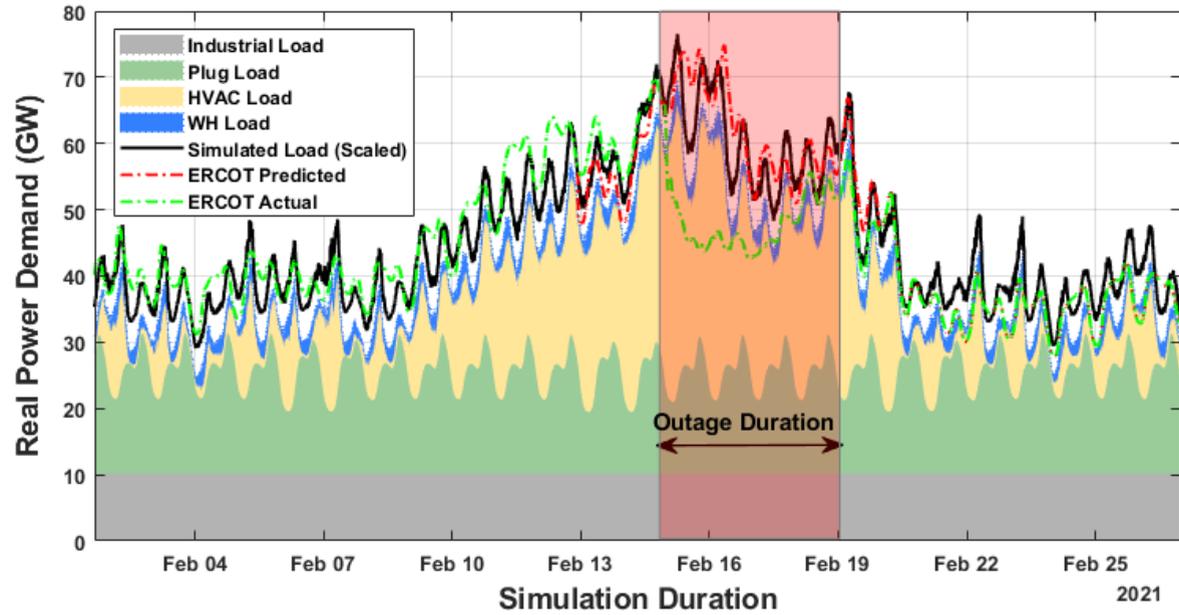
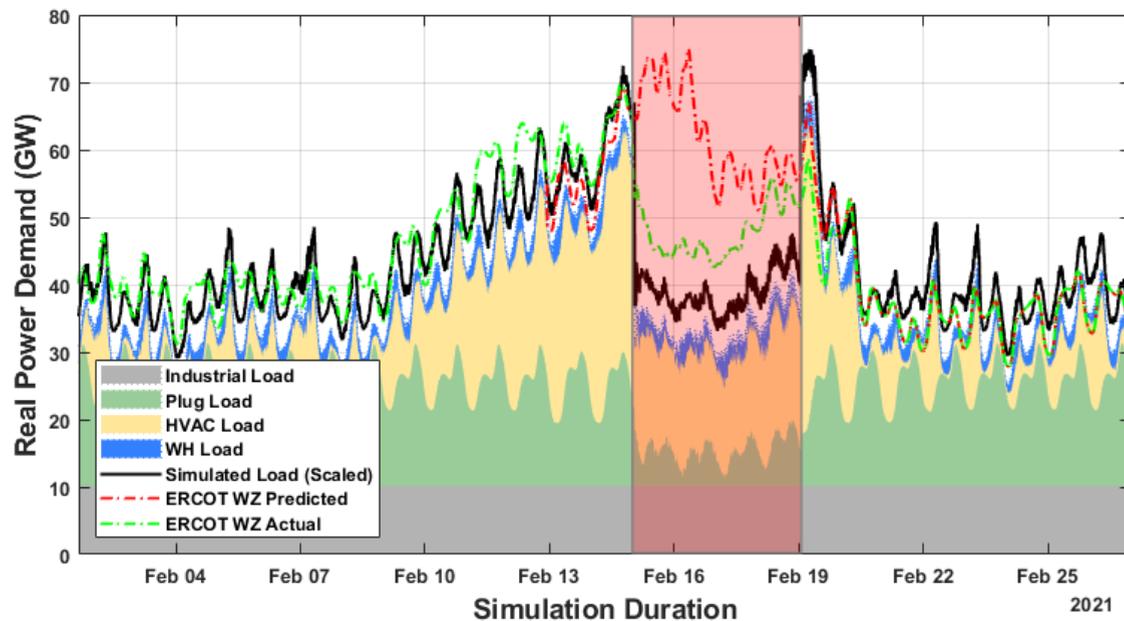


Fig. 8-Node Model of ERCOT region

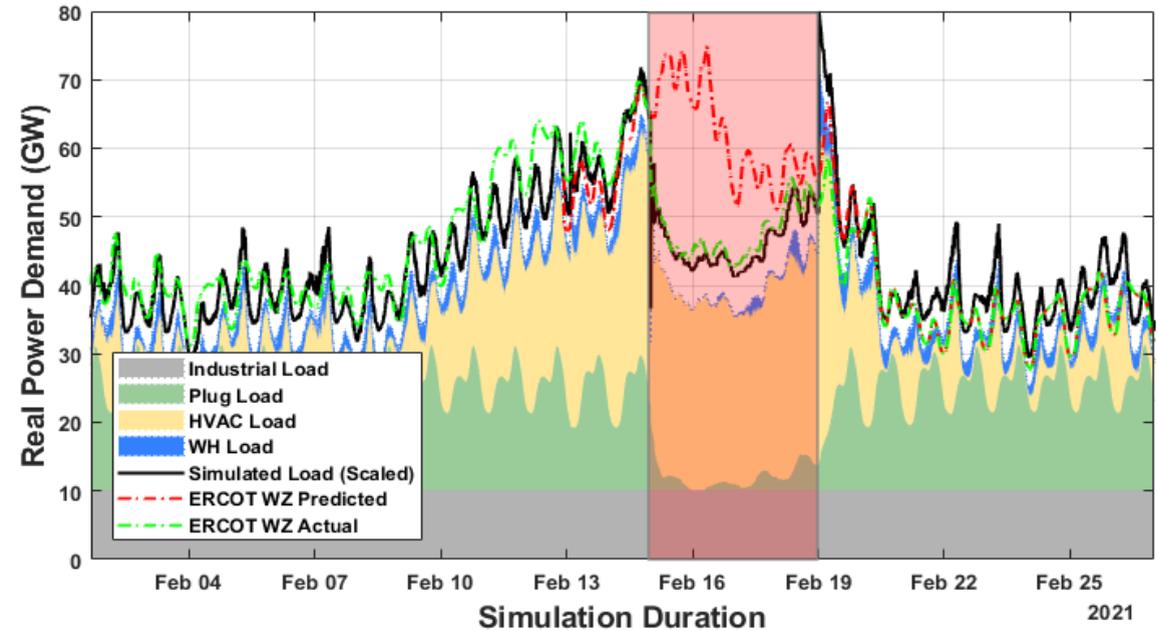
Grid Response for **Base** at the ERCOT-Level)



Grid Response for **AMI-RO** at the ERCOT-Level)

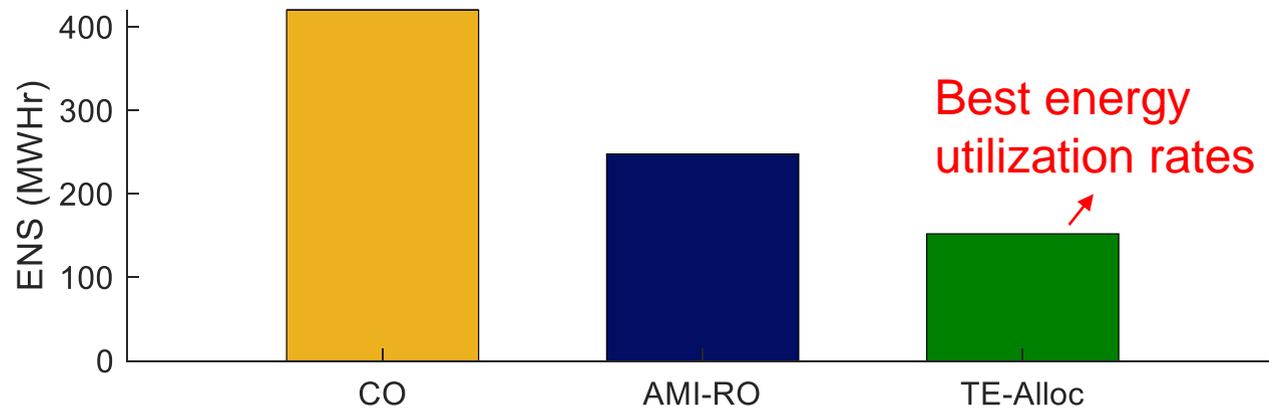
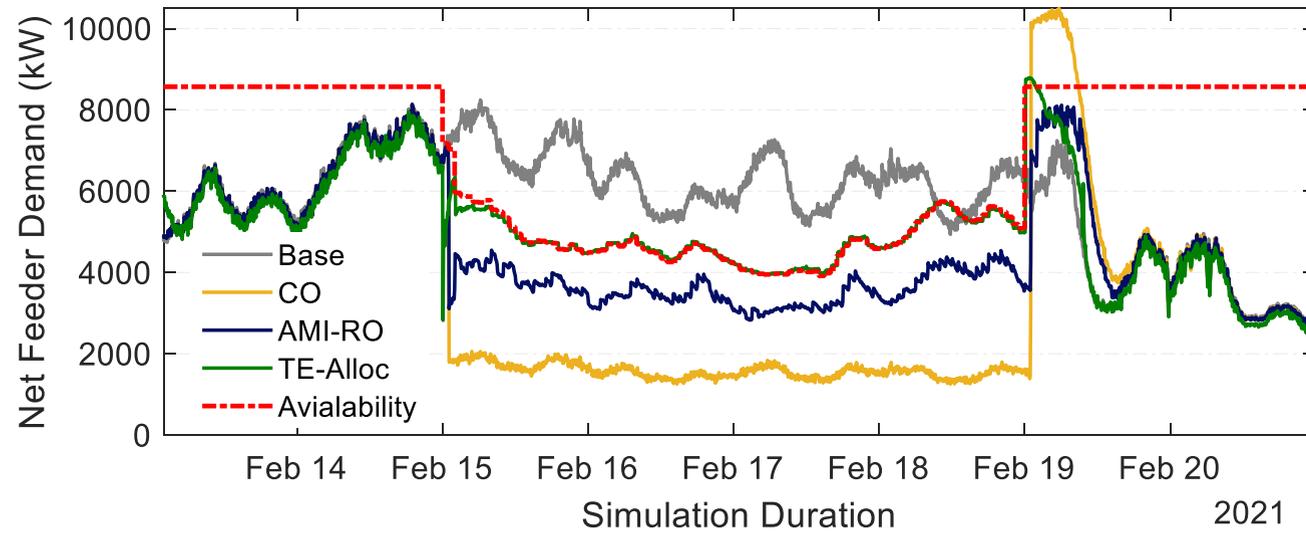


Grid Response for **TE-ALLOC** at the ERCOT-Level)

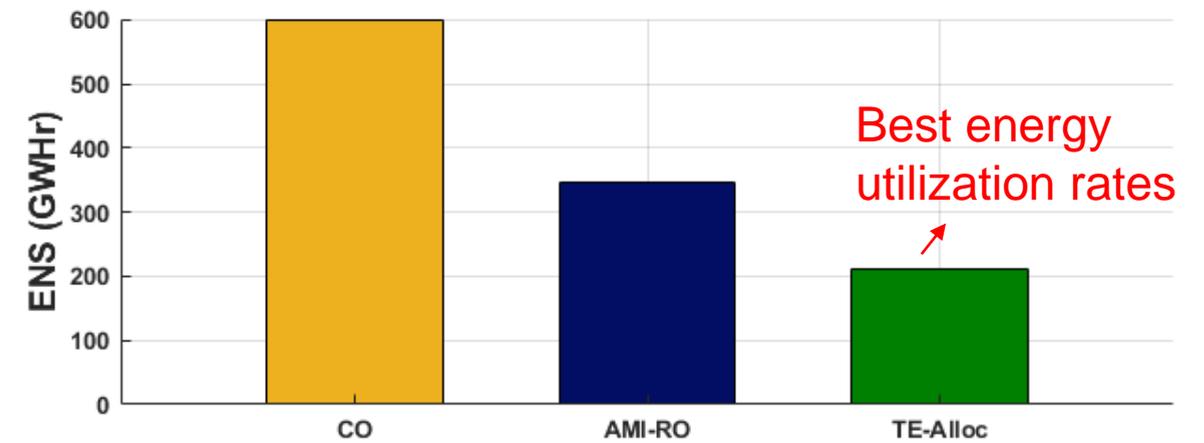
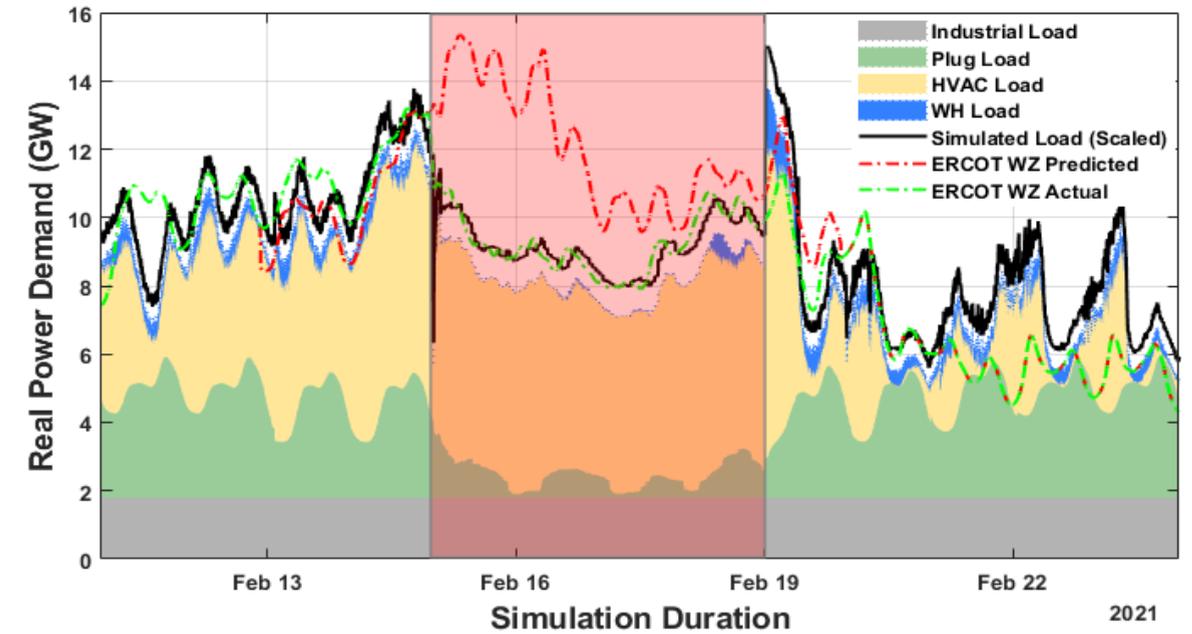


Demonstration

DSO Unscaled level



DSO Scaled level

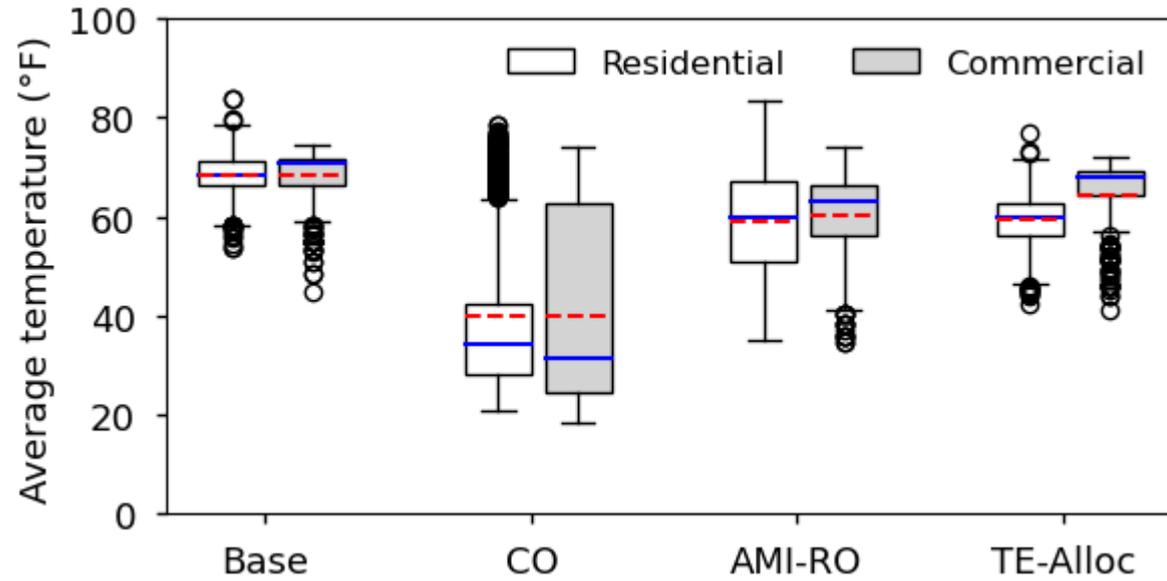


Grid response during extreme temperature outage: Substation demand for resilience mechanisms (top), and the energy not served (ENS) (bottom)

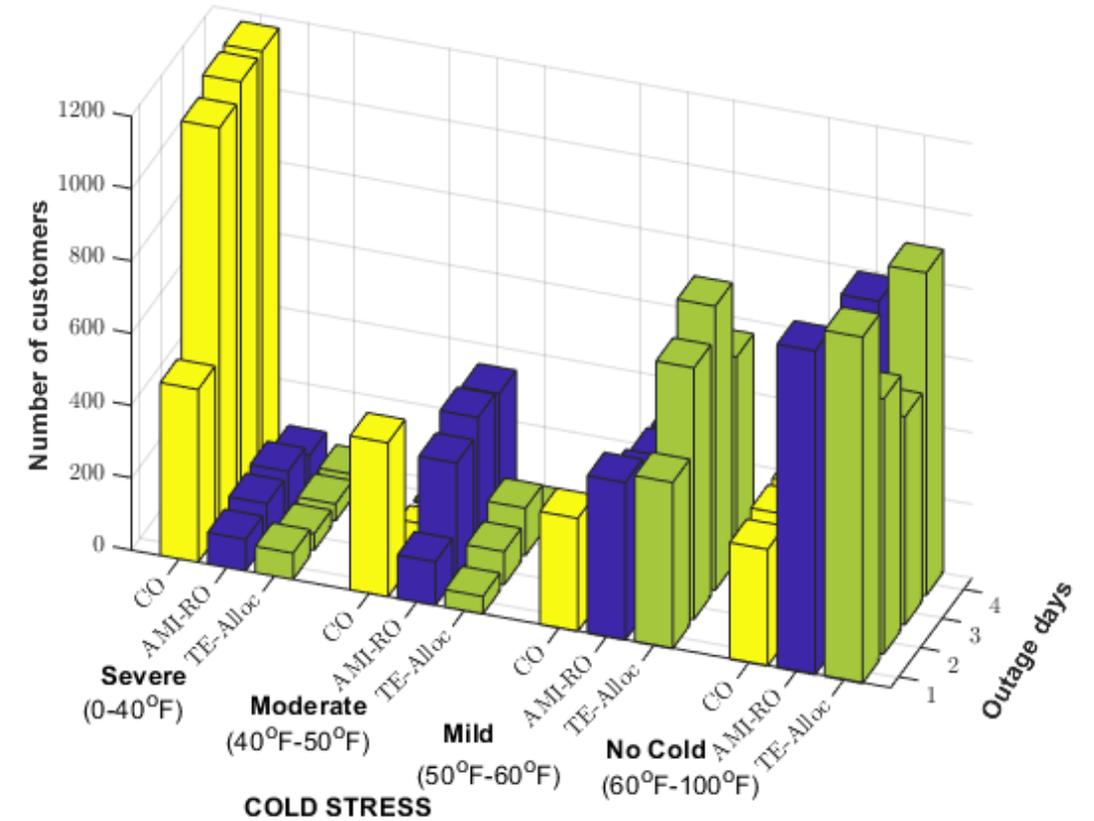
➤ **TE-Alloc facilitates an effective utilization of the available energy among customers throughout outage duration**

Exposure Analysis & Damage Estimation

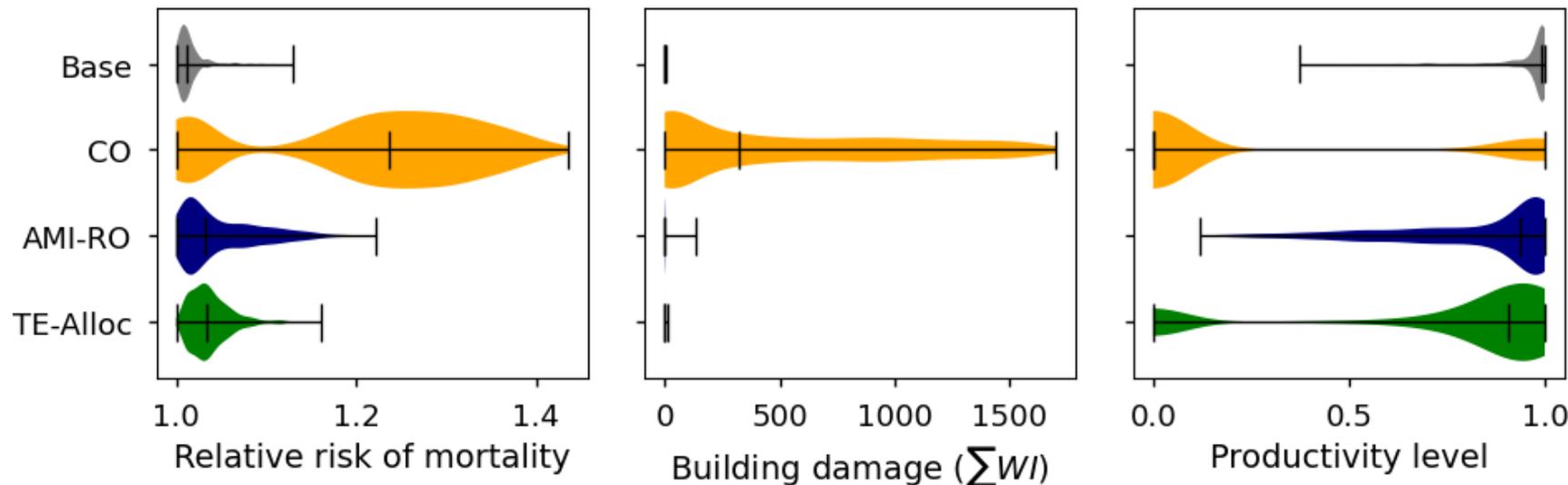
Average indoor temperature during outage period



Thermal stress levels w.r.t customers



Occupants and property damage level



- **TE-Alloc effectively managed most customers under Mild or No Cold stress throughout the event**
- **CO** : Higher mortality risks and widely varying building damage levels
- **AMI-RO & TE-Alloc** : Lower mortality risk and Higher productivity levels.

Stacking Investments for DSOs

➤ Capital and O&M Costs (Annualized)

- **CO:** OMS Software and Cyber Infrastructure
- **AMI-RO:** AMI Meters and Network
- **TE-ALLOC:** DER Network, Market Software

➤ Wholesale Power Purchases (Additional costs)

- Bilateral Purchases (PPA) – 60%
- DA and RT Markets (Scarcity prices)

➤ Lost Revenue

- Lost sale due to outages / load curtailment
- Based on fixed energy tariff and demand charge

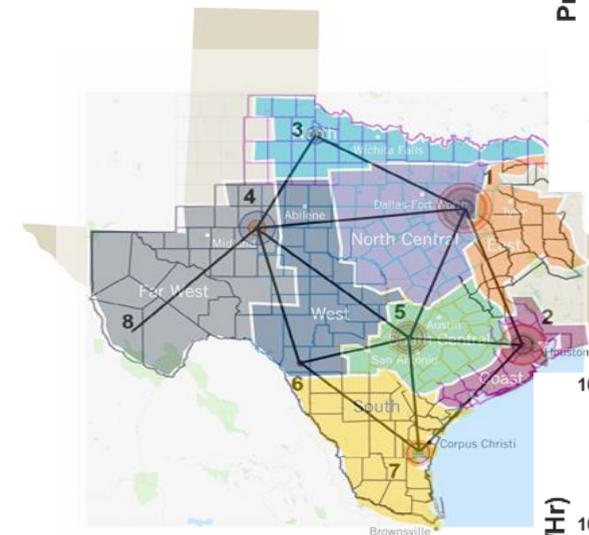


Fig. 8-Node Model of ERCOT

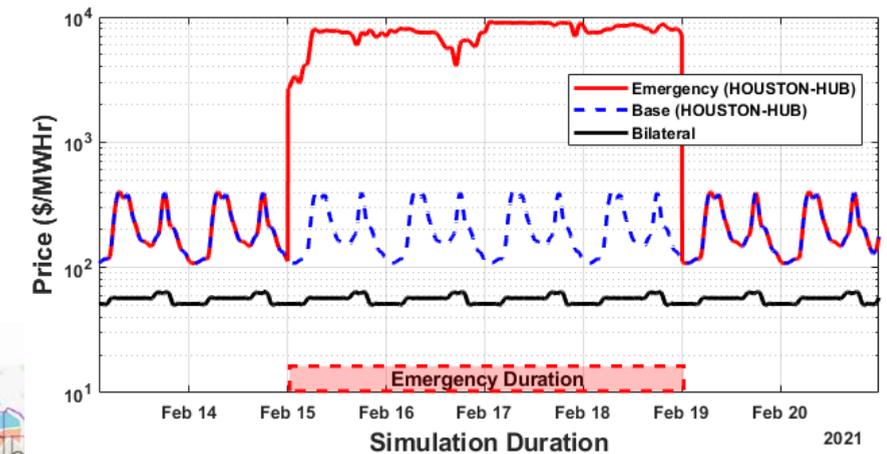


Fig. Wholesale purchase cost for DSO2

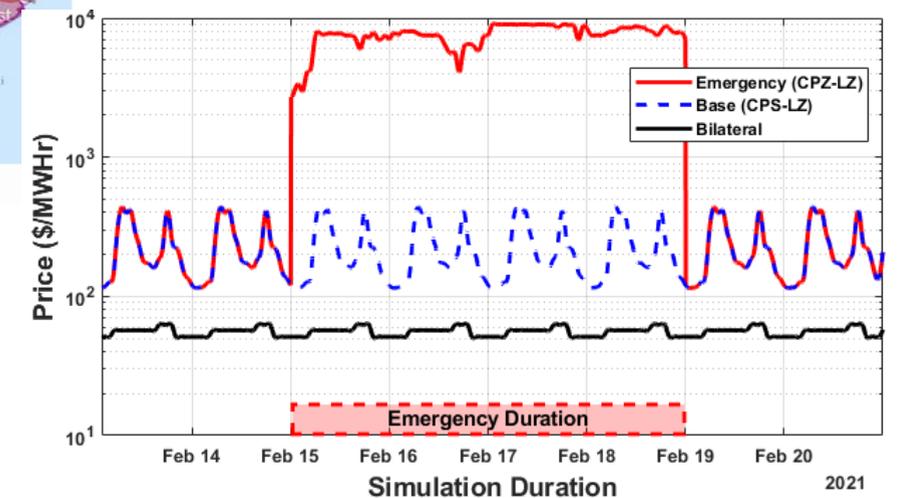


Fig. Wholesale purchase cost for DSO5

Valuation

Customer Costs

Customer Costs	Residential			Commercial		
	CO	AMI-RO	TE-Alloc	CO	AMI-RO	TE-Alloc
Monthly Energy Costs						
Capital (HEMS) \$	-	-	1.5	-	-	7.9
Energy Procurement (\$)	134.68	143.46	234.99	813.65	904.08	1218.33
Cost Per Customer (\$)	134.68	143.46	236.49	813.65	904.08	1226.23
Total Cost (scaled) (\$M)	1538.2	1633.3	2748.9	621.8	681.6	776.4
Damage / Loss Associated with the Event						
VSL (\$)	306.5	0	0	0	0	0
Medical (\$)	1458.7	318.0	257.7	0	0	0
Productivity Decrease (\$)	22.6	191.7	125.9	89.3	703.3	974.3
Building Maintenance (\$)	599.5	66.4	92.1	1535.8	163.3	98.0
Power Interruption (\$)	106.2	107.1	52.0	12930.6	6054.5	5572.9
Loss per Customer (\$K)	2.49	0.68	0.53	14.56	6.92	6.65
Total Loss (scaled) (\$B)	28.1	7.7	5.9	13.6	6.5	6.2

246 lives were lost as reported

\$80-120B in Losses (with indirect economic)

Energy Procurement: Higher in **AMI-RO** and **TE-Alloc** due to better utilization.

- **Loss per Customer:** Highest in **CO** case, indicating severe damage.
- **TE-Alloc:** Reduces total losses by **5%** compared to **AMI-RO** and **54%** compared to **CO** for commercial customers. For residential customers, **TE-Alloc** shows an **23%** reduction compared to **AMI-RO** and **79%** reduction compared to **CO**.

System-Level Cost Impacts

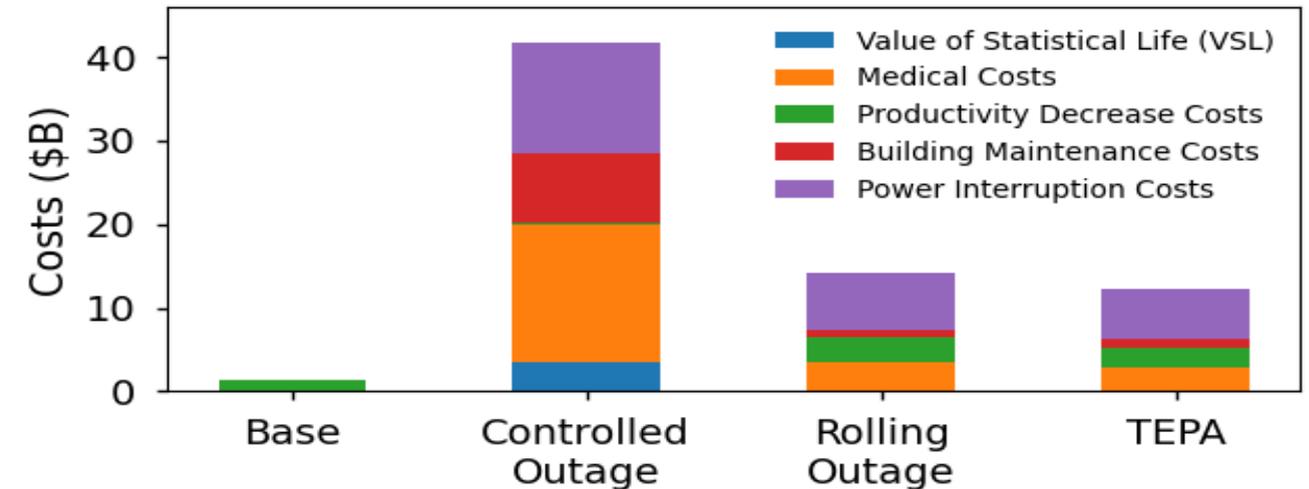
Category	CO	AMI-RO	TE-Alloc
Utility's Change in Capital & O&M Costs from BAU-case			
Capital (\$M)	37.11	226.85	275.81
O&M (\$M)	13.40	90.81	125.47
Utility's Change in Energy Purchase & Sales from BAU-case			
Wholesale Purchases (\$M)	3300.45	6774.54	8619.48
Revenue from Sale (\$M)	-387.10	-236.40	-153.66
Total Change in Utility's Costs from BAU-case			
Total Costs (\$M)	2963.86	6855.80	8867.10
System-Level Impact of Resilience Enhancement			
Increased DSO costs (\$B)	-	3.89	5.90
Avoided Customer Damage (\$B)	-	27.5	29.6

\$10B in Utility Losses Reported

- **Capital and Operational Costs:** TEPA and AMI-RO due to advanced infrastructure
- **Energy Purchase Costs:** TEPA and AMI-RO mechanisms incur additional costs due to higher utilization.
- **Revenue Loss:** DSOs face revenue loss due to high wholesale prices and limited availability.
- **Economic Viability:** Avoided customer damages and societal benefits (\$27.5B for AMI-RO and \$29.6B for TE-Alloc) far exceed the additional costs (\$3.89B for AMI-RO and \$5.90B for TE-Alloc).

Summary from Valuation results

- **Significant Non-Energy Impact Costs:** Extreme temperature-related outages can lead to substantial non-energy impact costs. Neglecting these factors can cause a significant underestimation of the true economic impact.
- **Advanced Resilience Mechanisms:** Efficient resource utilization reduces damages.
- **Trade-offs and Equitable Service:** Balancing energy allocation across customer groups is essential for equitable service, considering the trade-offs in damages.
- **Societal Benefits vs. Additional Costs:** While additional costs are incurred by the DSO to supply energy during extreme events, advanced resilience mechanisms prevent customer damages, resulting in societal benefits that far exceed these costs.

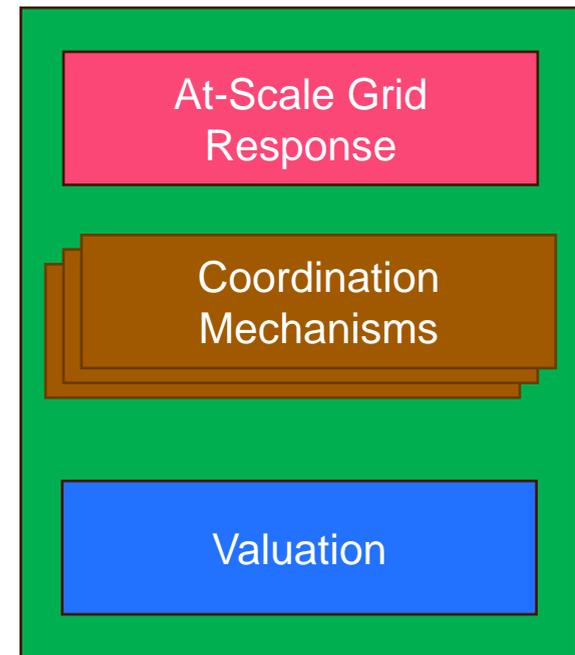


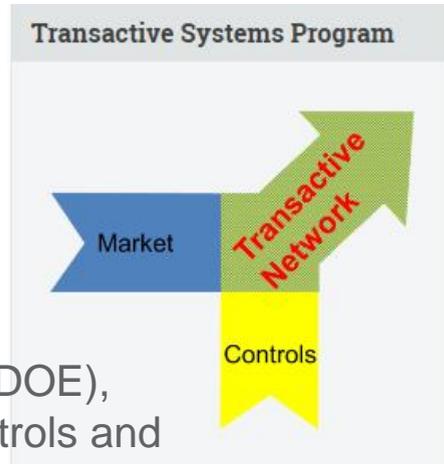
Category	CO	AMI-RO	TE-Alloc
System-Level Impact of Resilience Enhancement			
Increased DSO costs (\$B)	-	3.89	5.90
Avoided Customer Damage (\$B)	-	27.5	29.6

- Even after considering scarcity pricing of \$8000/MWHR, the Resilience Enhancement Mechanisms would drastically reduce (by ~70%) the avoided customer losses.

Publications from the DSO-RISE Study

- 1) Hanif, S., Mukherjee, M., Poudel, S., Yu, M.G., Jinsiwale, R.A., Hardy, T.D. and Reeve, H.M., 2023. **Analyzing at-scale distribution grid response to extreme temperatures.** *Applied Energy*, 337, p.120886.
- 2) S. Poudel, M. Mukherjee, R. A. Jinsiwale and S. Hanif, "**Resilience Assessment Framework For Distribution Systems Performance Under Extreme Conditions,**" *2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 2023, pp. 1-5, doi: 10.1109/ISGT51731.2023.10066427.
- 3) S. Poudel, M. G. Yu, M. Mukherjee, S. Hanif, T. D. Hardy and H. M. Reeve, "**A Framework to Design Consumer-Centric Operational Strategies for Resilience Enhancement,**" in *IEEE Transactions on Industry Applications*, vol. 60, no. 2, pp. 2332-2343, March-April 2024, doi: 10.1109/TIA.2023.3318581.
- 4) S. Bajagain, S. Poudel, M. G. Yu, and M. Mukherjee, "**Data-Driven Outage Management Scheme for Enabling Resilience During Extreme Events**", *2025 IEEE Power & Energy Society Grid Edge Technologies Conference & Exposition, San Diego, CA, January 2025. [Accepted]*
- 5) M. Mukherjee, T. E. McDermott, T. Hardy, A. Somani, S. Bender and M. Moore, "**Transactive Energy Rationing in Islanded Electric Power Systems,**" in *IEEE Transactions on Industry Applications*, vol. 59, no. 1, pp. 312-322, Jan.-Feb. 2023, doi: 10.1109/TIA.2022.3210080.
- 6) M. Mukherjee, M. Maharjan and T. Hardy, "**Transactive Emergency Power Allocation,**" *2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA, 2023*, pp. 1-5, doi: 10.1109/PESGM52003.2023.10252732.
- 7) Maharjan M., M. Mukherjee, and T.D. Hardy. 2024. "**Allocation-Based Transactive Coordination Mechanism for Resilience Enhancement.**" *In review, IEEE Transactions on Smart Grid.*
- 8) M. G. Yu, S. R. Bender, M. Mukherjee, T.D. Hardy, "**Comfort and Safety Metrics to Evaluate Customer Centric Resilience Enhancement Strategies**", *2024 IEEE Power & Energy Society General Meeting (PESGM)*, Seattle, WA, USA, 2024.
- 9) M. G. Yu, M. Mukherjee, S. Poudel, S.R. Bender, S. Hanif, T.D. Hardy and H.M. Reeve, "**A valuation framework for customers impacted by extreme temperature-related outages.**" *Applied Energy*, 368, p.123450.
- 10) Yu, M.G., Maharjan, M., Mukherjee, M., Poudel, S., Bender, S.R., Hardy, T.D. and Reeve, H.M., 2024. **Techno-Economic Analysis of Data-driven and Transactive Approaches for Resilience Enhancement.** *In review, IEEE Transactions on Industry Application.*





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Thank you

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