Improving Distribution Grid Resilience by Optimally Planning and Operating DERs

ESIG 2024 Fall Workshop

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Photo from iStock-627281636

Case Studies and Pilot Examples

1 **Hierarchical Control of BTM DERs in NZE Community**

2 **Equitable Service Restoration in Self-Healing Grids**

3 **Reconfigurable Communities with PVs and BESS**

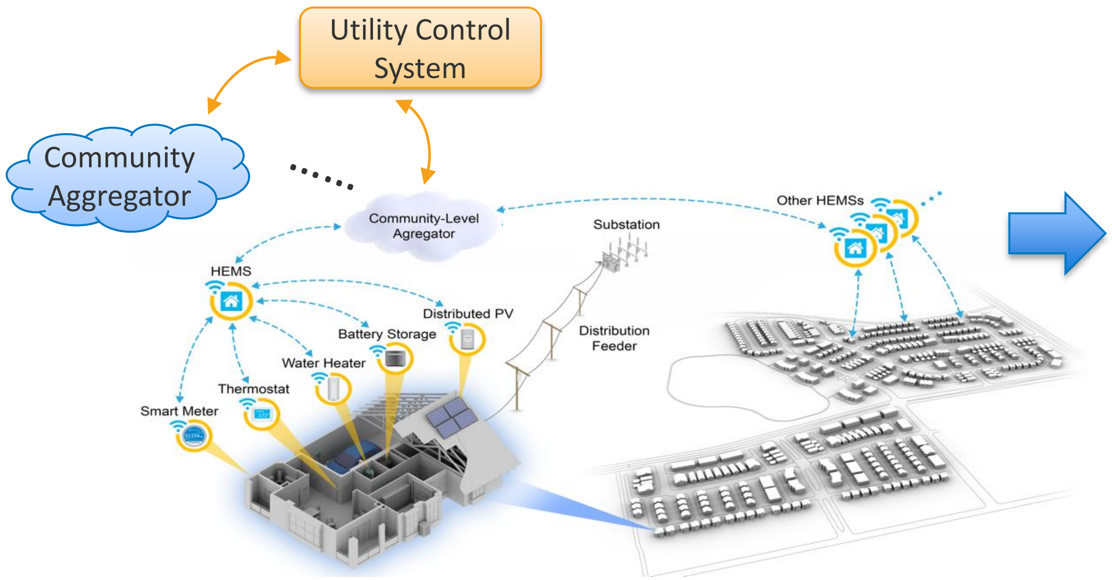
1. Hierarchical Control of BTM DERs in NZE Community

Project Overview

Challenges

- Net zero energy (NZE) communities are emerging, and the high-penetration PV in the communities may cause issues such as overvoltage, voltage flicker, and degraded power factor in the electrical distribution systems.
- Existing solutions have insufficient understanding of behind-the-meter assets or are not able to manage large-scale heterogeneous assets.

Our Solution: Develop a field-proven control system that can manage the behind-the-meter loads and distributed energy resources and coordinate them across different homes to improve grid reliability and resilience.



- **PV Self-Consumption** (reduce PV curtailment with flexible loads and batteries)
- **Grid Reliability** (reduce voltage violation; demand response; virtual power plant)
- **Grid Resilience** (Maximize the use of local PV and BESS to support loads)

10/2018	Project started
3/2020	Construction of the Fort Collins community delayed; identified Basalt Vista as the alternative field pilot site.
6/2020	Simulation studies completed
3/2021	Hardware-in-loop laboratory experiment completed
7/2021	Recruited field pilot participants at Basalt Vista
10/2021	Field deployment completed; field demonstration started
4/2022	Project ends, equipment decommissioning

Project Team: NREL, Holy Cross Energy, Fort Collins Utilities, Thrive Home Builders, Copper Labs, Habitat for Humanity, Conservation Labs, AO Smith

Photo credit: Anna Stonehouse
Habitat for Humanity Roaring Fork Valley

Hierarchical Control

HEMS Control

- **Objective**
  - Minimize net load consumption
  - Minimize user discomfort
- **Constraint**
  - Operational constraints for all controlled devices (PV, battery, HVAC, EWH)
- **Output**
  - Device setpoint

Aggregator Control

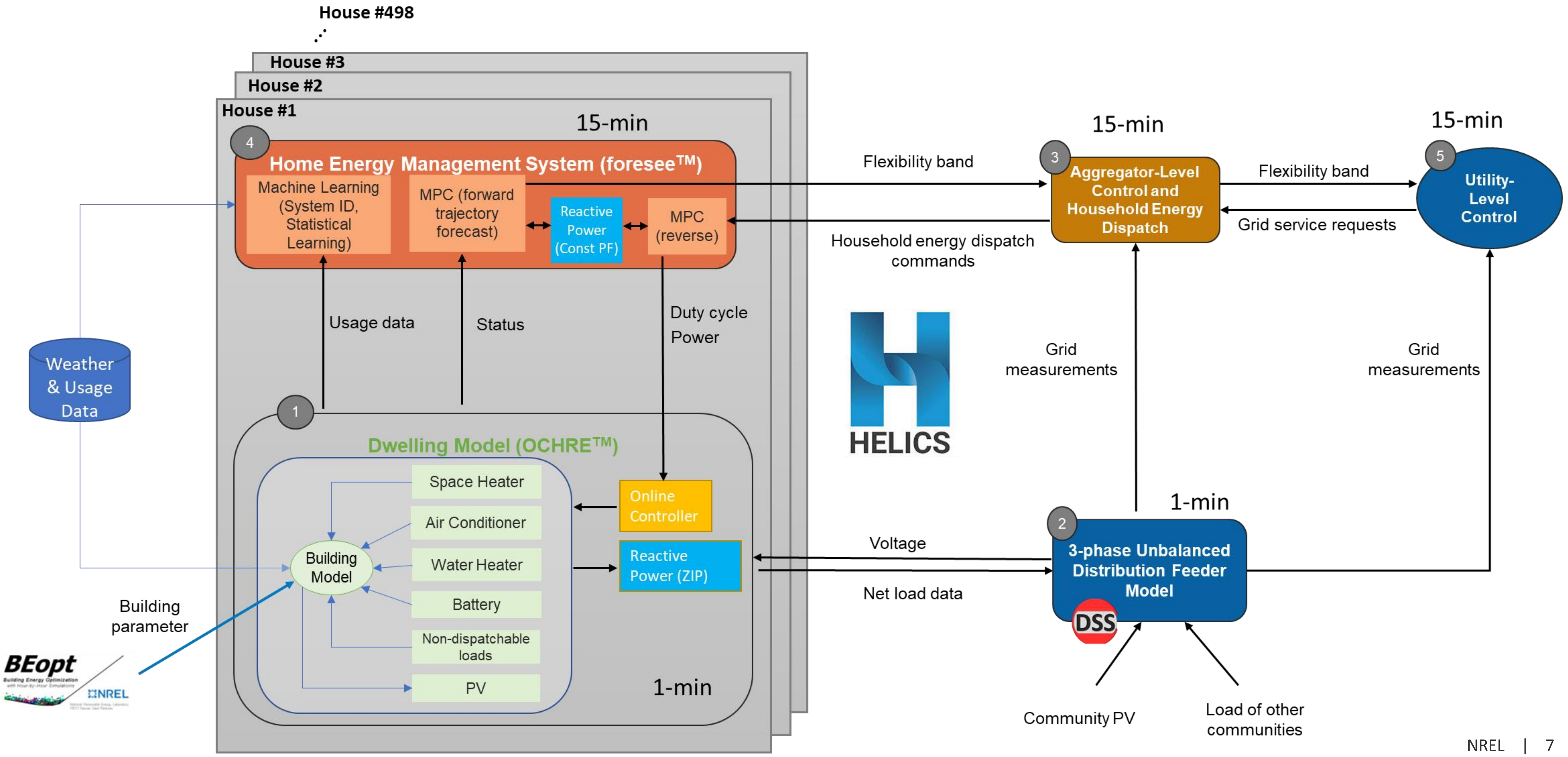
- **Objective**
  - Minimize deviations from HEMS bids
  - Minimize deviation from utility power request
- **Constraint**
  - Network voltage limits
  - HEMS power limits
- **Output**
  - P/Q dispatch signals for individual HEMSs

Utility Control

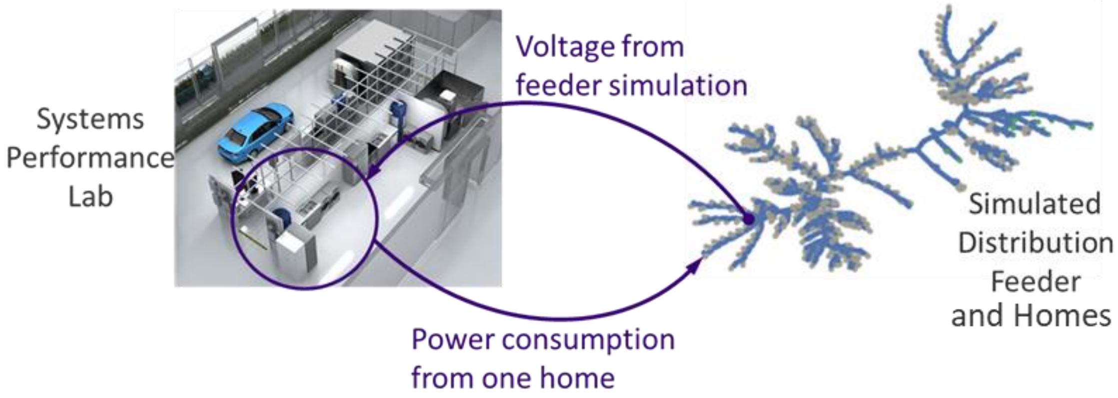
- **Objective**
  - Minimize deviations from aggregator bids
  - Specific grid service objectives
- **Constraint**
  - Network voltage limits
  - aggregator power limits
- **Output**
  - P/Q dispatch signals for individual aggregators

U. Kumar, F. Ding, et. al., "A network-aware distributed energy resource aggregation framework for flexible cost-optimal and resilient operations," IEEE Transactions on Smart Grid, vol. 13, no 2, March 2022.

Simulation Test Bed



Hardware-in-Loop Laboratory (HIL) Experiments



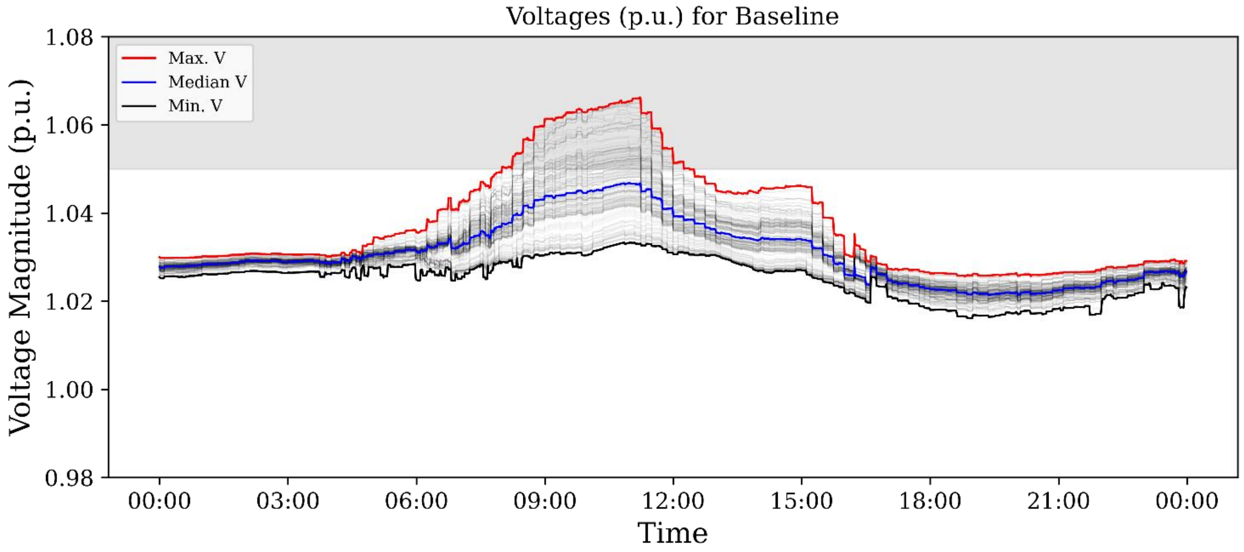
Supercomputer

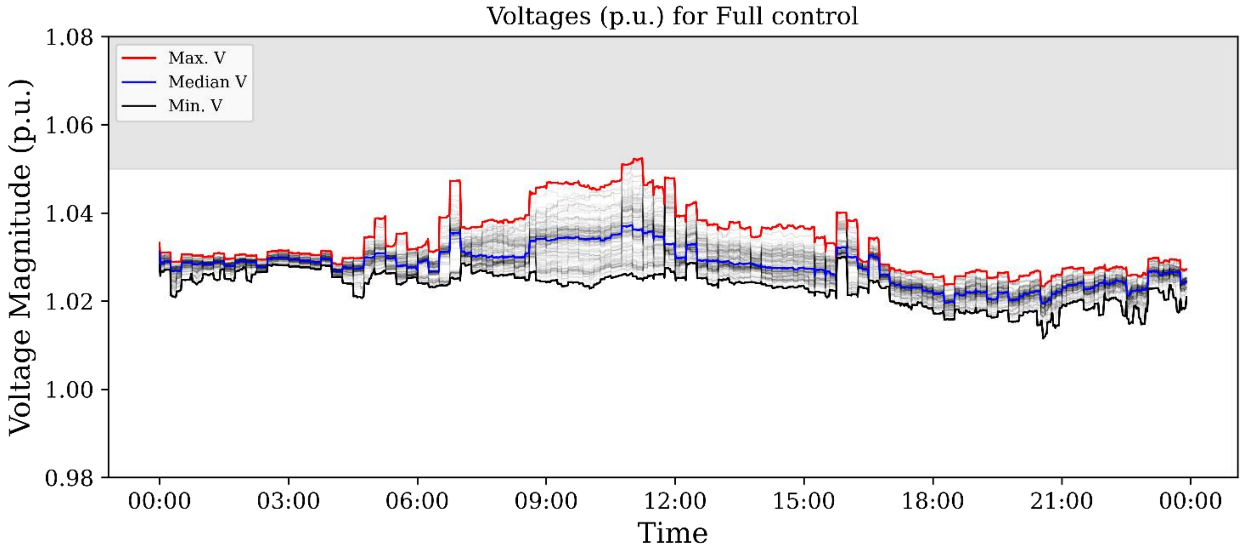
Smart home HIL with physical devices in a lab home and simulated homes and distribution feeder on the supercomputer

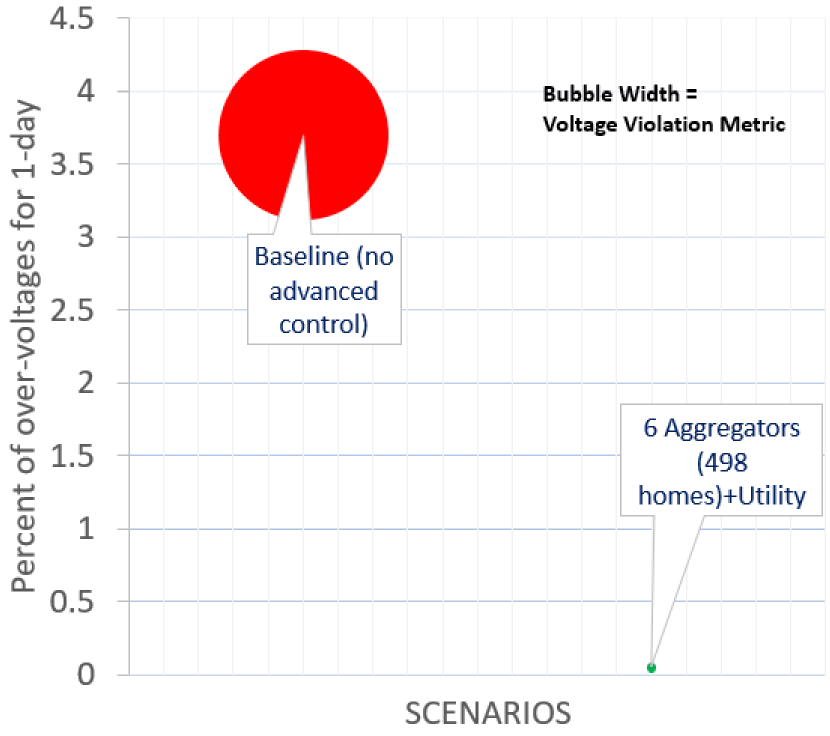
Physical equipment in the lab home verifies control performance at the device level, and the actual load profile from the lab home is injected back to the simulated community on the supercomputer.

Simulation Results – Grid Reliability (Shoulder Season)

Community-scale voltage data from grid reliability experiments

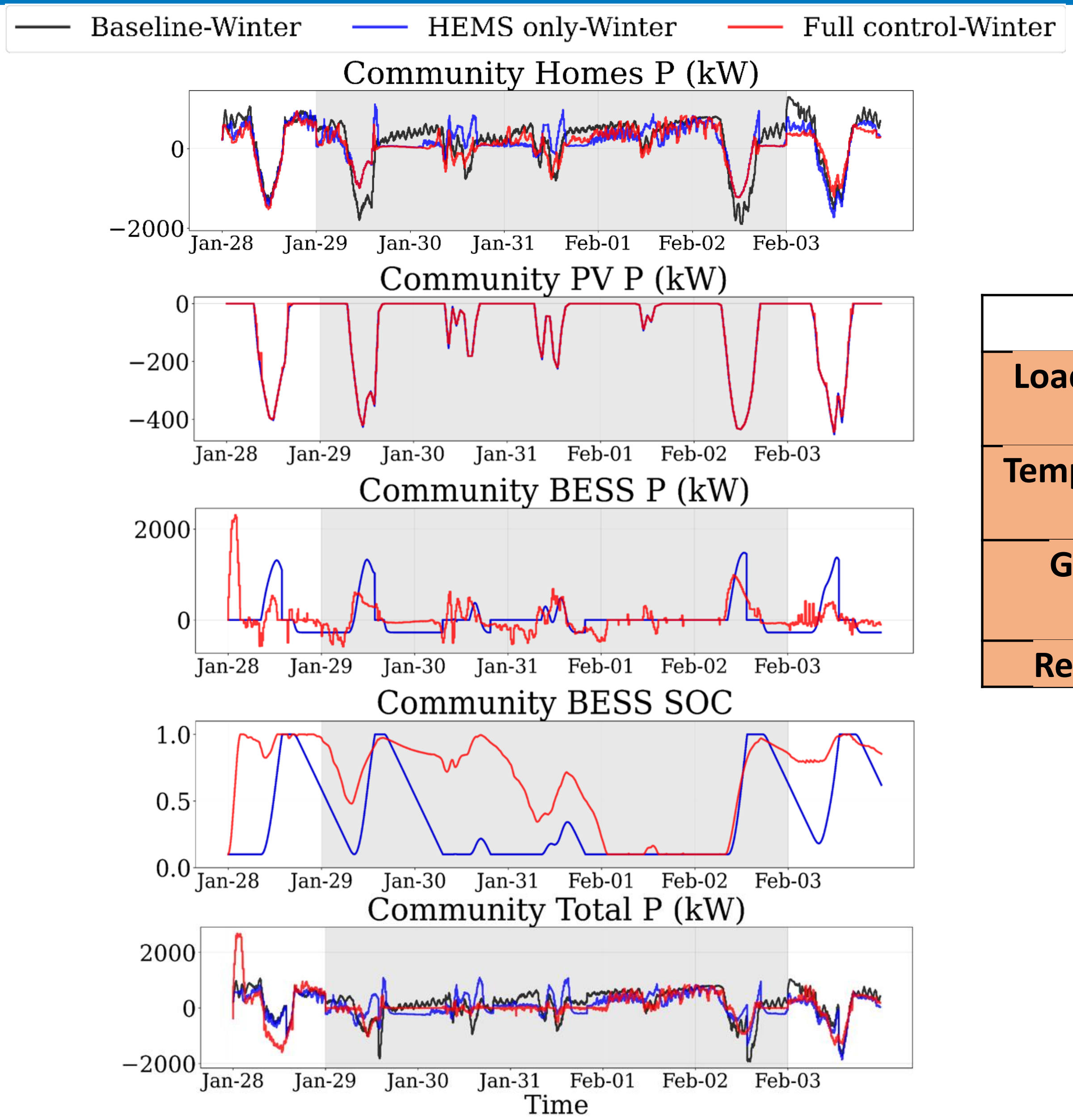






- Shoulder season was selected for HIL experiments because of the low load and high PV generation.
- The hierarchical control system significantly reduced overvoltages in the community.

Simulation Results – Grid Resilience (Winter Season)



	Baseline	HEMS only	Full control
Load shedding required (MWh)	32.61	25.11	14.19
Temperature satisfaction metric (r_{air})	1.0000	0.9999	0.9990
Grid independency metric (r_{dep})	0.3703	0.5152	0.7259
Resilience metric ($\mathcal{R}$)	0.4332	0.5636	0.7532

Basalt Vista Field Pilot Study

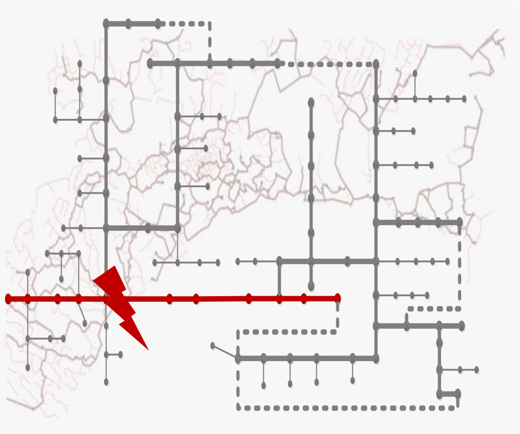
- Deployed the control solution in Basalt Vista Community in Colorado.
- Basalt Vista is an affordable housing community constructed for local schoolteachers. It has 12 duplex/triplex buildings with a total of 27 all-electric, net zero energy homes.
- Conducted the experiment at four homes locating at two service transformers.

Photo credit: Anna Stonehouse
https://habitatroaringfork.org/pages/basalt-vista

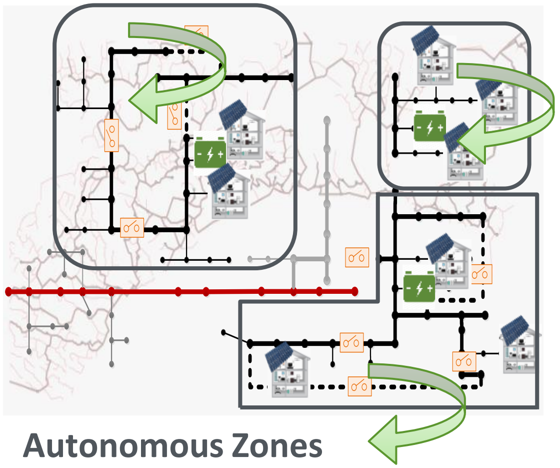
2. Equitable Service Restoration in the Self-Healing Grid

Self-Healing Distribution Grid with the use of DERs

- Increasing grid integration of DERs and grid-forming inverter-based resources at the Grid Edge
- Advances in distribution automation
- Development of advanced controls and communications



- Proactively reconfigure distribution grid into networked autonomous zones
- Each zone operates in islanded mode to support local customers
- Optimize the operation continuously



Autonomous Zones

— Physical infrastructure destroyed — Power outage areas — Energized areas

A new way to enable **fast, bottom-up service restoration** and significantly enhance resilience.

Leverage DER Flexibility for Resilience Service

Service restoration is conducted to minimize the weighted sum of load shedding, considering customer load types and social vulnerabilities.

Customer Type	DER Existence	Controllability of DERs by Grid Operator	Ability to Provide Flexibility	Restoration Priority Order
Critical customers	Maybe	No	No	First
Noncritical, service-providing customers	Yes	Not directly controllable, but follows the signal generated from the grid operator	Yes, and do provide	Second
Noncritical, no-service-providing customers	Yes	No	Yes, but do not provide	Third
Other customers	No	No	No	Last

Social Vulnerability to Power Outages

Overall Vulnerability

Health

- Older adults and children
- Residents who rely on electricity-dependent medical equipment
- Nursing home residents
- Residents with a mobility limitation
- Residents with an underlying condition that is sensitive to extreme temperatures (e.g., heart disease, diabetes, asthma)

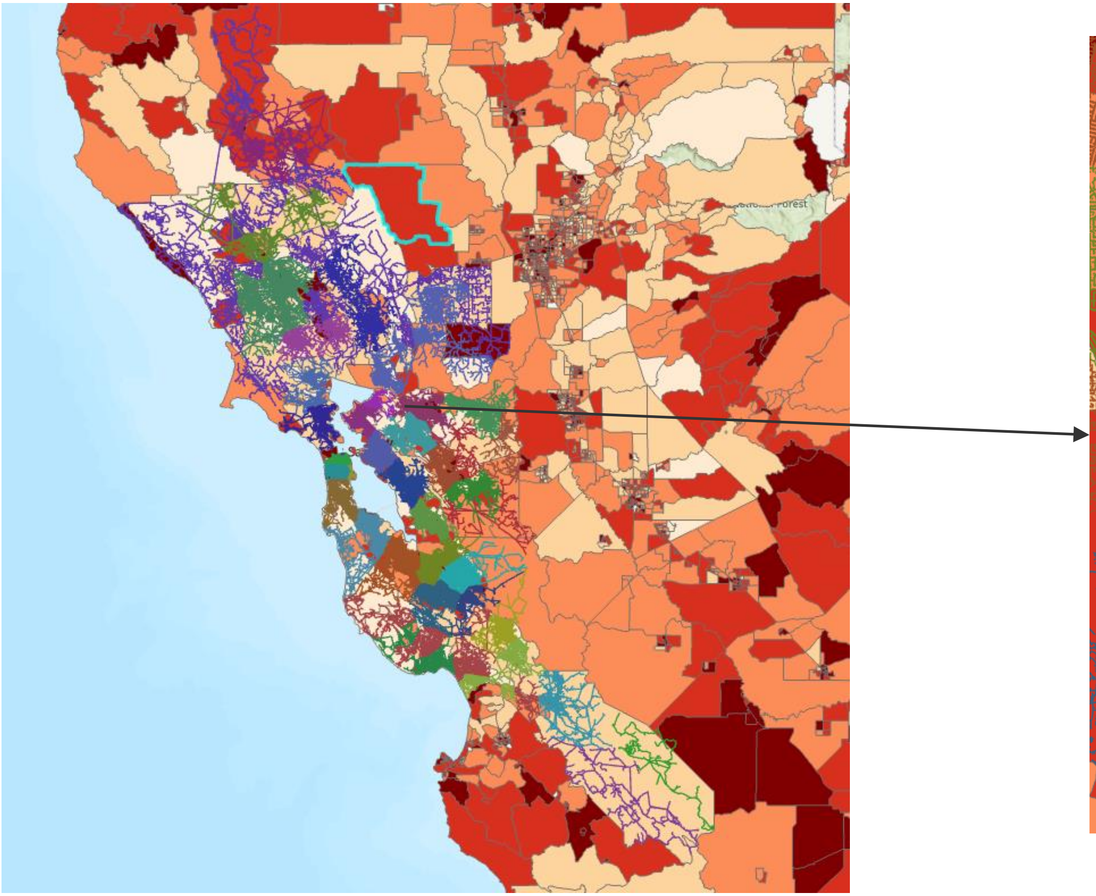
Preparedness

- Younger adults
- Households that speak limited English
- Households with children, large households
- People with low educational attainment
- Low-income households
- Elderly adults who live alone
- People who live in multi-family housing

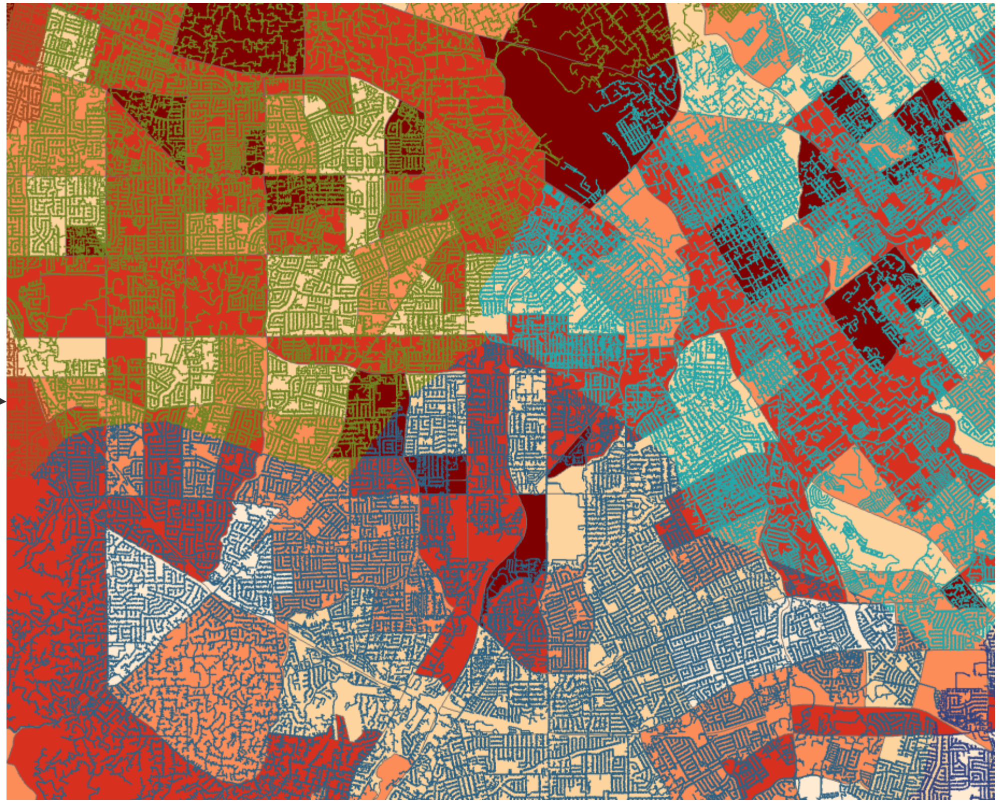
Evacuation

- Households with children, larger households
- People with work constraints
- Households with pets or livestock
- No fear of looting
- Households without access to vehicles
- Households far away from emergency shelters
- People with a disability
- Low-income households

Social Vulnerability to Power Outages



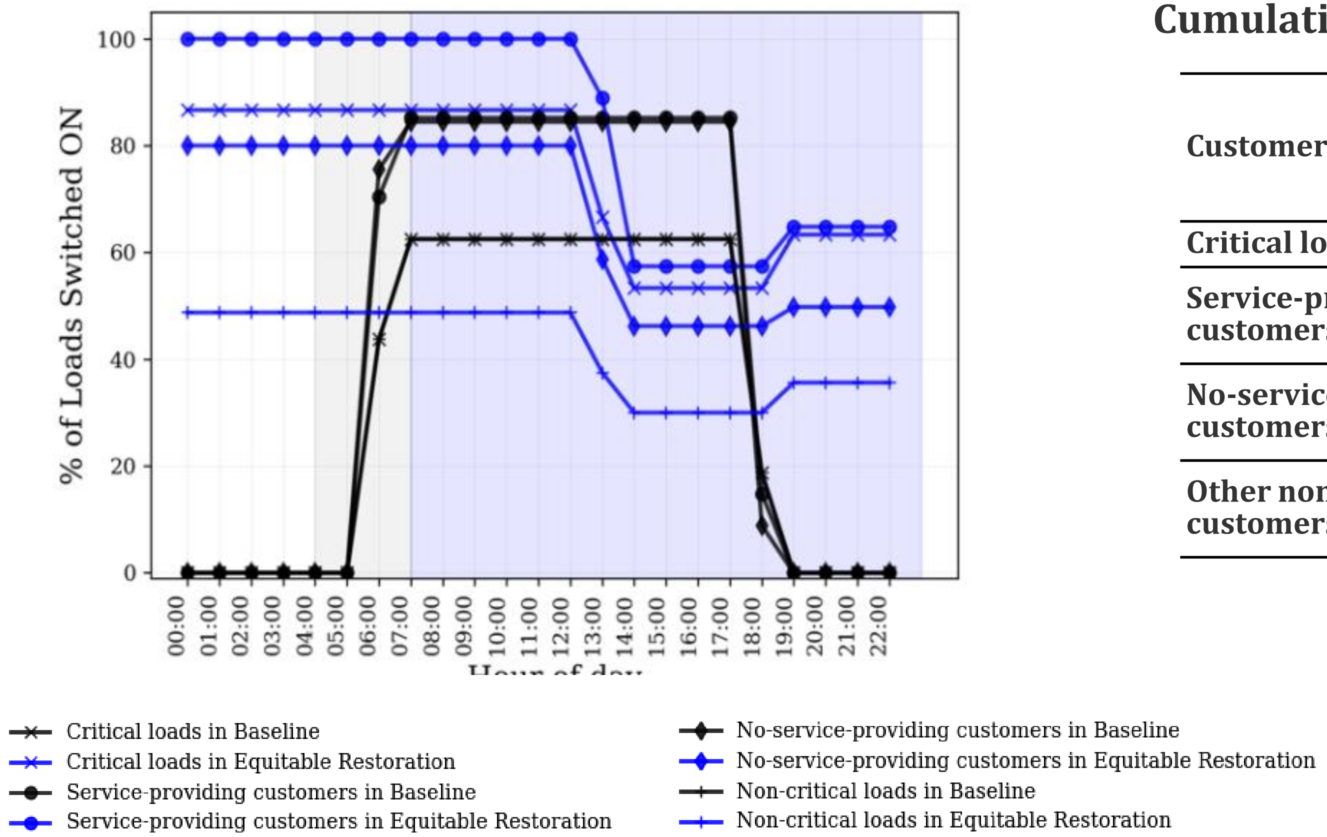
Full network



Zoom to show granularity

Case Study

Conducted simulation analysis using a distribution grid model in Georgia, consisting of two distribution feeders, with more than 1000 load nodes, three normally closed sectionalizing switches and two normally opened tie-switches.

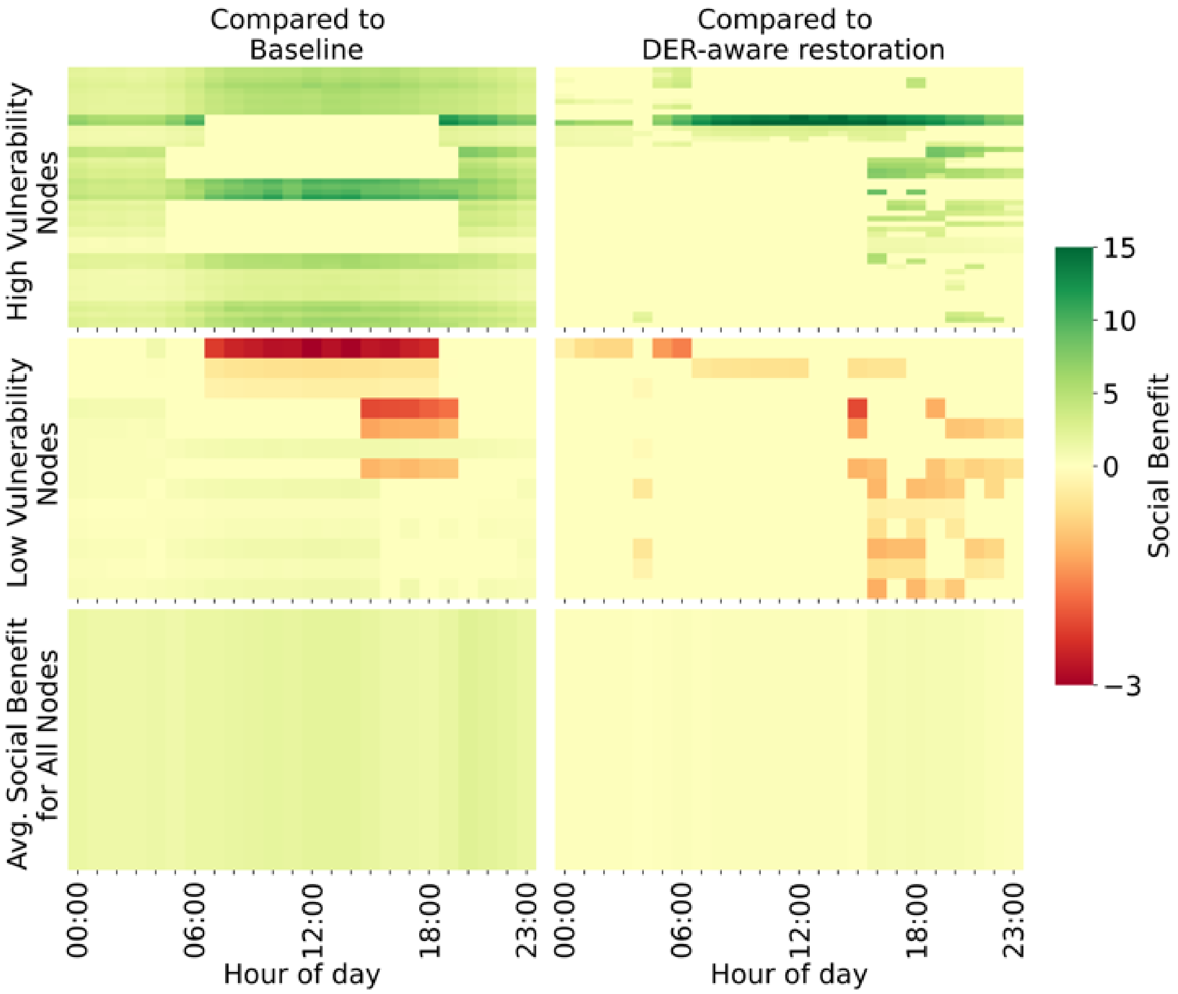


Cumulative percentage-duration of energization metric

Customer Type	Baseline (%-hours)	Equitable Restoration (%-hours)	Improvement (%)
Critical loads	750	1713	128.40
Service-providing customers	1022	1935	89.33
No-service-providing customers	1013	1528	50.84
Other noncritical customers	750	963	28.40

K. Utkarsh, F. Ding, J. Dugan, “DER-aware, equitable service restoration for enhanced grid resilience and mitigated social impact,” Applied Energy, under review.

Case Study



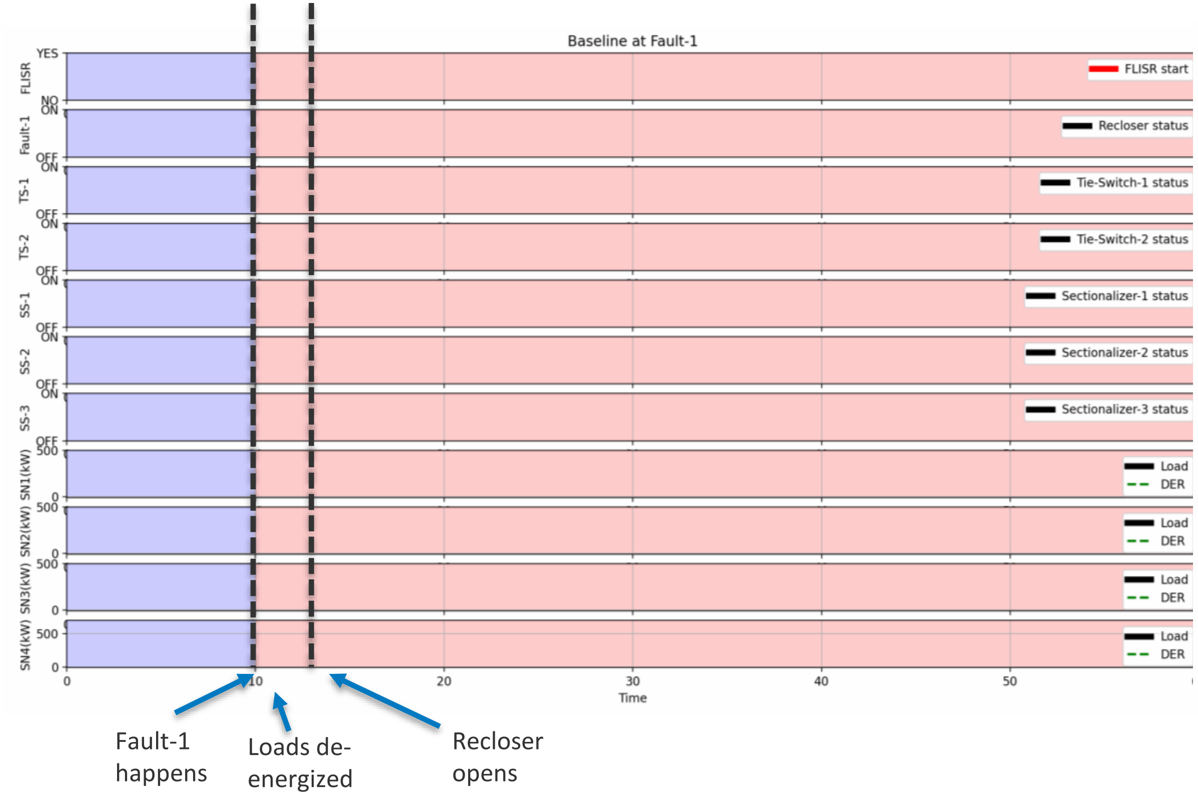
The results of *social benefit*, which is defined as the increase in supplied power compared to a base case weighted by social vulnerability.

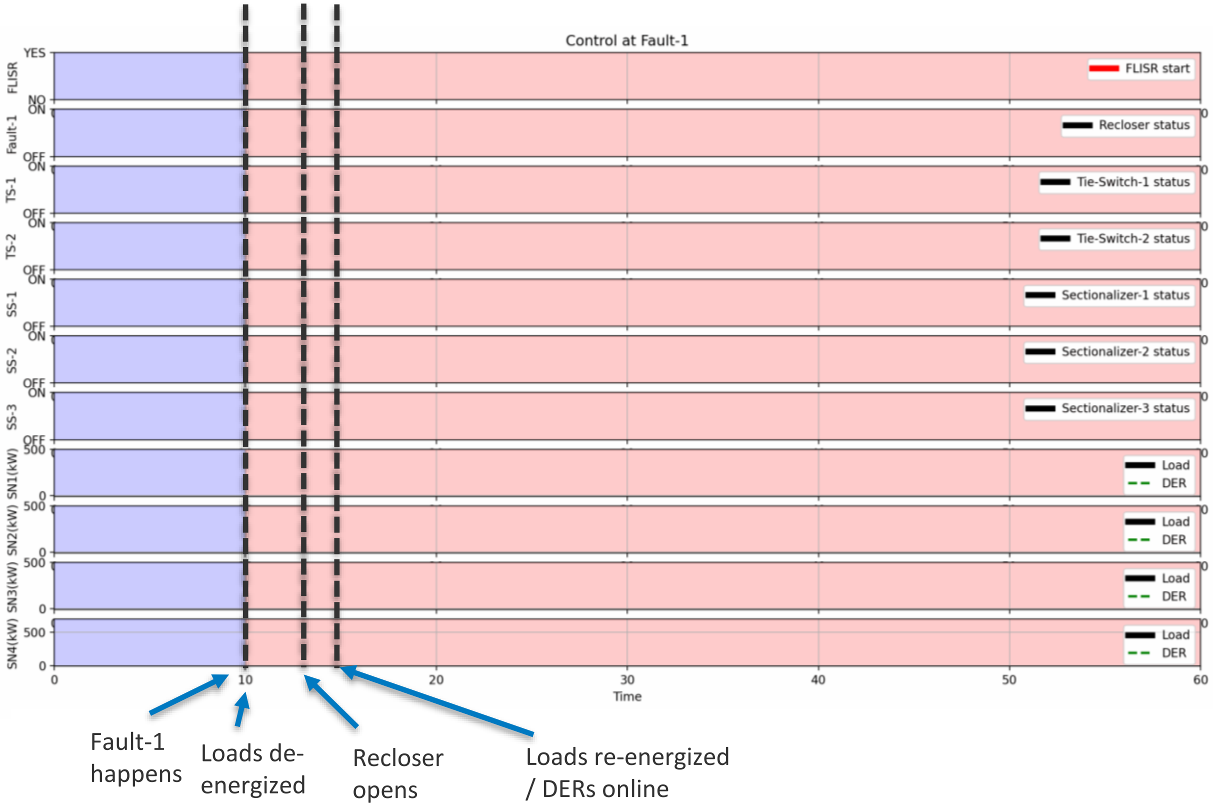
$$\beta_i = (P_i - P_i') \cdot S_i$$

K. Utkarsh, F. Ding, J. Dugan, "DER-aware, equitable service restoration for enhanced grid resilience and mitigated social impact," Applied Energy, under review.

A Case Study with the Integration of Commercial ADMS FLISR

- Integrated the DER-aware, equitable load restoration algorithm with an ADMS FLISR module
- Conducted test on the Georgia two-feeder system model





3. Reconfigurable Communities with PVs and BESS

Dynamically Reconfigurable Community Microgrids

Communities NEED resilience

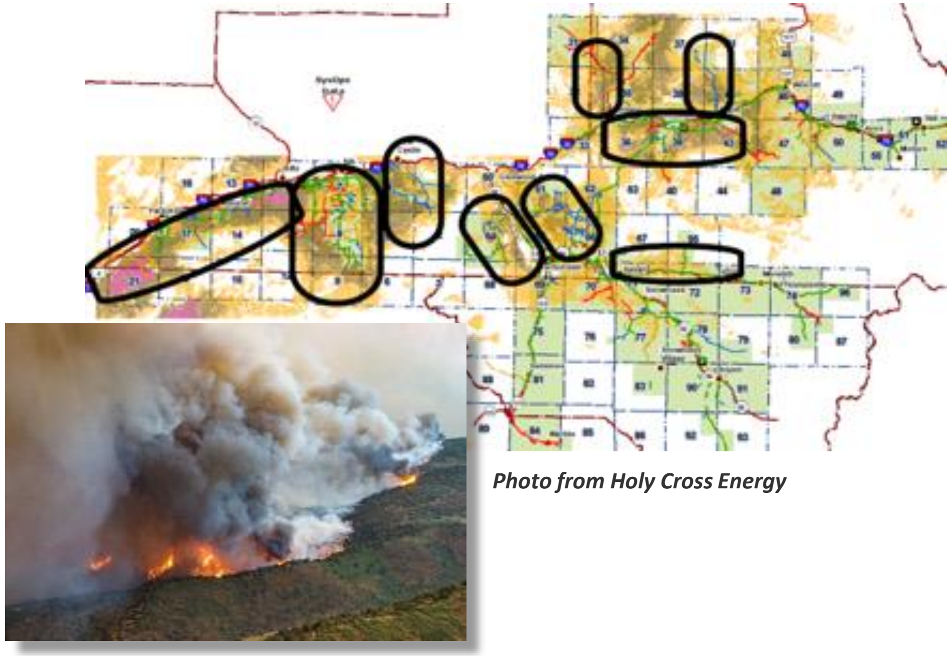


Photo from Holy Cross Energy

Pressing need to increase system resilience:

- Communities are asking for distributed clean energy solutions to realize community microgrids.

Unsolved key challenges:

- Lack of methods to partition grids for distributed control applications
- Inaccurate system models and limited communications networks during prolonged outages
- Need to maintain microgrid stability under various conditions.

Our solution

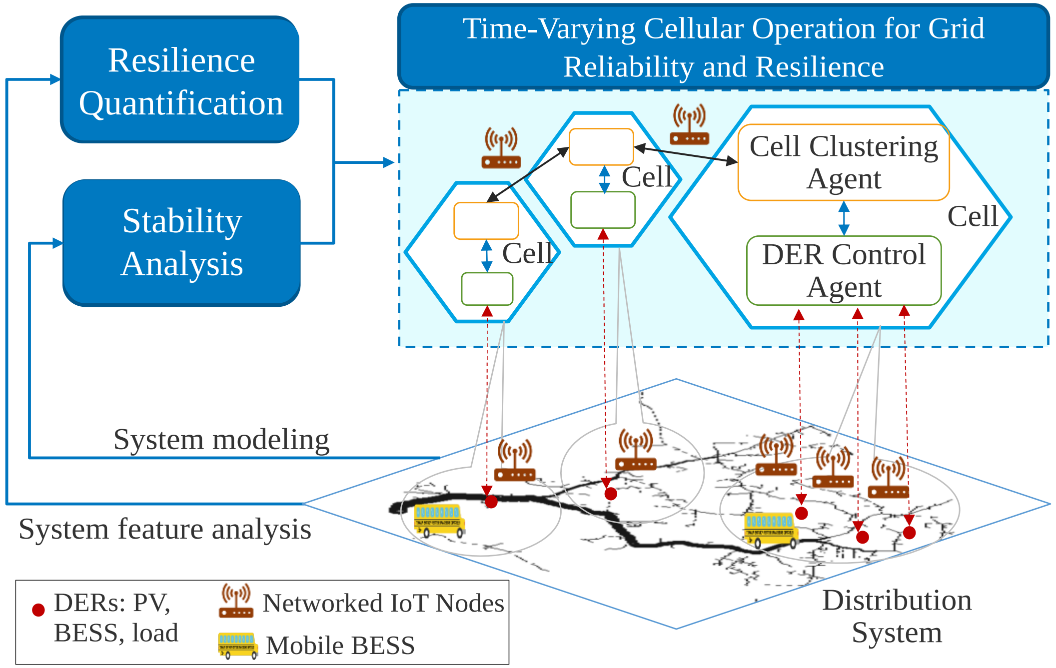
Organize the distribution system into dynamically reconfigurable community microgrids:

- Identify the segments of a distribution grid capable of operating as resilient community microgrids
- Ensure high local resilience inside each community microgrid
- Adapt to time-varying system conditions.

Project Overview

Objectives: Develop, validate, and demonstrate a cellular community microgrid formation and optimization approach to achieve resilient, stable, scalable operations for distribution feeders with PVs and mobile BESSs.

Technical Approach:



Outcomes:

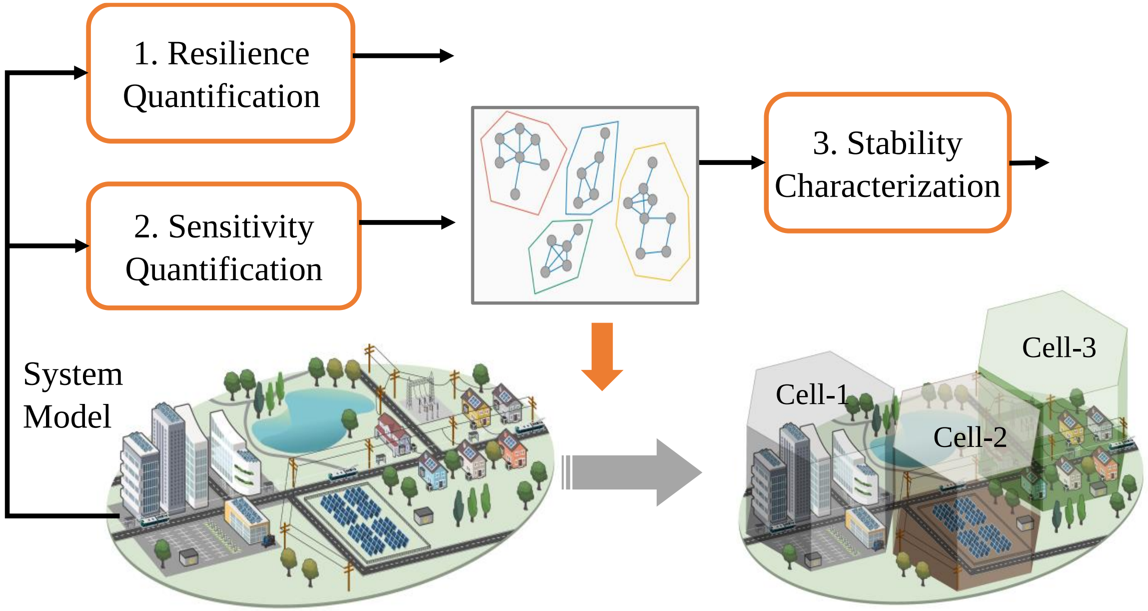
- ❑ **Innovation**
  - Resilient and stable cell microgrid organization scheme using machine learning and advanced stability designs
  - Distributed and adaptable cell management system realized using modern IoT platforms
- ❑ **Impact**
  - Solution that addresses an electric co-op's wildfire mitigation requirements
  - National scalable approach for operating multiple microgrids and increase system-level resilience

Project Team: NREL, University of Connecticut, Holy Cross Energy, Minsait ACS, NRECA

Technical Approach: Form Cells

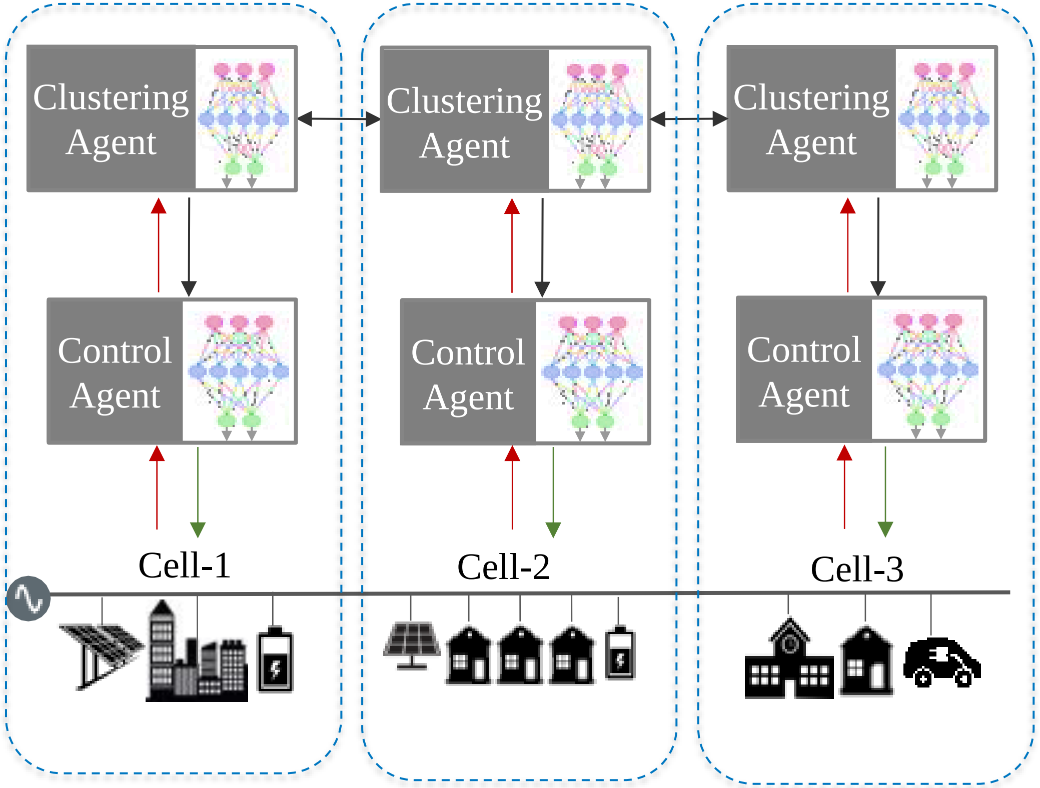
A ***cell*** is a group of interconnected PV, BESS, and buildings that comprises the smallest subset of the grid that is capable of independently operating by using its own resources.

1. Resilience quantification to preliminary identify resilient cells
2. Sensitivity analysis to obtain “loosely connected” cells
3. Stability analysis to guarantee cell stability in islanded mode.



Each identified cell has integrated resilience over a desired threshold and can achieve stable operation when it is disconnected from the grid.

Technical Approach: Operate Cells



Use **multi-agent deep reinforcement learning (MADRL)** to design a two-level control strategy:

- **Cell control agent:**
  - Control DERs inside the cell.
- **Cell clustering agents**:
  - Coordinate with other cells for network reconfiguration and service restoration.

Use machine learning to reduce the reliance on accurate system models and massive communications.

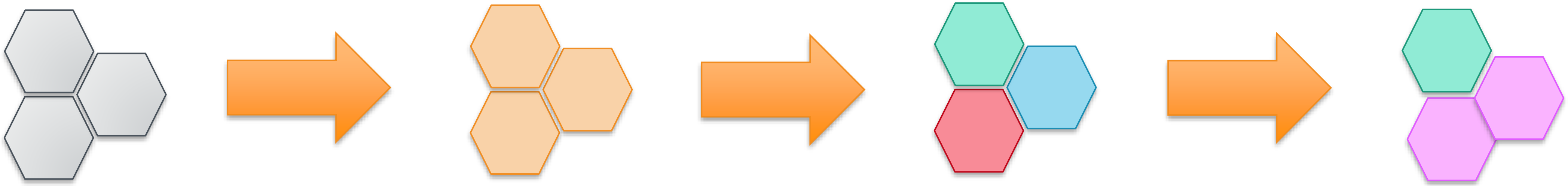
Cell-Based Resilient Operations

Black out across the whole distribution system

GFM/GFL inverters are energized and connected

DERs are dispatched for local load restoration

Cells are clustered to achieve highest system-level resilience



The focus of this stage is to get the network energized as soon as possible.

The focus of this stage is to optimize DER operations to maximize energy sustainability for each cell individually.

The focus of this stage is to 1) optimize DER by considering all cells as the whole system; 2) cluster cells to be adapted to system changes.

Resilience Quantification

Aggregating indices using self-organizing maps (SOMs) to obtain a final resilience index:

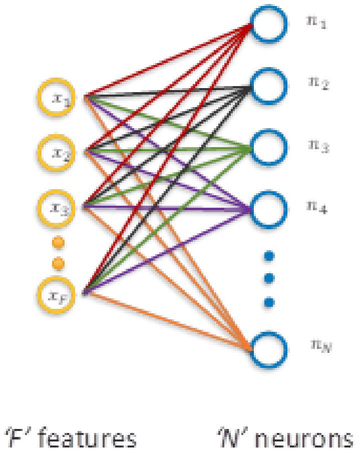
- SOMs belong to the category of competitive learning neural networks and are based on unsupervised learning.
- They can be used for clustering data without having prior knowledge of the class memberships of the input data.

Scenario 1

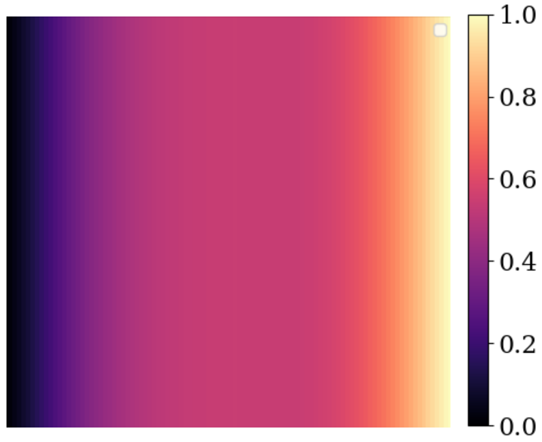
Scenario 2

…

Training data



Resilience of the cell



SOM heat map

K. Utkarsh, F. Ding, “Self-organizing map-based resilience quantification and resilient control of distribution systems under extreme events,” IEEE Transactions on Smart Grid, vol. 13, no. 3, May 2022.

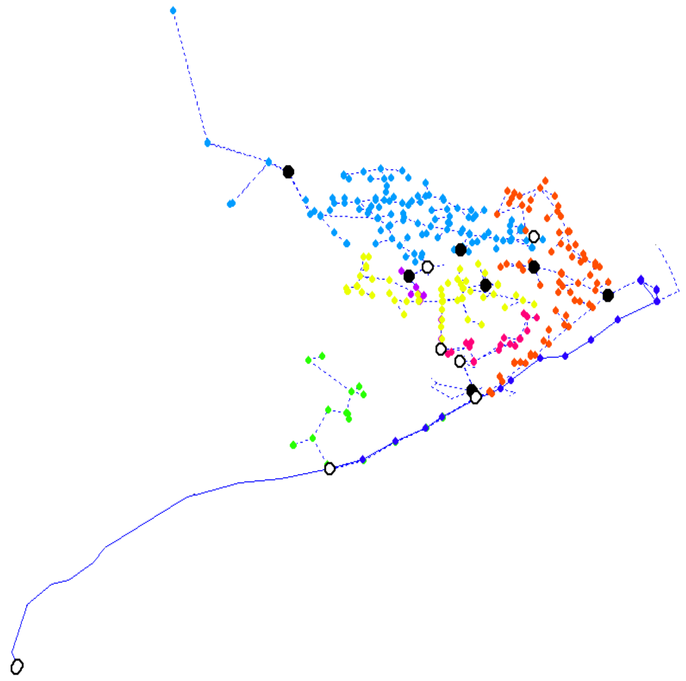
Resilience Quantification

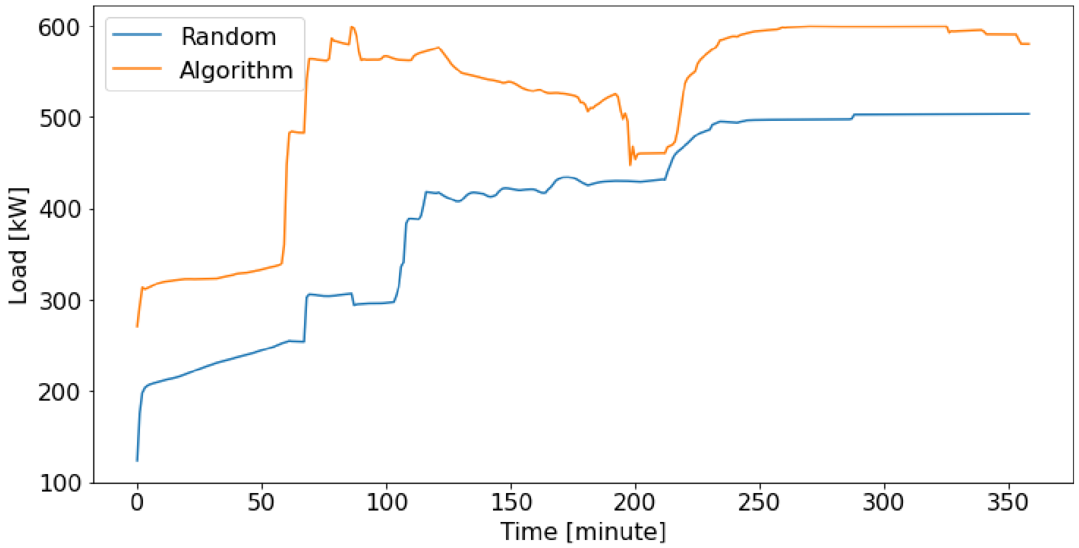
Calculating relevant indices to capture static and dynamic topological/operational features:

a. **Criticality of assets:** the impact of asset damage/loss on load shedding
b. **Sustainability:** considers whether the existing generation capability inside a cell is enough to enable the survival of critical loads for at least *T* time steps by ensuring power balance as well as node voltage feasibility within ANSI limits
c. **Availability of energy reserves:** the battery state of charge and diesel fuel reserves
d. **Generation diversity:** the geographic diversity of generation compared to that of the load nodes
e. **Feasible islands:** the ability of the assets within that cell to further form multiple feasible islands
f. **Path redundancy:** the number of possible parallel paths available from a generator node to a critical load node.

K. Utkarsh, F. Ding, "Self-organizing map-based resilience quantification and resilient control of distribution systems under extreme events," IEEE Transactions on Smart Grid, vol. 13, no. 3, May 2022.

Case Study





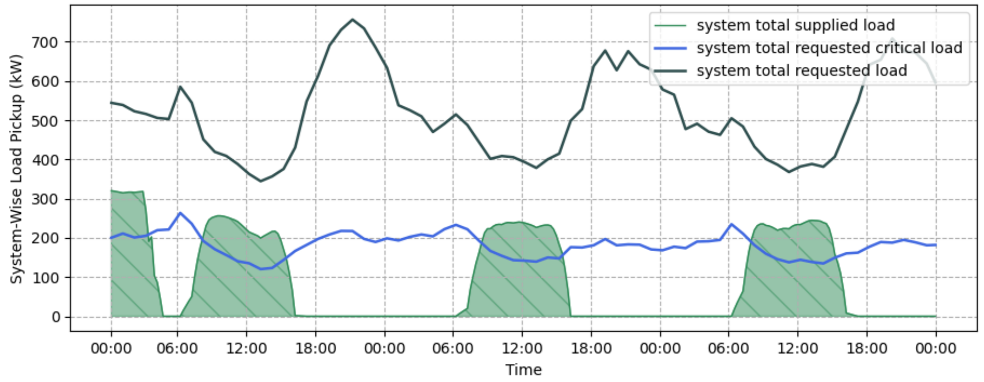
- Consider same assets available, compared the results for the defined seven cells with another group of seven randomly defined subnetworks
- Applied the same optimal critical load restoration approach for each individual cell/subnetwork

Load restored for random subnetworks = 2405 kWh
Load restored for optimal cells = 3116 kWh

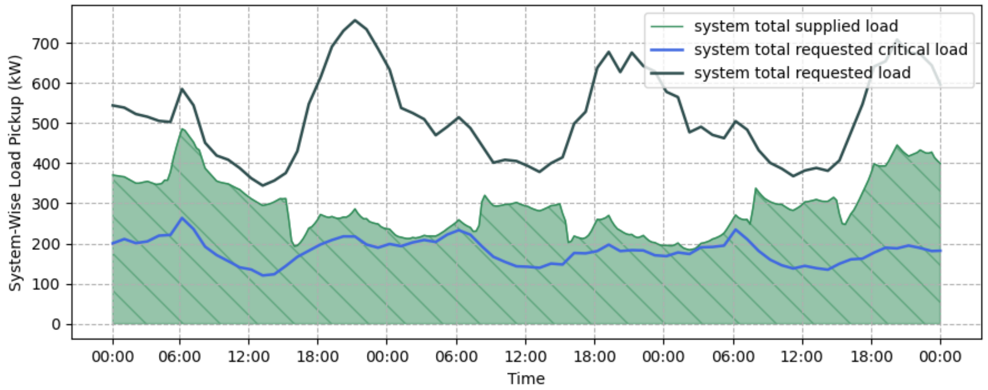
The total restored load for optimally planned microgrids (cells) is significantly higher than that for randomly defined microgrids.

MADRL for Cell-Based Restoration

Base case (no control/coordination)



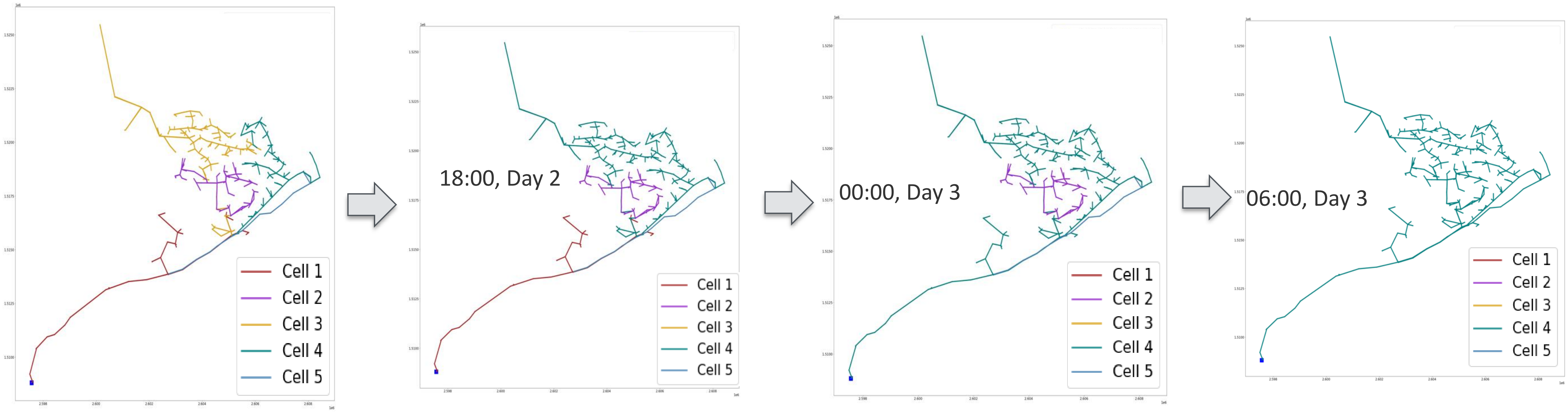
Critical load restoration agents only



System-Level Load Pickup	Critical Load Pickup (kWh)	Noncritical Load Pickup (kWh)	Total Load Pickup (kWh)
No Control	2,823	3,937	6,750
Control by CLR agents	13,051	7,890	20,941

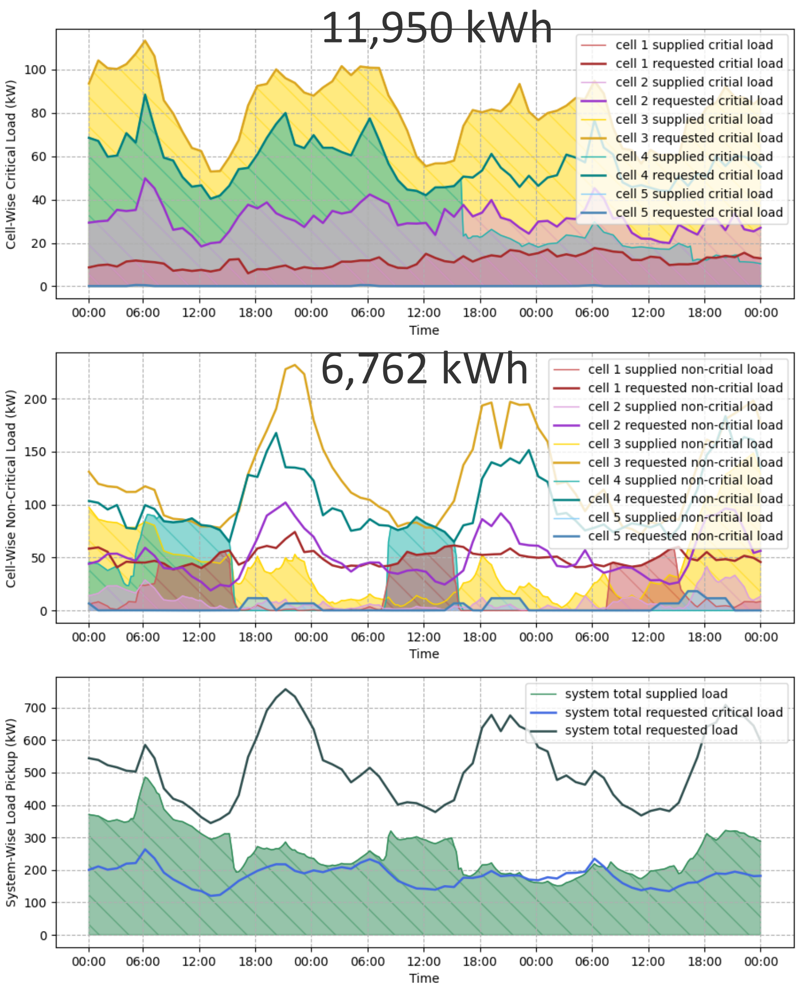
Cell Clustering for System-Wide Resilience

Cell 4 lost 80% PV and BESS starting 16:00 Day 2, but load requests remain same.



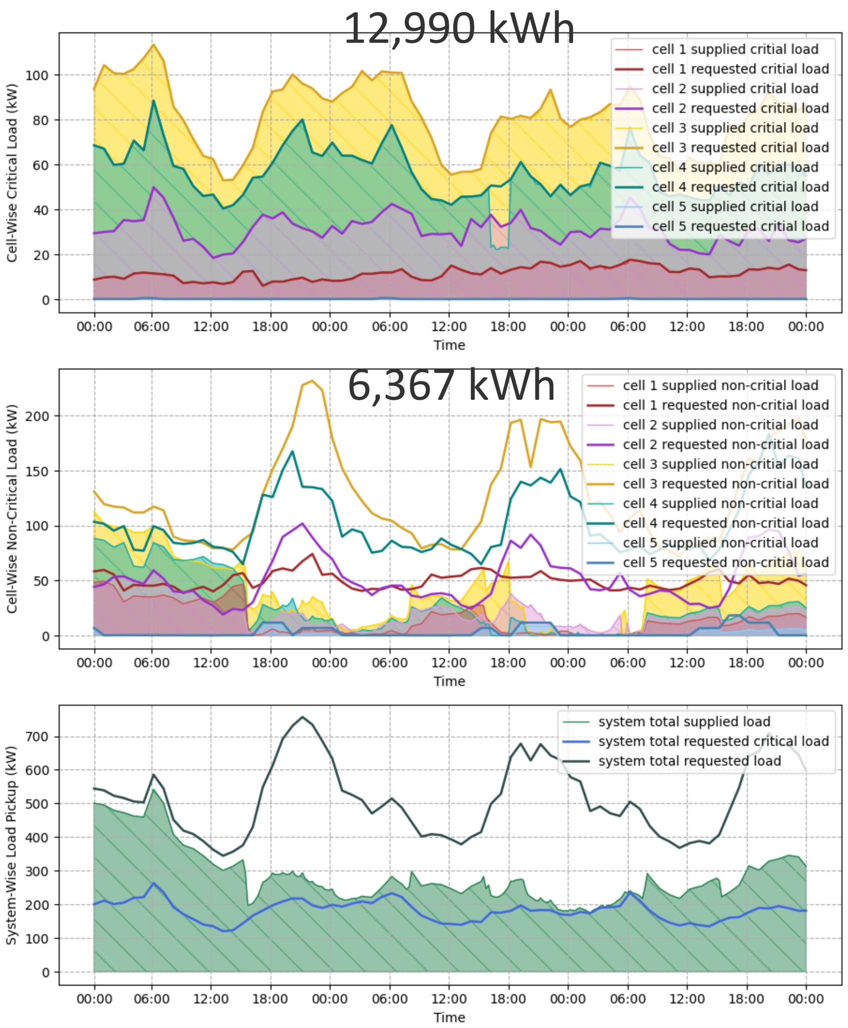
Cell Clustering for System-Wide Resilience

Without upper-level clustering agent



Total = 18,712 kWh

With upper-level clustering agent

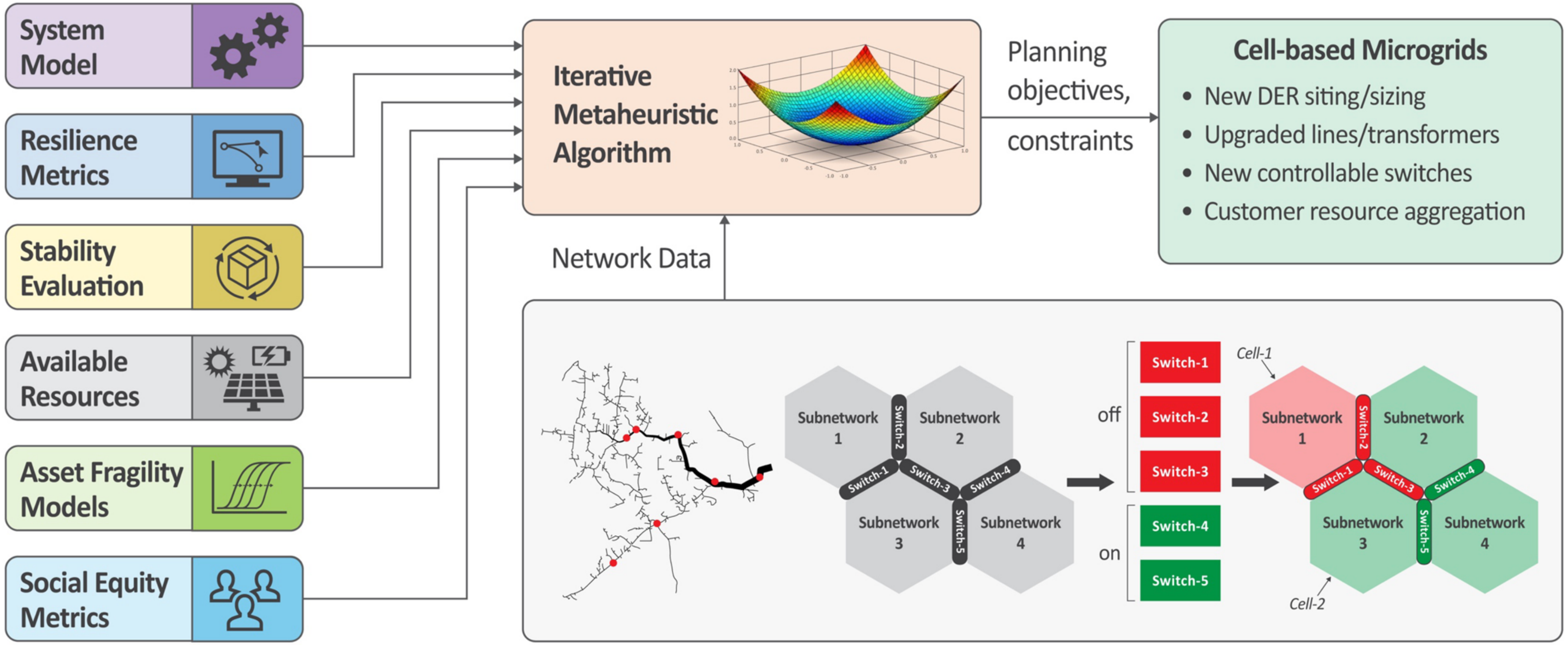


Total= 19,557 kWh

What is next?

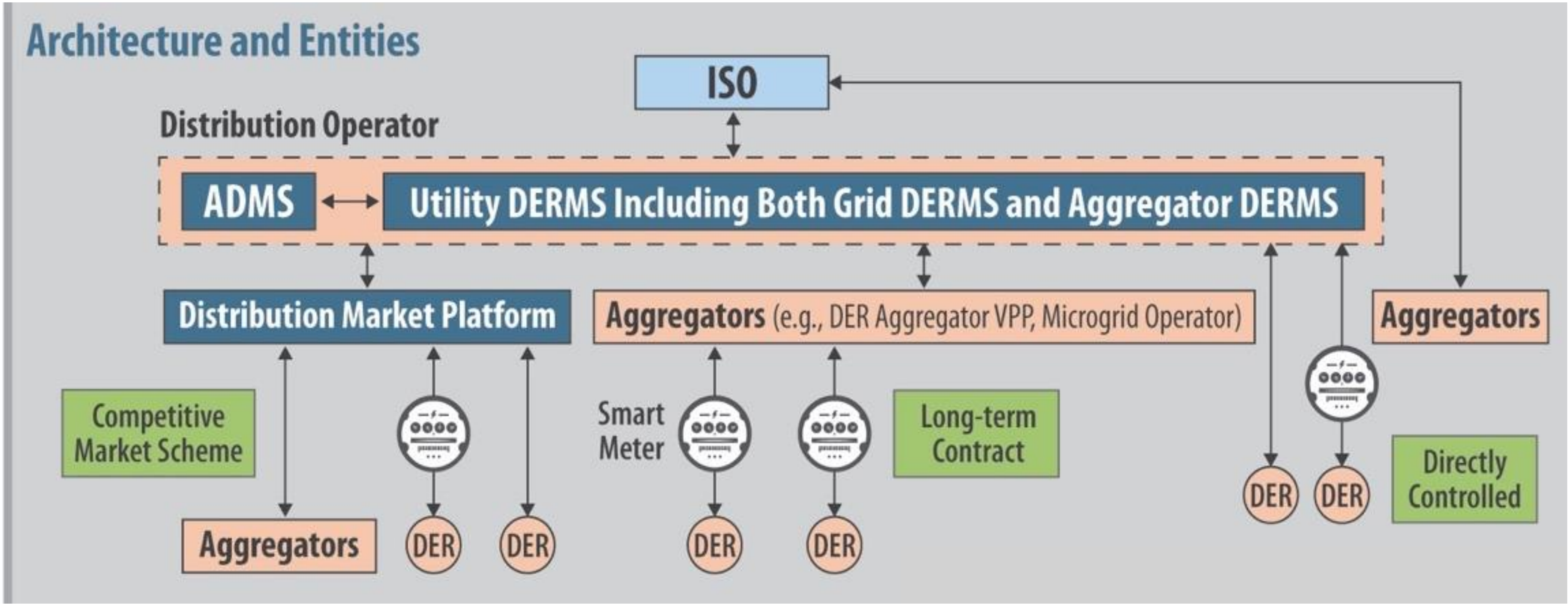
Resilient, Reliable and Equitable Planning of Microgrid Retrofits in Distribution Systems

Develop a software tool to conduct DER and microgrid planning considering resilience, reliability and equity.



Team: NREL, Electrical Power Engineers, Colorado Springs Utilities

Embracing the DERs for Bulk Grid Services



F. Ding, et. al., “Federated architecture for secure and transactive distributed energy resource management solutions (FAST-DERMS): System Architecture and Reference Implementation,” NREL Report, January 2022.

Thank You!

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