Transactive Energy: Coordination Strategies for Enabling DERs to Provide Grid Services

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AGI ESIC Seminar

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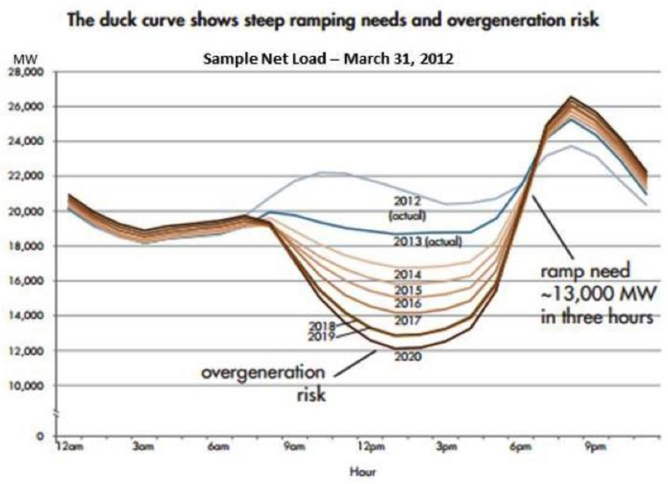
Outline

- Background and Motivation
- Transactive Energy
- TE: Enabling Different Coordination Architectures
  - Prosumer-to-Grid
  - Community-based
- TE during Emergency Conditions
- Modeling Capabilities
- Summary

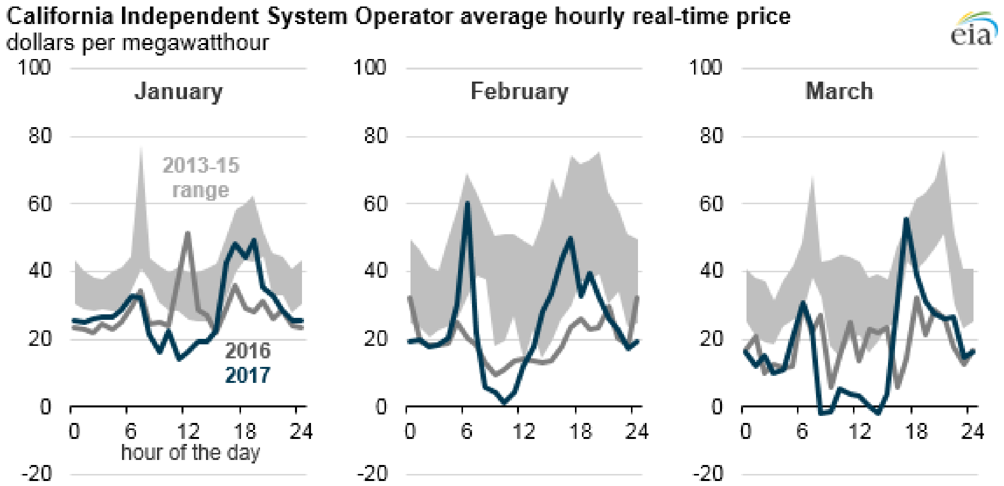
Background: Power System Economics

- Conventional Electricity Markets
  - Hierarchical top-down approach
  - Optimal resource allocation and pricing

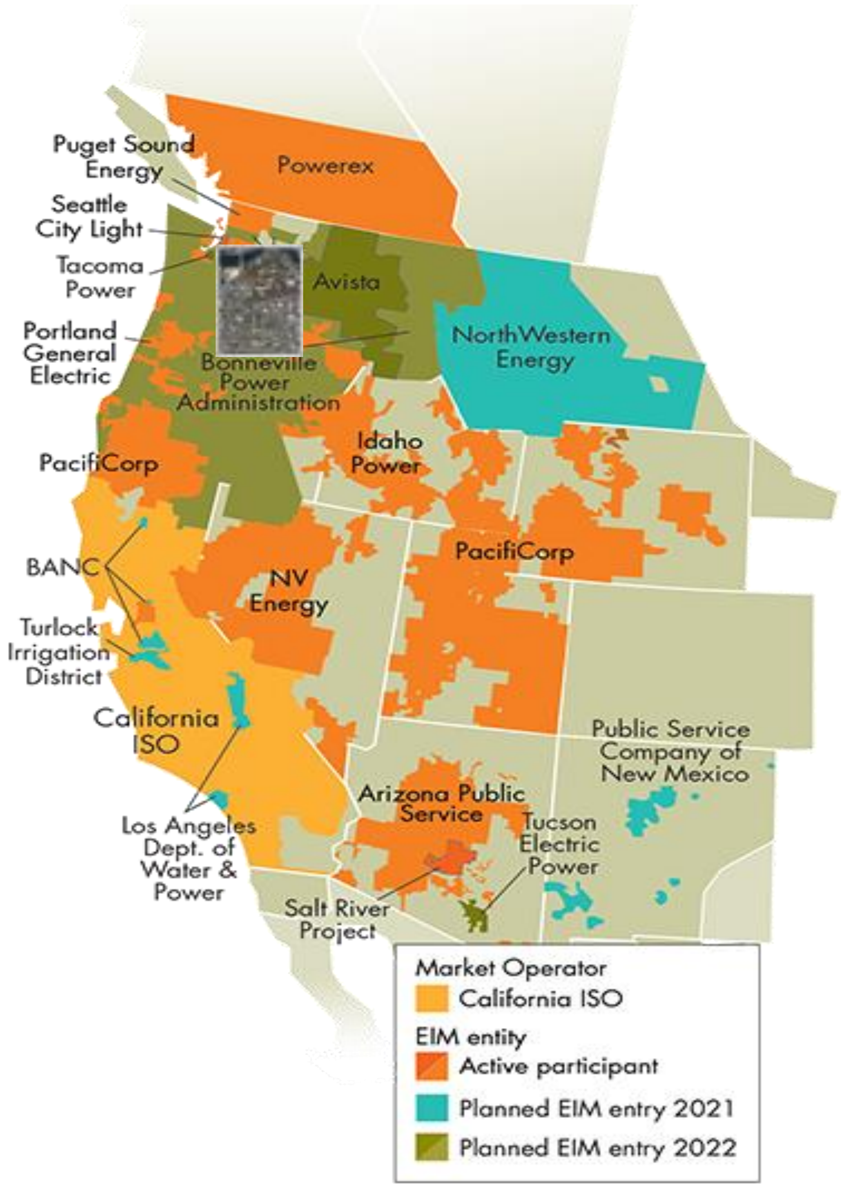
- Electric landscape is undergoing significant changes
  - Proliferation of renewable energy resources (declines in cost)
  - Increasingly savvy prosumers



(from the California Independent System Operator)

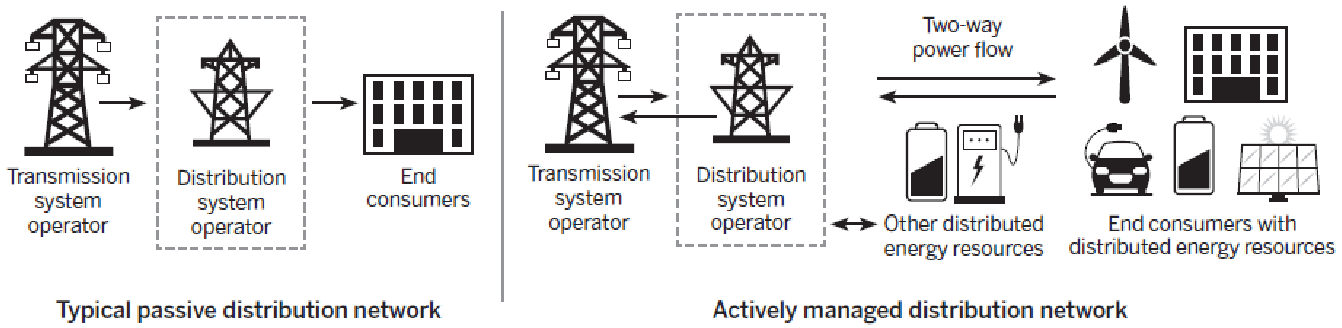


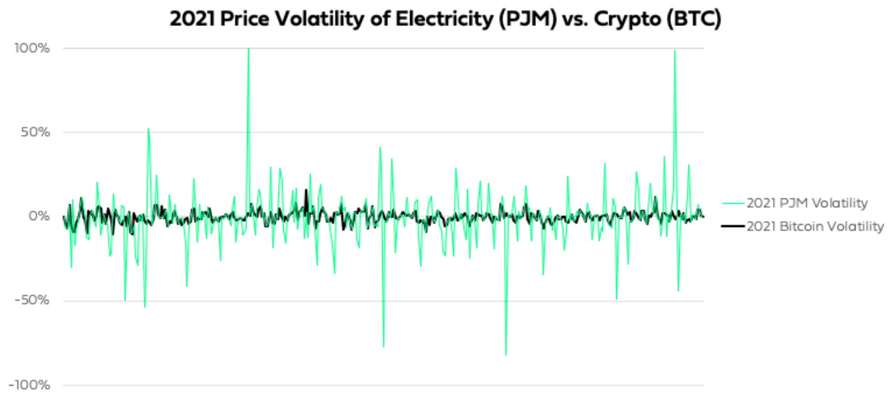
Source: https://www.eia.gov/todayinenergy/detail.php?id=30692



Source: http://www.caiso.com/participate/

Changing Landscape: Distribution System Operator



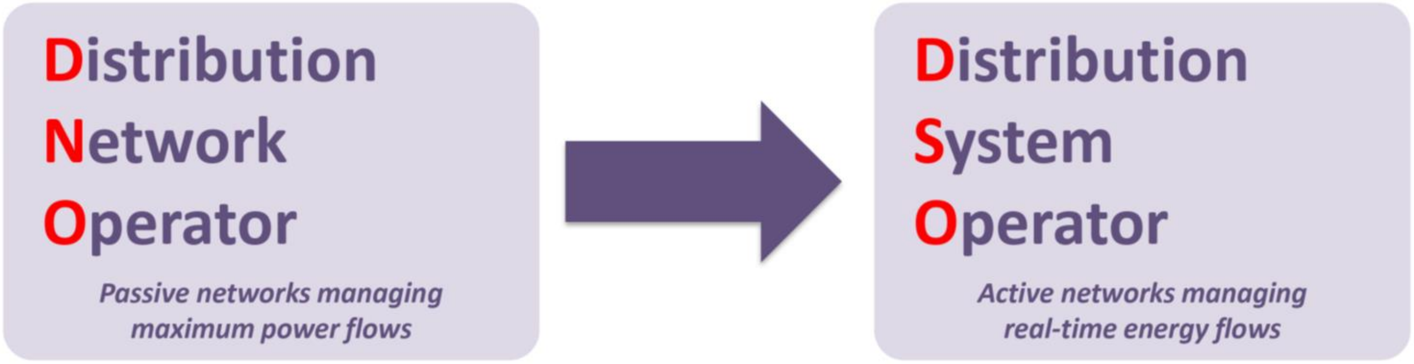


Source: https://climatetechvc.substack.com/p/-lessons-from-plaid-for-a-future

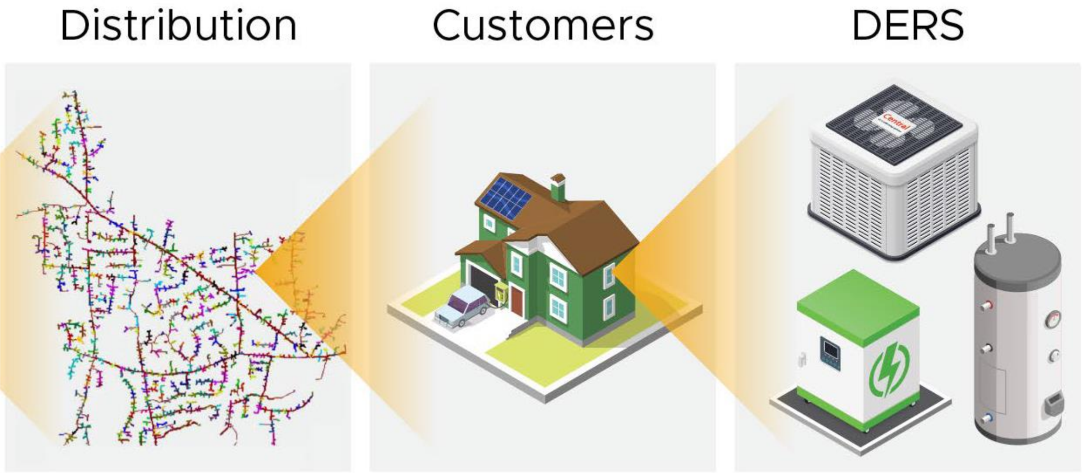
Share Price of selected German Utilities vs. DAX 2006-2015

Source: www.finanzen.net

- Distribution System Operator
  - Operational:
  - Limited to no visibility or control
- Business:
  - Reduction in the utility's net energy sales
  - Increased costs - variability and unpredictability



Customers: Consumers to Prosumers



- Consumers into “prosumers”
  - Increasing awareness coupled with decline in cost
  - Favorable regulations
  - Advancement of ICT and HEM
- Prosumers
  - Proactively manage their underlying DERs
- Consumer-centric economies:
  - Cloud based operations for distributed systems
  - Blockchain for decentralized mechanisms

- FERC Order 2222
  - Enables DERs to participate in the regional organized wholesale markets through aggregations.

Transactive Energy

“A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.”

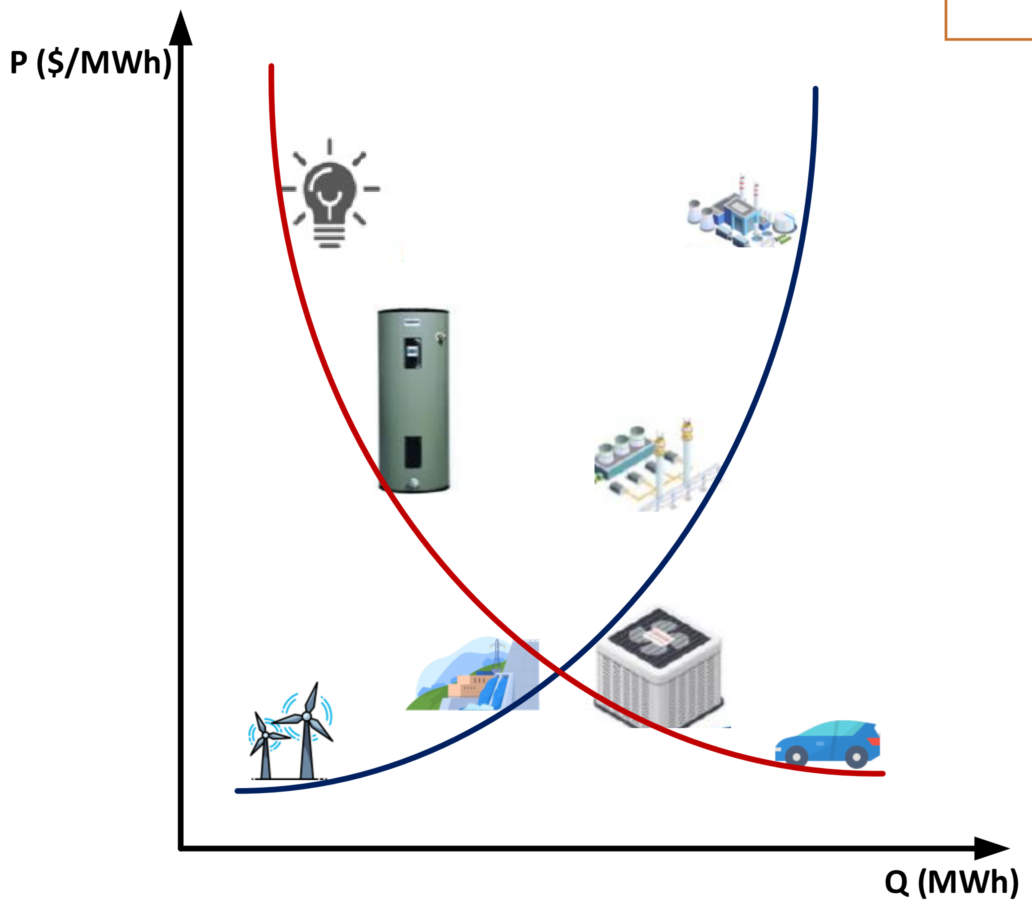


Fig. Responsiveness of DERs

- Orchestrating the coordinated operation of DERs
- Provides market-based mechanisms
  - Integrating DERs to participate in the electricity markets
  - Achieved through device-specific intelligent agents
- Effectiveness of TE system have illustrated through
  - Several field demonstration
  - Several co-simulation frameworks

Implementing TE systems for customer coordination.

Transactive Energy: Towards Enabling Different Coordination Architectures

Future consumer-centric coordination envisages structured organization:

- Prosumer to Grid
  - Prosumers actively participate in market
  - Centralized – moderated through aggregators/LSE
- Organized Prosumer Groups (Community Based)
  - Group of prosumers pools resources
  - Decentralized – Transact energy with other communities/DSO
- Peer-to-peer
  - Directly interconnect with each other, trading energy services
  - Fully Decentralized

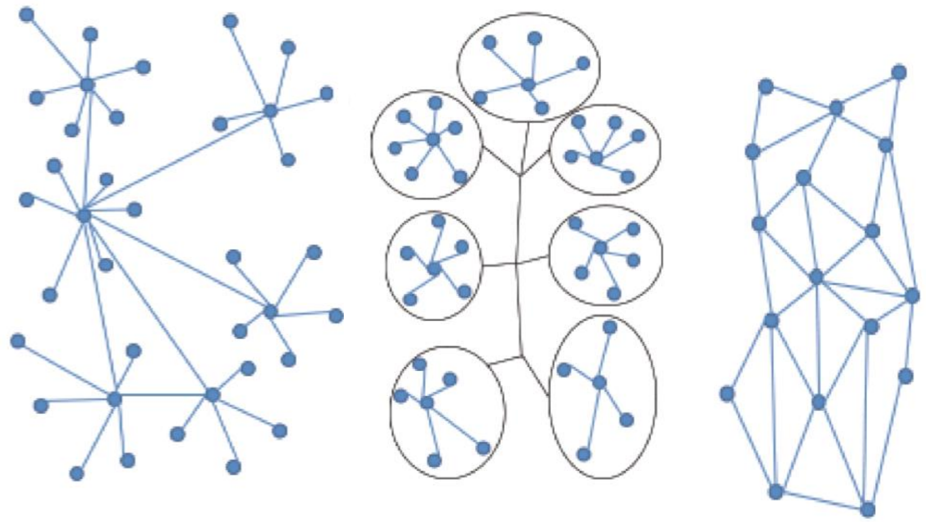


Fig. Structural attributes of prosumer markets: Prosumer-to-grid, organized prosumer group, peer-to-peer models.

Prosumer-to-Grid Coordination: Hierarchical Architecture

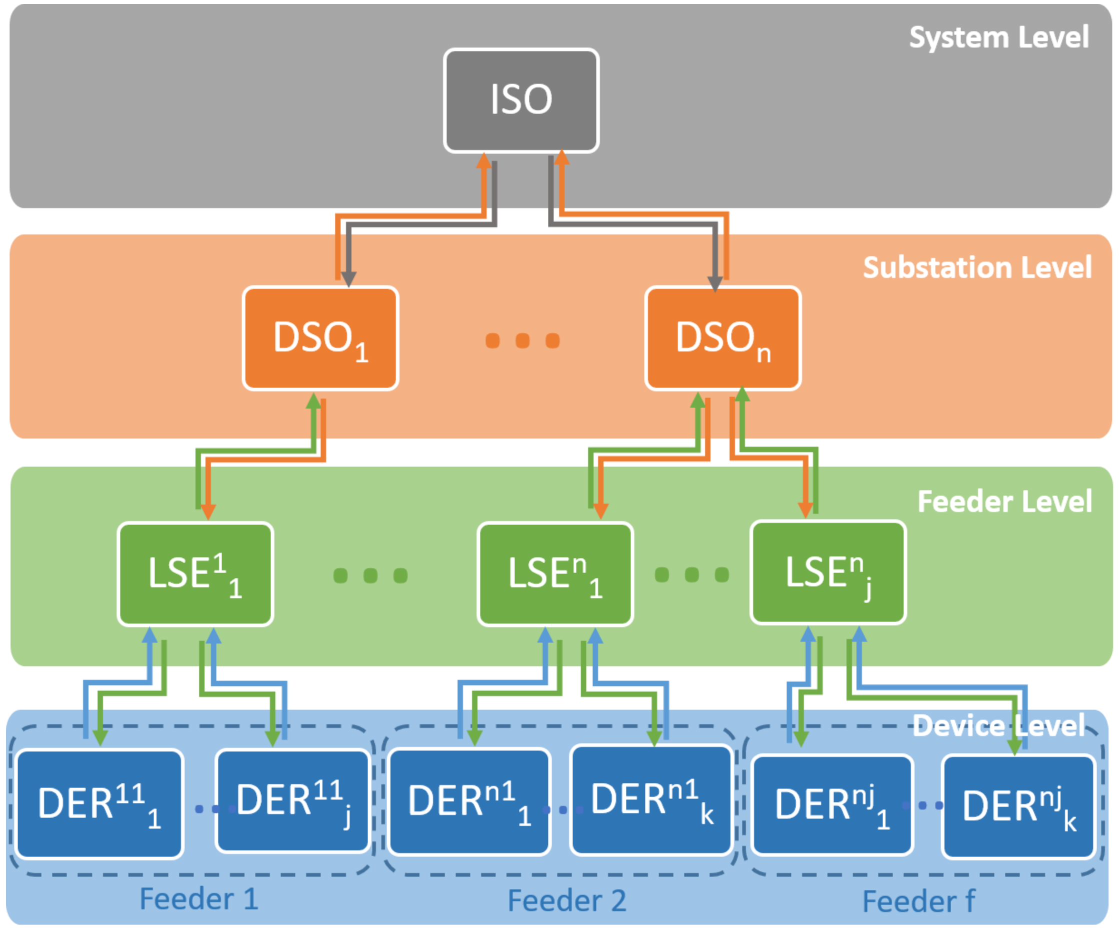


Fig: TE architecture for Prosumers-to-Grid Coordination

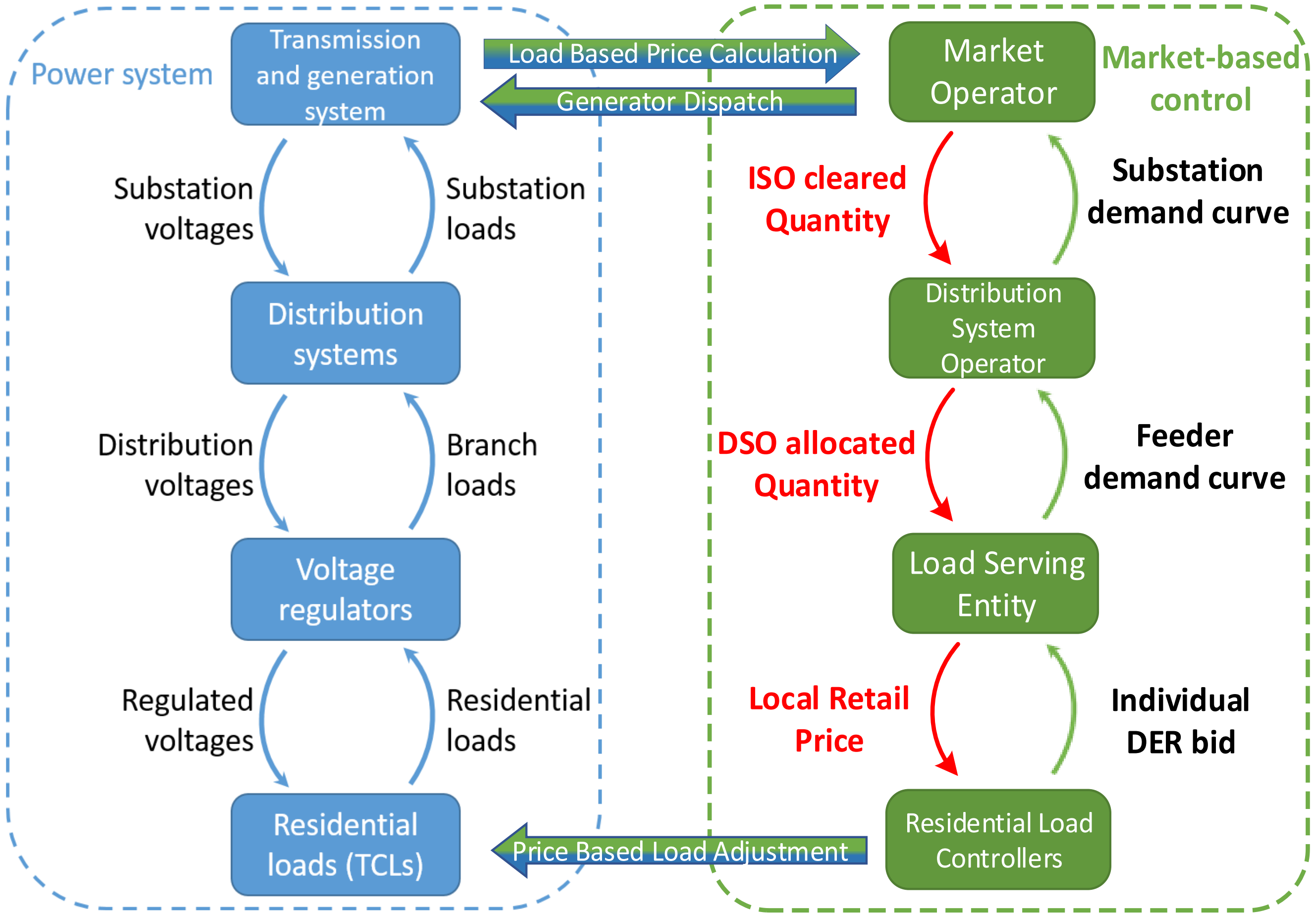


Fig: Model architecture of the proposed incentive-based control mechanism

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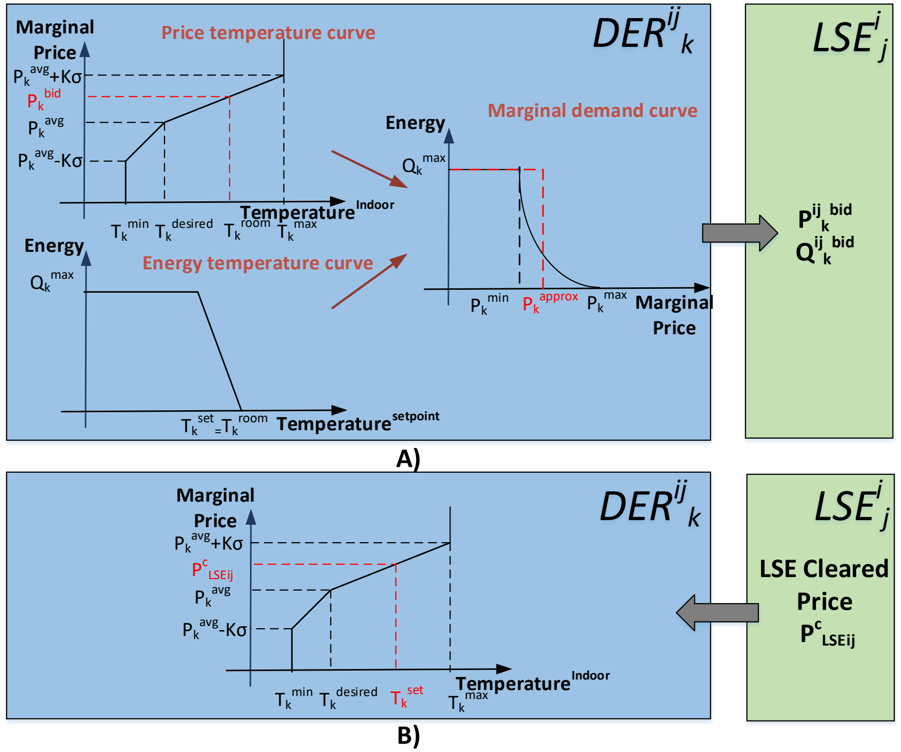
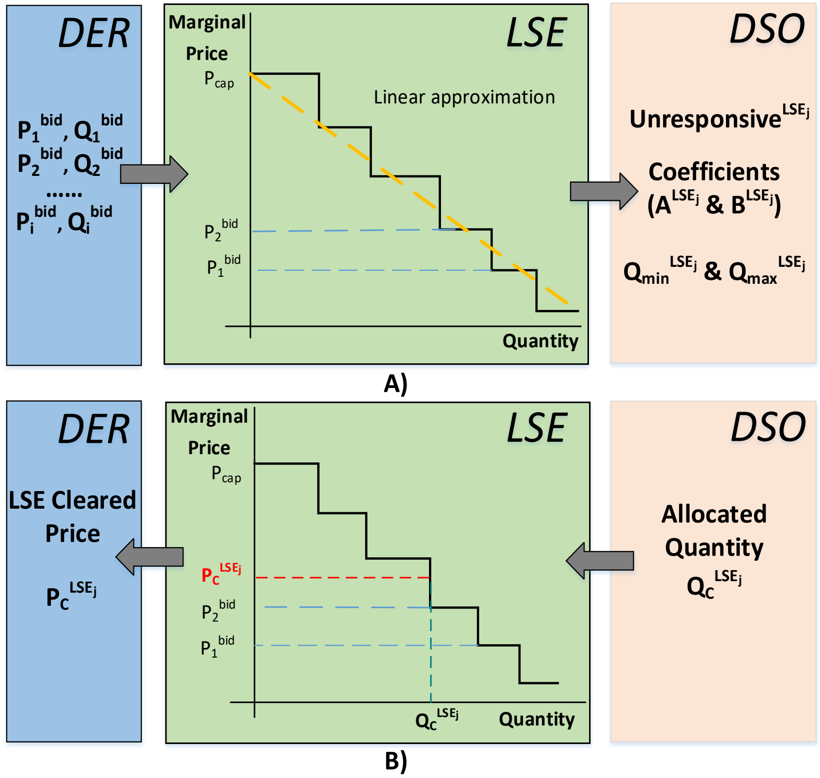
Prosumer-to-Grid Coordination: DER Integration and Dispatch Strategy

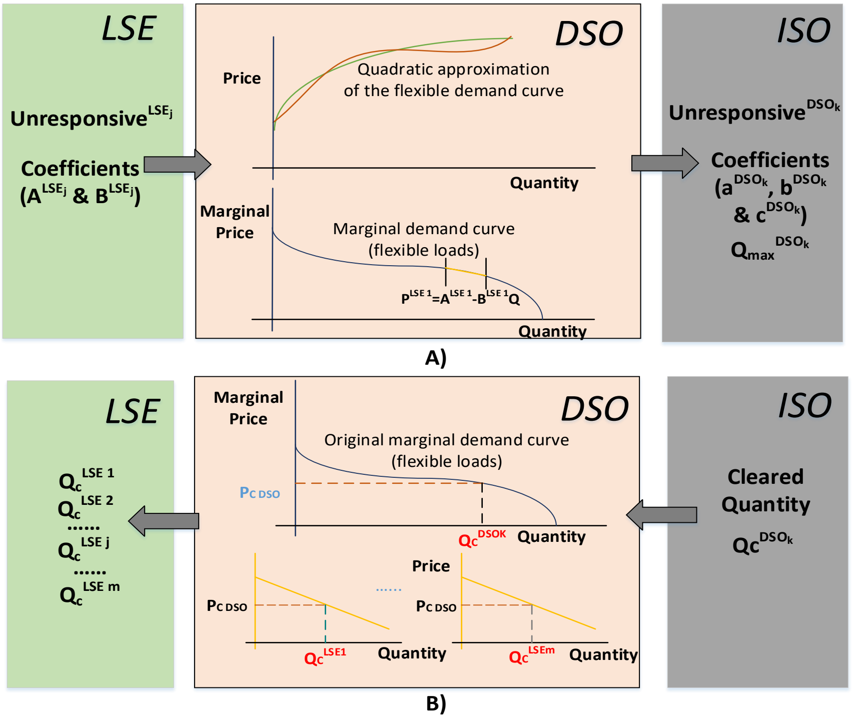
Device level

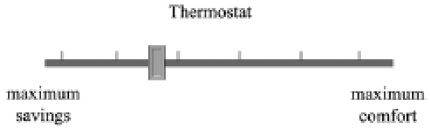


Feeder level



Substation level





$$Q^{LSE^i_j}(P) = \sum_{i=1}^{n} Q_k^{ijbid}(P_k^{ijbid}) \quad \text{if } 0 \leqslant P_k^{ijbid} < P_{cap}$$

$$P^{LSE^i_j}(Q) \cong A^{LSE^i_j} - B^{LSE^i_j}\cdot Q, \quad Q_{min}^{LSE^i_j} \leqslant Q \leqslant Q_{max}^{LSE^i_j}$$

$$Q^{DSO_i}(P) = \sum_{j=1}^{m} Q^{LSE^i_j}(P)$$

$$P^{DSO_i}_{demand}(Q) = \int_0^{Q_{max}^{LSE^i_j}} P^{DSO_i}(Q)\cdot dQ$$

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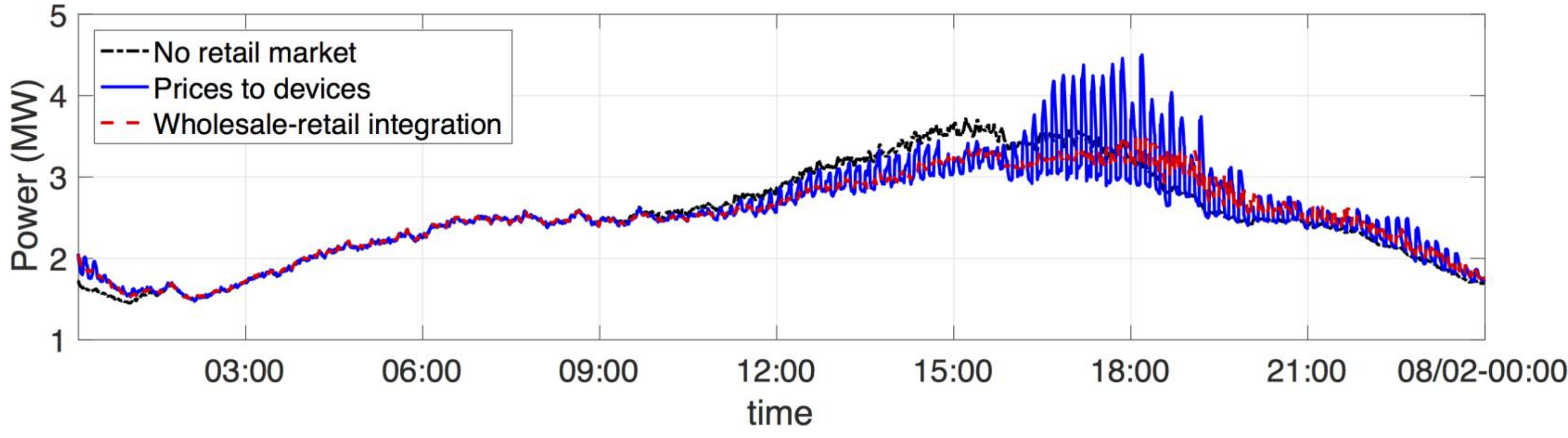
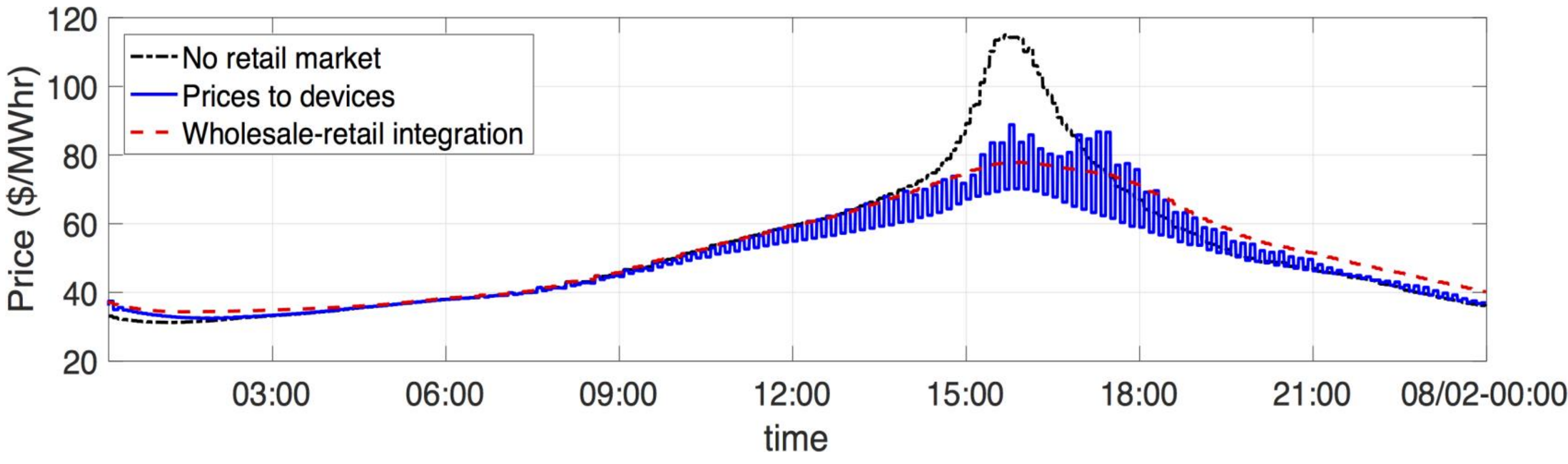
Why Integrated T&D simulations ?

- Comparison of price-responsive only (**one-way**) vs bidding (**two-way**) transactive control
- Transmission system model of WECC in MATPOWER connected to distribution circuits in GLD with 25% controllable load.
- Results show one-way control can produce oscillations while two-way does not.





Reference: J. Hansen, T. Hardy and L. Marinovici, "Transactive Energy: Stabilizing Oscillations in Integrated Wholesale-Retail Energy Markets," 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2019, pp. 1-5, doi: 10.1109/ISGT.2019.8791658.

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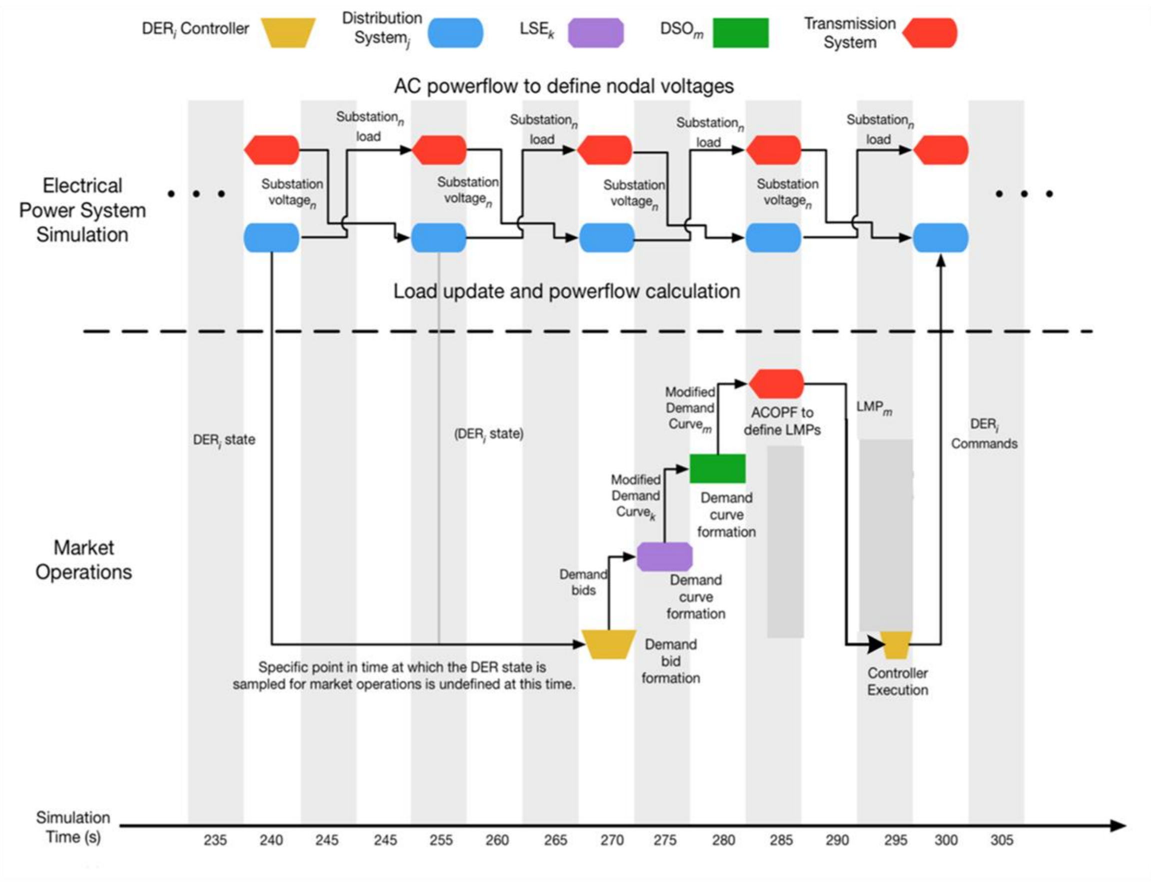
Prosumer-to-Grid Coordination: Co-simulation & Use-Case

Price-priority dispatch of flexible loads



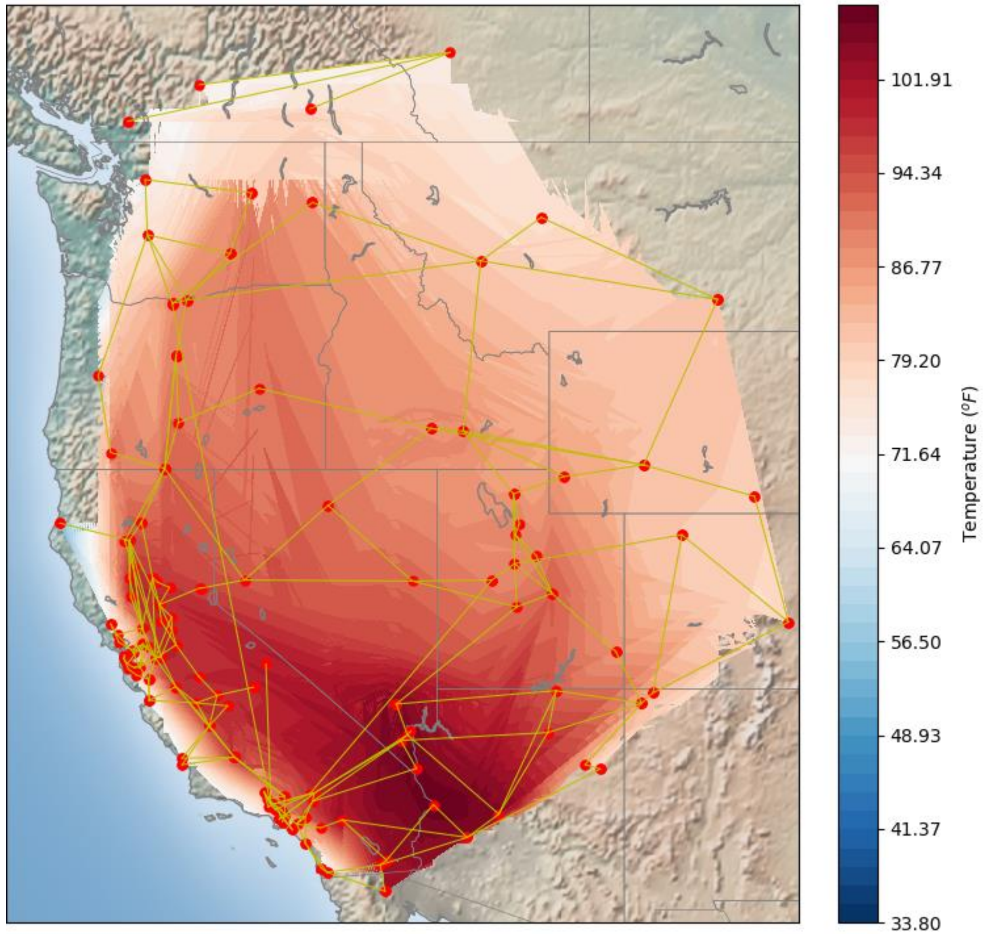


Fig. WECC 240 network topology showing the modeled bus, transmission lines, and modeled outdoor air temperatures.

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Prosumer-to-Grid Coordination: Demonstration

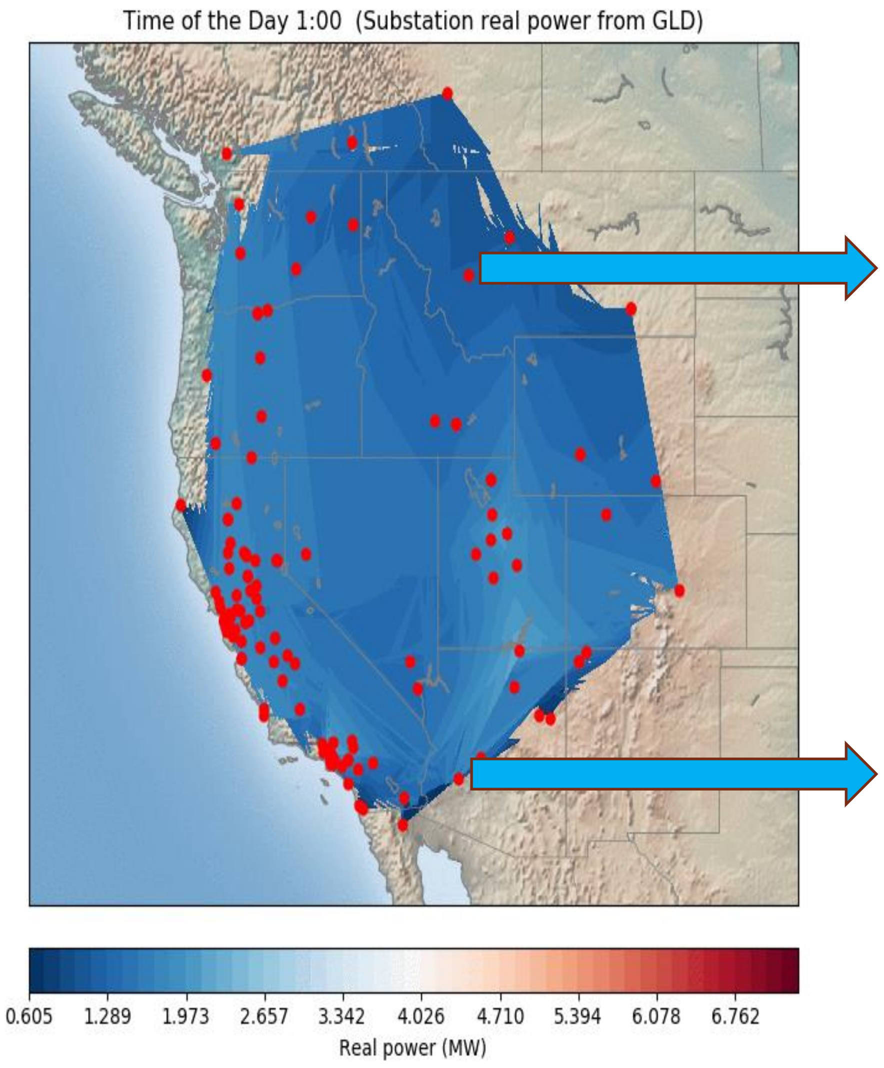
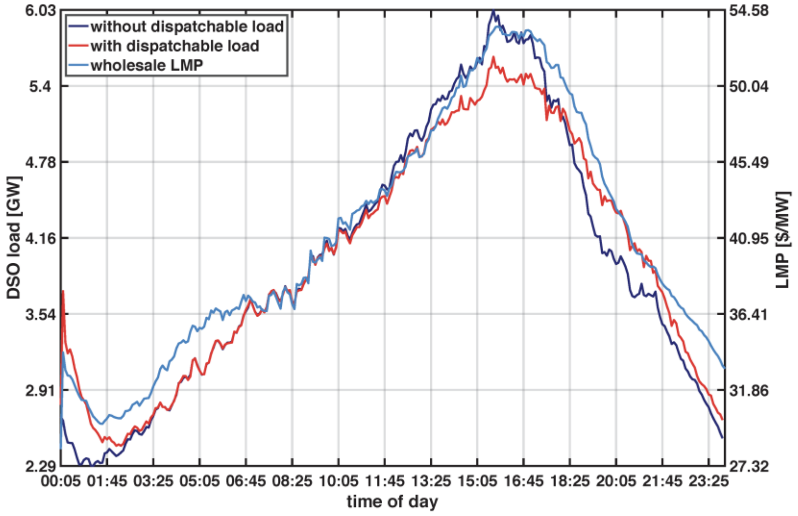
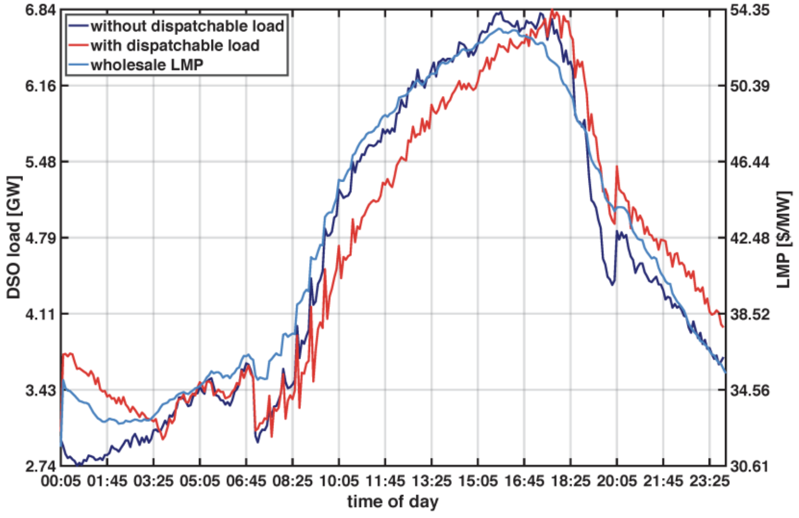


Fig. WECC 240 network topology showing typical feeder demand at different locations.

Bus at Montana



Bus at Arizona



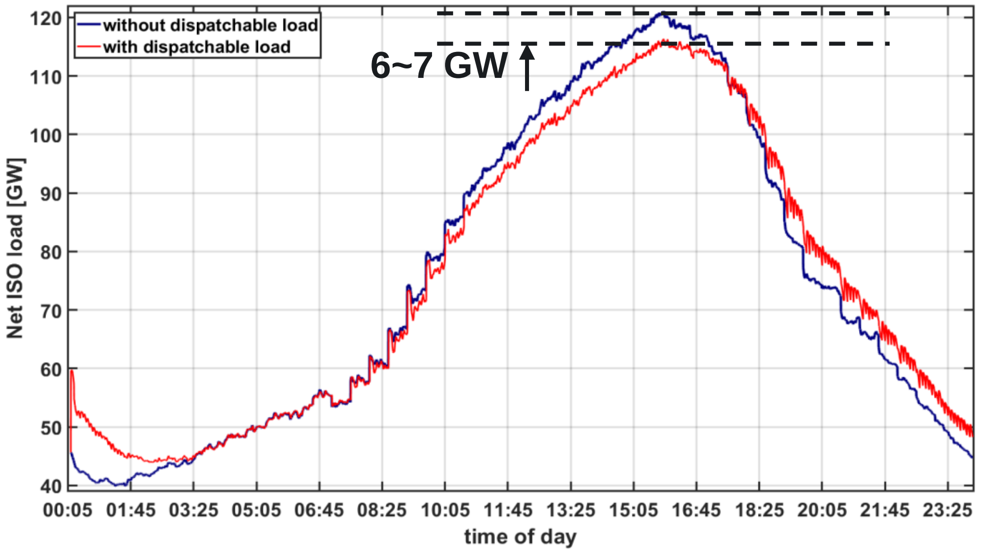


Fig. Combined load of the all buses connected to the WECC-240 system (ISO Level)

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Key Learnings

- TE Concepts
  - Cobweb effect on decoupled implementations
  - Spatial Variation of flexibility

- Software Skillsets
  - Distribution System Simulator
    - End-user load modelling
    - Thermostatic loads
  - Co-simulation Tool
    - Framework for Network Co-simulation (FNCS)
  - Wholesale Market Emulation
    - MATPOWER/PYPOWER
  - High Performance Computers
    - SLURM scripting

CCSI Control of Complex Systems Initiative

GridLAB-D

FNCS

MATPOWER

Community-Based Coordination

- Community Based Markets
  - Group of smart consumers (prosumers) pools resources
  - Transactive Communities (TC)
    - Distributed transactions with TCs/DSO
  - Simplified interface to existing market constructs

- Evaluate stakeholders benefits & market feasibility
  - Prosumers
    - Owning DG or demand-side DERs
  - Community Manager
    - Cumulative flexibilities of the TCs
    - Allocation and prices from the community market ($\lambda_{CM_k}^{Cleared}$ & $Q_{CM_k}^{Cleared}$)
  - DSO - Electricity Price & surplus capacity

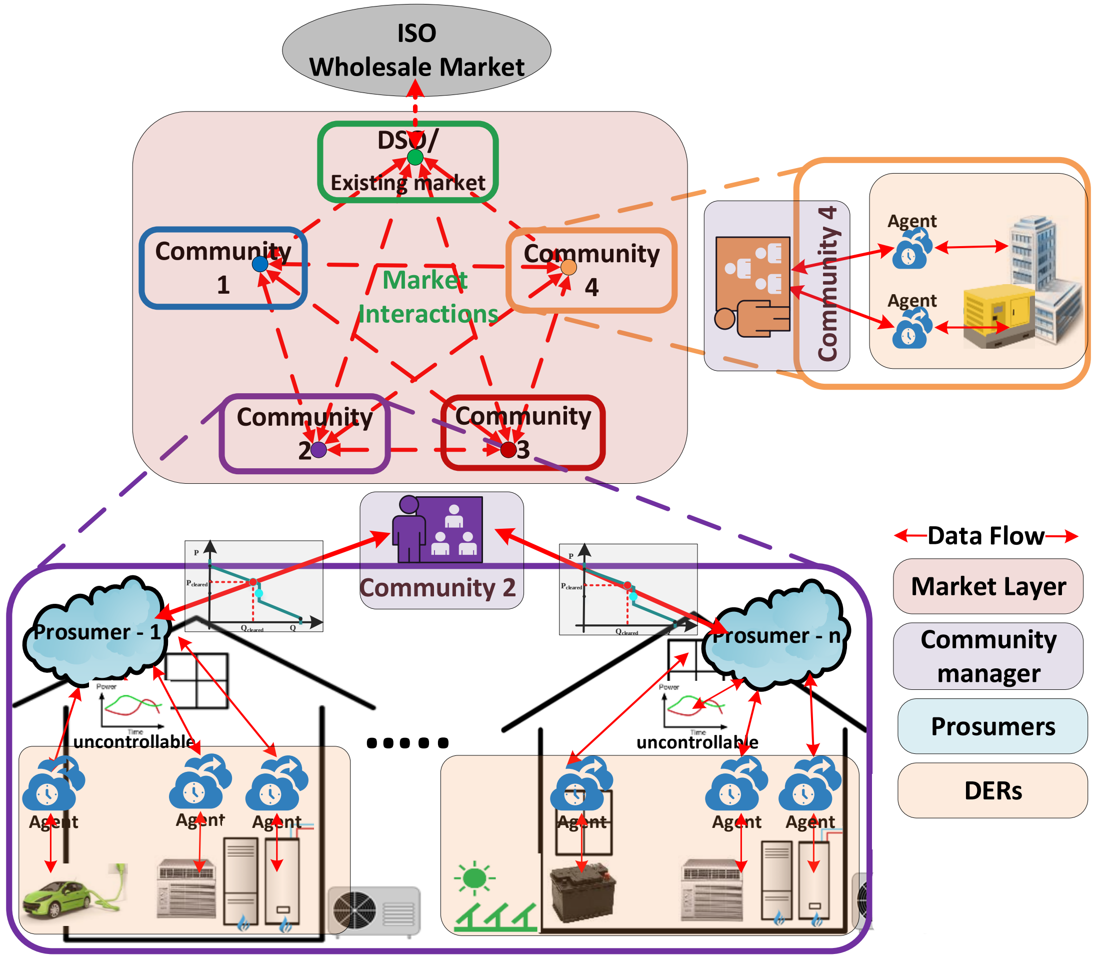

Fig: Overview of the coordination architecture

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Community-Based Coordination

- Development of consensus-based transactive mechanism
  - Distributed optimal dispatch of price-responsive load and generation

$$Max.SW = -\sum_{t=0}^{24}\sum_{k=1}^{N_{TC}} C_{k,t}\left(Q_{k,t}\right); \in \{TC_1 \,..TC_N \,\&\, DSO\}$$

  - $S.T. \sum_{k=1}^{N_{TC}} Q_{k,t} = 0 \; \forall \; t \in \{0{,}24\}$

$$Q_{k,t}^{min} \leq Q_{k,t} \leq Q_{k,t}^{max} \;, \Delta Q_{k,t}^{lower} \leq \Delta Q_{k,t} \leq \Delta Q_{k,t}^{upper}$$

  - Implementation of both **DA and RT** retail energy markets

- Distributed Optimization and Co-Simulation
  - Modeling communication between different participants using HELICS
    - HELICS Publications & Inputs: Between the DERs (GridLAB-D) and TC (Python) during bidding and dispatch
    - HELICS Endpoints: Between the Transactive Communities (in Python) and DSO (in Python), during iterative market clearing.
    - HELICS Filters: To emulate asynchronous communication delays during iterative market clearing modeled using bounded uniform distributions

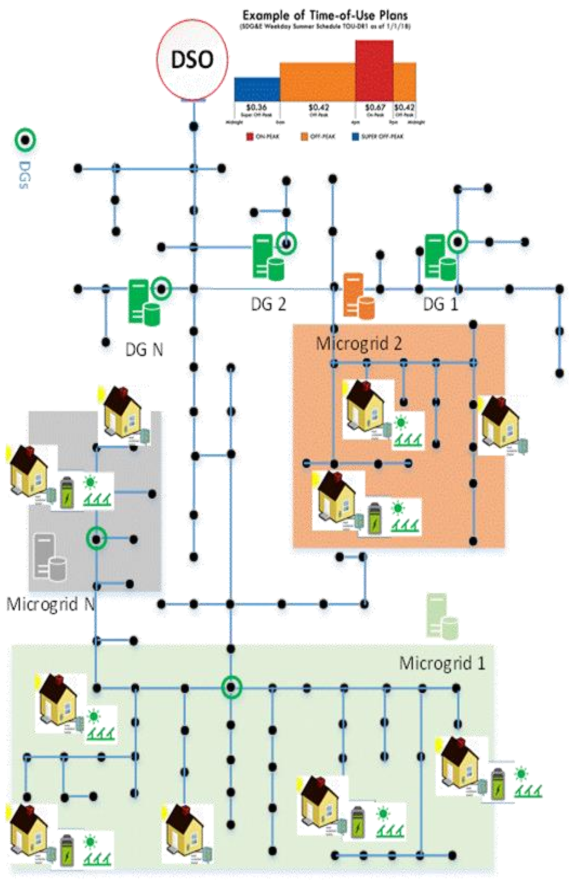

Fig. Consensus based Market Mechanism

Reference: M. Mukherjee, T. Hardy, J. Fuller and A. Bose, "Transactive Implementation of Decentralized Electricity Market for Grid-Edge Systems," *2021 IEEE Power & Energy Society General Meeting (PESGM)*, 2021, pp. 1-5, doi: 10.1109/PESGM46819.2021.9638098.

Community-Based Coordination

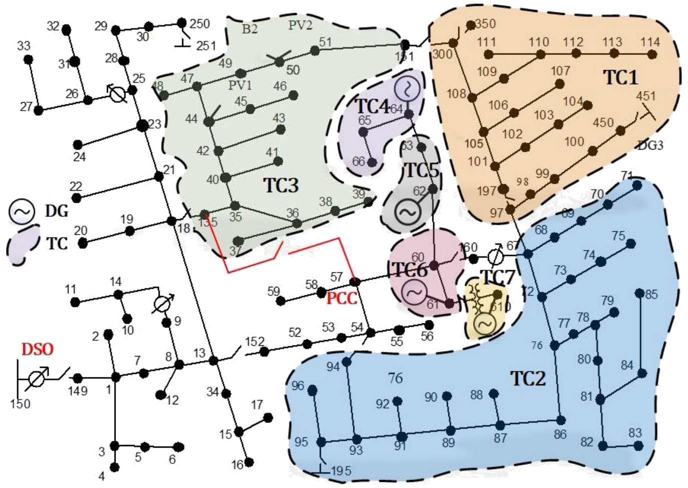

Fig. Modified IEEE-123 node system with TCs

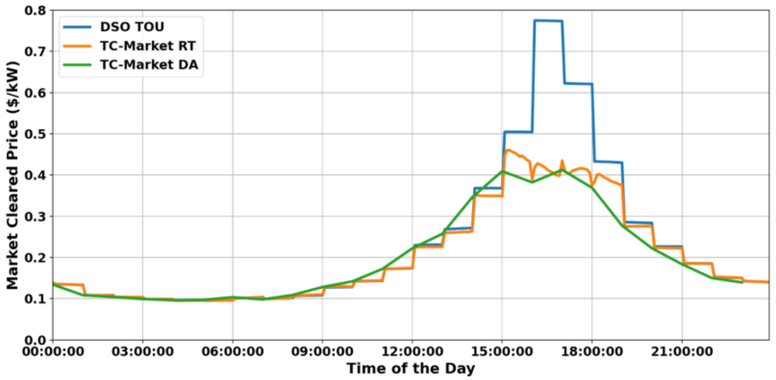

Fig. Market Clearing Prices (DA & RT)

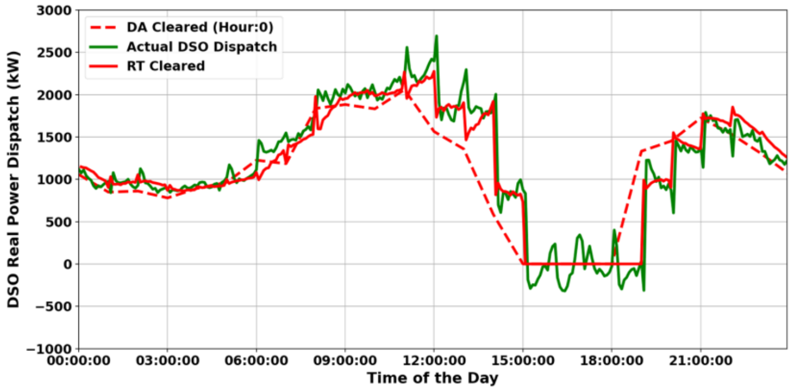

Fig. DSO cleared quantities & actual dispatch

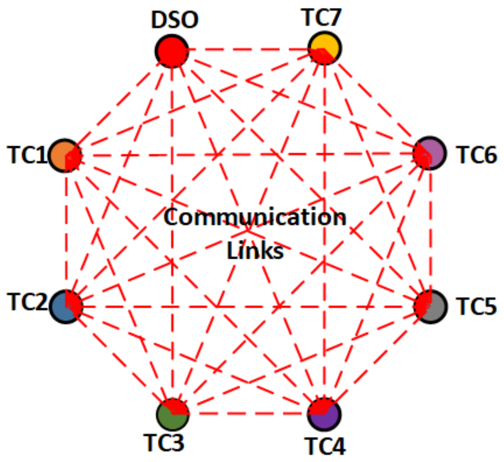

Fig. Communication topology for TCs

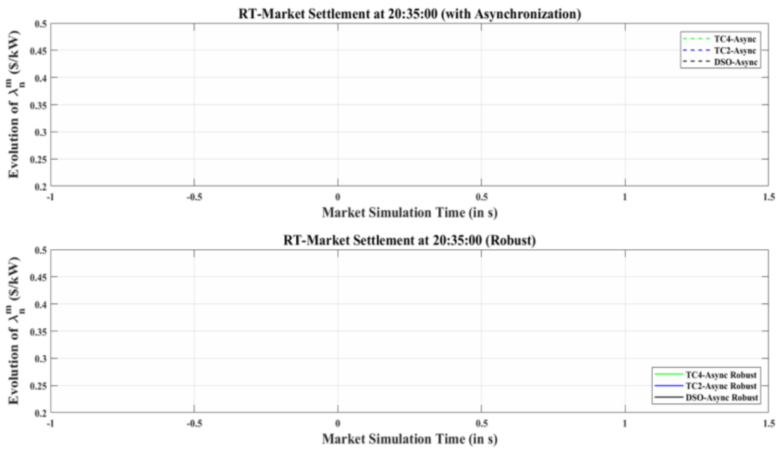

Fig. Iterative evolution of price for TCs and DSO during a market cycle

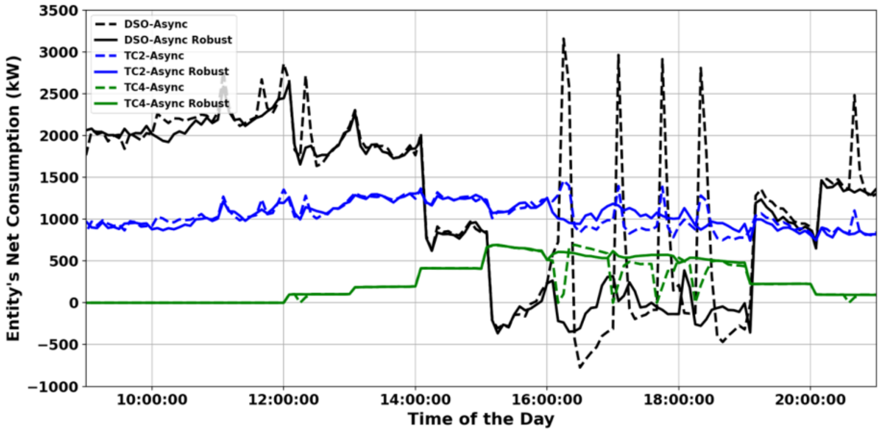

Fig. TC-market for delay-prone communication

Reference: Monish Mukherjee, Trevor Hardy, Jason C. Fuller, Anjan Bose, "Implementing multi-settlement decentralized electricity market design for transactive communities with imperfect communication", Applied Energy, Volume 306, Part A, 2022, https://doi.org/10.1016/j.apenergy.2021.117979.

Key Learnings

- TE Concepts
  - Consensus-based distributed coordination
  - Impacts on asynchronous communication systems
  - Potential Impacts on Wholesale Markets at higher penetrations (ongoing effort)

HELICS+

PNNL-WSU DGRP

- Software Skillsets
  - Distribution System Simulator
    - End-user load modelling
    - Thermostatic loads
  - Co-simulation Tool
    - Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS)

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Transactive Energy During Emergency Conditions

- Extreme Events – Extreme Outages
  - Major modern-day concerns of utilities is dealing with extreme outages and consequently, its repercussions on the lives of people in society and social aspects

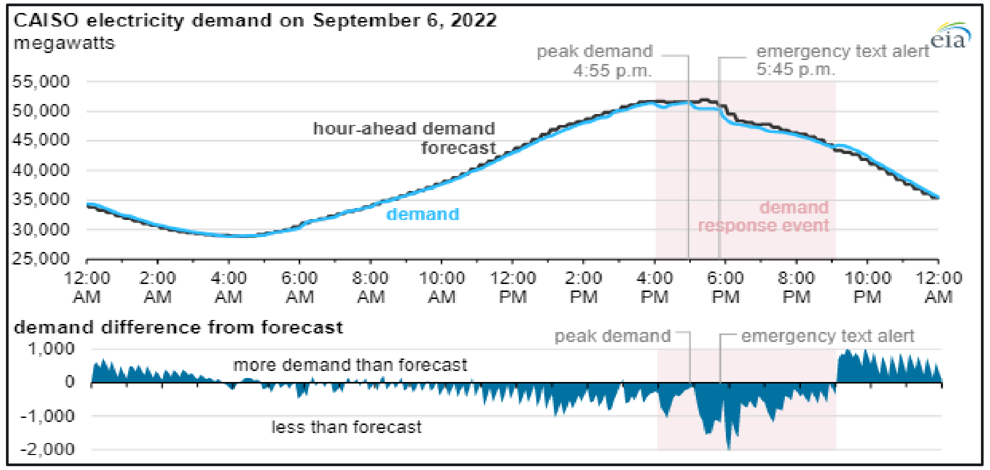
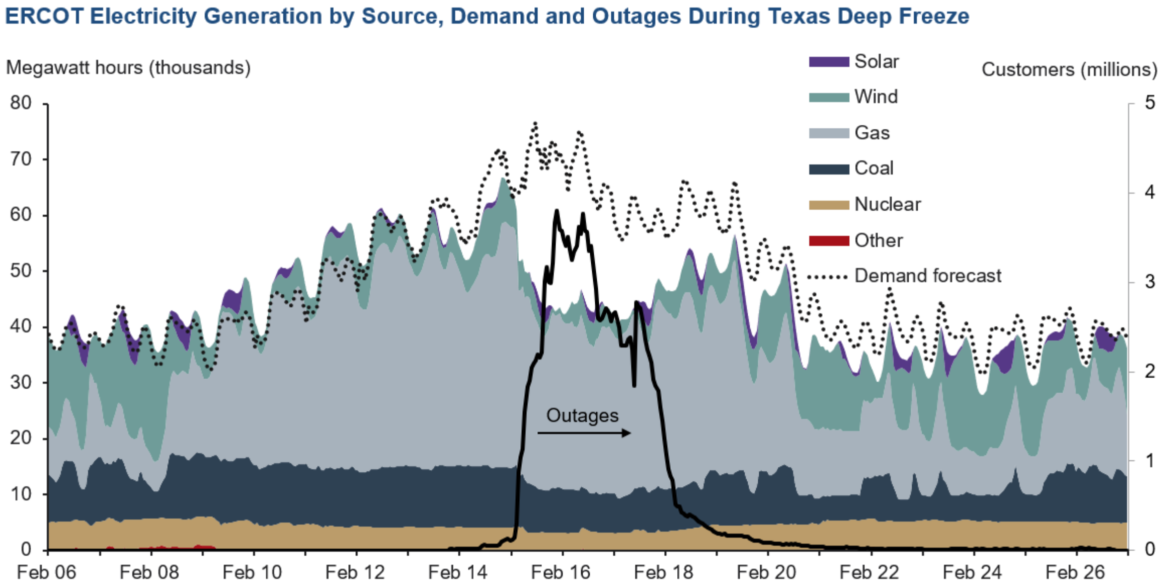


Fig. California consumers respond to text-alerts during heat wave



"How devastating was 2021's deadly Texas freeze, exactly?"
https://en.wikipedia.org/wiki/2021_Texas_power_crisis

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Transactive Emergency Power Allocation

- Text Alerts
  - Situational awareness to customers
  - No guarantees to avoid widespread outages

- Rolling Blackouts:
  - Lower-priority customers have high-priority loads (i.e., refrigeration, telecom., etc) that should also be serviced (if at all possible)

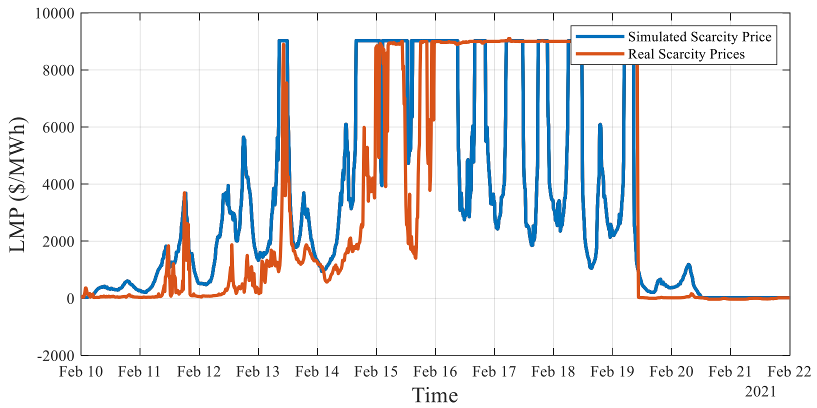

Fig. ERCOT market Prices during Texas Freeze events

- **Energy/Power Allocation**
  - Customers be provided with energy allocation
  - How can allocation be effectively implemented for electrical energy systems ?

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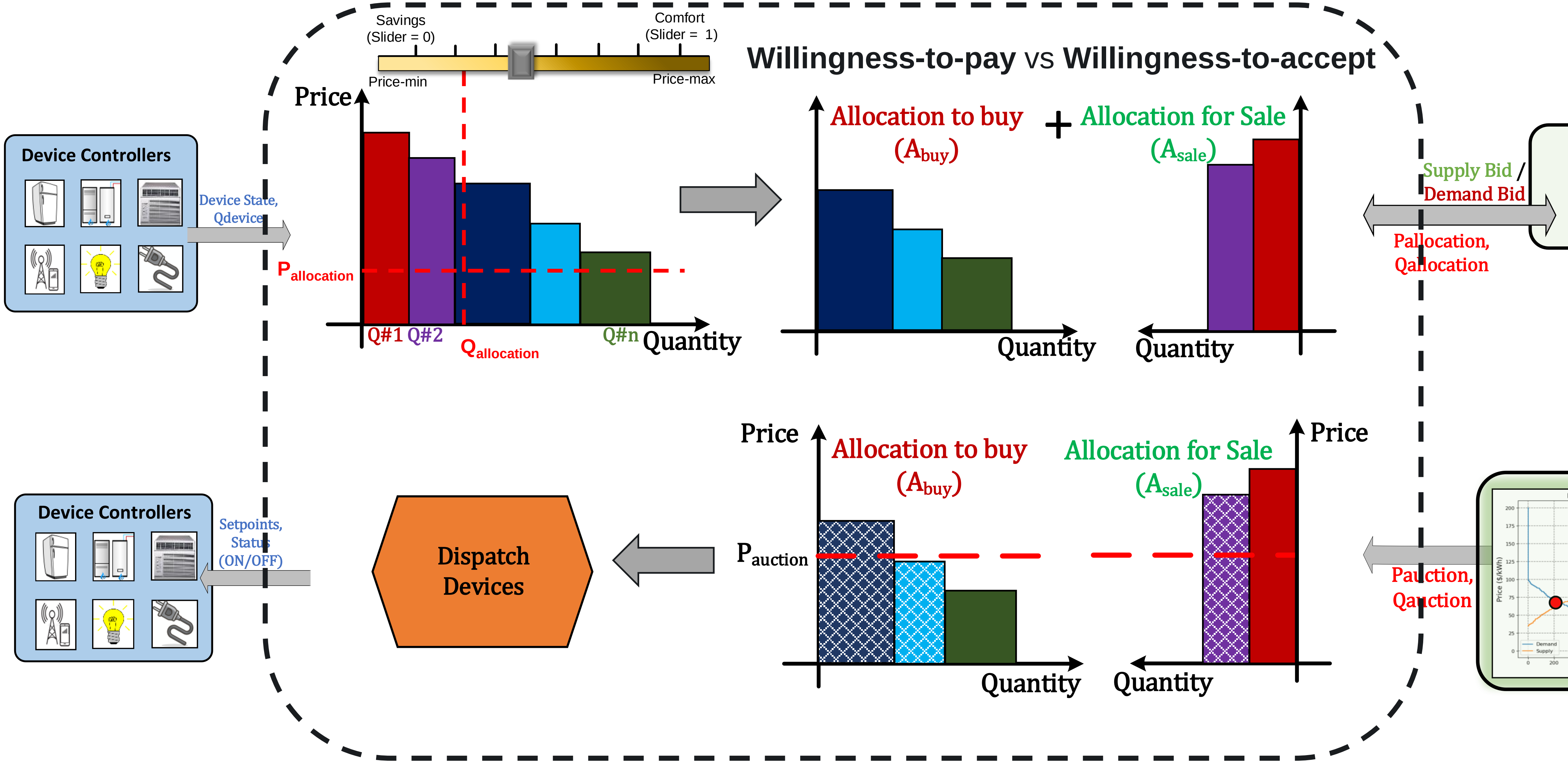
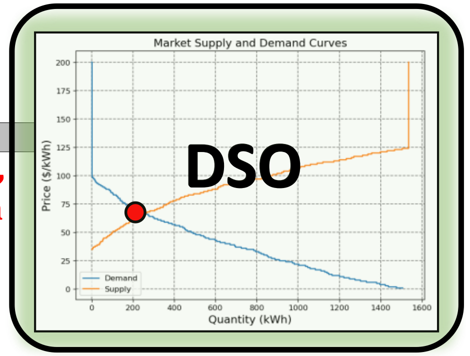
Transactive Emergency Power Allocation Mechanism





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Proof-of-Concept Demo

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Market | Transactive Network | Controls
Transactive Systems Program

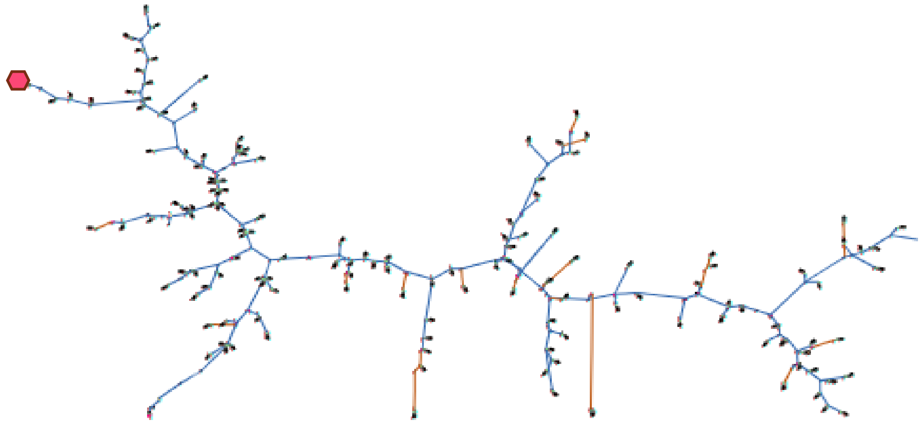


Fig. Test system - Prototypical feeder R4-25.00-1.

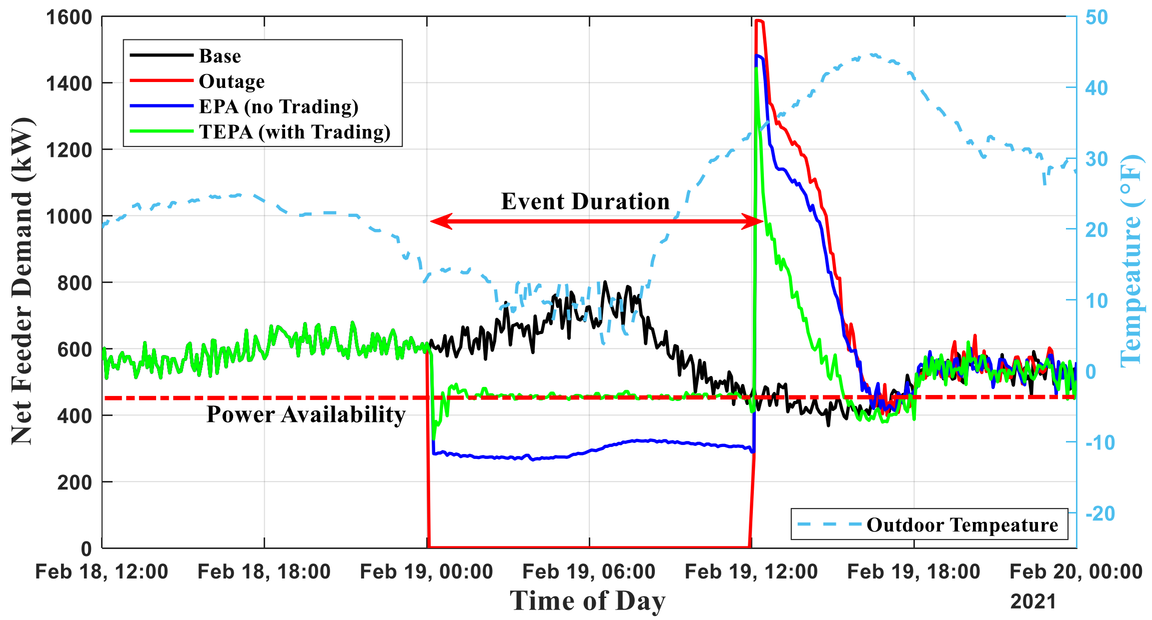
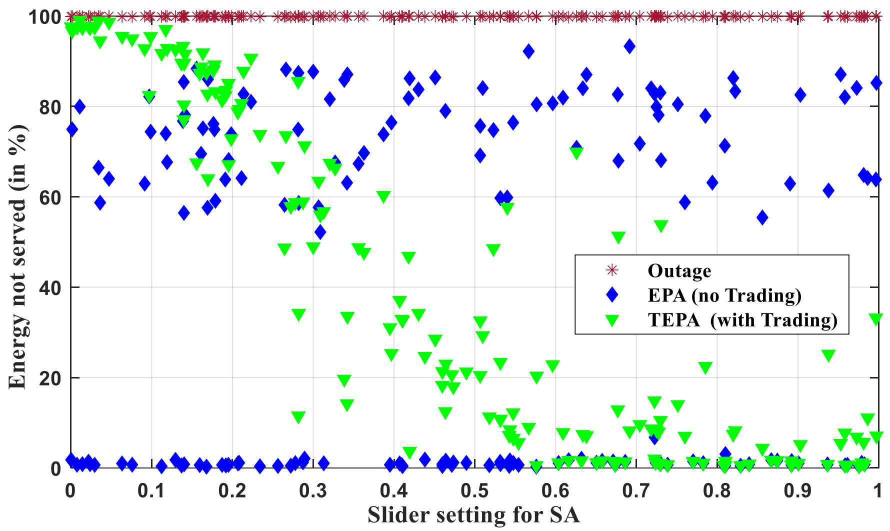
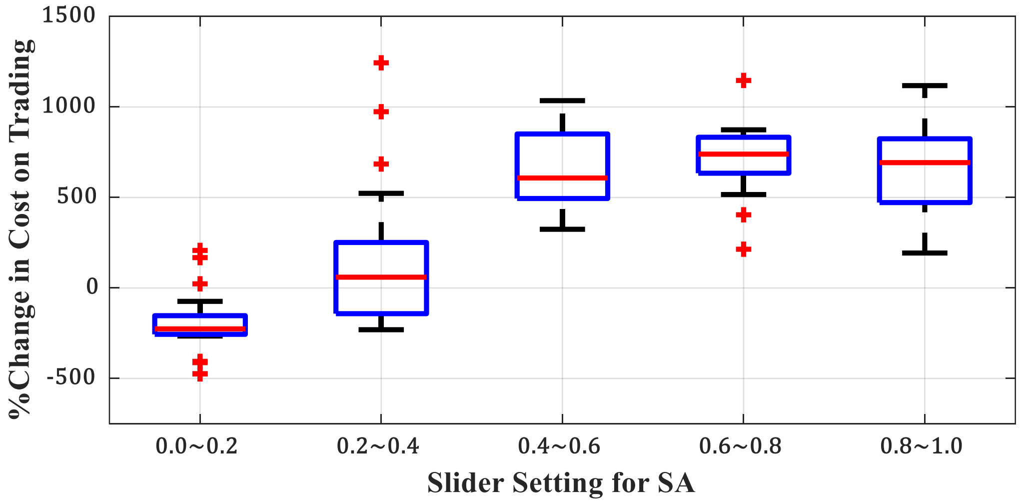


Fig. Impact of the TEPA on Feeder demand





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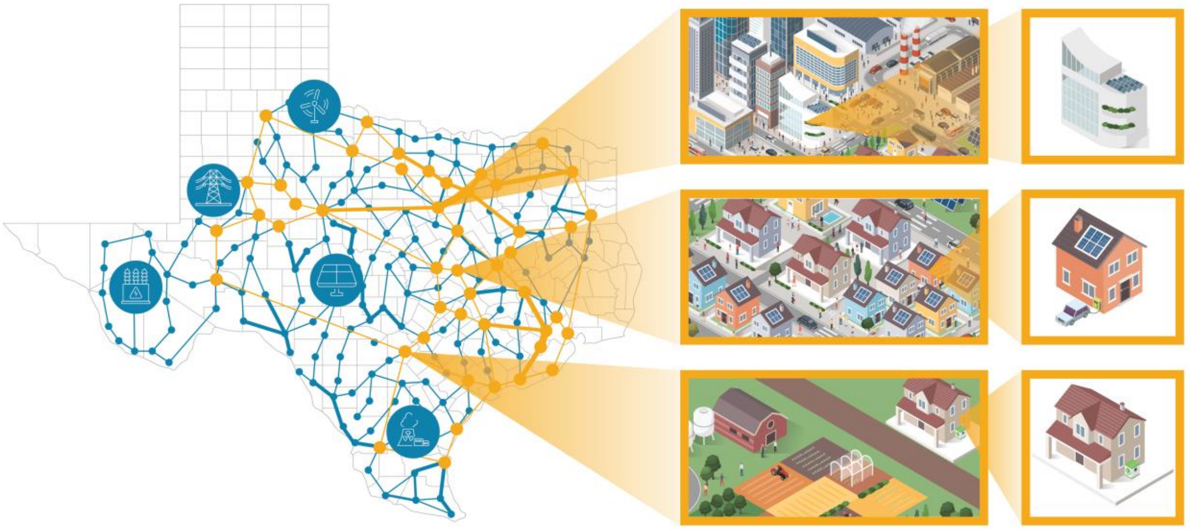
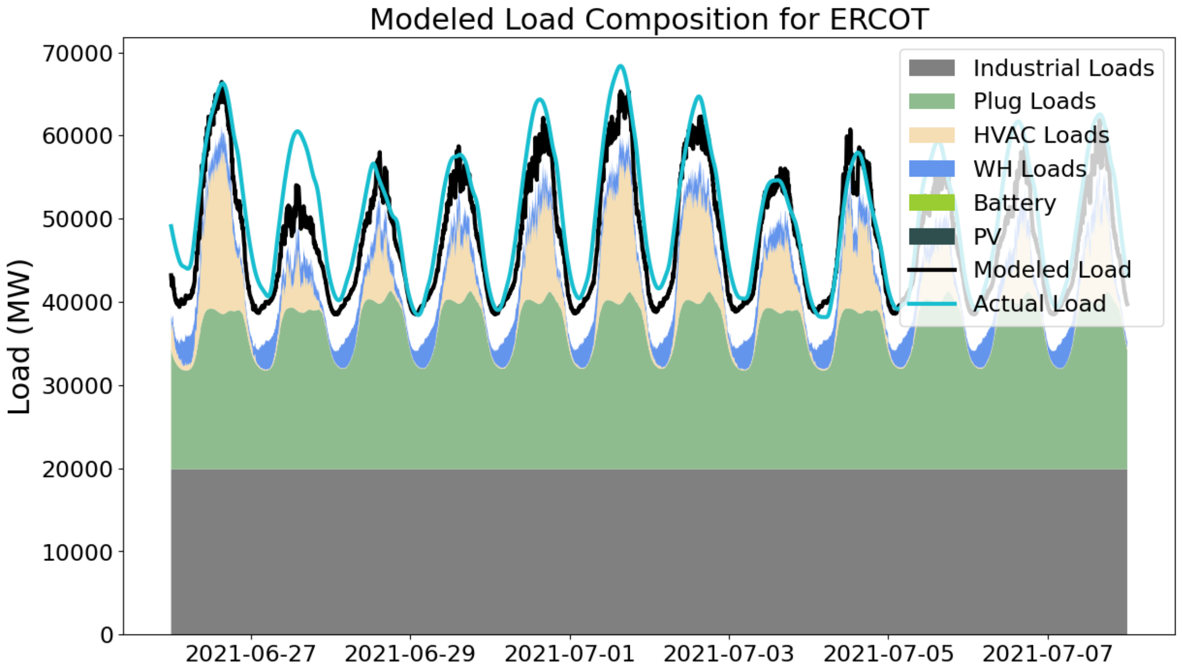
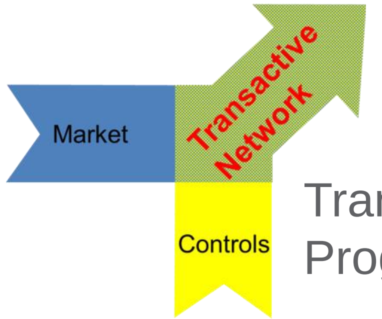
Modeling Distribution Grid Response: DSO+T Study on ERCOT







Transactive Systems Program

DSO+T Study: https://www.pnnl.gov/projects/transactive-systems-program/dsot-study

Reference: Reeve, H. M., Singhal, A., Tbaileh, A., Pratt, R. G., Hardy, T. D., Doty, J. D., ... & Oster, M. R. (2022). *DSO+ T: Integrated System Simulation DSO+ T Study: Volume 2* (No. PNNL-32170-2). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

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Modeling Distribution Grid Response: During Extreme Weather Conditions

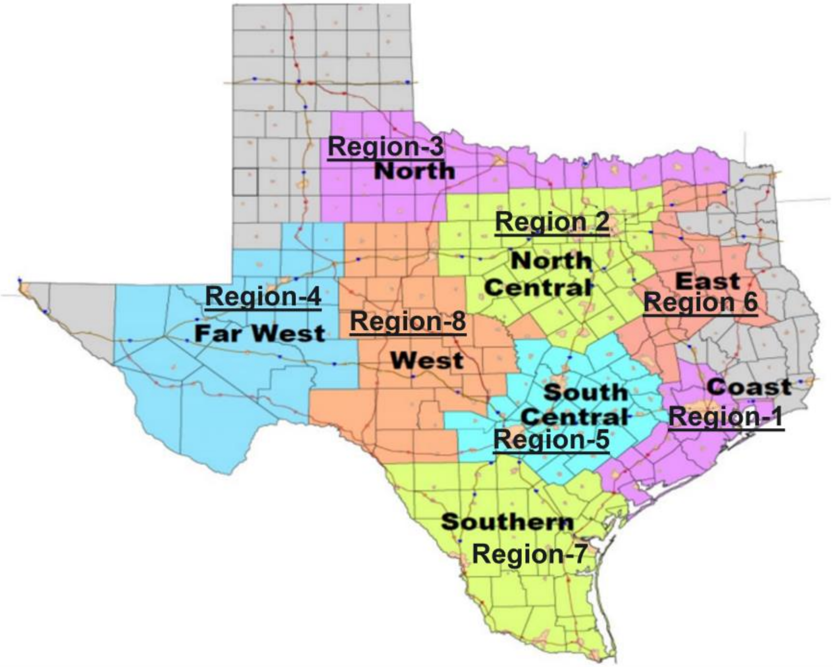
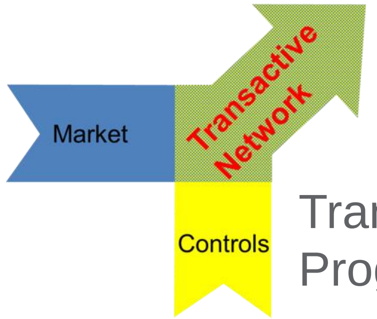


Fig. 8-Node Model of ERCOT region



Transactive Systems Program

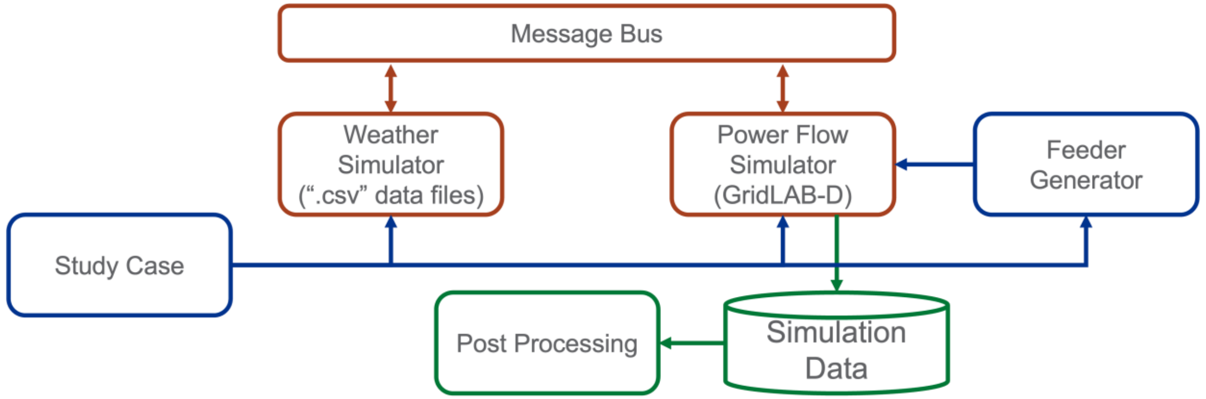
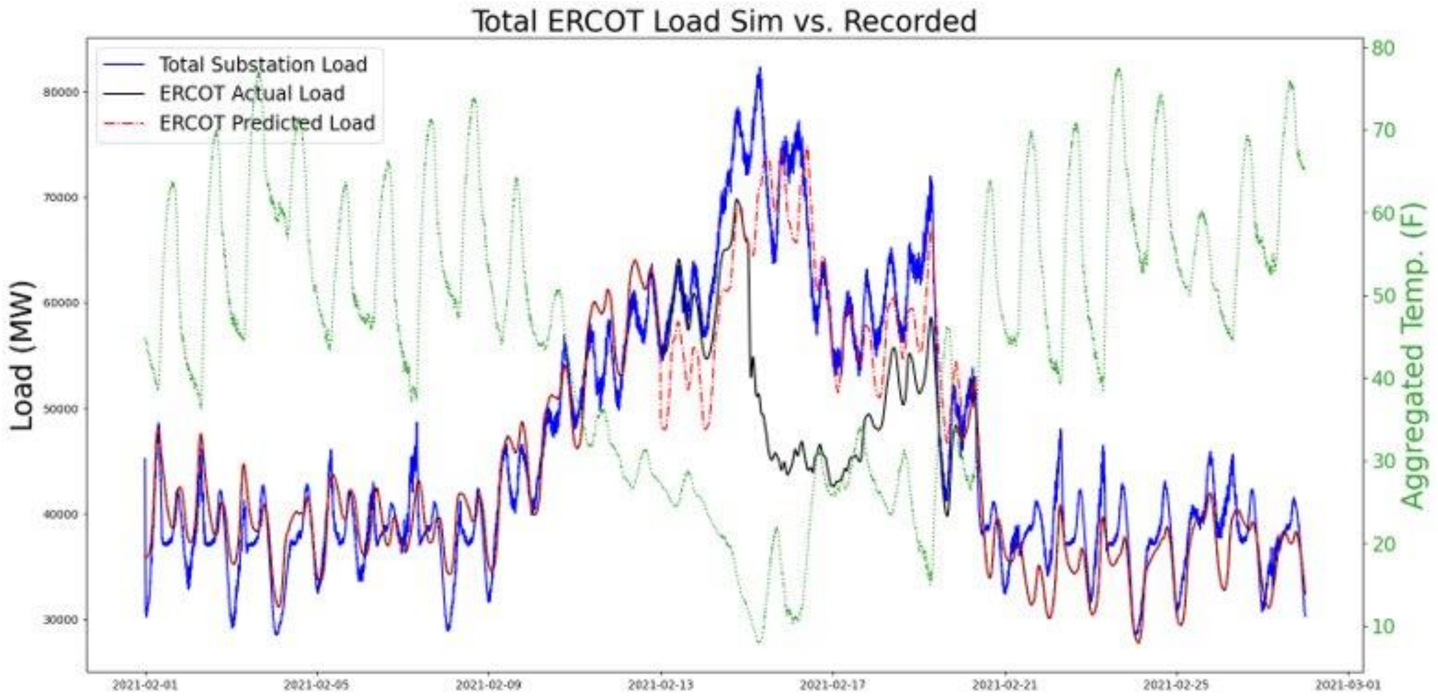


Fig. Modeling and simulation platform



Reference: Hanif, S., Mukherjee, M., Poudel, S., Yu, M. G., Jinsiwale, R. A., Hardy, T. D., & Reeve, H. M. (2023). Analyzing at-scale distribution grid response to extreme temperatures. Applied Energy, 337, 120886.

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Modeling Distribution Grid Response: VT (ISO-NE)

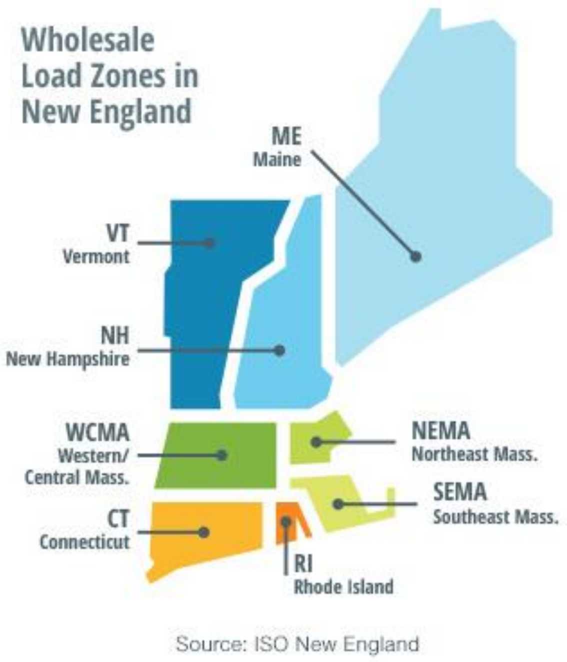


Fig. ISO NE Load Zones

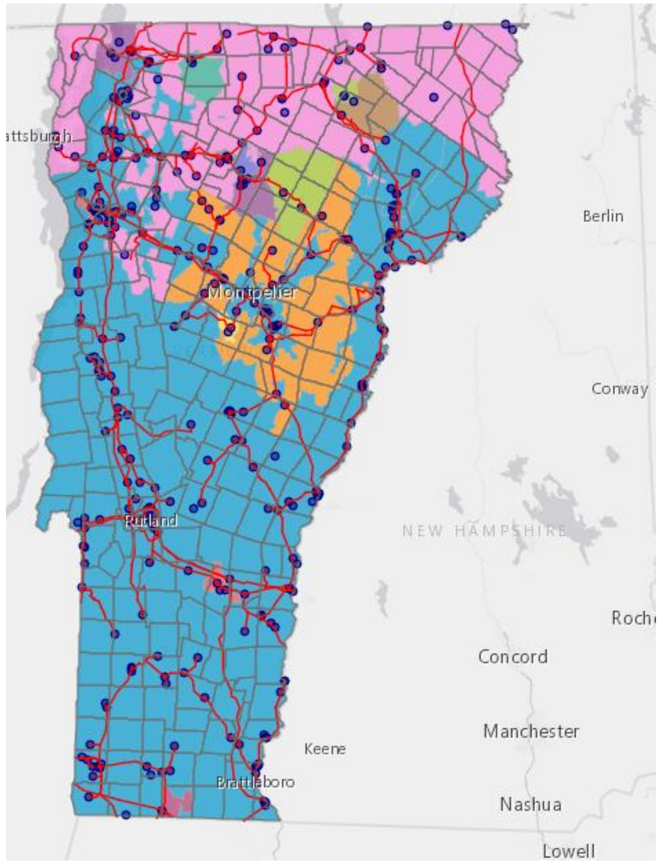
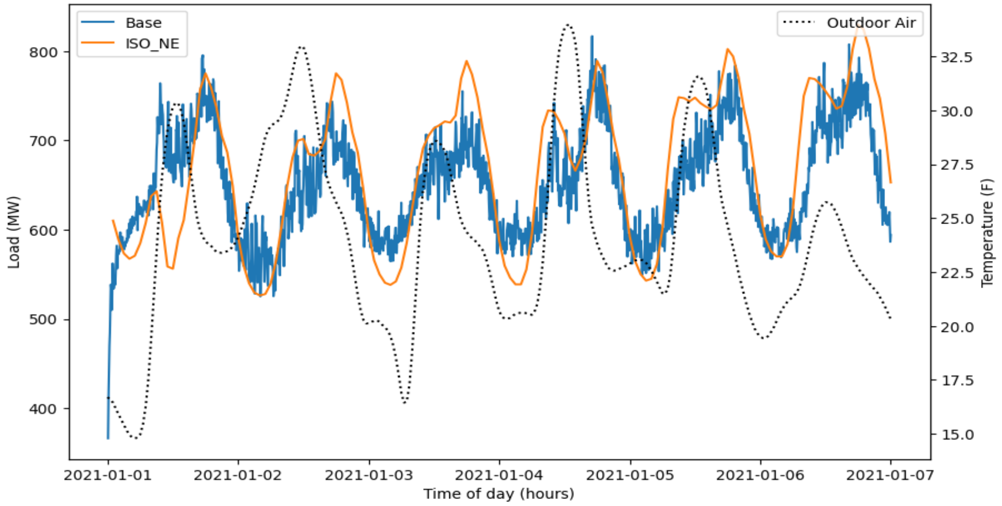
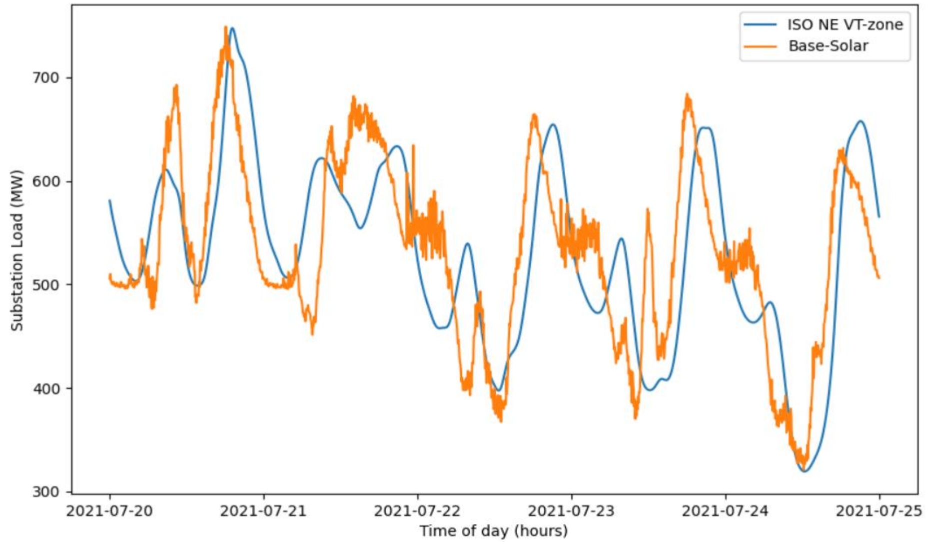


Fig. Distribution Utilities at the VT-Load zones





MAPLE-LEAF

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Wholesale Market Emulation

- MATPOWER + **M**ATPOWER **O**ptimal **S**cheduling **T**ool (MOST)
  - AC Power Flow: Determine system states for bulk power systems
  - Deterministic OPF for Single period & Multi Period: DA & RT Markets
  - Stochastic DC OPF to account for renewable uncertainty
  - Dispatchable Demand**:** Facilities DSO Bidding
  - Grid Scale Storage

- Integration using HELICS based MOST Wrapper
  - HELICS based Communication between ISO ← →DSO
    - System states between the T&D Systems
    - Market States between DSO and ISO.
  - Translation of (DA and RT) bids from DSO to equivalent representation inside Matpower objects for simulating OPFs.

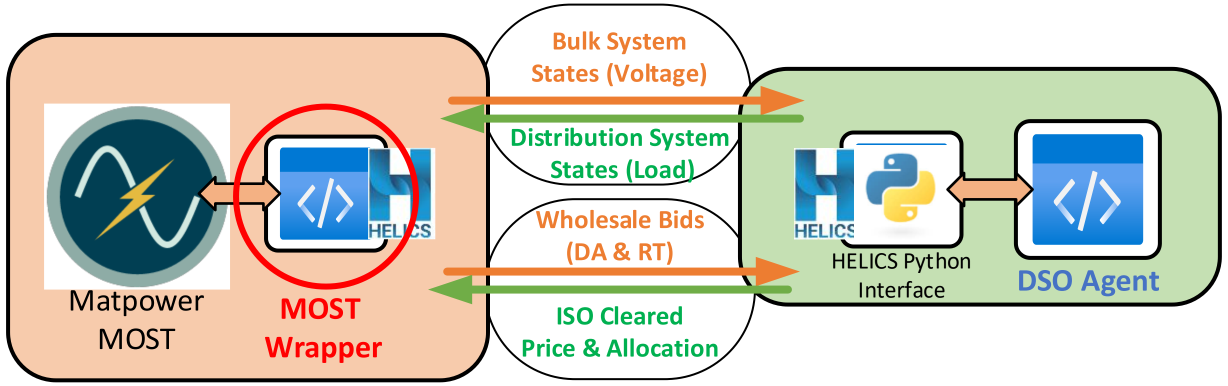
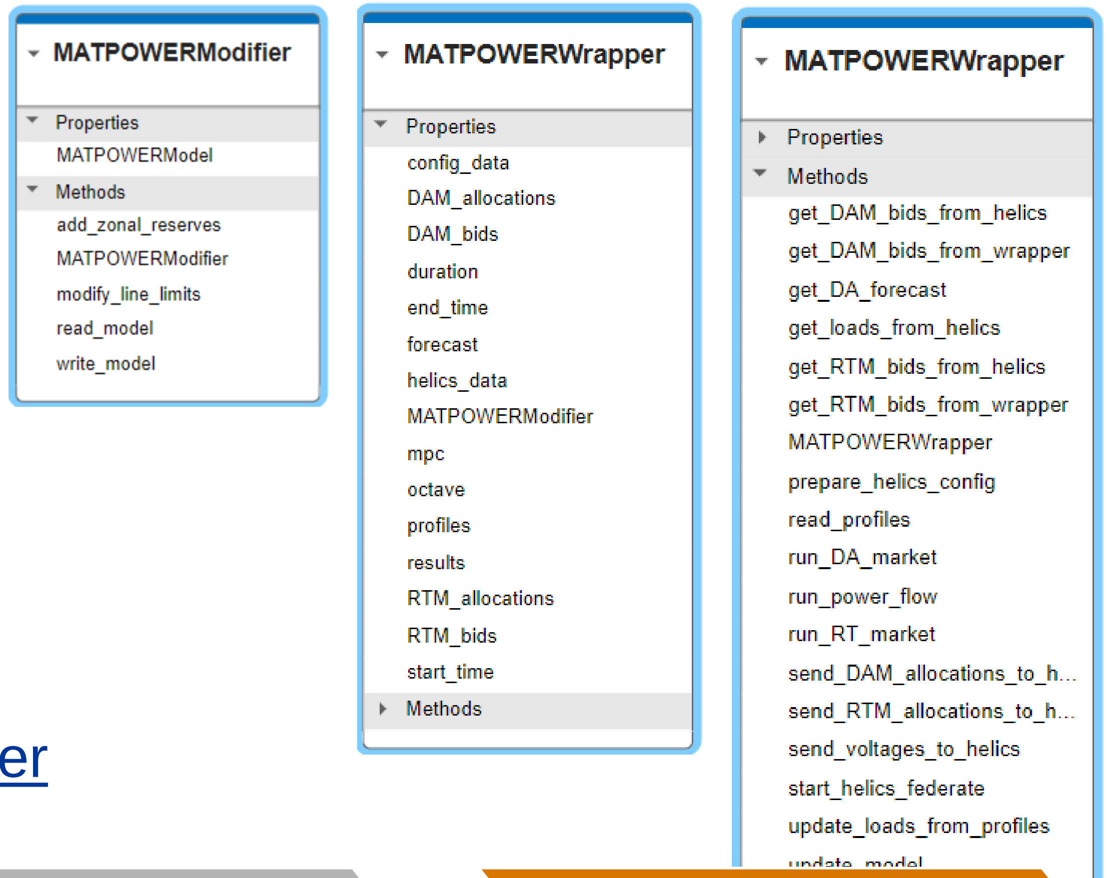


Fig. ISO-DSO interaction facilitated by the MATPOWER-MOST Wrapper



Code base: https://github.com/GMLC-TDC/MATPOWER-wrapper

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Wholesale Market Emulation

Fig. 8-Node Model of ERCOT region

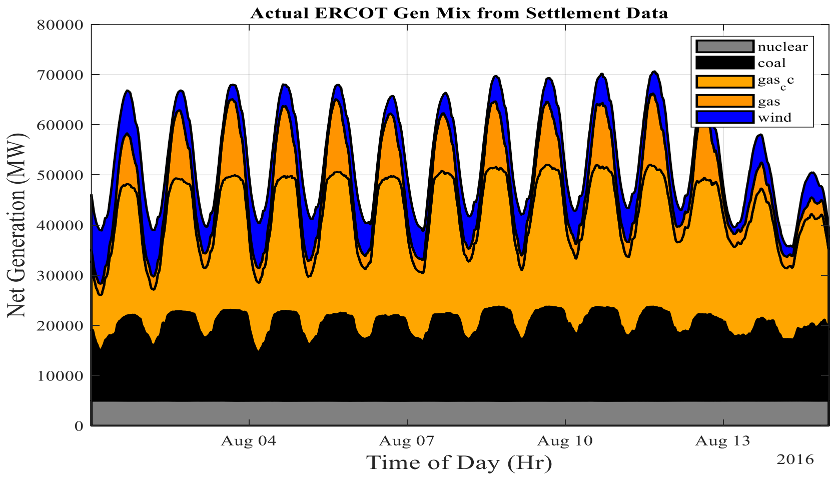

Fig. Actual Generation Mix of ERCOT for Aug 2016

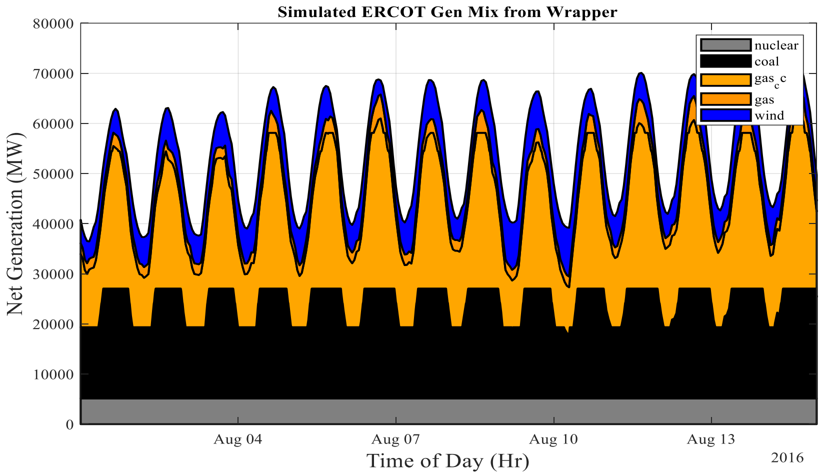

Fig. Simulated Generation Mix of ERCOT for Aug 2016

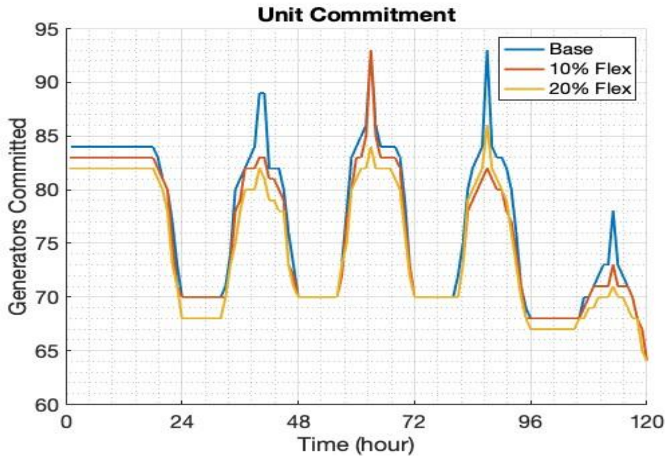

Fig. Impact of Flexibility on Unit Commitment Decisions

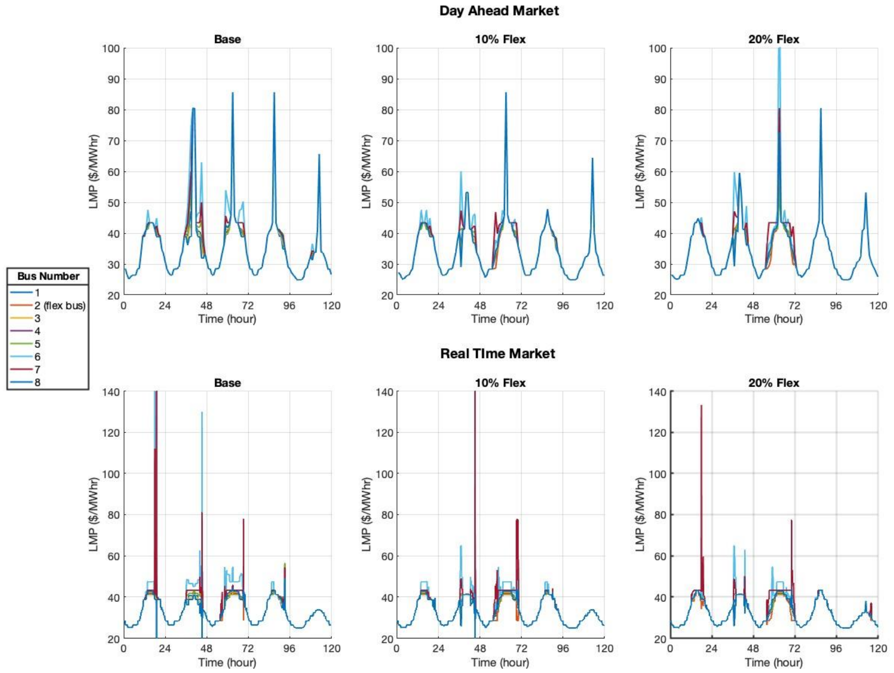

Fig. Variation of DA and RT Prices for different Flexibilities at Bus 2

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Summary

The Use-cases presents different flavors of how Transactive Energy can

- Effectively enable DERs to through different Coordination Architectures
  - Prosumer-to-Grid
  - Community-based Coordination
- Effectively enable customers to provide different Grid Services
  - Congestion Management (Peak load Reduction)
  - Emergency Support (Emergency load reduction support)

- Simulation Support for TE systems
  - Distribution Grid Response Modelling
  - Wholesale Electricity Market Emulation
  - Key Resources for users:
    - Transactive Energy Simulation Platform: https://github.com/pnnl/tesp
    - MATPOWER-Wrapper: https://github.com/GMLC-TDC/MATPOWER-wrapper

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Thank you