

Intelligent Electrification & Grid Optimization

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Co-founder



International Conference on Sustainable Technology and
Advanced Computing in Electrical Engineering (ICSTACE 2023)
Sardar Vallabhbhai National Institute of Technology (Surat, Gujarat, India)



Legal Disclaimer

M. Almassalkhi is a co-founder of and holds equity in *Packetized Energy*, which actively commercialized energy/grid technologies.



Acknowledgements

Active/recent collaborators

- Prof. Pierre Pinson (DTU/Imperial)
- Prof. Henrik Madsen (DTU)
- Dr. Sam Chevalier (DTU/UVM)
- Dr. Sarnaduti Brahma (UVM/Siemens)
- Prof. Hamid Ossareh (UVM)
- Prof. Luis Duffaut Espinosa (UVM)
- Dr. Paul Hines (EnergyHub)
- Prof. Jeff Frolik (UVM)
- Prof. James Bagrow (UVM)
- Prof. Sumit Paudyal (FIU)
- Prof. Dennice Gayme (JHU)
- Prof. Enrique Mallada (JHU)
- Dr. Dhananjay Anand (JHU)
- Dr. Soumya Kundu (PNNL/UVM)
- Prof. Roland Malhamé (Poly Montreal)
- Prof. Timm Faulwasser (TU-Dortmund)
- Dr. Alexander Engelmann (TUD)
- Dr. Tillmann Mühlfordt (DB Systel GmbH)
- Dr. Ning Qi (Tsinghua)
- Prof. Ian Hiskens (UMICH)
- Prof. Johanna Mathieu (UMICH)

Current group members

- Mr. Hani Mavalizadeh (PhD student)
- Mr. Waheed Owonikoko (PhD Student)
- Mr. Mazen El-Saadany (PhD Student / starts August, 2022)
- Ms. Rebecca Holt (undergraduate researcher)
- Ms. Kendall Meinhofer (undergraduate researcher)
- Ms. Emily Ninestein (undergraduate researcher)

Graduated group members

- Dr. Adil Khurram (PhD EE'21) → Scientist @ UCSD (San Diego, CA)
- Dr. Nawaf Nazir (PhD EE'20) → Research @ PNNL (Richland, WA)
- Dr. Mahraz Amini (PhD EE'19) → Strategy @ NatGrid (Dallas, TX)
- Mr. Micah Botkin Levy (MSEE'19) → Modeling @ Form Energy (SF, CA)
- Mr. Zach Hurwitz (MSME'19) → Engineer @ Siemens (ME)
- Mr. Lincoln Sprague (MSEE'17) → Compliance @ Dynapower (VT)
- Ms. Anna Towle (BSEE'16) → Trader @ Fortum (Sweden)



VECTORS: Vermont Energy Center for conTrol and Optimization of Resilient Systems

Objective: sustain and strengthen UVM's research impact in the area of understanding, controlling, and optimizing sustainable, resilient, and autonomous systems and networks by leveraging a group of diverse, interdisciplinary, and research-active faculty.



Mads R. Almassalkhi
(Founding Director)



Jeff Frolik



Amrit Pandey



Sam Chevalier
(Starts Aug 2023)



Hamid Ossareh



James Bagrow



Luis D. Espinosa

Broad expertise

- Power/energy
- Grid modeling
- Networks
- Optimization
- Dynamics
- IoT
- Data science
- Machine learning



VECTORS works with industry & research partners

Recent and ongoing industry-supported projects with



Sandia
National
Laboratories



Recent and ongoing federal partners



NIST
National Institute of
Standards and Technology



Recent success with translational research

Packetized Plug-in Electric Vehicle Charge Management

Pooya Rezaei, *Student Member, IEEE*, Jeff Frolik, *Senior Member, IEEE* and Paul Hines, *Member, IEEE*

Packetized energy management: asynchronous and anonymous coordination of thermostatically controlled loads

Mads Almassalkhi, *Member, IEEE*



Jeff Frolik, *Senior Member, IEEE*



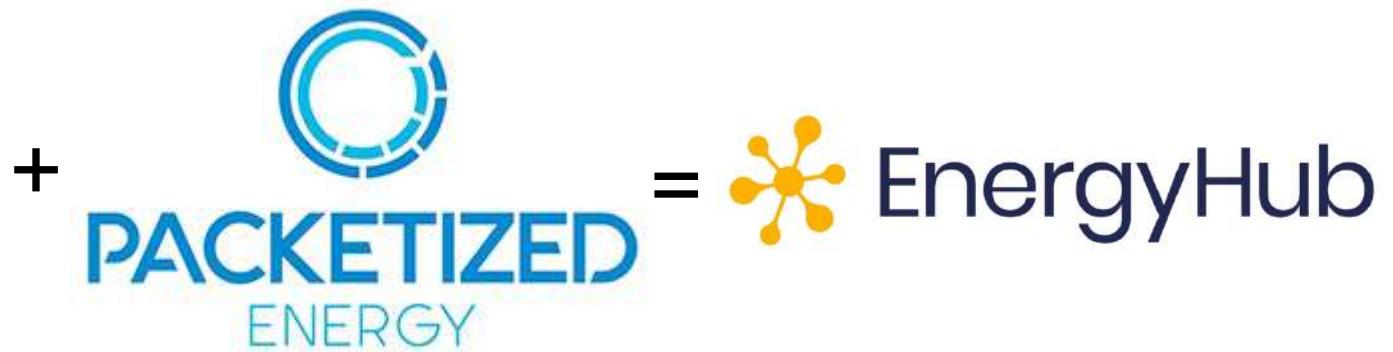
Paul Hines, *Senior Member, IEEE*



Abstract—Because of their internal energy storage, electrically powered, distributed thermostatically controlled loads (TCLs) have the potential to be dynamically managed to match their aggregate load to the available supply. However, in order to facilitate consumer acceptance of this type of load management, TCLs need to be managed in a way that avoids degrading perceived quality of service (QoS), autonomy, and privacy. This paper presents a real-time, adaptable approach to managing TCLs that both meets the requirements of the grid and does not require explicit knowledge of a specific TCL's state. The method leverages a packetized, probabilistic approach to energy delivery that draws inspiration from digital communications. We demonstrate the packetized approach using a case-study of 1000 simulated water heaters and show that the method can closely track a time-varying reference signal without noticeably degrading the QoS. In addition, we illustrate how placing a simple ramp-rate limit on the aggregate response overcomes synchronization effects that arise under prolonged peak curtailment scenarios.

"fairness" properties with regard to providing statistically identical grid access to each load.

With the proposed PEM architecture, the grid operator or aggregator only requires a two dimensional measurement from the collection of loads: aggregate power consumption and an aggregate request process. This represents a significant advantage over aggregate model-estimator-controller state-space approaches in [4], which requires an entire histogram of states from the collection of loads to update a state bin transition model. In [4], this is addressed through an observer design to estimate the histogram based on aggregate power consumption; however, in some cases, the model may not be observable [5]. Recent work has extended [4] to include higher order dynamic models and end-user and compressor delay constraints [6] and stochastic dynamical performance bounds [7]. Similar to the mean-field



Numerous academic papers+ research funding
+ Lots of IP + industry partners
(2012-present)



Co-founded startup company
(2016)

Company acquired
(2022)

1000X

Accessing scale: from 700 devices to 700,000!



CANARY MEDIA



EnergyHub buys Packetized Energy to get millions of thermostats and EVs to help balance the grid

Utilities need to orchestrate energy-smart devices at a massive scale. This startup's radically distributed approach could help.

3 March 2022



yahoo!

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A BUSINESSWIRE COMPANY

EnergyHub Acquires Packetized Energy to Extend High-Value Grid Service Capabilities



March 1, 2022 · 3 min read



Vermont is amazing platform for power/energy R&D

- ✓ Population: 650,000 people with a peak load of ca. 1GW
 - ▶ *AMI deployed at >95% of customers in State Vermont Renewable Portfolio Standard (RPS): 75% by 2032*
- ✓ Small state → easy to collaborate, create change, have impact
- ✓ Close partnerships with nationally-recognized innovative industry
 - ▶ *VELCO, GMP, BED, VEIC, Dynapower, Vermont Gas, Beta Technologies, etc.*
- ✓ Joint appointment program with national lab (PNNL)
- ✓ Strong presence with competitive federal E programs
 - ▶ *Past funding from ARPA-E NODES, SETO ENERGISE, NSF CAREER, CRISP, DOE GMLC*
- ✓ Outstanding interdisciplinary collaborations with the UVM *Complex Systems Center* and *Gund Institute for Environment*
- ✓ **VT is #2 state in U.S. for Clean Energy Momentum (UofCS, 2017)**
 - 5.4% of workforce is clean energy economy (#1 in 2021)
 - ▶ *Next largest are at ~3%*
 - 99.9% of VT *generation* is renewable (#1 in US in 2019)
 - 66% of consumed electricity is renewable (2019)
 - 15% of electricity from solar PV (#4 in US in 2020; #6 per capita)
 - 5.4% of new cars sold are EVs in 2021 (VT was #9 in 2018)



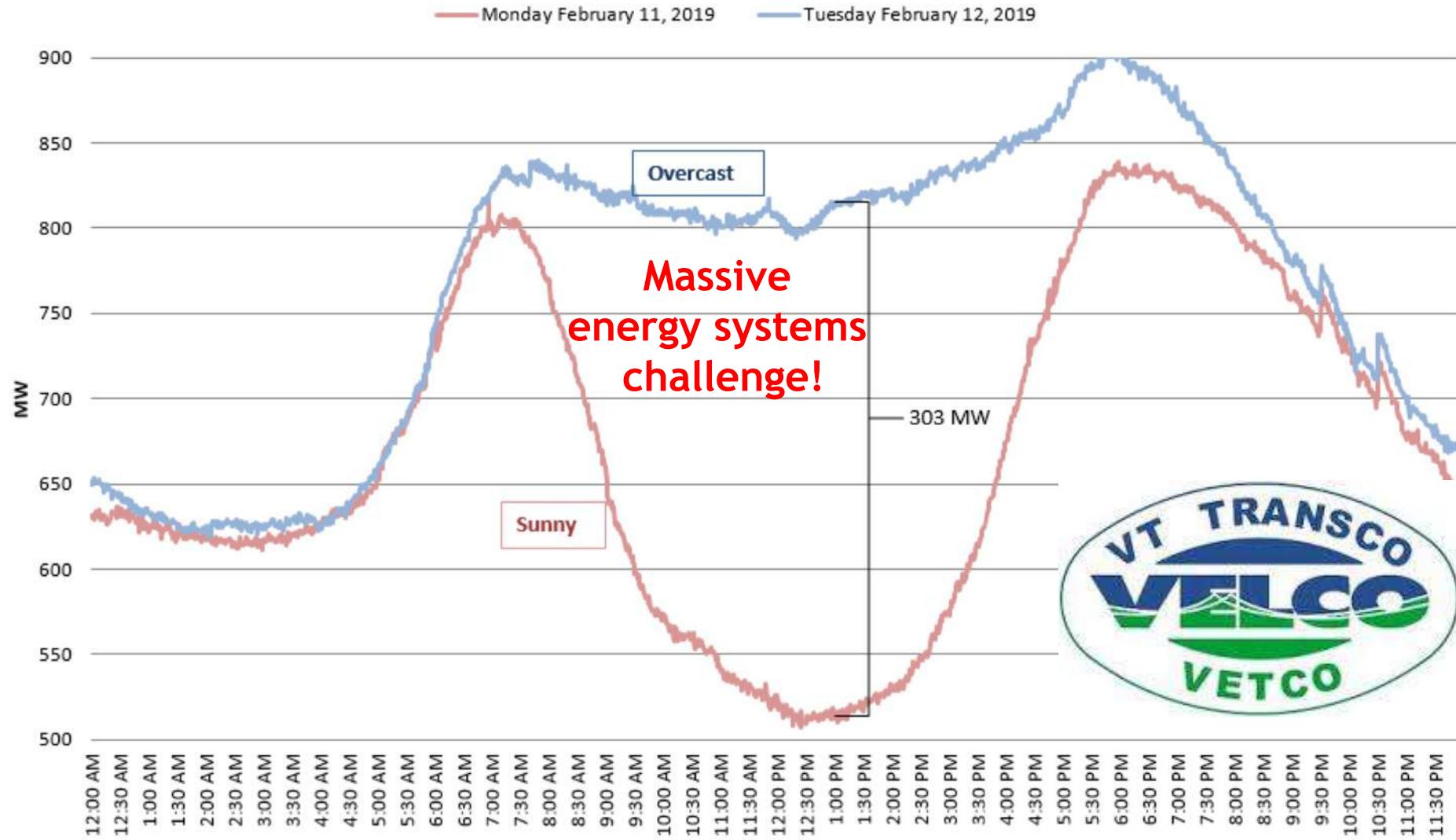
Vermont is America's living energy laboratory



First efficiency utility
in the U.S. (2000)



First U.S. utility to become
100% renewable (2014)



Why does it matter? Economies are going green!



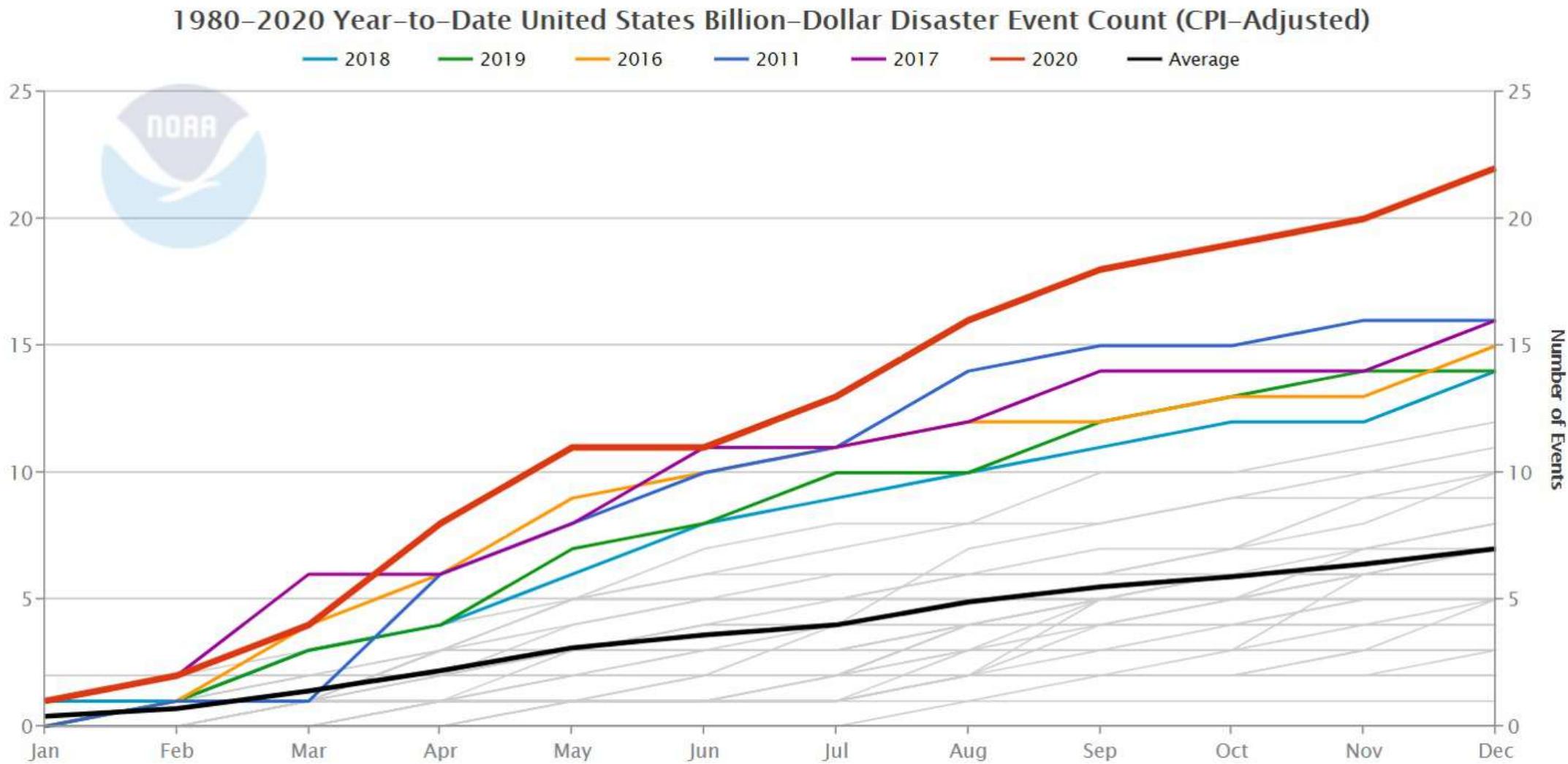
Annual sales revenue

Jobs supported

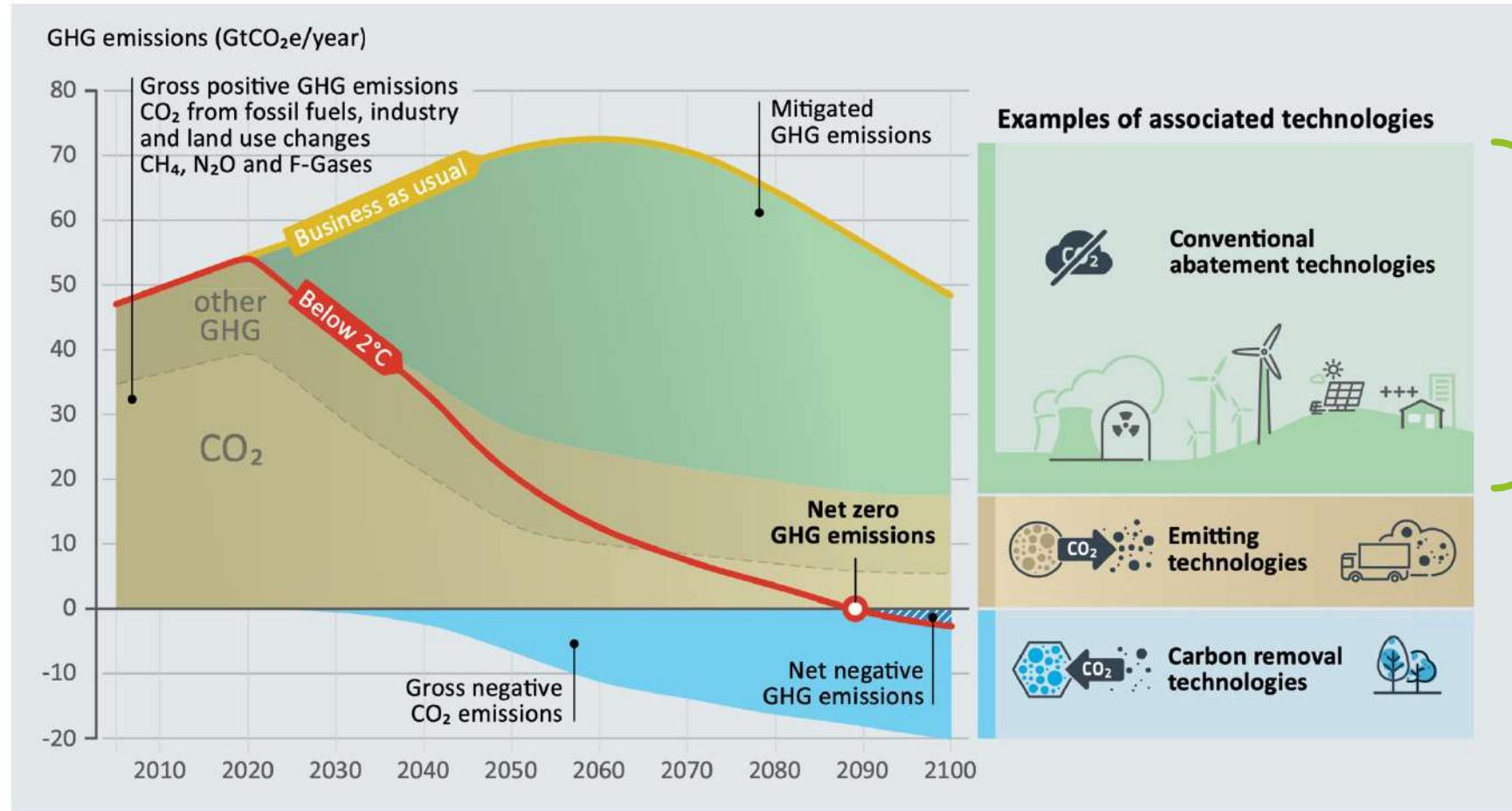
Green economy := environmental, low carbon and renewable energy activities



Why does it matter? Inaction is inexcusable!



Solutions? If they work, they will matter!



Requires massive TW-scale renewable integration

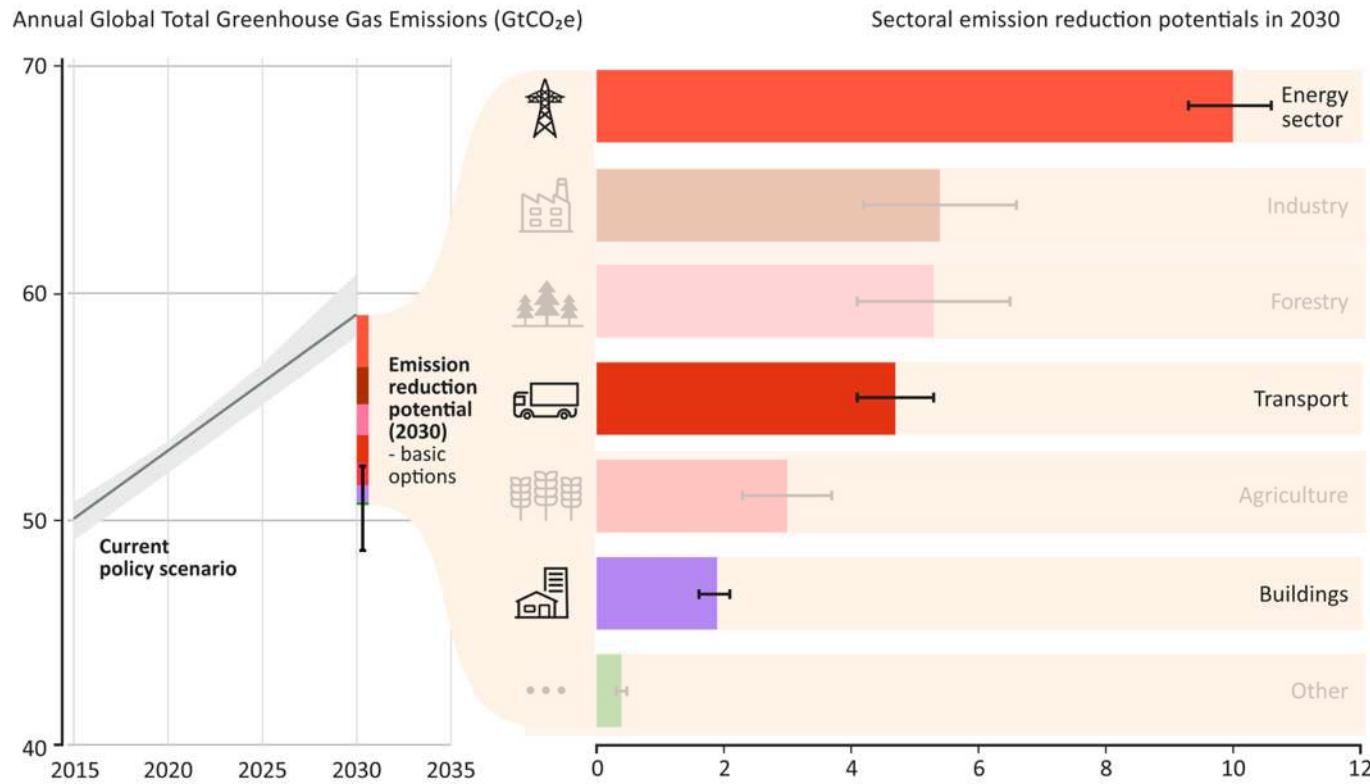
A massive power systems challenge!

Key: Re-think power engineering as climate-change mitigation engineering



Flexibility can help: *intelligent electrification*

Energy, transportation, and building sectors are key!



Combine renewable and efficiency with **electrification of end use**. [1]

Flexible demand enables significantly more renewable generation and reduces duck-curve ramping effects [2]

59GW of DR today will become 200GW of flexible demand by 2030 [3]

How to coordinate millions of smart electric loads?

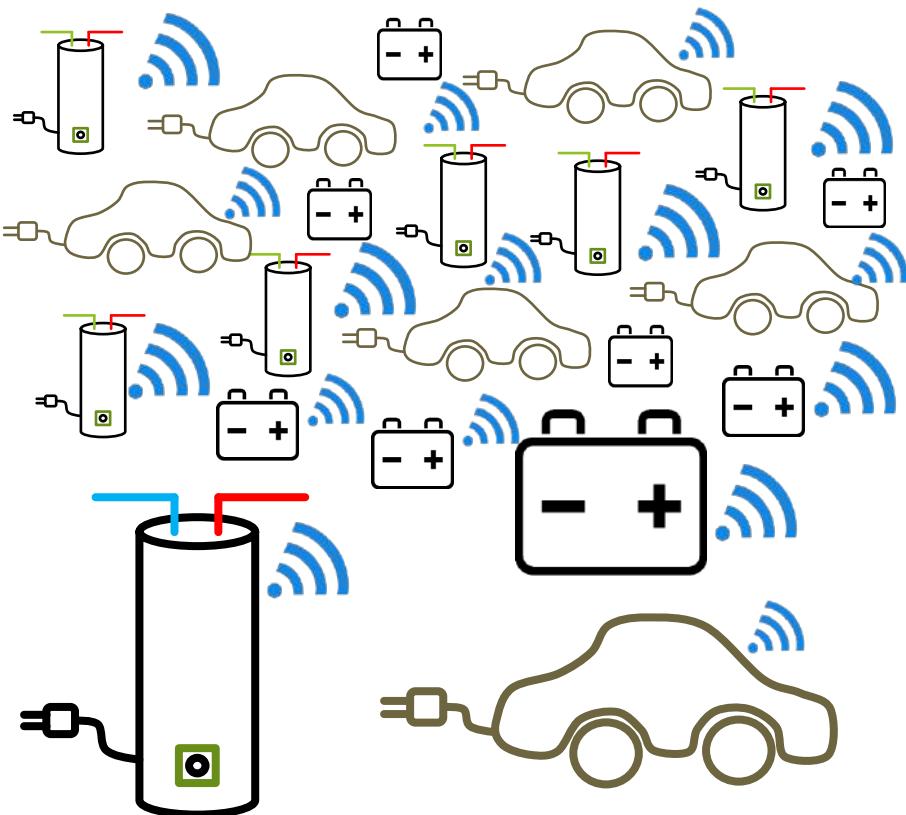
[1] UN Environmental Program, Emission Gap Report 2019 (source for figure, too)

[2] Goldenberg, et al, "Demand Flexibility: The Key To Enabling A Low-cost, Low-carbon Grid," Tech. Rep., Rocky Mountain Institute, 2018.

[3] Hledik et al, "The National Potential for Load Flexibility: Value And Market Potential Through 2030," Tech. Rep., The Brattle Group, 2019.

Simple idea: turn connected loads into flexible demand

Demand-side DERs + communication + control



Every neighborhood¹, feeder, or city^{2,3,4}
can become a dispatchable resource



[1] Chakraborty ,et al, Virtual Battery Parameter Identification using Transfer Learning based Stacked Autoencoder, ICLMA, 2018

[2] Hao, et al, Aggregate Flexibility of Thermostatically Controlled Loads. IEEE Transactions on Power Systems. 2014

[3] Hughes, et al, Identification of Virtual Battery Models for Flexible Loads. IEEE Transactions on Power Systems. 2018

[4] A. Khurram, et al, "Real-time Grid and DER Co-simulation Platform for Validating Large-scale DER Control Schemes," IEEE Transactions on Smart Grid, (accepted 2022).



Technical challenges for intelligent electrification

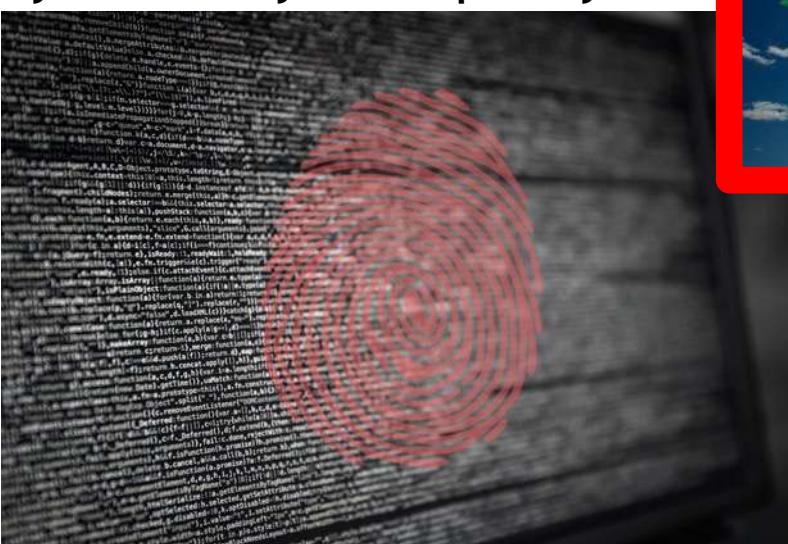
Comfort & convenience (local)



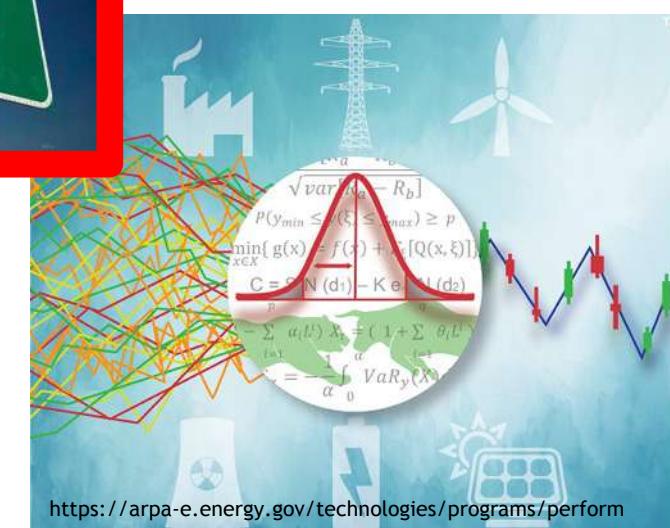
Grid conditions & reliability (global)



Cyber-security & Data privacy



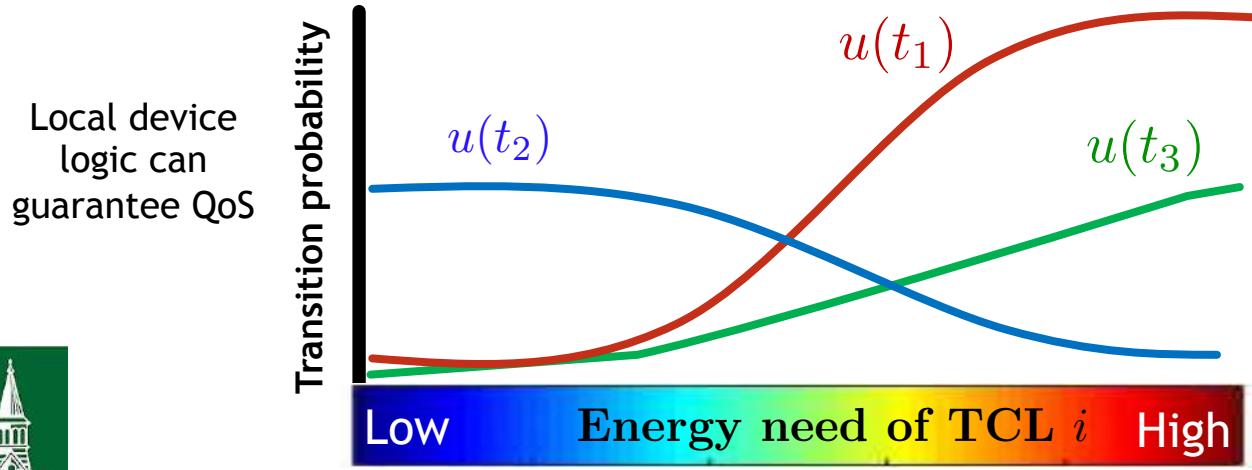
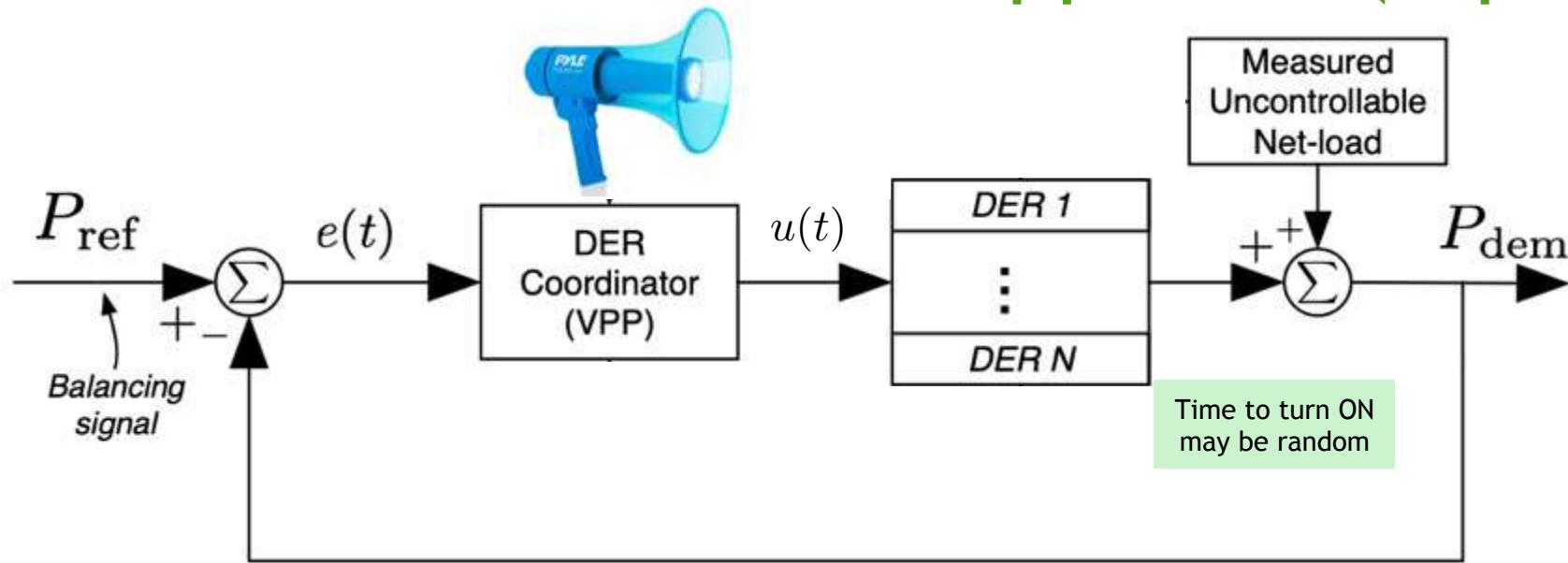
Business models & risk management



<https://arpa-e.energy.gov/technologies/programs/perform>



Method #1: Broadcast-based approach (top-down)



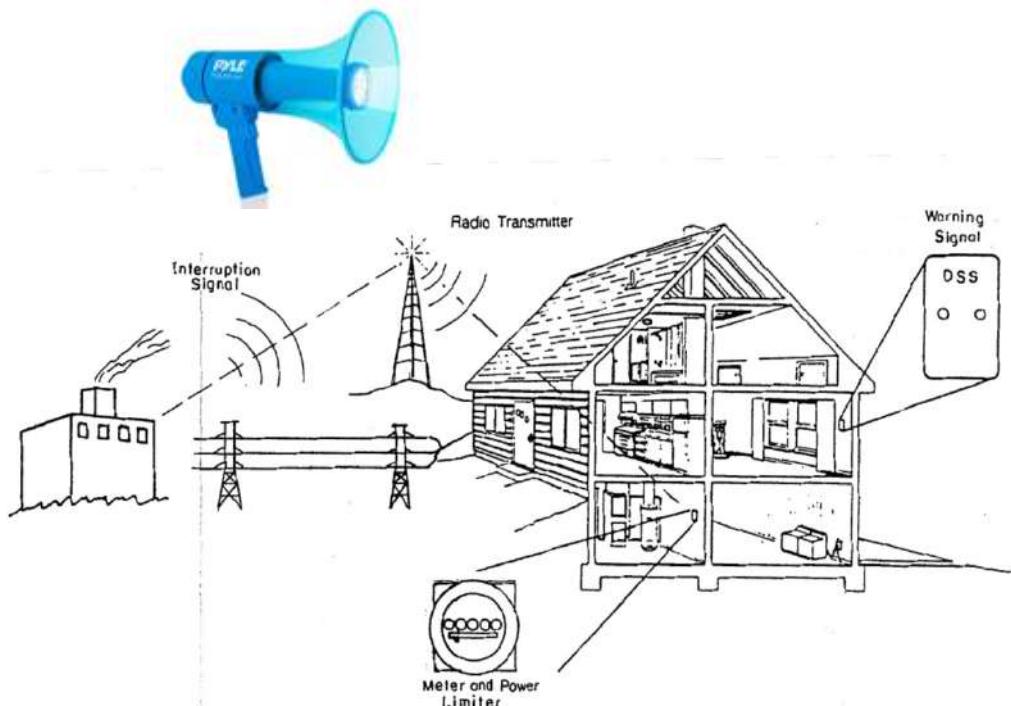
Broadcast control signal to all devices **synchronously**.
Control signal may be **explicit price or implicit PDF**.

Depends on feedback from estimate and/or all devices streaming back data/status or is **open-loop**

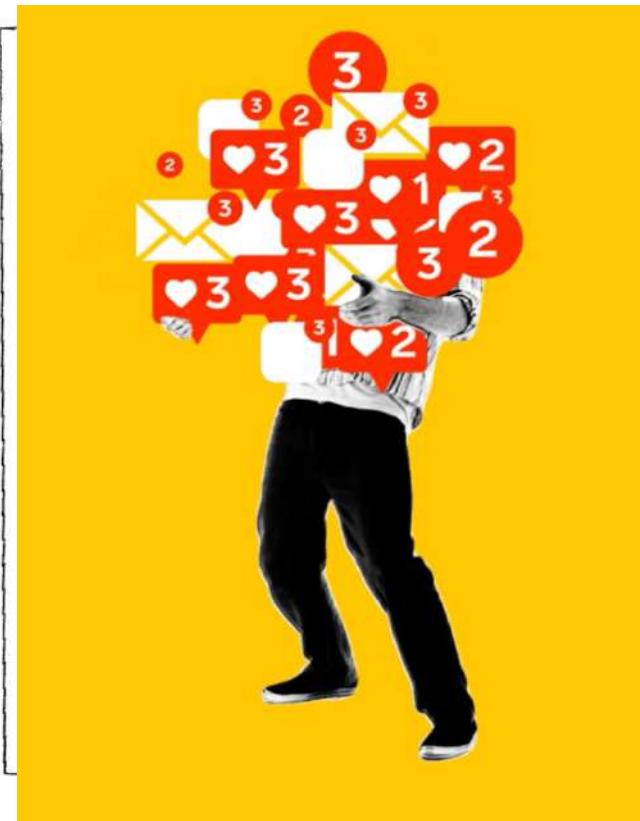
But challenging to distinguish individual device constraints or grid location (i.e., DER cycling and local grid conditions).

Broadcast control example: California in 1982

Demand subscription service (DSS): radio-controlled fuse limits demand to subscribed level



Thanks to Shmuel Oren for sharing this story from SCE in 1982



Today, some utilities use SMS

Human becomes the actuator in-the-loop



Source: VectorStock.com/7537816

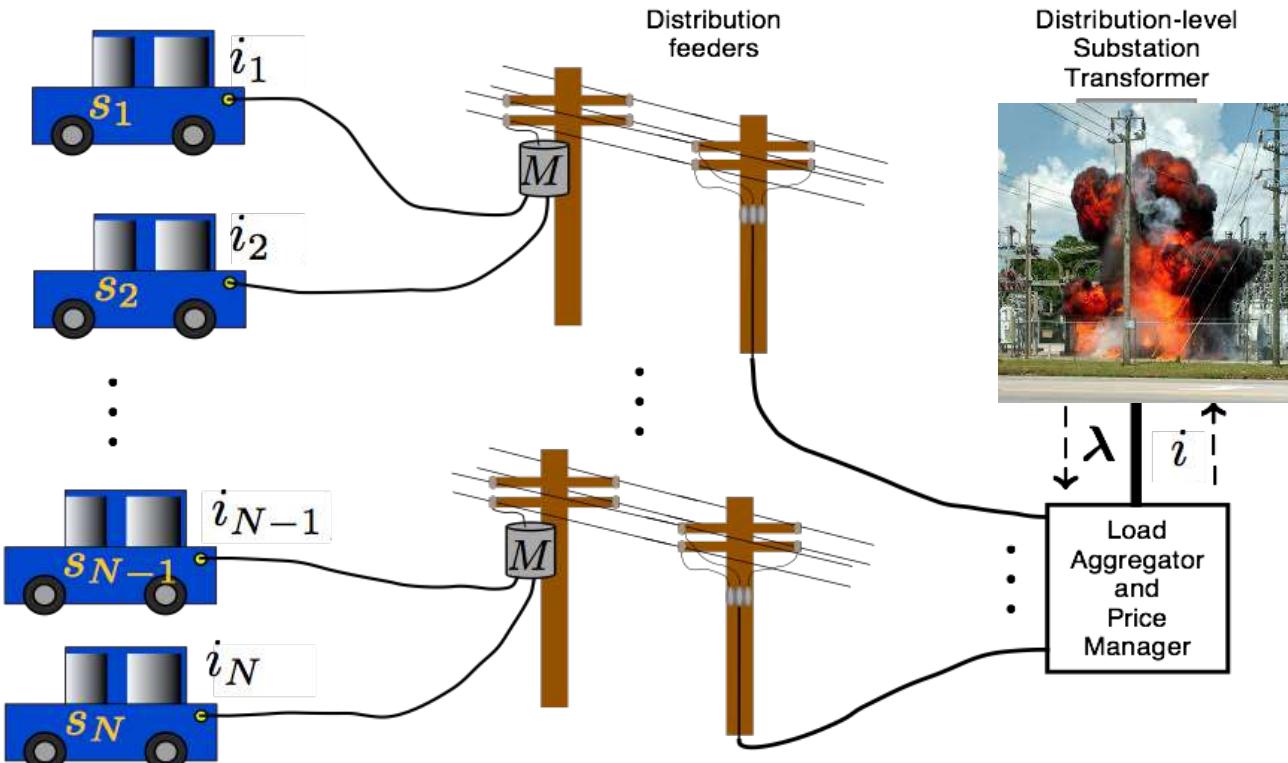
Another example: direct load control or TOU pricing

We can do better than
sprinkler control



Consider indirect control: EV charging scenario

Consider a fleet of EVs served by a transformer (with dynamic temperature rating)



EV objective: charge quickly!

$$s_n[k+1] = s_n[k] + \eta_n i_n[k]$$

Transformer challenge:
uncoordinated charging \rightarrow overload
 \rightarrow overheat \rightarrow insulation loss

Transformer temperature: $T[k] \leq T^{\max}$

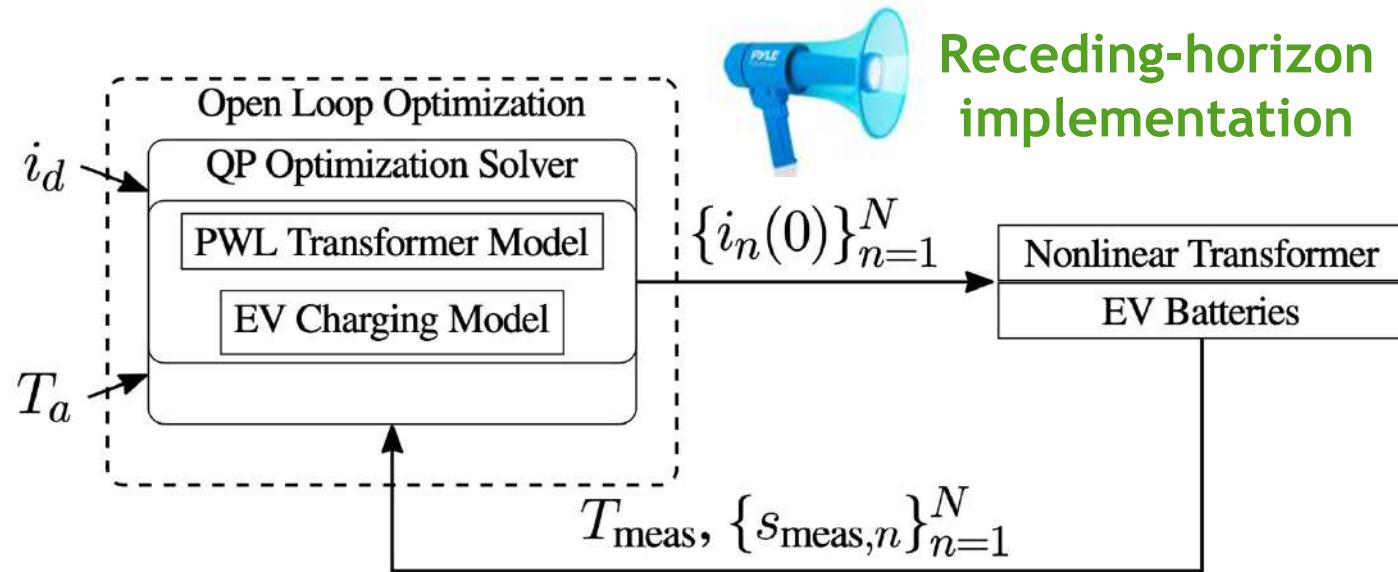
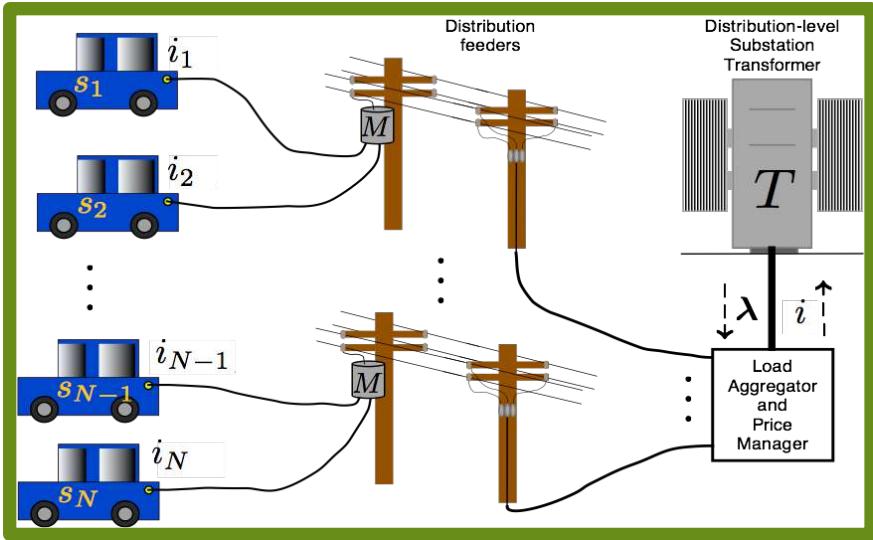
$$T[k+1] = \tau T[k] + \gamma(i_{\text{total}}[k])^2 + p T_{\text{amb}}[k]$$

Aggregate current couples decisions:

$$i_{\text{total}}[k] = i_{\text{bgd}}[k] + \sum_{n=1}^N i_n[k]$$

EV charging scenario: direct load control

With full information (EV + Transformer), solve open-loop optimal control problem



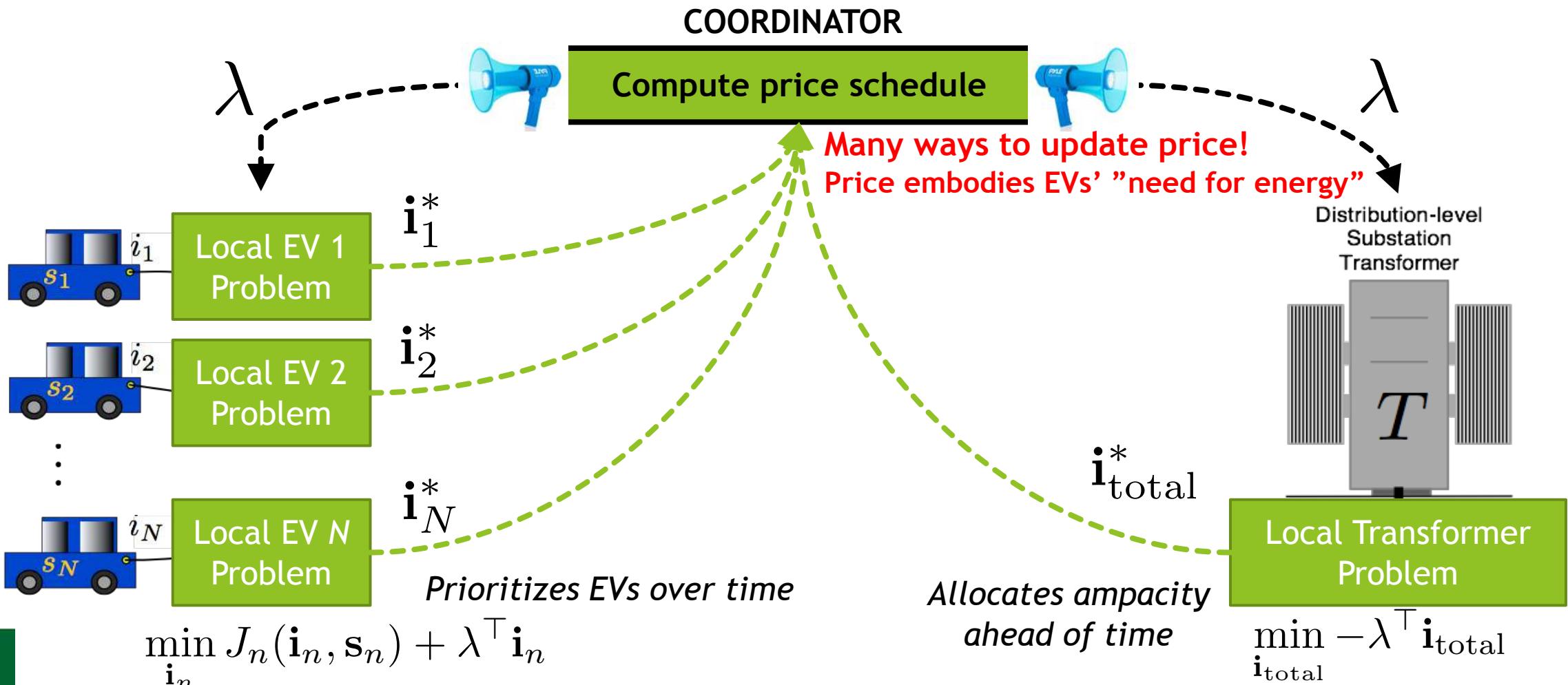
$$\min_{i_n[k]} \sum_{n=1}^N \sum_{k=0}^{K-1} q_n(s_n[k+1] - 1)^2 + r_n(i_n[k])^2 =: \sum_{n=1}^N J_n(\mathbf{i}_n, \mathbf{s}_n)$$

charge quickly!

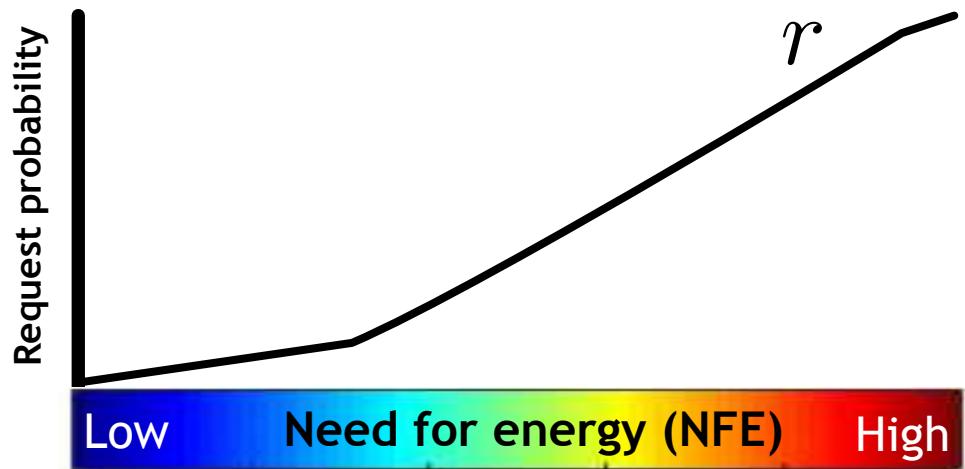
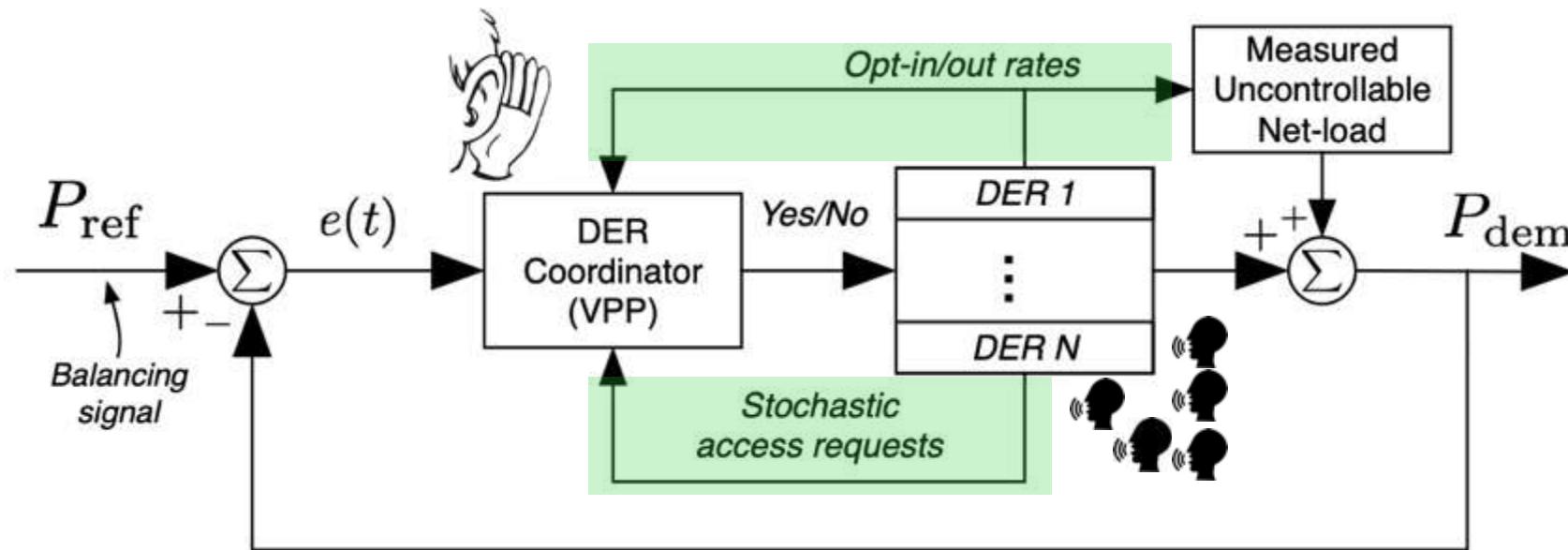
limit high currents

EV charging scenario: indirect load control

With limited information (EVs do not share specs), solve distributed control problem



Method #2: Device-driven (bottom-up) coordination



Leverage asynchronous device-to-cloud comms to have devices request temporary access to energy

Controller accepts or denies packet request, so can estimate total demand (enables feedback).

Request can embed local grid measurements to adapt scope of control to non-wire alternatives.



Inspired by the Internet: coordination of DERs

*Packetization of data
on Internet*



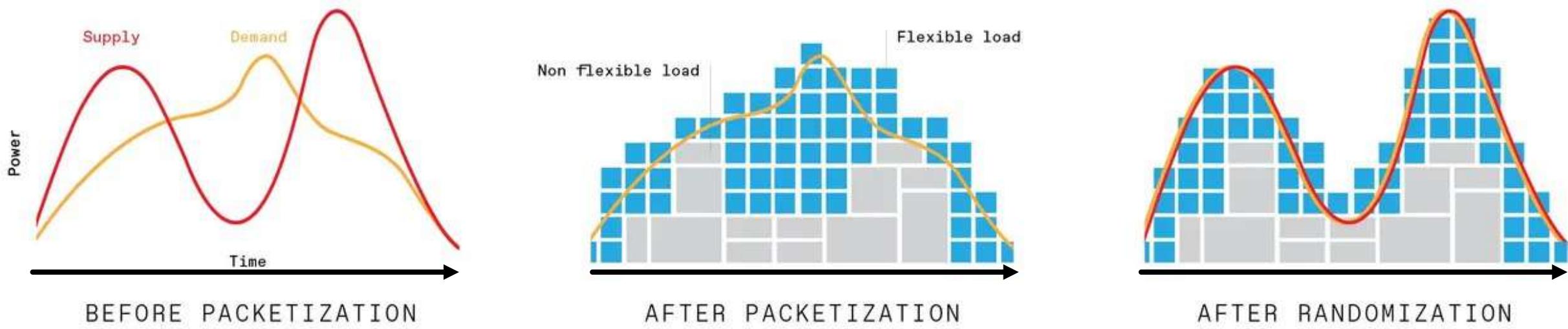
*Random access
protocols*

Method is called packetized energy management (PEM)



PEM for a fleet: coordination & flexibility

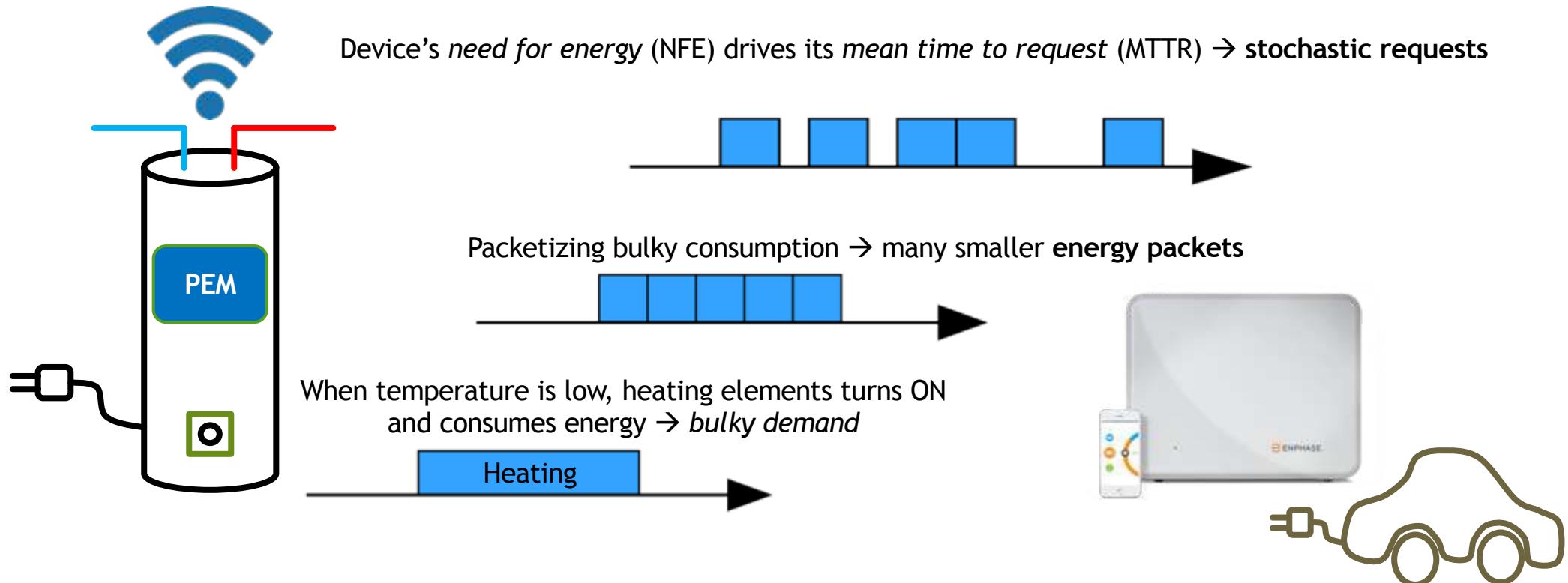
- Inspired by how the Internet works: PEM is a scalable concept
 - Bottom-up approach: local intelligence enables devices to learn their **need for energy** (comfort)
 - Randomization of requests: device stochastically request a packet based on **need for energy**
 - Packetization of device demand: all devices interact with coordinator the same way (requests)



TLDR: PEM effectively solves a hard scheduling problem *in real-time*

PEM for one load: ensures *quality of service* (QoS)

Energy packet = constant power consumed over fixed epoch = 



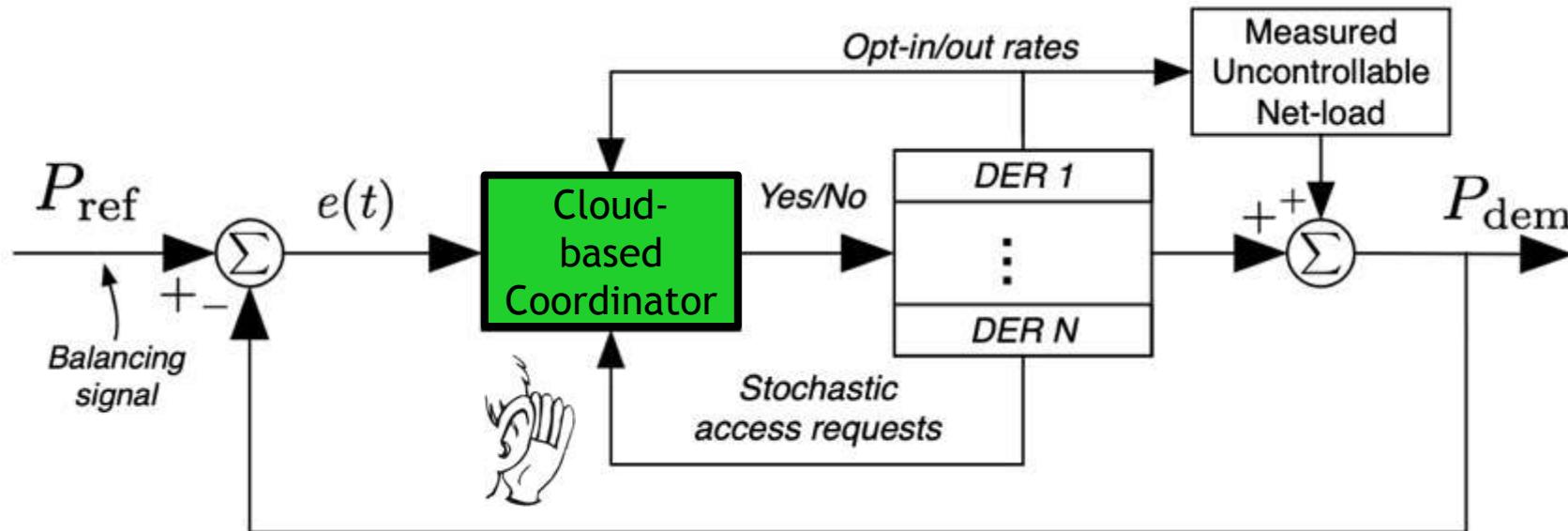
M. Almassalkhi, et al, "Packetized energy management: asynchronous and anonymous coordination of thermostatically controlled loads," ACC, 2017

M. Almassalkhi, et al, "Asynchronous Coordination of Distributed Energy Resources with Packetized Energy Management," 20th In: Meyn S., Samad T., Hiskens I., Stoustrup J. (eds) *Energy Markets and Responsive Grids*. The IMA Volumes in Mathematics and its Applications,, pp 333-361, vol 162. Springer, 2018.

Closing the loop with PEM's packet requests

- Coordinator accepts/denies request based on power reference tracking error, so control mechanism is simple, but powerful

Modulate acceptance rate of packet requests → Regulate aggregate demand

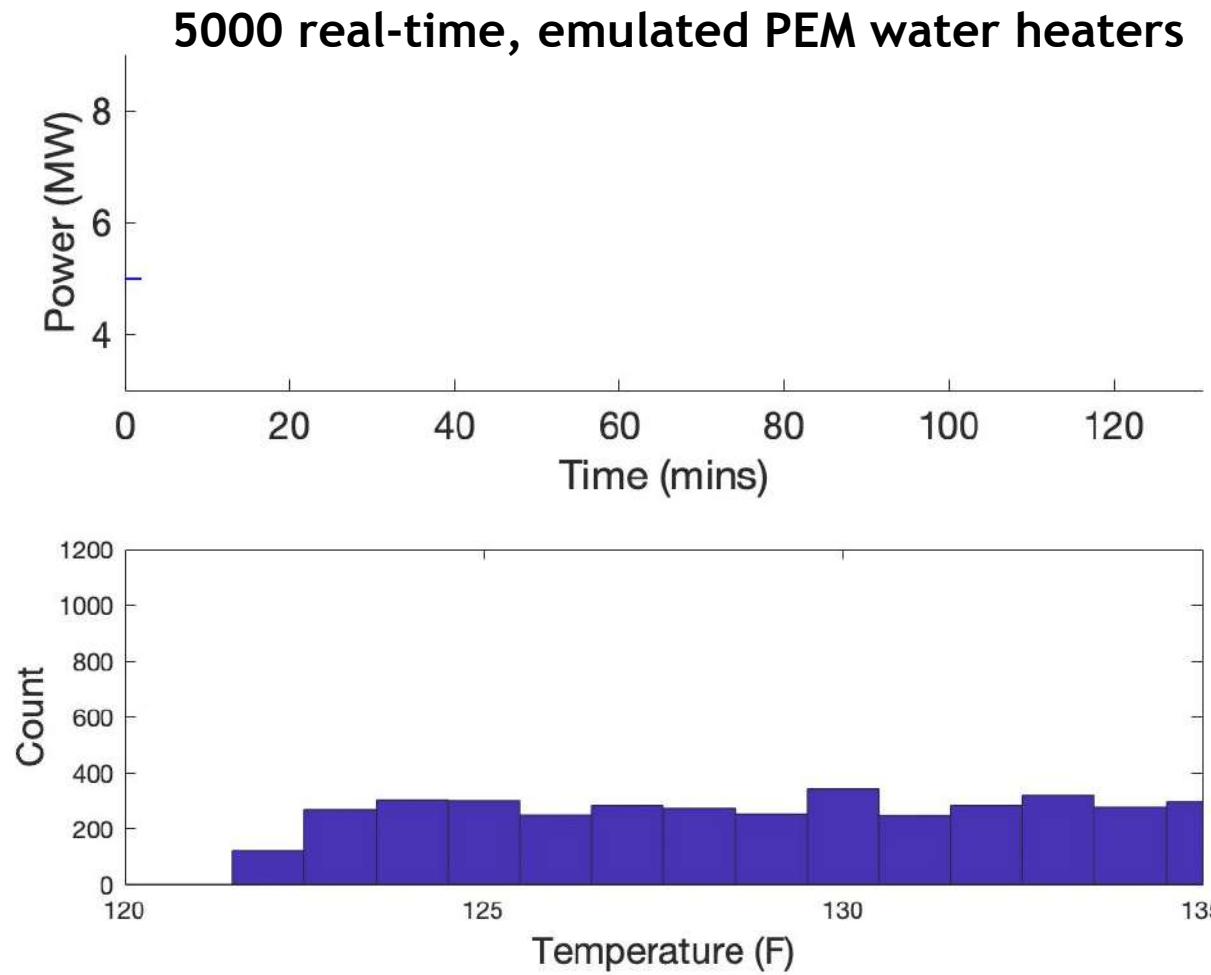
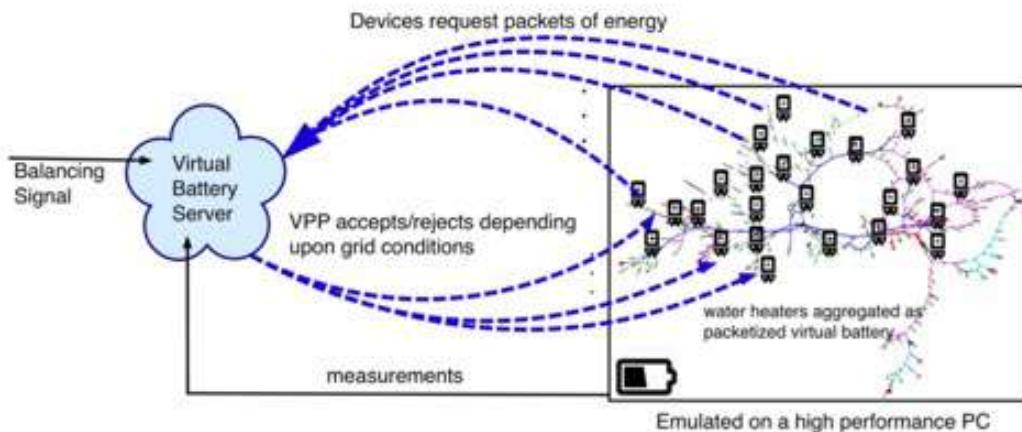


Incoming request rates are based on devices' NFE and leads to light event-based comm overhead!





Built scalable, real-time DER cyber test-bed



M. Amini, et al. "A Model-Predictive Control Method for Coordinating Virtual Power Plants and Packetized Resources, with Hardware-in-the-Loop Validation". In: *IEEE PES General Meeting*. Atlanta, Georgia, 2019

A. Khurram, M. Amini, L. Duffaut Espinosa, P. H. Hines, and M. Almassalkhi, "Real-time Grid and DER Co-simulation Platform for Validating Large-scale DER Control Schemes," *IEEE Transactions on Smart Grid*, 2022





arpa-e

Completed field trial with > 150 loads in 2019

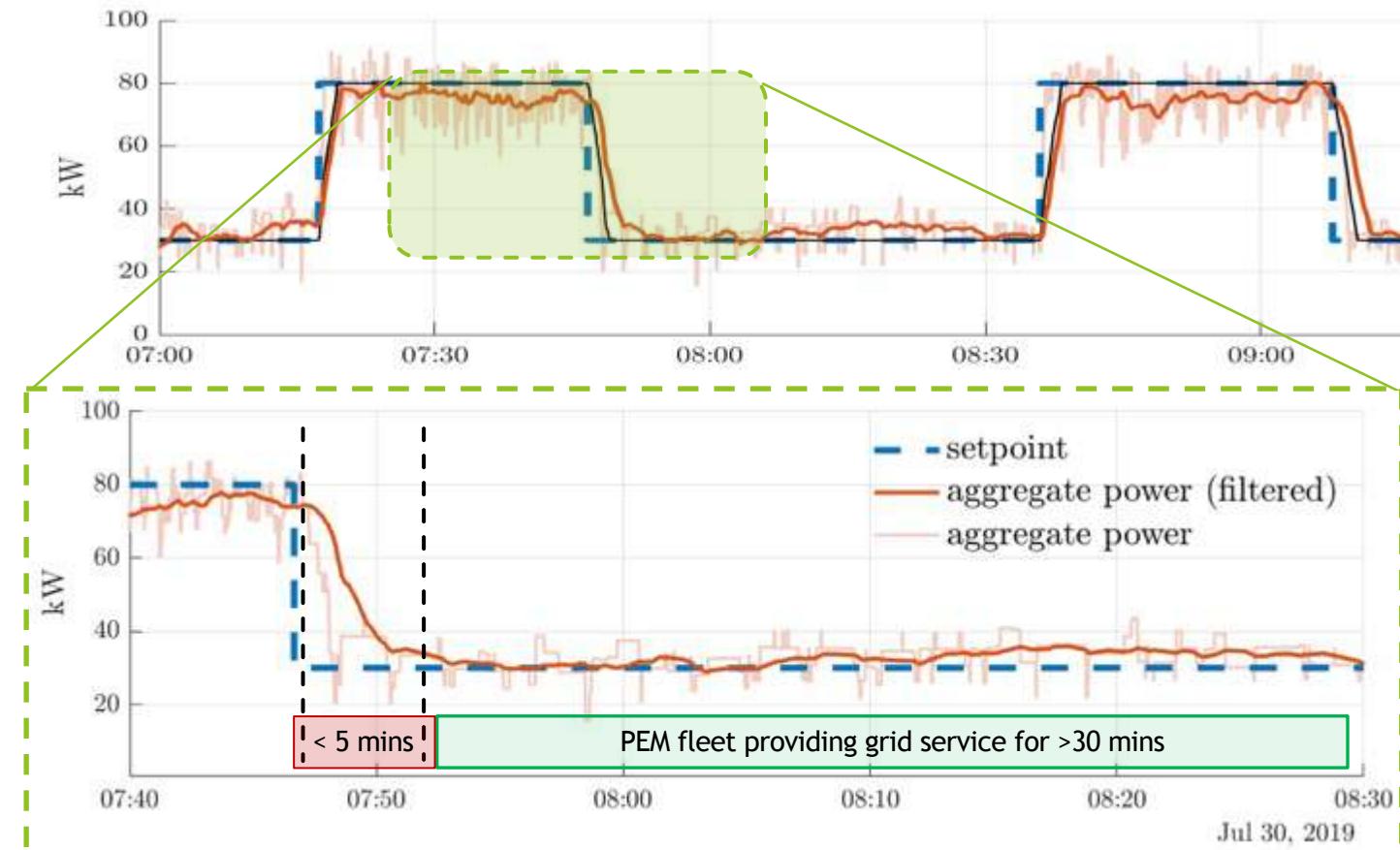


The
UNIVERSITY
of VERMONT



vermont electric power company
VELCO

PACKETIZED
ENERGY

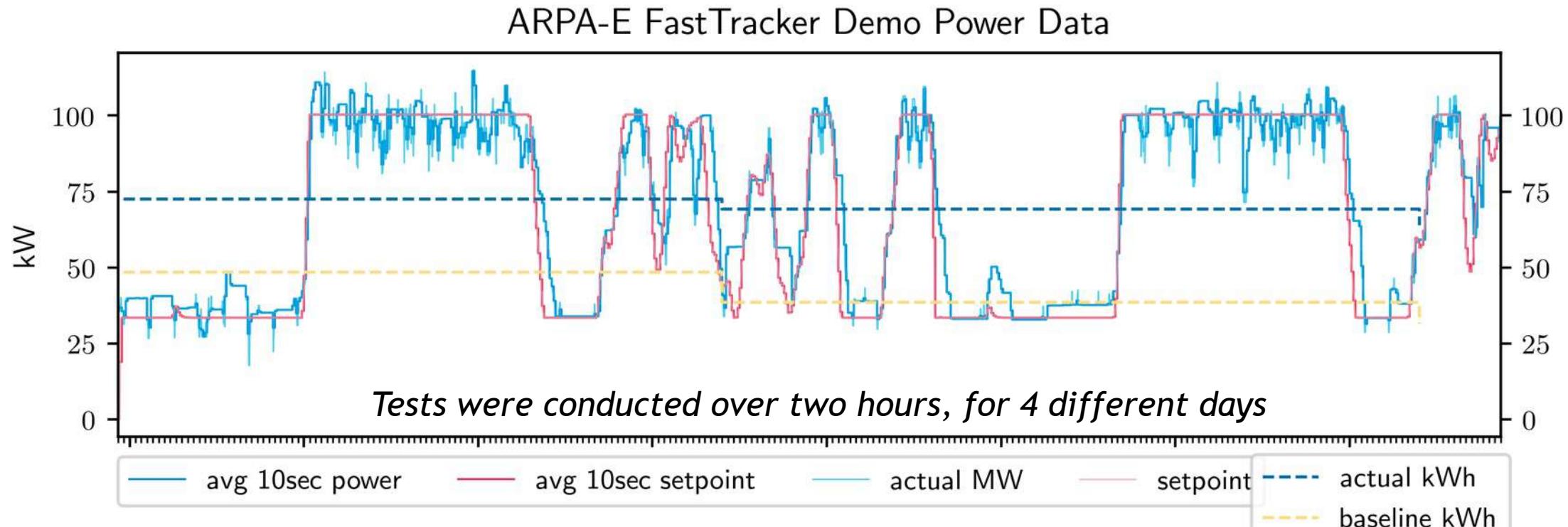


Actively studying the dynamics of the “Aggregation” based on communication & controls



Faster: demo w/ 200+ homes in December 2021

PEM demonstrates frequency regulation!



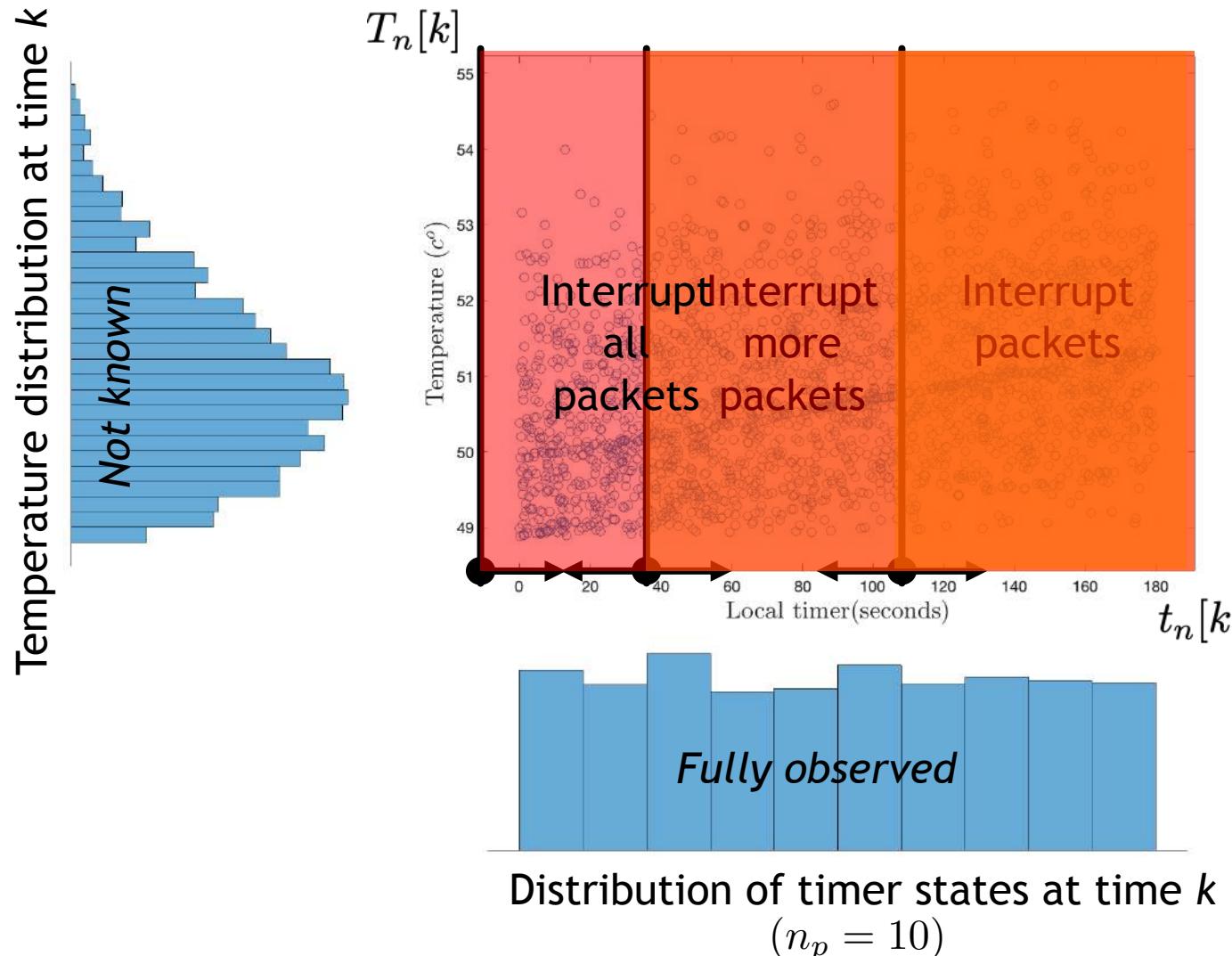
Pay-for-performance:
PJM Performance score

accuracy	delay	precision	composite
0.9509	0.9948	0.8281	0.9246

Better than PJM's avg system performance (80-90%) and outperforms all assets but MW-scale energy storage

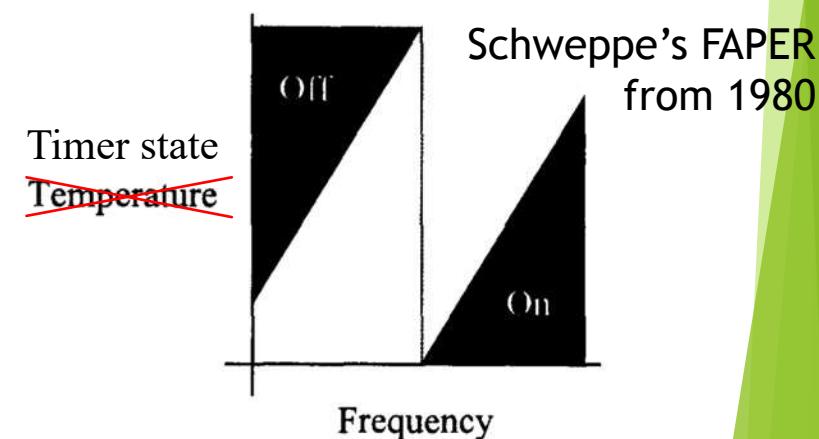


Even faster: damping with decentralized PEM



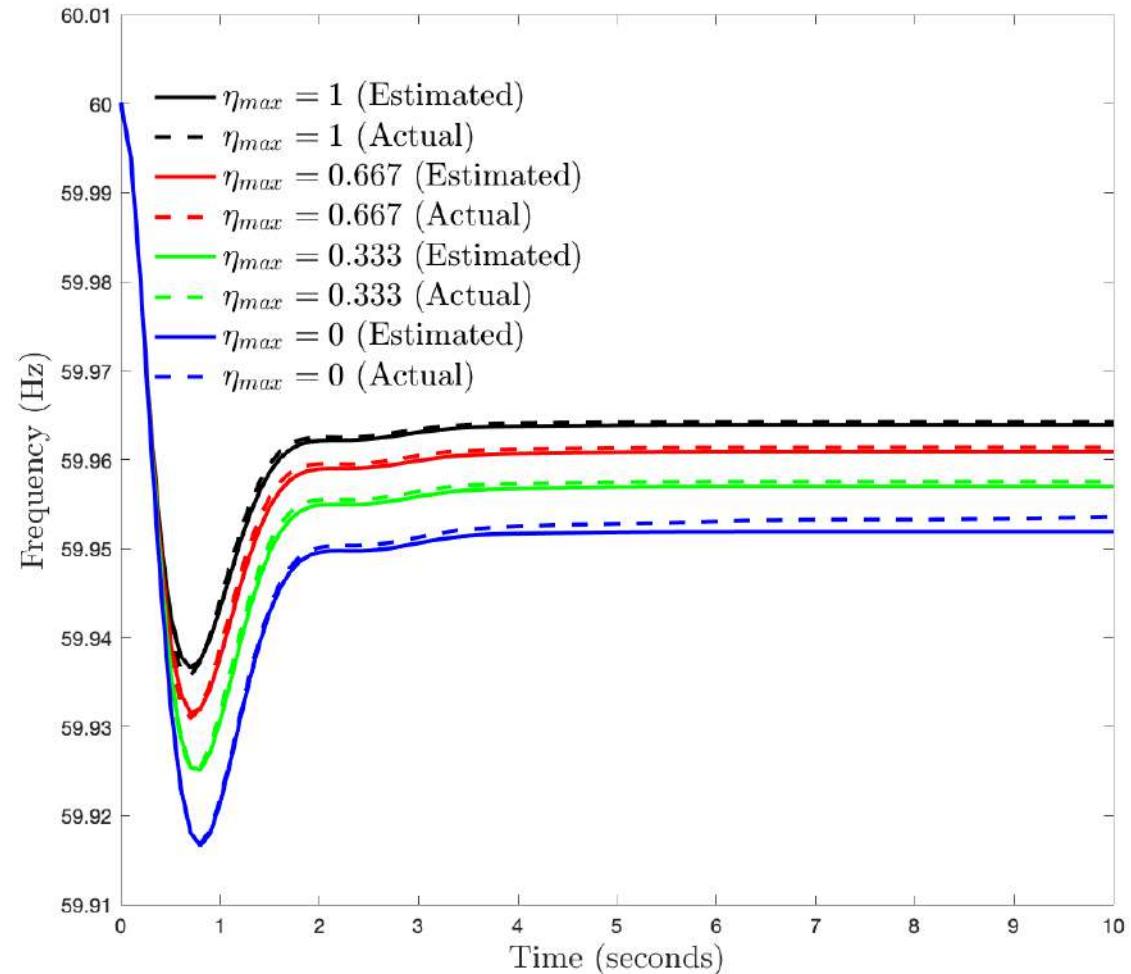
In PEM, TCLs consuming a packet are defined by their temperature states (not directly observable) and timer state (known)

Adapt PEM to leverage local measurements with a local control policy to inform a TCL when to interrupt its packet



Frequency-responsive PEM (fully decentralized)

- ▶ We adapt PEM scheme for fast frequency response.
- ▶ Design local control law around packet interruption threshold mechanism that begets responsiveness to frequency.
- ▶ Importantly, we show how DER coordinator can estimate the equivalent damping *online* from previously accepted packets
- ▶ Working to quantify tradeoff between synthetic damping and frequency regulation services.



Back to EV charging: exploring NFE



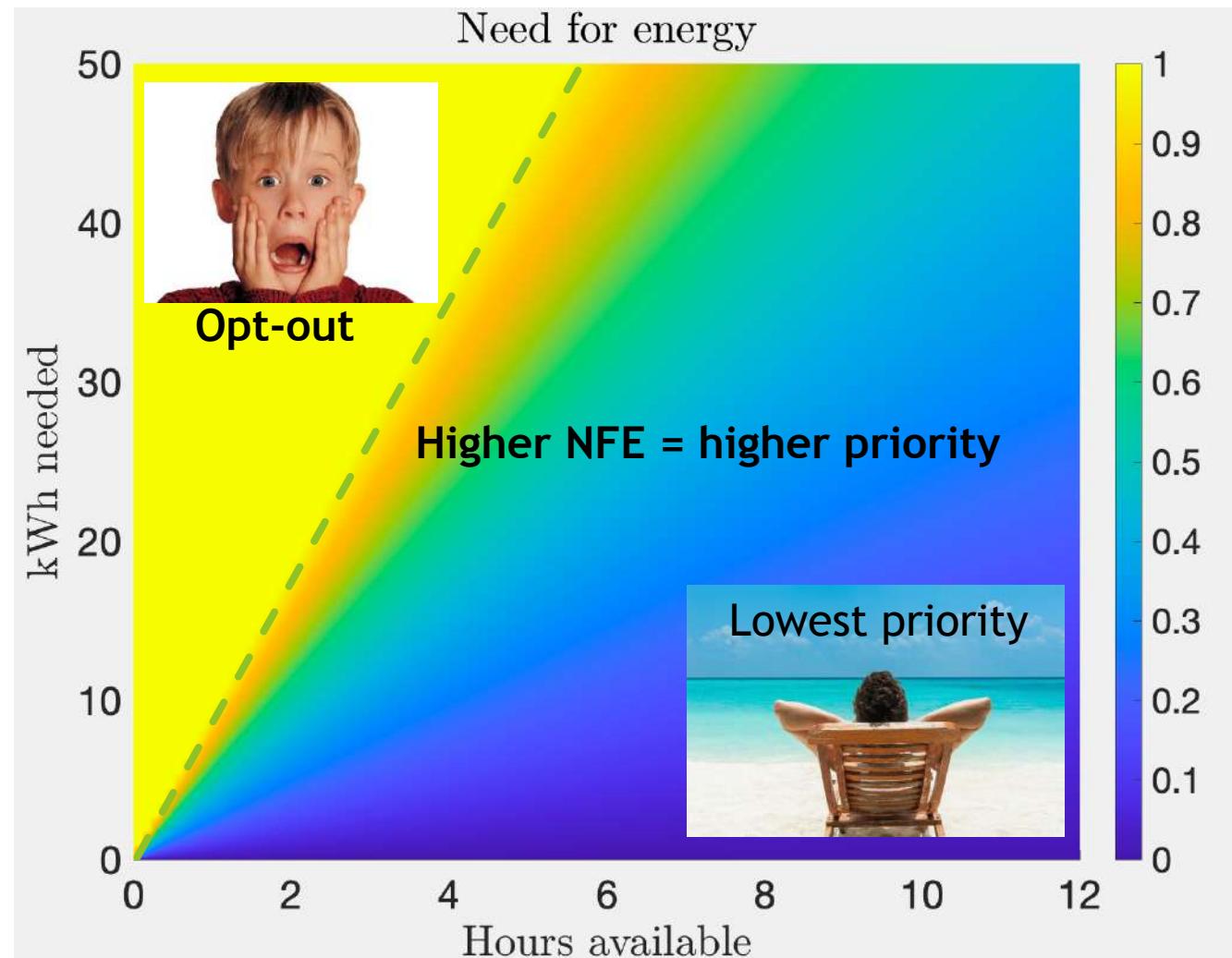
$$\text{NFE}_n[k] = \frac{\text{kWh needed}}{\eta_n p_n^{\max}(\text{hours left})}$$

NFE dynamically prioritizes EVs

if $\text{NFE} \geq 1 \rightarrow$ Not enough time left to charge
 \rightarrow EV n opts out (desperate NFE)

if $\text{NFE} \sim 0 \rightarrow$ No need to charge (low NFE)

Larger NFE \rightarrow lower mean time-to-request (MTTR)
 \rightarrow higher request probability



Look-ahead PEM: need for energy (NFE)

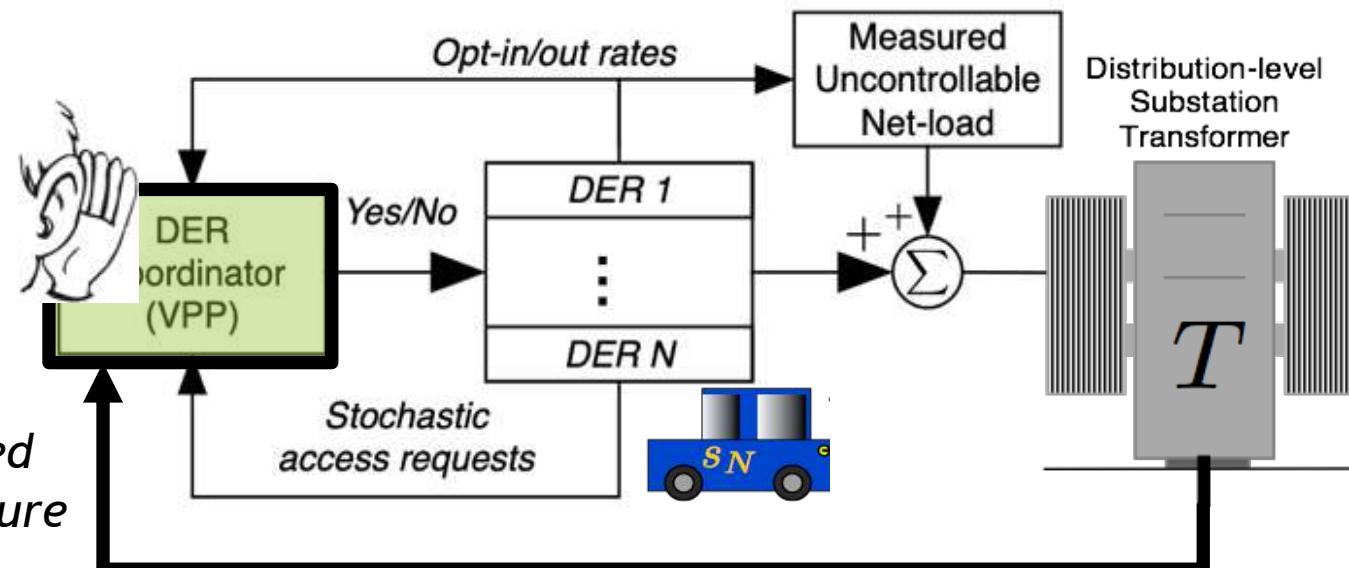
Coordinator optimally accepts packet requests while keeping transformer from overloading

PEM COORDINATOR

Look-ahead acceptance of incoming requests over a small packet window via MIP

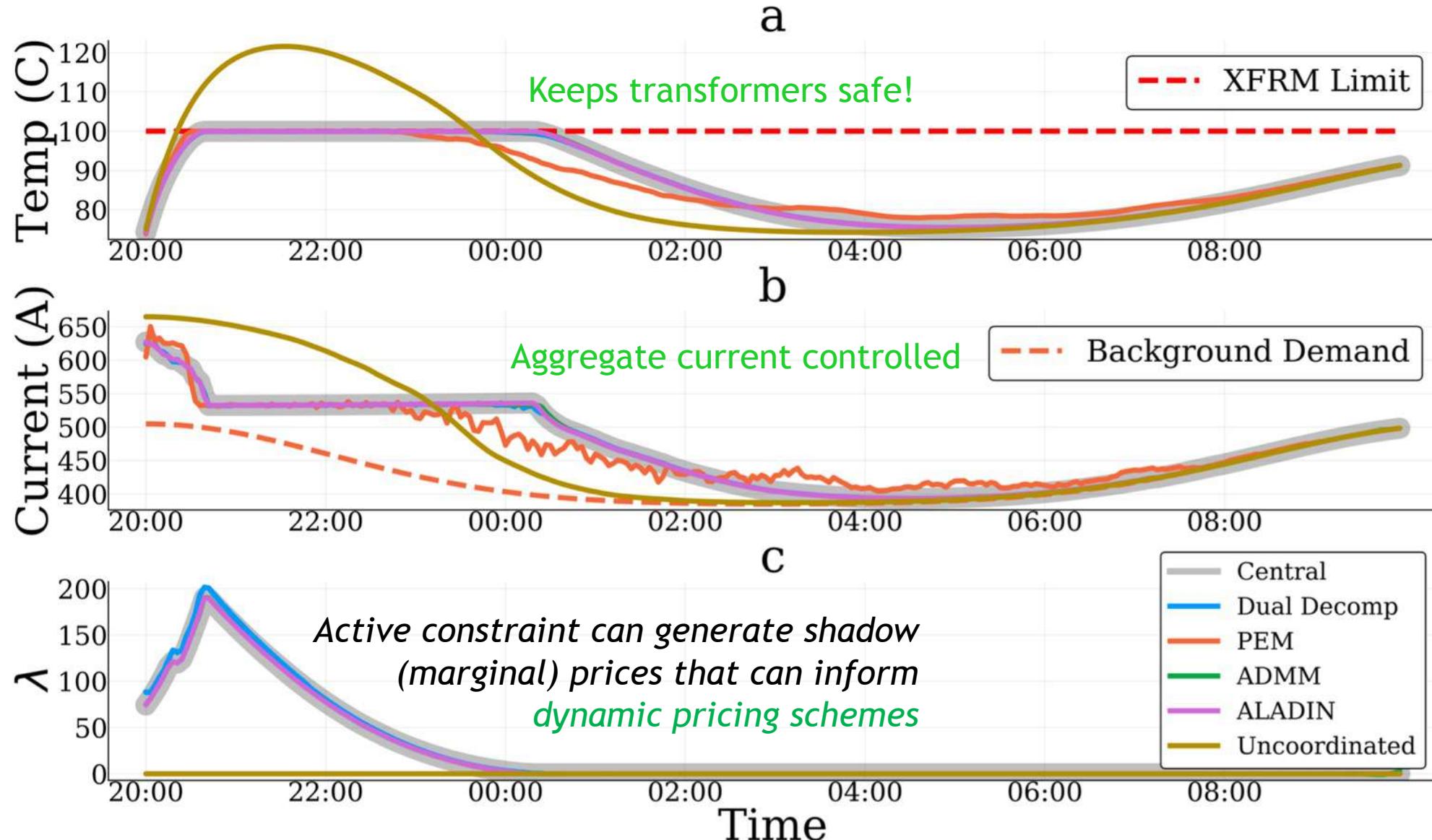
Predictive model of temperature dynamics

Measured temperature



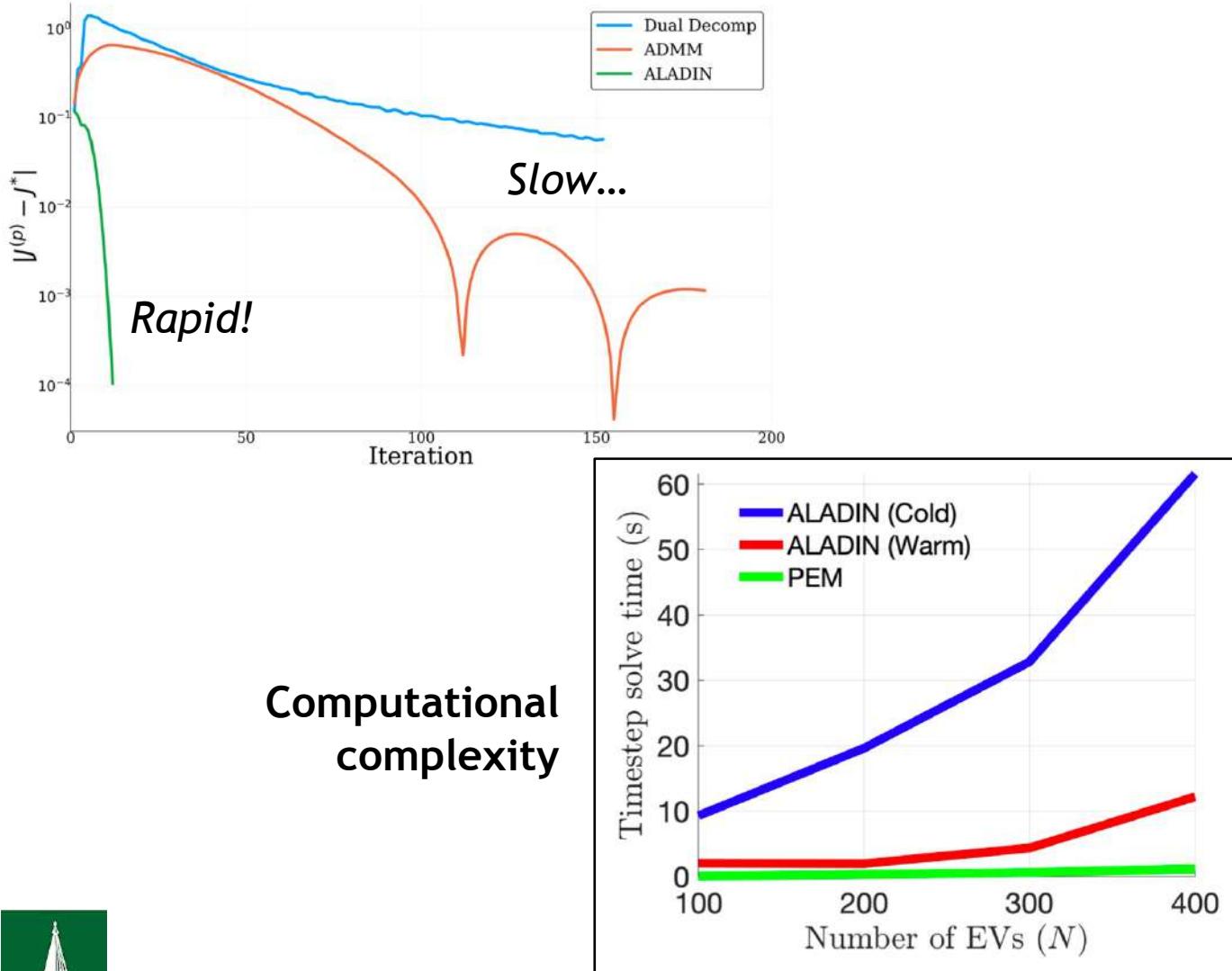
Key: the number of incoming requests is $\ll N$

Comparing indirect control methods for EV charging



Comparing different methods for EV charging: P^3

Rates of convergence of price signals depend on info shared



Privacy

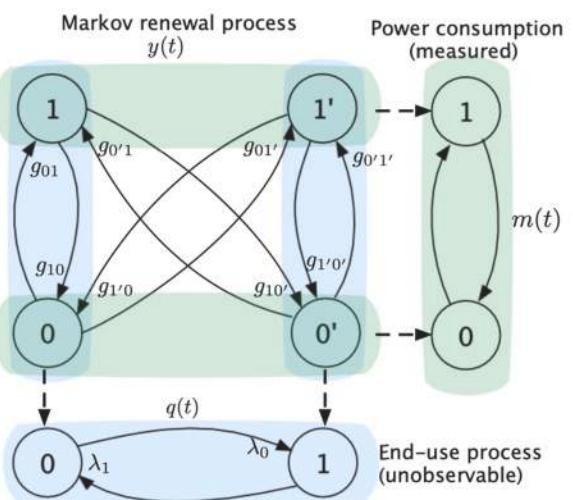
Processing

Algorithms have different (data) privacy, processing, and performance guarantees, and assumptions

- Central
- ALADIN
- ADMM
- Dual Decomp
- PEM

Ongoing research directions with PEM @ scale

1
Estimate background end-use



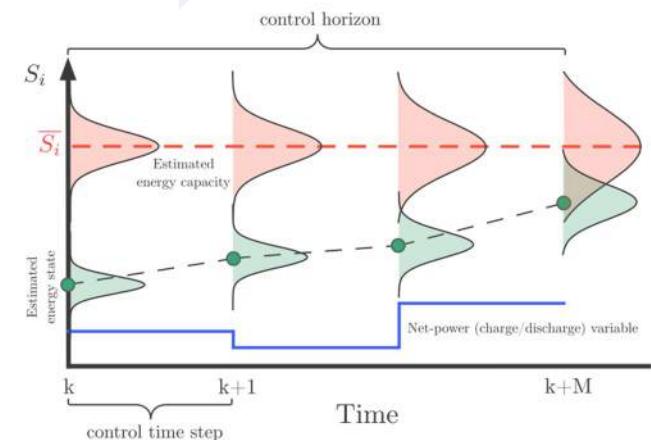
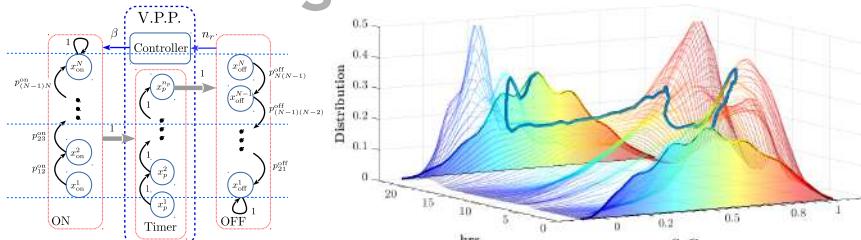
Stochastic end-use



3
Optimal dispatch

Uncertain resource

2
Modeling and control



(1) A. Khurram, Luis Duffaut Espinosa, Roland Malhamé, Mads Almassalkhi, "Identification of Hot Water End-use Process of EWHs from Energy Measurements," EPSCR, 2020

(2a) L. Duffaut and M. Almassalkhi, "A packetized energy management macromodel with QoS guarantees for demand-side resources," IEEE Trans. on Power Systems, 2020

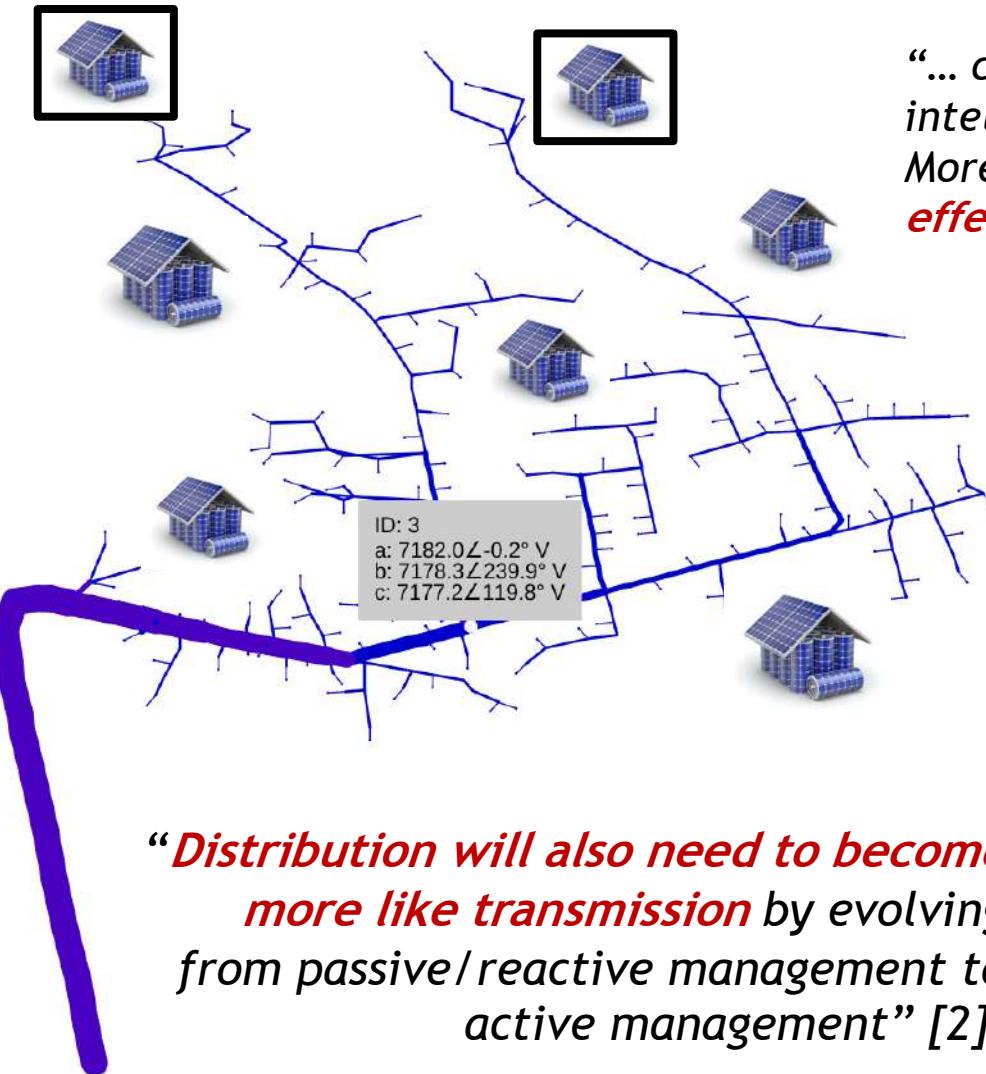
(2b) L. Duffaut, A. Khurram, and M. Almassalkhi "Reference-Tracking Control Policies for Packetized Coordination of Diverse DER Populations," IEEE Trans. on Control Systems Tech., 2021

(2c) L. Duffaut Espinosa, A. Khurram, and M. Almassalkhi, "A Virtual Battery Model for Packetized Energy Management," in IEEE Conference on Decision and Control (CDC), 2020

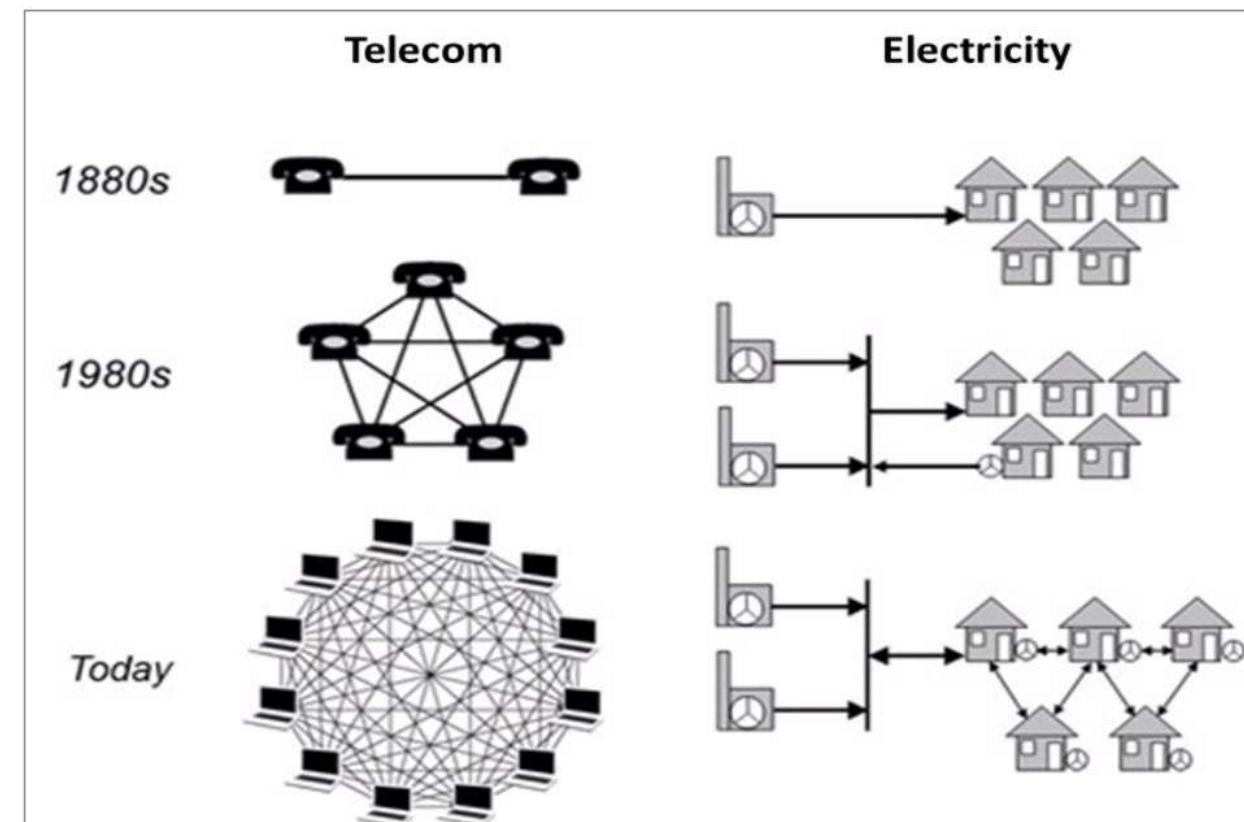
(3a) M. Amini and M. Almassalkhi, "Corrective optimal dispatch of uncertain virtual energy resources," IEEE Transactions on Smart Grid, 2020

(3b) N. Qi, P. Pinson, et al, "Chance Constrained Economic Dispatch of Generic Energy Storage under Decision-Dependent Uncertainty," (under review)

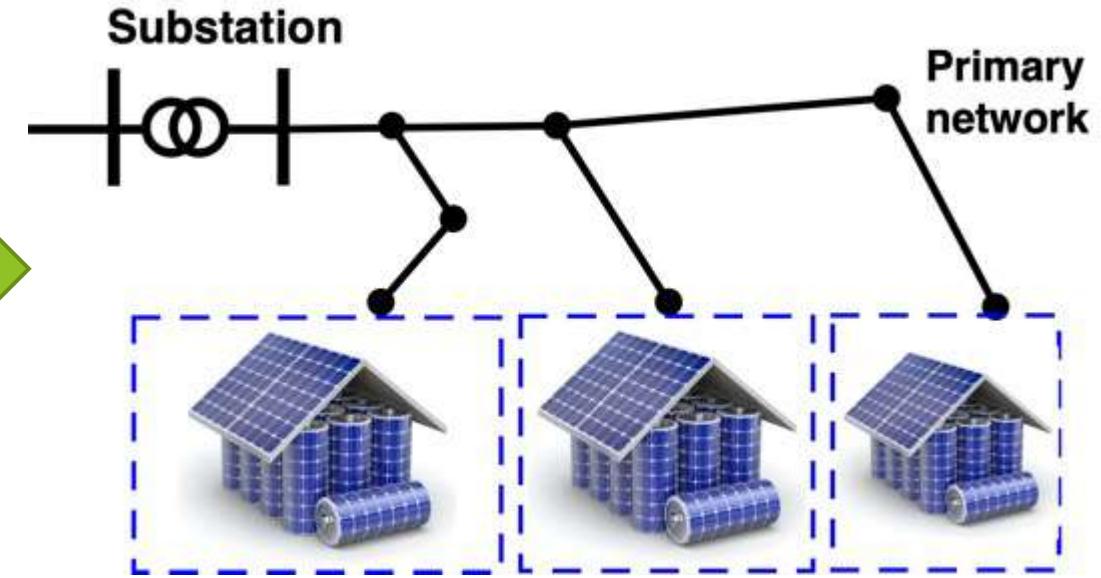
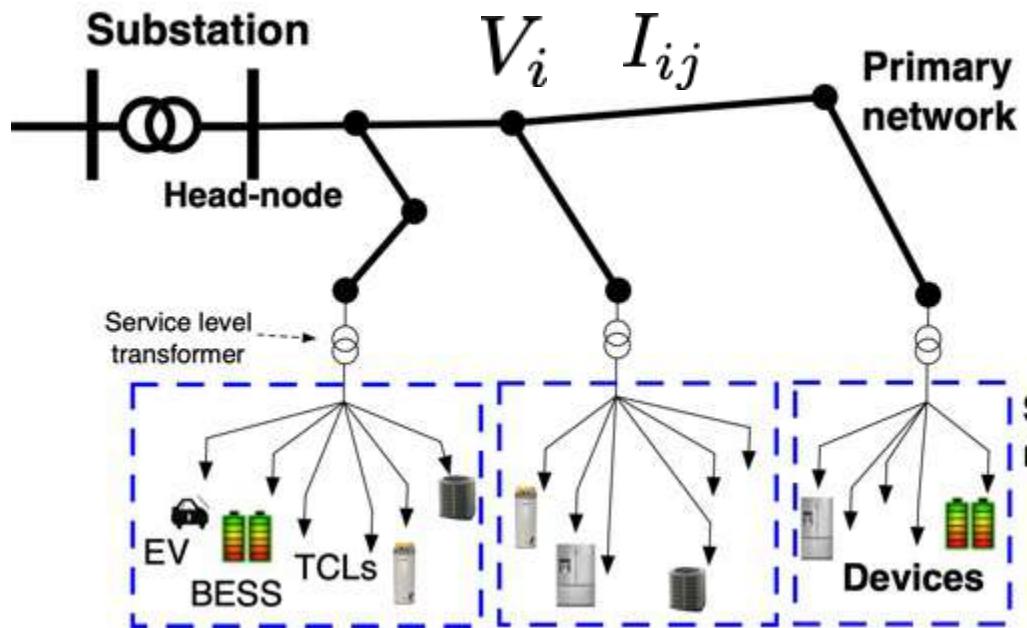
What active role should the grid operator play?



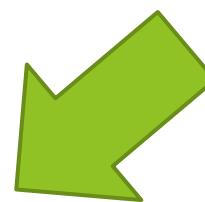
“... create open networks that increase value through the interaction of intelligent devices on the grid and prosumerization of customers Moreover, even **greater value can be realized through the synergistic effects of convergence of multiple networks**” [1].



Motivating example: characterize aggregate resource



**Bid flexibility
into whole-sale
ISO market (MW)**



$$\Delta p := \left[\sum_{i=1}^n m_i, \sum_{i=1}^n M_i \right]$$



Motivating example: disaggregation of control signals

Can we solve disaggregation in real-time?

- Solve grid optimization problem repeatedly
 - + Guarantees grid reliability!
 - Can DisAgg problem be solved fast [W, X, Y, Z]?
 - Can we provide admissibility guarantees?

Requested
flexibility from
ISO (MW)

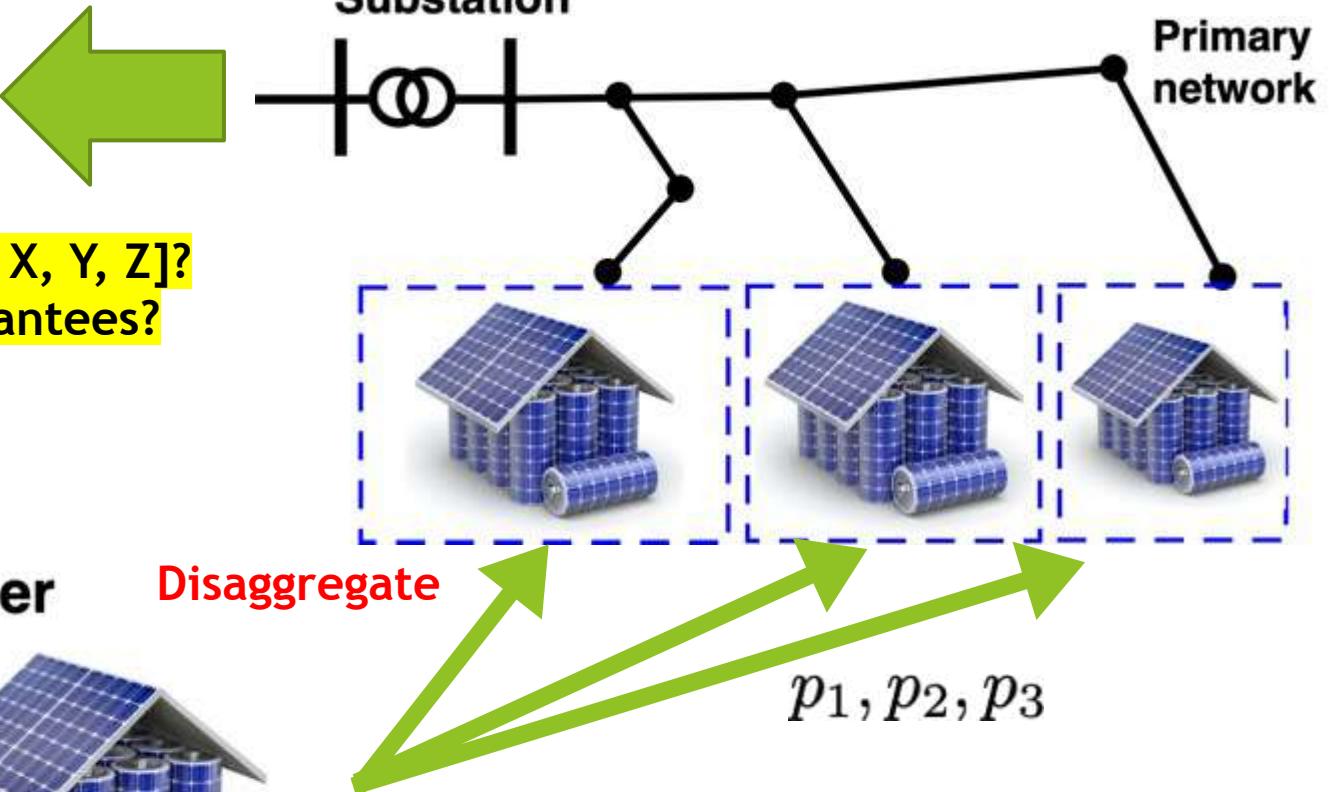


Feeder



Disaggregate

p_1, p_2, p_3



[W] Almassalkhi, et al, "Hierarchical, Grid-Aware, and Economically Optimal Coordination of Distributed Energy Resources in Realistic Distribution Systems," Energies, 2020.

[X] Nawaf Nazir, Pavan Racherla, and Mads Almassalkhi, "Optimal multi-period dispatch of distributed energy resources in unbalanced distribution feeders", IEEE Trans. on Power Systems, 2020

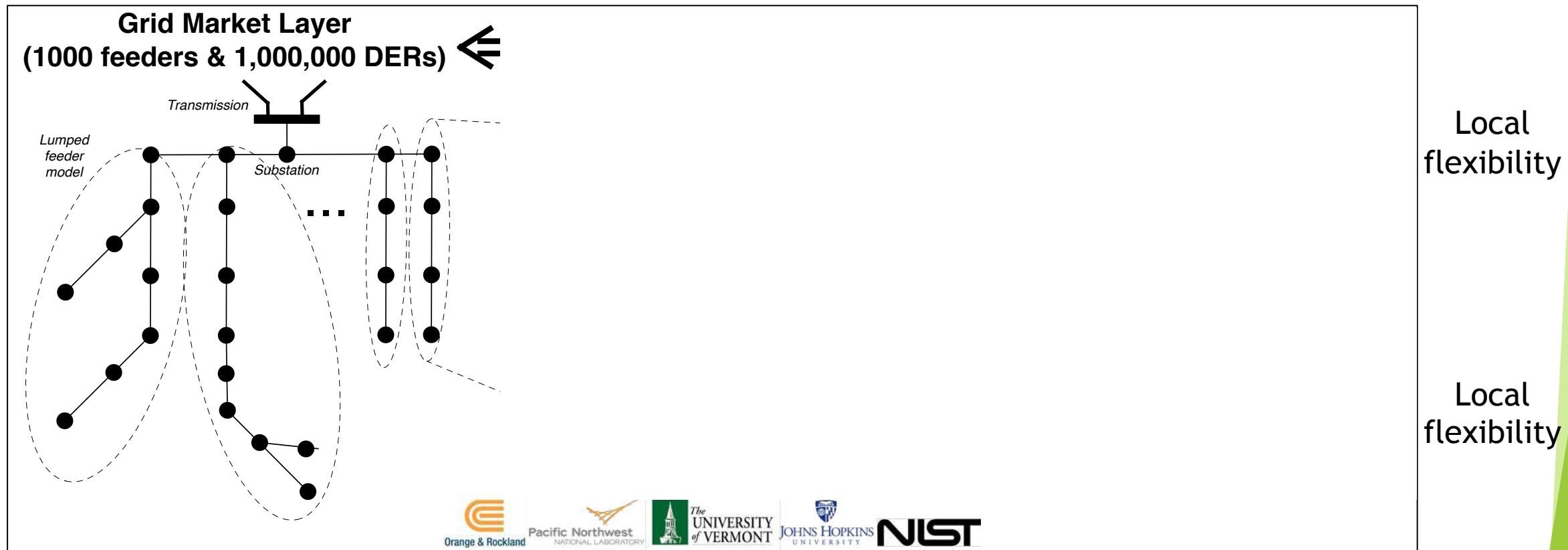
[Y] Nawaf Nazir and M. Almassalkhi, "Voltage positioning using co-optimization of controllable grid assets," IEEE Trans. on Power Systems, 2020.

[Z] S. Brahma, Nawaf Nazir, et al, "Optimal and resilient coordination of virtual batteries in distribution feeders," IEEE Trans. on Power Systems, 2020



Past experience with "utility-centric" approaches

Utility-centric = utility does it all: network ops, DER coordination/dispatch, markets



[W] Almassalkhi, et al, "Hierarchical, Grid-Aware, and Economically Optimal Coordination of Distributed Energy Resources in Realistic Distribution Systems," Energies, 2020.

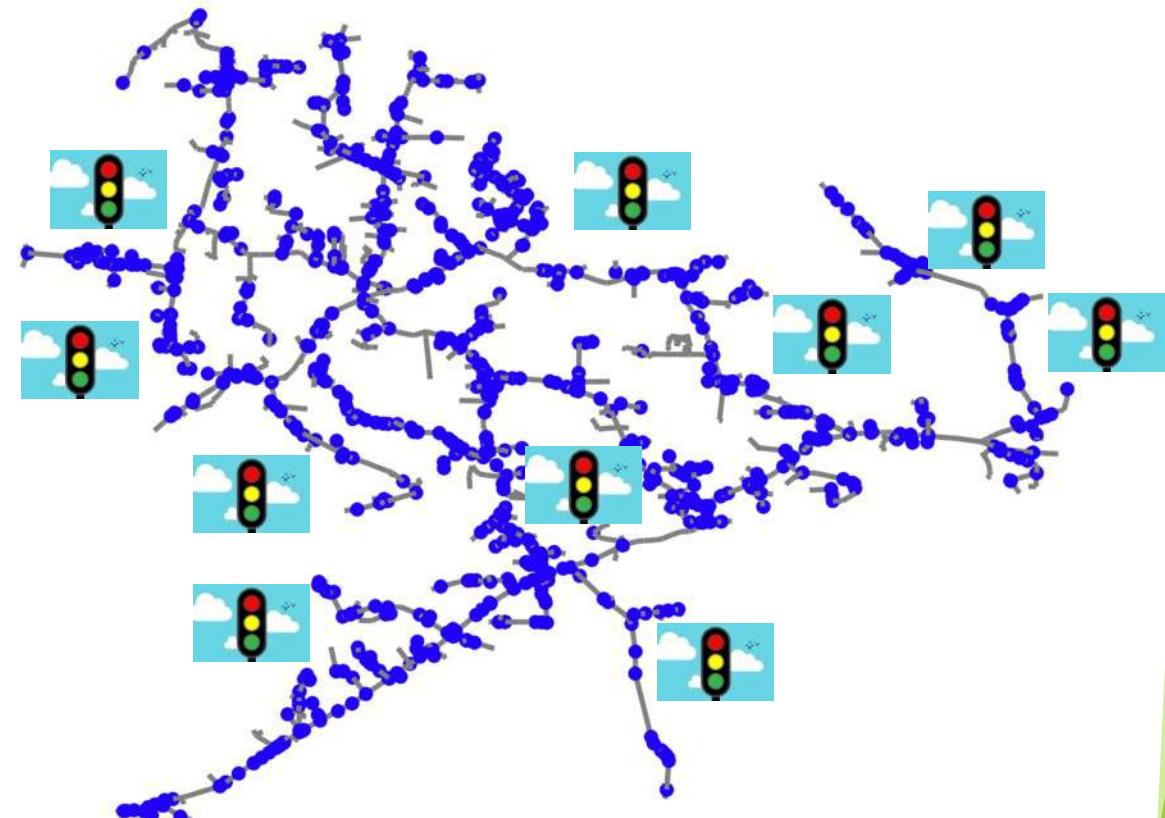
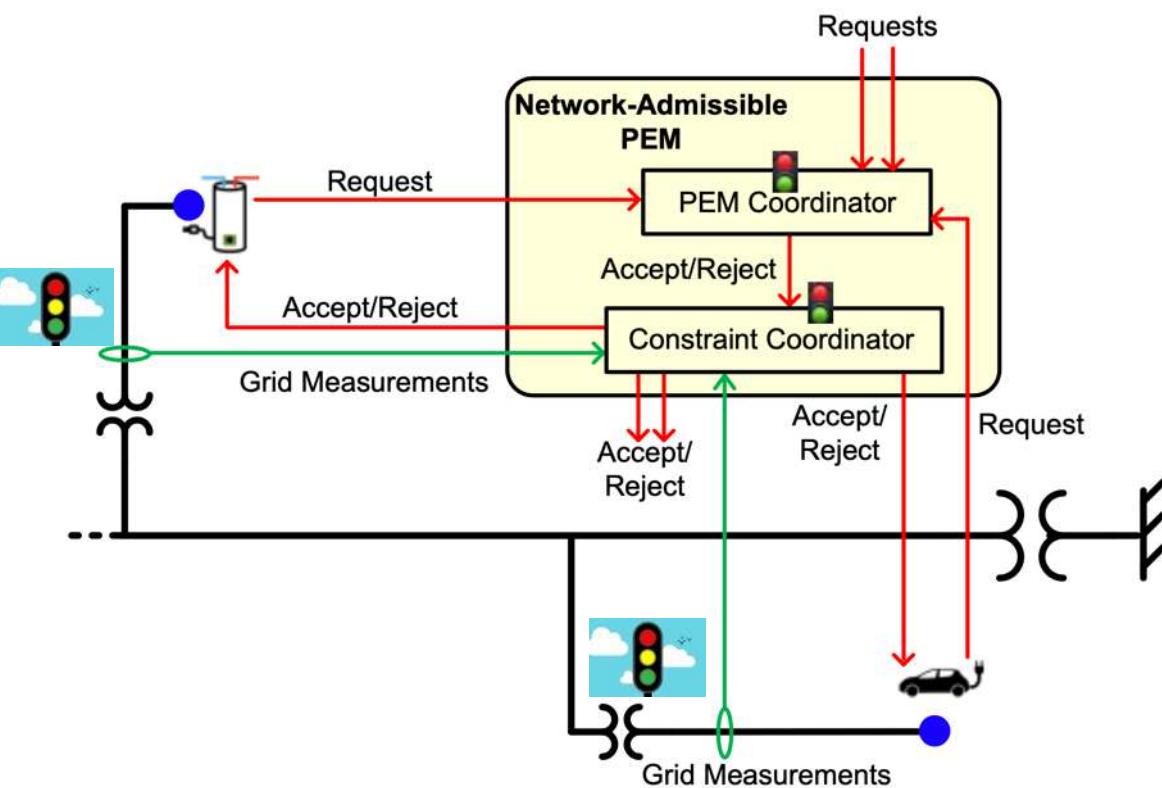
[X] Nawaf Nazir, Pavan Racherla, and Mads Almassalkhi, "Optimal multi-period dispatch of distributed energy resources in unbalanced distribution feeders", IEEE Trans. on Power Systems, 2020

[Y] Nawaf Nazir and M. Almassalkhi, "Voltage positioning using co-optimization of controllable grid assets," IEEE Trans. on Power Systems, 2020.

[Z] S. Brahma, Nawaf Nazir, et al, "Optimal and resilient coordination of virtual batteries in distribution feeders," IEEE Trans. on Power Systems, 2020

Past experience with network-aware PEM

Grid-aware PEM augments packet request mechanism with live grid conditions + traffic-light device logic



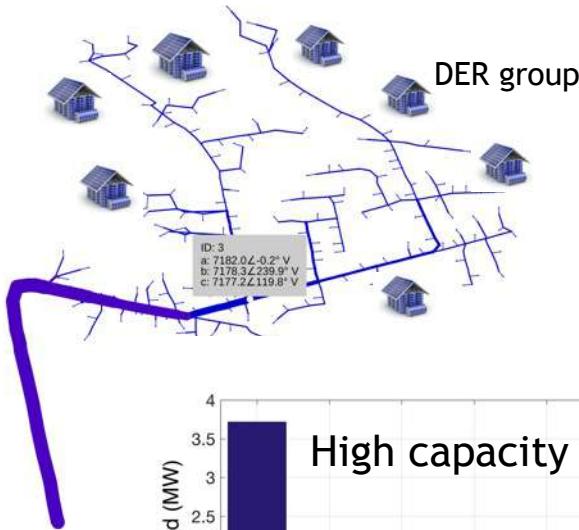
Open questions: measurement types, locations, update rates, data integrity, etc...



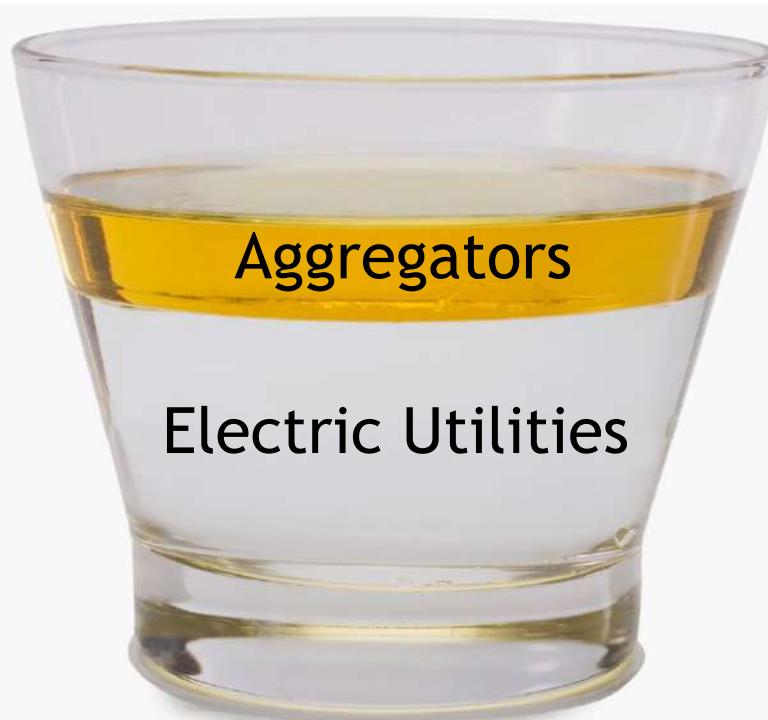
Fundamental asymmetries in information & control

Utility (grid information+data)

- Need to ensure grid reliability
- Need to protect grid data
- **Lack access to devices**
- **Knows grid capacity**



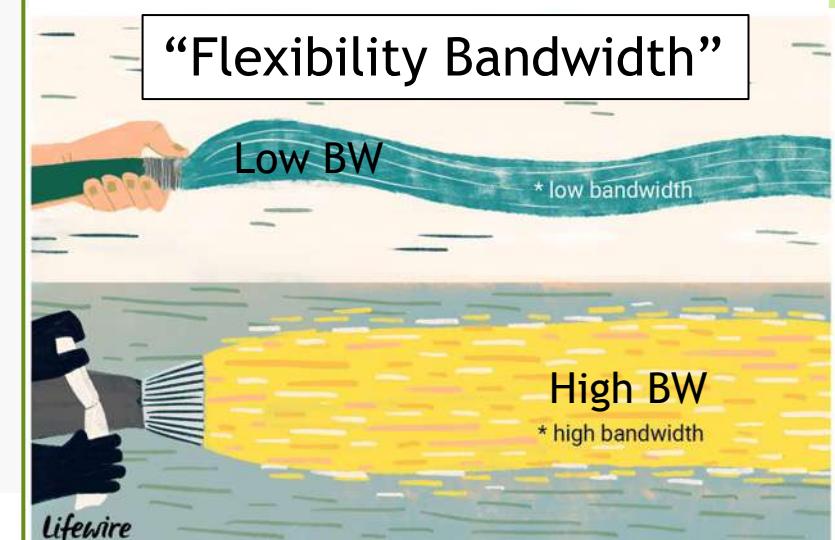
Prices to devices?



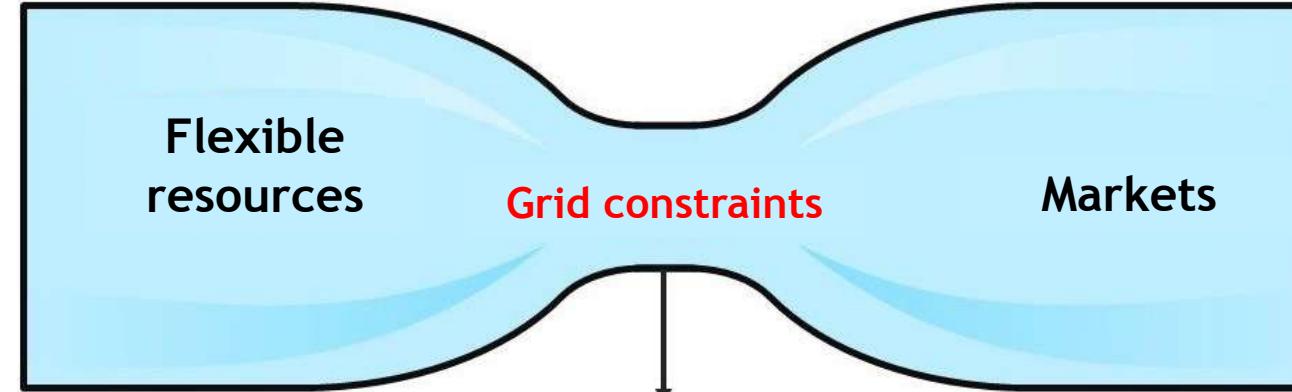
Let's try something different!

Aggregators (device access, markets)

- Need to ensure device QoS
- Need to provide market services
- **Lacks access to grid data**
- **Knows device flexibility**



Rethink Utility/aggregator cooperation: *think like ISP*

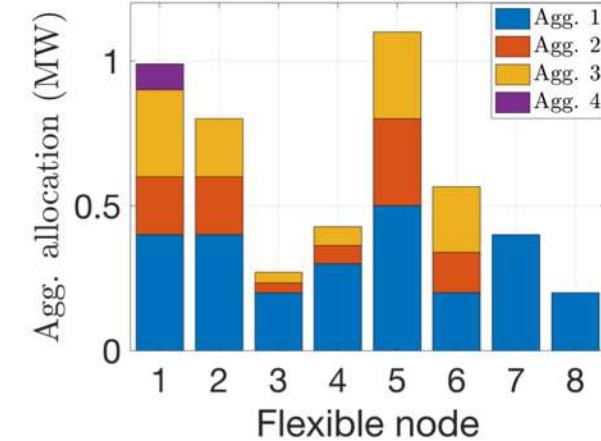


Aggregators:
flexibility from
coordinated devices

Utility: Find hosting capacity (HC) for each node

Aggregator is
allocated portion of
available HC at node i

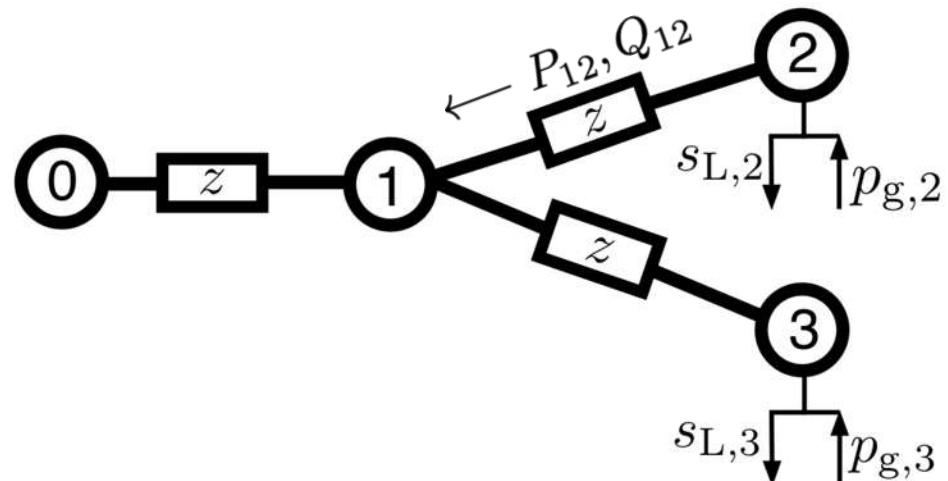
Aggregator bids for
priority access to HC



Finding set of admissible (active) injections

- ▶ Simple 3-node balanced distribution feeder with 2 controllable nodes modeled with *DistFlow*:

$$v_i := |V_i|^2 \text{ and } l_{ij} := |I_{ij}|^2$$



$$v_j = v_i + 2r_{ij}P_{ij} + 2x_{ij}Q_{ij} - |z_{ij}|^2l_{ij}$$

$$P_{ij} = p_j + \sum_{h:h \rightarrow j} (P_{jh} - r_{jh}l_{jh})$$

$$Q_{ij} = q_j + \sum_{h:h \rightarrow j} (Q_{jh} - x_{jh}l_{jh})$$

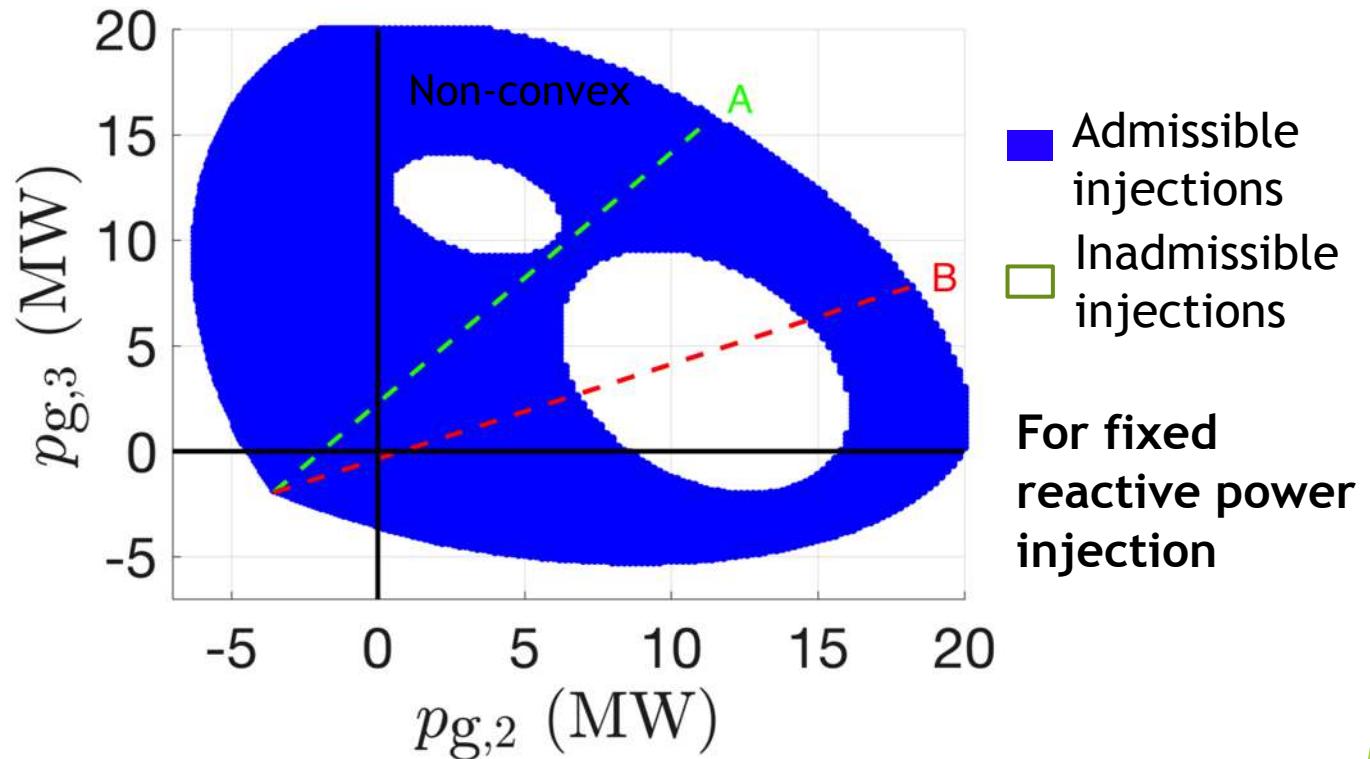
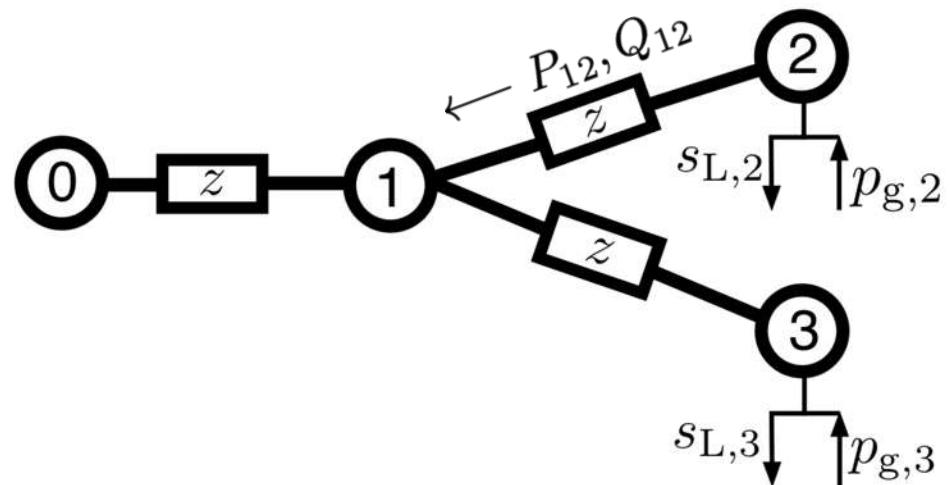
$$l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j}, \quad \text{The only nonlinear relation}$$

Network limits: $v_i \in [\underline{v}_i, \bar{v}_i]$, $l_{ij} \in [\underline{l}_{ij}, l_{ij}]$



Finding set of admissible (active) injections

- ▶ Simple 3-node balanced distribution feeder with 2 controllable nodes

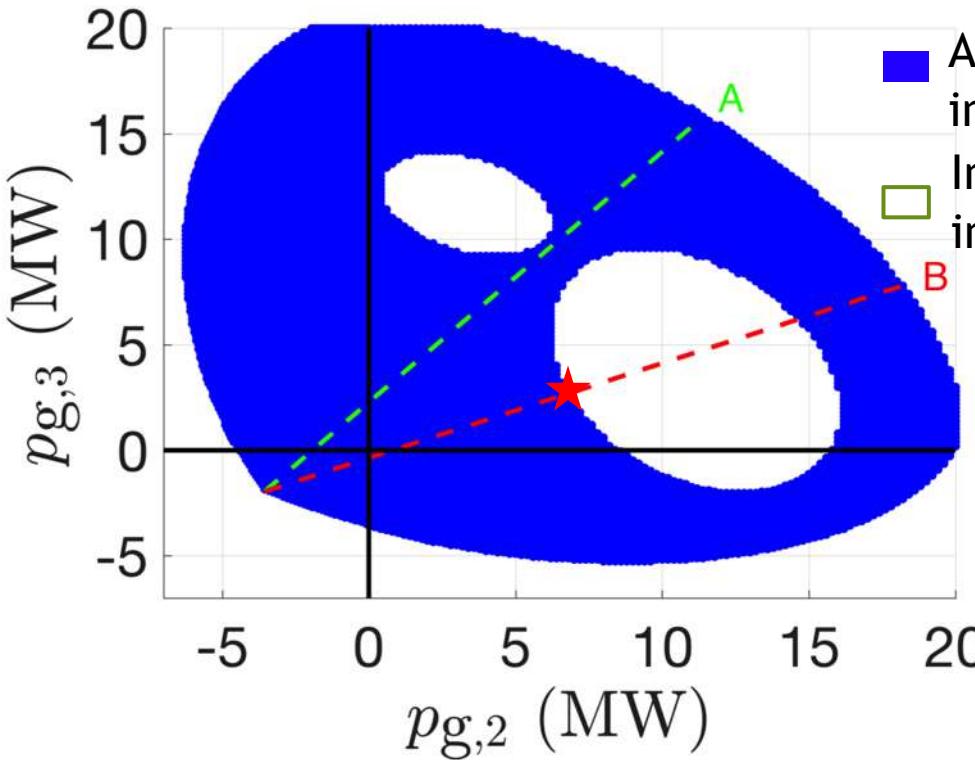


Network limits: $v_i \in [\underline{v}_i, \bar{v}_i]$, $l_{ij} \in [\underline{l}_{ij}, \bar{l}_{ij}]$

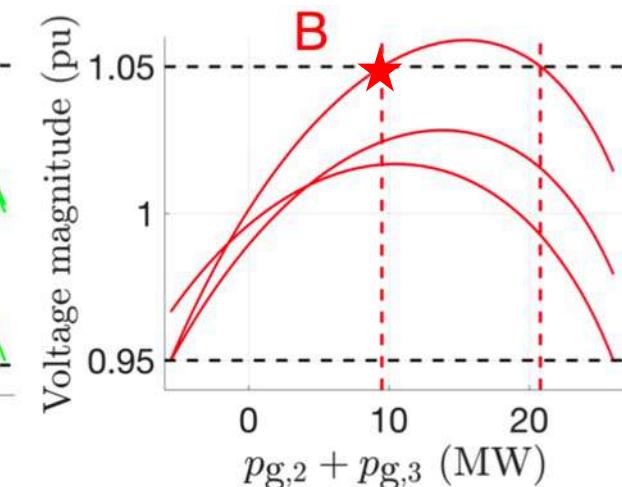
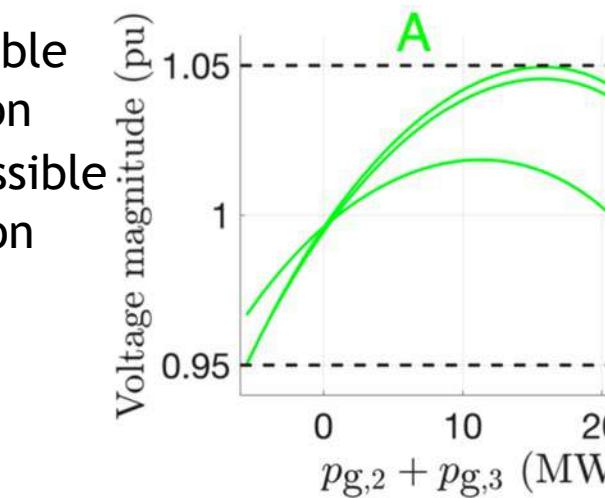


Finding set of admissible (active) injections

- ▶ Simple 3-node balanced distribution feeder example:



■ Admissible injection
□ Inadmissible injection



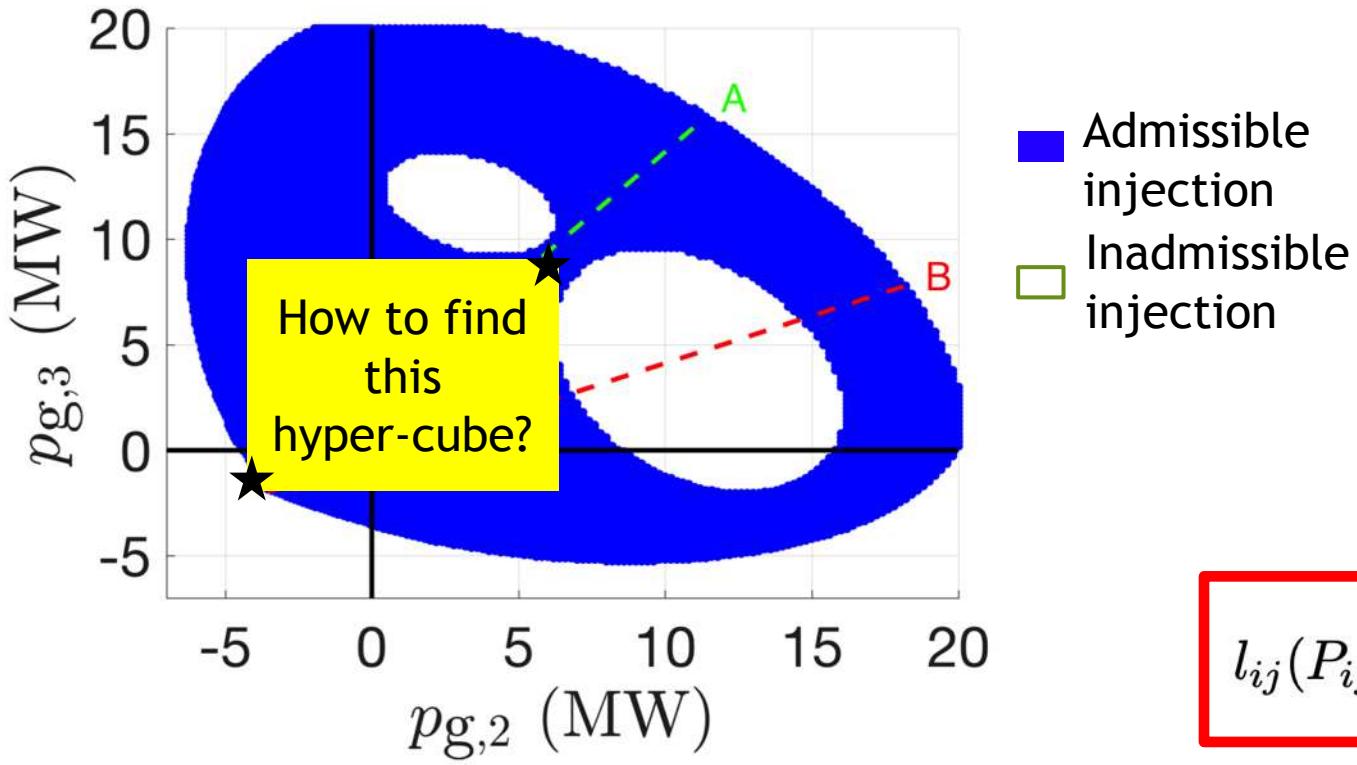
The two controllable active power resources are limited in aggregate by the network - i.e., their individual limits are coupled



Network limits: $v_i \in [v_i, \bar{v}_i]$, $l_{ij} \in [l_{ij}, \bar{l}_{ij}]$

Finding set of admissible (active) injections

► Goal: find largest hyperrectangle to determine p_g limits (decoupled)



$$v_j = v_i + 2r_{ij}P_{ij} + 2x_{ij}Q_{ij} - |z_{ij}|^2 l_{ij}$$

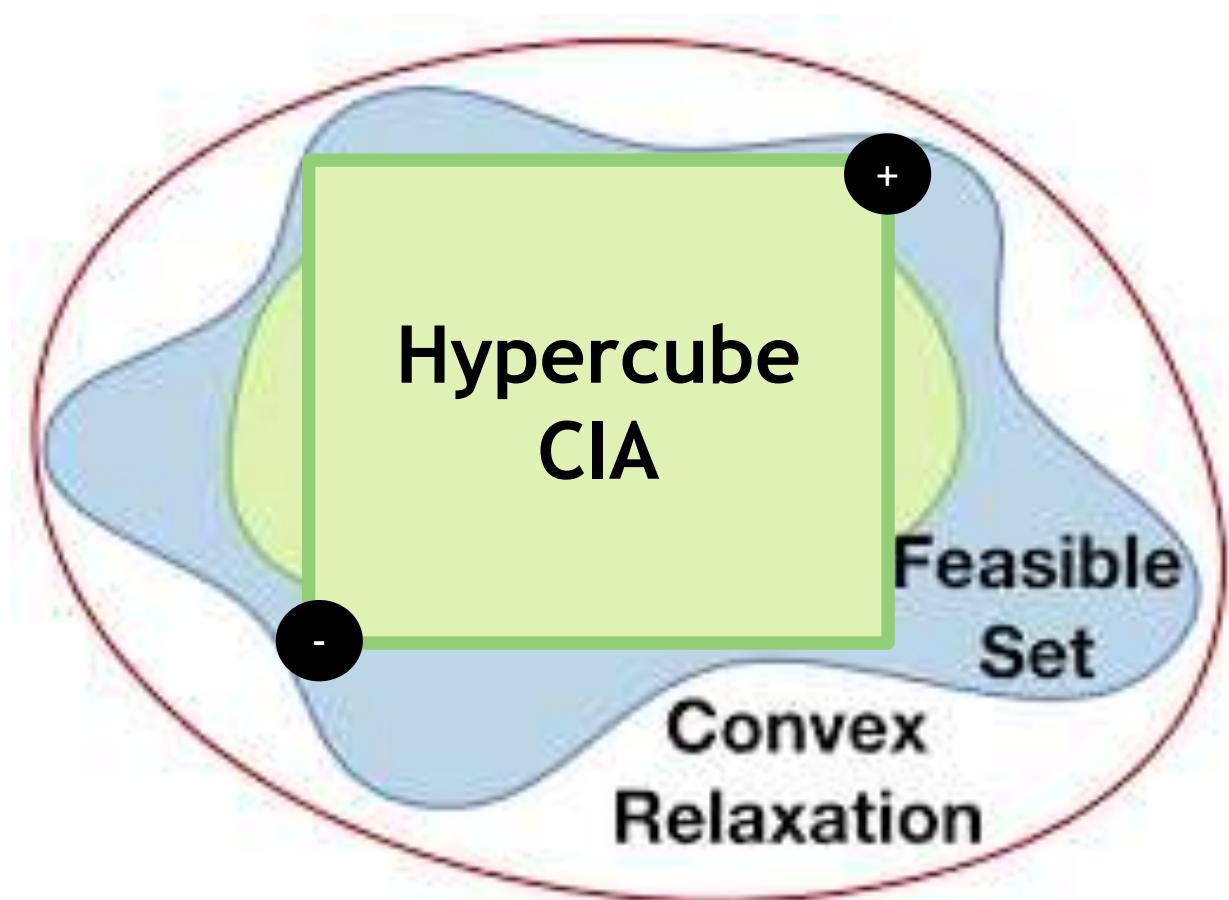
$$P_{ij} = p_j + \sum_{h:h \rightarrow j} (P_{jh} - r_{jh}l_{jh})$$

$$Q_{ij} = q_j + \sum_{h:h \rightarrow j} (Q_{jh} - x_{jh}l_{jh})$$

$$l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j},$$

Idea: replace non-convex constraint with a convex inner approximation

Convex inner approximation unlocks hosting capacity



Feasible set contains all dispatch solutions that are admissible (i.e., satisfy all constraints)

Convex relaxation contains feasible set + some solutions that are not admissible (infeasible).

Convex inner approximation (CIA) contains a convex subset of admissible solutions (suboptimal).

Goal: find largest hypercube to determine HC

Approach: eliminate non-convexity via convex bounds

$$l_{\text{lb},ij} \leq l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j} \leq l_{\text{ub},ij}$$

Shown to be affine

Shown to be convex

Original Image source: D. Lee, H. D. Nguyen, K. Dvijotham and K. Turitsyn, "Convex Restriction of Power Flow Feasibility Sets," in *IEEE Transactions on Control of Network Systems*, vol. 6, no. 3, pp. 1235-1245, Sept. 2019.



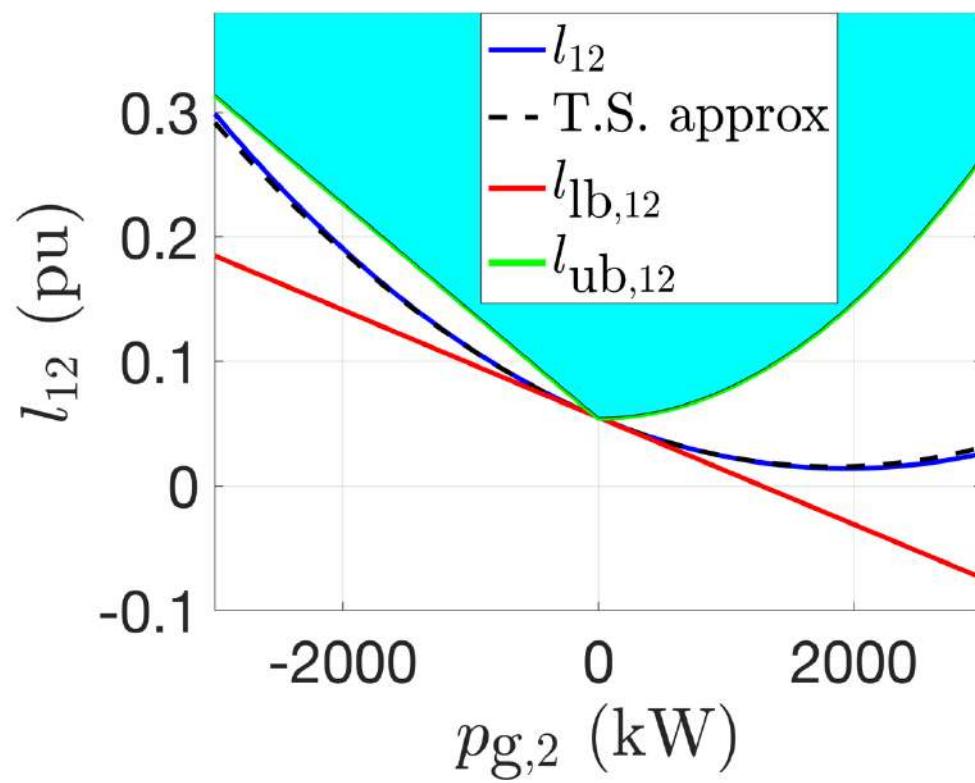
For mathematical details, please see:

Nawaf Nazir and Mads Almassalkhi. "Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks," *IEEE TPWRS*, 2021.

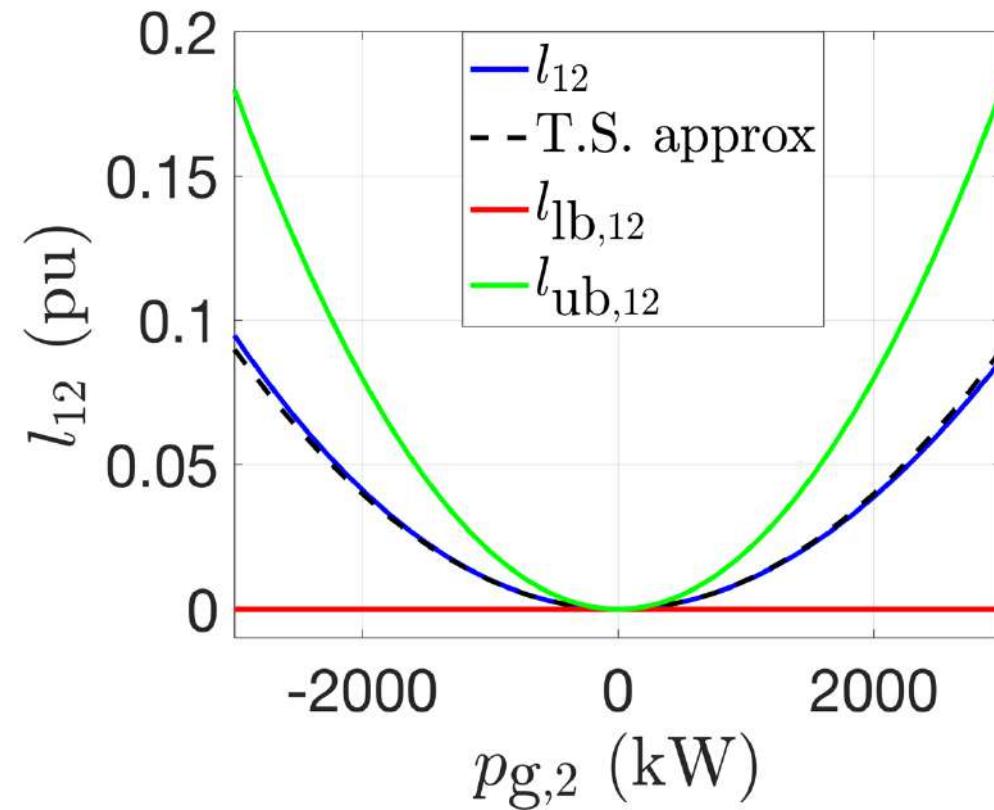
Convex inner approximation via proxy variables

$$l_{\text{lb},ij} \leq l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j} \leq l_{\text{ub},ij}$$

Full-load conditions



No-load conditions



For mathematical details, please see:

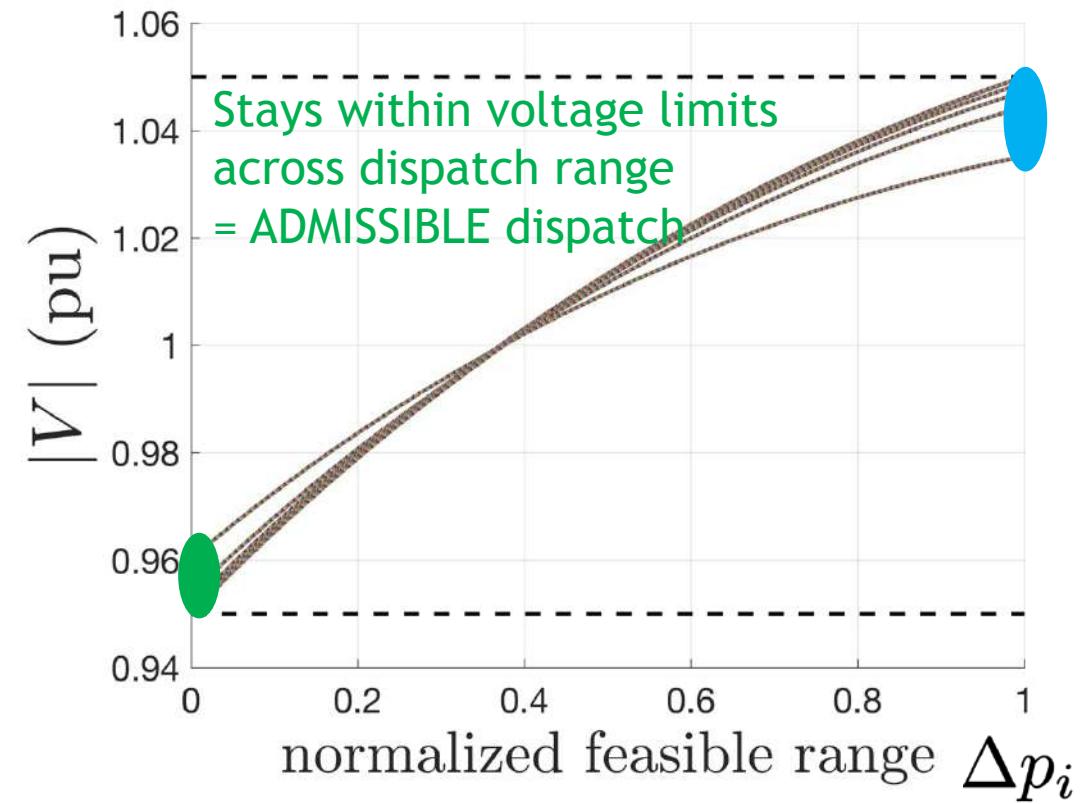
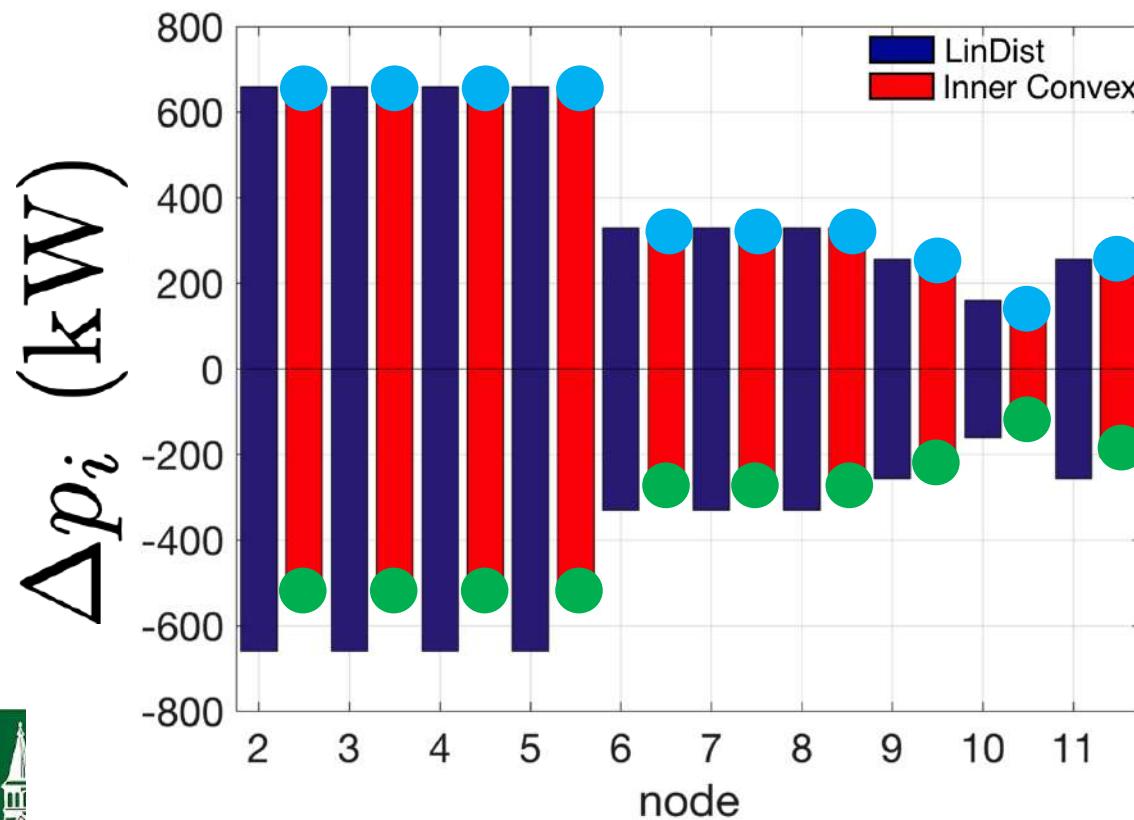
Nawaf Nazir and Mads Almassalkhi. "Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks," IEEE TPWRS, 2021.



Hypercube yields the nodal hosting capacities

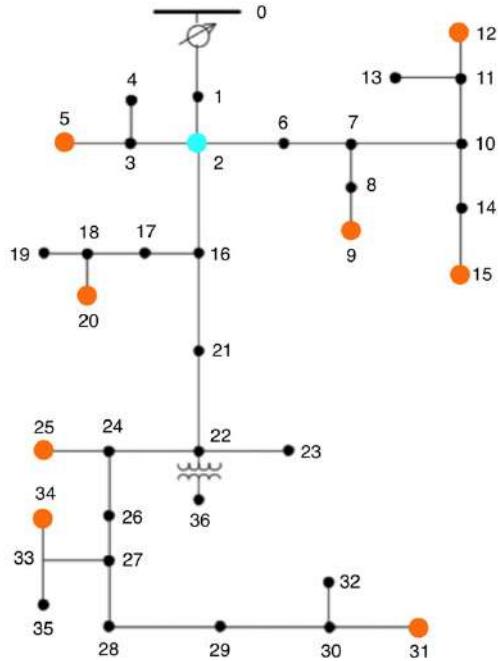
- Consider flexible resources on 10 nodes in a small network: a *10-dimensional hypercube*

$$\Delta p_i := [p_i^-, p_i^+]$$

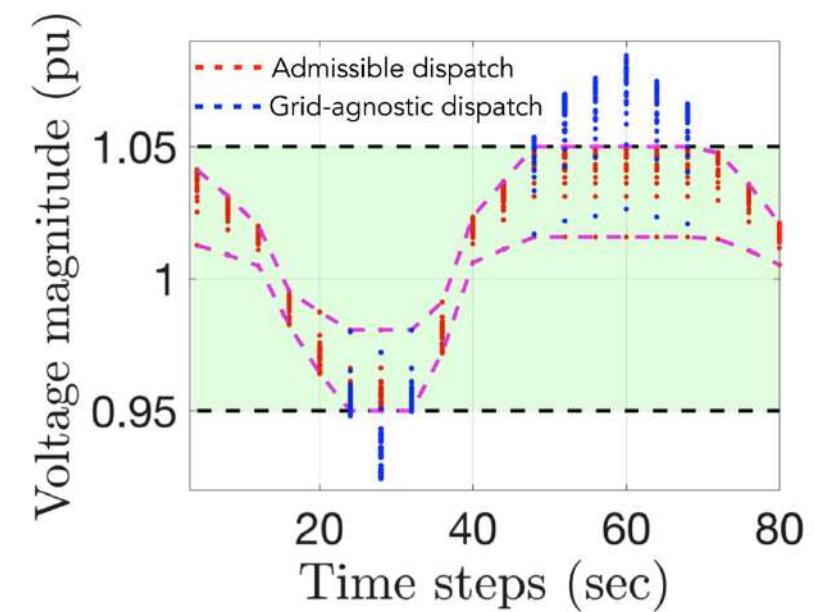
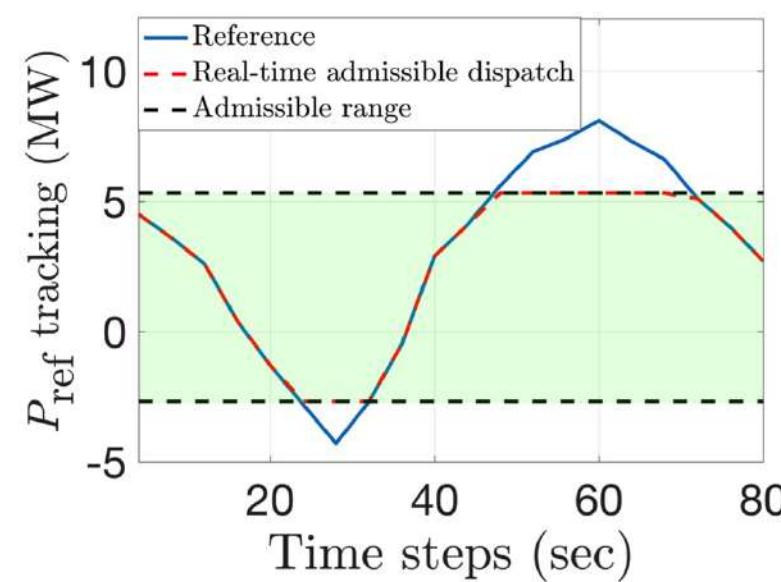
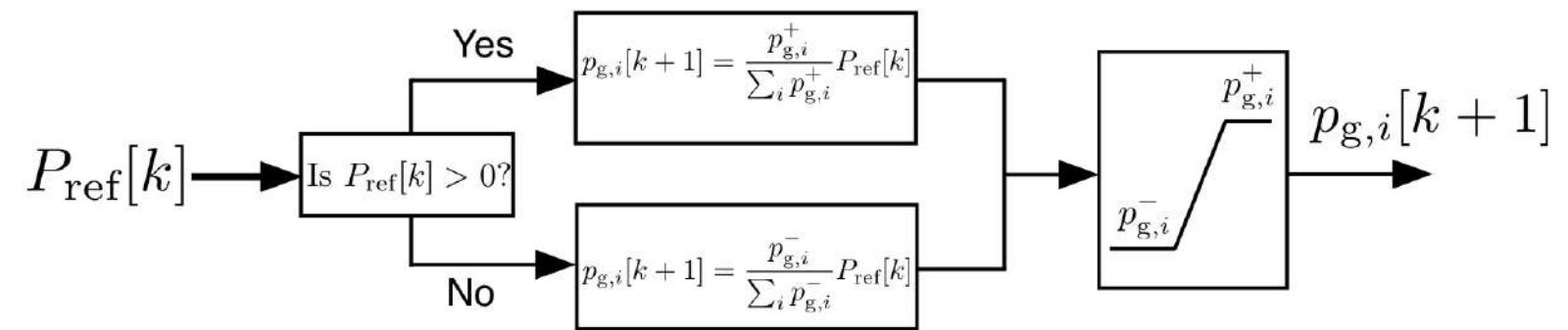


CIA enables real-time, grid-aware disaggregation

Nodal hosting capacities $[p_i^-, p_i^+]$ enable an open-loop, distributed, and **grid-aware DER control policy**



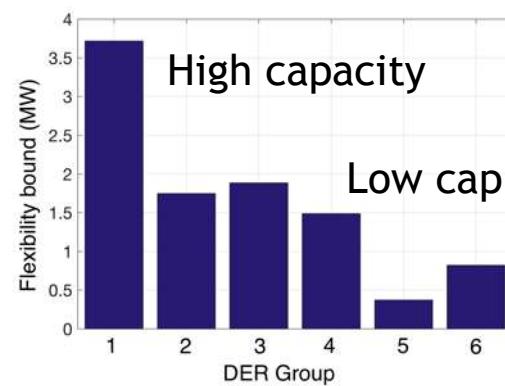
IEEE 37-node network
(from Baker/Dall'Anese)



Summary: DHC overcomes data/control asymmetry!

Utility (grid information+data)

- Dynamic hosting capacities capture grid conditions and limits



Available hosting capacity

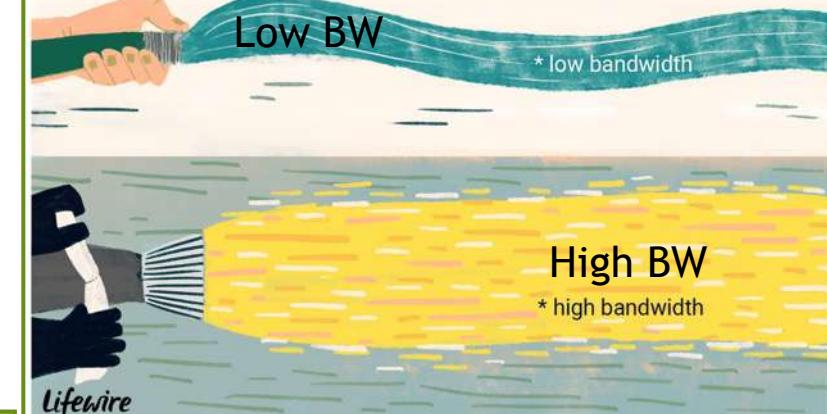


Future work: find optimal control/price signals

Aggregators (device access, markets)

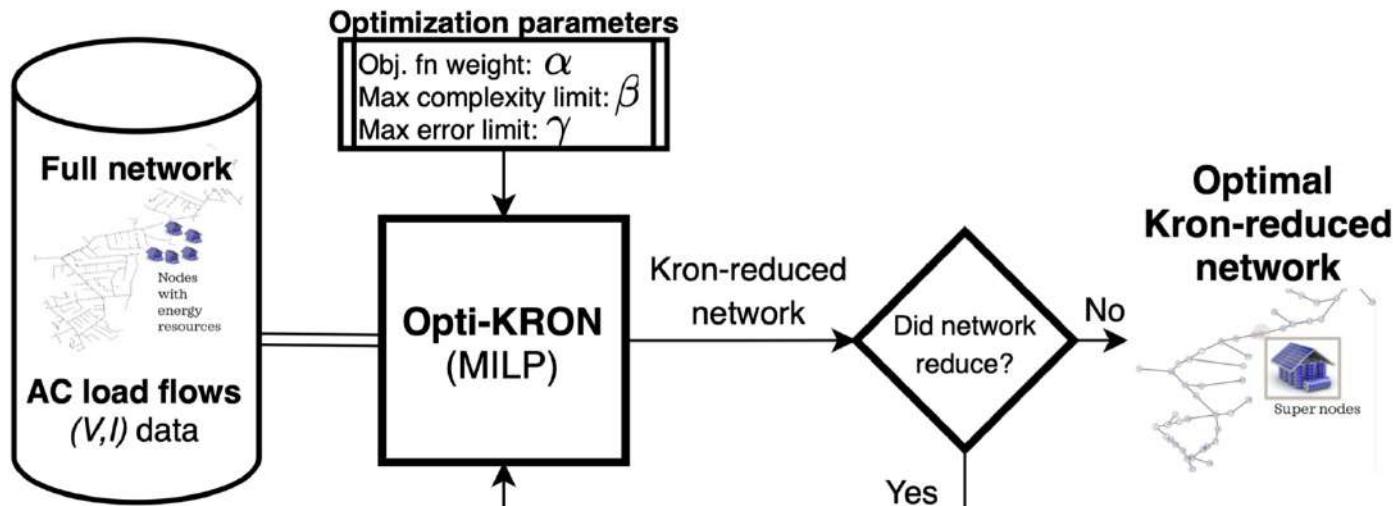
- Flexibility captures device availability and comfort limits

“Flexibility Bandwidth”

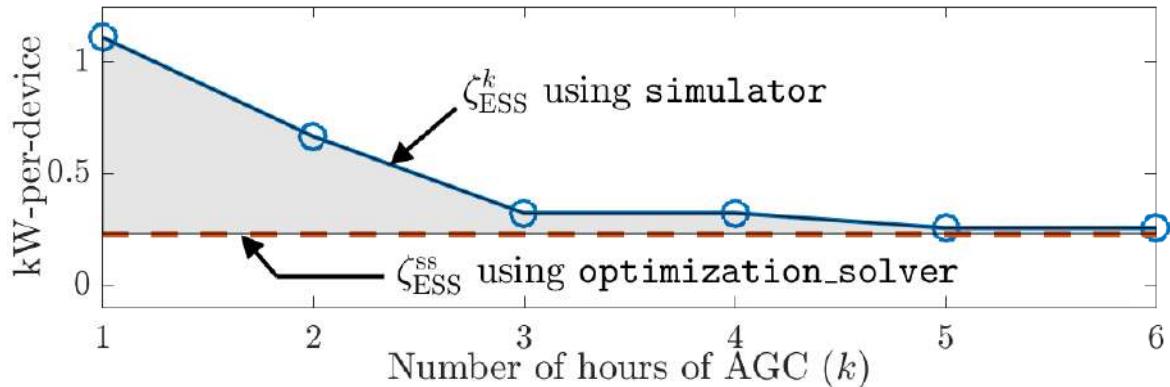


Other interesting topics we didn't get to today

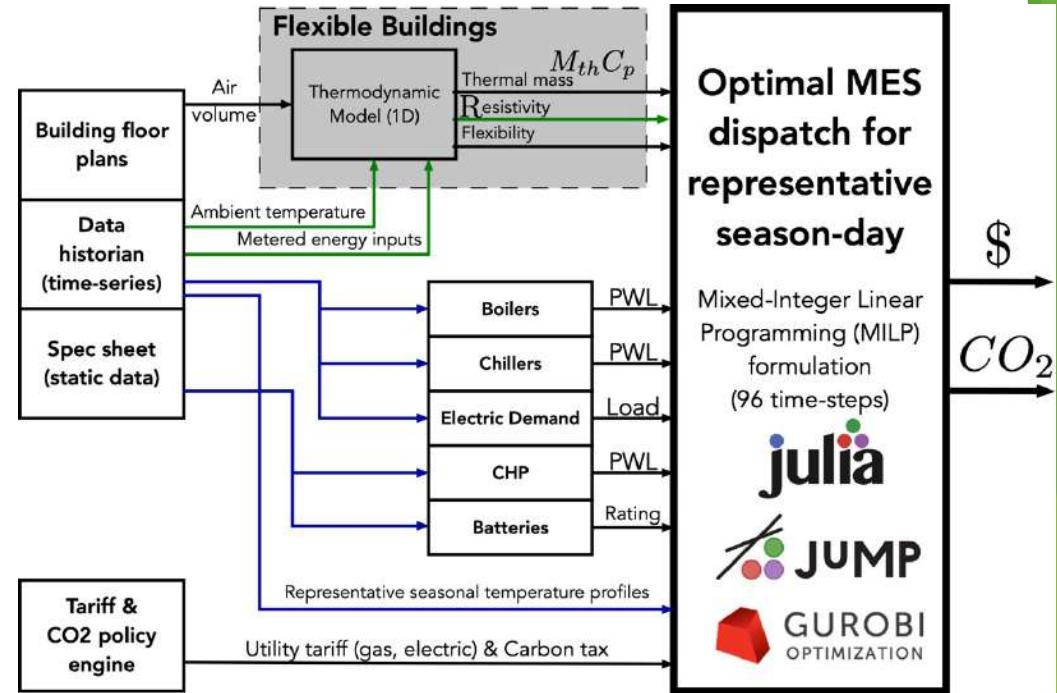
Optimal Kron-based network reduction (Opti-KRON)



Characterize flexibility from fleets of DERs as *virtual*/battery



Multi-energy systems / sector coupling



Thank you! Questions? Comments?



malmassa@uvm.edu



@theEnergyMads



<https://madsalma.github.io>

Traditional demand response



Today's flexibility: *not your parent's DR*



Apply now! Multiple fully-funded PhD positions starting Fall 2023:

Slides unlocked by great questions



Short Bio



school
tems
systems
zation
l systems
rbor, Michigan)

Startup company
VC-funded energy
optimization
SaaS company for
industrial energy
plants
(Chicago, IL)

ROOT3

University of Vermont (UVM)
Leading a number of DOE projects
Co-founded cleantech startup
NSF CAREER Awardee
Joint appt @ PNNL
Sabbatical @ DTU



2021-22

2008

2013

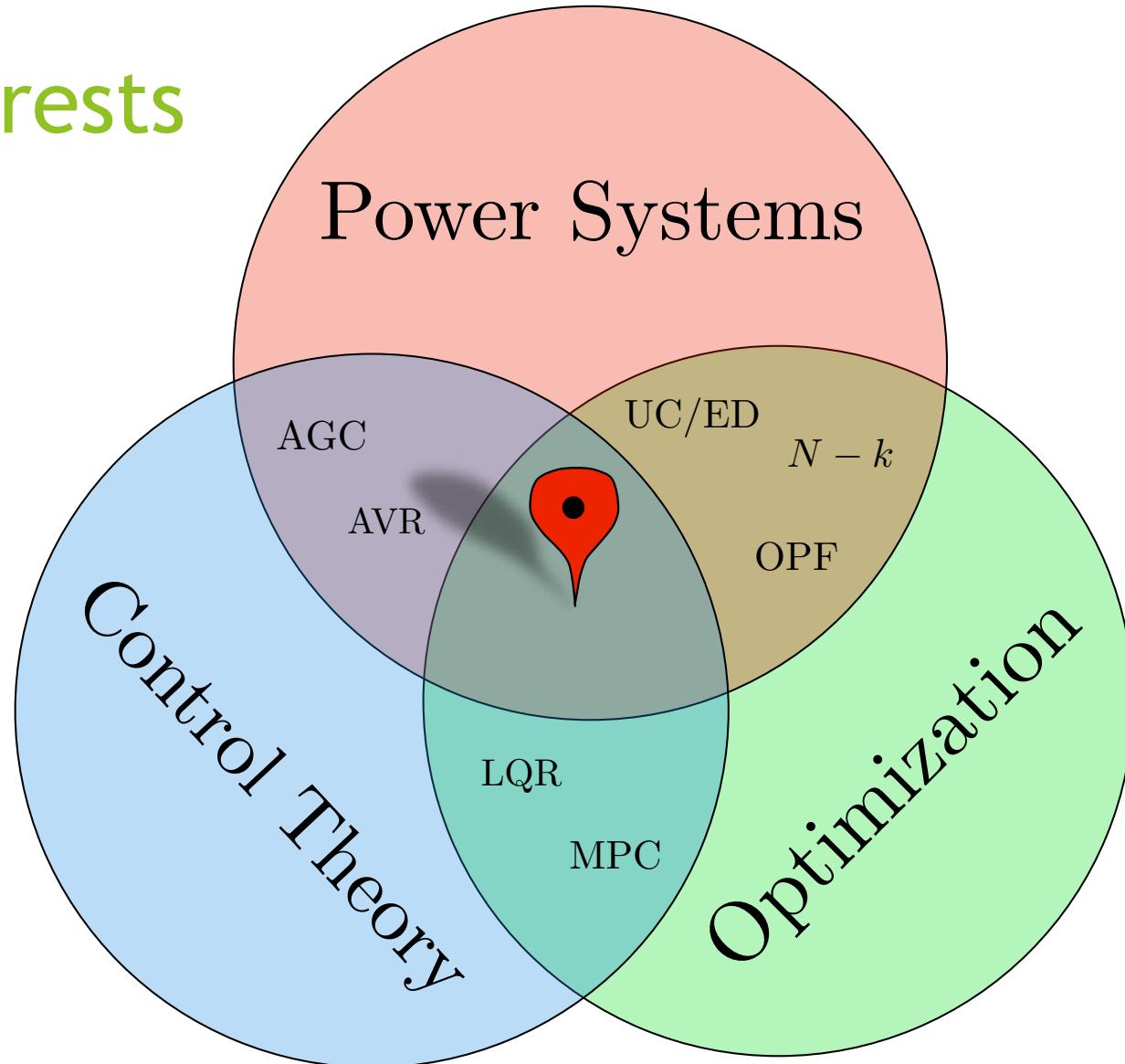
2014 2016 2017

2021

General research interests

Teaching background

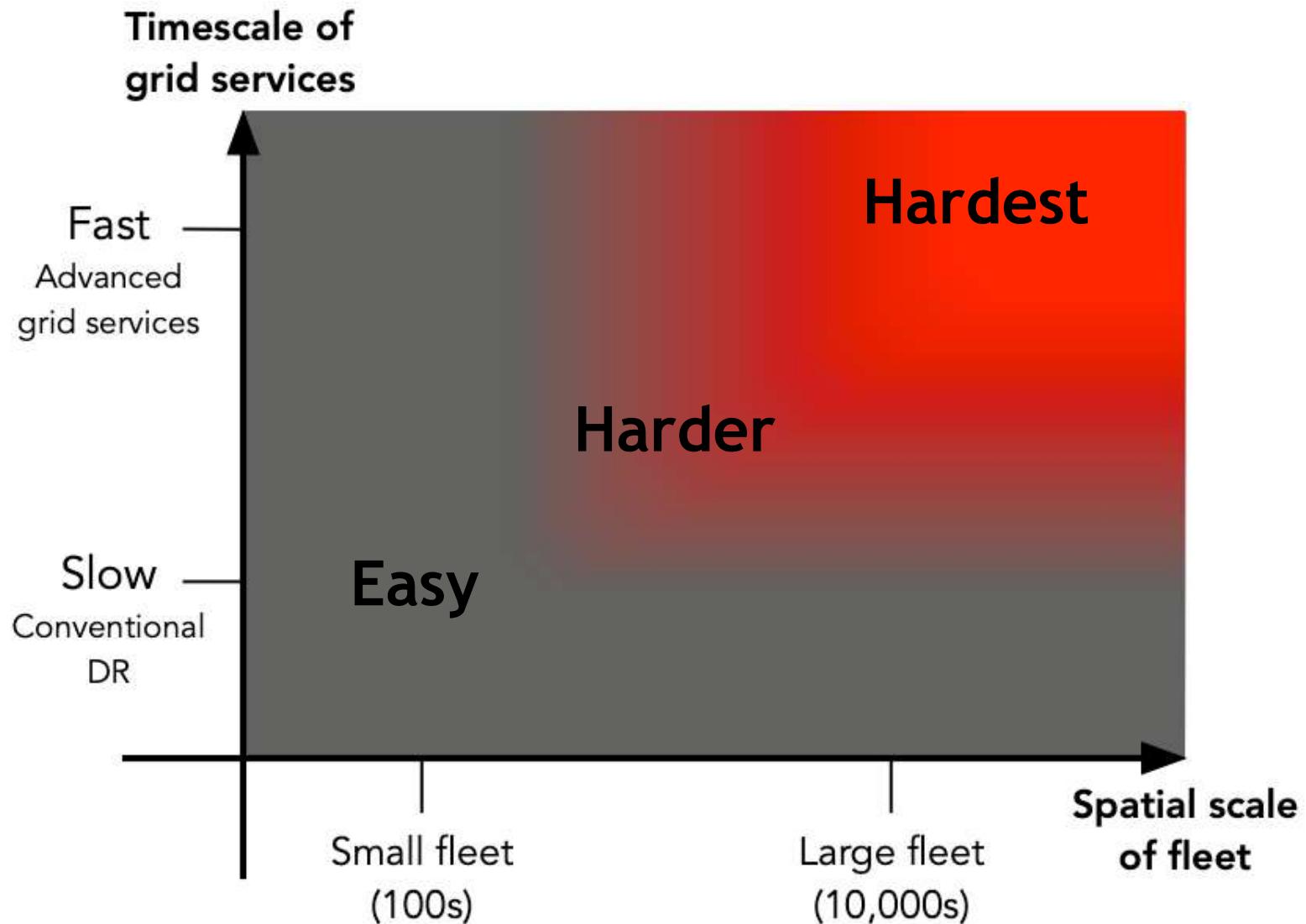
- Power systems analysis
- Energy conversion & machines
- Control systems
- Linear system theory (grad)
- Convex optimization (grad)



Practical, yet rigorous approach to power systems via control and optimization theory

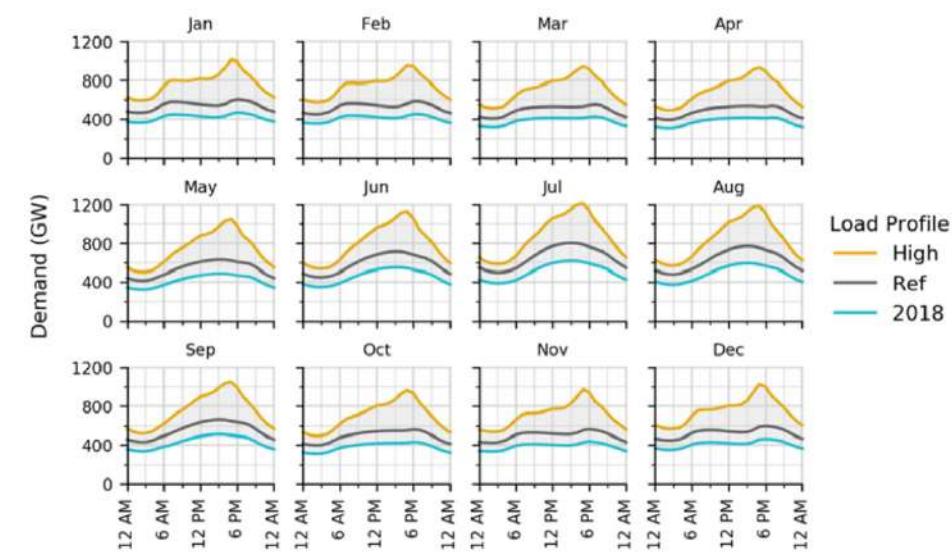
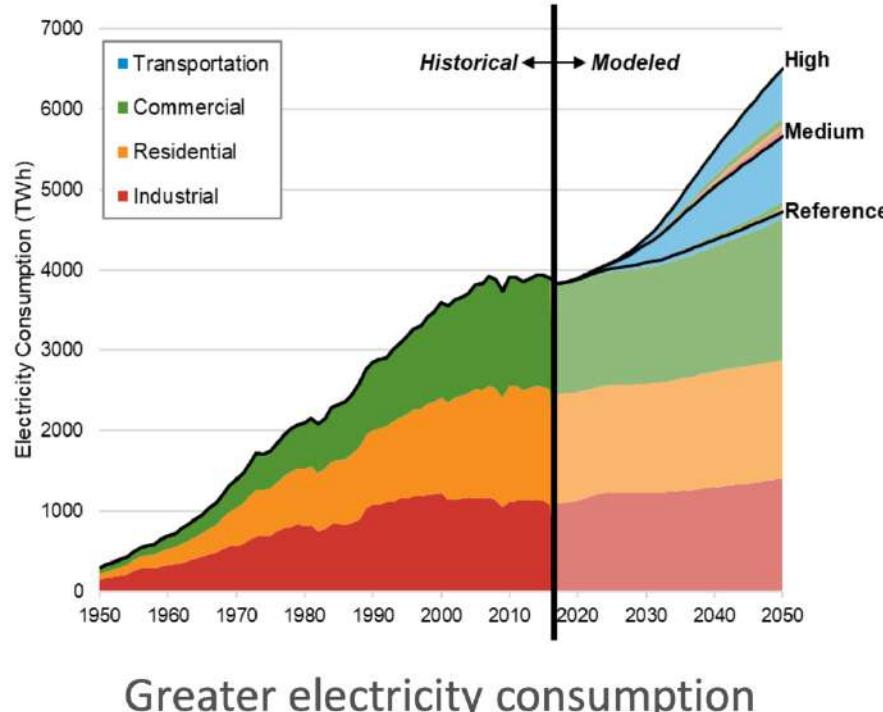


Coordination requires control + comms + data



Intelligent electrification is necessary

Vehicle electrification dominates incremental growth in annual electricity demand



Possibly higher, sharper,
and more frequent peaks in
2050
(in the absence of demand flexibility)

Value-stacking can be significant for flexibility

GRID BALANCING,
ANCILLARY SERVICES



LMP ENERGY ARBITRAGE,
RENEWABLE SMOOTHING



AVOIDED T&D CAPEX,
NON-WIRES ALTERNATIVES,
DIST. GRID MANAGEMENT
(UTILITY)



AVOIDED GEN CAPACITY
(ISO)



\$100 to \$1000
per kW_{flex} per year*

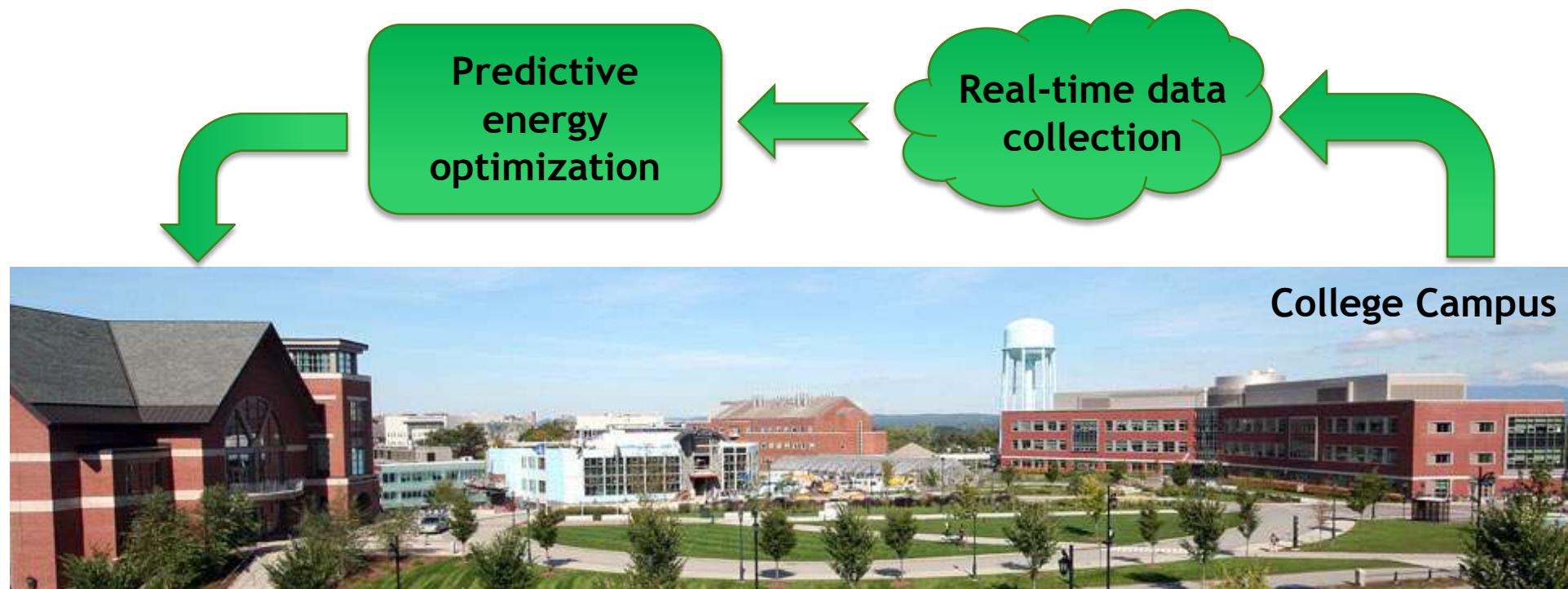


“Prosumer”
“Virtual battery”
“Virtual power plant”

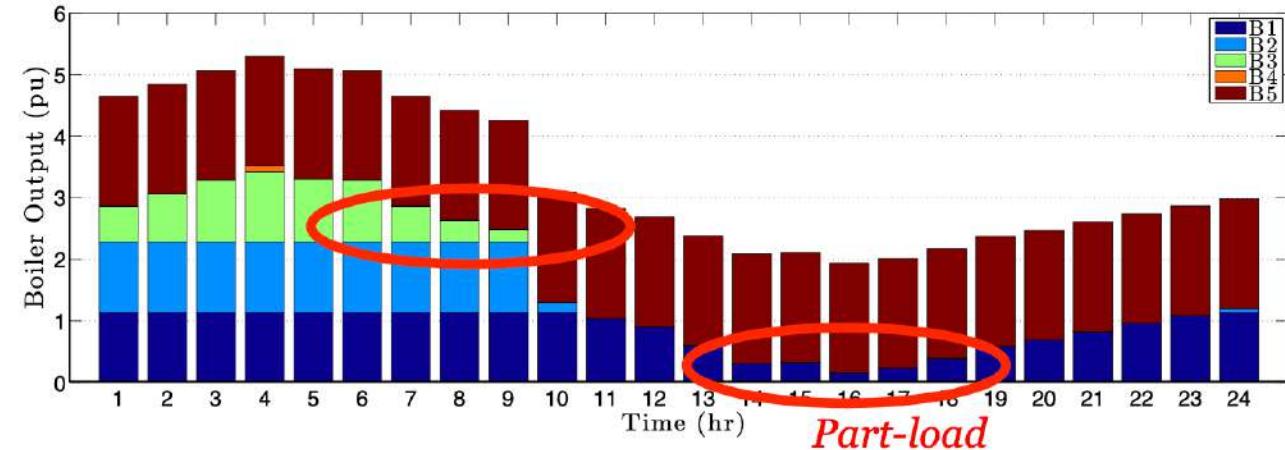
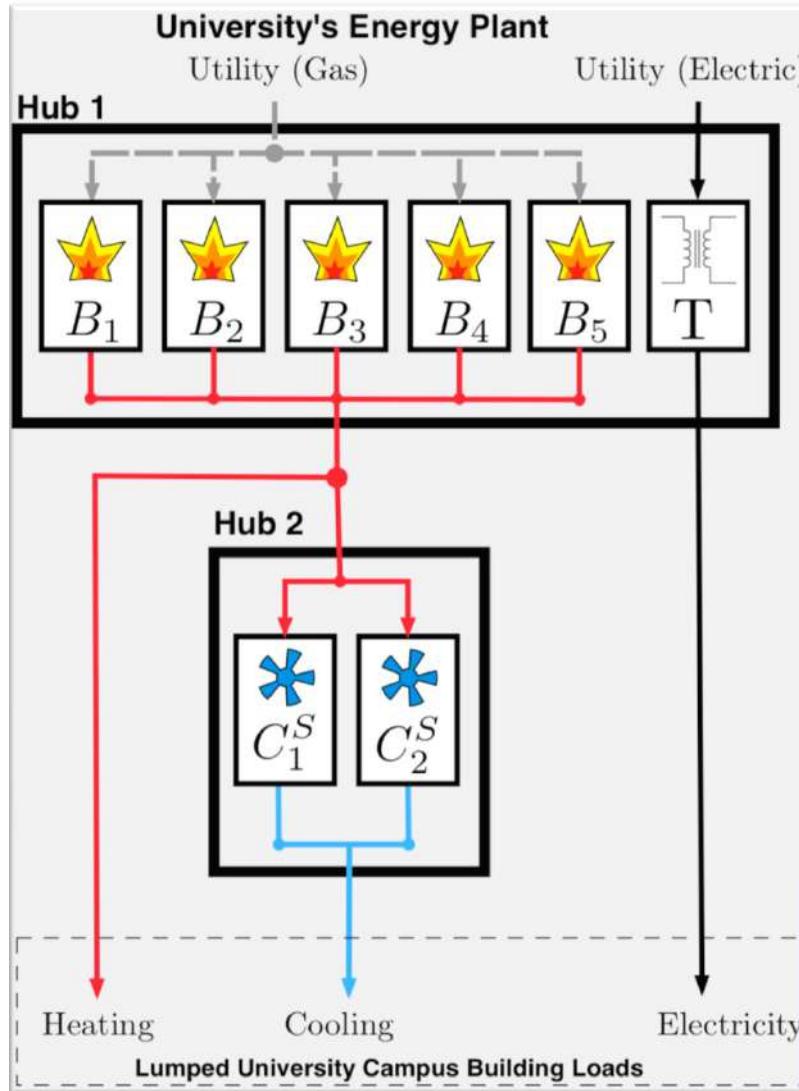


*Values from representative 2019 ISO New England market prices and services

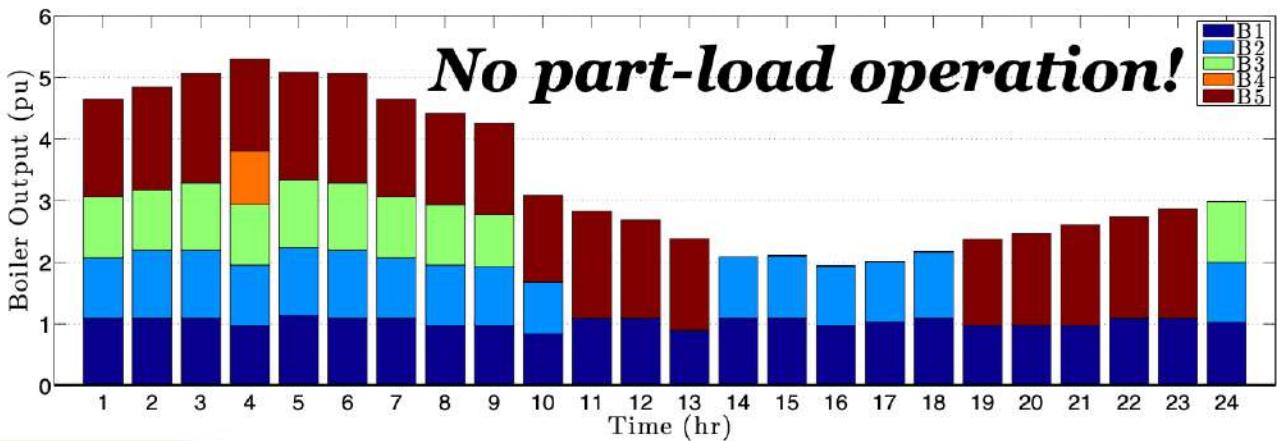
Some other interests on energy optimization



Multi-energy system optimization with energy hubs



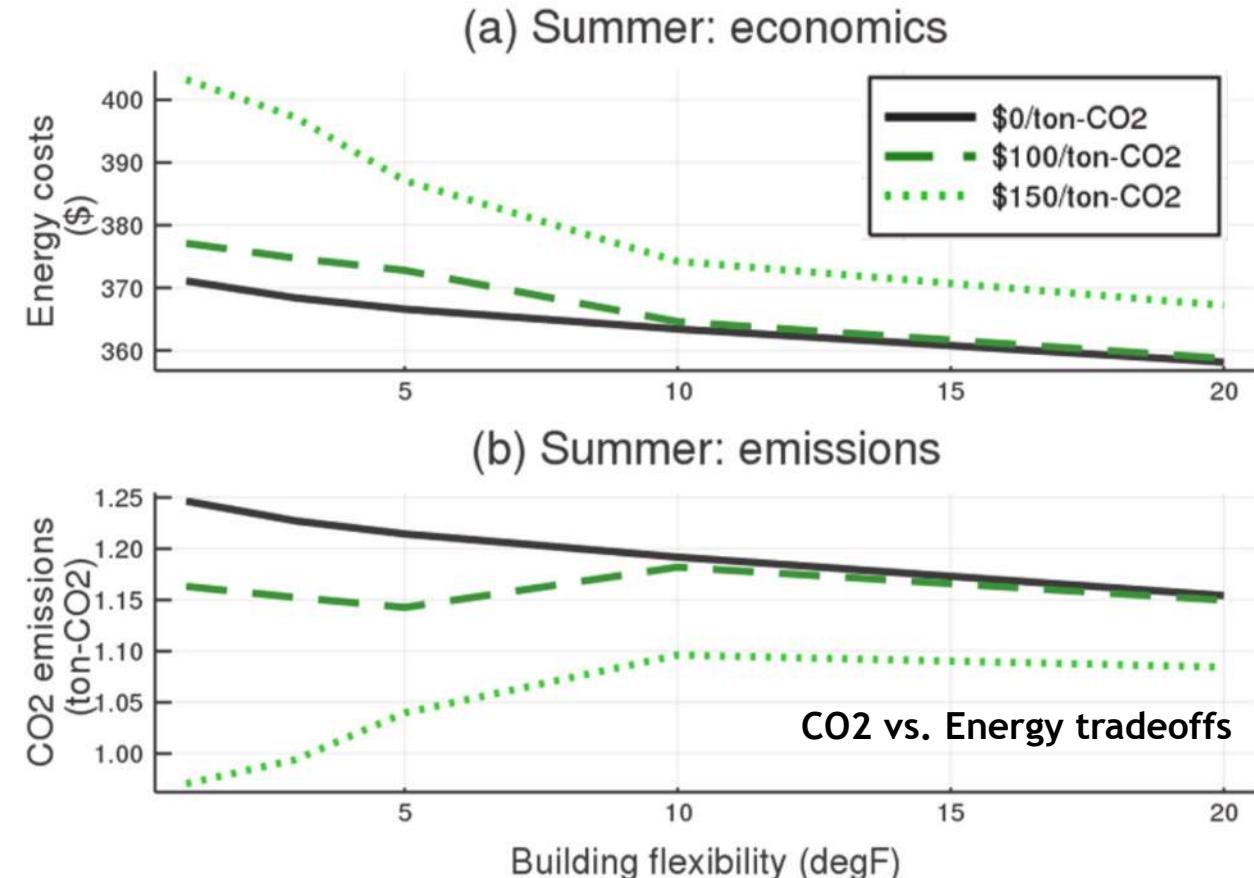
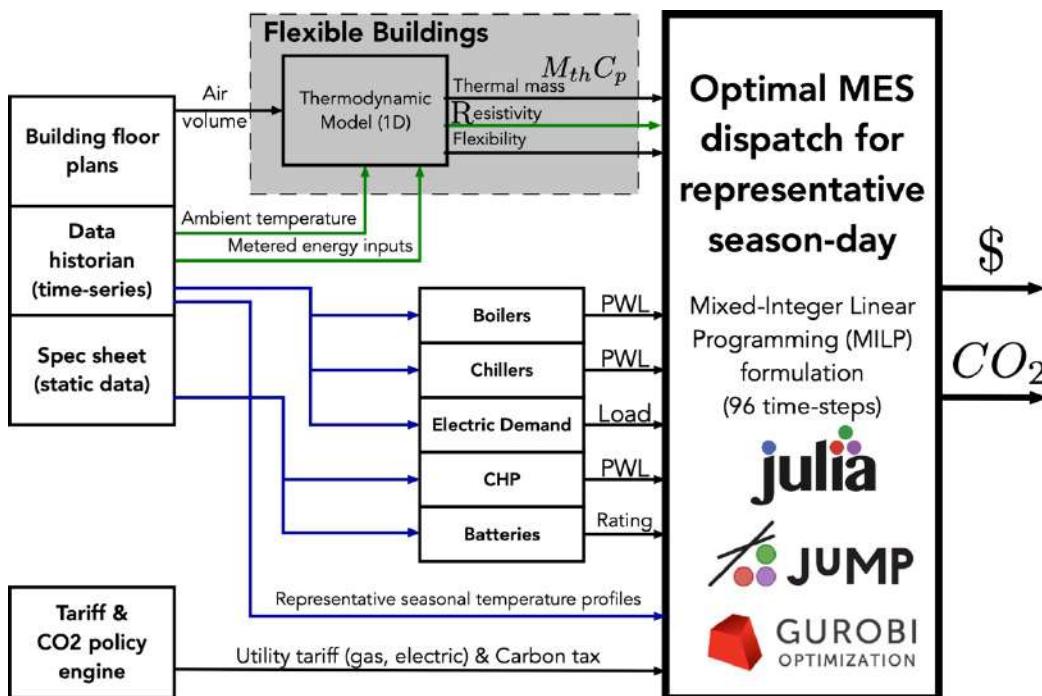
Dispatch with linearized boiler models



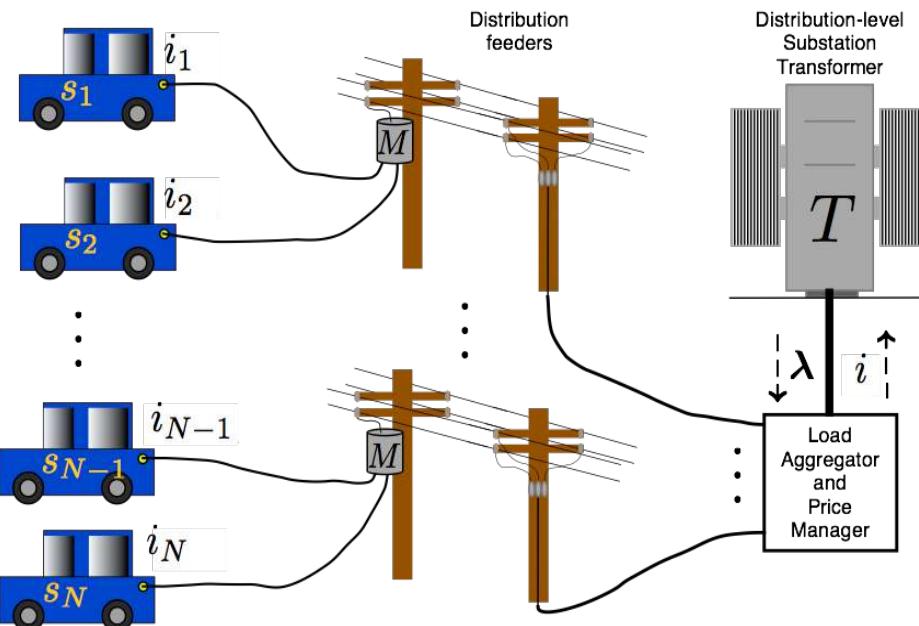
Dispatch with nonlinear boiler models

MES optimization with flexible buildings

Flexibility can reduce impact of CO₂-tax

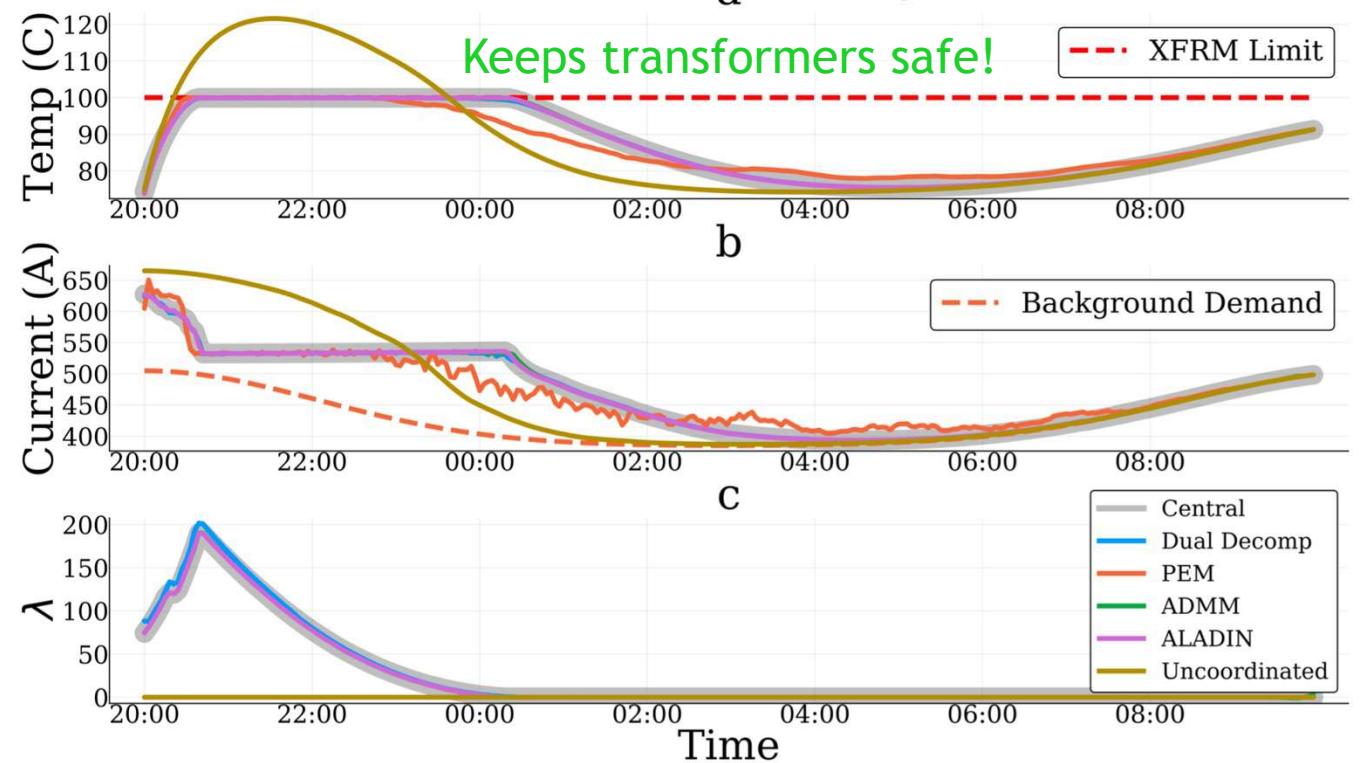


EV charging & Dynamic Xfmr Rating

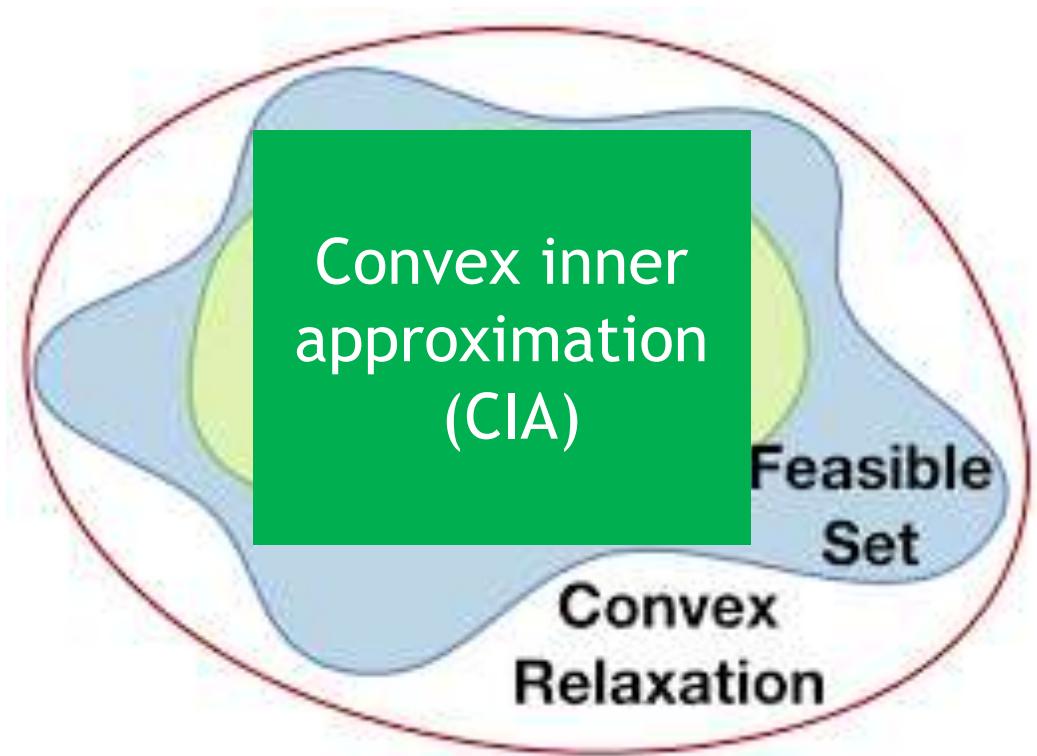


Active constraints generate shadow (marginal) prices that can inform dynamic pricing schemes

Algorithms have different data (privacy), computing, and performance guarantees/assumptions



What about conservativeness of CIA?



Original Image source: D. Lee, H. D. Nguyen, K. Dvijotham and K. Turitsyn, "Convex Restriction of Power Flow Feasibility Sets," in *IEEE Transactions on Control of Network Systems*, vol. 6, no. 3, pp. 1235-1245, Sept. 2019.

Comparing hosting capacity results*

System	CIA (MW)	NLP (MW)	CR (MW)
13-node	[-1.5, 9.1]	[-1.5, 9.7]	[-1.5, 12]
37-node	[-2.7, 5.3]	[-2.7, 5.3]	[-2.7, 16]
123-node	[-4.5, 13.9]	[-4.5, 14]	[-4.5, 24]

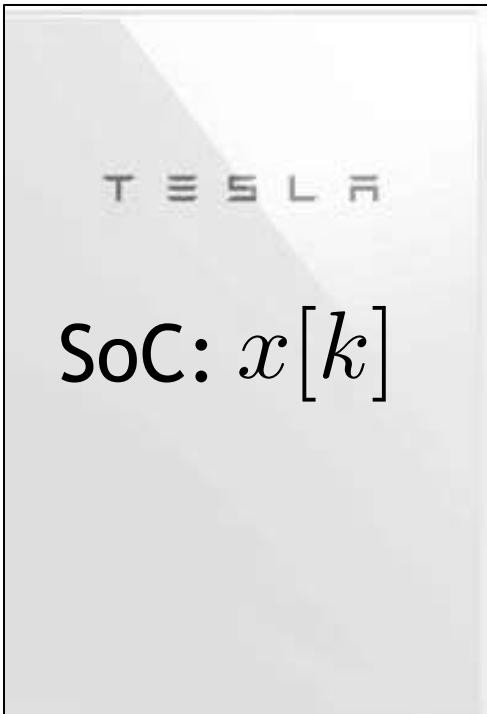
Convex relaxation (CR) over-estimates maximum reactive power capability

Nonlinear (NLP) has no optimality guarantees AND does not guarantee that entire range is admissible (i.e., no holes)

Proposed (CIA) method is not overly conservative and entire range is admissible

*Nawaf Nazir and Mads Almassalkhi. "Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks." (Rev02)

Another inner approximation: fast battery dispatch



Net-charge
 $u_c[k] - u_d[k]$
 Grid

Nonlinear Battery Dispatch Model

$$x[k+1] = \alpha x[k] + \Delta t \eta_c u_c[k] - \frac{\Delta t}{\eta_d} u_d[k], \quad \forall k \in \mathcal{T}$$

~~$u_c[k]u_d[k] < 0 \quad \forall k \in \mathcal{T}$~~ Non-convex
 (Simultaneous discharging)

$$x[0] = x_0$$

$$0 \leq u_c[k] \leq P, \quad \forall k \in \mathcal{T}$$

$$0 \leq u_d[k] \leq P \quad \forall k \in \mathcal{T}$$

$$0 \leq x[k+1] \leq E, \quad \forall k \in \mathcal{T}$$

Linear (Robust) Battery Dispatch Model

$$\bar{x}[k+1] = \alpha \bar{x}[k] + \Delta t \eta (u_c[k] - u_d[k]), \quad \forall k \in \mathcal{T}$$

$$\underline{x}[k+1] = \alpha \underline{x}[k] + \Delta t \left(\eta_c u_c[k] - \frac{u_d[k]}{\eta_d} \right), \quad \forall k \in \mathcal{T}$$

$$0 \leq u_c[k] \leq P, \quad \forall k \in \mathcal{T}$$

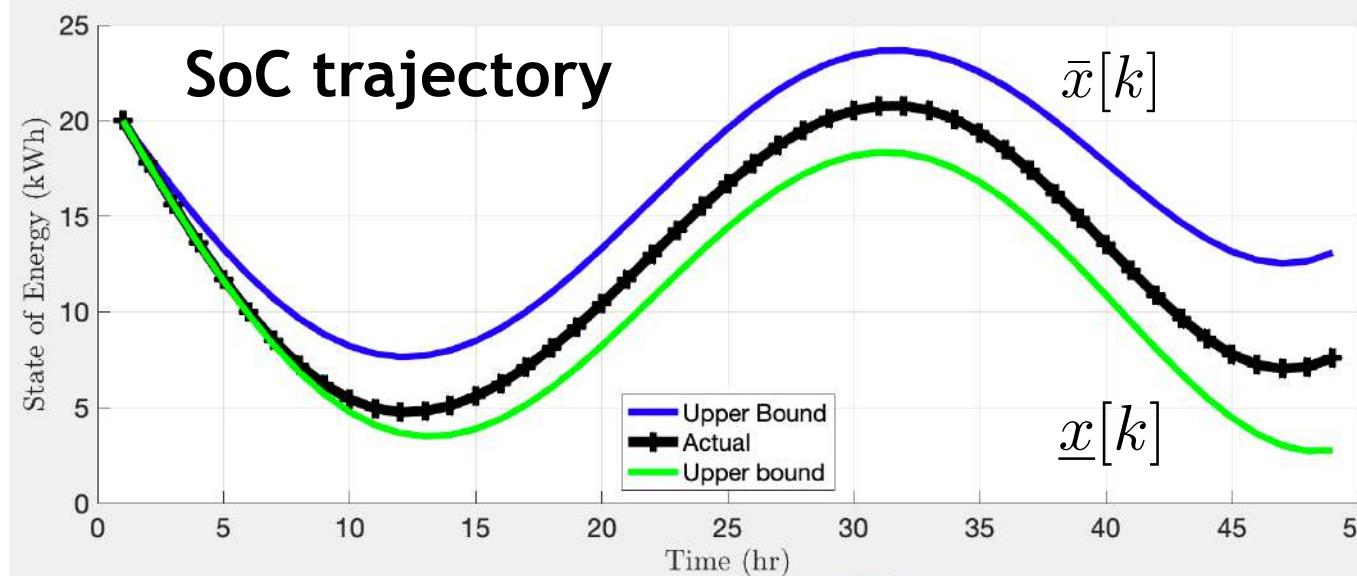
$$0 \leq u_d[k] \leq P \quad \forall k \in \mathcal{T}$$

$$0 \leq \underline{x}[k+1], \quad \forall k \in \mathcal{T}$$

$$\bar{x}[k+1] \leq E, \quad \forall k \in \mathcal{T}$$

$$x[0] = x_0$$

Simultaneous dis/charging
 no longer has negative
 side-effects!

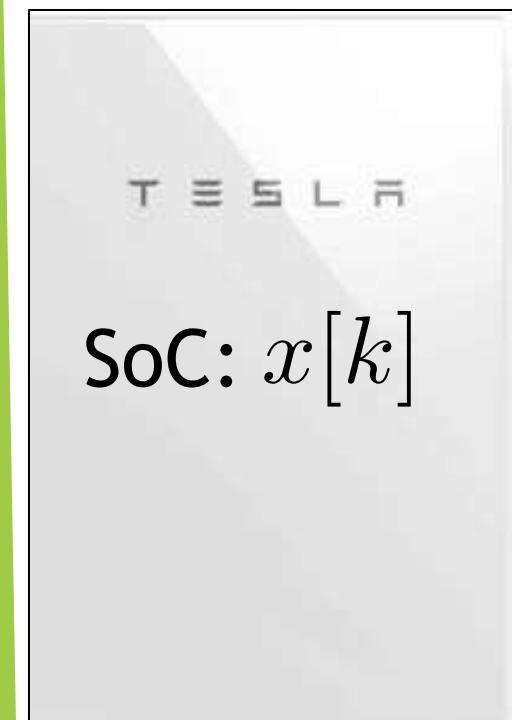


Bounds ensure that any
 optimal linear dispatch
 can be realized on actual
 (non-linear) battery



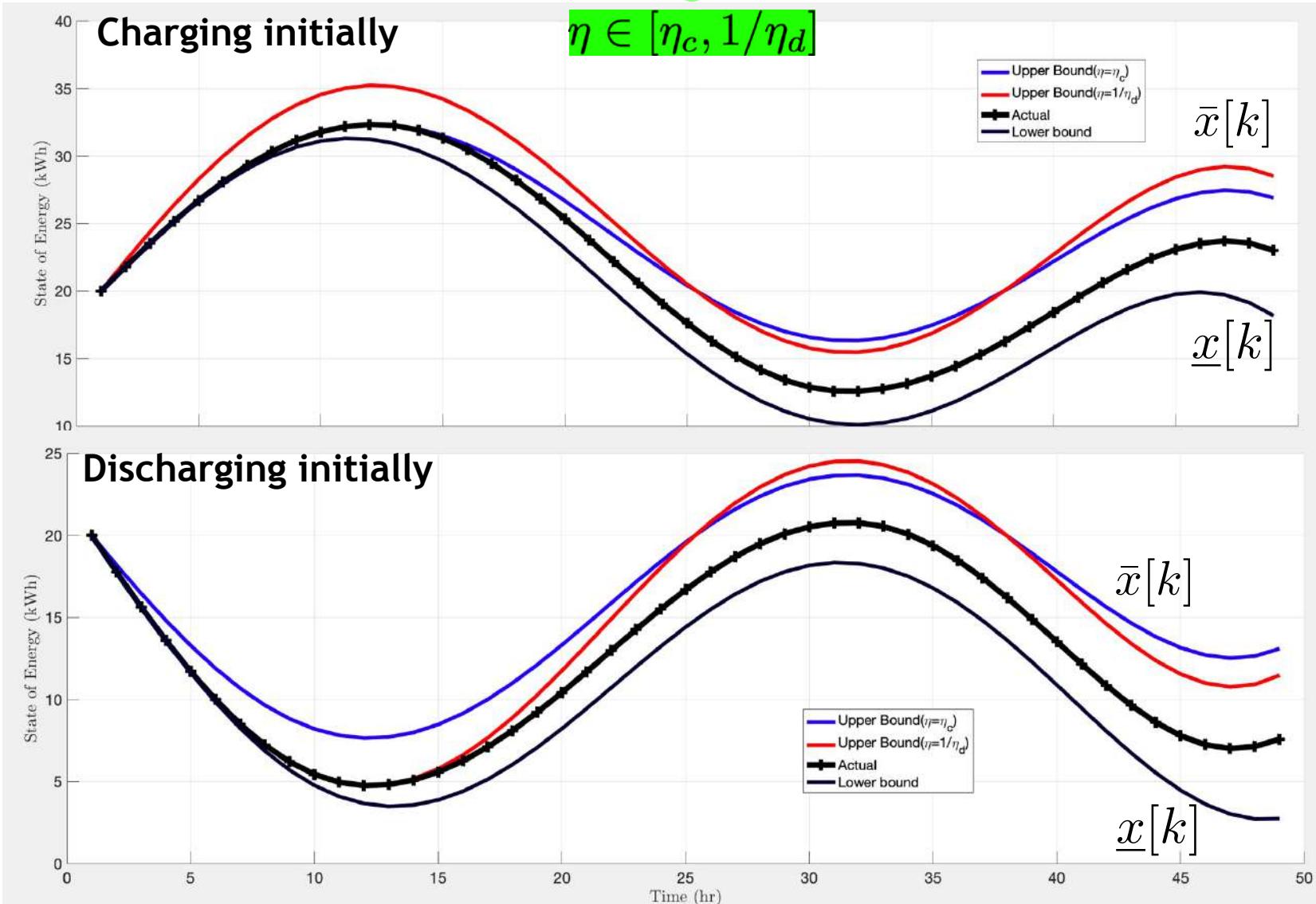
SoC bounds' conservativeness depends on input seq

Upper bound: $\bar{x}[k + 1] = \alpha\bar{x}[k] + \Delta t\eta(u_c[k] - u_d[k]), \quad \forall k \in \mathcal{T}$



Net-charge
 $u_c[k] - u_d[k]$

Grid



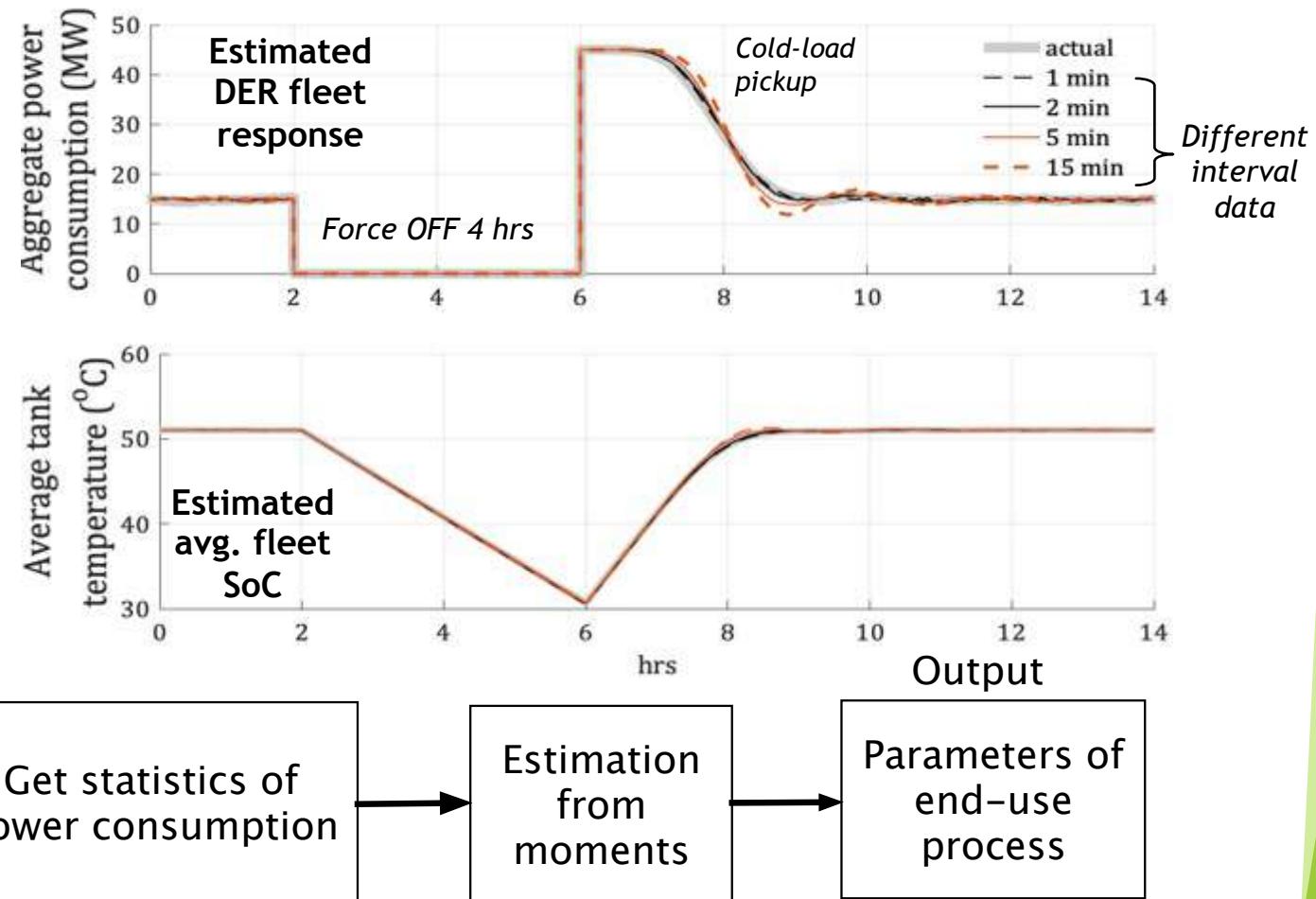
Wait! There is more...





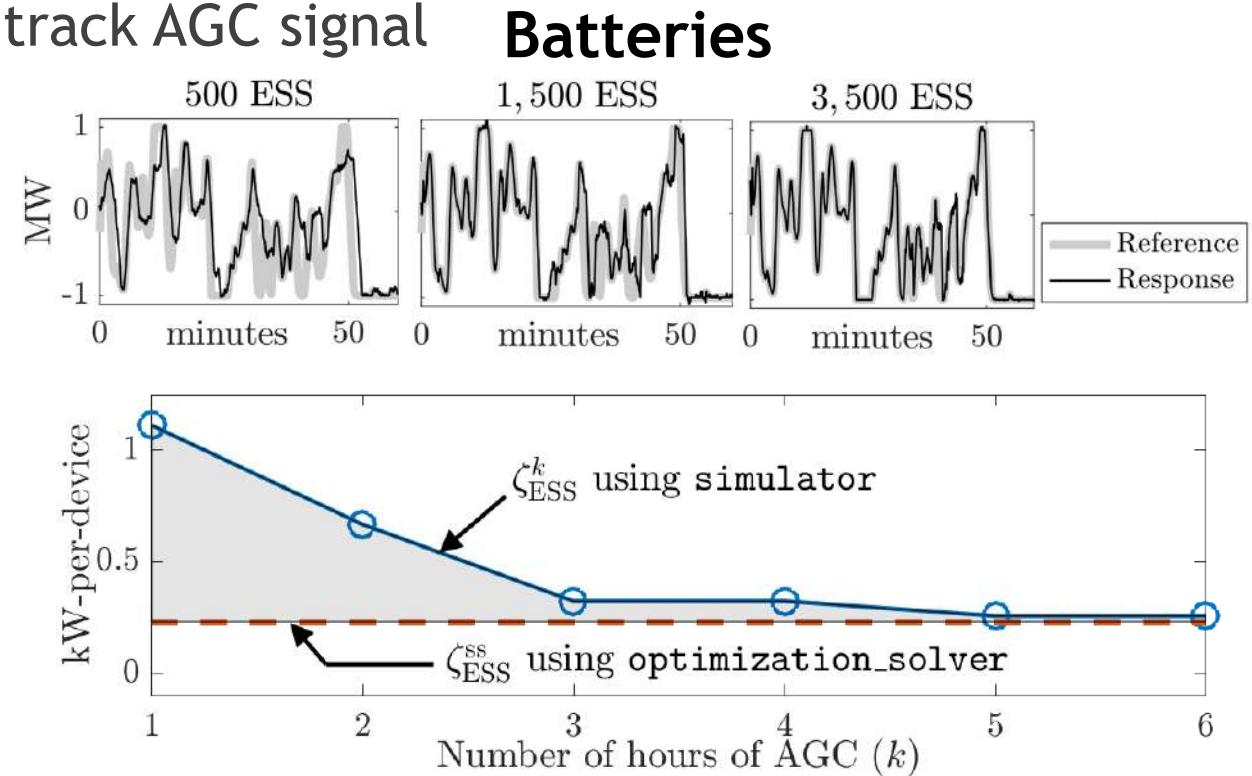
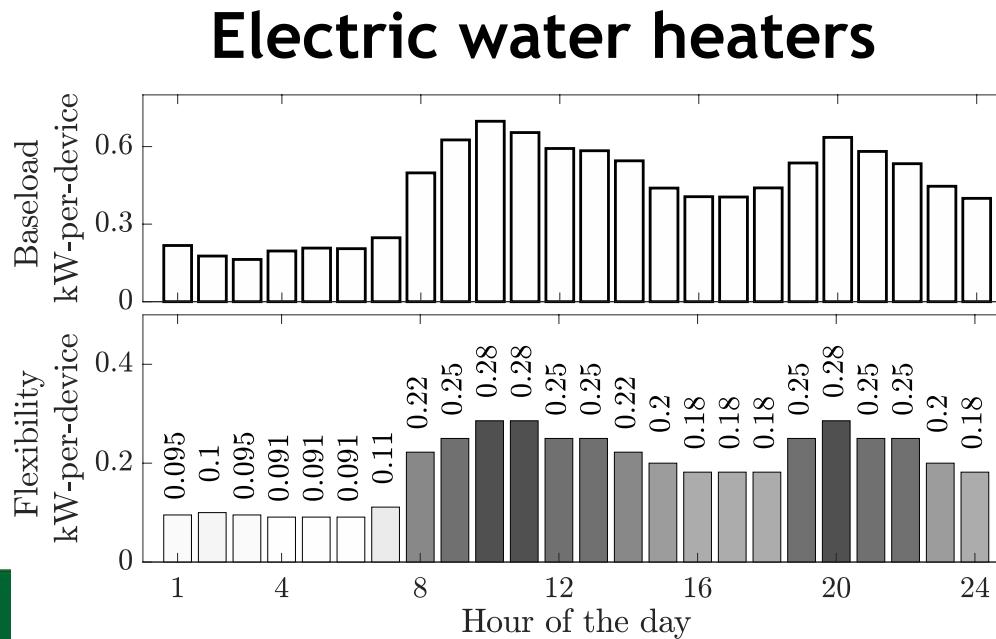
1 Estimate DER end-use (nominal demand)

- ▶ Problem: how do people interact with DERs nominally?
- ▶ Outcome: from just kWh interval meter data and tank parameters, we can estimate how much people use hot water



Estimating power capacity/flexibility of VB

- ▶ Data-driven methodology to answer questions:
 - ▶ How many devices for 1MW flexibility?
 - ▶ What is flexibility (\pm kW) per device?
- ▶ Define flex-kW by fleet's ability to track AGC signal



Behind-the-meter loads in the news!



Nest



Google LLC, Ecobee Inc., and Vivint Inc. failed to convince the Western District of Texas to transfer suits alleging the companies infringed EcoFactor Inc.'s smart home patents.

Photographer: David Paul Morris/Bloomberg

Google, Others Must Face Smart Thermostat Patent Suits in Texas

April 19, 2021, 4:08 PM



- Suits challenge smart thermostat technology
- Northern California not clearly more convenient

Google LLC, Ecobee Inc., and Vivint Inc. failed to convince the Western District of Texas to give up suits alleging the companies infringed EcoFactor Inc.'s patents covering smart home energy-saving technology.



Perry Cooper
Legal Reporter



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