Intelligent Electrification & Grid Optimization

Mads R. Almassalkhi, Ph.D.

Chief Scientist (joint appointment)

Pacific Northwest NATIONAL LABORATORY

Associate Professor Electrical Engineering

The UNIVERSITY of VERMONT

Co-founder

PACKETIZED ENERGY

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 Mühlpfordt (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

Recent and ongoing federal partners

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*

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***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

\+ PACKETIZED ENERGY = EnergyHub

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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businesswire

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*

Efficiency Vermont

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

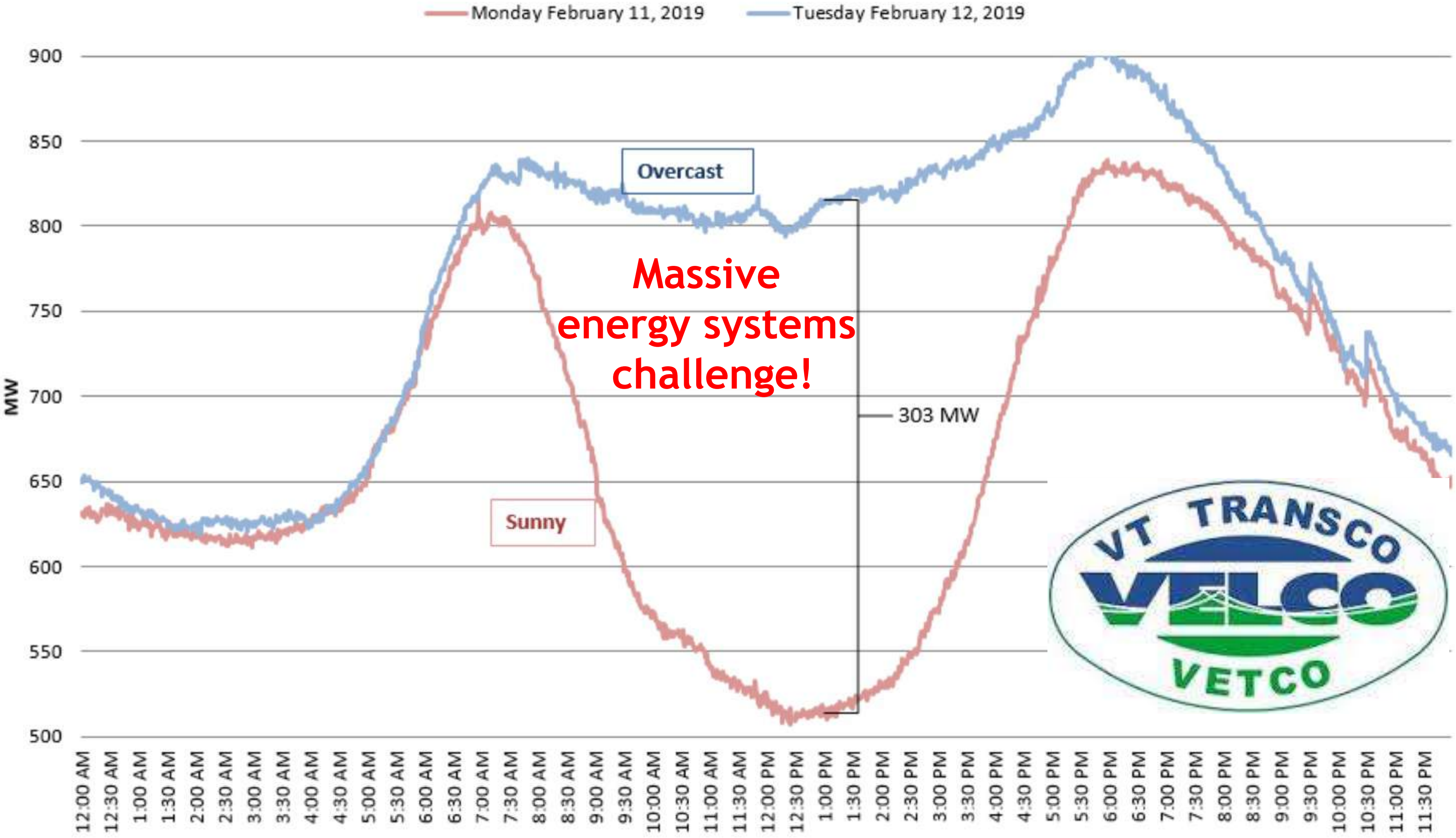
Burlington Electric Department

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

FAST COMPANY

GREEN MOUNTAIN POWER

#1 in 2018 (Energy)
#5 in 2019 (Energy)



VT TRANSCO VELCO VETCO

Why does it matter? Economies are going green!

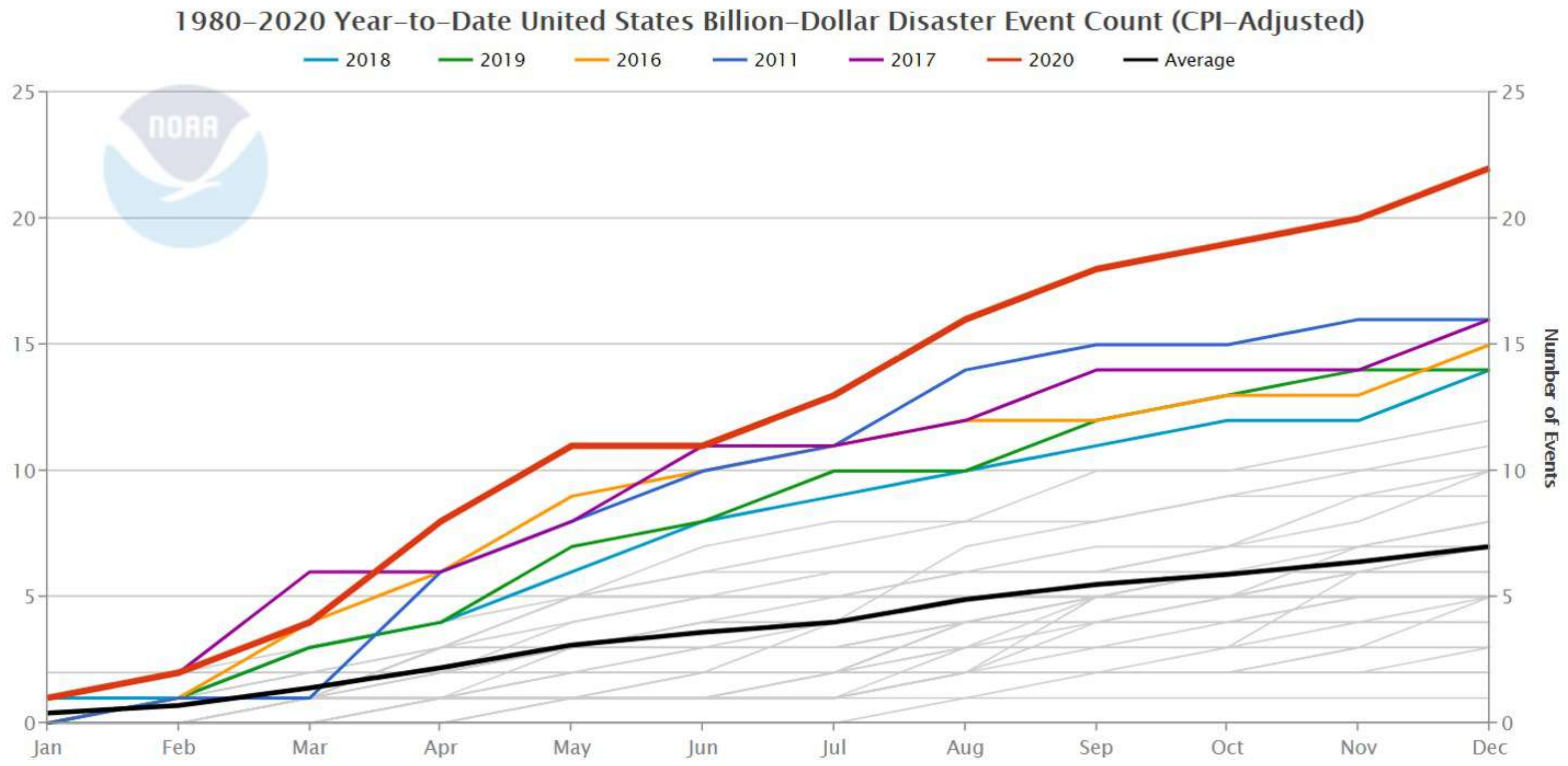
$1.3T — Annual sales revenue

10M — Jobs supported

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

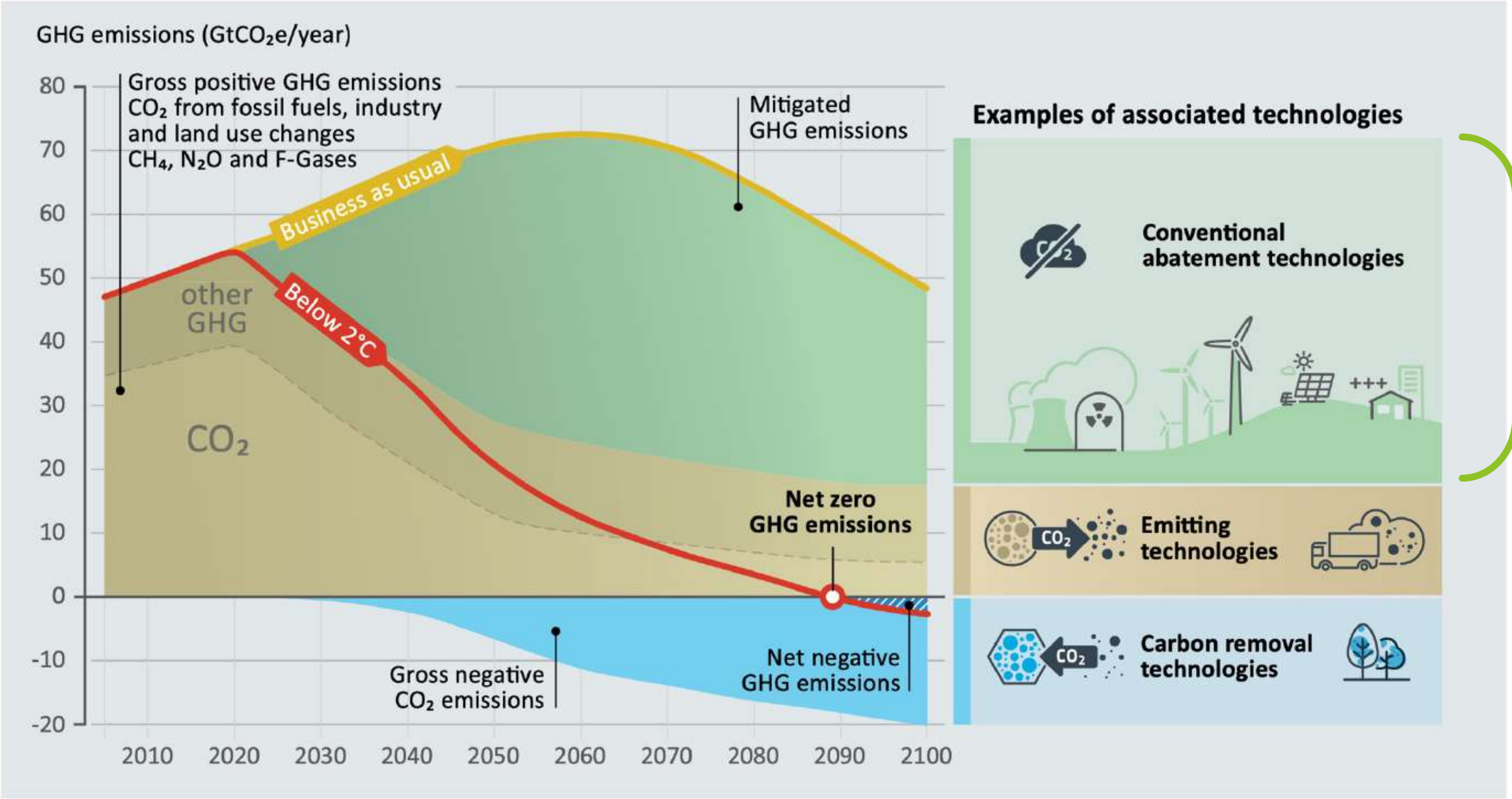
Georgeson, L., Maslin, M. “Estimating the scale of the US green economy within the global context.” *Palgrave Communications* 5, 121 (2019)

Why does it matter? Inaction is inexcusable!



NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2020)

Solutions? If they work, they will matter!



Requires massive TW-scale renewable integration

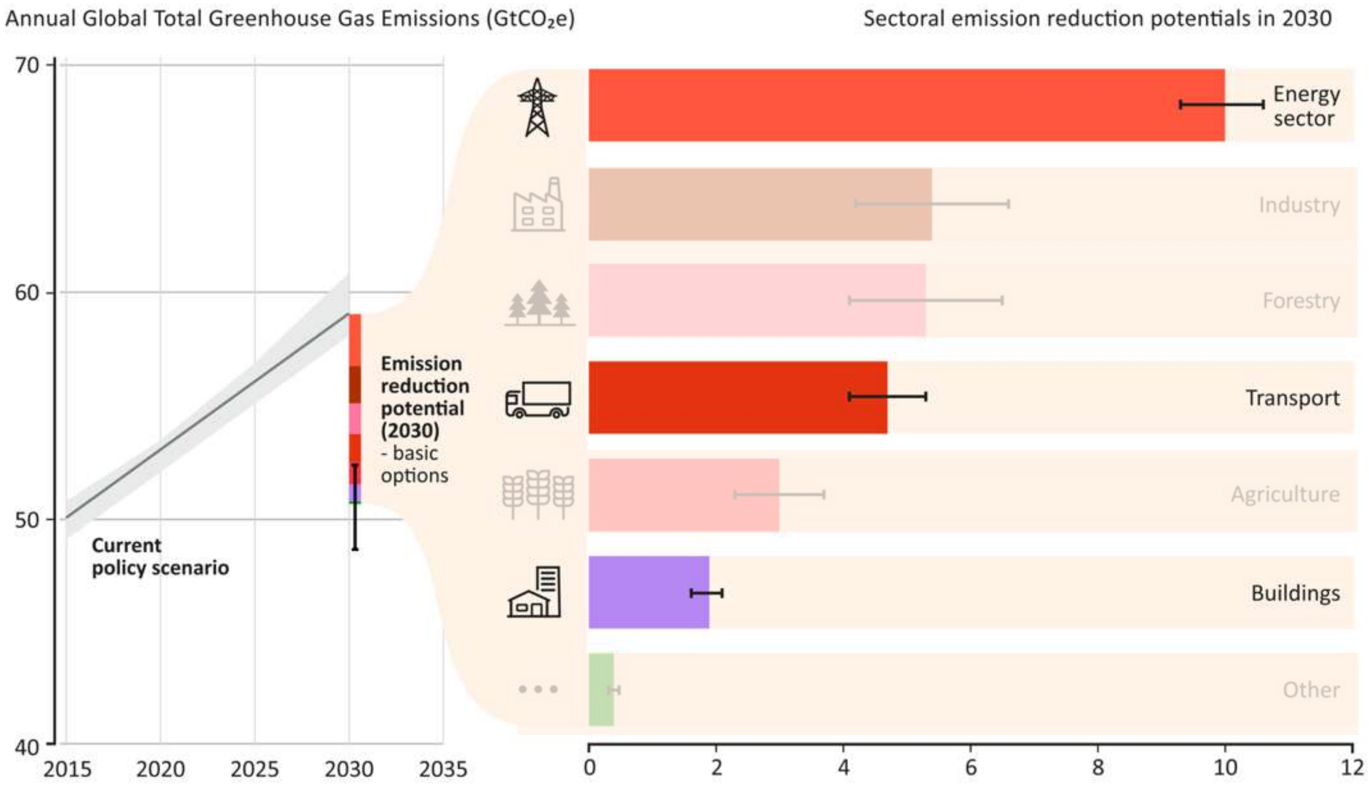
A massive power systems challenge!

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

UN Environmental Program, Emission Gap Report 2017 (Chapter 7)

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]

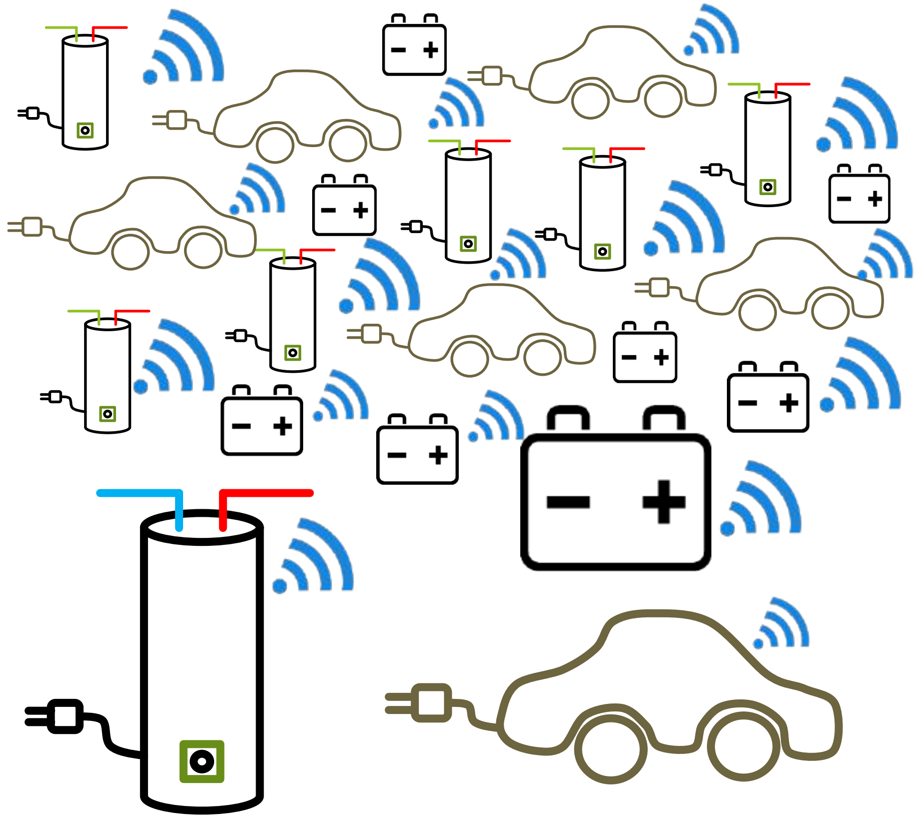
59GW of DR today will become **200GW of flexible demand by 2030** [3]

How to coordinate <u>millions</u> 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



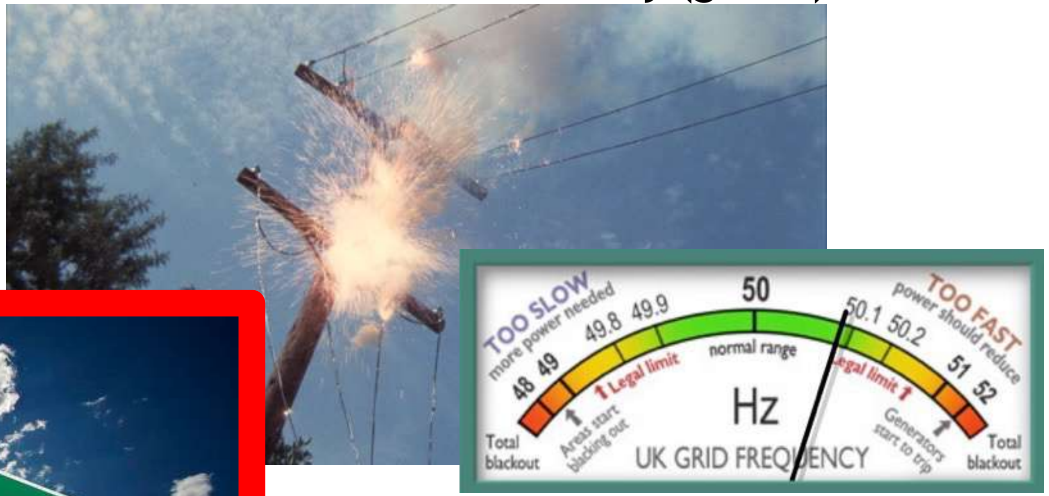
Every neighborhood[1], feeder, or city[2,3,4] can become a dispatchable resource

[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

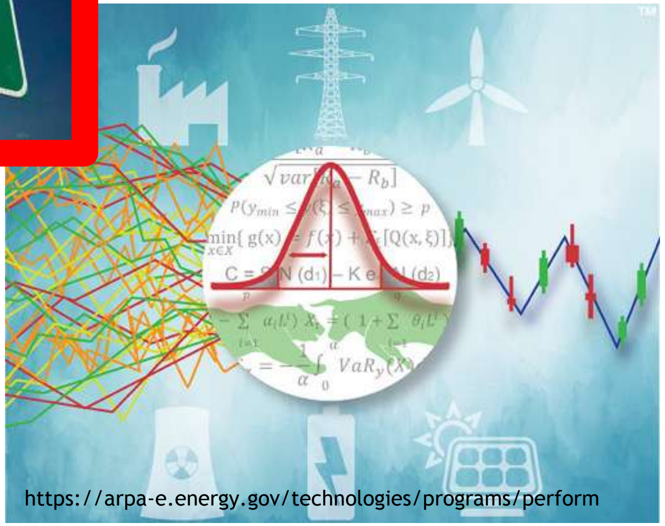
Comfort & convenience (local)

Grid conditions & reliability (global)



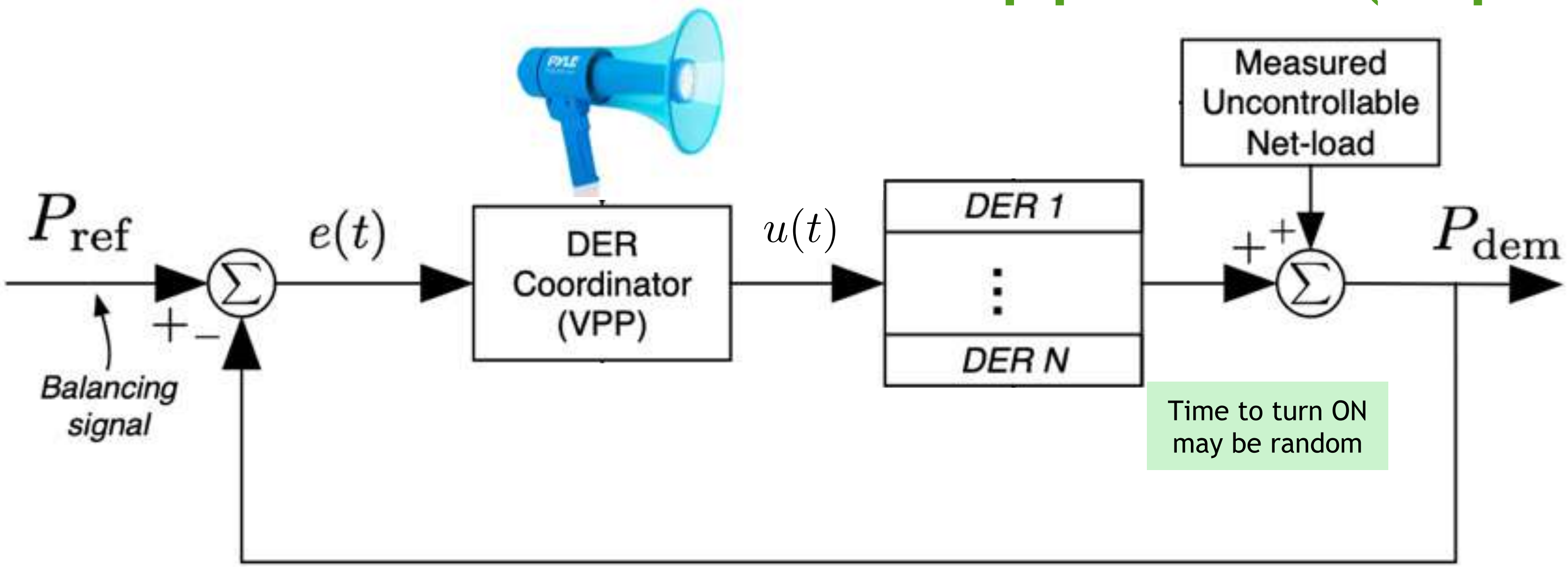
Cyber-security & Data privacy

Business models & risk management

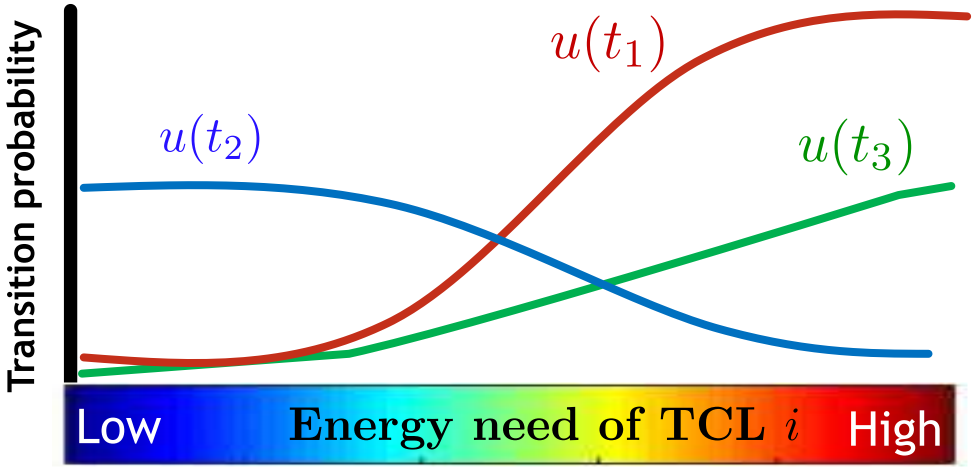


https://arpa-e.energy.gov/technologies/programs/perform

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



Local device logic can guarantee QoS



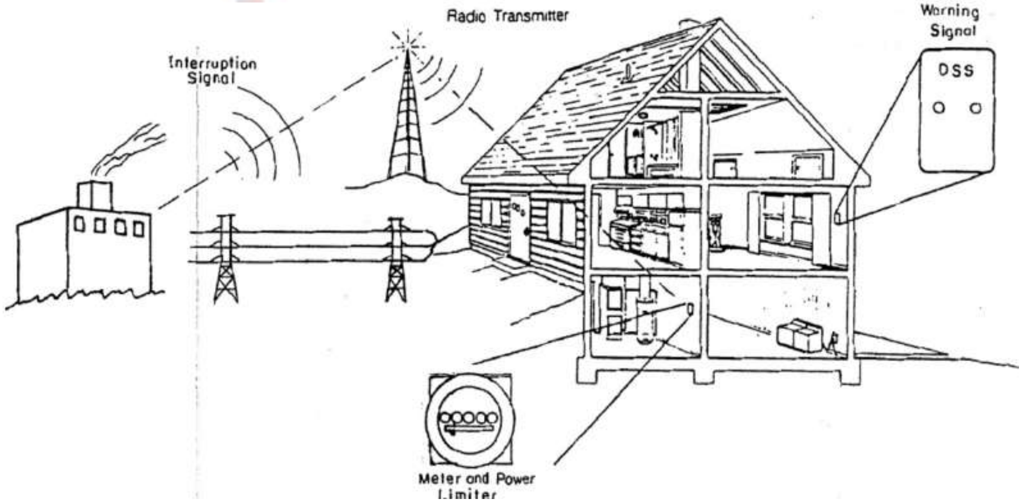
Broadcast control signal to all devices **synchronously.** Control signal may be **explicit price or implicit PDF.**

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

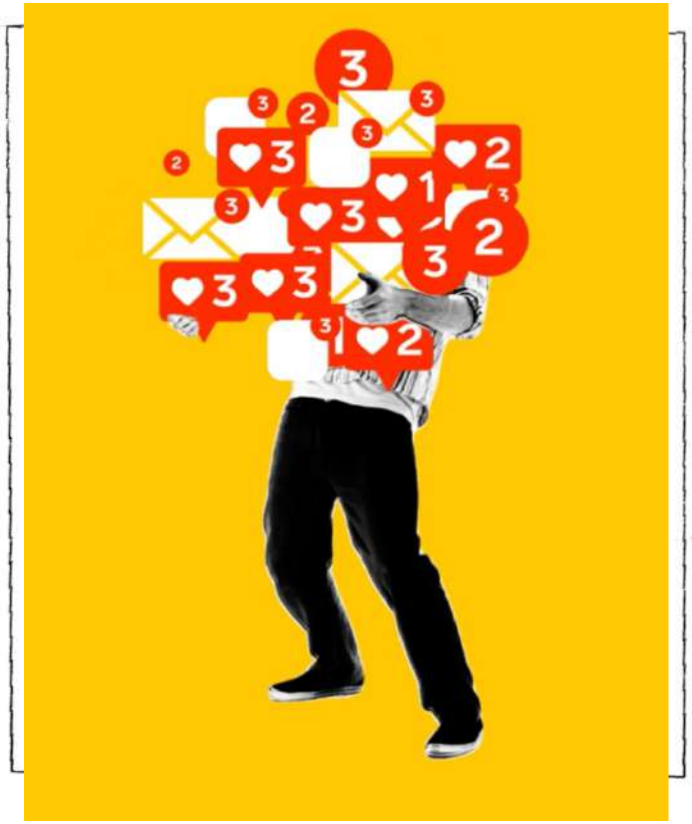
<u>**But**</u> challenging to distinguish individual device constraints or grid location (i.e., DER cycling and local grid conditions).

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

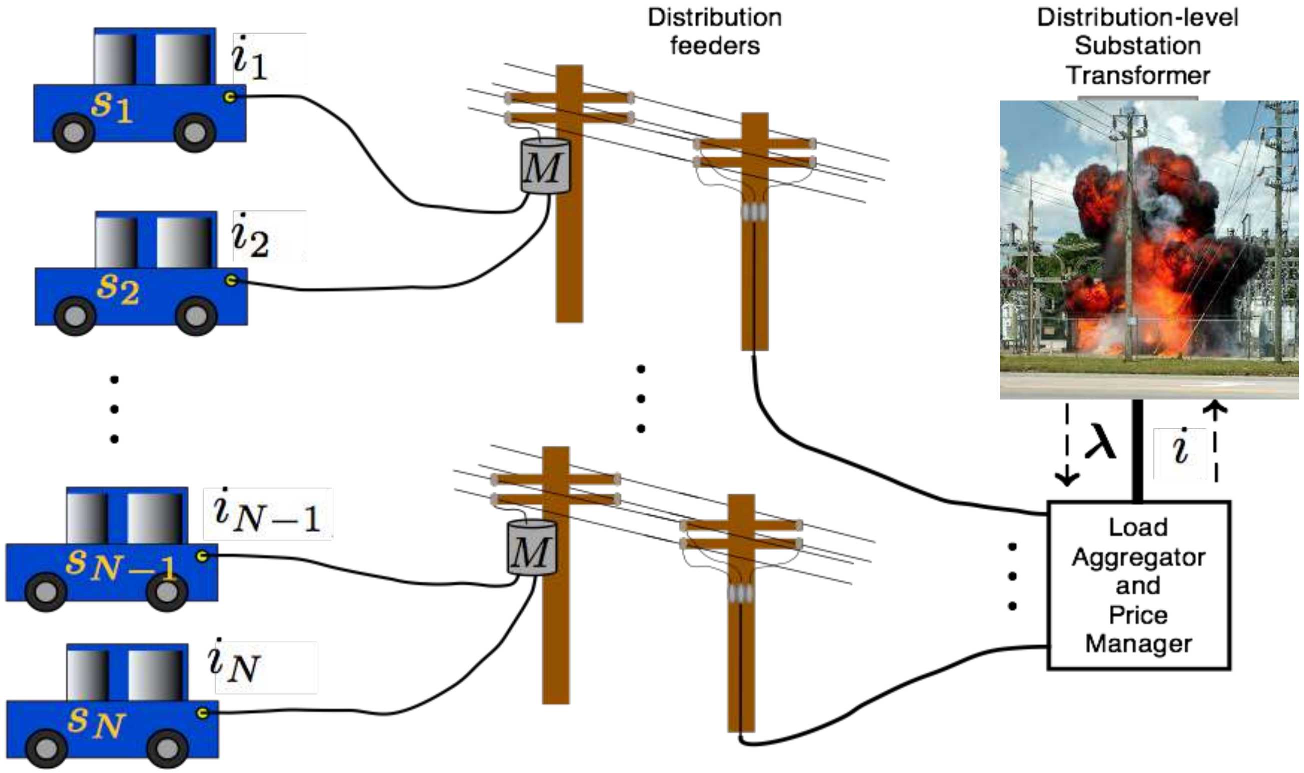
Human becomes the actuator in-the-loop

Source: VectorStock.com/7537816

Another example: direct load control or TOU pricing

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 ➔ overload
➔ overheat ➔ insulation loss

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

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

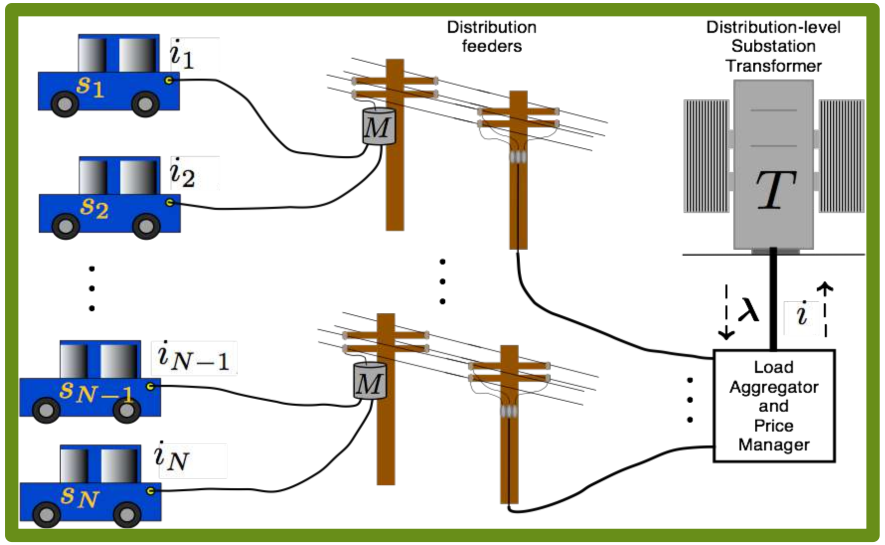
Aggregate current couples decisions:

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

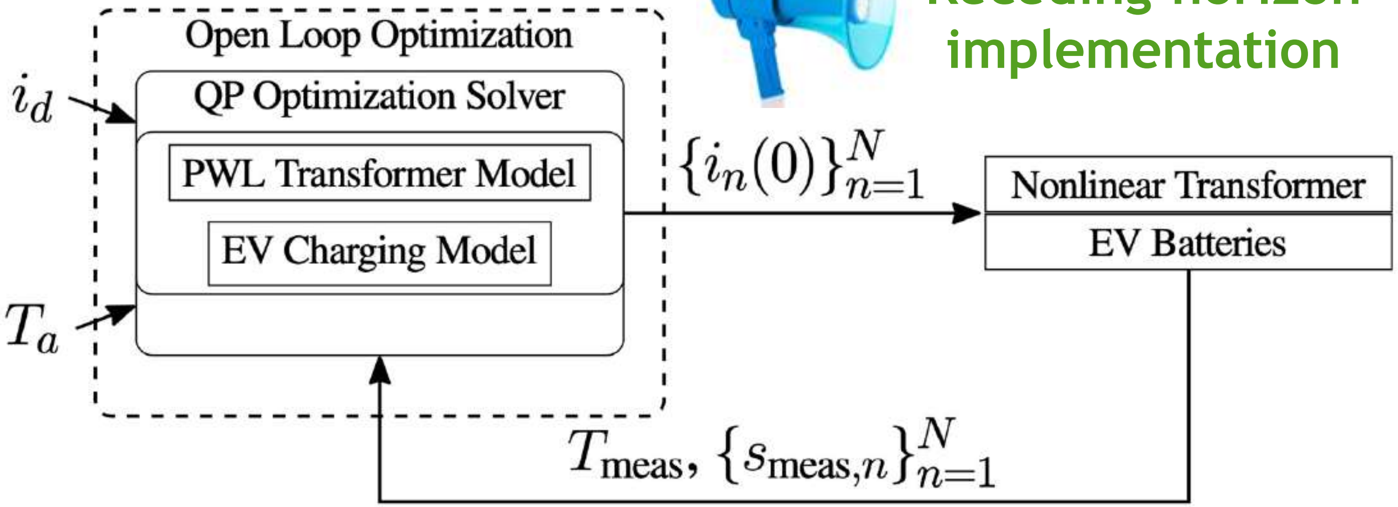
M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

EV charging scenario: direct load control

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



Receding-horizon implementation



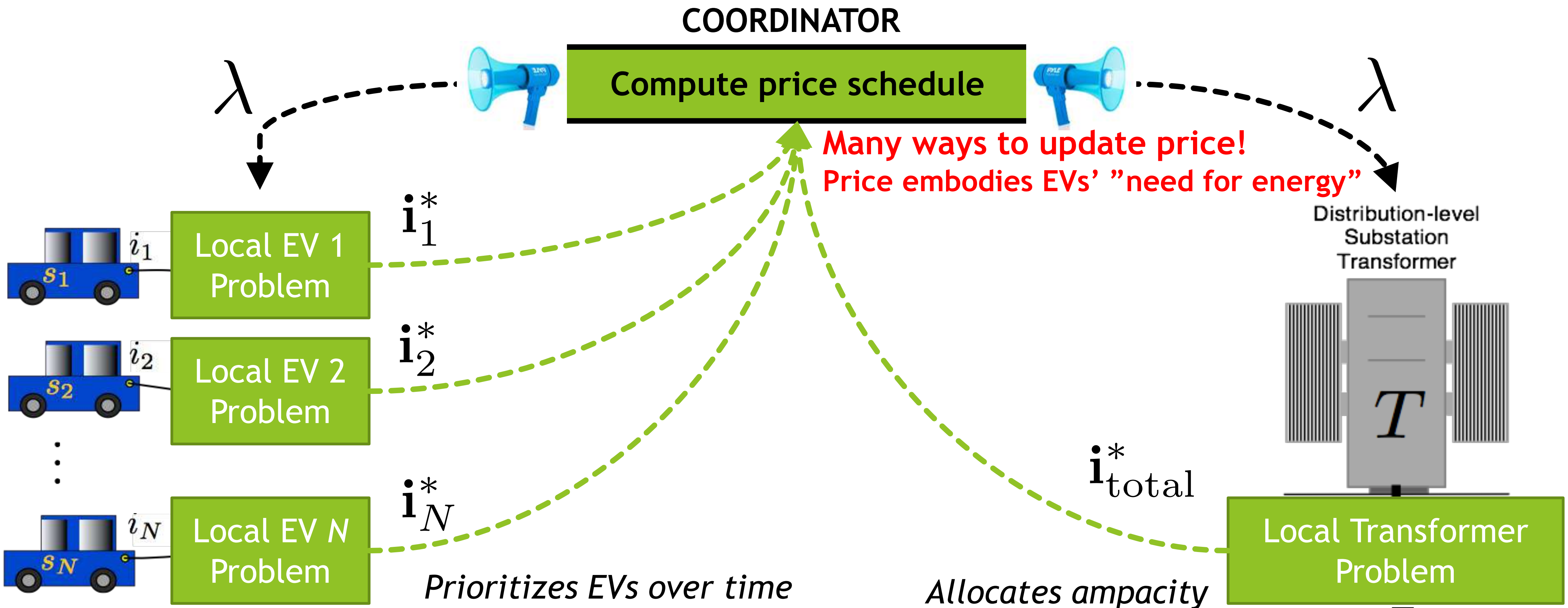
charge quickly! *limit high currents*

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

M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

EV charging scenario: indirect load control

With <u>limited</u> information (EVs do not share specs), solve <u>distributed control problem</u>



Prioritizes EVs over time

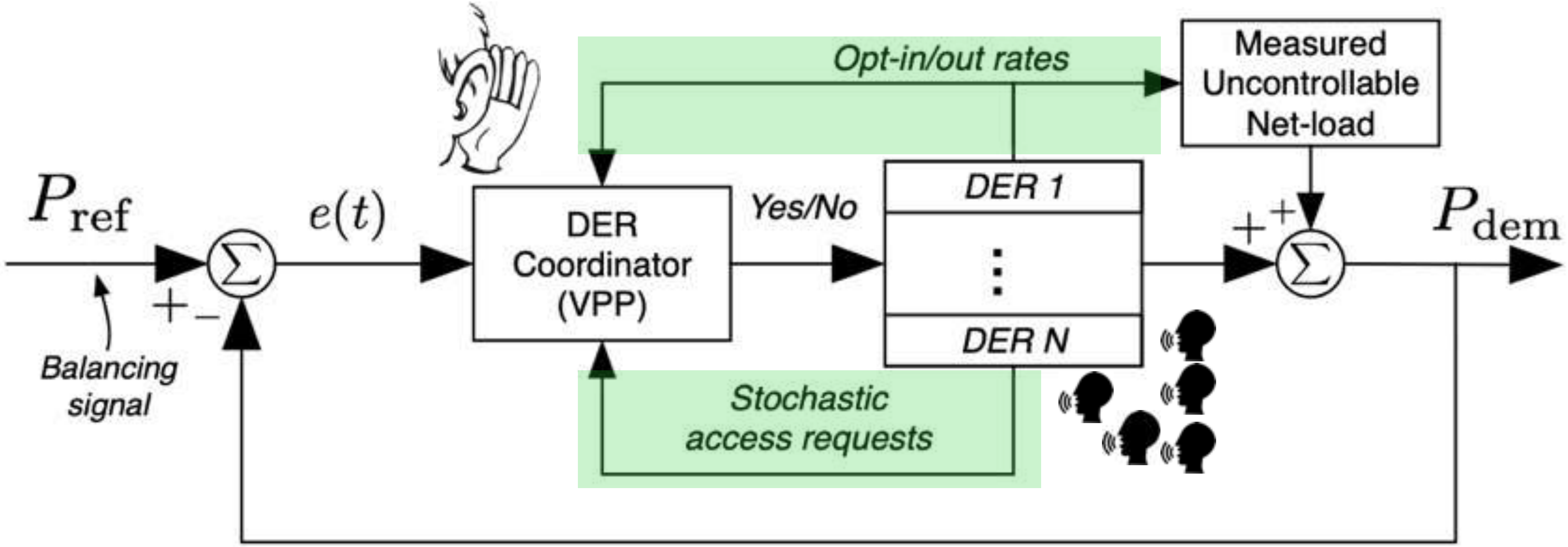
$$\min_{\mathbf{i}_n} J_n(\mathbf{i}_n, \mathbf{s}_n) + \lambda^\top \mathbf{i}_n$$

Allocates ampacity ahead of time

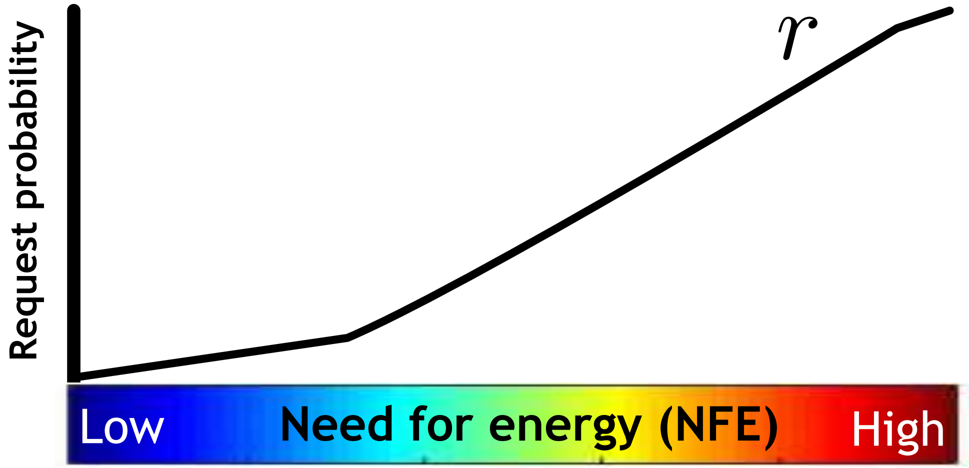
$$\min_{\mathbf{i}_{\text{total}}} -\lambda^\top \mathbf{i}_{\text{total}}$$

M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

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



Local device logic guarantees QoS



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

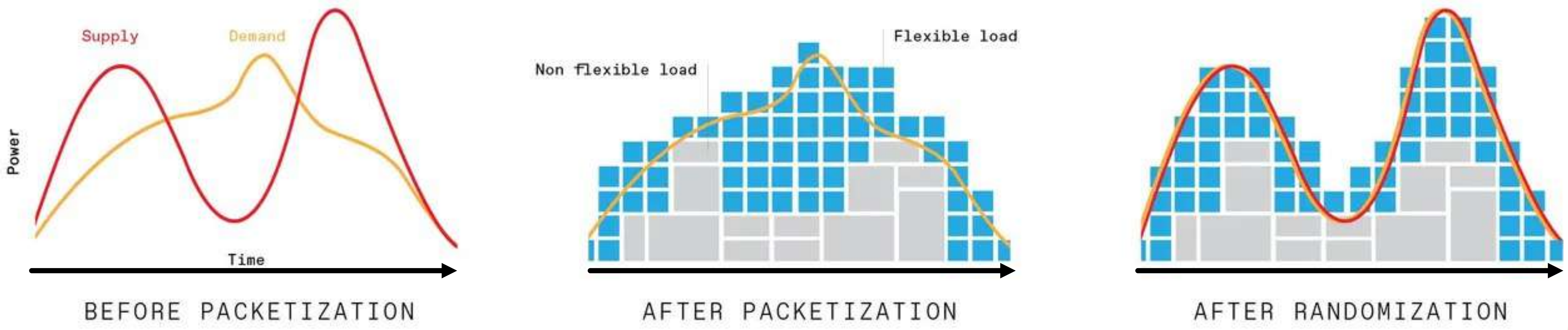
Packetization of data on Internet

Random access protocols

Method is called <u>packetized energy management</u> (PEM)

PEM for a fleet: coordination & flexibility

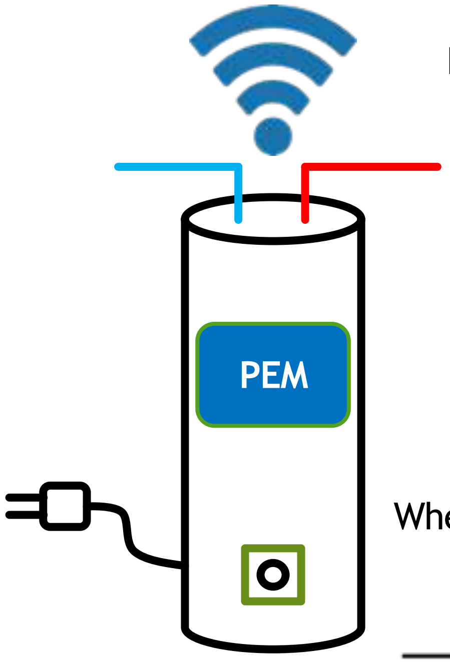
- **Inspired by how the Internet works:** PEM is a scalable concept
  - **Bottom-up** approach: local intelligence enables devices to learn their **need for energy** (comfort)
  - **Randomization** of requests: device stochastically request a packet based on **need for energy**
  - **Packetization**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



Device's *need for energy* (NFE) drives its *mean time to request* (MTTR) → **stochastic requests**

Packetizing bulky consumption → many smaller **energy packets**

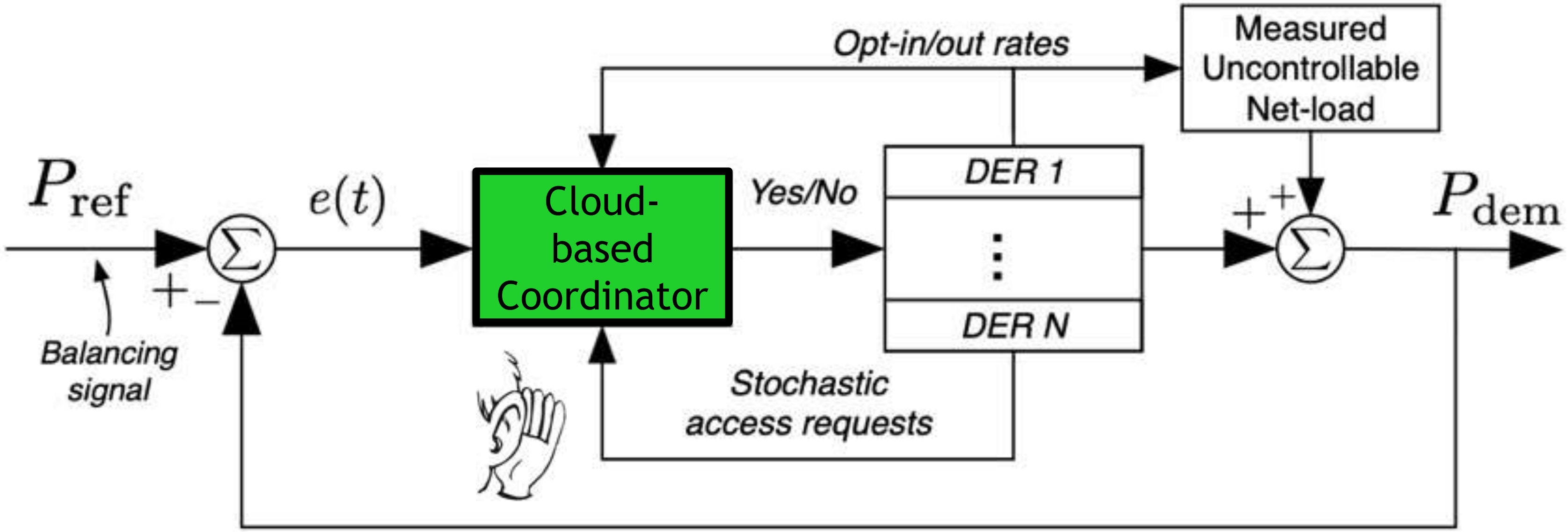
When temperature is low, heating elements turns ON
and consumes energy → *bulky demand*

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

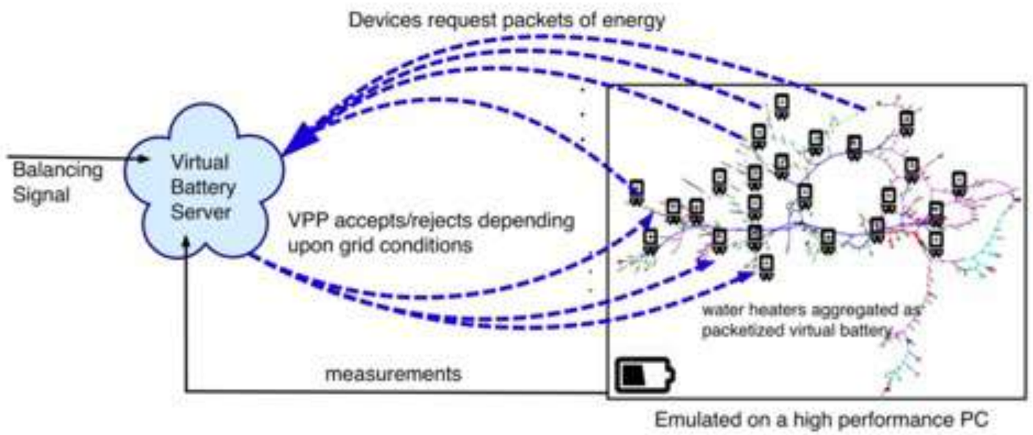
- Coordinator accepts/denies request based on power reference tracking error, so control mechanism is simple, but powerful

<u>Modulate acceptance rate of packet requests</u> ➔ Regulate aggregate demand

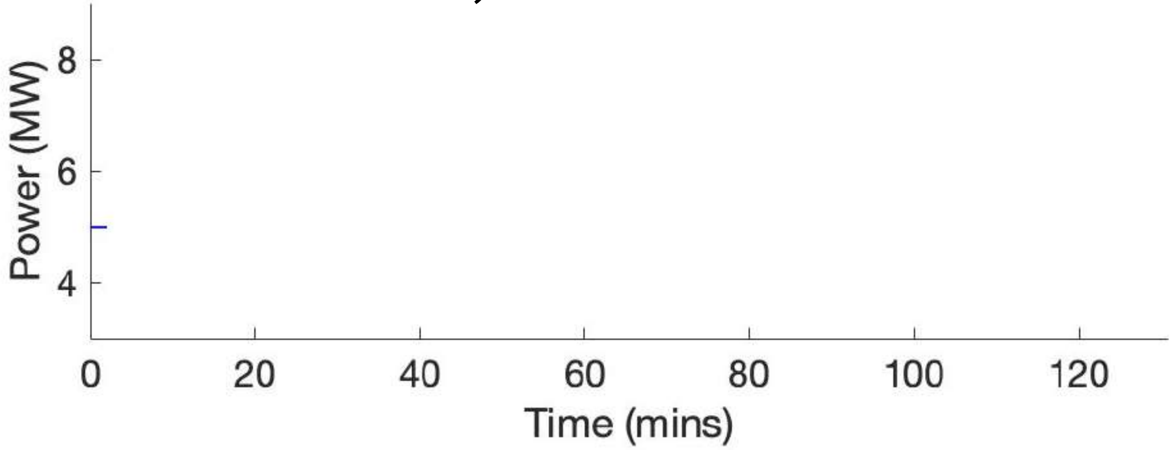


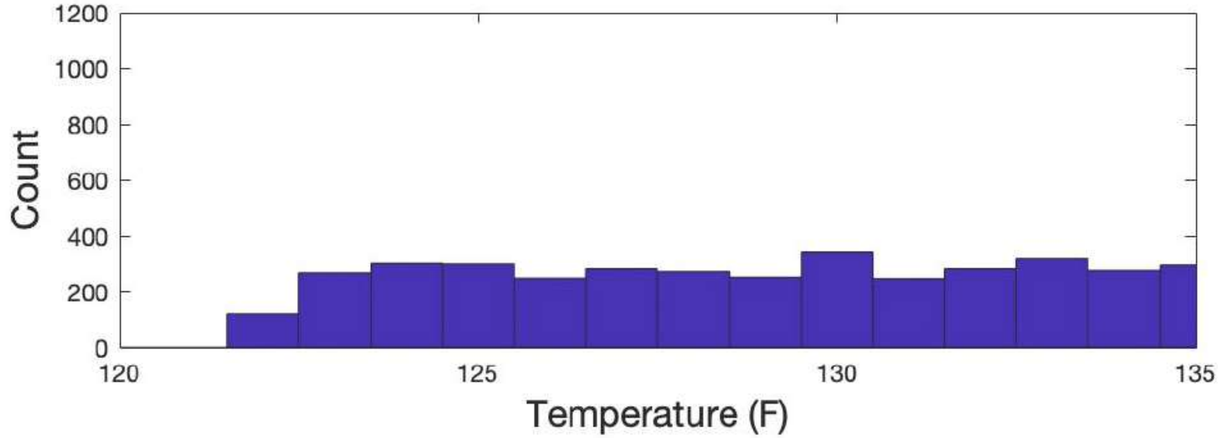
Incoming request rates are based on devices' <u>NFE</u> and leads to light event-based comm overhead!

Built scalable, real-time DER cyber test-bed



5000 real-time, emulated PEM water heaters

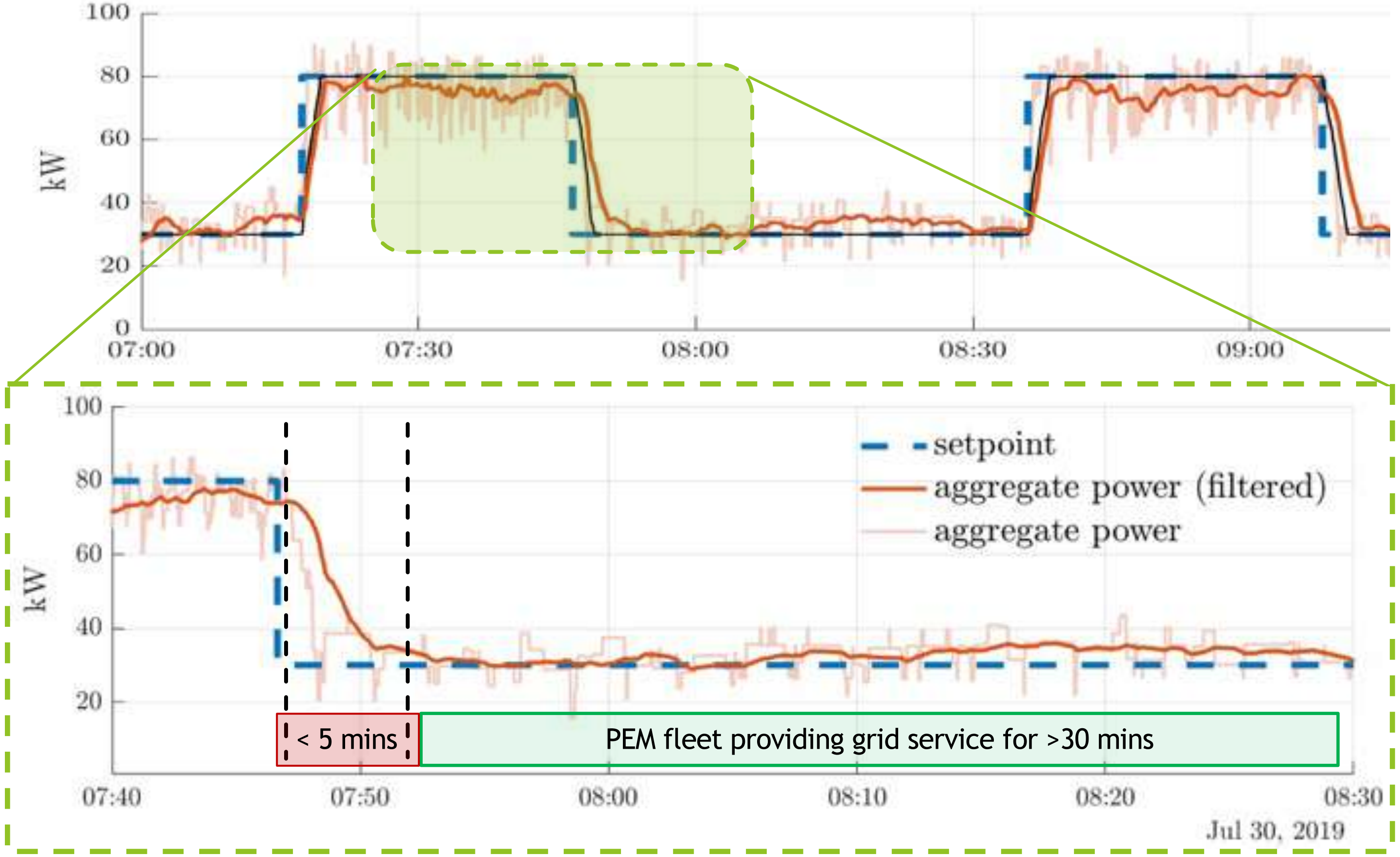




M. Amini, et al. “A Model-Predictive Control Method for Coordinating Virtual Power Plants and Packetized Resources, with Hardware-in-the-Loop Validation”. In: *IEEE PES General Meeting*. Atlanta, Georgia, 2019

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

Completed field trial with > 150 loads in 2019

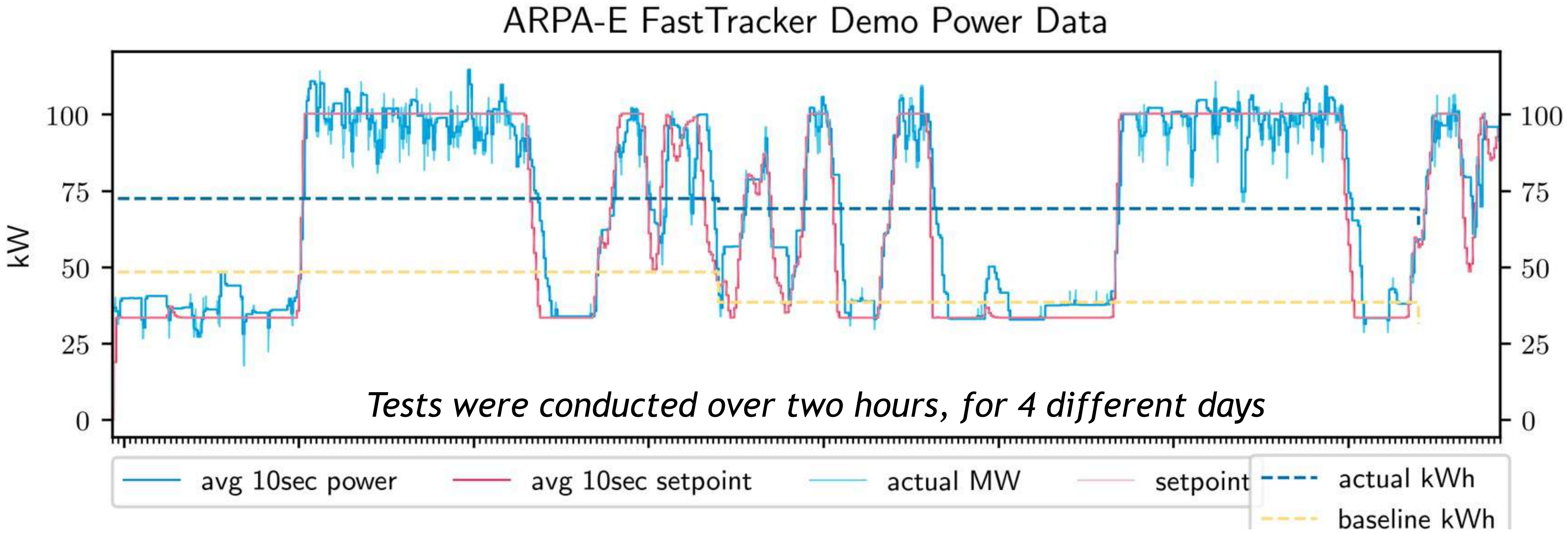


Actively studying the dynamics of the "Aggregation" based on communication & controls

S. Brahma, A. Khurram, H. Ossareh, and M. Almassalkhi, "Optimal Frequency Regulation using Packetized Energy Management," Under review (Rev02)

Faster: demo w/ 200+ homes in December 2021

PEM demonstrates frequency regulation!



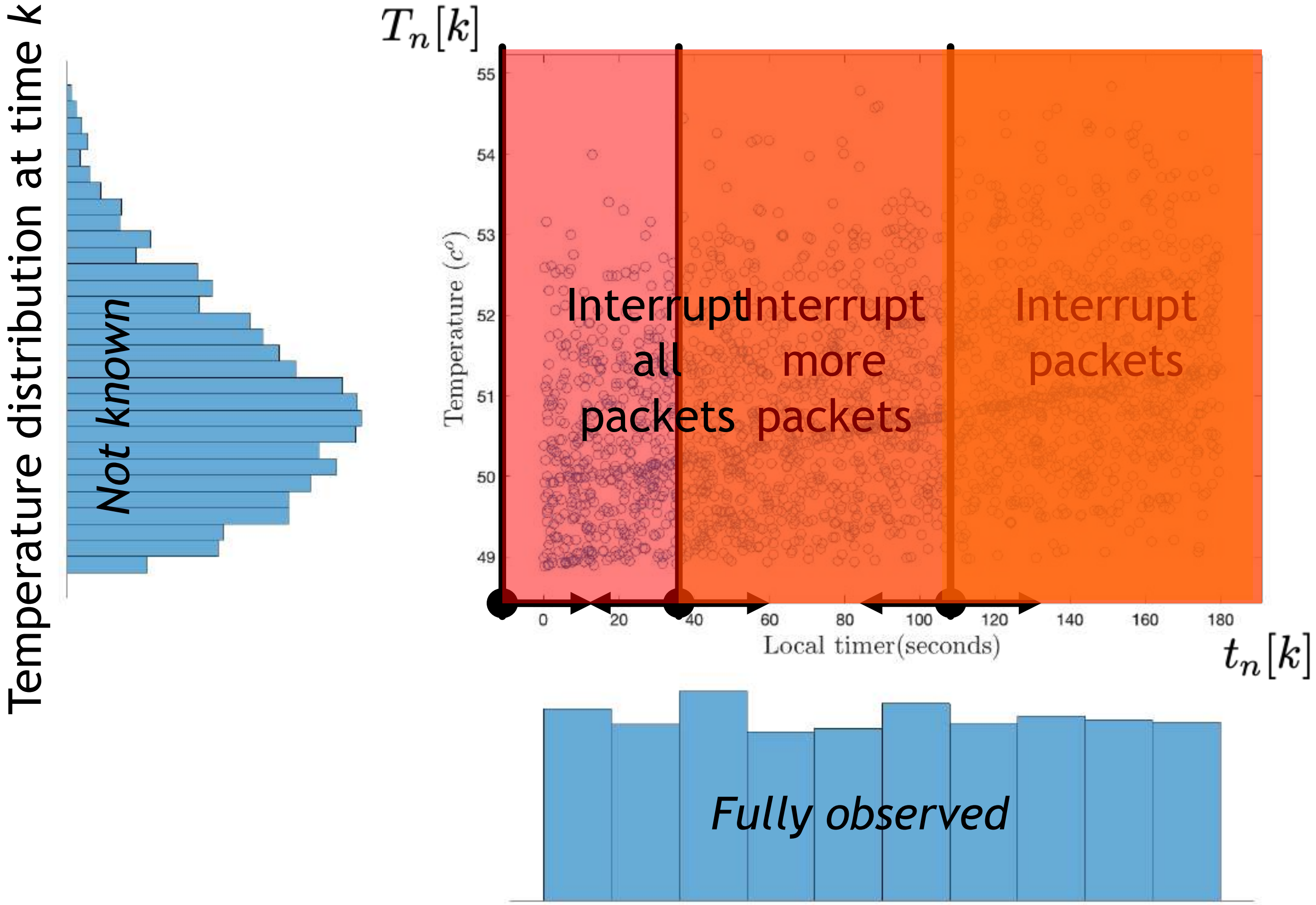
Pay-for-performance:
PJM Performance score

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

M. Almassalkhi, J. Frolik, and P. Hines, "How To Prevent Blackouts By Packetizing The Power Grid" *IEEE Spectrum*, February, 2022.

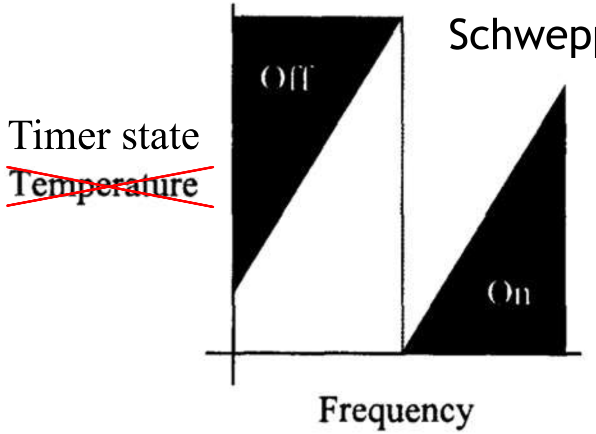
Even faster: damping with decentralized PEM



Distribution of timer states at time *k*
$(n_p = 10)$

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 <u>*interrupt*</u> its packet

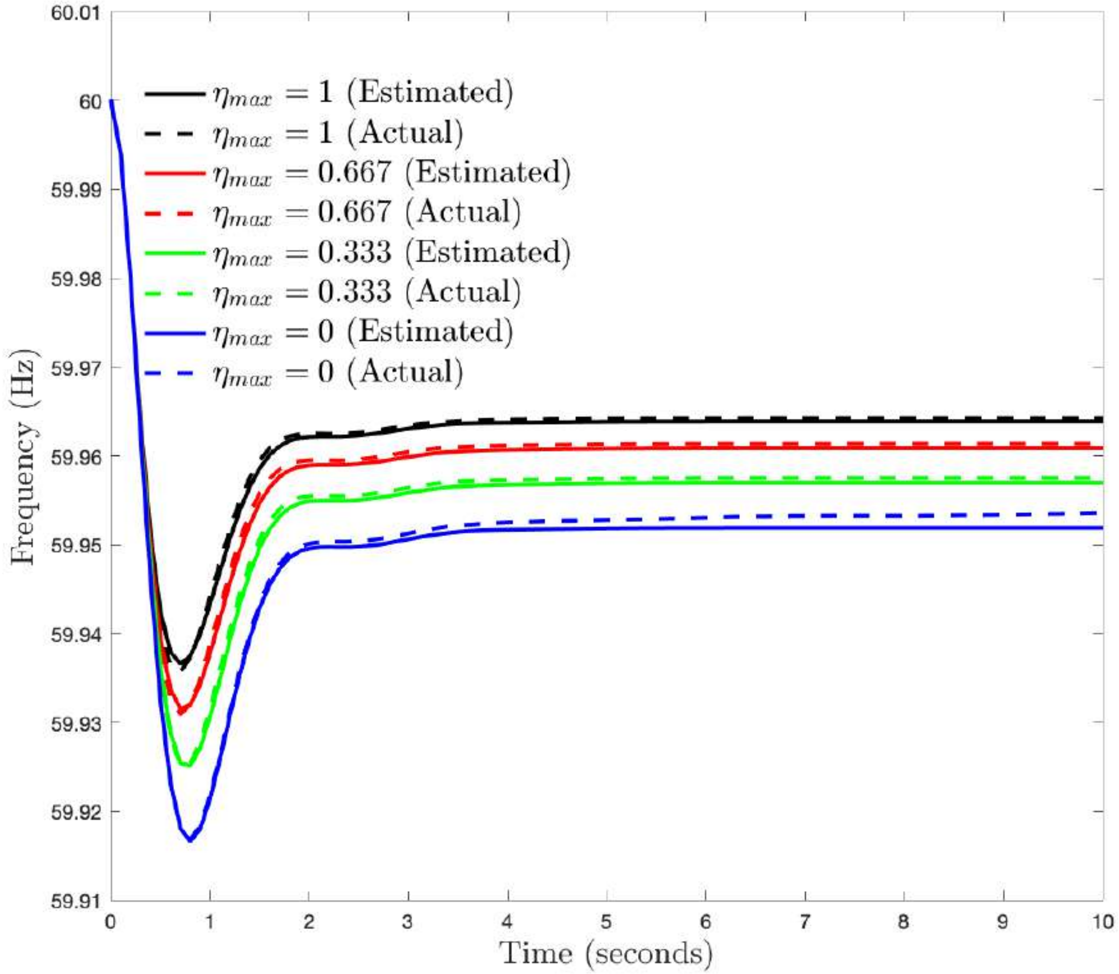


Schweppe's FAPER from 1980

H. Mavalizadeh, L. Duffaut Espinosa, and M. Almassalkhi, "*Decentralized Frequency Control using Packet-based Energy Coordination,*" IEEE SmartGridComm, 2020

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.



H. Mavalizadeh, L. Duffaut Espinosa, and M. Almassalkhi, "*Decentralized Frequency Control using Packet-based Energy Coordination*," IEEE SmartGridComm, 2020

Back to EV charging: exploring NFE

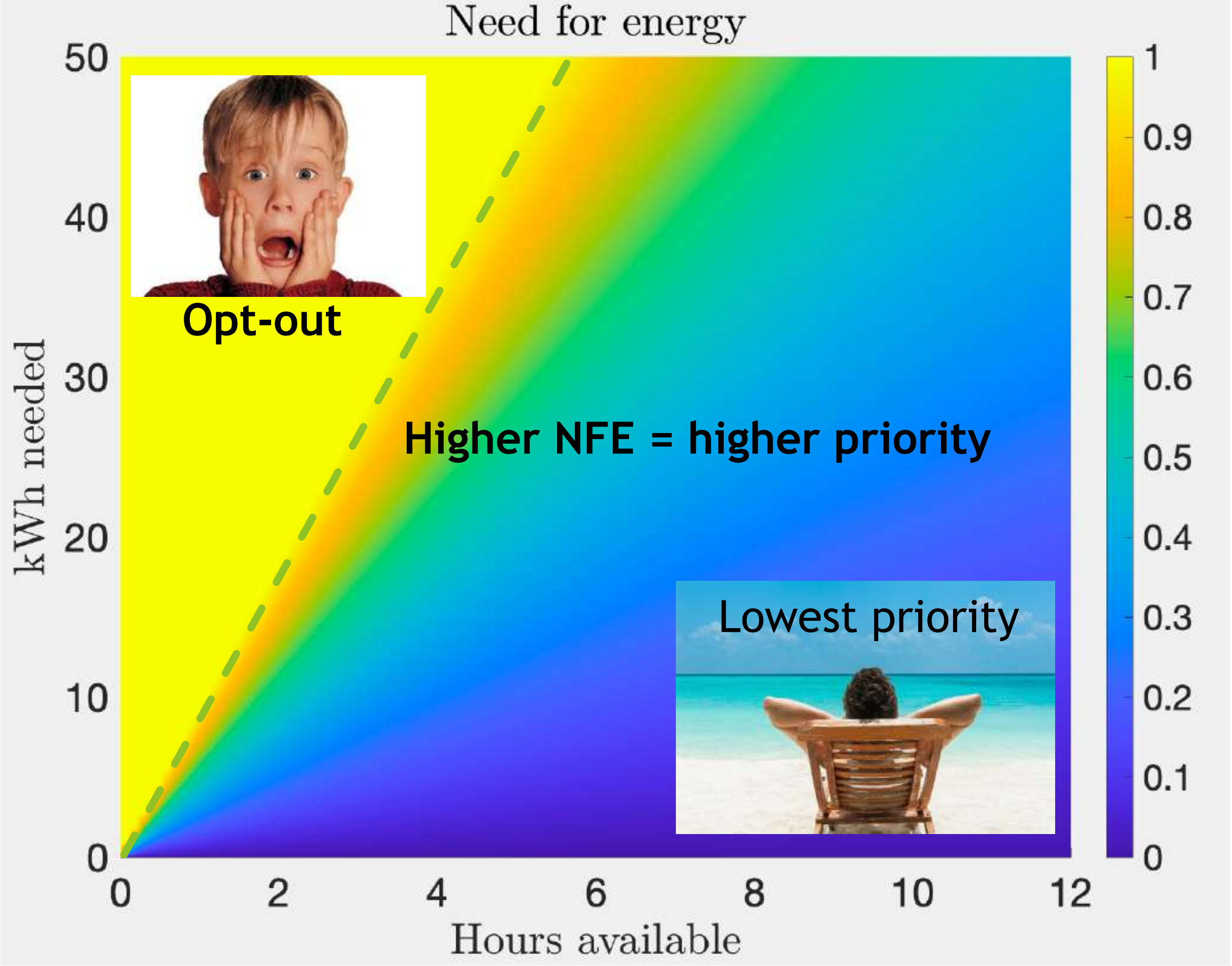
$$\text{NFE}_n[k] = \frac{\text{kWh needed}}{\eta_n p_n^{\max}(\text{hours left})}$$

NFE dynamically prioritizes EVs

if NFE ≥ 1 ➔ Not enough time left to charge
➔ EV n opts out (desperate NFE)

if NFE ~ 0 ➔ No need to charge (low NFE)

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



M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

Look-ahead PEM: need for energy (NFE)

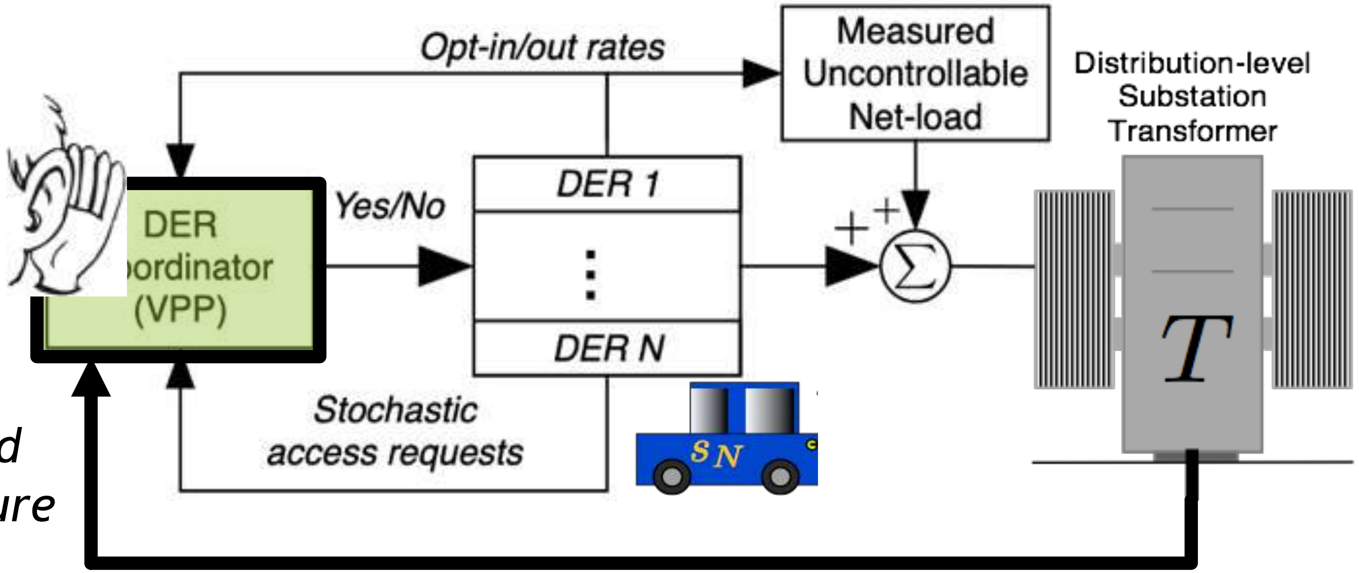
Coordinator optimally accepts packet requests while keeping transformer from overloading

PEM COORDINATOR

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

Predictive model of temperature dynamics

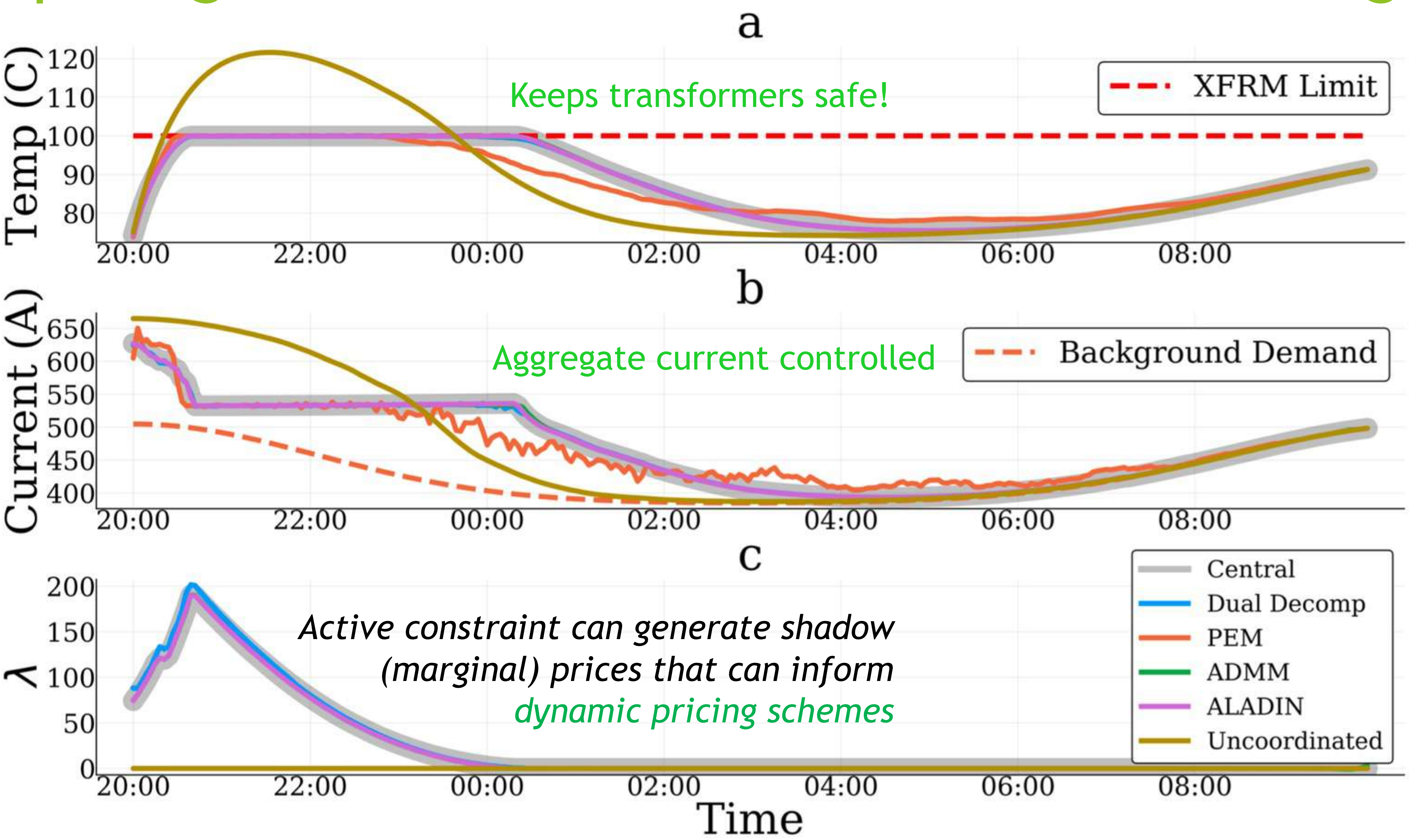
Measured temperature



Key: the number of incoming requests is << *N*

M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

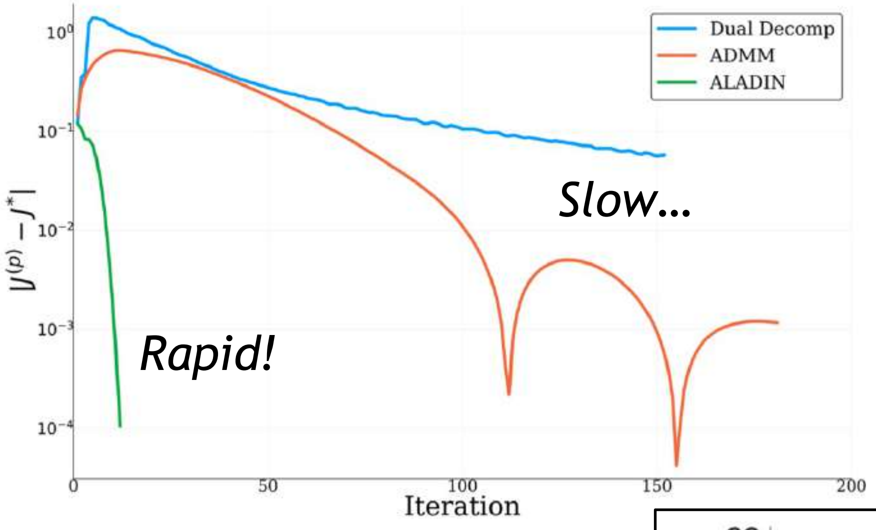
Comparing indirect control methods for EV charging



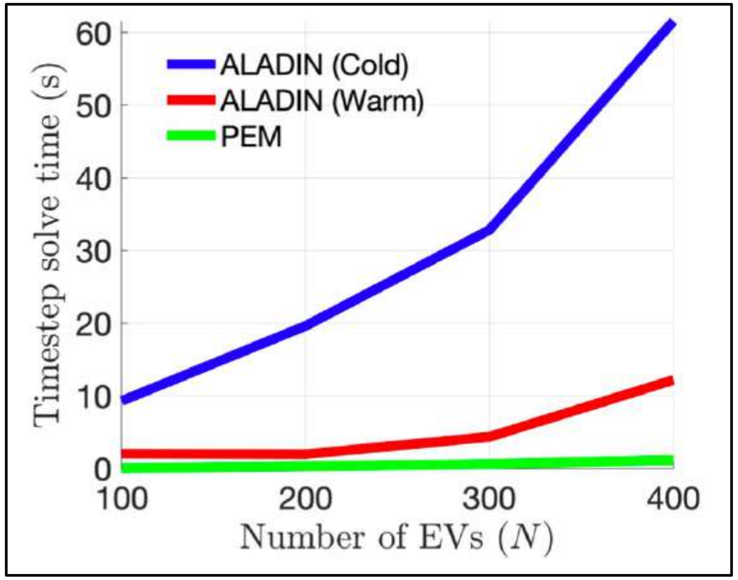
M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

Comparing different methods for EV charging: P^3

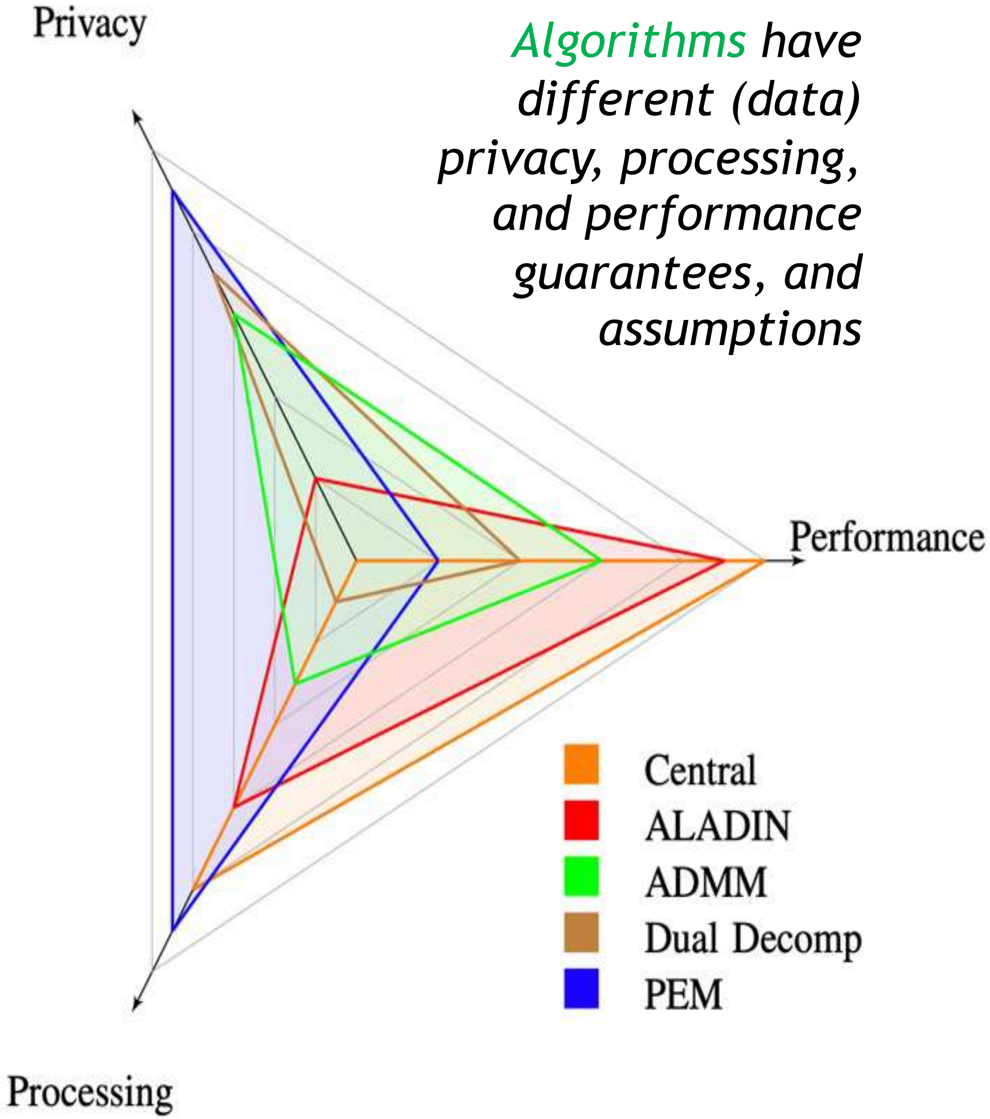
Rates of convergence of price signals depend on info shared



Computational complexity



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

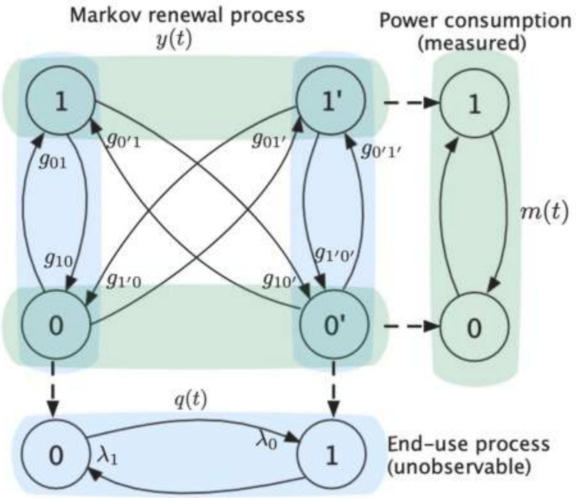


M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

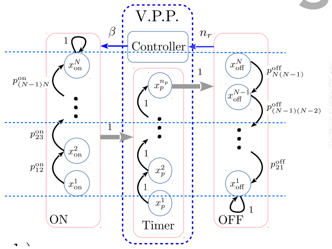
Ongoing research directions with PEM @ scale

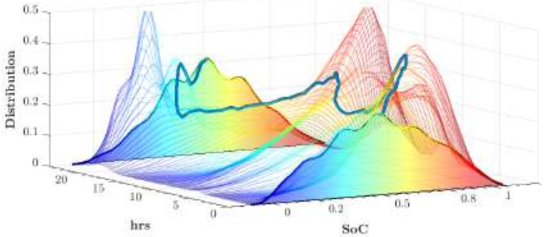
1
Estimate background end-use

Stochastic end-use



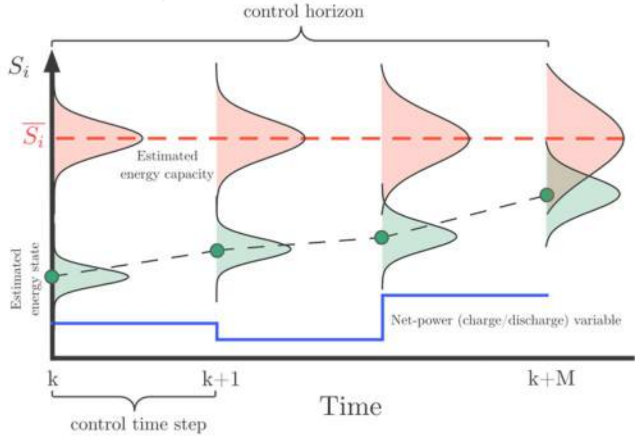
2
Modeling and control





Uncertain resource

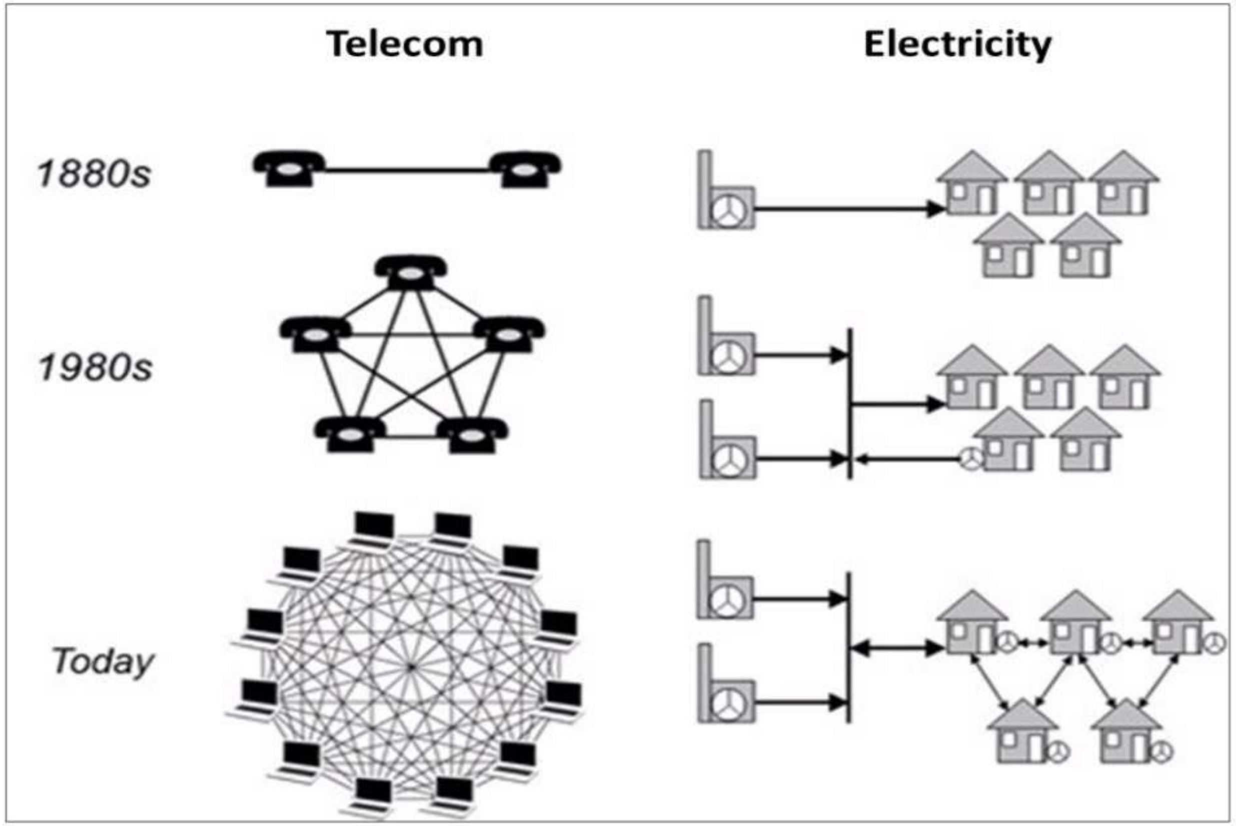
3
Optimal dispatch



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

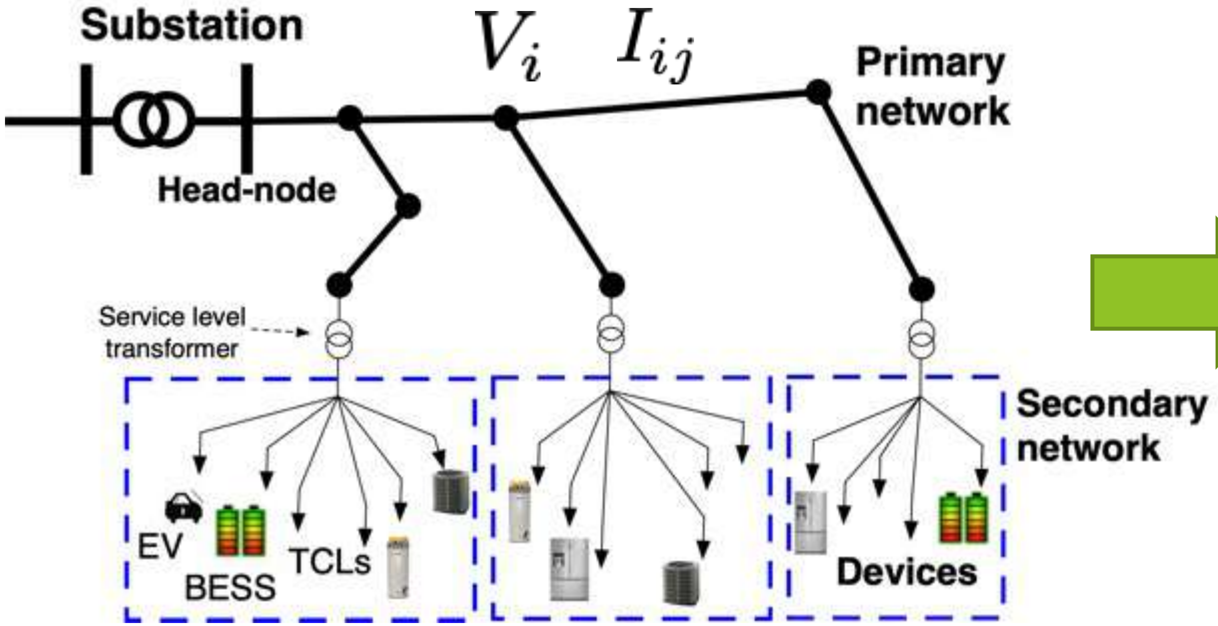
What active role should the grid operator play?

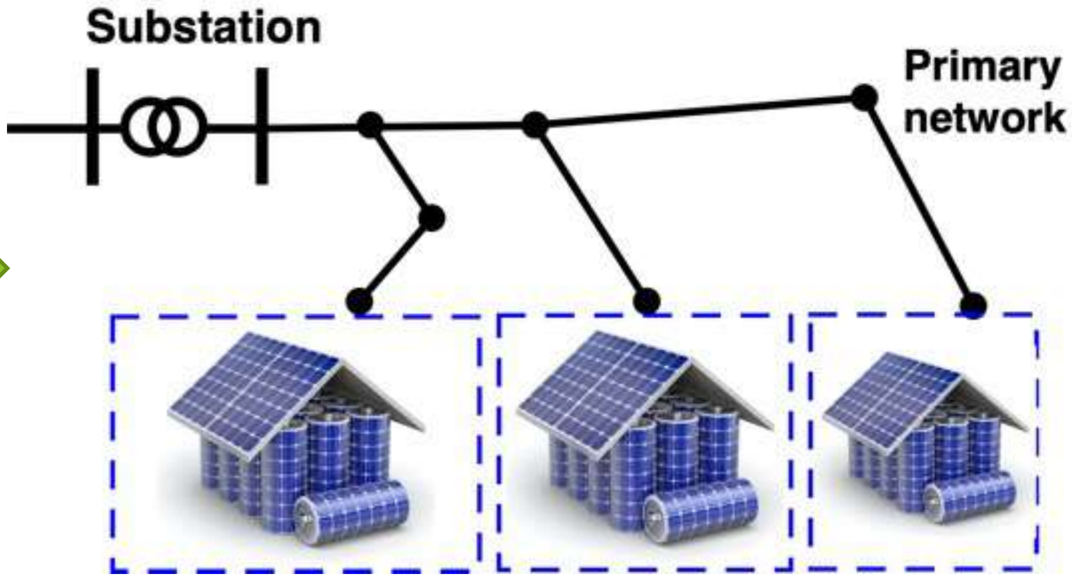
"… create open networks that increase value through the interaction of intelligent devices on the grid and prosumerization of customers Moreover, even ***greater value can be realized through the synergistic effects of convergence of multiple networks****"* [1].



*"****Distribution will also need to become more like transmission*** *by evolving from passive/reactive management to active management"* [2].

Motivating example: characterize aggregate resource





$$m_i \le p_i \le M_i$$

Feeder

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

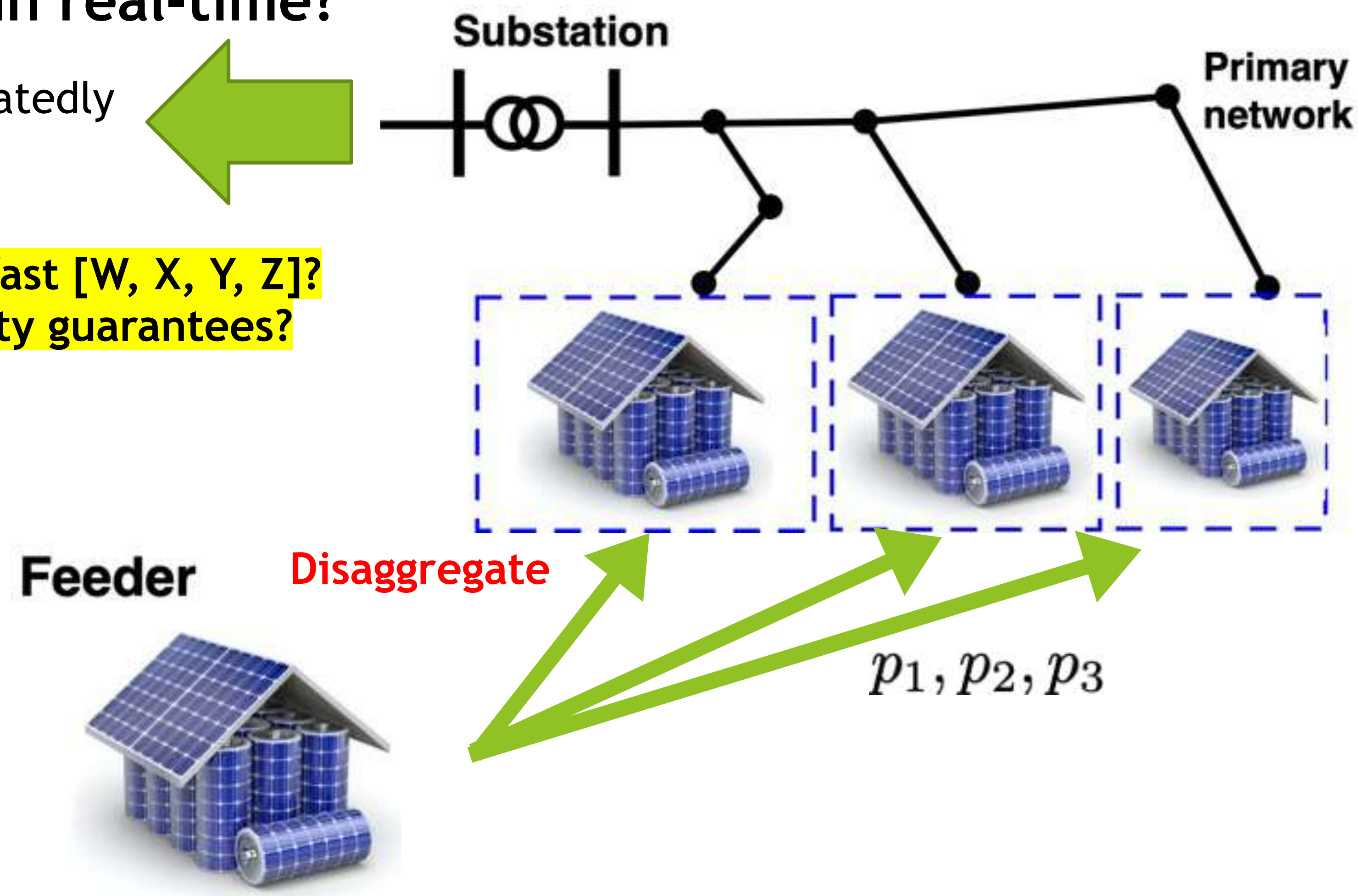
Bid flexibility into whole-sale ISO market (MW)

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)

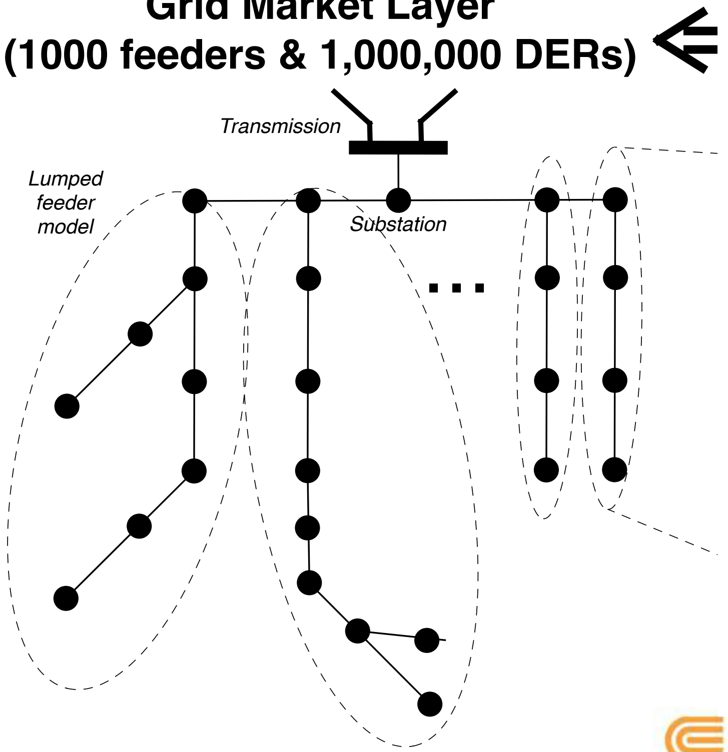


[W] Almassalkhi, et al, "Hierarchical, Grid-Aware, and Economically Optimal Coordination of Distributed Energy Resources in Realistic Distribution Systems," Energies, 2020.
[X] **Nawaf Nazir**, Pavan Racherla, and Mads Almassalkhi, "Optimal multi-period dispatch of distributed energy resources in unbalanced 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

Grid Market Layer
(1000 feeders & 1,000,000 DERs)



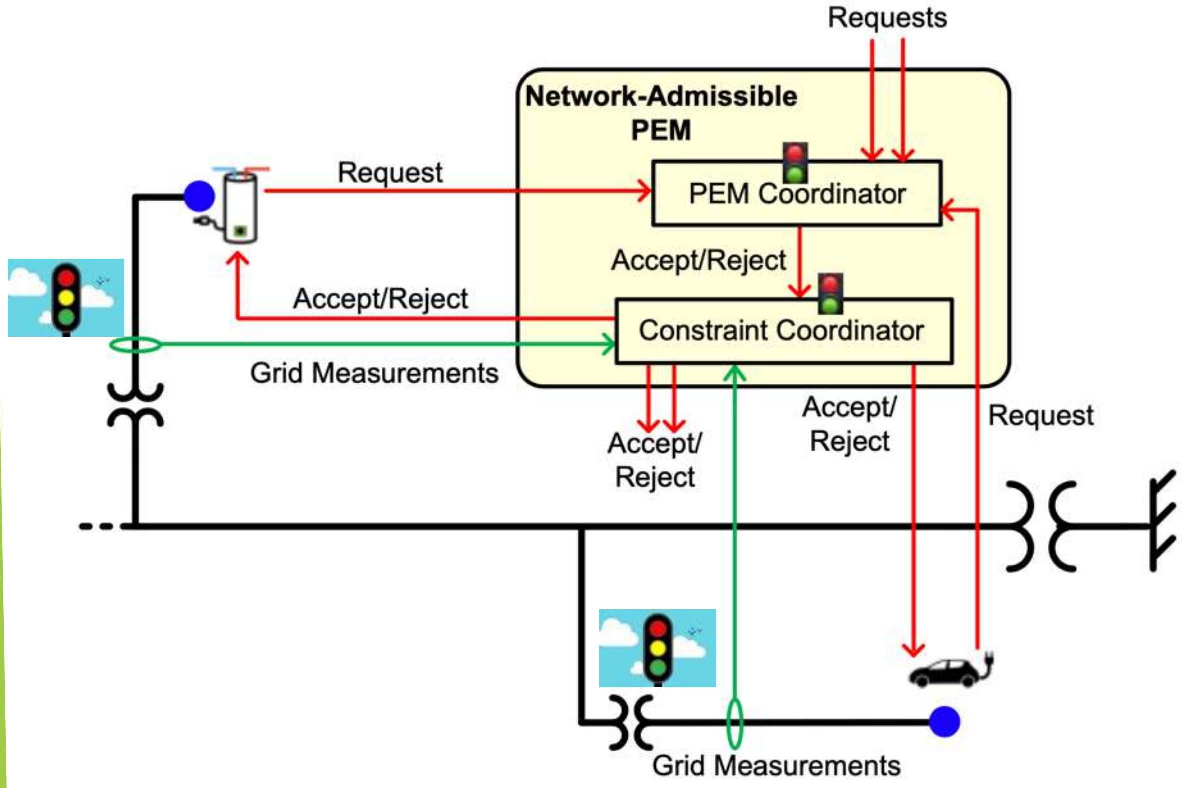
Local flexibility

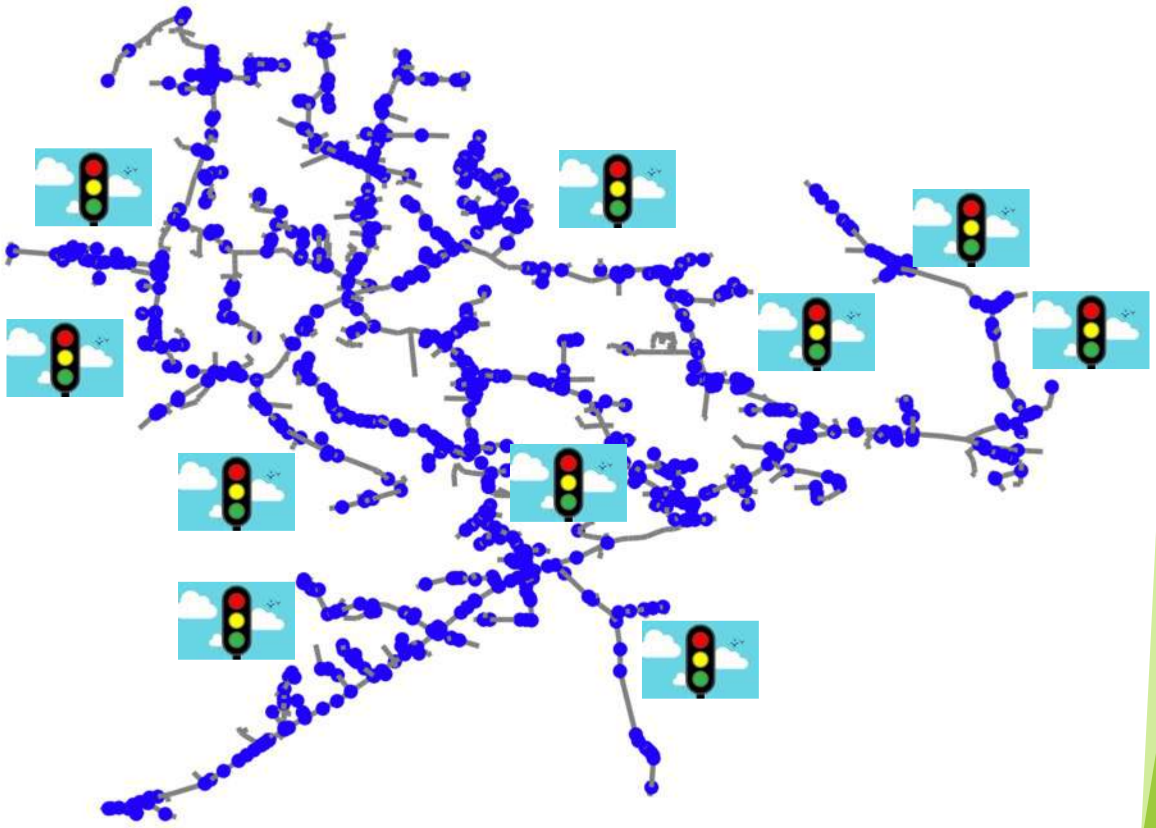
Local flexibility

[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



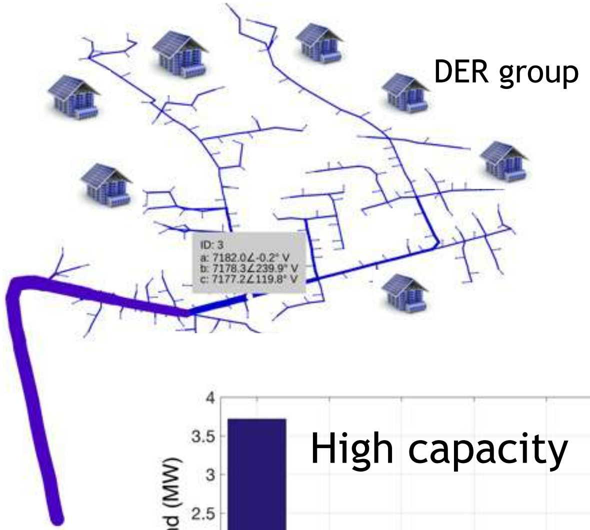


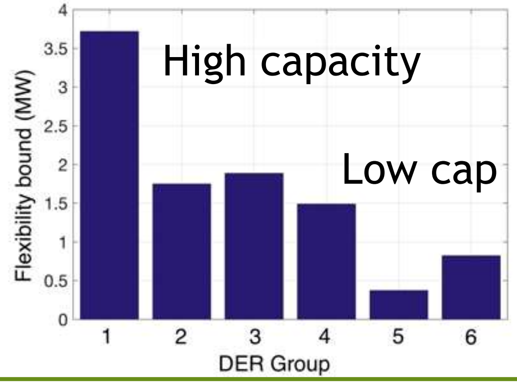
Open questions: measurement types, locations, update rates, data integrity, etc…

A. Khan, S. Paudyal, and M. Almassalkhi, "Performance Evaluation of Network-Admissible Demand Dispatch in Multi-Phase Distribution Grids,". *IREP* 2022 (to appear)

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

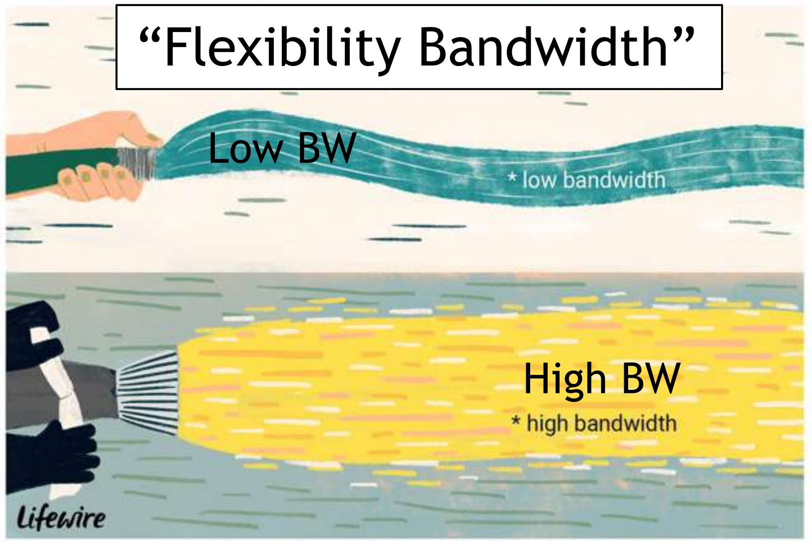




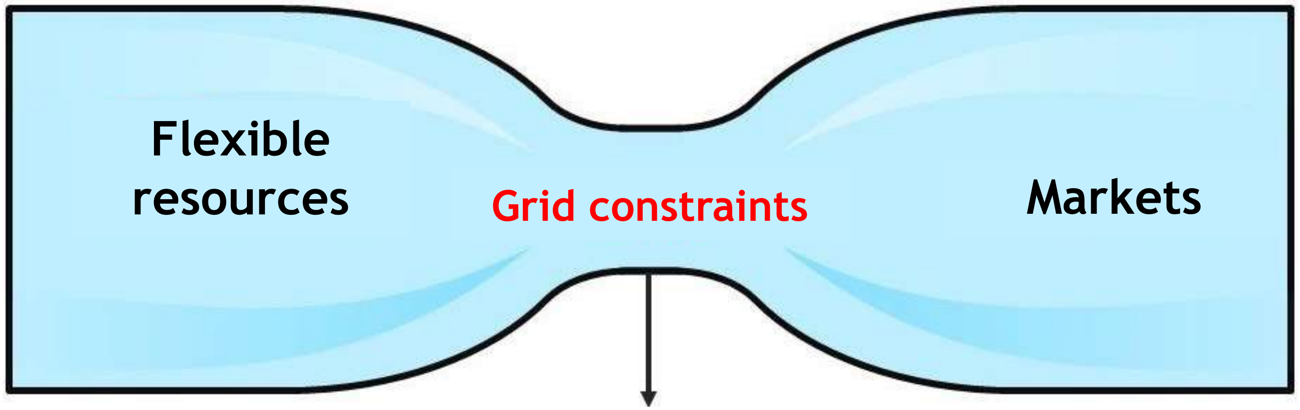
Prices to devices?

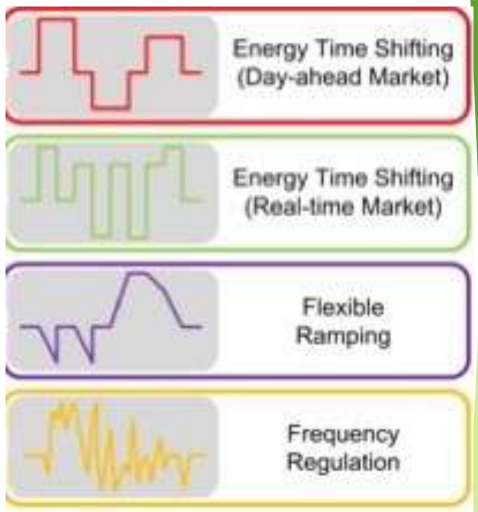
Let’s try something different!

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*



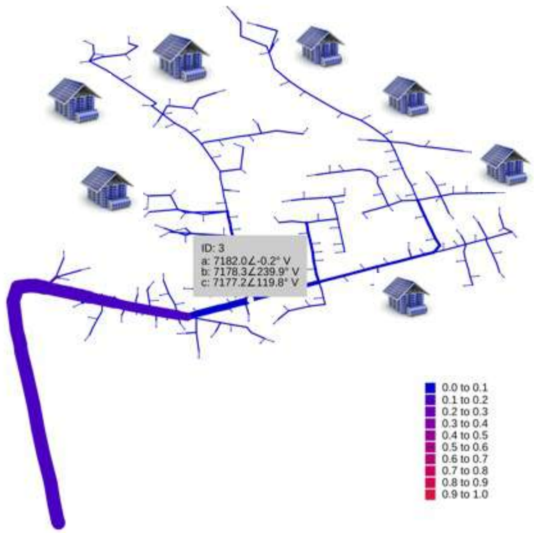


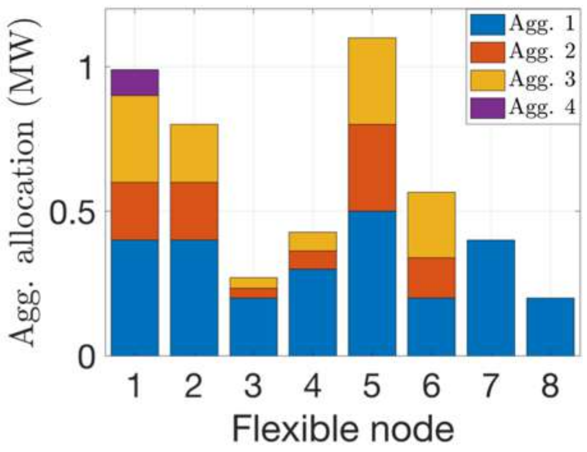
Utility: Find hosting capacity (HC) for each node

Aggregators: flexibility from coordinated devices

Aggregator is allocated portion of available HC at node *i*

Aggregator bids for priority access to HC

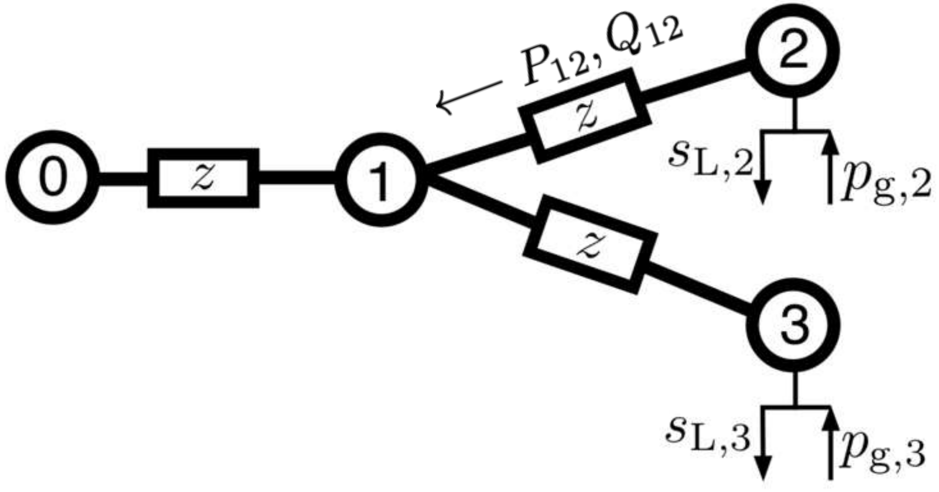




Finding set of admissible (active) injections

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

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



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

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

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

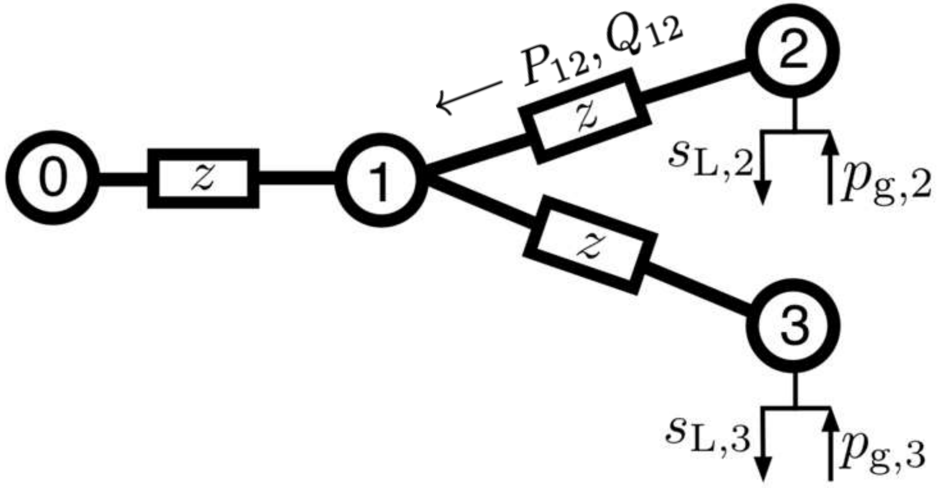
$$l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j},$$

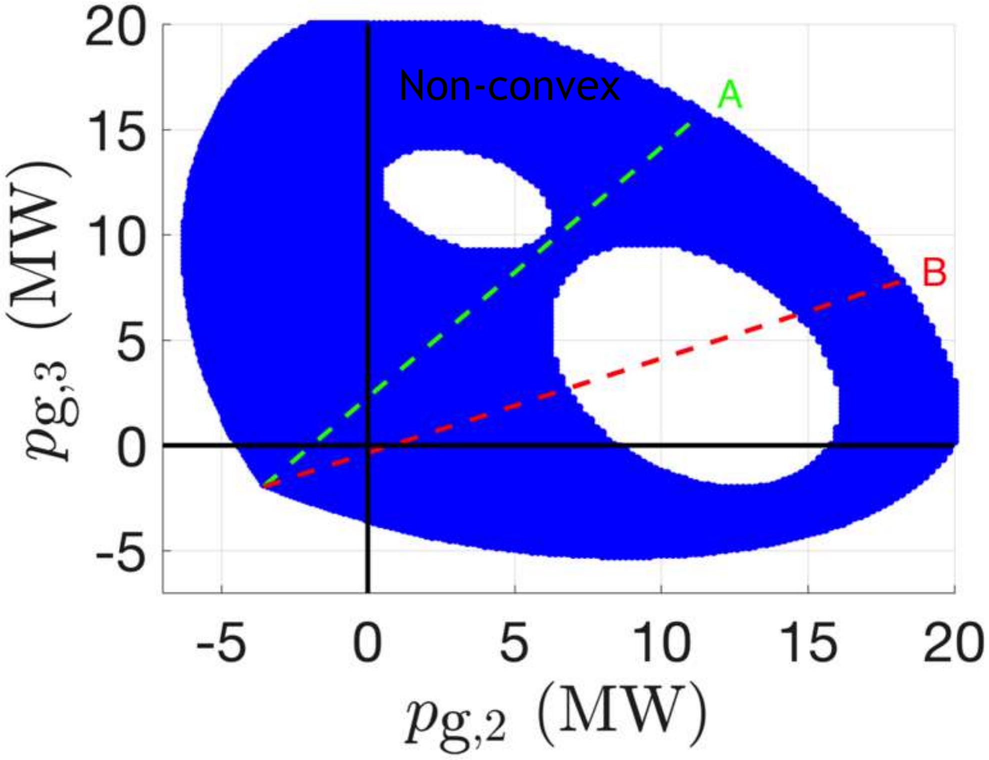
The only nonlinear relation

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





Admissible injections

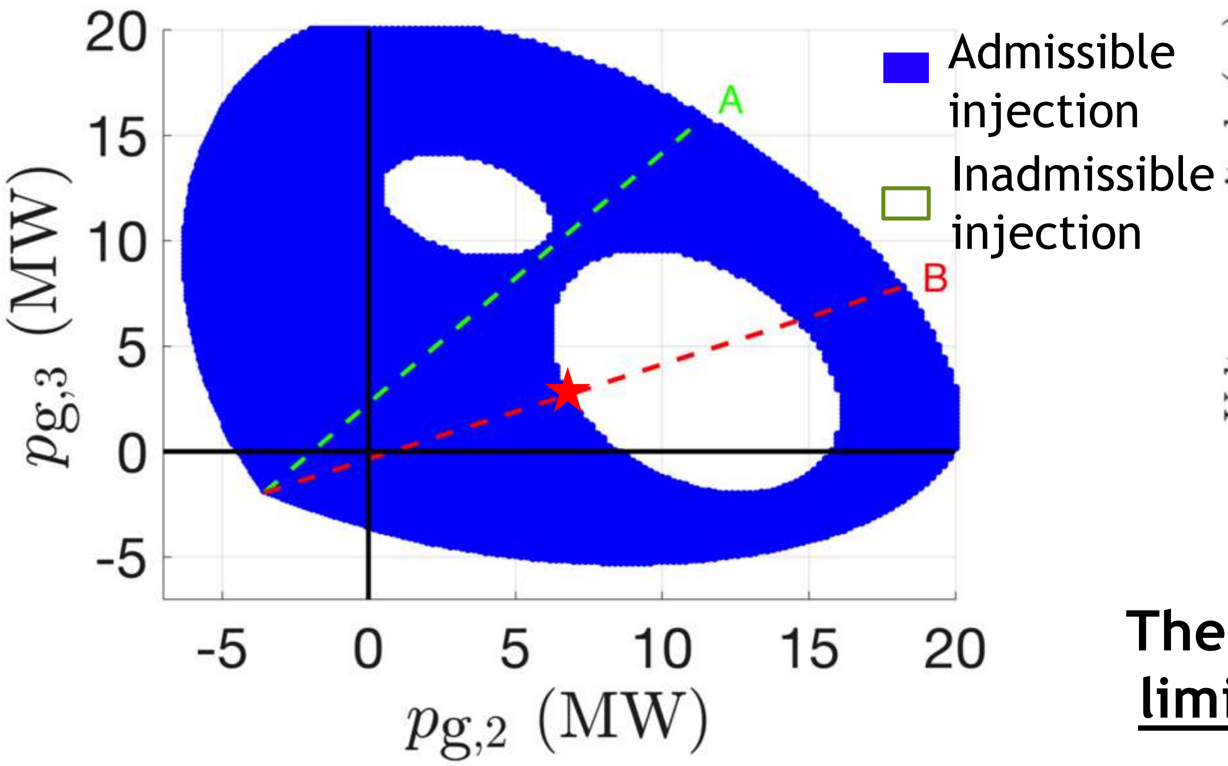
Inadmissible injections

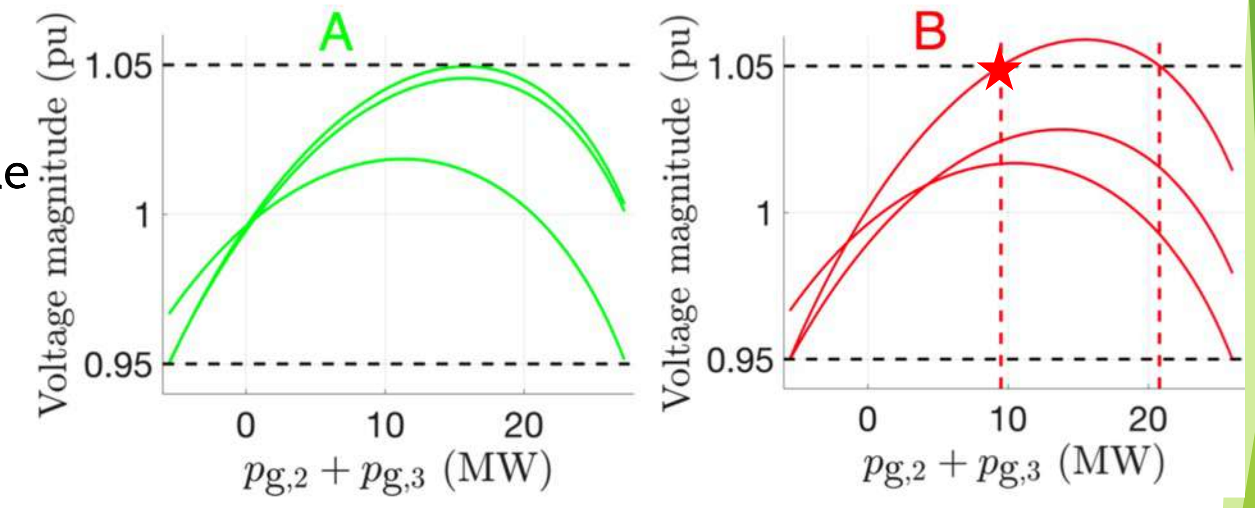
For fixed reactive power injection

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:



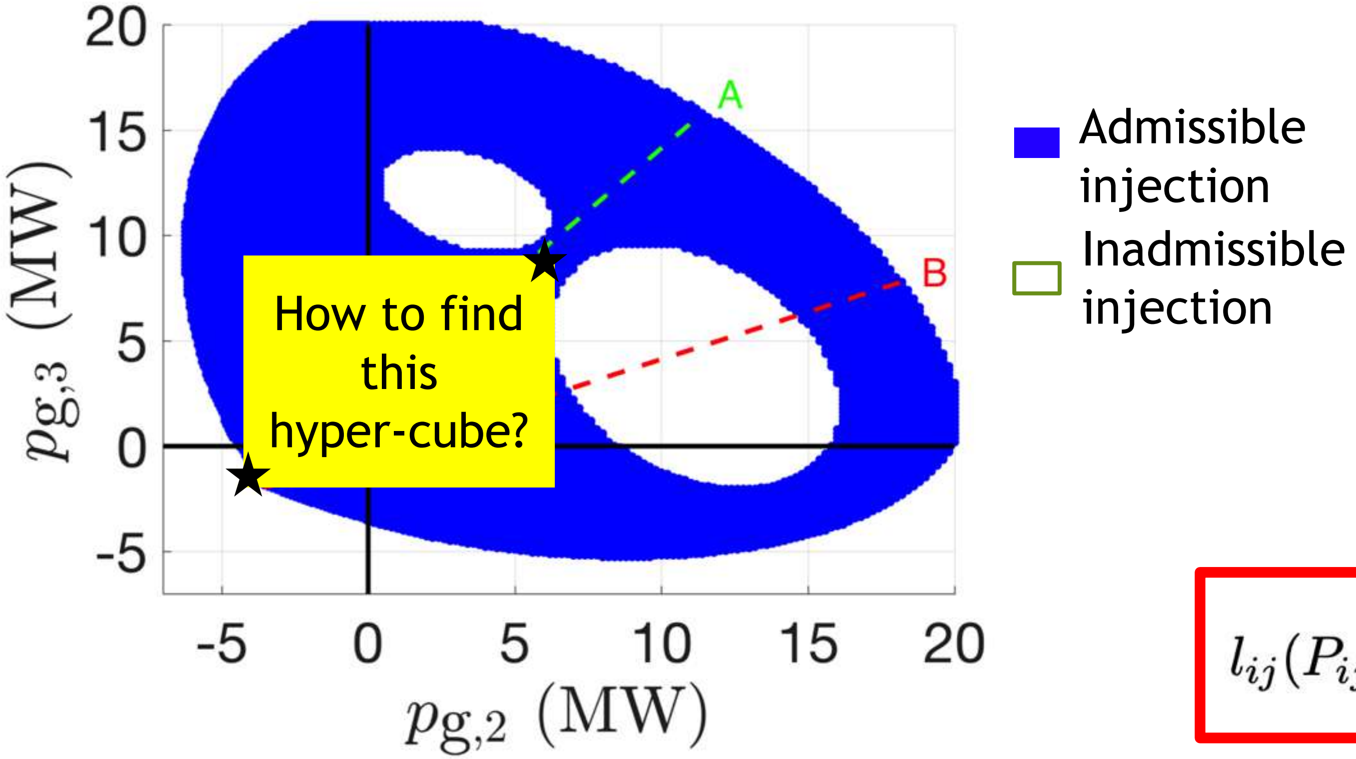


The two controllable active power resources are <u>limited in aggregate by the network</u> - i.e., their individual limits are coupled

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

- **Goal:** find largest hyperrectangle to determine p_g limts (decoupled)



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

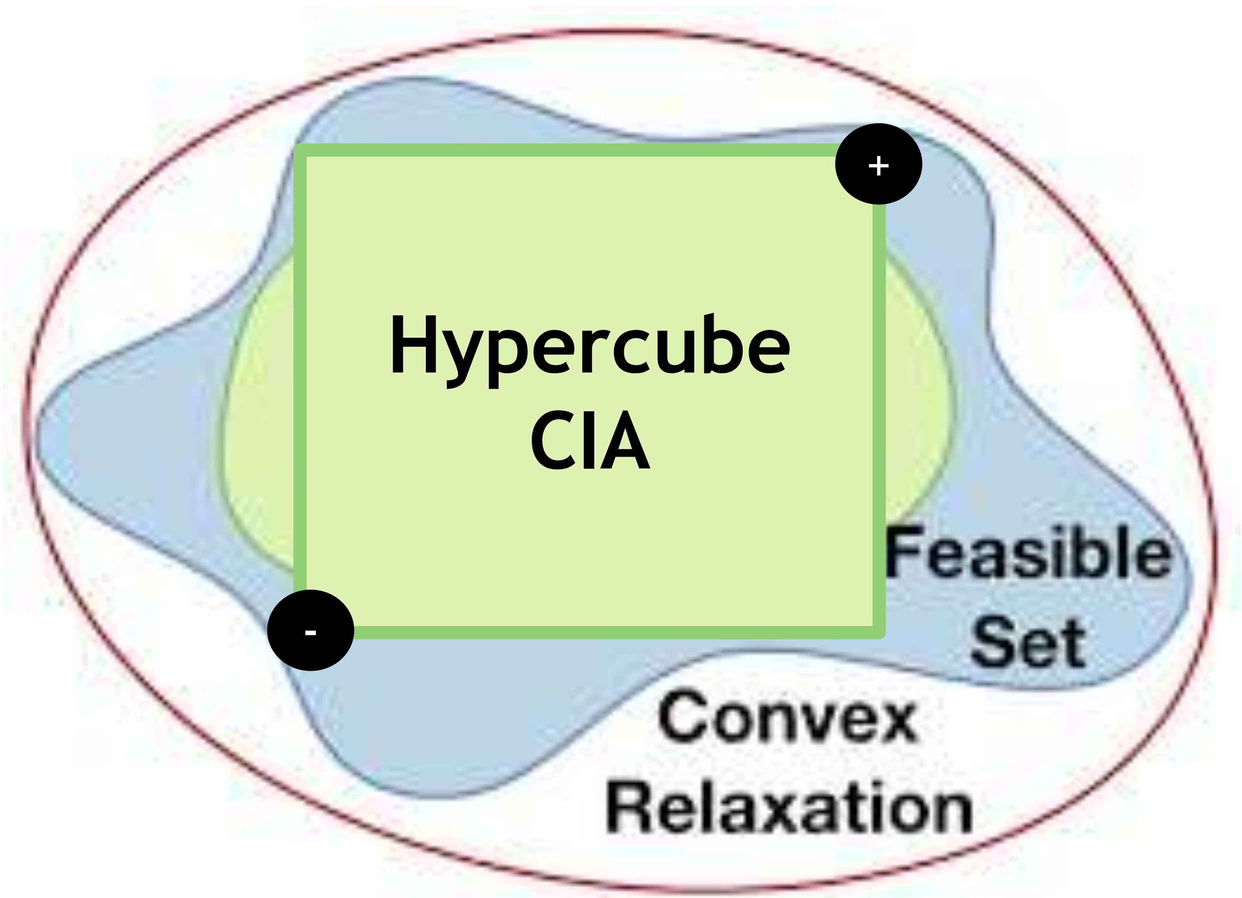
$$P_{ij} = p_j + \sum_{h:h\to j} (P_{jh} - r_{jh}l_{jh})$$

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

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

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

Convex inner approximation unlocks hosting capacity



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.

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

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

Shown to be affine

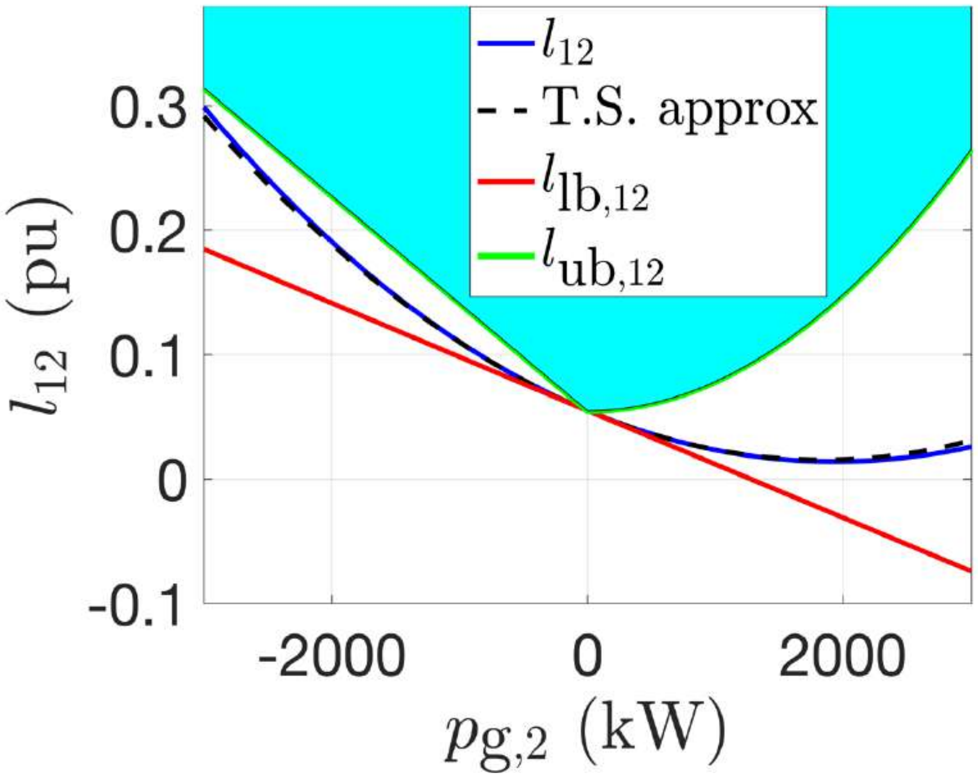
Shown to be convex

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.*

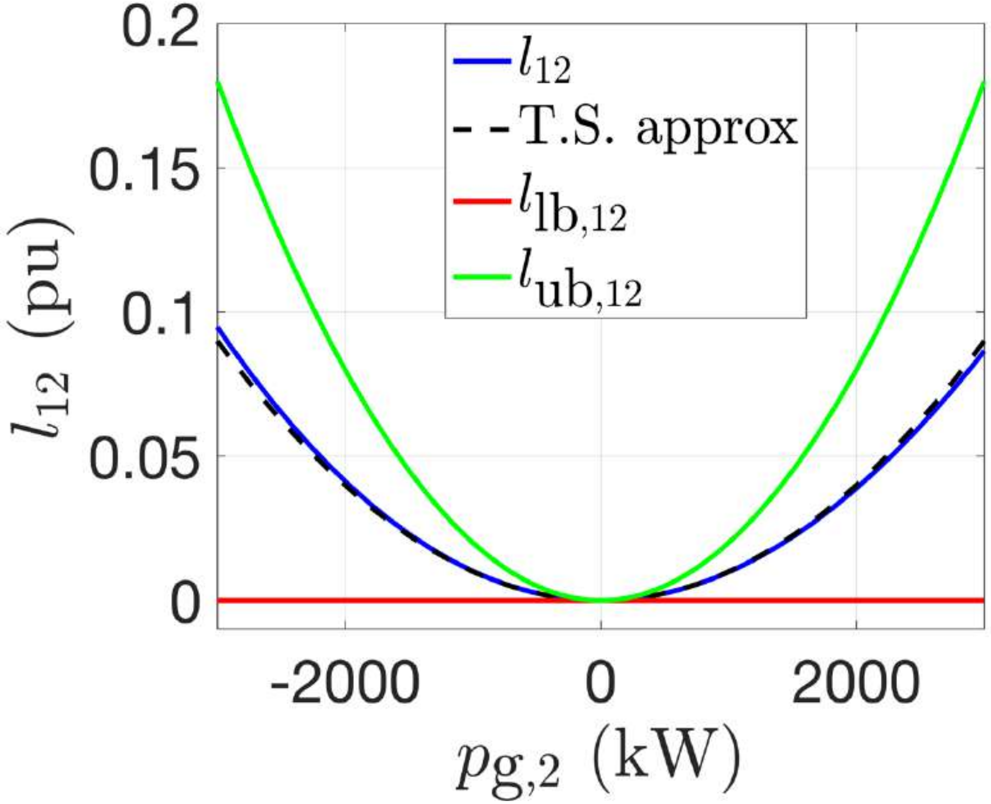
Convex inner approximation via proxy variables

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

Full-load conditions



No-load conditions



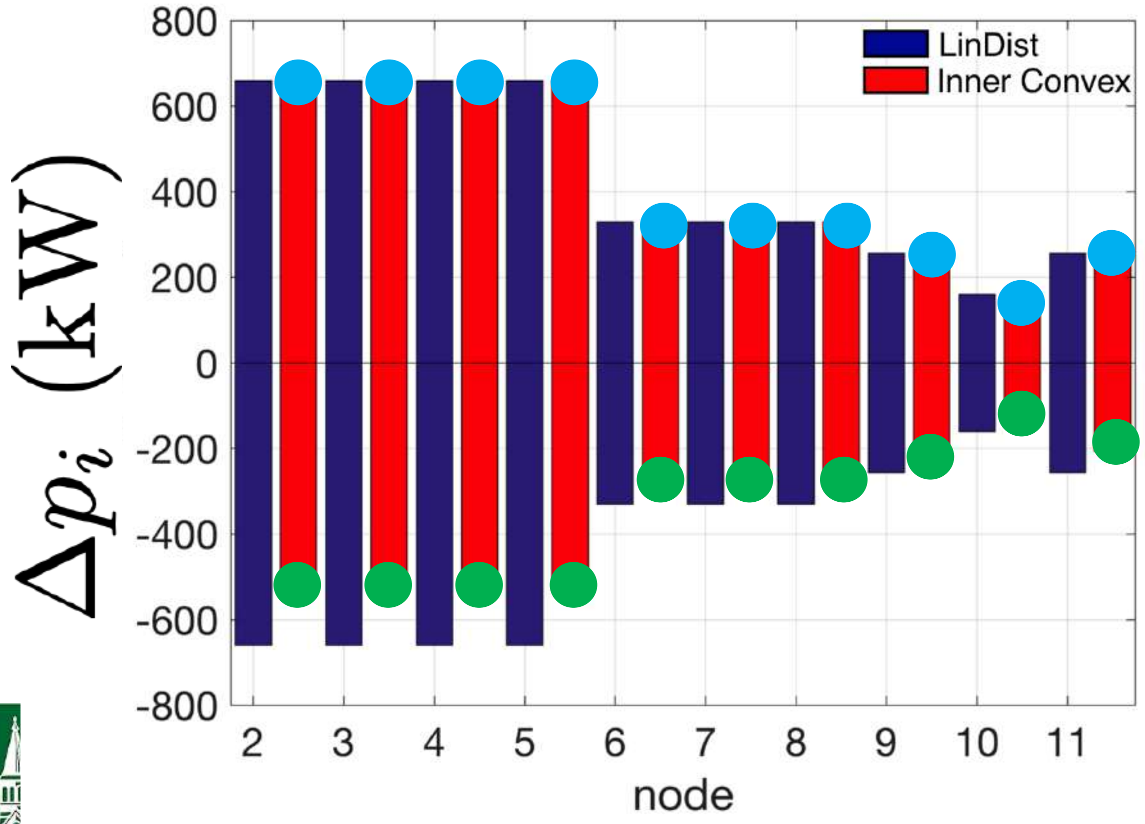
For mathematical details, please see:

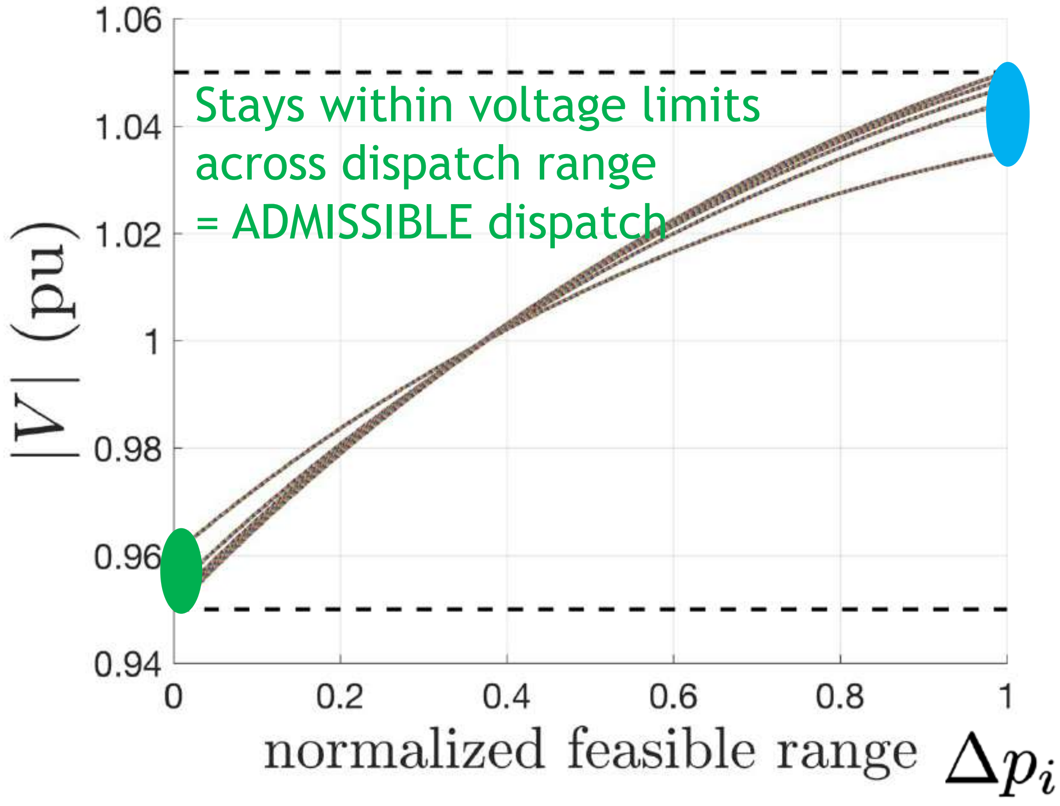
Nawaf Nazir and Mads Almassalkhi. "*Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks," IEEE TPWRS, 2021.*

Hypercube yields the nodal hosting capacities

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

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

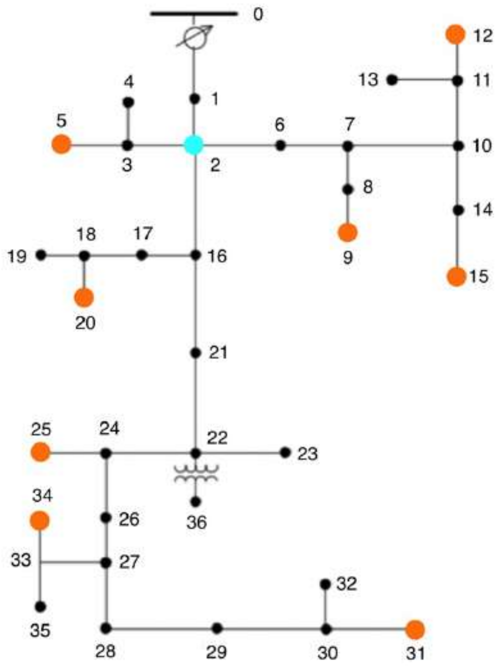




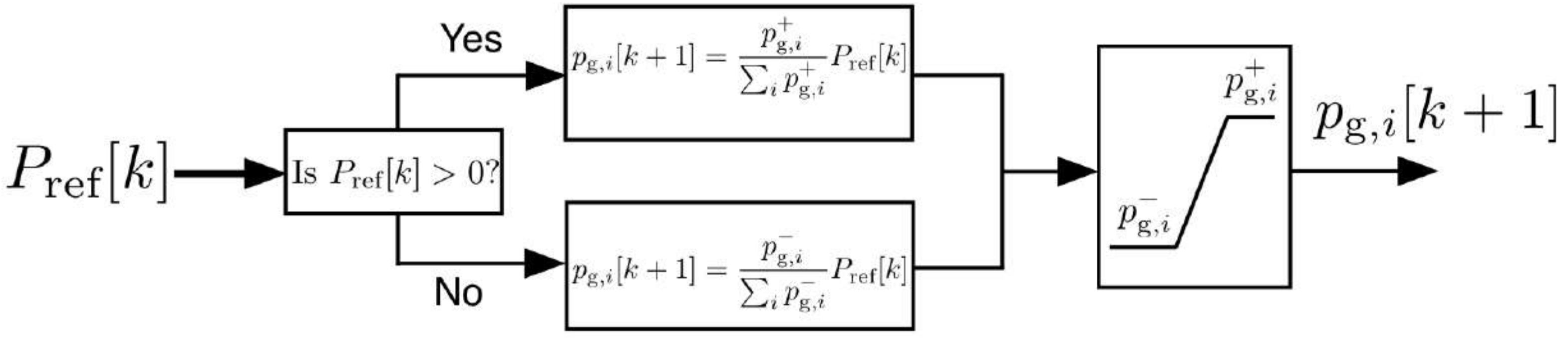
N. Nazir and M. Almassalkhi, "Convex inner approximation of the feeder hosting capacity limits on dispatchable demand," IEEE Conference on Decision and Control (CDC), 2019.

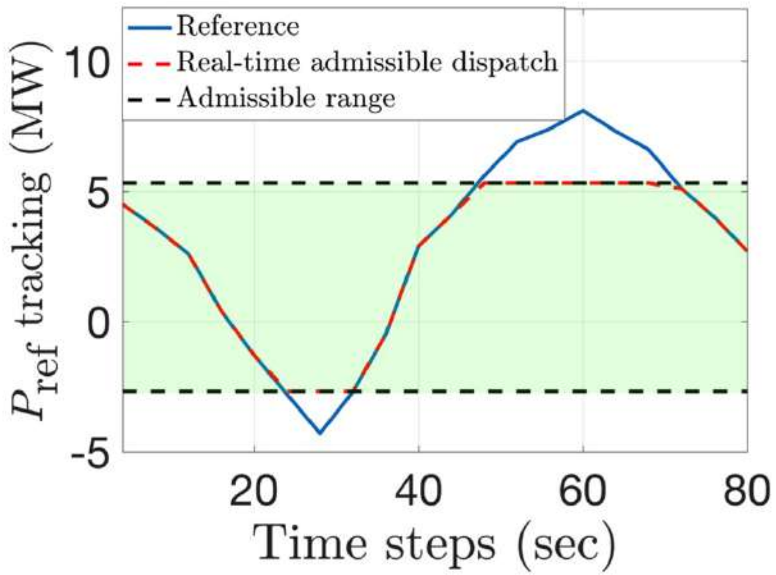
CIA enables real-time, grid-aware disaggregation

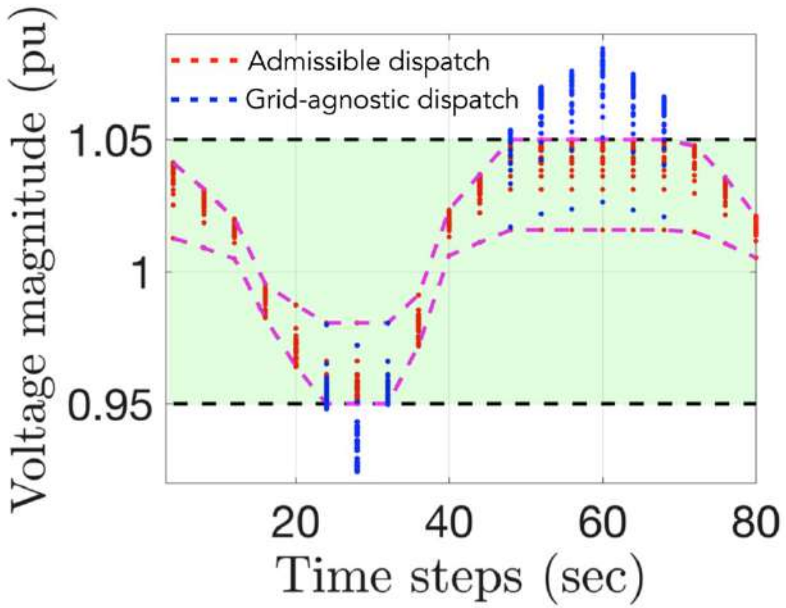
Nodal hosting capacities $[p_i^-, p_i^+]$ enable an open-loop, distributed, and **grid-aware DER control policy**



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



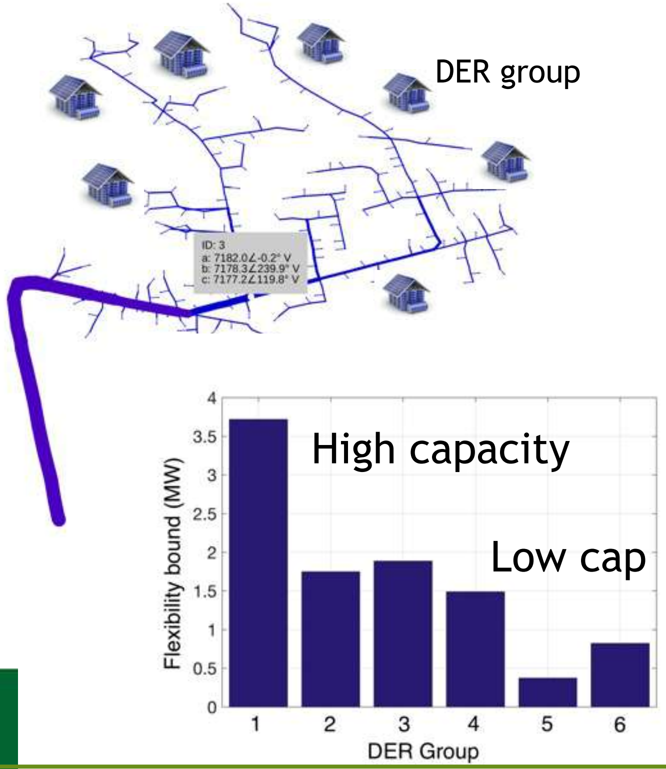




N. Nazir and M. Almassalkhi, "Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks", IEEE Transactions on Power Systems, 2021

Summary: DHC overcomes data/control asymmetry!

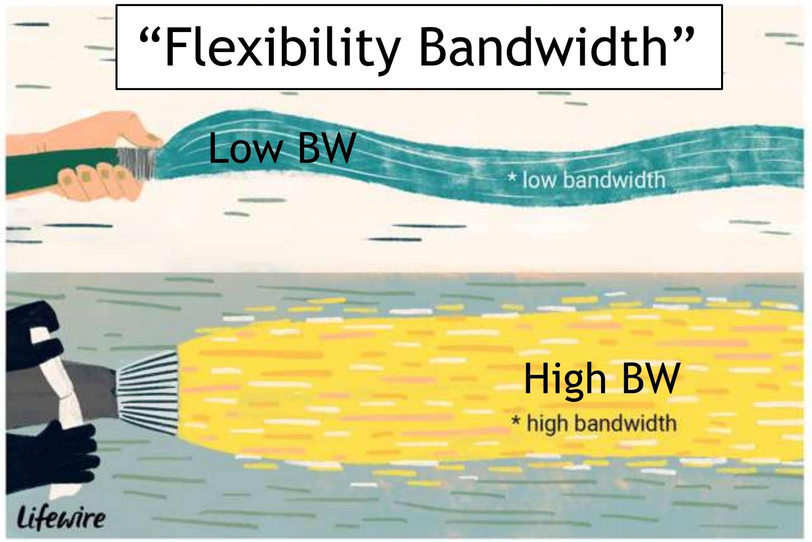
Utility (grid information+data)
- Dynamic hosting capacities capture grid conditions and limits



Available hosting capacity

Future work: find optimal control/price signals

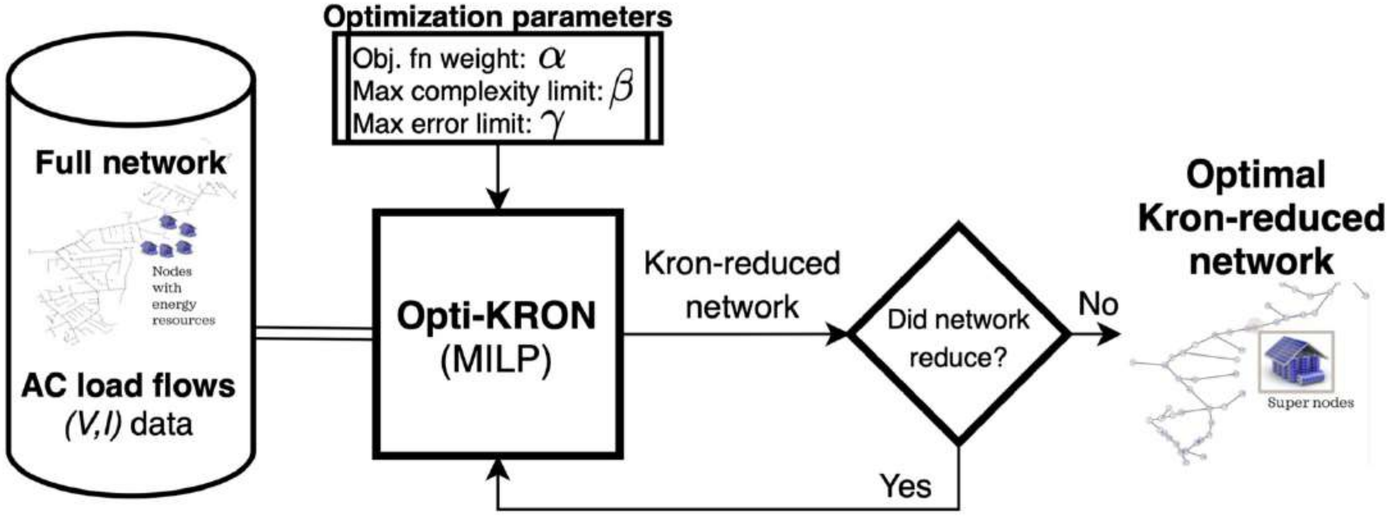
Aggregators (device access, markets)
- Flexibility captures device availability and comfort limits



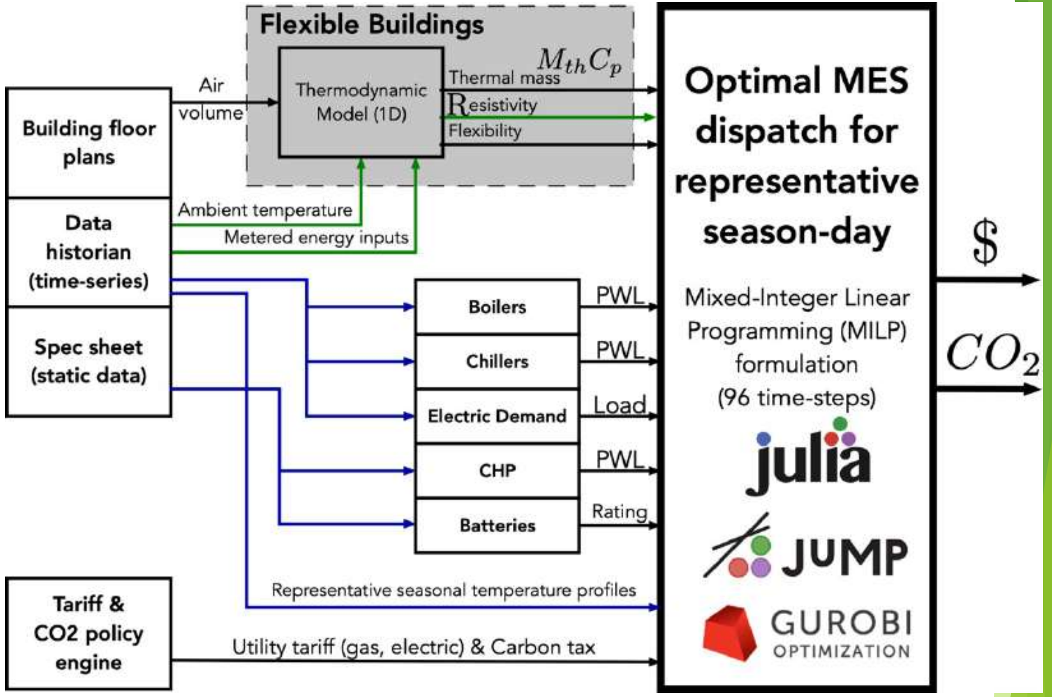
Available flexibility

Other interesting topics we didn't get to today

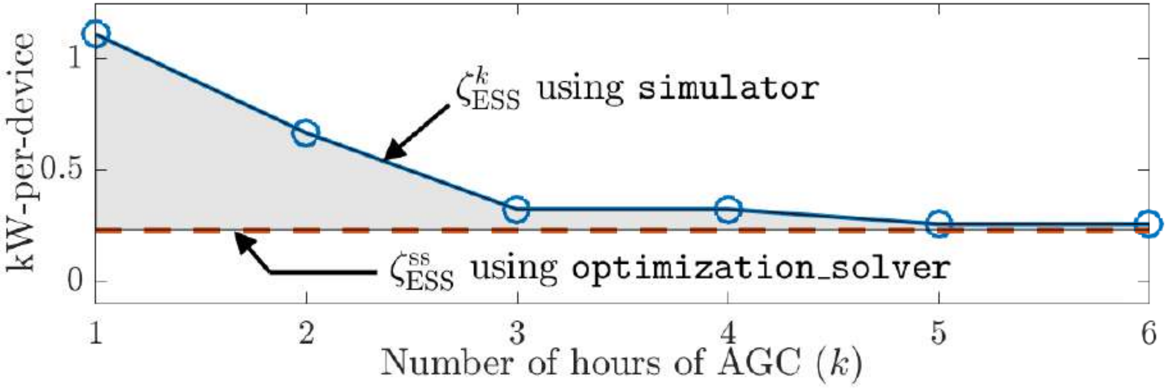
Optimal Kron-based network reduction (Opti-KRON)



Multi-energy systems / sector coupling



Characterize flexibility from fleets of DERs as *virtual* battery

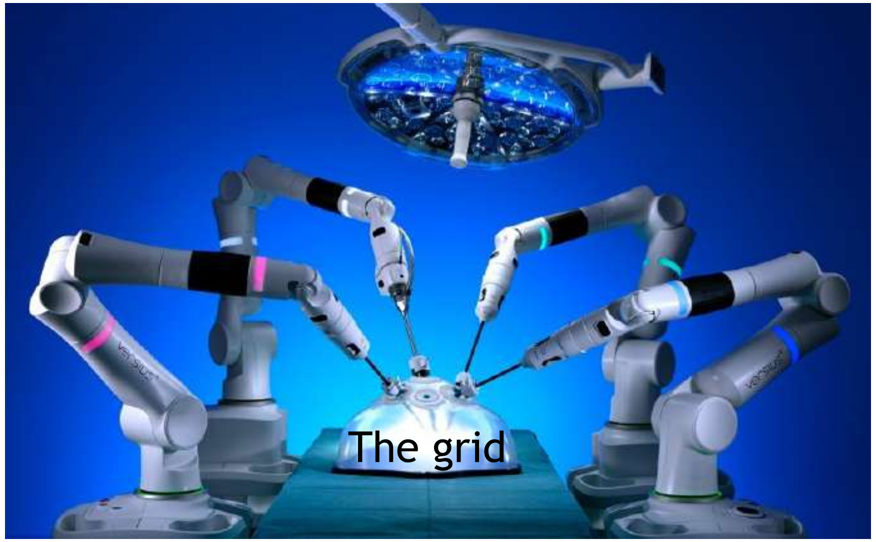


Thank you! Questions? Comments?

malmassa@uvm.edu @theEnergyMads https://madsalma.github.io

Traditional demand response

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



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