The Battle for Grid Flexibility

Control architectures, information gaps, and grid optimization

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PACKETIZED ENERGY

Changing Electric Energy Systems Spring Series 2023

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MIT Electric Energy Systems Group

Acknowledgements

Active/recent collaborators

- Prof. Pierre Pinson (Imperial)
- Prof. Henrik Madsen (DTU)
- Dr. Soumya Kundu (PNNL/UVM)
- Dr. Sam Chevalier (DTU/UVM)
- Prof. Amrit Pandey (UVM)
- Prof. Hamid Ossareh (UVM)
- Prof. Luis Duffaut Espinosa (UVM)
- Dr. Paul Hines (EnergyHub)
- Prof. Jeff Frolik (UVM)
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- Prof. Dennice Gayme (JHU)
- Prof. Enrique Mallada (JHU)
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- Ms. Emily Ninestein (undergraduate researcher)
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- Mr. Zach Hurwitz (MSME'19) → Energy @ Siemens (ME)
- Mr. Lincoln Sprague (MSEE'17) → Compliance @ Dynapower (VT)
- Ms. Anna Towle (BSEE'16) → Trader @ Fortum (Sweden)

VECTORS: interdisciplinary Energy & Autonomy group

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

Bindu Panikkar

Hamid Ossareh

James Bagrow

Luis D. Espinosa

Jeff Marshall

Sam Chevalier
(Starts Aug 2023)

Broad expertise

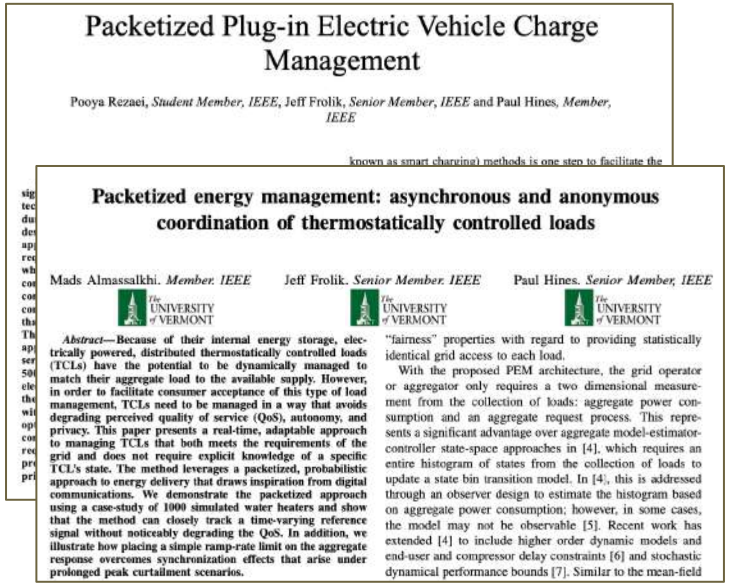
- Energy justice
- Power/energy systems
- Grid modeling
- Optimization
- Control theory
- Network science
- IoT/Comms
- Data science
- Machine learning

Impactful R&D with industry & research partners

Recent and ongoing industry-supported projects with

Recent and ongoing funding 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*

known as smart charging) methods is one step to facilitate the

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 + PACKETIZED ENERGY

Numerous academic papers+ research projects+ IP + industry partners (2012-present)

Co-founded startup company (2016)

Company acquired! Technology now has access to scale: 1,000,000 devices (2022)

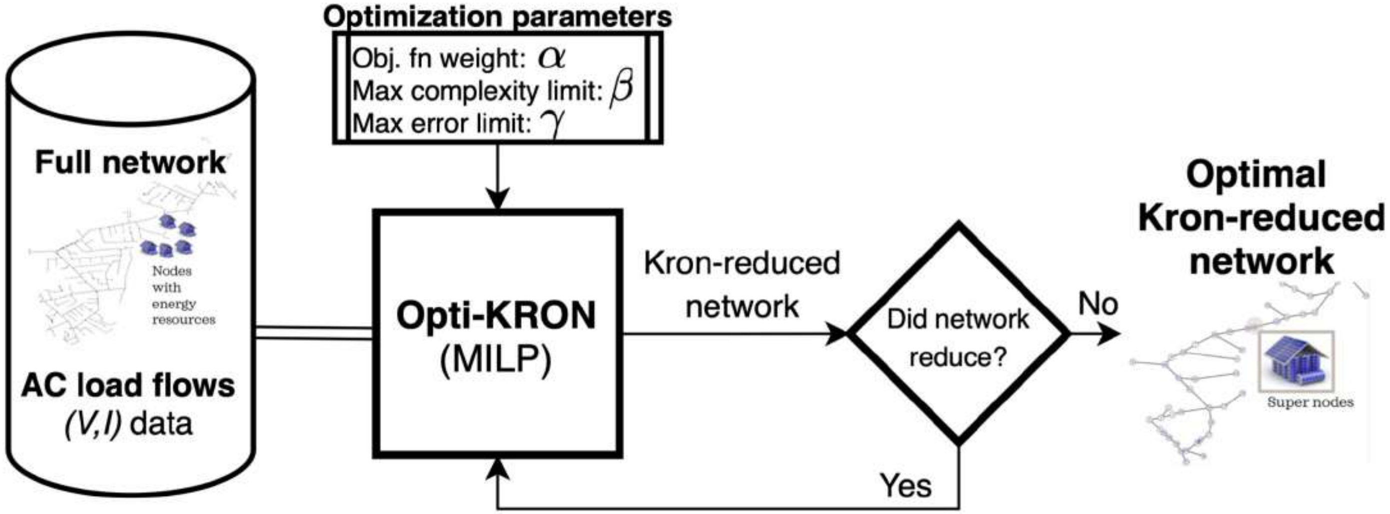
Vermont is amazing platform for power/energy R&D

- ✓ 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, test ideas, create change, make an impact
- ✓ Close partnerships with nationally-recognized innovative industries
  - *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*

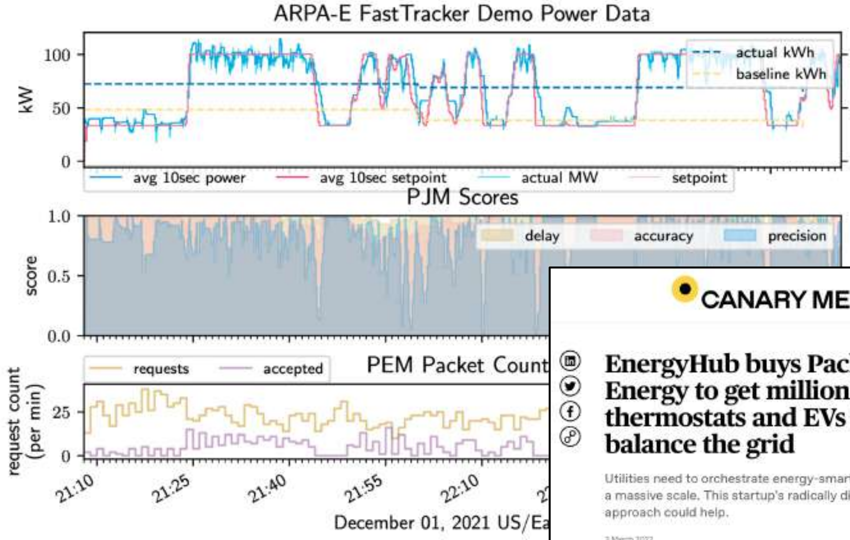
- ✓ **VT is #2 state in U.S. for Clean Energy Momentum** (UofCS, 2017)
  - 5.4% of workforce is clean energy economy (#1 in 2021)
    - *Next largest are at ~3%*
  - 99.9% of VT *generation* is renewable (#1 in US in 2019)
  - 66% of consumed electricity is renewable (2019)
  - 15% of electricity from 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)

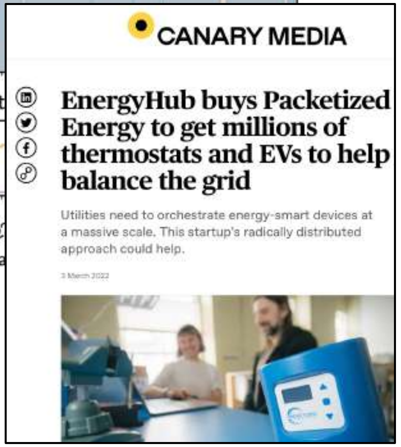
What I will not talk about today

Optimal (physics-informed) network reductions



Packetized energy management

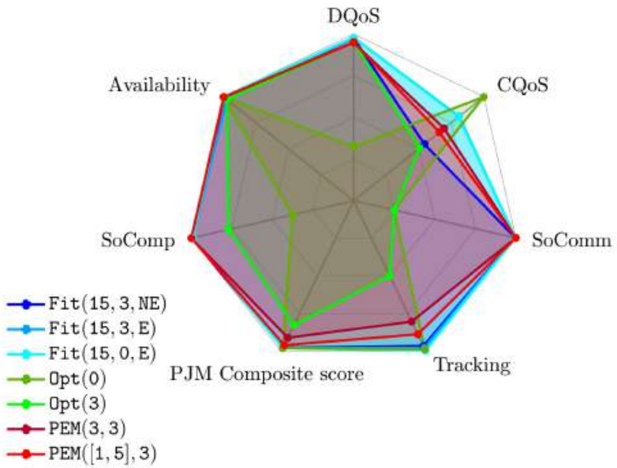


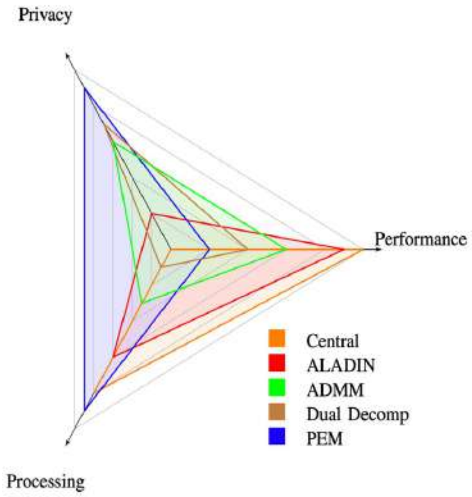

CANARY MEDIA

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.

Methodologies for characterizing DER algorithms





Collision-free trajectory optimization of swarms

Green economies are rising….

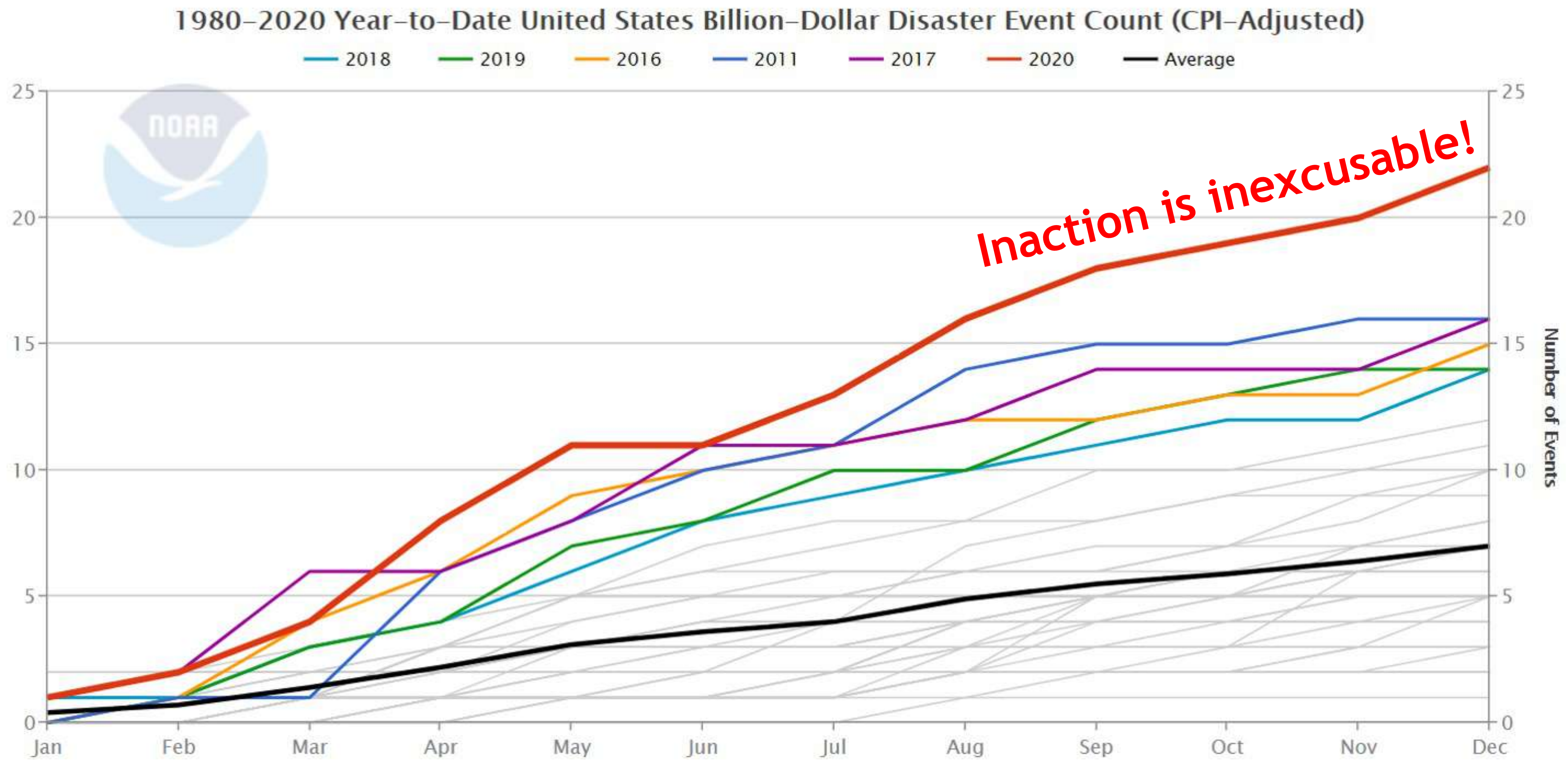
$1.3T — Annual sales revenue

10M — Jobs supported

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

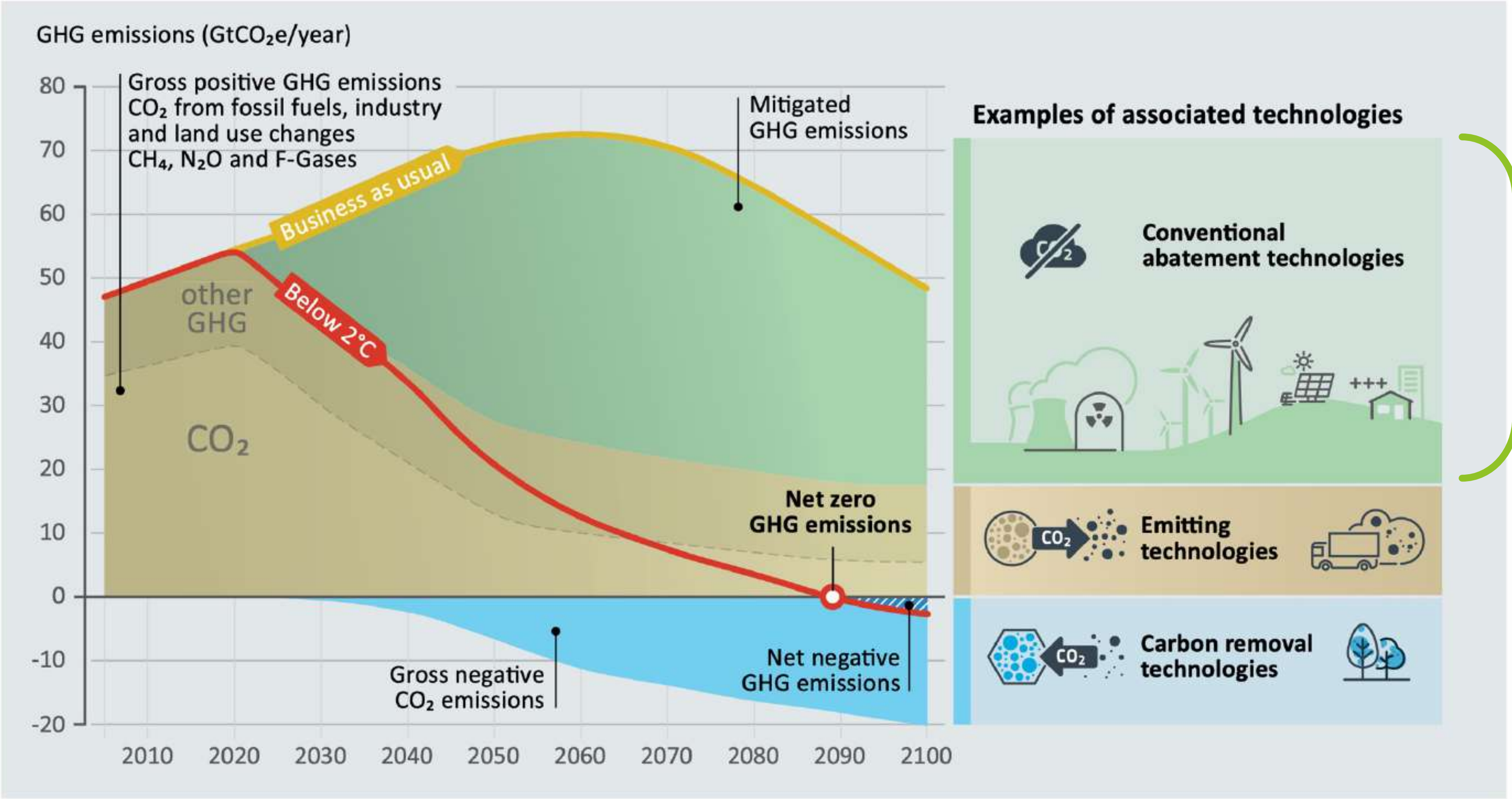
Georgeson, L., Maslin, M. "Estimating the scale of the US green economy within the global context." *Palgrave Communications* 5, 121 (2019)

...but so are climate challenges



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

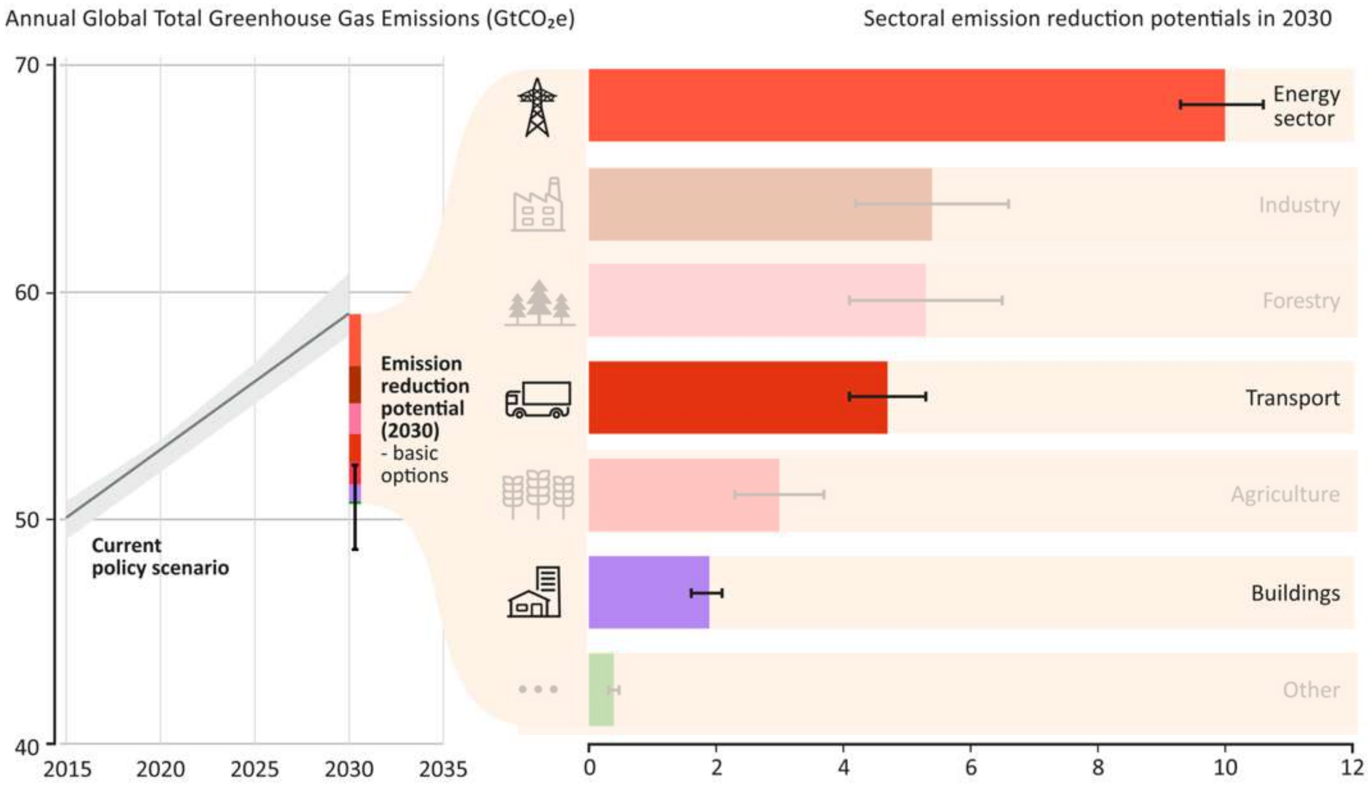
A massive power systems challenge!

Key: power systems *is* climate change mitigation engineering with a global impact!

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]

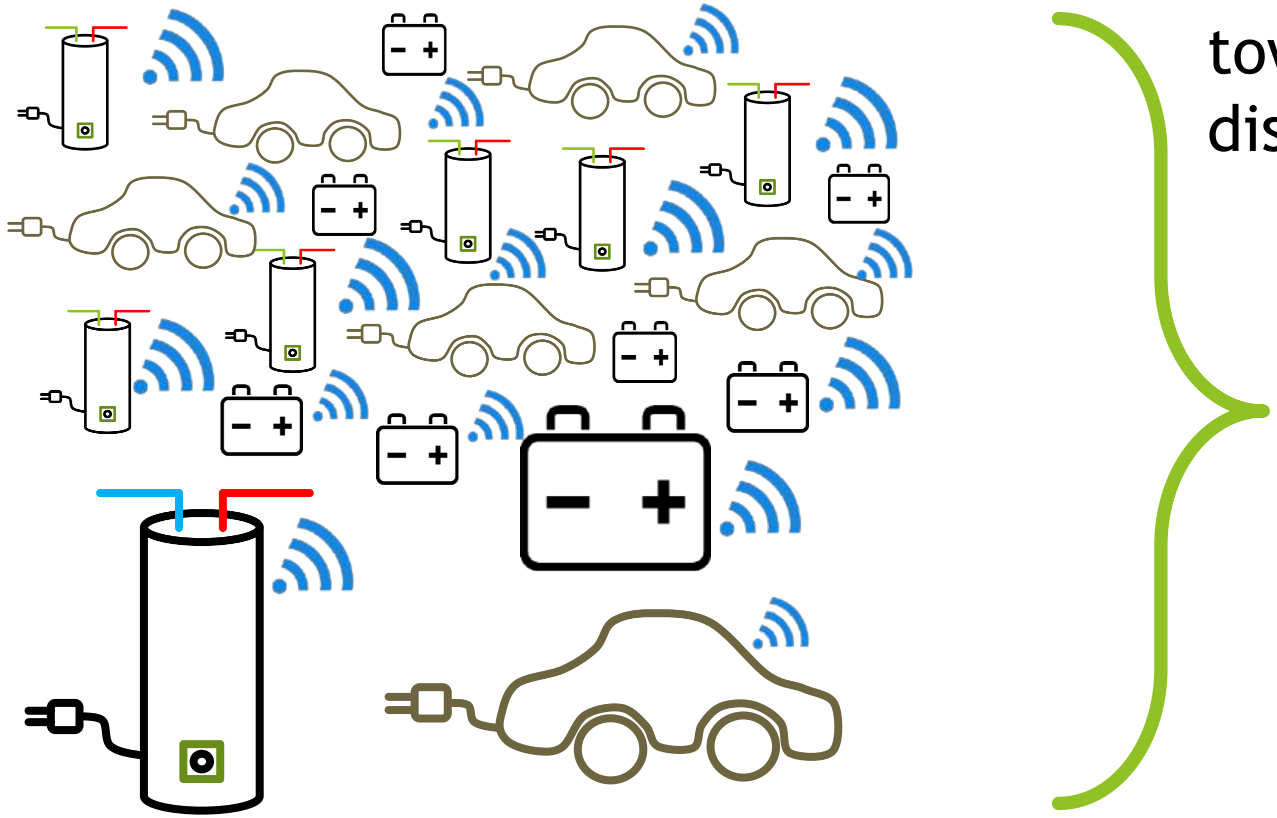
59GW of DR today will become **200GW of flexible demand by 2030** [3]

Need to coordinate billions of energy resources!

[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 device, home, neighborhood, town, and state can become a dispatchable resource

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

AVOIDED GEN CAPACITY

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

Virtual power plant™
Virtual battery™
Prosumer™

TESLA

sunrun

GENERAC

EnergyHub

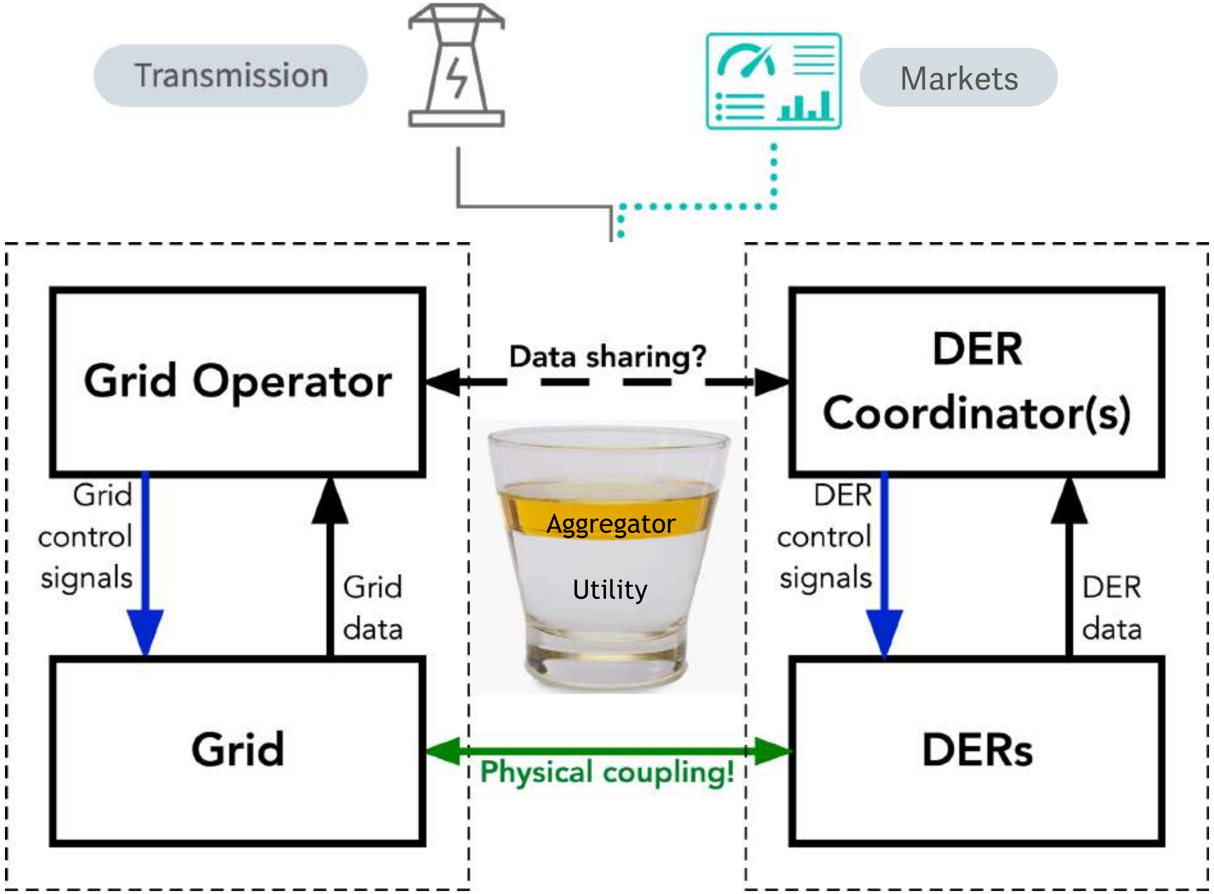
*Values from representative 2019 ISO New England market prices and services and from RMI/Brattle.

DER coordination is ~~hard and complicated~~ fun

Who knows what? Who controls what?

Reliability

Risks



Energy needs (QoS)

How can we define *flexibility* (kW_{flex})?

- Asset being responsive to (incentive/control) signals
  - Ability to defer/change (net) consumption?
  - *Flexibility* of a stand-alone battery is straight-forward

Key parameters of a battery's flexibility

- State of charge (SoC)
- Ramp-rate (change in power)
- Net injections (power limits)
- Capacity (energy limits)

How much power, how fast, and for how long?
➔ *Magnitude, response rate, and duration*

For heterogenous mix of DERs, it's complicated!

1

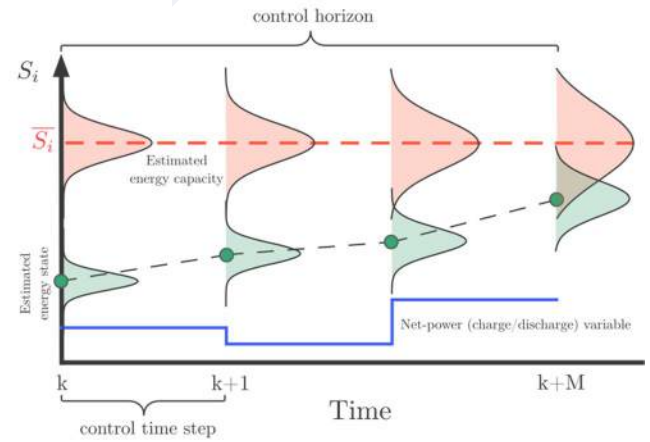
Estimate background end-use needs (QoS)

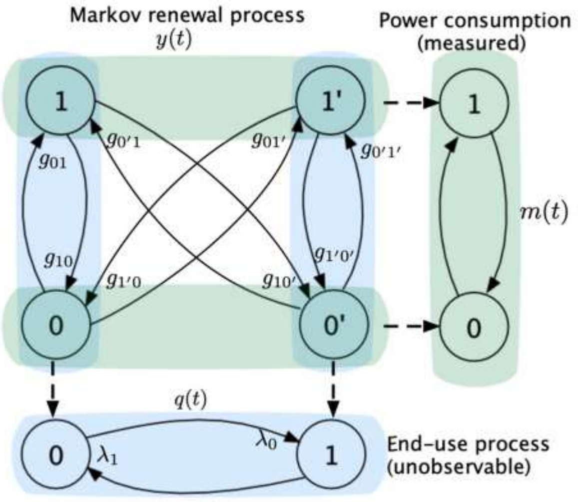
Stochastic end-use

Uncertain resource

3

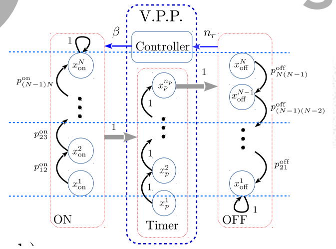
Optimal dispatch

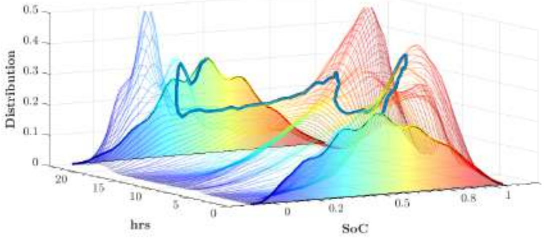




2

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," 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, 2021
(2b) L. Duffaut, **A. Khurram**, and M. Almassalkhi "Reference-Tracking Control Policies for Packetized Coordination of Heterogeneous 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, M. Almassalkhi, et al, "Chance-constrained economic dispatch of generic energy storage under decision-dependent uncertainty," IEEE Trans. on Sust. Energy, 2023

Example: field trial with coordinating 150 loads (2019)

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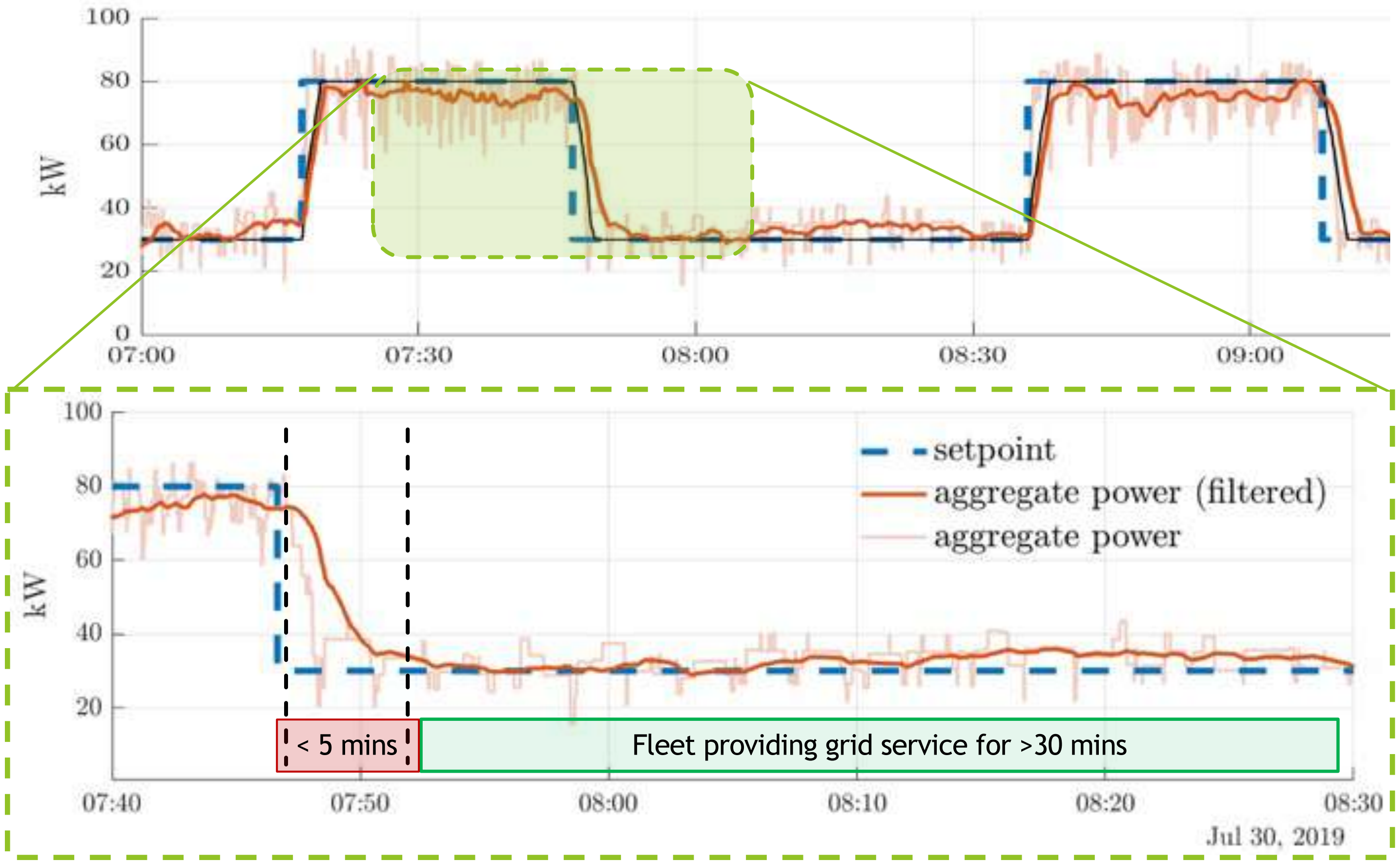
VERMONT ELECTRIC COOP

BURLINGTON Electric DEPARTMENT

GREEN MOUNTAIN POWER

vermont electric power company VELCO

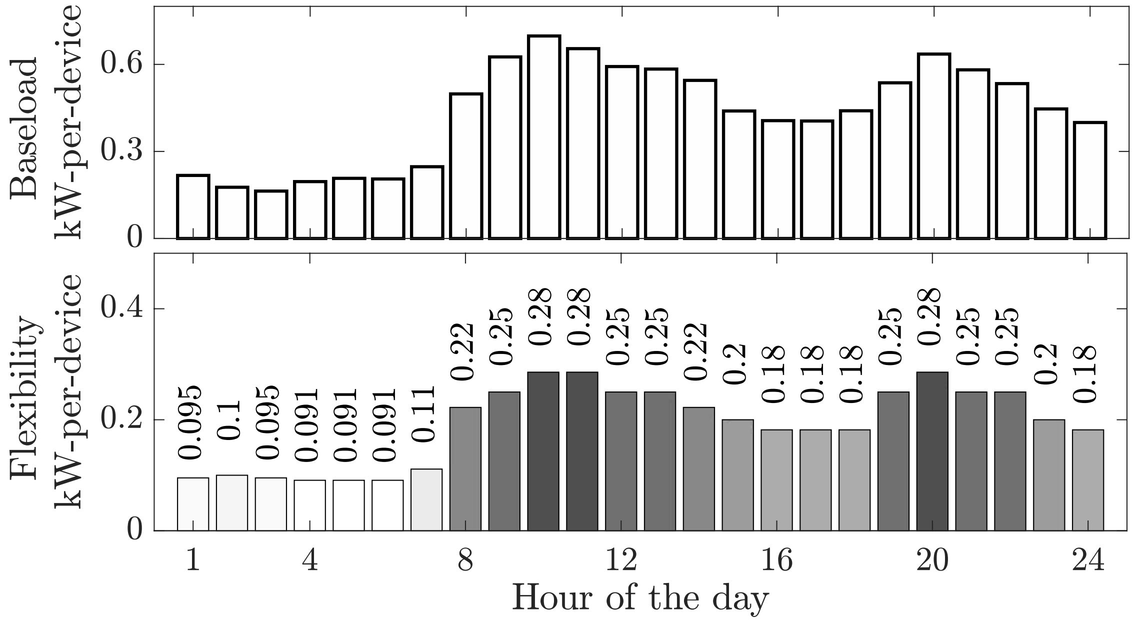
PACKETIZED ENERGY



Dynamics depend on control architecture + parameters + end-users

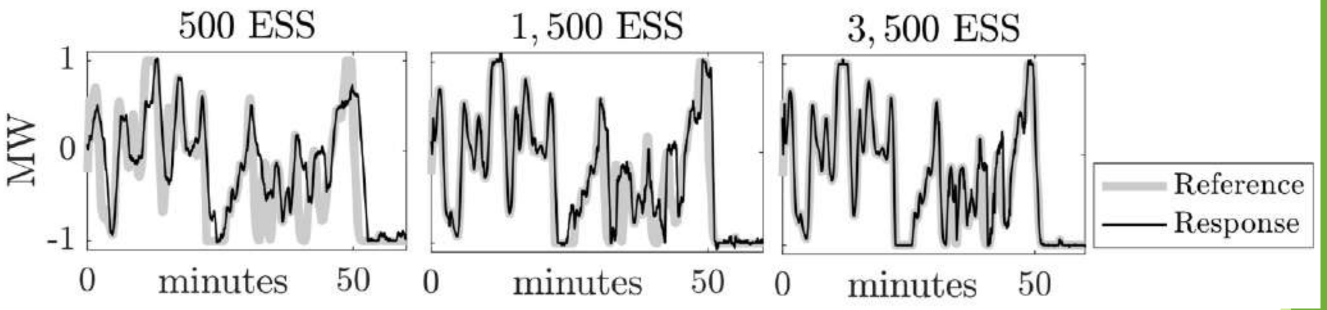
How many DERs are needed for ±1MW of freq reg?

Electric water heaters

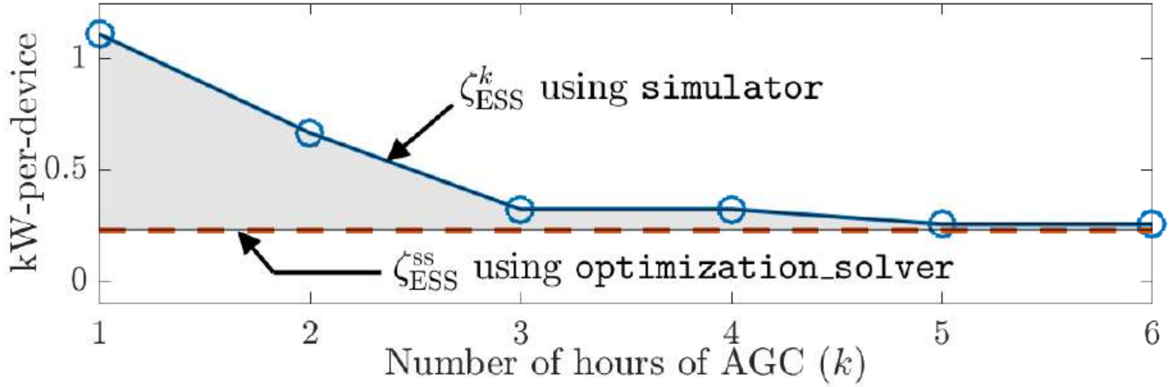


Up to 10,000 EWHs at night and 4000-5000 during day

Batteries



Available flexibility depends on duration



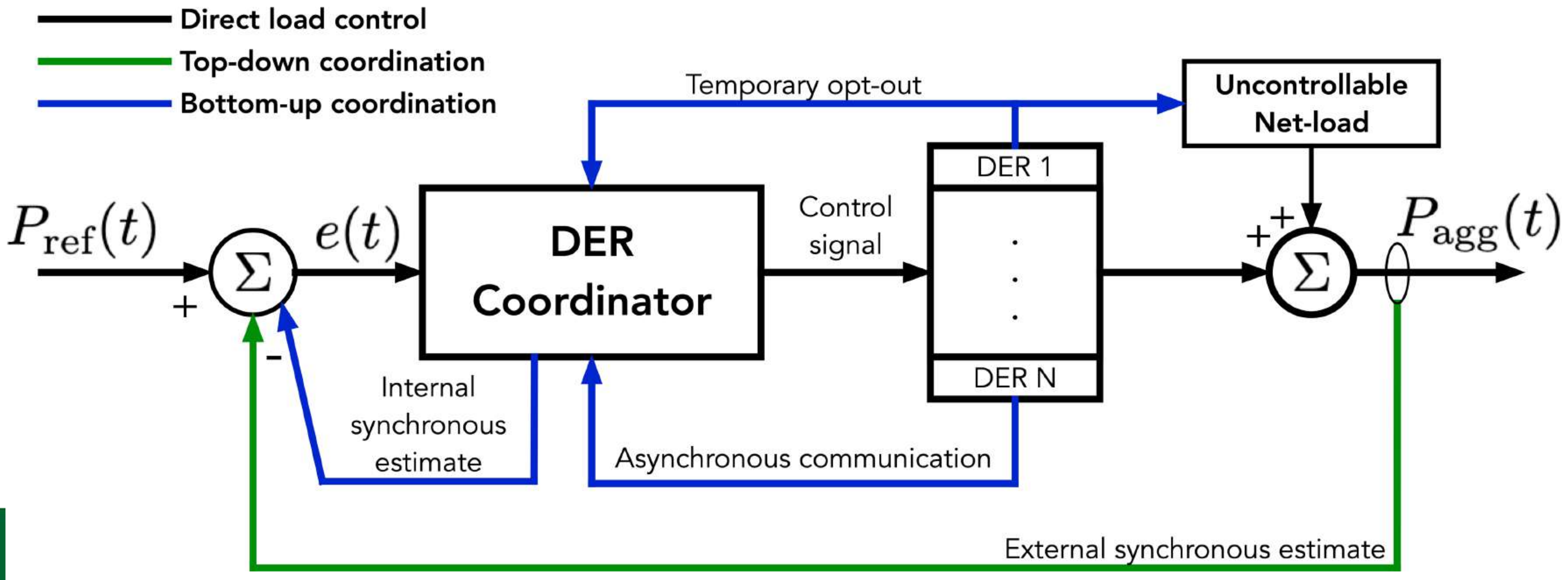
End-user behaviors & constraints and DER controller affect available flexibility

Adil Khurram, L. Duffaut Espinosa, R. Malhame, and M. Almassalkhi, "*Identification of Hot Water End-use Process of Electric Water Heaters from Energy Measurements*," PSCC+EPSR, 2020

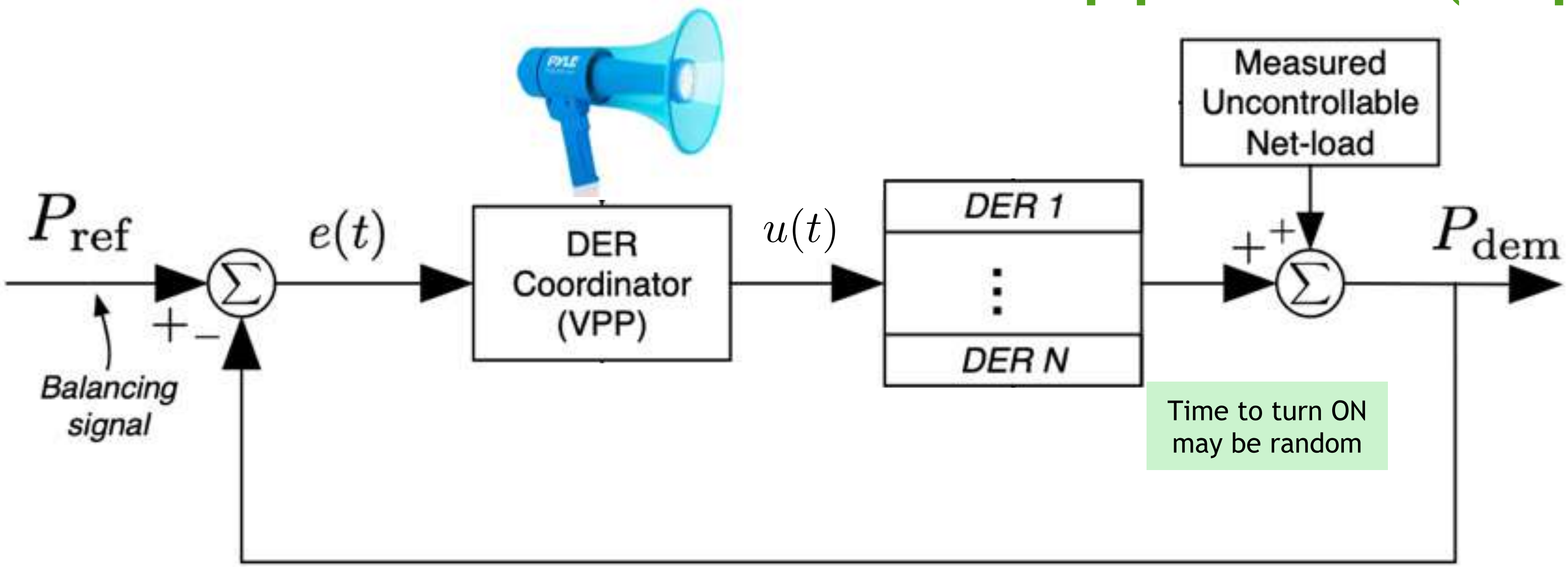
Adil Khurram, L. Duffaut Espinosa, M. Almassalkhi, "*A Methodology for quantifying flexibility in a fleet of diverse DERs*," IEEE PES PowerTech, 2021.

DER coordination requires a control architecture

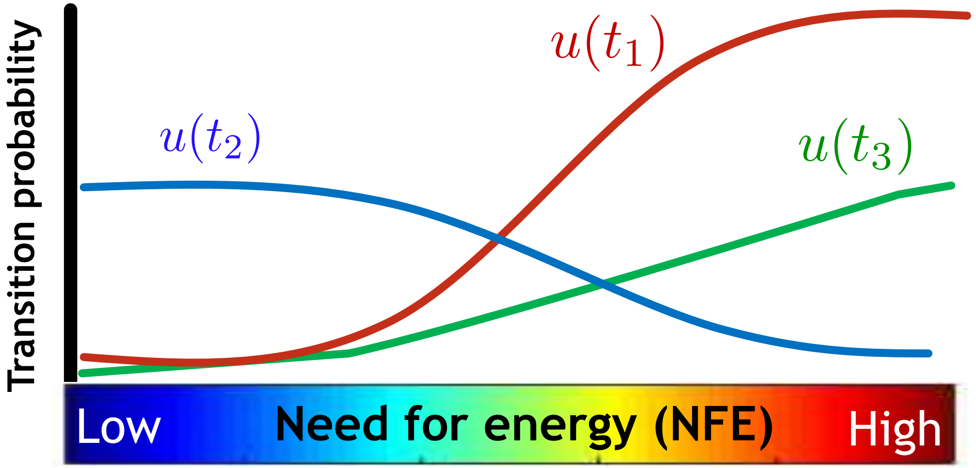
How to control DERs? What's measured/estimated?



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



Local device logic can guarantee QoS



Broadcast control signal to all devices **synchronously**. Control signal is **explicit incentive (transactive) or pdf.**

Requires feedback from actual/estimated demand and/or having devices stream back data/status. Else is **open-loop**

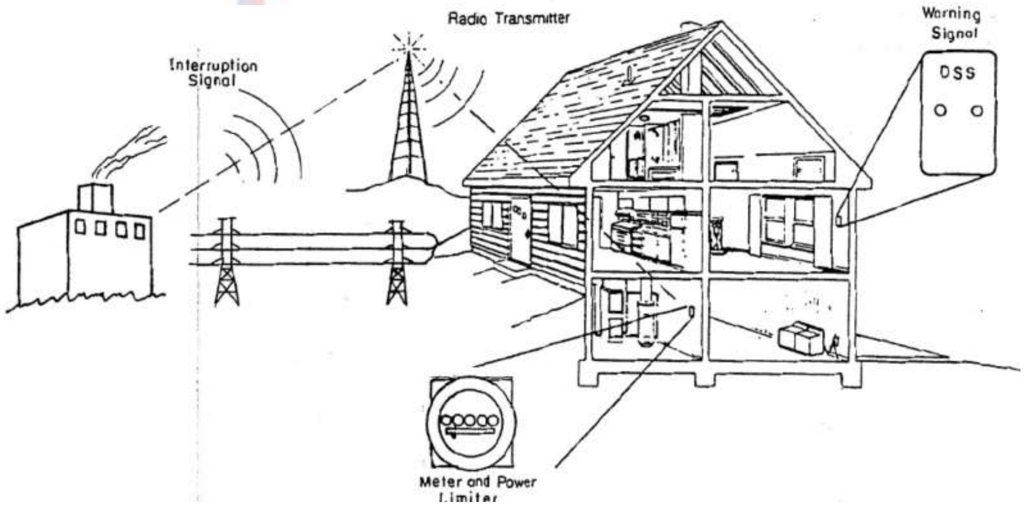
But challenging to get feedback, hard to distinguish individual device constraints or grid locations (i.e., DER cycling and local grid conditions).

Chen, Y., Hashmi, M.U., Mathias, J., Bušić, A., Meyn, S. *Distributed Control Design for Balancing the Grid Using Flexible Loads*. Energy Markets and Responsive Grids. IMA, 2018.
J. L. Mathieu, S. Koch and D. S. Callaway, *State Estimation and Control of Electric Loads to Manage Real-Time Energy Imbalance*, IEEE Transactions on Power Systems, 2013.

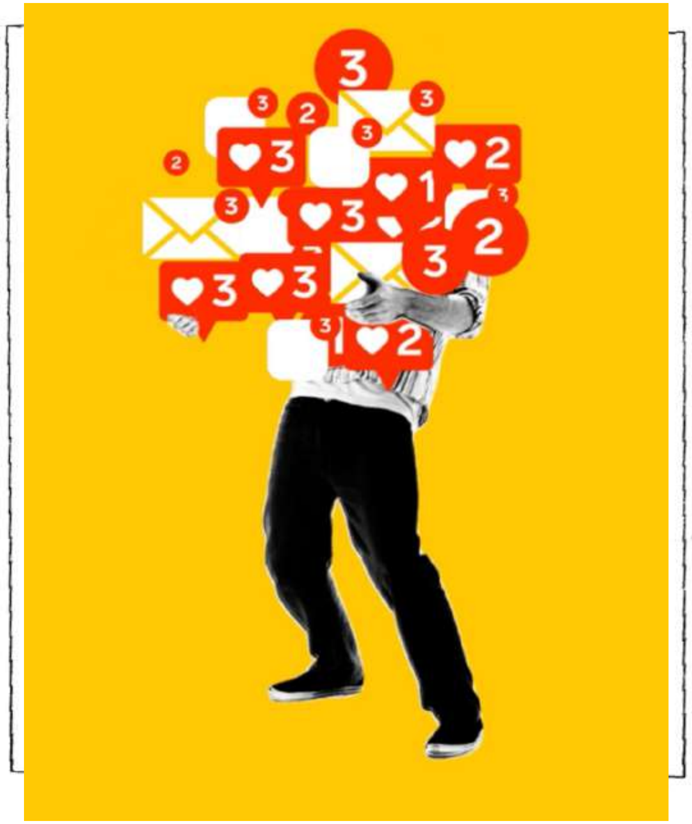
Direct load control or TOU pricing (open-loop)

Broadcast control example: California in 1982

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



Source: Shmuel Oren, 1982



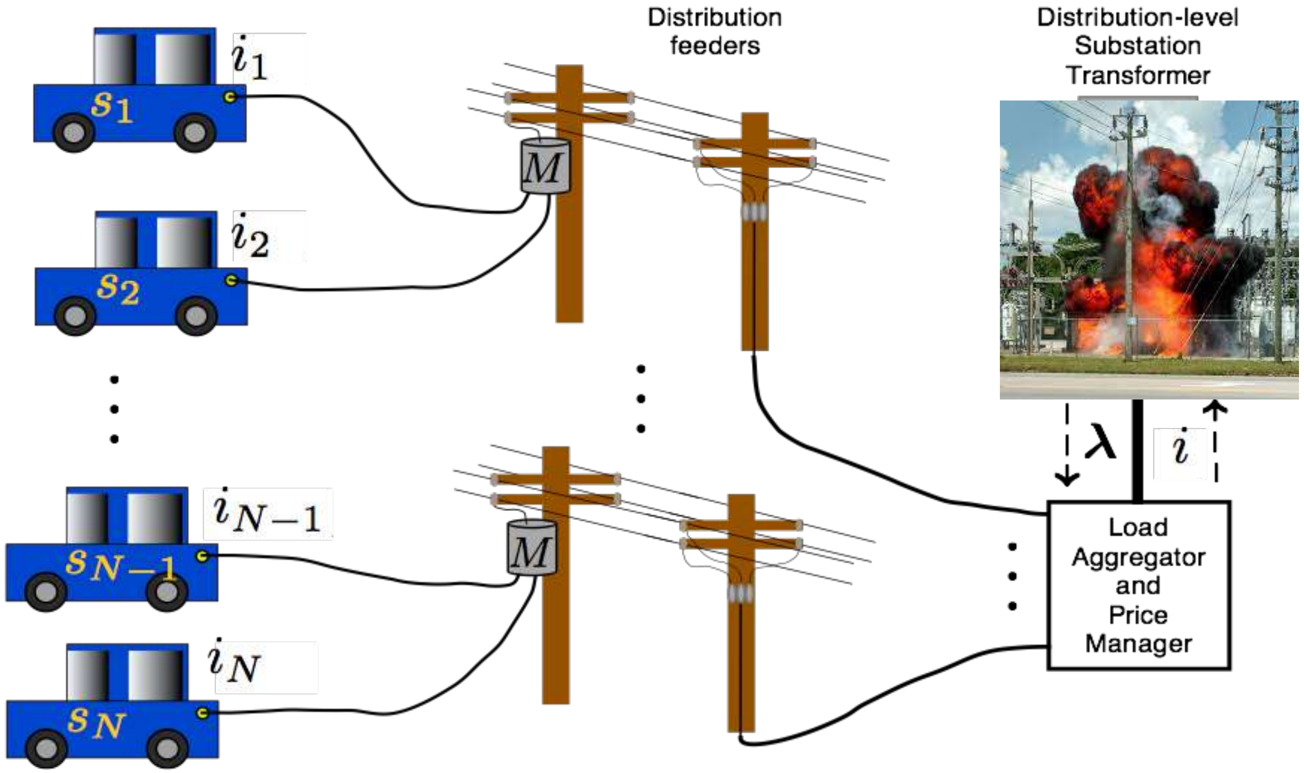
Today many utilities use SMS

Human becomes the actuator in-the-loop

Source: VectorStock.com/7537816

Illustrating indirect control: EV charging scenario

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



EVs' objectives: charge quickly!

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

Transformer challenge: uncoordinated charging ➔ overload ➔ insulation loss

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

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

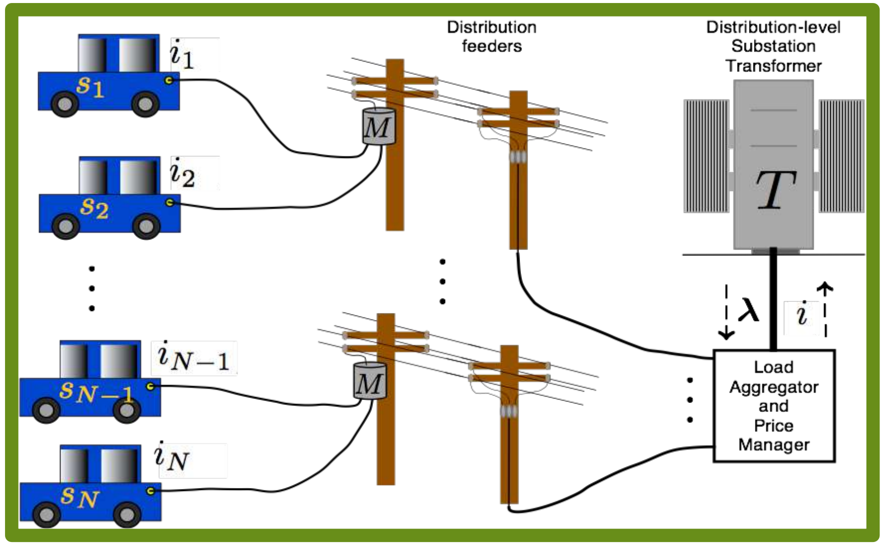
Aggregate current:

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

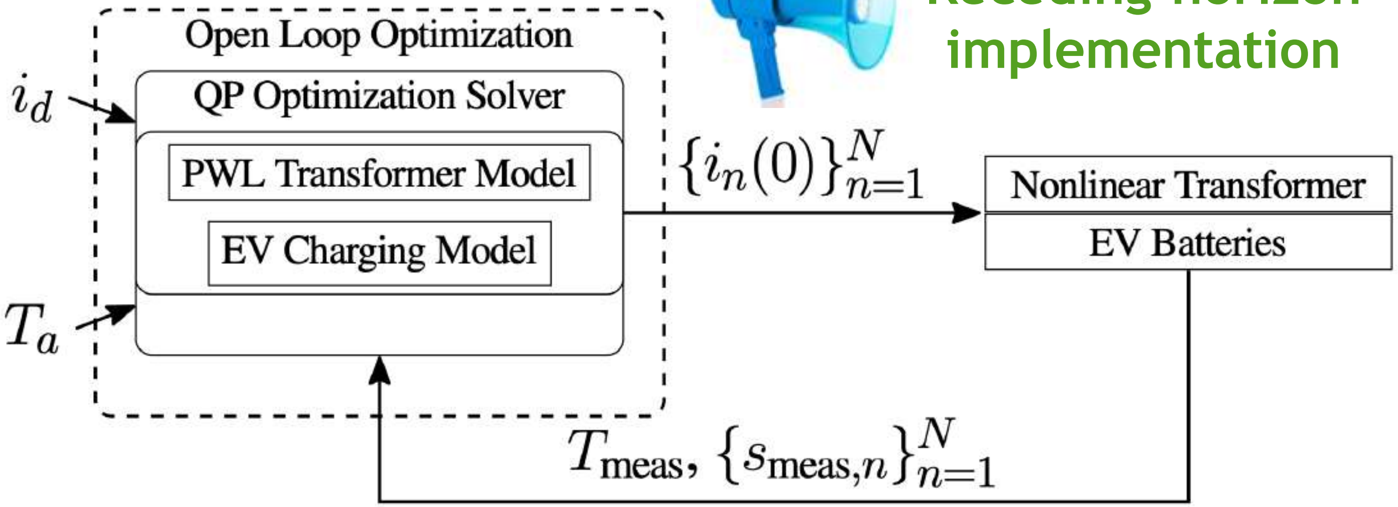
M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

EV charging scenario: direct load control

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



Receding-horizon implementation



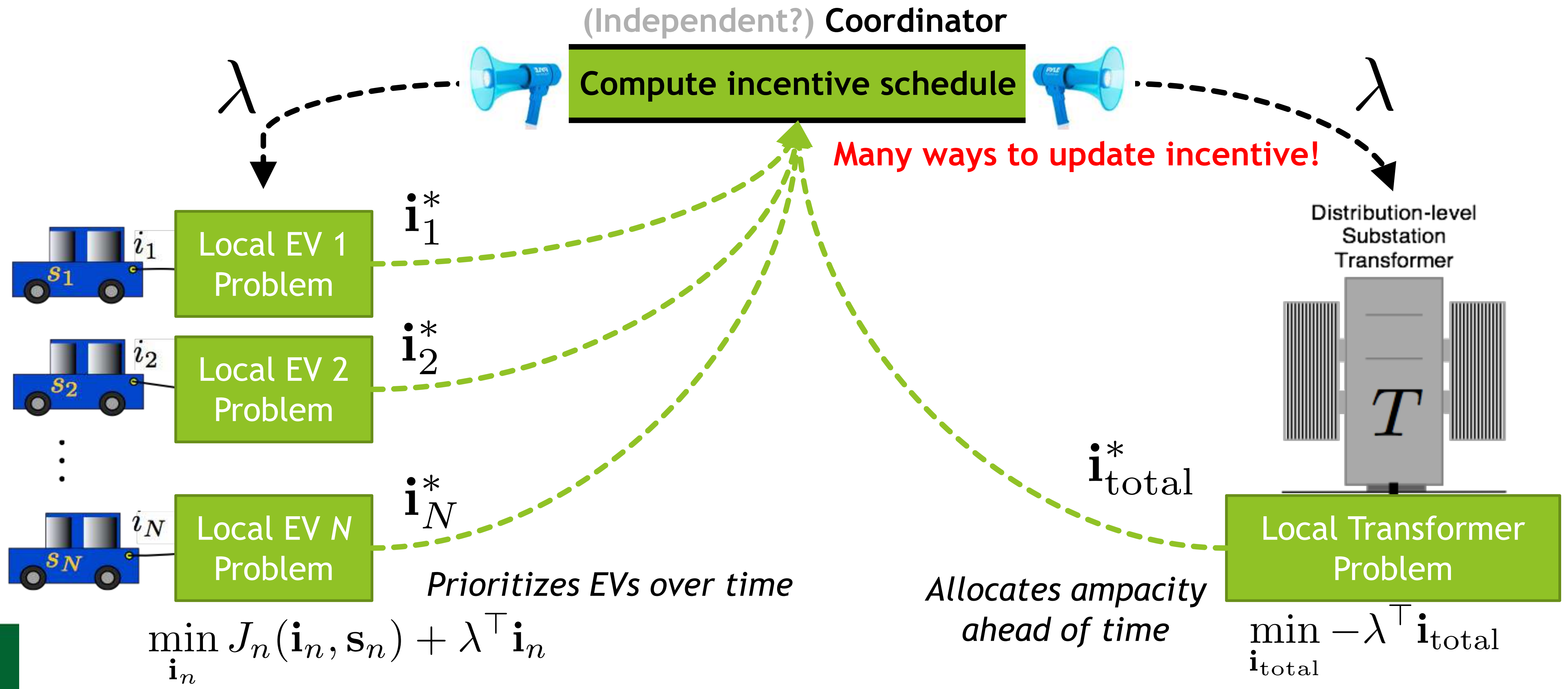
charge quickly! *limit high currents*

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

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.

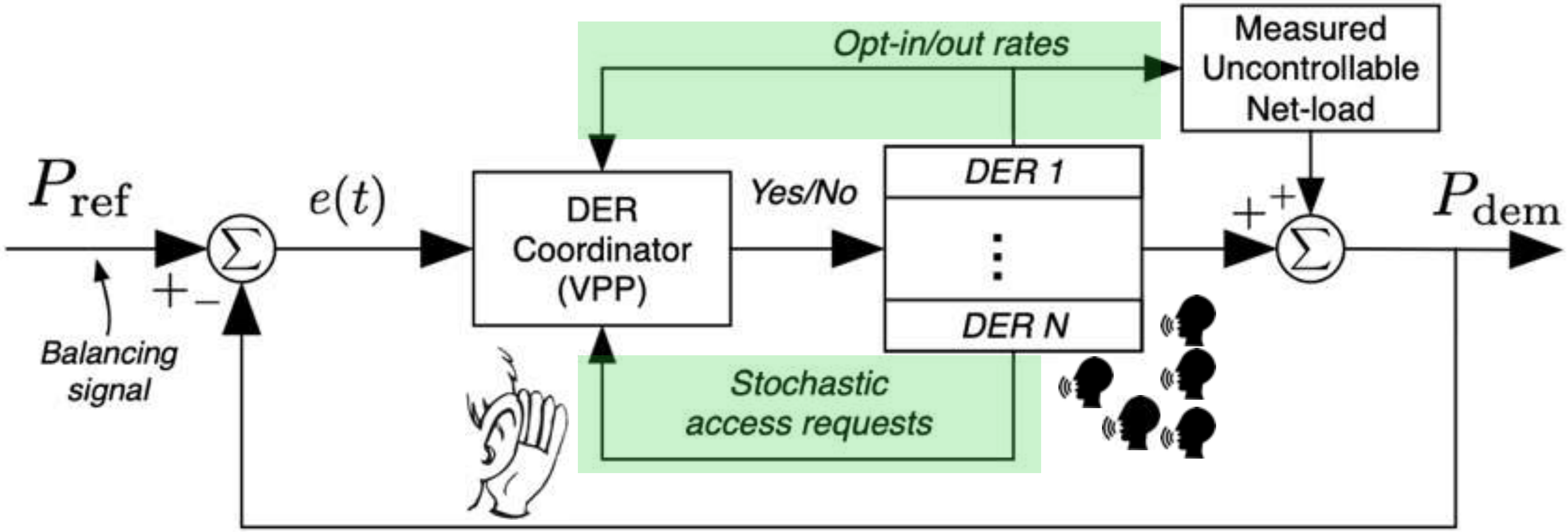
EV charging scenario: indirect load control

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

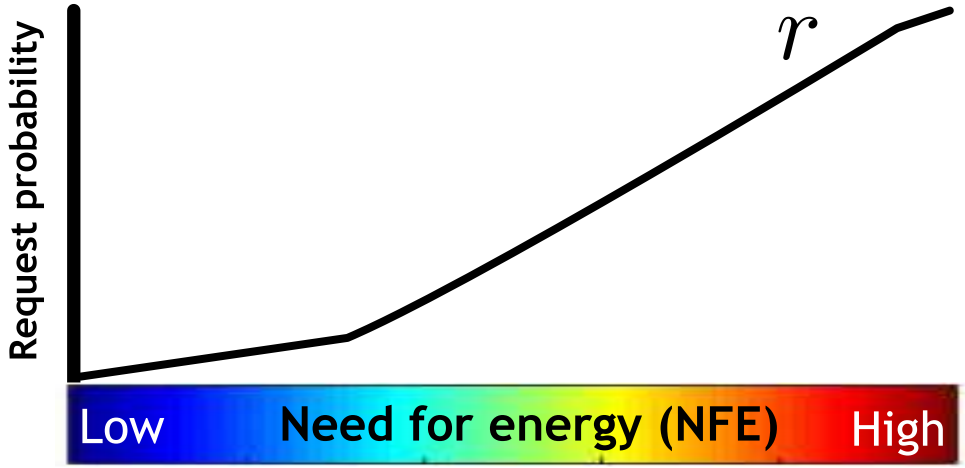


M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," *IEEE Transactions on Control Systems Technology*, 2021.

Architecture #2: Device-driven approach (bottom-up)



Local device logic can guarantee QoS



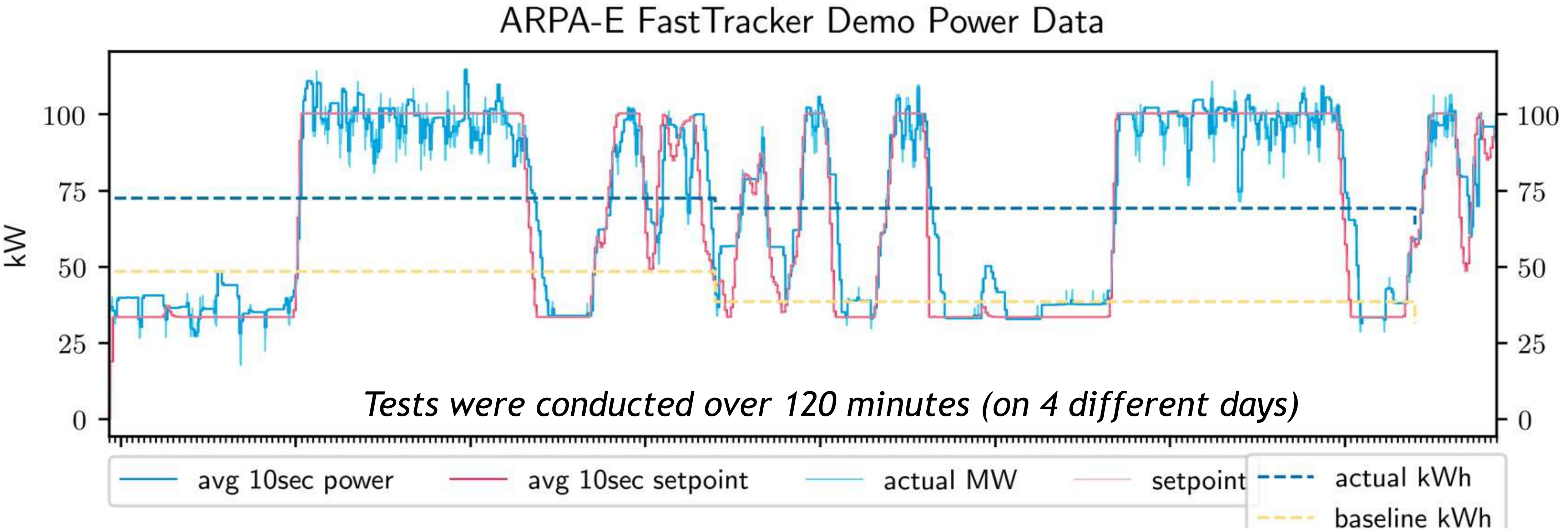
Leverage **asynchronous** device-to-cloud comms to have devices **request** temporary access to grid

Controller processes <u>all</u> incoming requests, so **can estimate total demand of fleet (feedback)**

Request logic can include device constraints to manage **device health, QoS,** and can embed local network location to enable <u>**network-aware coordination**</u>

Example: field trial with 200+ loads in 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

S. Brahma, A. Khurram, H. Ossareh, and M. Almassalkhi, "*Optimal Frequency Regulation using Packetized Energy Management*," IEEE Transactions on Smart Grid, 2023
M. Almassalkhi, J. Frolik, and P. Hines, "*How To Prevent Blackouts By Packetizing The Power Grid*" *IEEE Spectrum*, February, 2022.

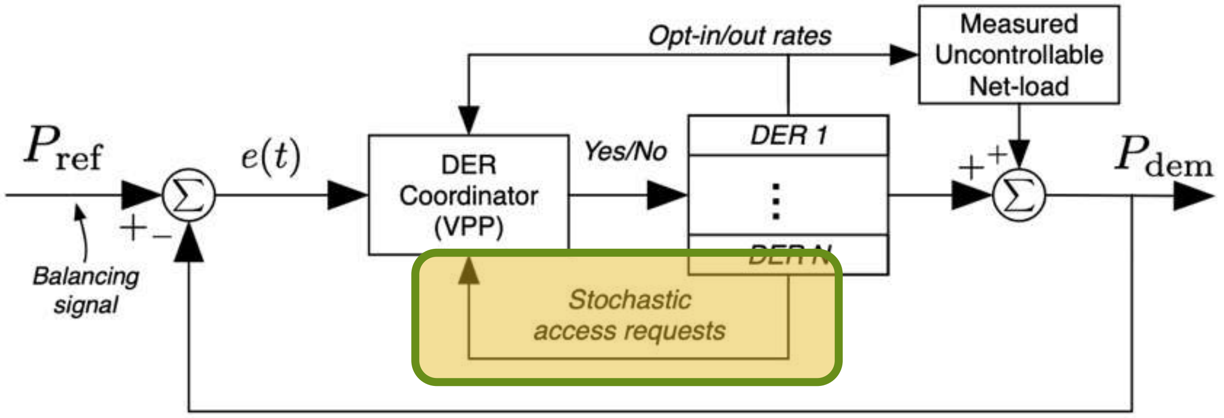
New device-level logic enhances fleet's performance

Control of Aggregate Air-Conditioning Load using Packetized Energy Concepts

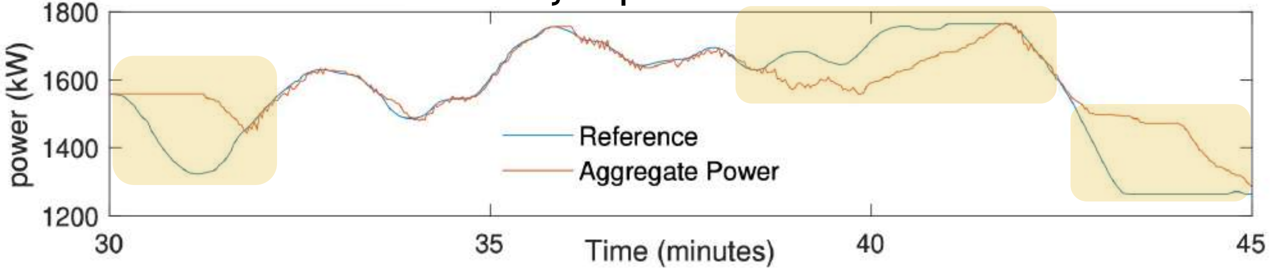
Oluwagbemileke Oyefeso, Gregory S. Ledva, Mads Almassalkhi, Ian A. Hiskens, and Johanna L. Mathieu

Abstract—**The paper extends the packetized energy management (PEM) control strategy to enable coordination of compressor-based thermostatically controlled loads (TCLs), such as air conditioners. This establishes a new method of harnessing the flexibility of this ubiquitous resource, enabling a variety of grid services, such as frequency regulation. In the original PEM scheme, resources request energy packets and turn on if their request is approved. That PEM scheme has been further extended by introducing the concept of turn-off requests. We find that this increases flexibility and improves tracking performance. Through a case study involving over 1000 air conditioners, we evaluate the performance of a population of TCLs providing frequency regulation under PEM, highlighting both the capabilities and limitations. Simulations indicate our controller extensions significantly increase resource availability and tracking performance. We show that it is possible to achieve RMS tracking error below 2% when providing more than 250 kW of frequency regulation.**

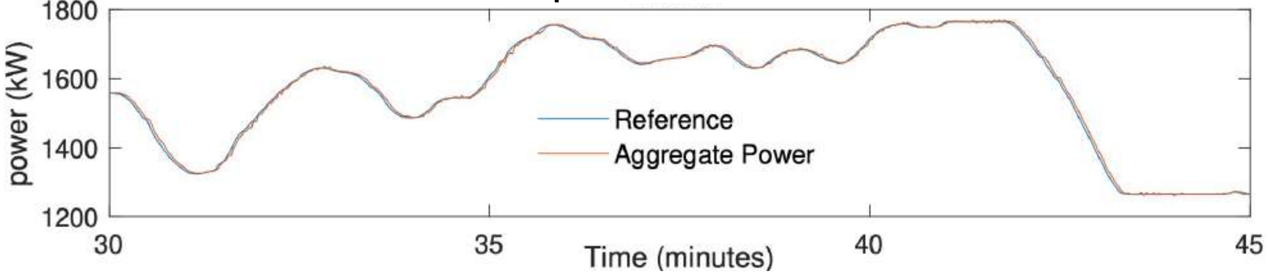
t^{on}_{locked}	Compressor turn-on lock-out time [s].
t^{off}_{locked}	Compressor turn-off lock-out time [s].
t^{on}_{min}	Energy packet minimum epoch length [s].
t^{on}_{max}	Energy packet maximum epoch length [s].
t_{comp}	Compressor lock-out timer [s].
t_n	Elapsed epoch time for AC n [s].
T_a	Indoor Air Temperature [°C].
T_m	Inner Mass Temperature [°C].
T_o	Outdoor Air Temperature [°C].
T^{set}_n	Temperature set-point [°C].
T^{min}_n	Lower dead-band temperature [°C].
T^{max}_n	Upper dead-band temperature [°C].
U_a	Conductance of building envelope [kW/°C].



With only requests to turn ON



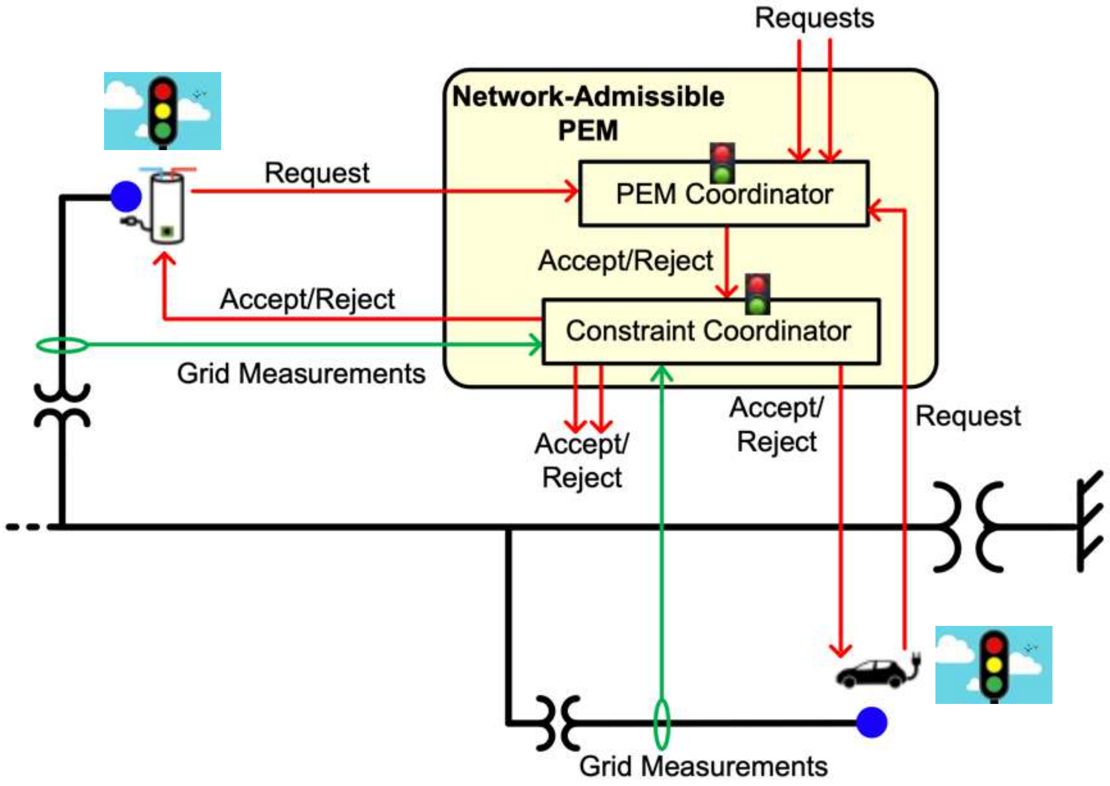
With both requests to turn ON and turn OFF

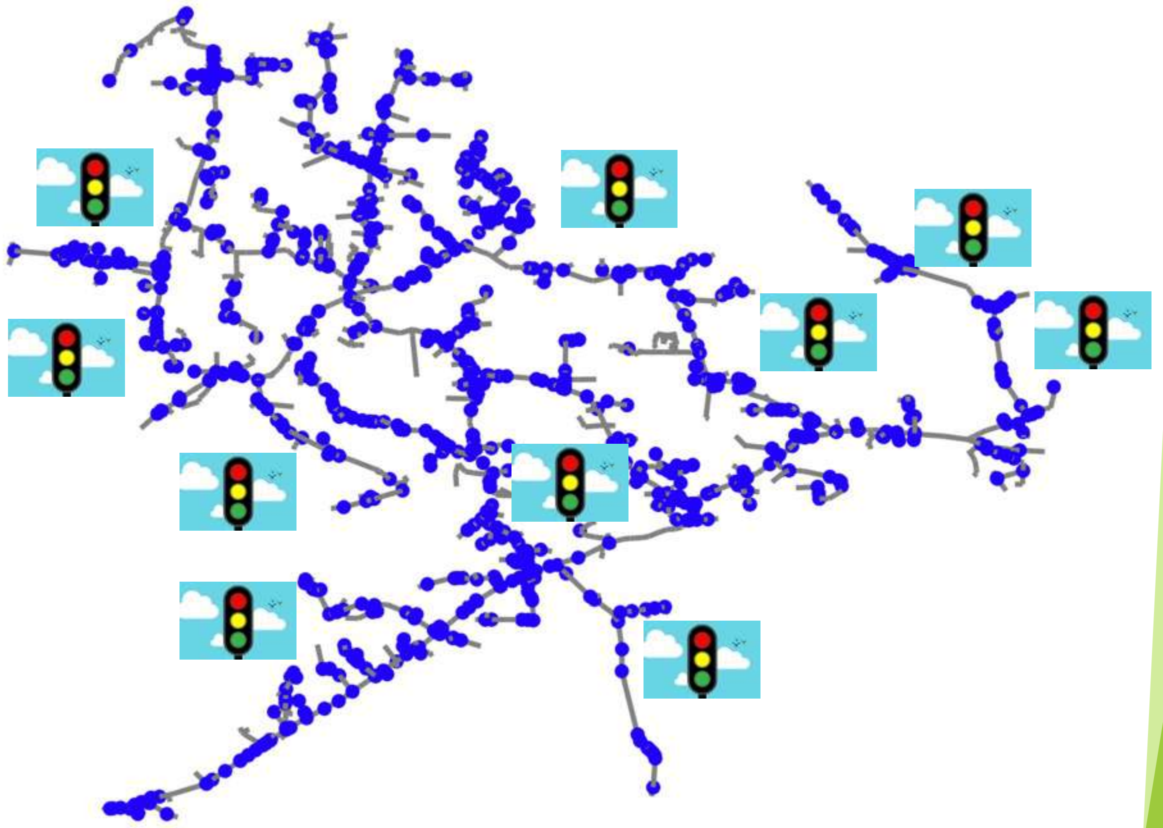


O. Oyefeso, G. Ledva, I. Hiskens, M. Almassalkhi, and J. Mathieu, "*Control of Aggregate Air-Conditioning Load using Packetized Energy Concepts*," IEEE CCTA 2022.

Augmenting device logic with local grid data

Local sensing augments device logic with live grid conditions + traffic-light device logic

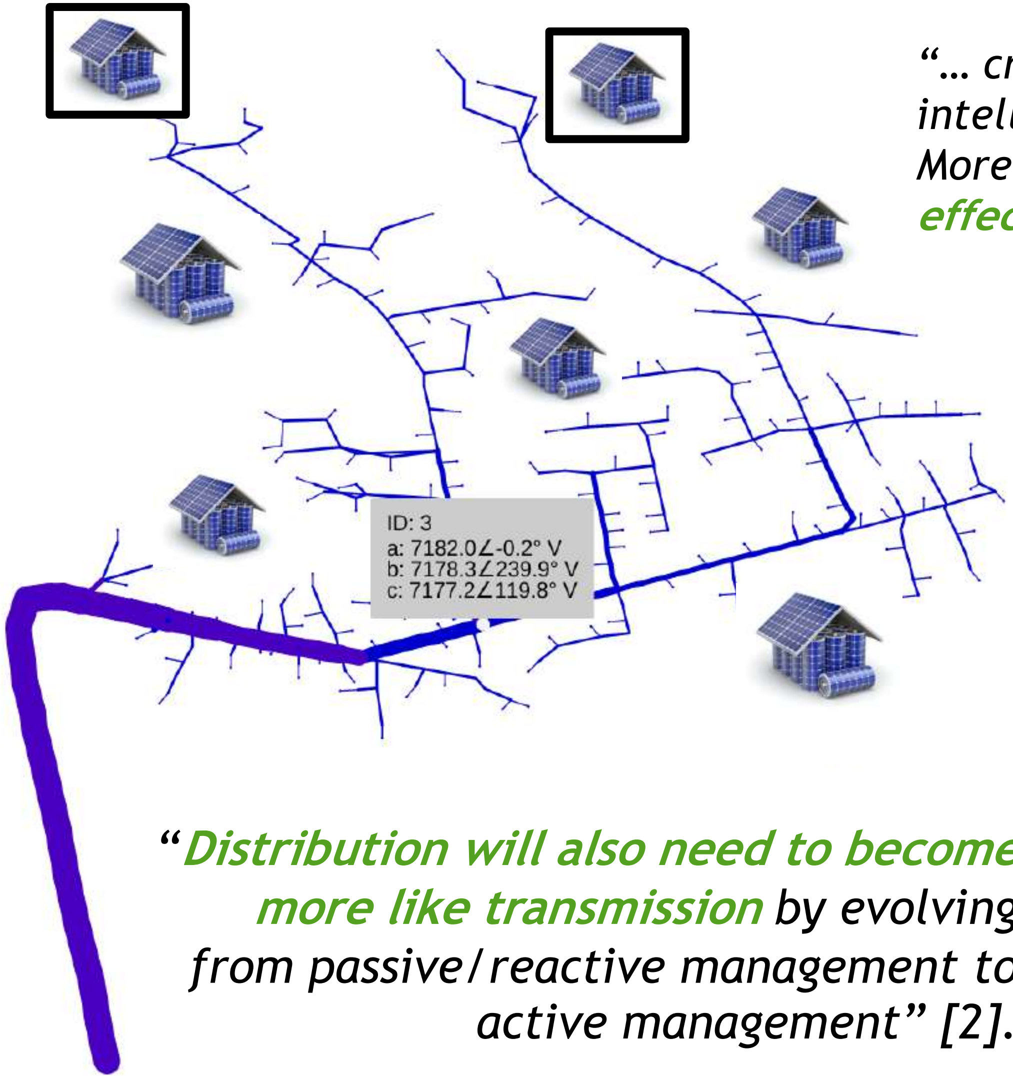




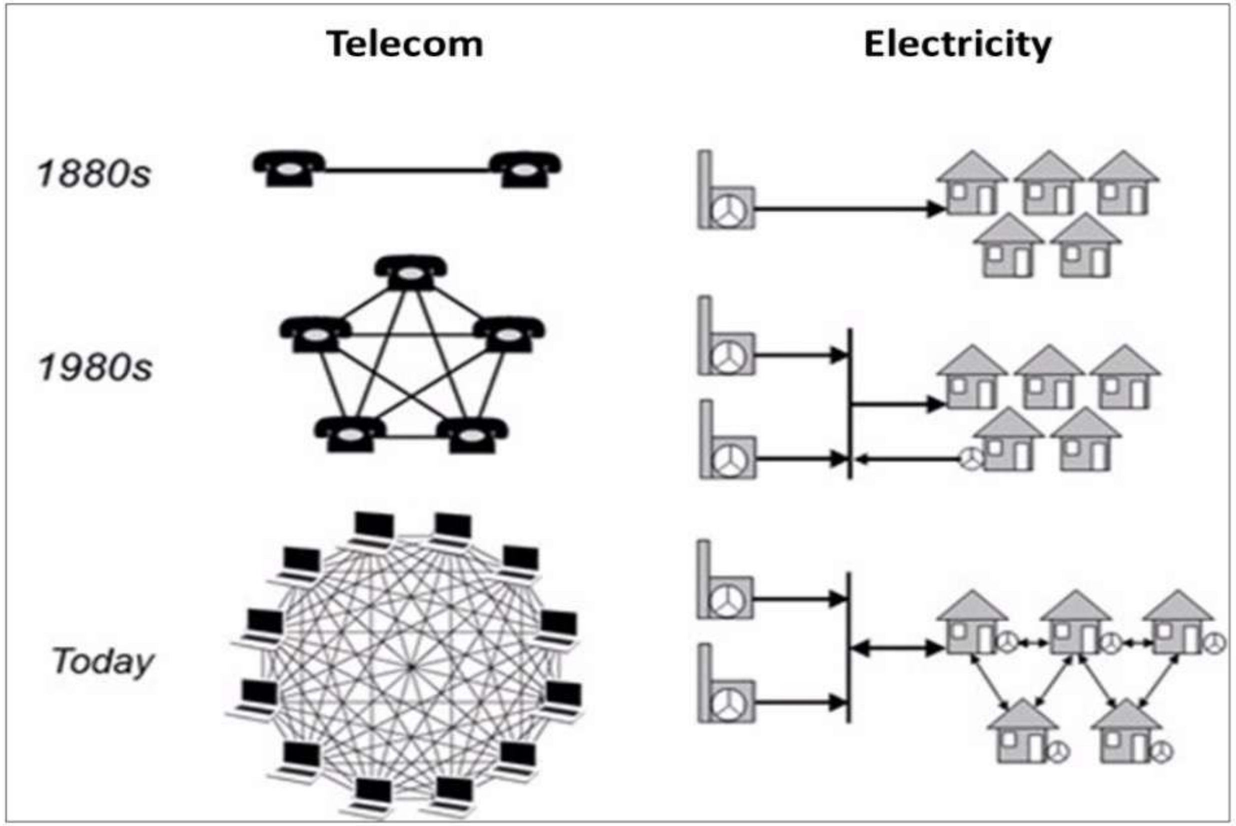
Many open questions: measurement types, locations, update rates, data integrity, etc…

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

What active role should the grid operator play?

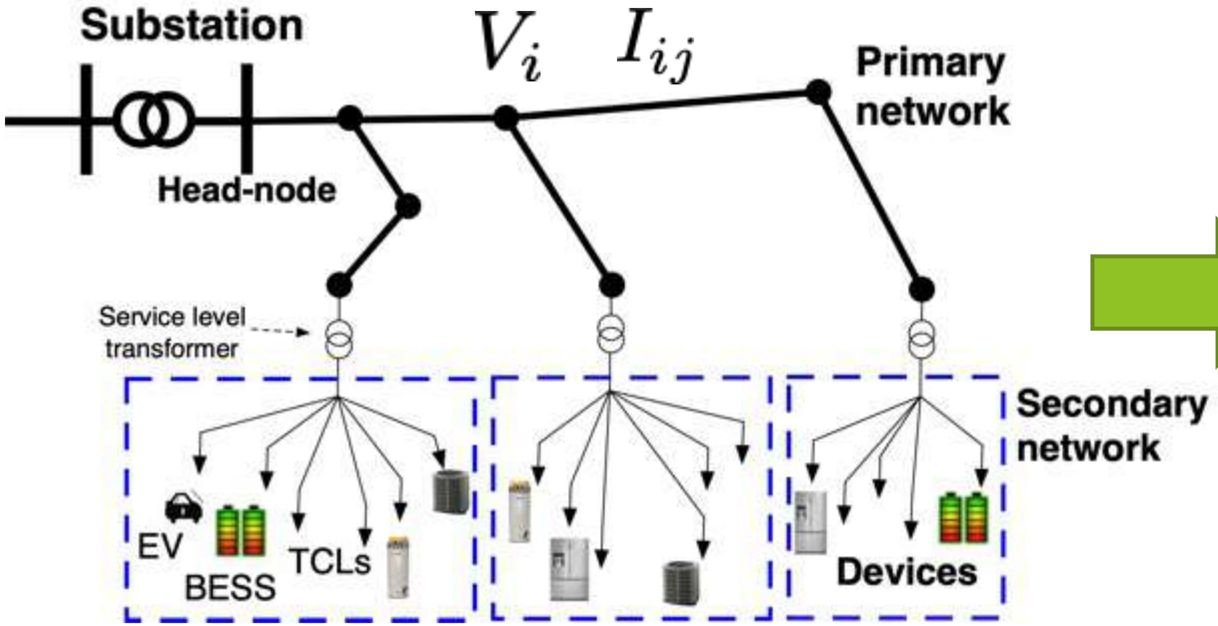


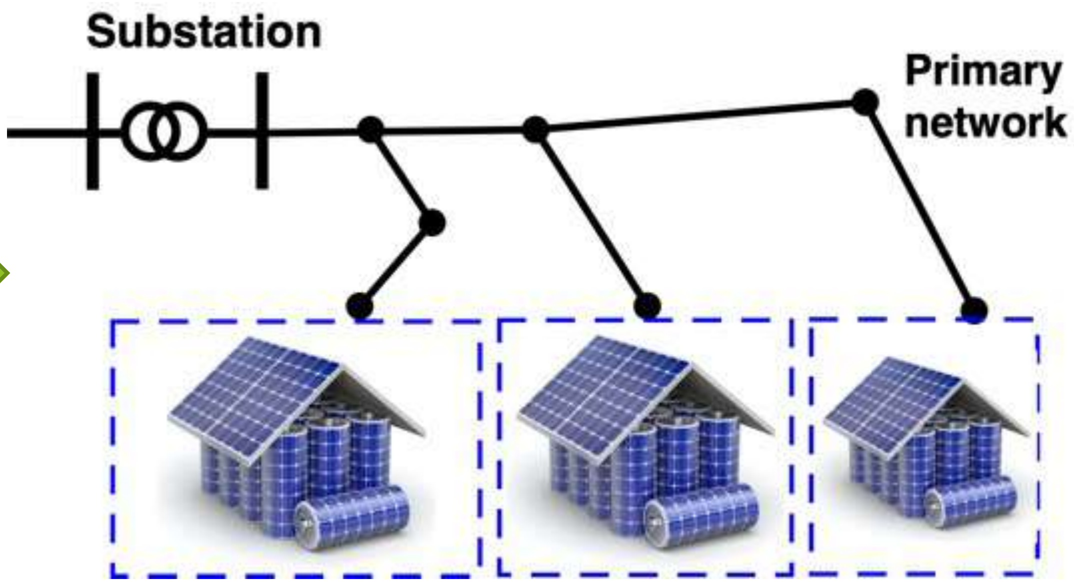
*"… create open networks that increase value through the interaction of intelligent devices on the grid and prosumerization of customers Moreover, even **greater value can be realized through the synergistic effects of convergence of multiple networks**" [1].*



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

Motivating example: aggregating flexible resources





$$m_i \le p_i \le M_i$$

Feeder

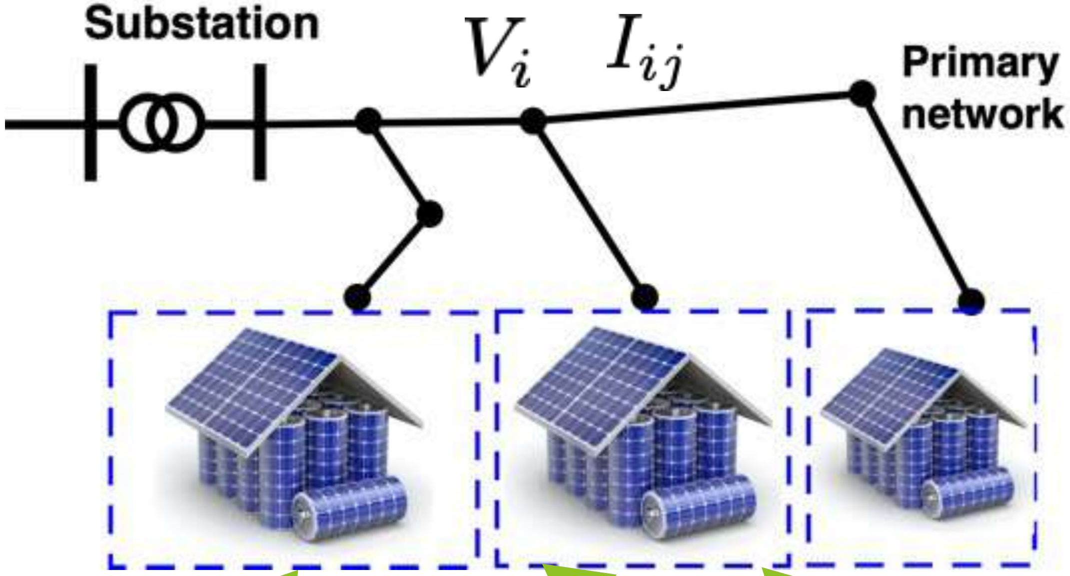
$$\Delta p := \left[\sum_{i=1}^{n} m_i, \sum_{i=1}^{n} M_i\right]$$

Bid flexibility into whole-sale ISO market (MW)

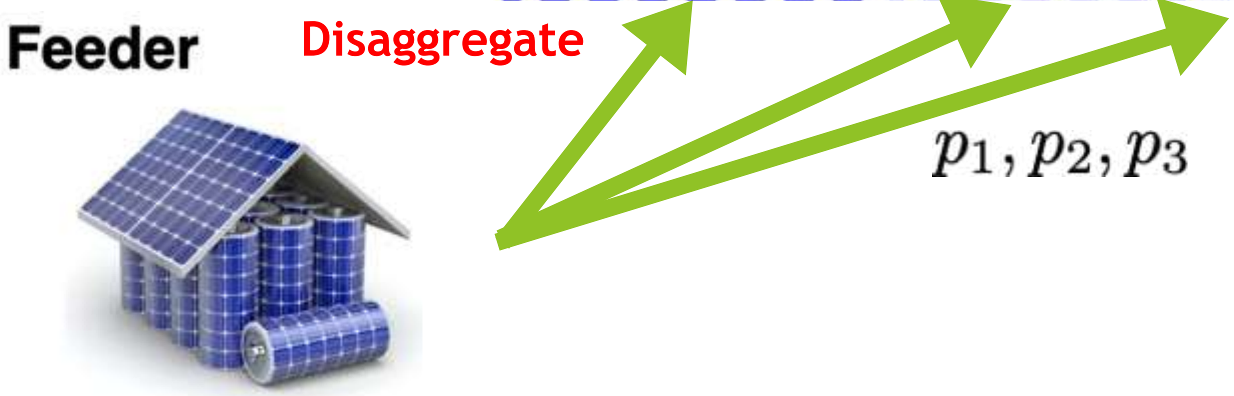
Motivating example: disaggregating flexible resources

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?



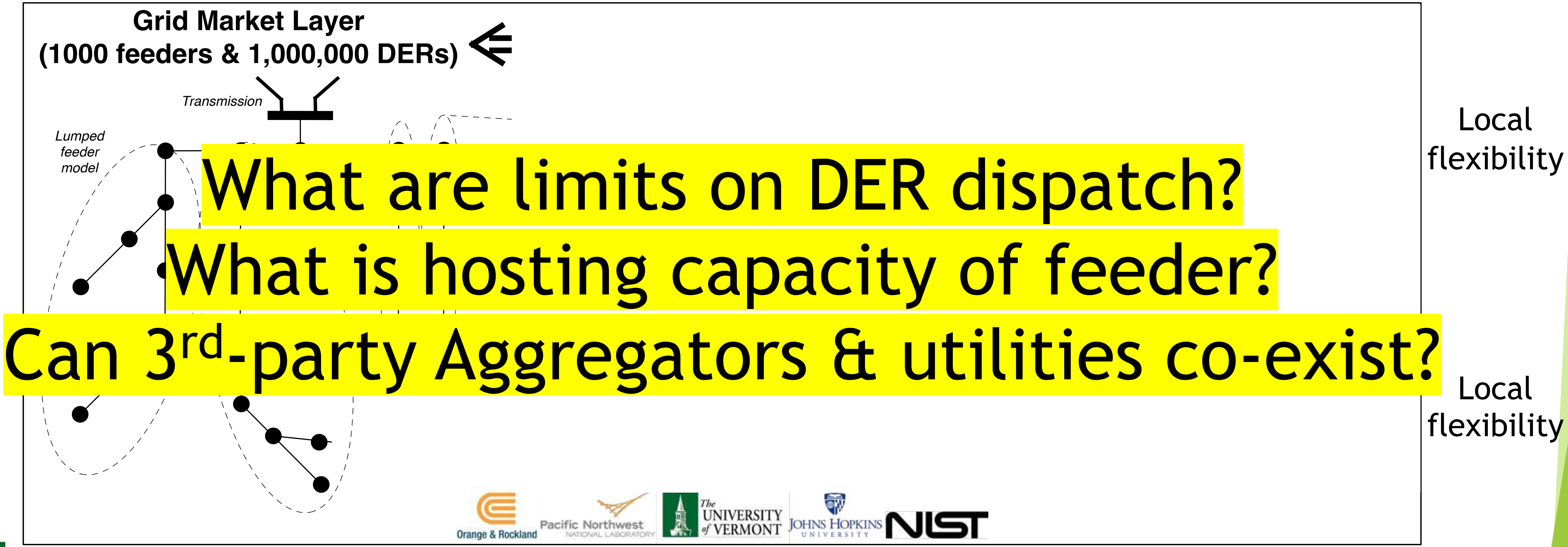
Requested flexibility from ISO (MW)



[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, 2021.
[Z] S. Brahma, Nawaf Nazir, et al, “Optimal and resilient coordination of virtual batteries in distribution feeders,” IEEE Trans. on Power Systems, 2021

Past experiences with "utility-centric" approaches

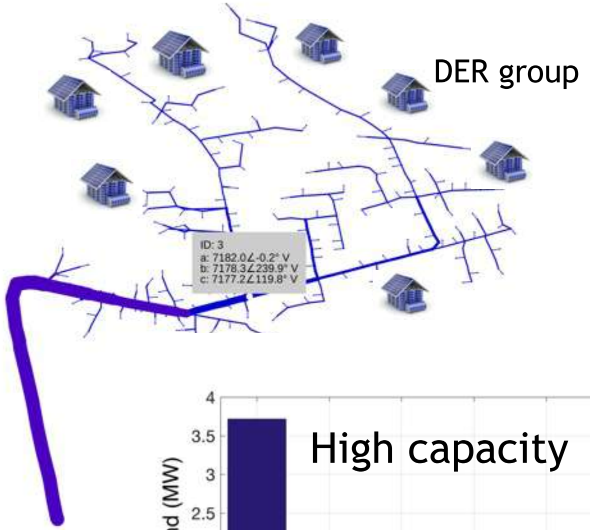
Utility-centric = utility does it all: network ops, DER coordination/dispatch, markets

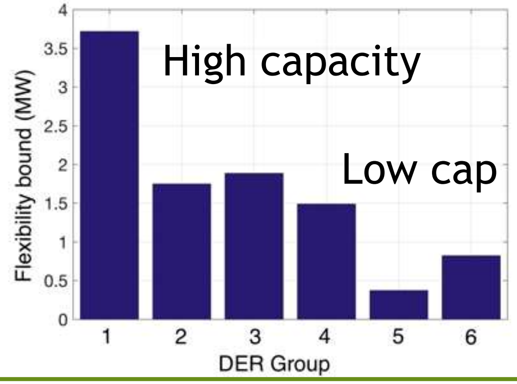


[W] Almassalkhi, et al, "Hierarchical, Grid-Aware, and Economically Optimal Coordination of Distributed Energy Resources in Realistic Distribution Systems," Energies, 2020.
[X] **Nawaf Nazir**, Pavan Racherla, and Mads Almassalkhi, "Optimal multi-period dispatch of distributed energy resources in unbalanced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

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

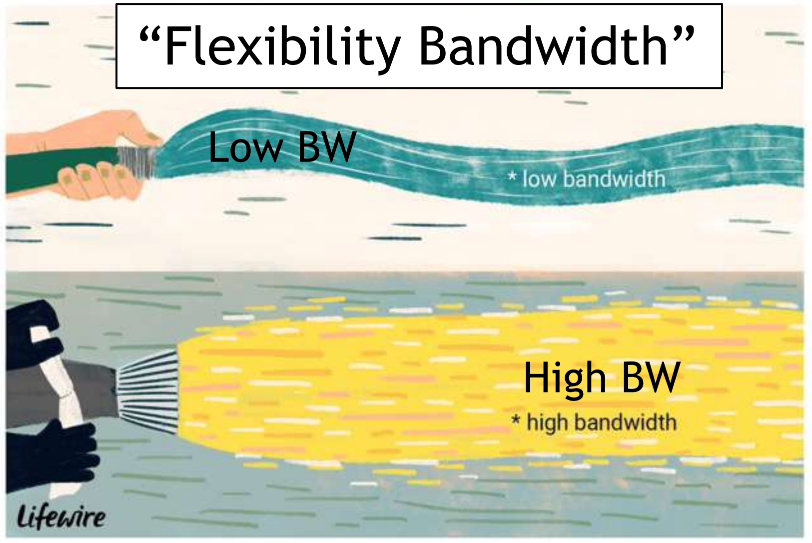




Prices to devices? DLMPs?

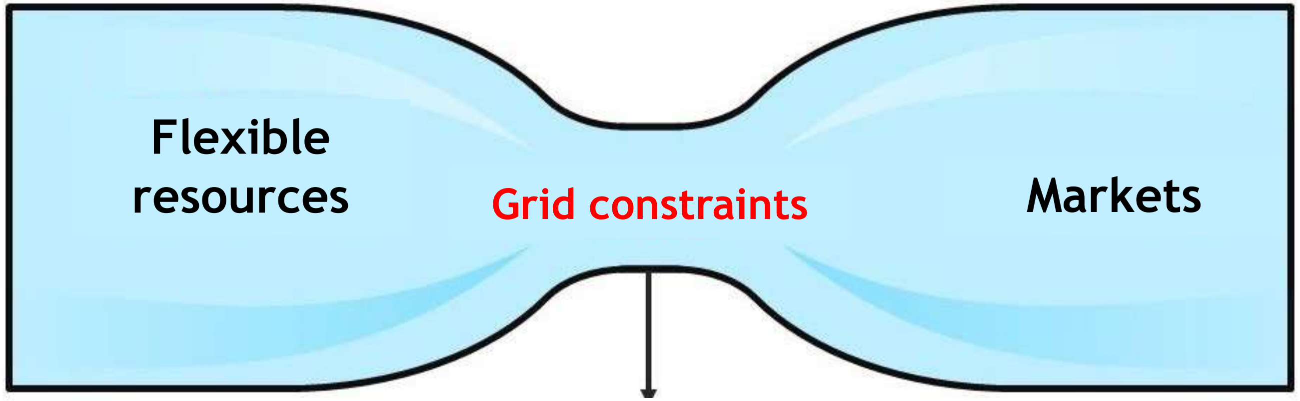
Let's try something different!

Aggregators (device access, markets)
- Need to ensure device QoS
- Need to provide market services
- Lacks access to grid data
- Knows device flexibility

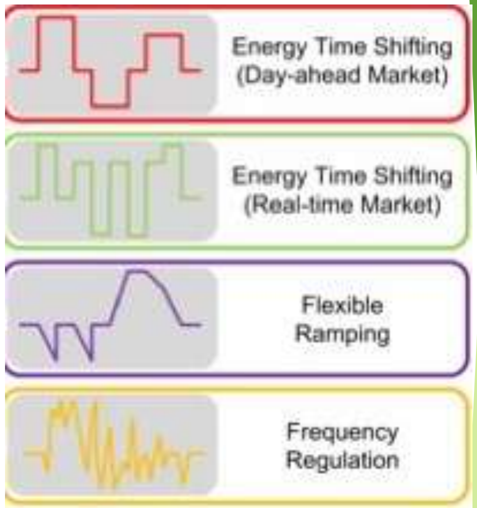


Idea: *think like an internet service provider (ISP)*

Aggregators: flexibility from coordinated devices

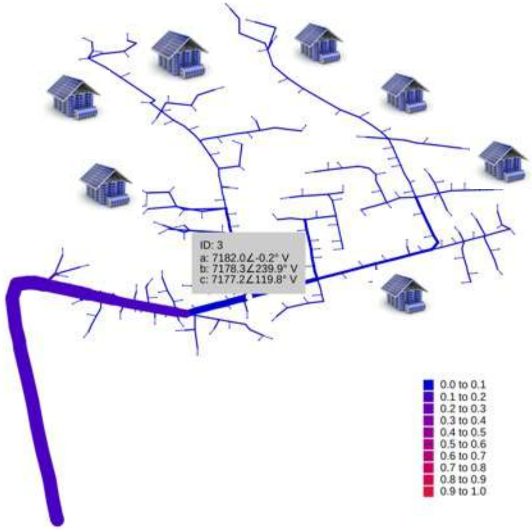


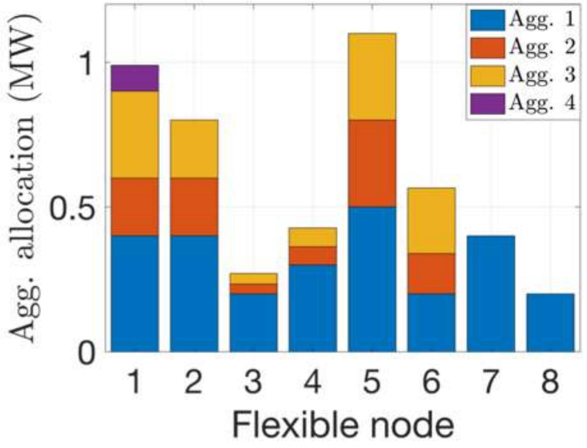
Utility: Decompose feeder HC at each node



Aggregator is allocated portion of available HC at node i

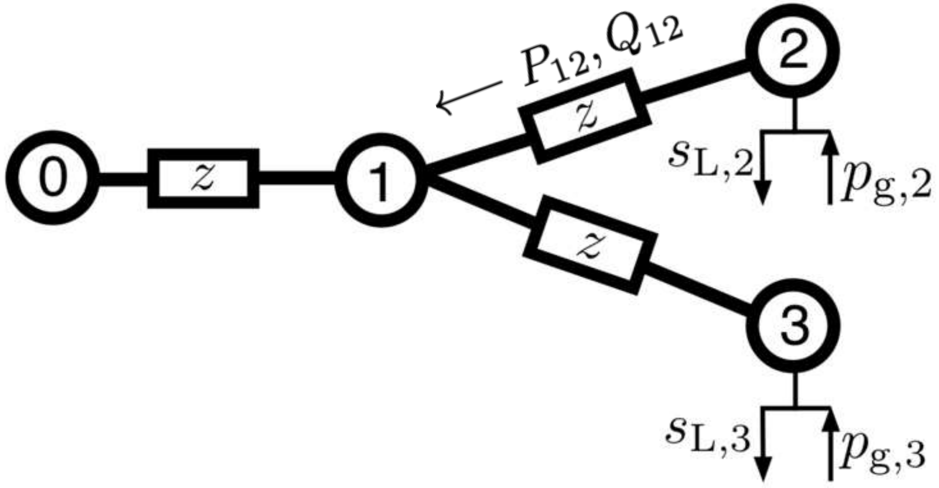
Aggregator bids for priority access to HC





Finding set of admissible (active) injections

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



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

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

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

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

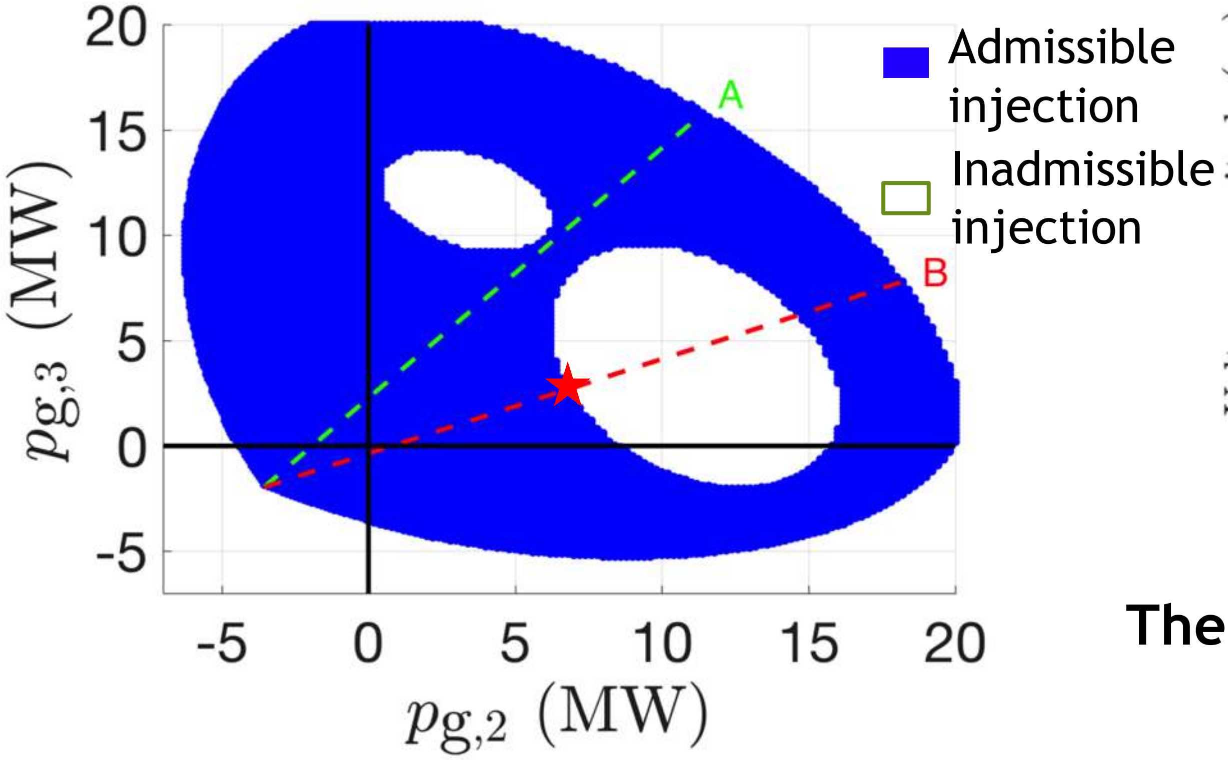
$$l_{ij}(P_{ij}, Q_{ij}, v_j) = \frac{P_{ij}^2 + Q_{ij}^2}{v_j},$$

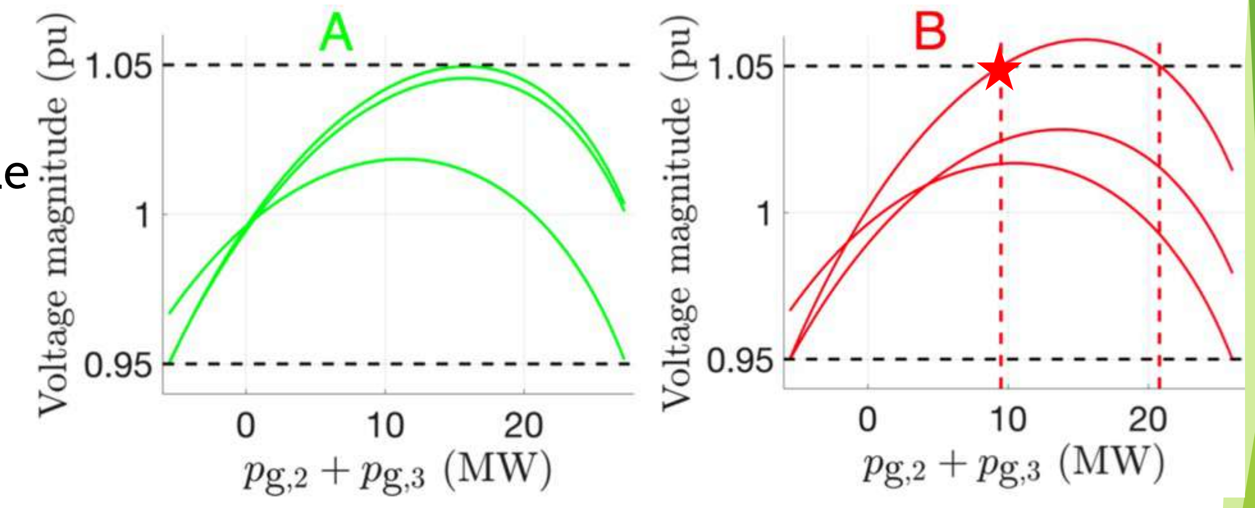
The only nonlinear relation

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 example:



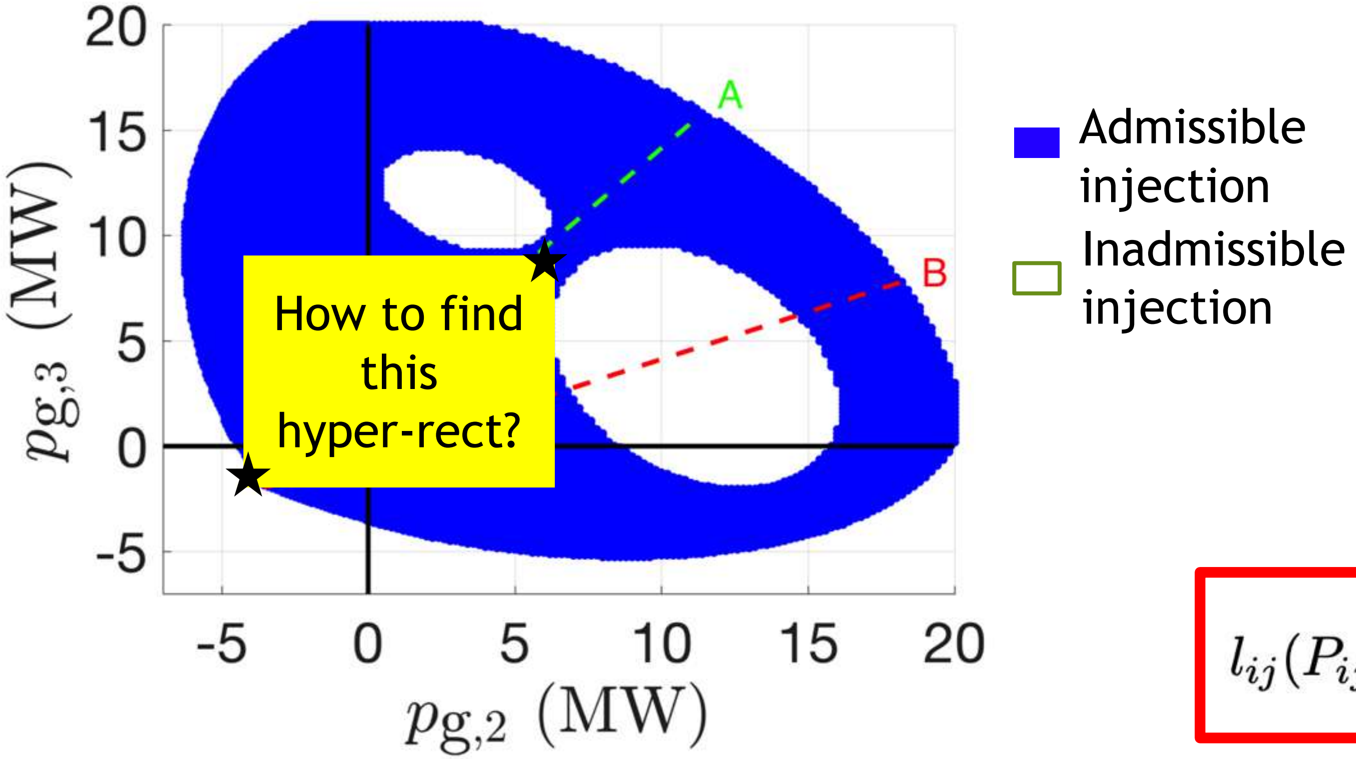


Network limits: $v_i \in [\underline{v}_i, \bar{v}_i], l_{ij} \in [\underline{l}_{ij}, \bar{l}_{ij}]$

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

Finding set of admissible (active) injections

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



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

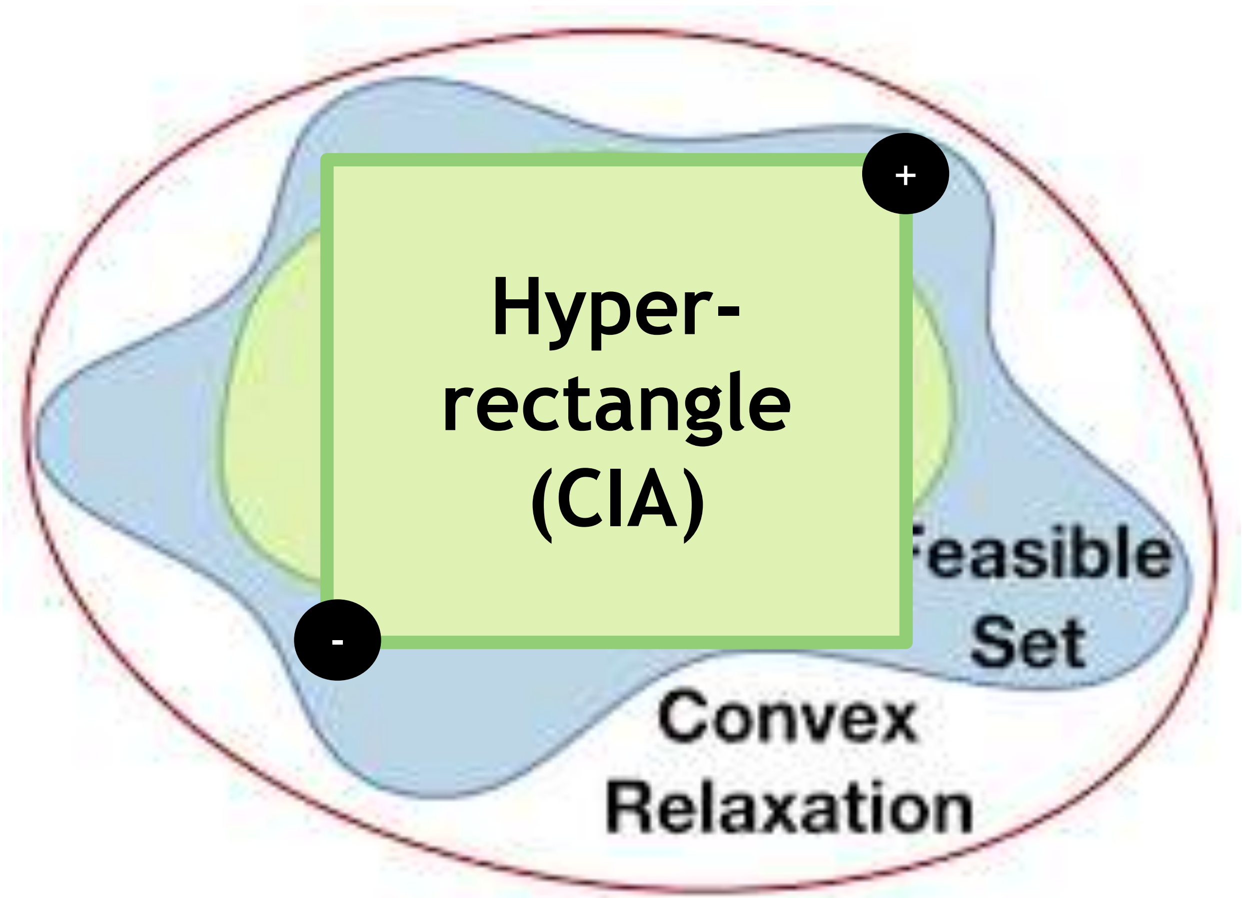
$$P_{ij} = p_j + \sum_{h:h\to j} (P_{jh} - r_{jh}l_{jh})$$

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

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

Idea: replace non-convex constraint with a convex inner approximation (CIA)

Convexity, optimality, and admissibility



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 NLP constraints)

Convex relaxation contains feasible set + some solutions may not be not admissible at optimality.

Convex inner approximation (CIA) contains a convex subset of the admissible solutions (but is 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 real-time disaggregation of distributed energy resources in radial networks,*" *IEEE TPWRS, 2021.*

Convex inner approximation and *proxy* variables

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

Then, we can create *proxy* variables that upper (+) and lower (-) bound the physical (P, Q, V)

$$P^+ := Cp - D_{\mathrm{R}} l_{\mathrm{lb}}$$
$$P^- := Cp - D_{\mathrm{R}} l_{\mathrm{ub}}$$
$$Q^+ := Cq - D_{\mathrm{X}_+} l_{\mathrm{lb}} - D_{\mathrm{X}_-} l_{\mathrm{ub}}$$
$$Q^- := Cq - D_{\mathrm{X}_+} l_{\mathrm{ub}} - D_{\mathrm{X}_-} l_{\mathrm{lb}}$$
$$V^+ := v_0 \mathbf{1}_n + M_{\mathrm{p}} p + M_{\mathrm{q}} q - H_+ l_{\mathrm{lb}} - H_- l_{\mathrm{ub}}$$
$$V^- := v_0 \mathbf{1}_n + M_{\mathrm{p}} p + M_{\mathrm{q}} q - H_+ l_{\mathrm{ub}} - H_- l_{\mathrm{lb}}$$

Given a nominal operating point, $x_{ij}^0 := (P_{ij}^0, Q_{ij}^0, v_j^0)$

$$\boxed{l_{ij} \approx l_{ij}^0 + \mathbf{J}_{ij}^\top \delta_{ij} + \frac{1}{2}\delta_{ij}^\top \mathbf{H}_{\mathrm{e},ij}\delta_{ij}}$$

$$\delta_{ij} := \begin{bmatrix} P_{ij} - P_{ij}^0 \\ Q_{ij} - Q_{ij}^0 \\ v_j - v_j^0 \end{bmatrix}, \quad \mathbf{J}_{ij} := \begin{bmatrix} \frac{\partial l_{ij}}{\partial P_{ij}} \\ \frac{\partial l_{ij}}{\partial Q_{ij}} \\ \frac{\partial l_{ij}}{\partial v_j} \end{bmatrix}\Bigg|_{x_{ij}^0} = \begin{bmatrix} \frac{2P_{ij}^0}{v_j^0} \\ \frac{2Q_{ij}^0}{v_j^0} \\ -\frac{(P_{ij}^0)^2+(Q_{ij}^0)^2}{(v_j^0)^2} \end{bmatrix}$$

$$\mathbf{H}_{\mathrm{e},ij} := \begin{bmatrix} \frac{2}{v_j^0} & 0 & \frac{-2P_{ij}^0}{(v_j^0)^2} \\ 0 & \frac{2}{v_j^0} & \frac{-2Q_{ij}^0}{(v_j^0)^2} \\ \frac{-2P_{ij}^0}{(v_j^0)^2} & \frac{-2Q_{ij}^0}{(v_j^0)^2} & 2\frac{(P_{ij}^0)^2+(Q_{ij}^0)^2}{(v_j^0)^3} \end{bmatrix} \succeq 0^*$$

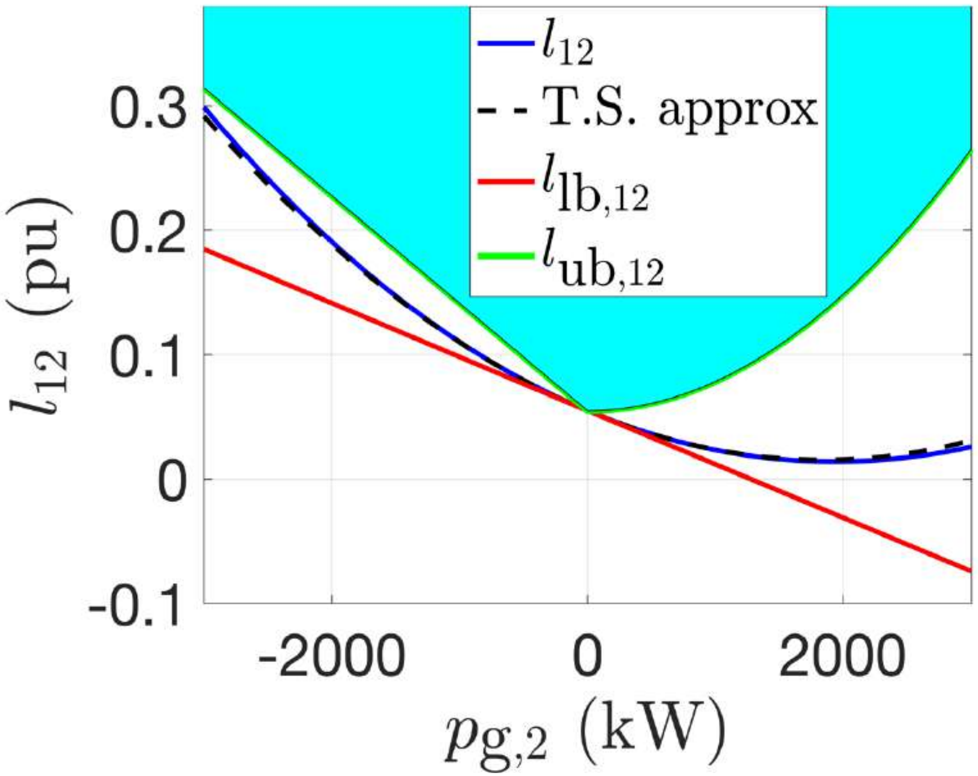
and from this model, we can explicitly define upper and lower bounds on l_{ij} that yield a convex inner approximation.

Nawaf Nazir and Mads Almassalkhi. "*Grid-aware aggregation and real-time disaggregation of distributed energy resources in radial networks,*" *IEEE TPWRS, 2021.*
N. Nazir and M. Almassalkhi, "*Voltage Positioning Using Co-Optimization of Controllable Grid Assets in Radial Networks*," in *IEEE TPWRS*, 2021.

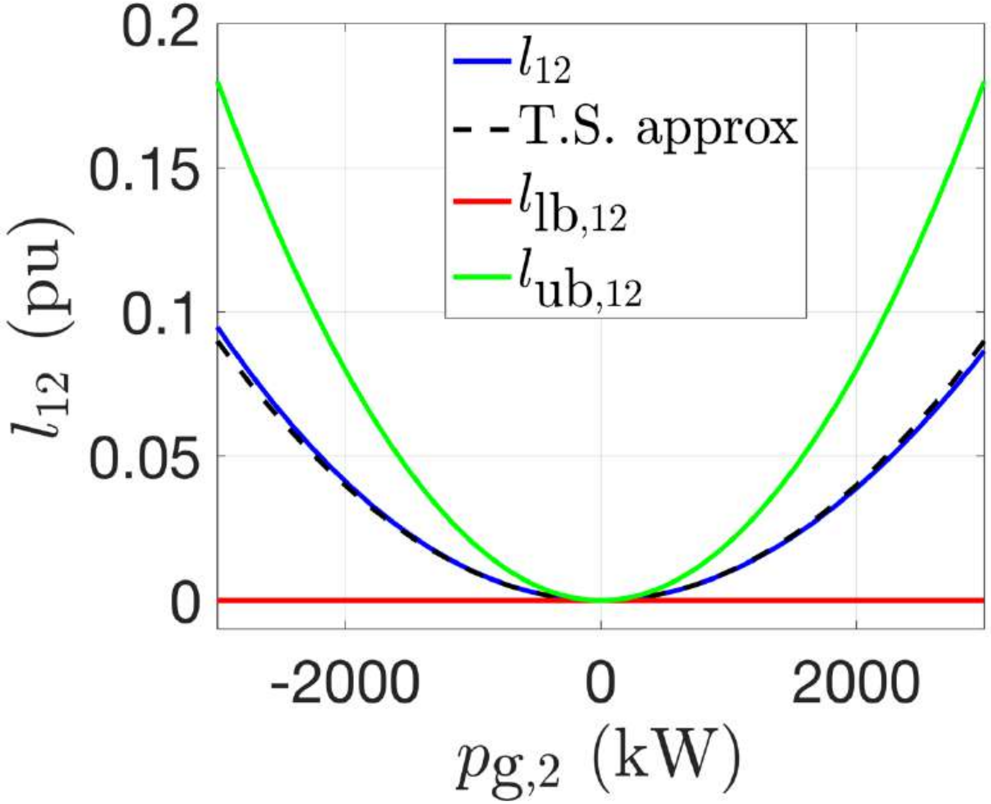
Convex inner approximation via proxy variables

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

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.*

Determining admissible injection limits

p_i^+ **maximum** active power injection at *each* node:

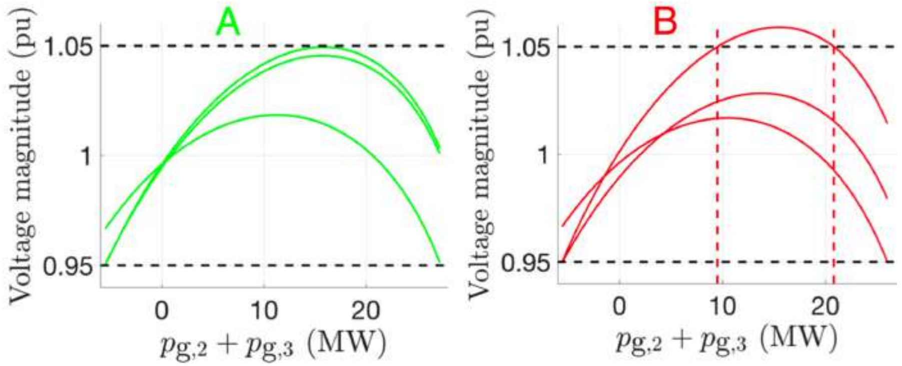
$$p^+(x^0) = \arg\max_p \sum_{i=1}^{N} f_i(p_i)$$
$$\text{s.t. } p \in \mathcal{X}(x^0)$$

p_i^- **minimum** active power injection at *each* node:

$$p^-(x^0) = \arg\min_p \sum_{i=1}^{N} f_i(p_i)$$
$$\text{s.t. } p \in \mathcal{X}(x^0)$$

Theorem: If $p_i \in [p_i^-, p_i^+]\ \forall i \Rightarrow \underline{V} \leq V^-(p) \leq V(p) \leq V^+(p) \leq \overline{V}$

Proof is conditioned upon: *dV⁺/dp, dV⁻/dp ≥ 0*



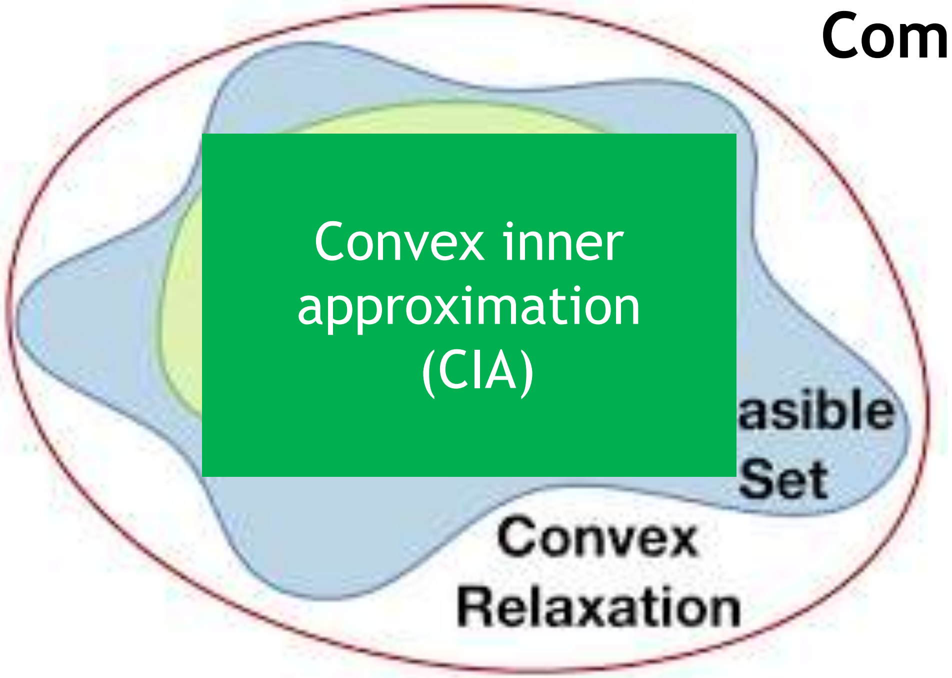
Monotonicity conditions:

More load → higher voltage

Less load → lower voltage

Bonus: *objective is feeder's hosting capacity!*

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 grid flexibility bounds

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]

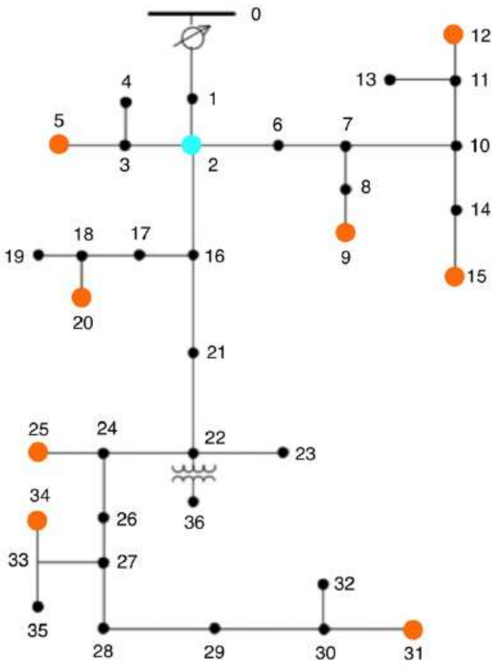
Convex relaxation (CR) over-estimates maximum reactive power capability

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

Conclusion: proposed (CIA) method is **not overly conservative** and entire range is admissible

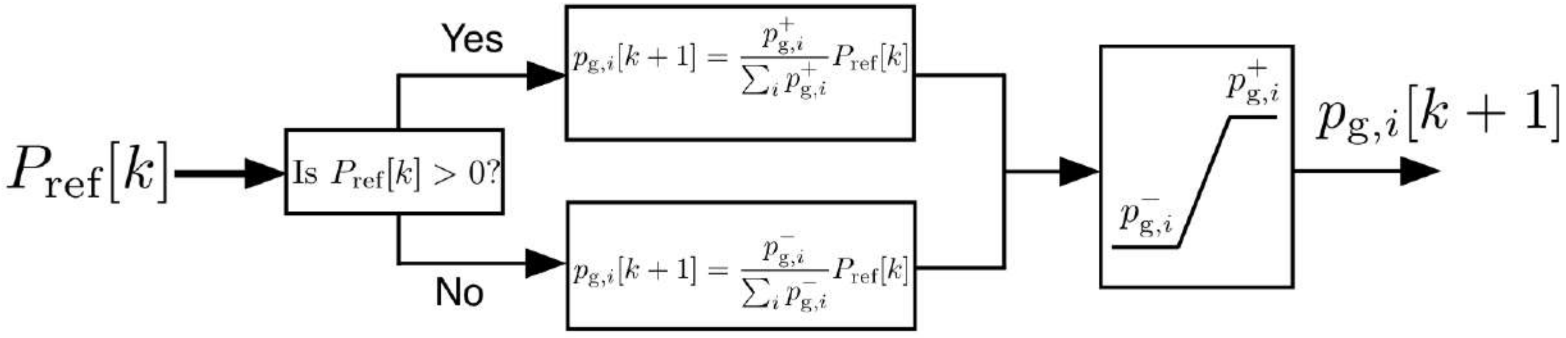
CIA enables real-time, grid-aware disaggregation

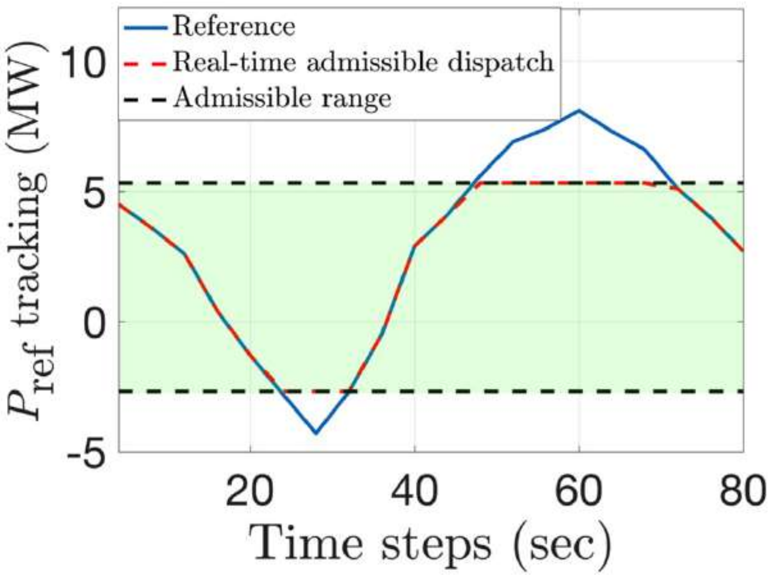
Nodal hosting capacities $[p_i^-, p_i^+]$ enable an open-loop, distributed, and **grid-aware DER control policy**

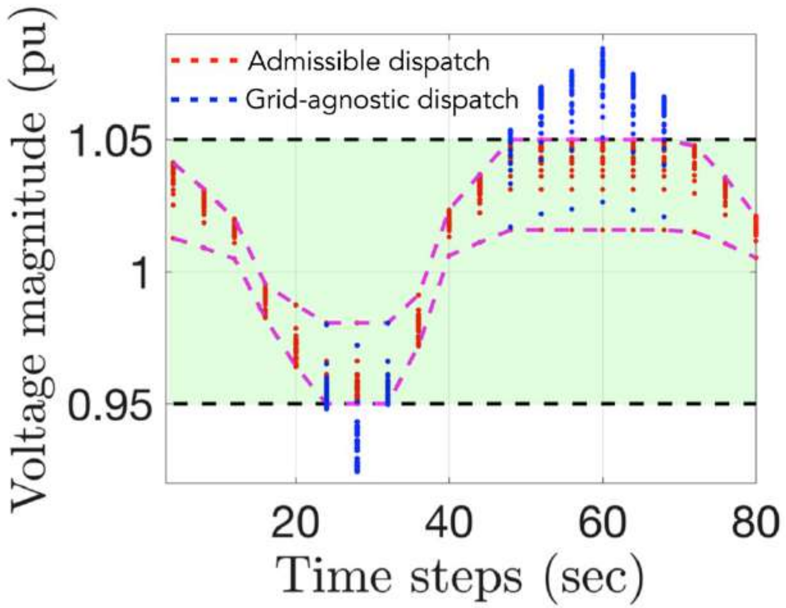


IEEE 37-node network

(from Baker/Dall'Anese)



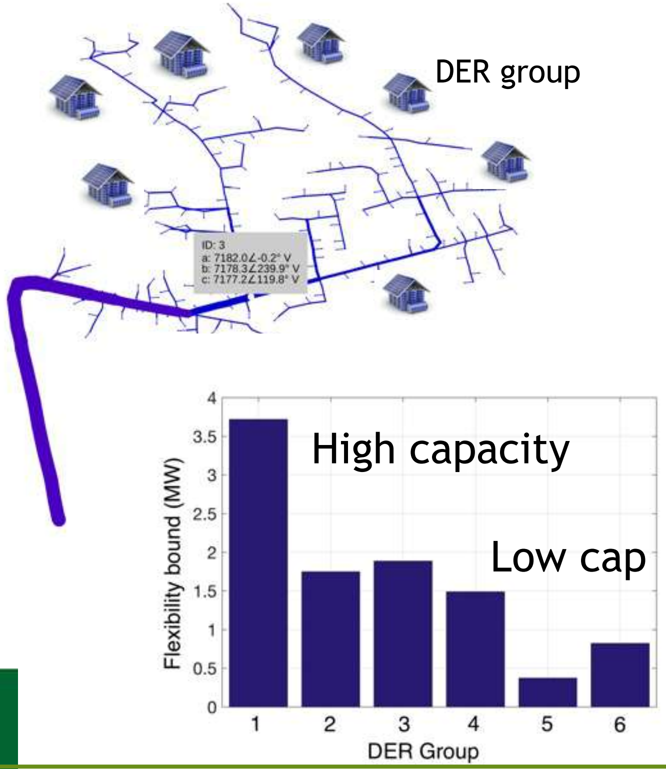




N. Nazir and M. Almassalkhi, "Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks", IEEE Transactions on Power Systems, 2021

Summary: DHC overcomes data/control asymmetry

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

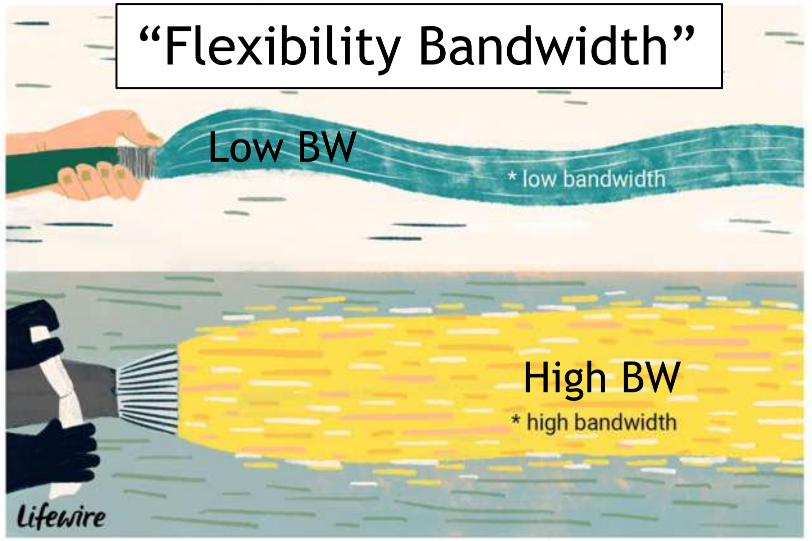


Available hosting capacity

Future work: find optimal control/price signals

Available flexibility

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



N. Nazir and M. Almassalkhi, "Market mechanism to enable grid-aware dispatch of Aggregators in radial distribution networks,". *IREP Bulk Power System Dynamics and Control Symposium*, 2022.

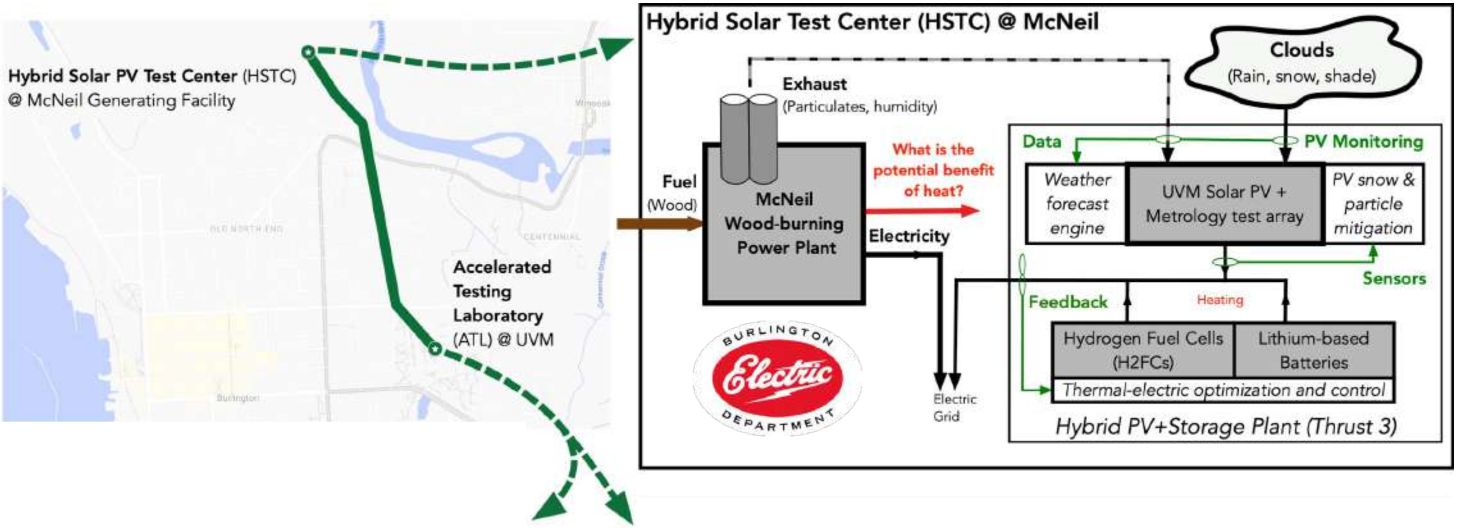
Bonus topic: Hybrid Energy Systems

From virtual batteries to physical batteries

What is a hybrid energy system?

Hybrid energy systems = *Coupling Heat* + *PV* + *Storage* + *Hydrogen* + *Power* = Lots of Data = Learning

HSTC = Hybrid Solar Test Center (1 mile from campus)



Field deployment and validation of R&D
- thermal-electric modeling, control, optimization, operations, planning
- grid services
- reliability
- lifetime analysis

Source: https://www.rechargenews.com/energy-transition/cop-26-are-energy-islands-the-missing-link-to-make-europes-net-zero-continent-dream-a-reality-/2-1-1077266

Main objectives of DOE project (2023-2027)

Long-term planning

1

Hybrid energy system **degradation and lifetime economics and performance.** Develop quasi-accelerated degradation models of solar PV in northern climates.

Short-term operations

2

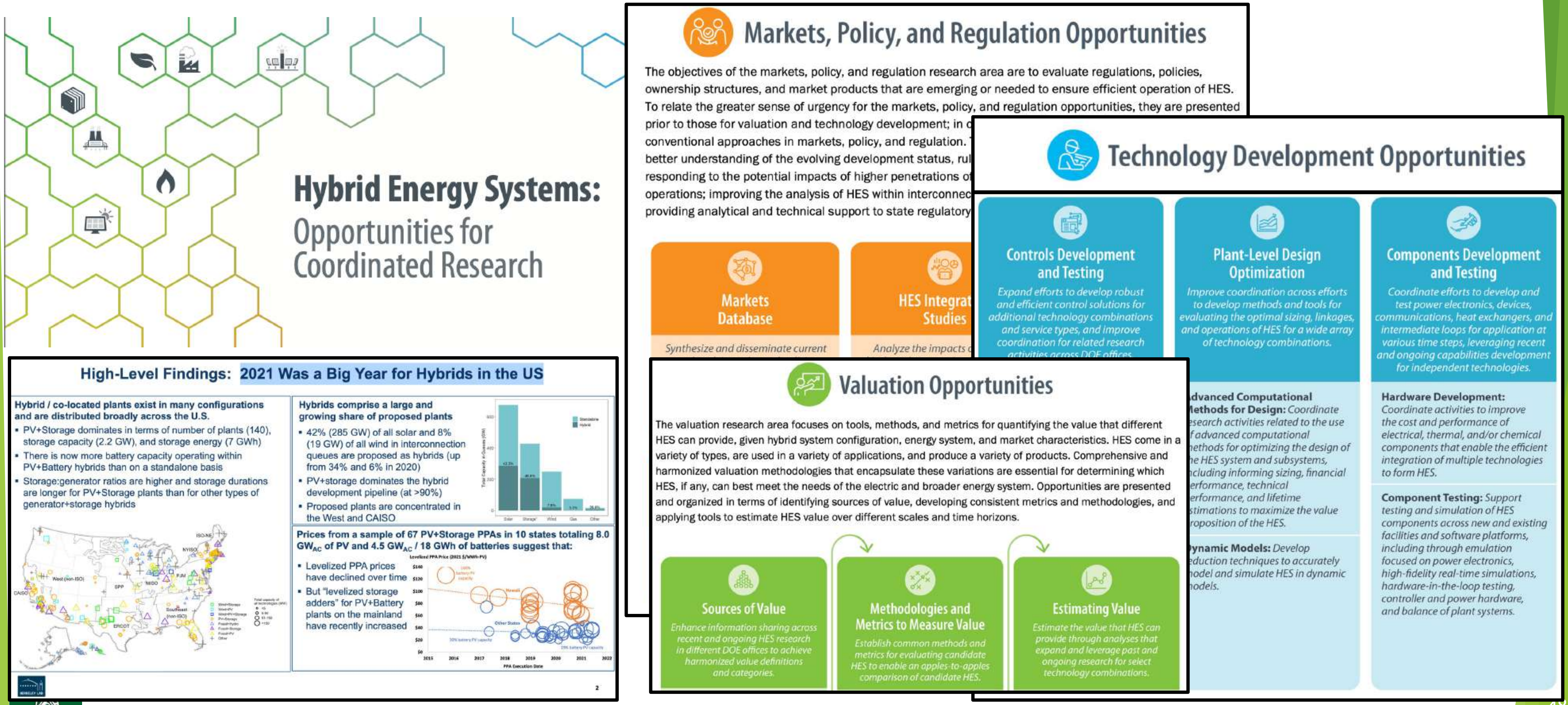
Optimize and control the hybrid energy system's performance across weather/climate conditions and **demonstrate advanced grid services** that support reliability and resilience across seasons.

National impact

3

Develop nationally competitive energy research infrastructure in Vermont that supports national priorities around combating climate change & clean energy **workforce development.**

DOE is looking for answers, too!



DOE reports from 2022

Thank you! Questions? Comments?

malmassa@uvm.edu

@theEnergyMads

https://madsalma.github.io

Traditional demand response

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