Enabling energy flexibility with distributed control of residential kW scale devices

What can we learn from how the Internet works?

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PACKETIZED ENERGY

INNOVATION CENTRE DENMARK

Towards Large Scale Integration

Innovation Centre Denmark & Energy Cluster Denmark

June 22, 2021

Legal Disclaimer

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

PACKETIZED ENERGY

Other reasons to be excited about summer 2021

Department of Energy

Secretary Granholm, Danish Climate, Energy, and Utilities Minister Jørgensen Establish Historic Agreement Focused on Clean Energy Research, Science Collaboration

JUNE 7, 2021

U.S. green economy is growing…

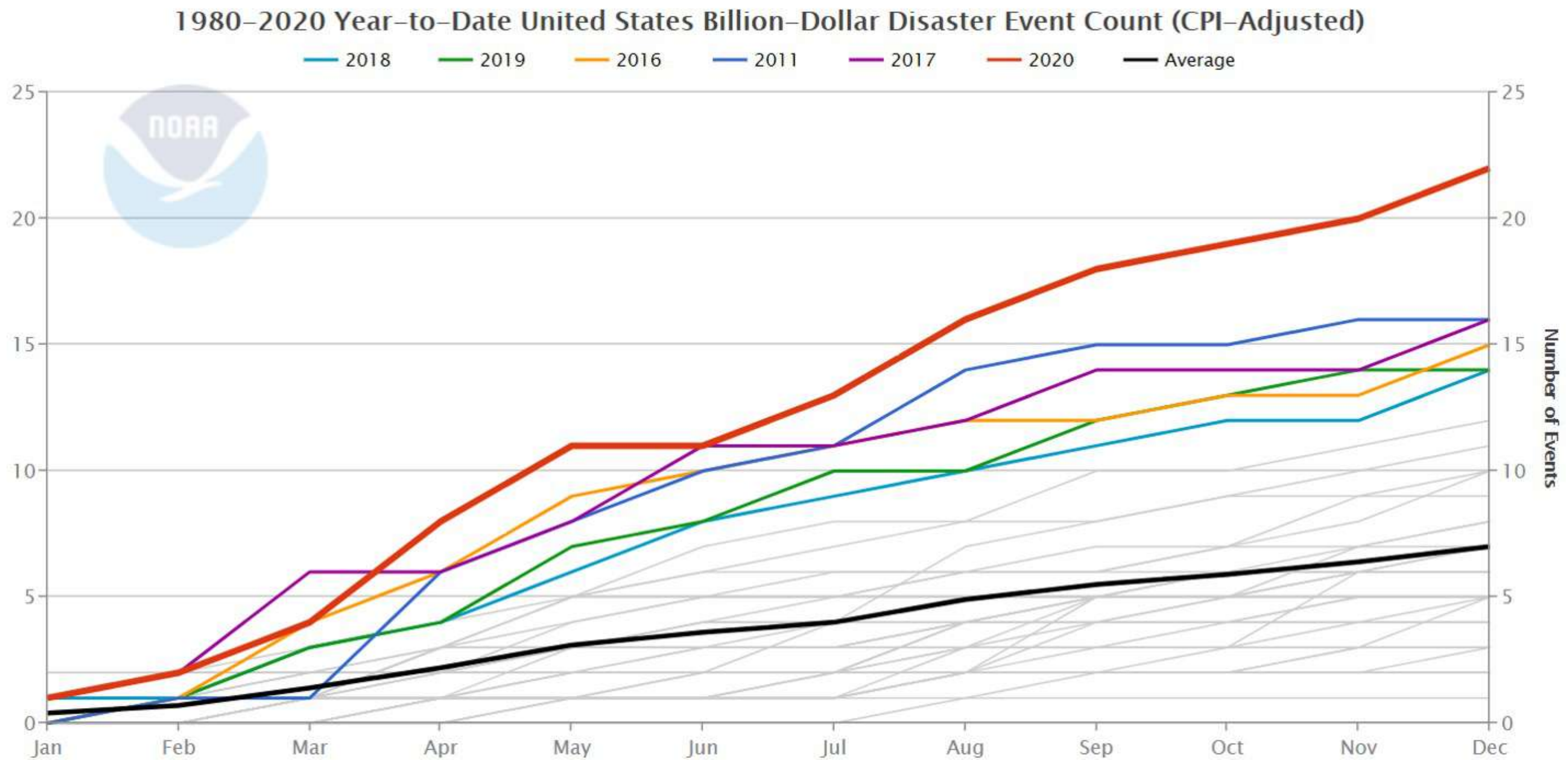
$1.3T Annual sales revenue

10M Jobs supported

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

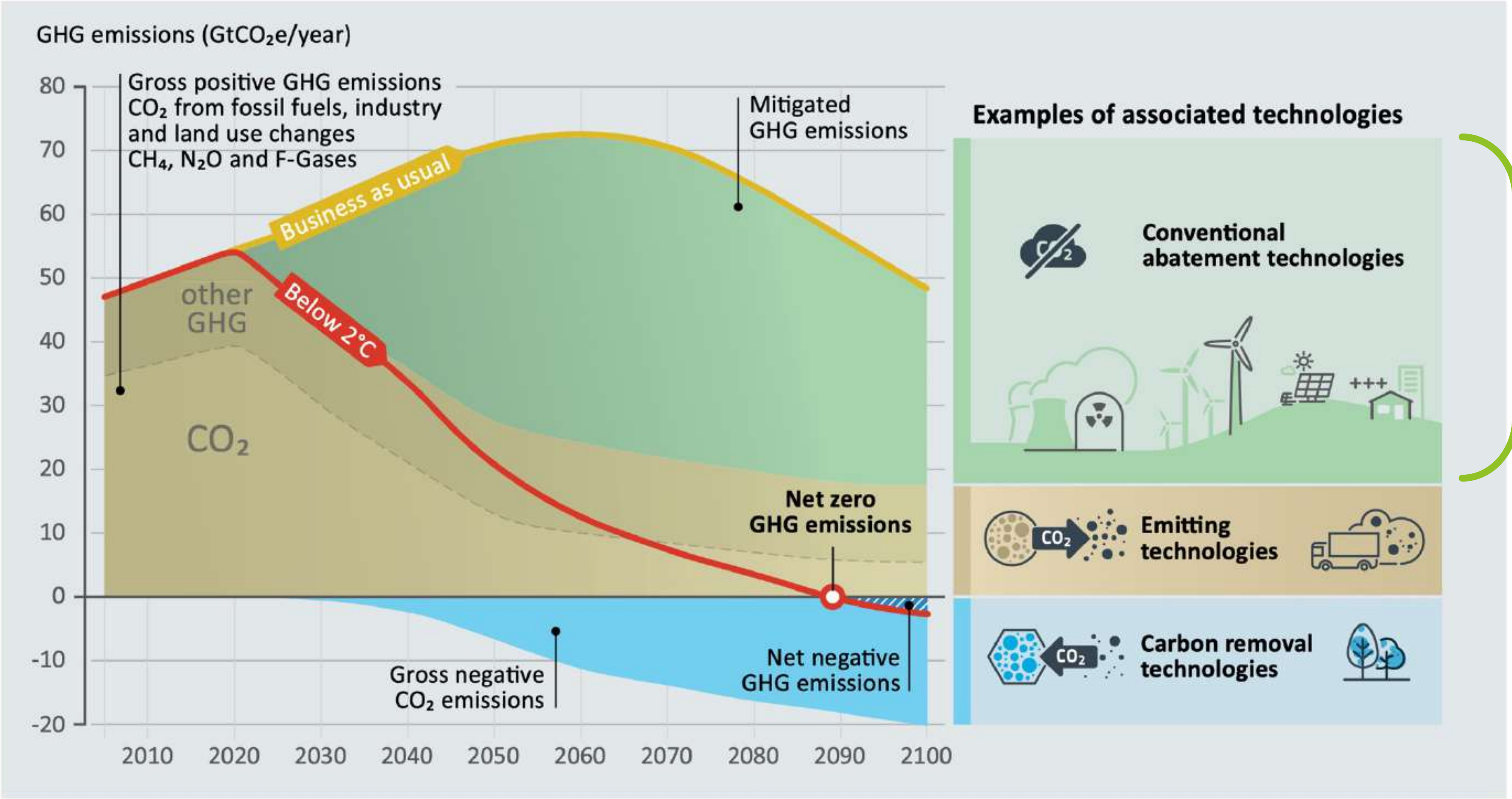
Georgeson, L., Maslin, M. "Estimating the scale of the US green economy within the global context." *Palgrave Communications* 5, 121 (2019)

… 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!



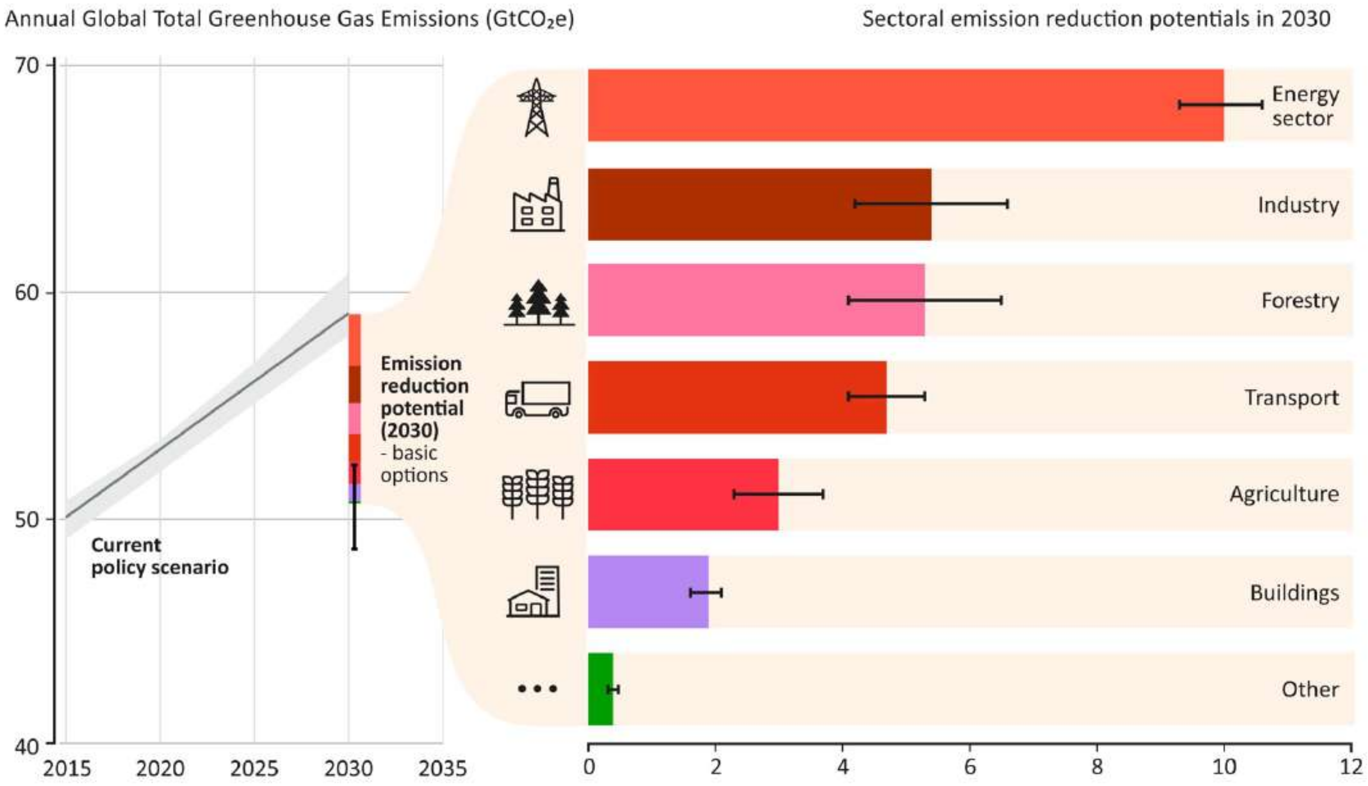
Requires massive TW-scale renewable integration

A massive power systems challenge!

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

Beneficial electrification and flexible demand

Energy sector, transportation, and buildings 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]

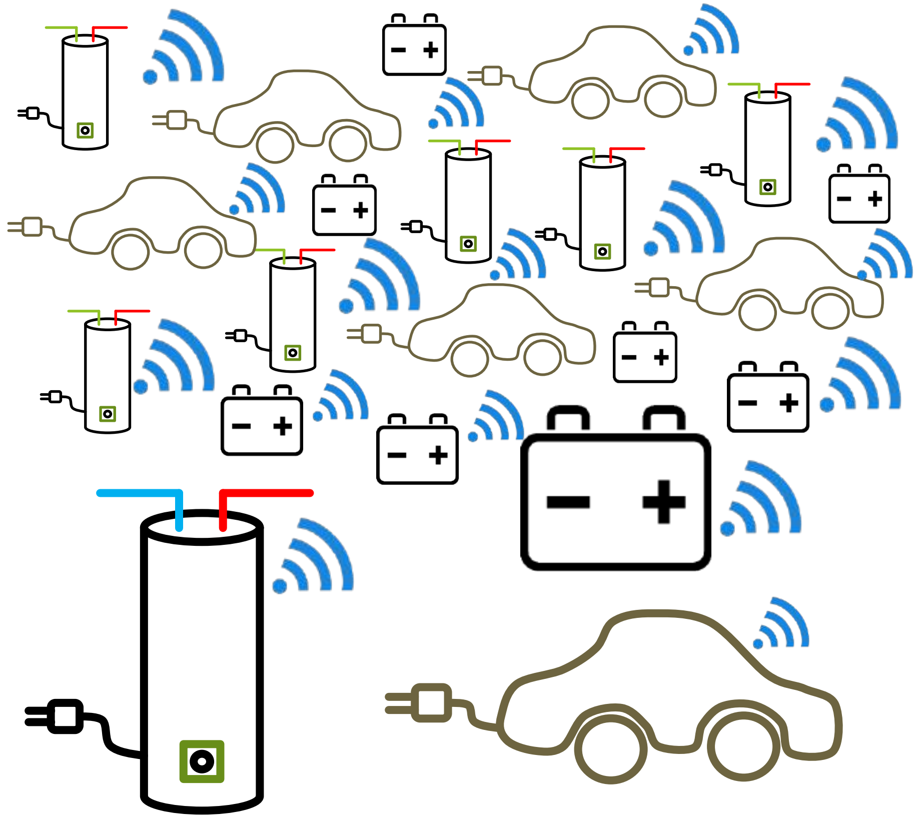
59GW of DR today will become **200GW of flexible demand by 2030** [3]

Need to manage millions of kW-scale 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 be coordinated as a single resources: *a virtual battery (VB)*

[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] **Khurram**, A., *et al.*, "Real-world, full-scale validation of power balancing services from packetized virtual batteries," in *IEEE PES ISGT*, Washington, D.C., 2019.

No free lunch: respect the human in the loop

Almost all flexible demand today = static DR programs:

- ComEd Smart HVAC progra
- *"Fenway frank problem"*, '

NAVIGANT

National Grid Smart Energy Solutions

Final Evaluation Report

Prepared for:

National Grid

nationalgrid

Submitted by:
Navigant
1375 Walnut Street
Suite 200
Boulder, CO 80302

303.728.2500
navigant.com

May 5, 2017

- ***10% of participants overriding 3hr even***
- ***25% are overriding events.***

Smart Thermostat Energy Saving: Texas Power Companies Remotely Raise Temperature at Home

Teejay Boris, Tech Times | 20 June 2021, 04:06 am

An energy-saving program in Texas left some residents sweating inside their homes after power companies remotely raised the temperature in their smart thermostats.

Data-driven Identification of Occupant
ostat-Behavior Dynamics

ınind Sharma[a]

ʲil and Environmental Engineering, Northeastern University, Boston, 02151, MA, USA

behavior drives significant differences in building energy use, even in automated
istrust in the automation causes them to override settings. This results in responses
oth the occupants' and/or the building automation's objectives. The transition toward
cient buildings will make this evermore important as complex building control systems
for comfort, but also changing electricity costs. This paper presents a data-driven
thermal comfort behavior dynamics which are not captured by standard steady-state
ch as predicted mean vote.

el captures the time it takes for a user to override a thermostat setpoint change as a
nual setpoint change magnitude. The model was trained with the ecobee Donate Your
min. resolution data from 27,764 smart thermostats and occupancy sensors. The
n-level model shows that, on average, a 2°F override will occur after ~30 mins. and an

% of 27,000 Ecobee smart ermostat users override a point change of 2°F within 30 minutes [1]

[1] Michael B Kane and Kunind Sharma, "Data ... 2.06705, 2019.

QoS-aware coordination with distributed control

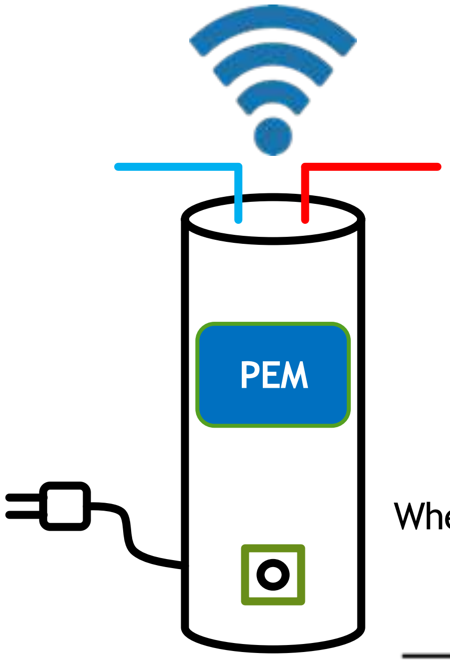
Packetization of data on Internet

Random access protocols

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

PEM for a single load: ensures privacy and comfort

Energy packet = constant power consumed over fixed epoch =



Prioritize energy packets stochastically based on device “need” → **anonymous requests**

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

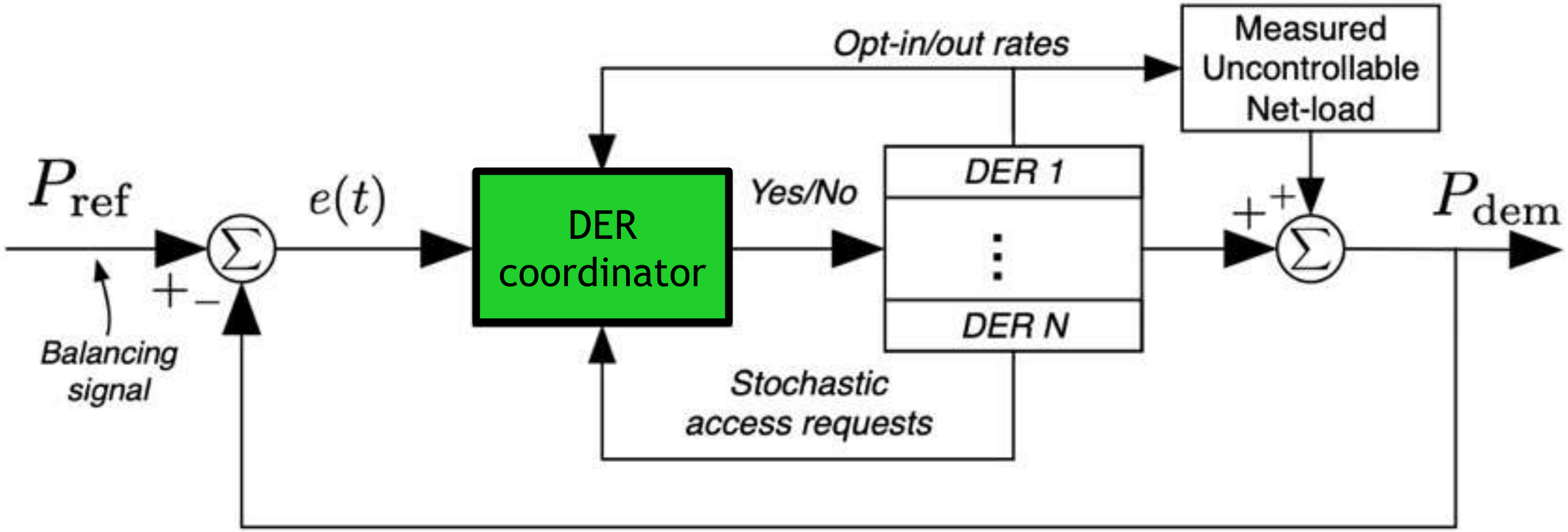
When temperature is low, heating elements turns ON
and consumes energy → *bulky demand*

M. Almassalkhi, J. Frolik, and P. D. H. Hines, “Packetized energy management: asynchronous and anonymous coordination of thermostatically controlled loads,” American Control Conference, 2017

PEM with a fleet of DERs

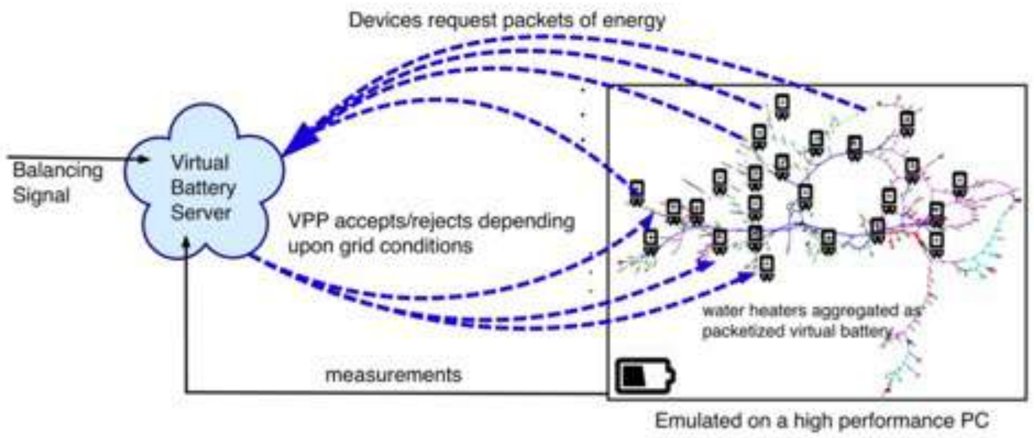
- Device coordinator accepts/denies request based on tracking errors, so control mechanism is simple, but powerful

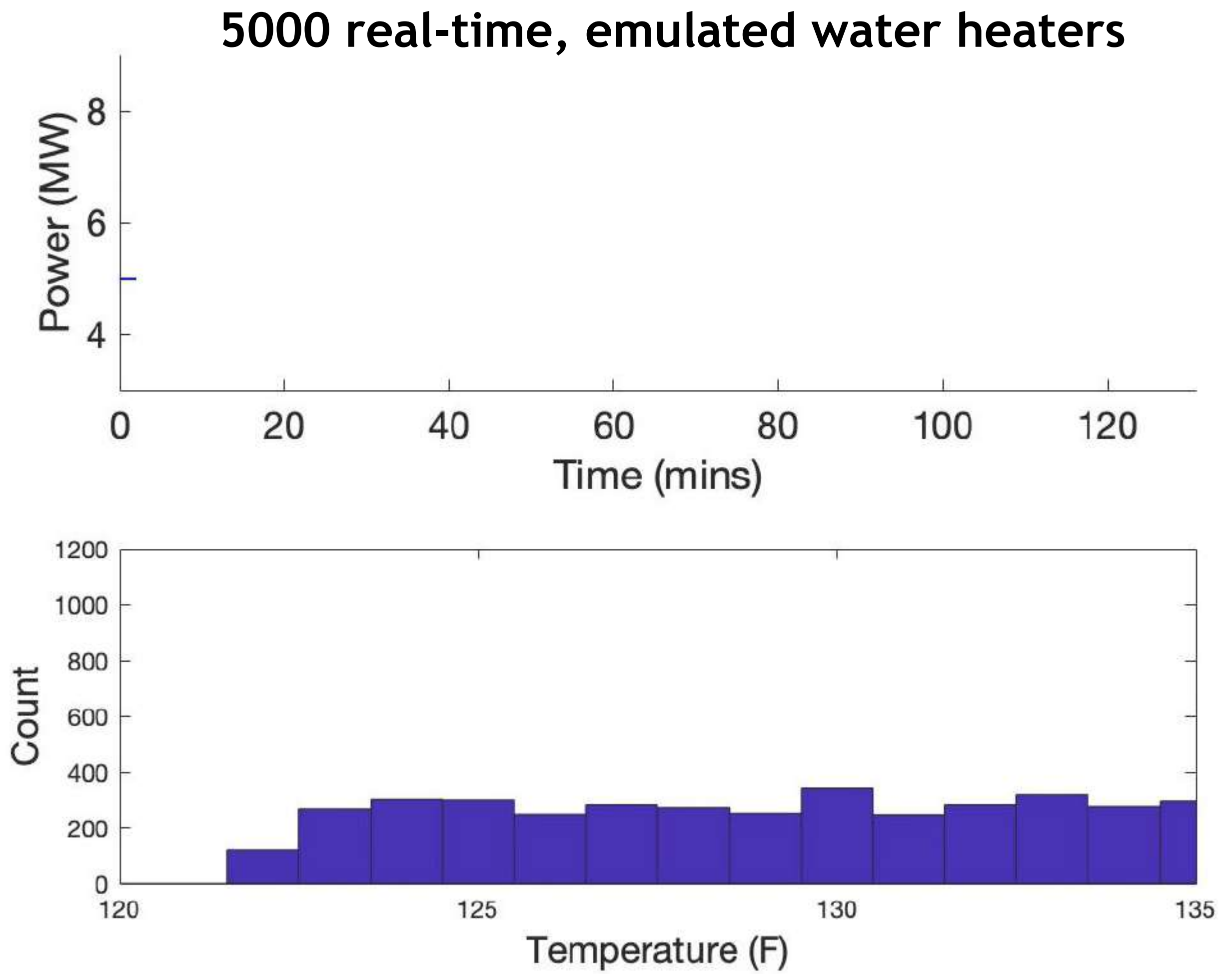
Modulate acceptance rate of packet requests ➔ Regulate aggregate demand



Randomizing requests based on energy need leads to very light communication overhead at scale!

Built real-time, cyber-coupled DER test-bed





Mahraz 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

Completed field trial with > 150 homes in Vermont

The UNIVERSITY of VERMONT

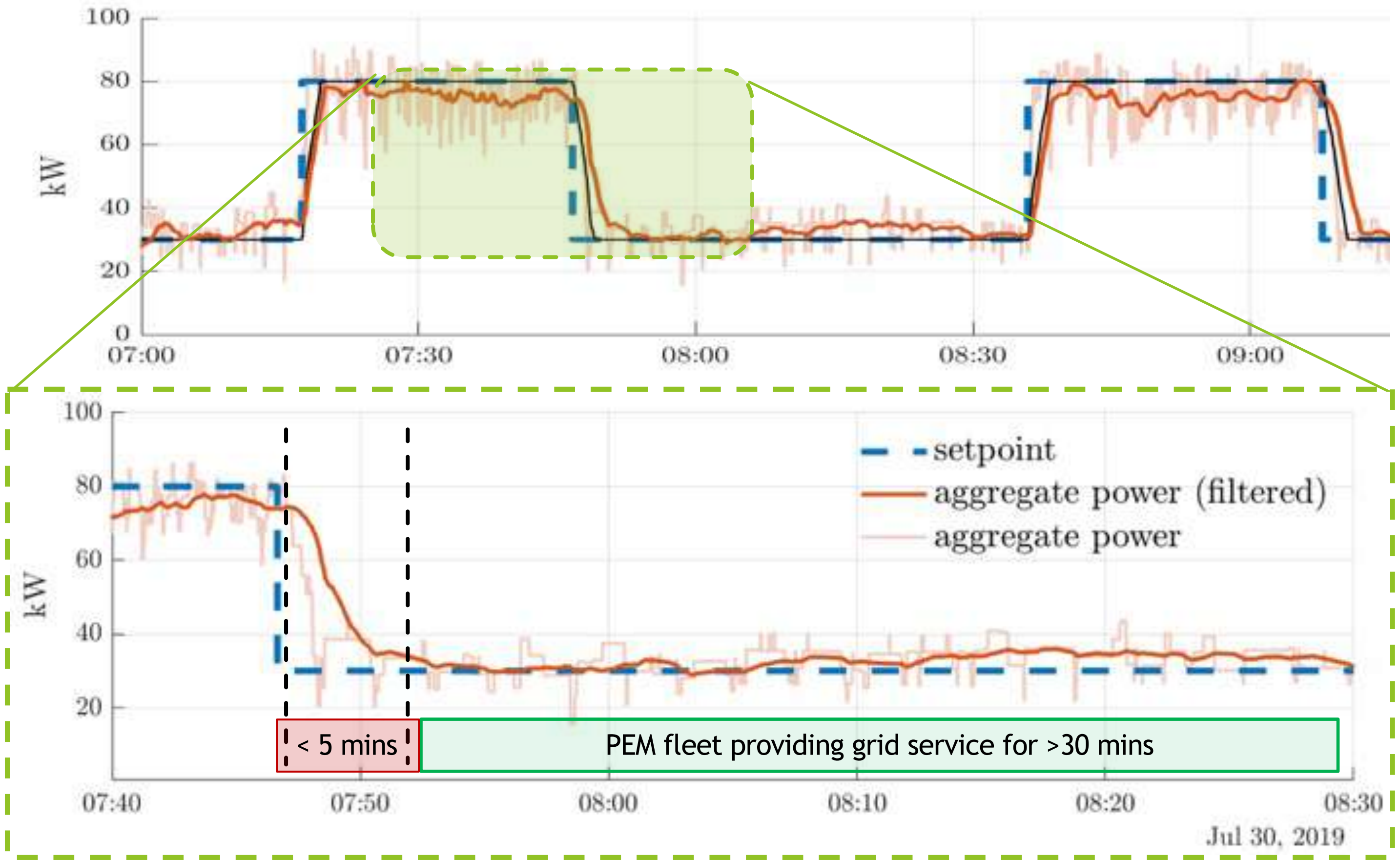
VERMONT ELECTRIC CO OP

BURLINGTON Electric DEPARTMENT

GREEN MOUNTAIN POWER

vermont electric power company VELCO

PACKETIZED ENERGY

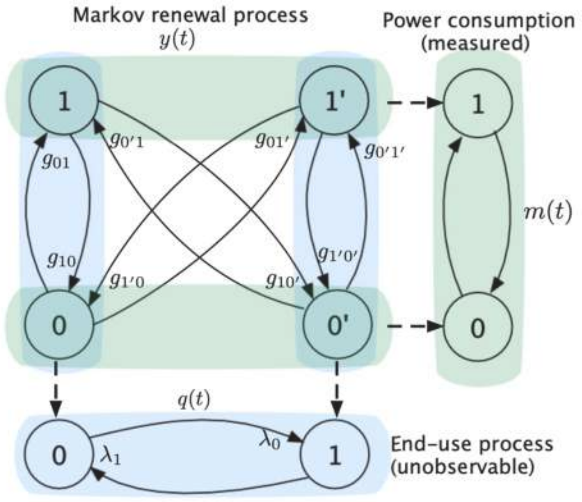


Lesson: dynamics of the "Aggregation" depends on communication & control methods

Key technical challenges with coordinating @ scale

1

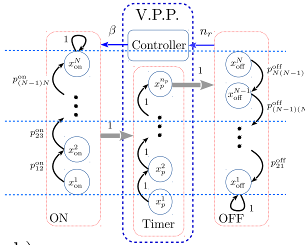
Estimate background DER end-use

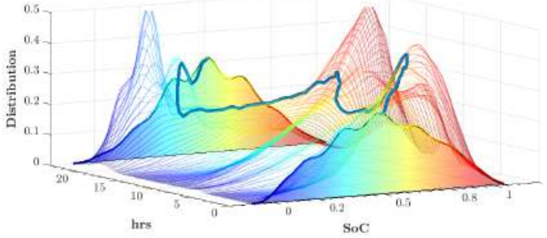


Stochastic end-use

2

Modeling and control

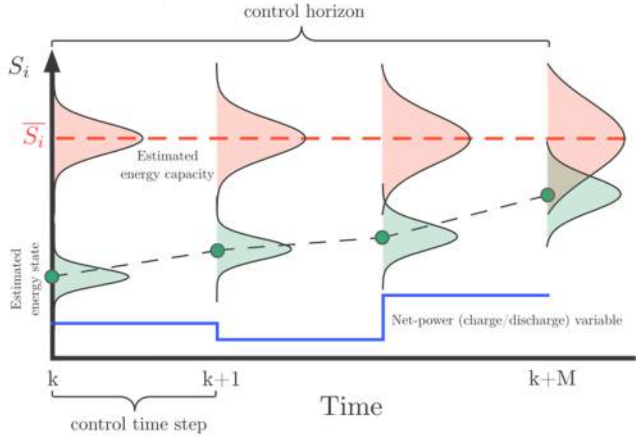




Uncertain resource

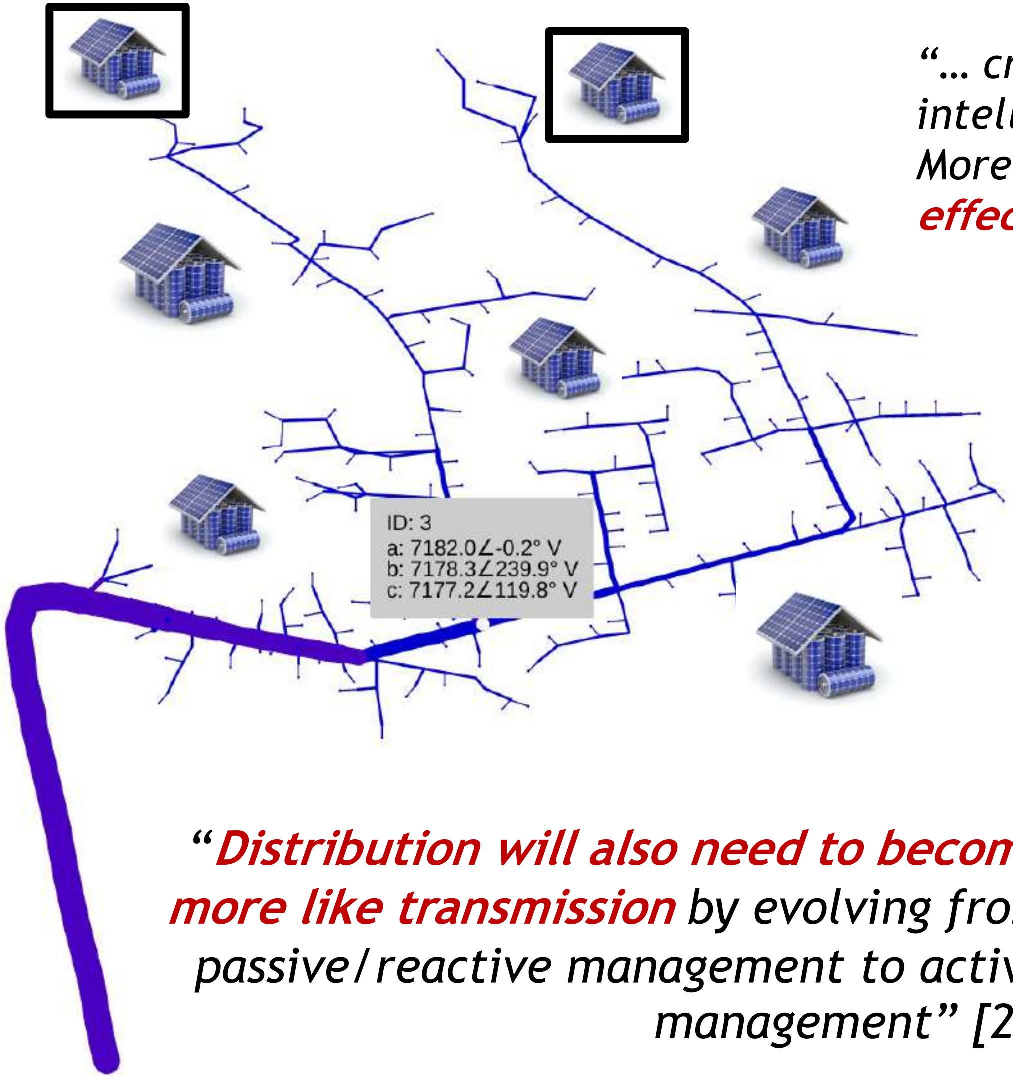
3

Optimized dispatch

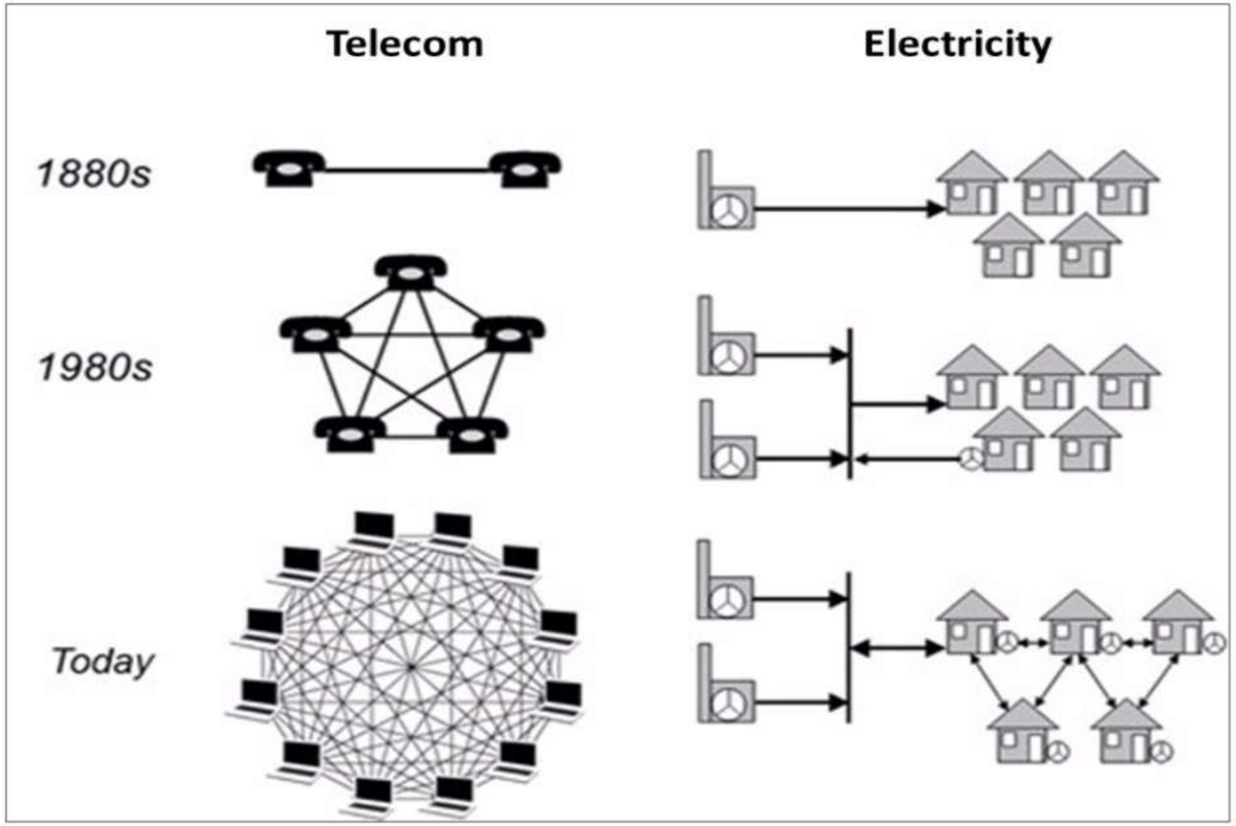


(1) **A. Khurram**, Luis Duffaut Espinosa, Roland Malhamé, Mads Almassalkhi, "*Identification of Hot Water End-use Process of EWHs from Energy Measurements*," EPSR, 2020.
(2a) L. Duffaut and M. Almassalkhi, "A packetized energy management macromodel with QoS guarantees for demand-side resources," IEEE 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., 2020.
(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.
(3) **M. Amini** and M. Almassalkhi, "Corrective optimal dispatch of uncertain virtual energy resources," IEEE Transactions on Smart Grid, 2020.

And what role should the grid/network 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].*



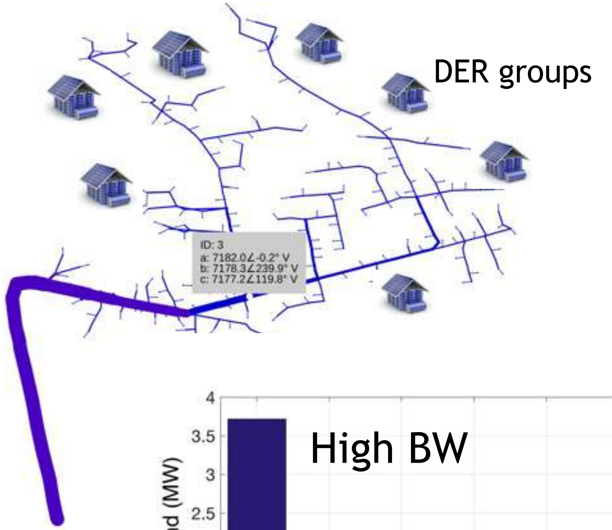
*"**Distribution will also need to become more like transmission** by evolving from passive/reactive management to active management" [2].*

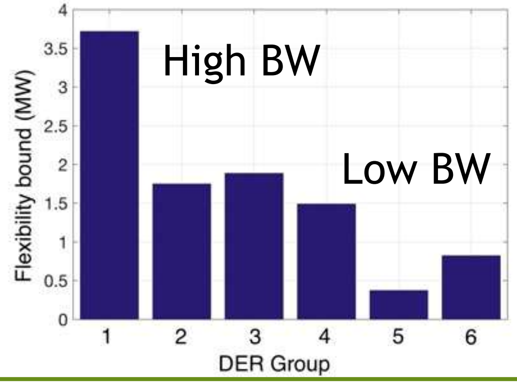
Source [1]: Taft/DOE, Grid Architecture 2, 2016

Source [2]: De Martini/EEI, Future of Distribution, 2012

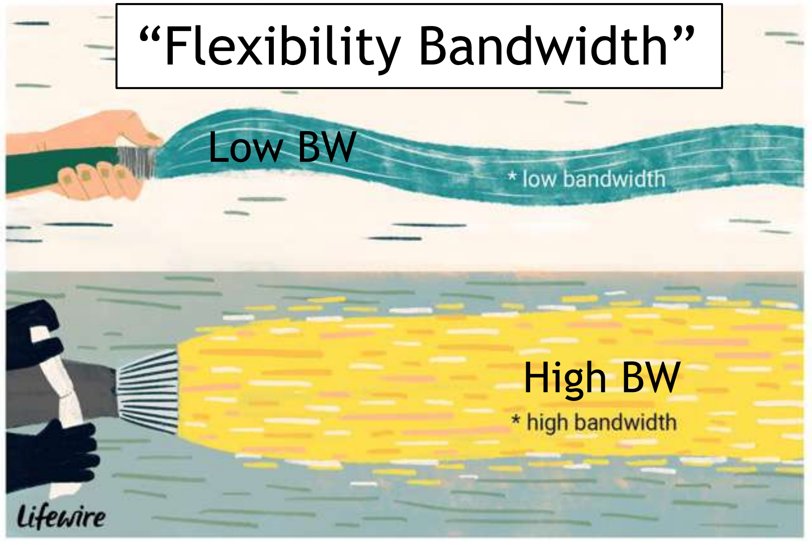
Utility & Aggs: asymmetry of information & control

Utility (grid information/data)
- Need to ensure grid reliability
- Need to protect grid data
- Lack access to devices
- Knows grid availability

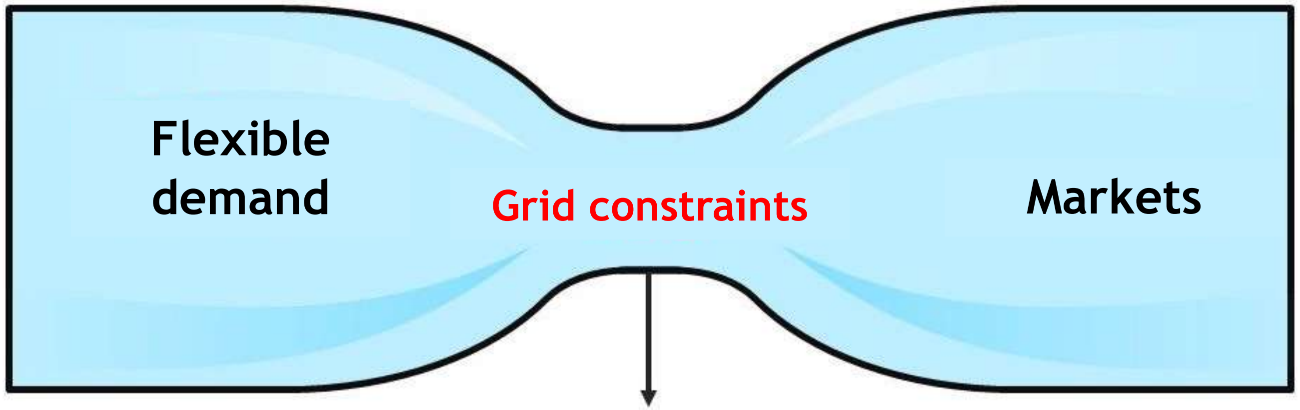


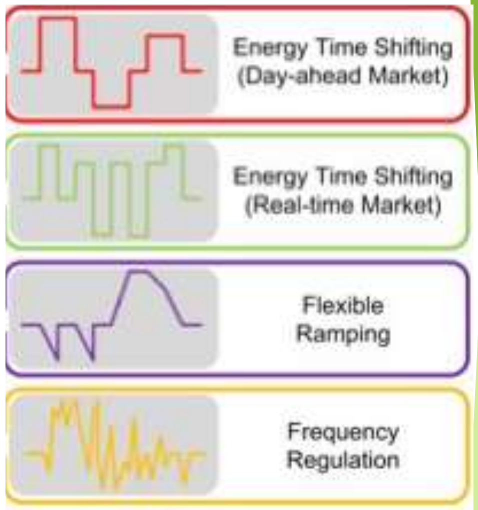


Aggregators (device access, markets)
- Need to ensure device QoS
- Need to provide market services
- Lack access to grid data
- Knows device availability



Rethink utility/DSO and aggregator cooperation: ISP





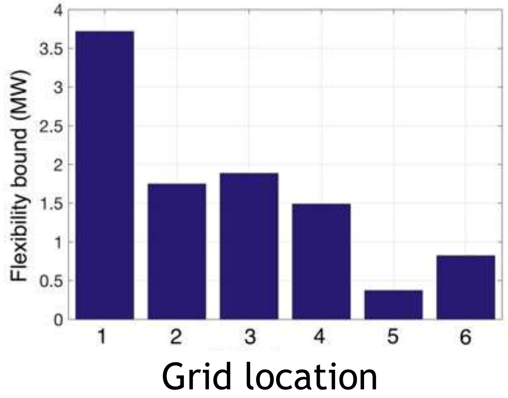
Aggregator: responsive flexibility from coordinated DERs

Utility: Dynamic hosting capacity

Offer nodal hosting flexibility bandwidth $[p_i^-, p_i^+]$

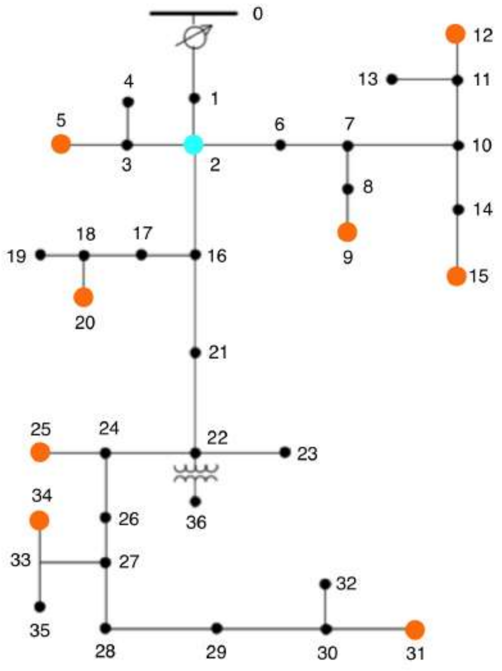
KEY!

Deliver valuable flexibility services $p_i(t)$

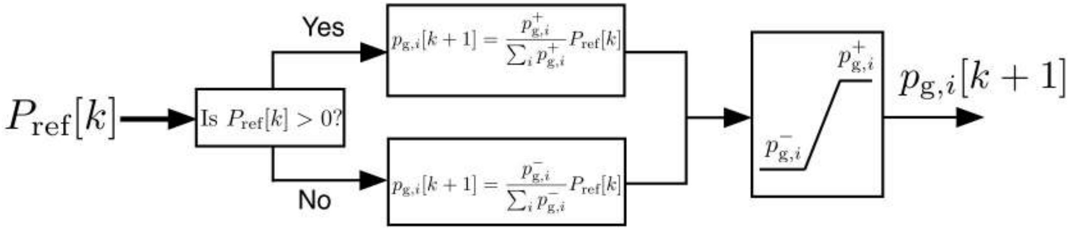


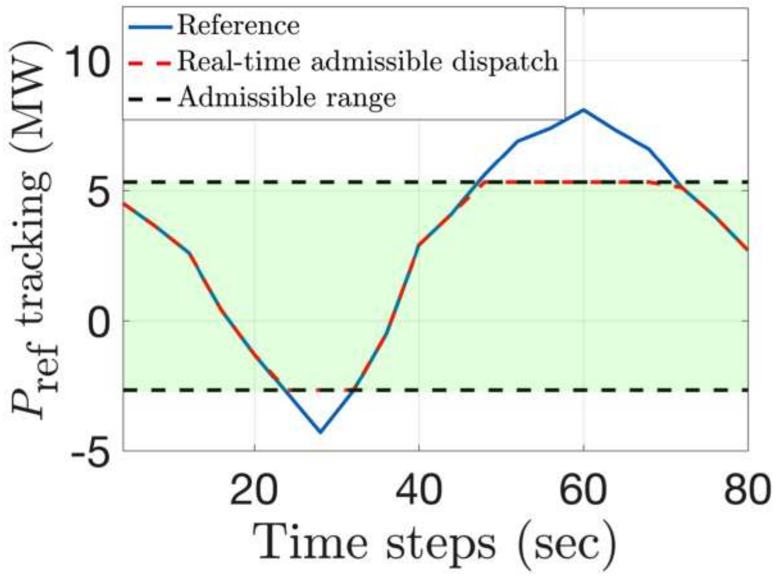
Example of dynamic nodal hosting capacity

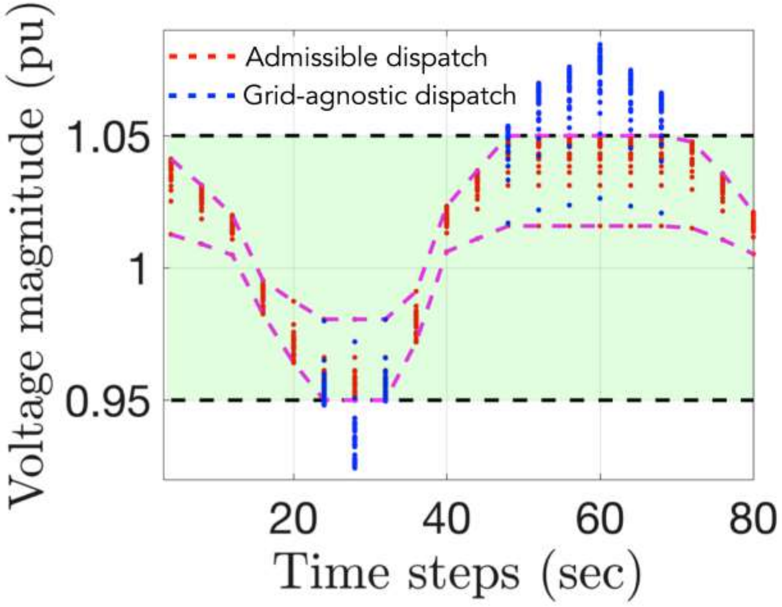
Nodal hosting capacities $[p_i^-, p_i^+]$ enable an open-loop, distributed, and **grid-aware DER control policy**



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







More details:

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.
-, "Grid-aware aggregation and realtime disaggregation of distributed energy resources in radial networks", under review in IEEE Transactions on Power Systems (Rev02), 2021

Summarizing

1. **Distributed control of DERs needs to be aware of**
   - customer expectations and requirement (comfort & privacy)
   - device operating requirements (cycling)
   - grid requirements (voltage, power ratings)
   - communication costs at scale (need low cost)
2. **Utilities/DSO and Aggregators need tools to cooperate across devices and grid to ensure**
   - reliable grid operation
   - access to markets for DERs
   - empower people to become part of (socio-techno-economic) climate solutions
3. **Internet-like thinking can unlock energy flexibility at scale**

Thank you! Any questions or comments?

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See you in Denmark in 2021-22!

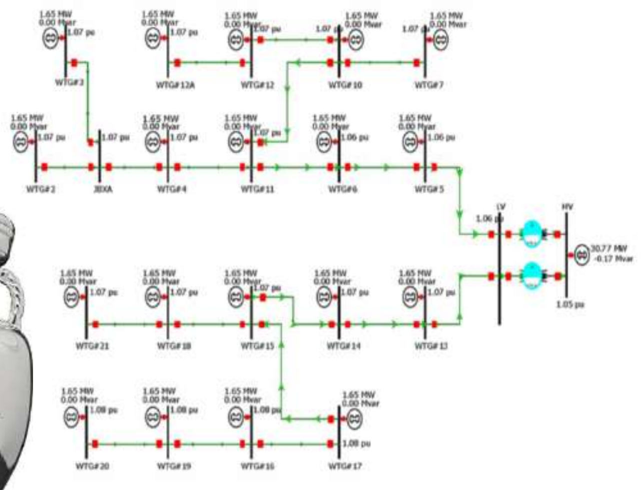
DTU AAU

Sabbatical

2021-22

7th International Conference on

Smart Energy Systems



Coming to a folkeskole near you! ☺

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Acknowledgements

Active/recent collaborators

- Prof. Hamid Ossareh (UVM)
- Prof. Luis Duffaut Espinosa (UVM)
- Prof. Paul Hines (UVM & PE)
- Prof. Jeff Frolik (UVM & PE)
- Prof. James Bagrow (UVM)
- Prof. Yves Dubief (UVM)
- Mr. Sarnaduti Brahma (UVM)
- Prof. Sumit Paudyal (FIU)
- Prof. Dennice Gayme (JHU)
- Prof. Enrique Mallada (JHU)
- Dr. Soumya Kundu (PNNL)
- Prof. Roland Malhamé (Poly Montreal)
- Prof. Timm Faulwasser (TU-Dortmund)
- Dr. Tillmann Mühlpfordt (KIT→DB Systel GmbH)
- Mr. Alexander Engelmann (KIT)
- Mr. Sharabh R Shukla (MTU→ ENGIE)

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- Mr. Adil Khurram (PhD EE'21)
- Mr. Hani Mavalizadeh (PhD student)
- Mr. Sam Knox and Ms. Rebecca Holt (BSEE REUs)

Former group members

- Dr. Nawaf Nazir (PhD EE'20) → PNNL (Richland, WA)
- Dr. Mahraz Amini (PhD EE'19) → NatGrid (Boston, MA)
- Mr. Micah Botkin Levy (MSEE'19) → eIQmobility (SF, CA)
- Mr. Zach Hurwitz (MSME'19) → Siemens Energy (ME)
- Mr. Lincoln Sprague (MSEE'17) → Dynapower (VT)
- Ms. Anna Towle (BSEE'16) → Fortrum (Sweden)

Anti-causal slides

The value of flexibility can be significant

GRID BALANCING,
ANCILLARY SERVICES

LMP ENERGY ARBITRAGE,
RENEWABLE SMOOTHING

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

AVOIDED GEN CAPACITY
(ISO)

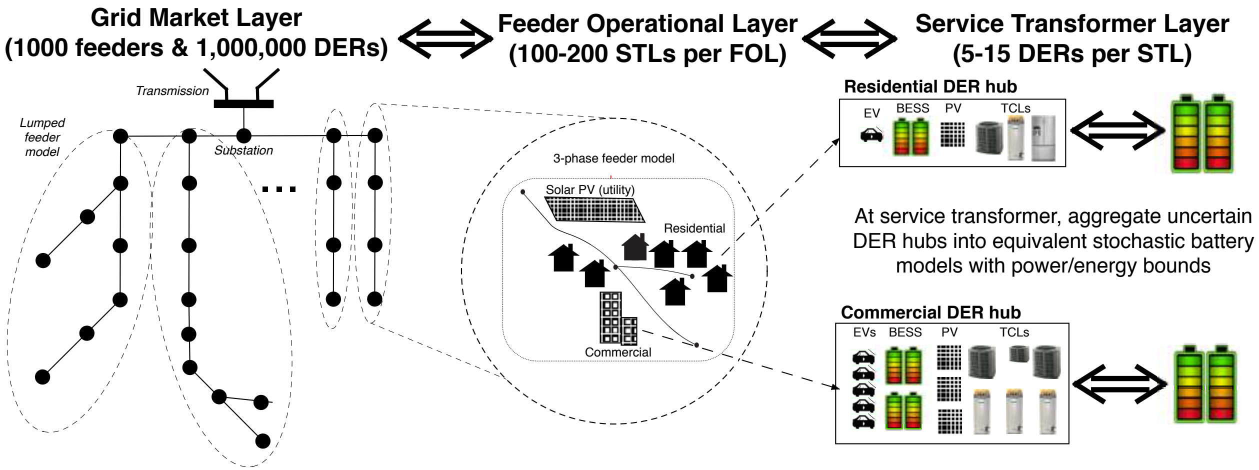
$100 to $1000
per kW_{flex} per year*

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

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

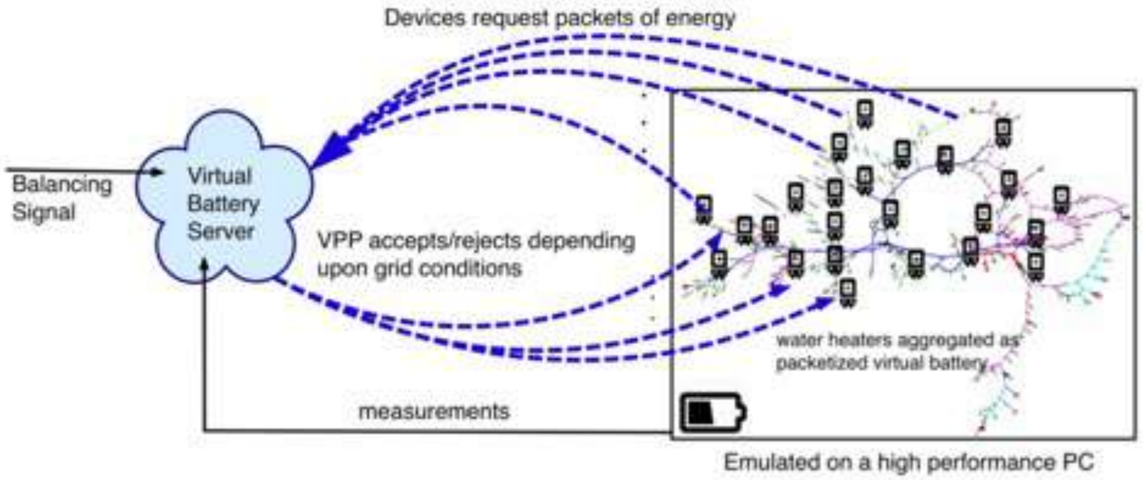
Realizing flexible demand requires control+comms+data

1. Utility/DSO-centric approach



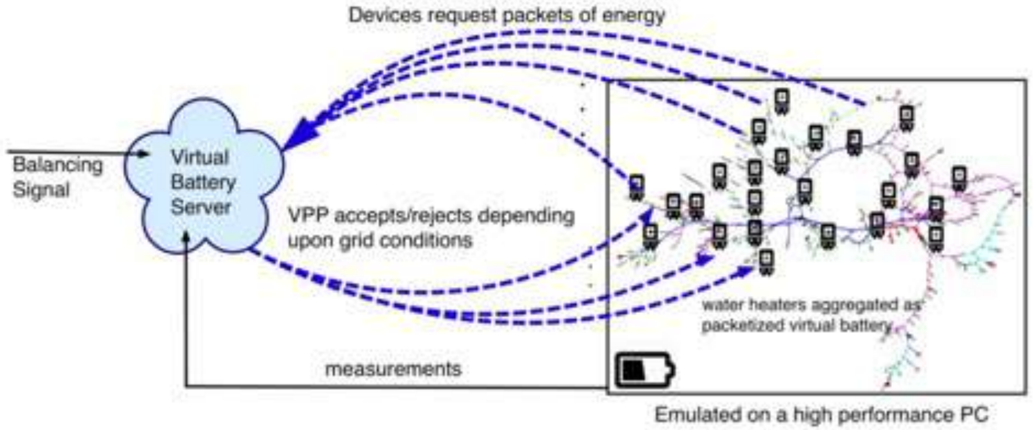
1. Relies on full **network model** (utility)
2. Hierarchical coordination/computation
3. Fits within **existing utility communication** infrastructure/protocols (non-public networks)

2. Aggregator/Device-centric approach

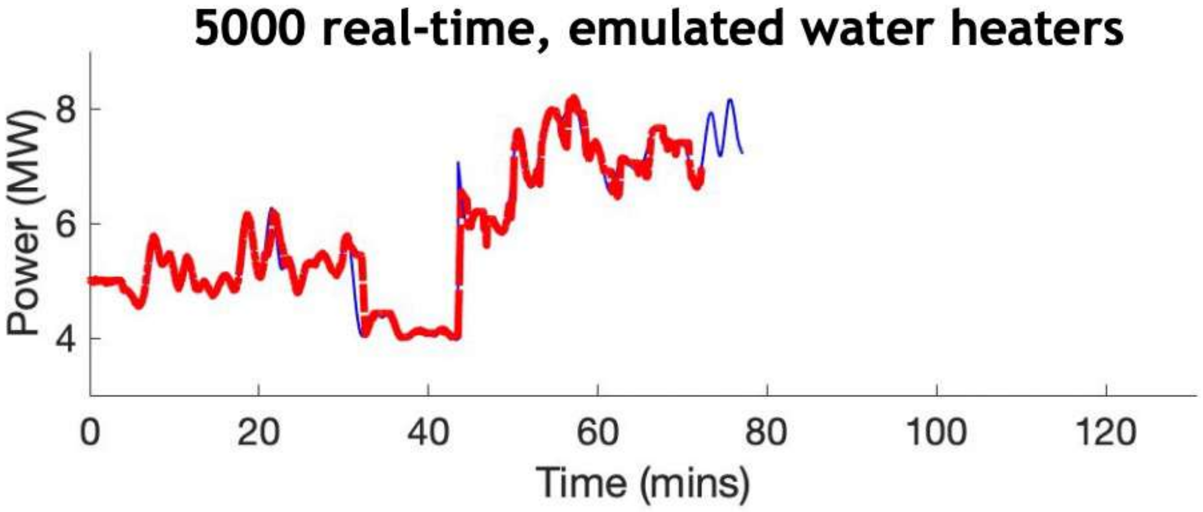


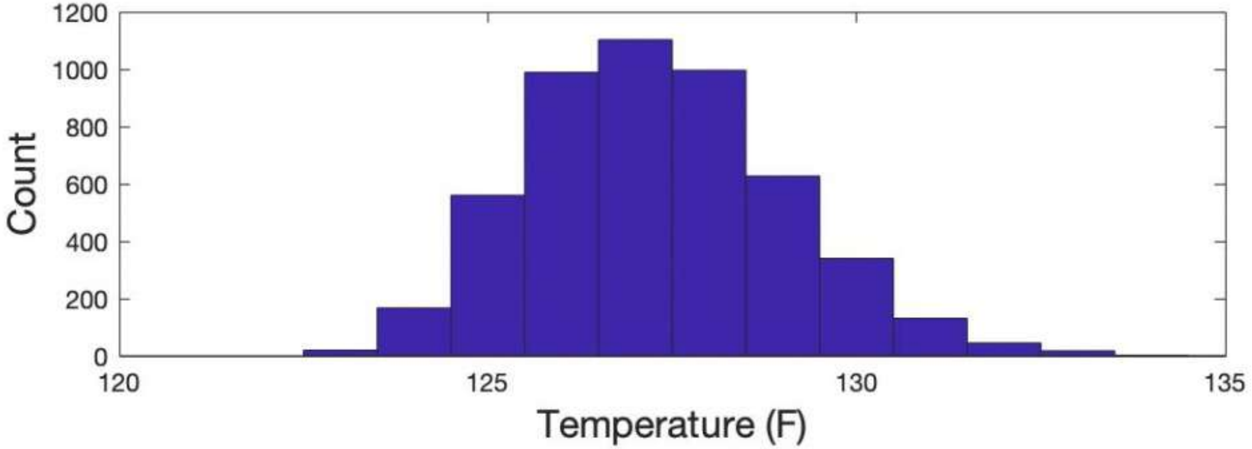
1. Requires **device access** to compute/sense (OEMs)
2. Coordination becomes **decentralized computing;** live sensing locally can help
3. Does not fit directly within existing utility comm infrastructure (**public networks**)

Built real-time, cyber-coupled DER test-bed



OPAL-RT TECHNOLOGIES

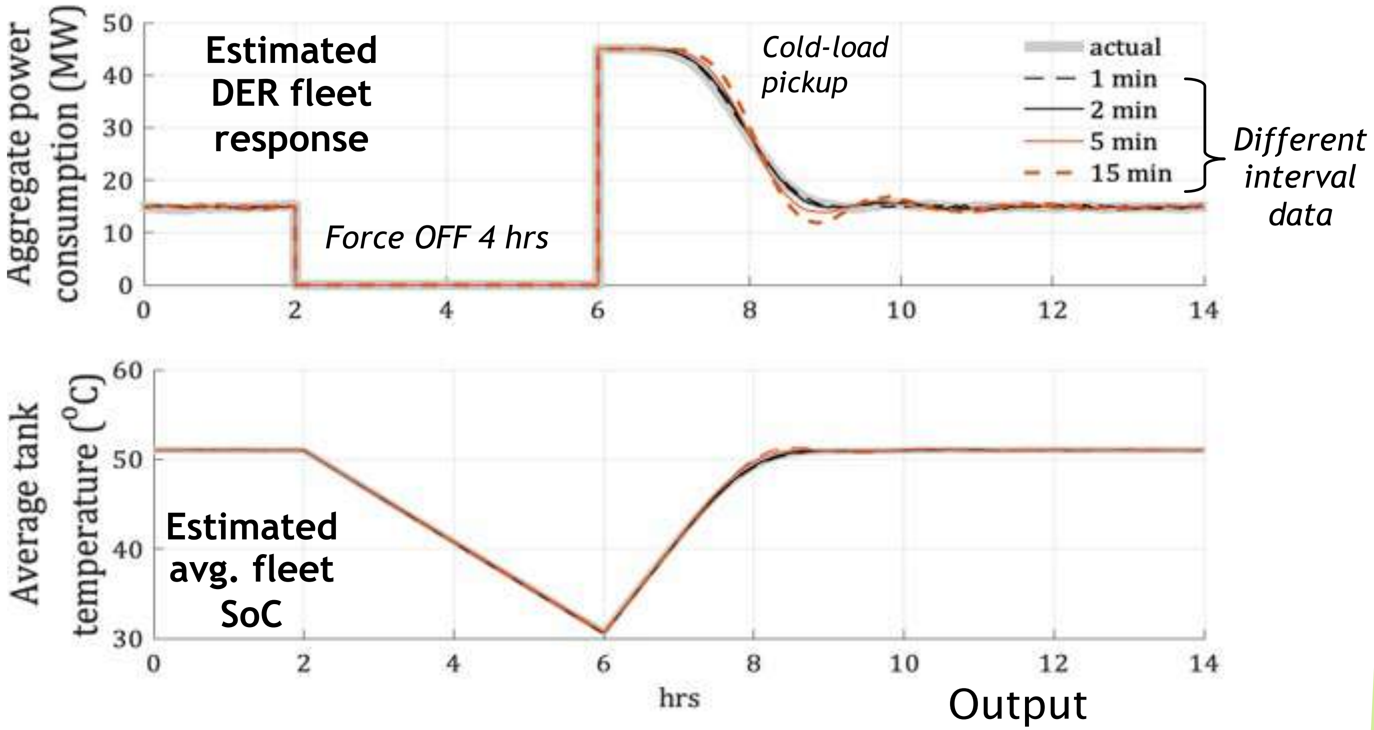




Mahraz Amini, Adil Khurram, et al. "A Model-Predictive Control Method for Coordinating Virtual Power Plants and Packetized Resources, with Hardware-in-the-Loop Validation". In: *IEEE PES General Meeting*. Atlanta, Georgia, 2019

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



Input

1. Measured kWh data
2. EWH parameters e.g. tank size, rating of heating element

→ Get statistics of power consumption → Estimation from moments →

Output

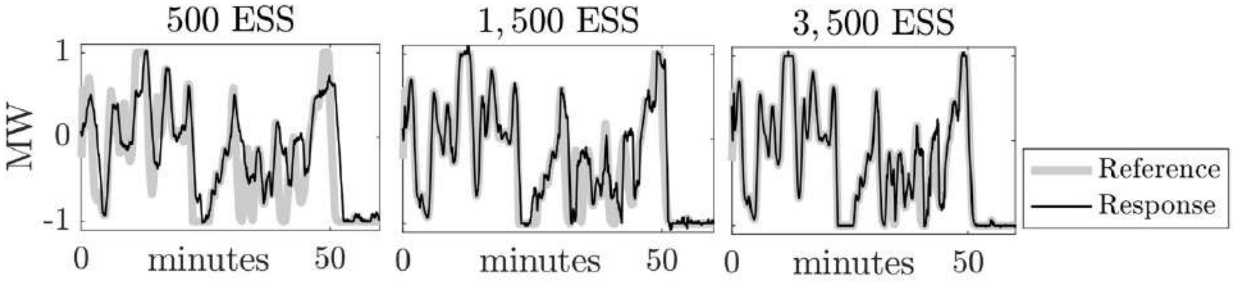
Parameters of end−use process

Adil Khurram, Luis Duffaut Espinosa, Mads Almassalkhi, Roland Malhamé, "*Identification of Hot Water End-use Process of Electric Water Heaters from Energy Measurements*," accepted for the Power Systems Computation Conference, Lisbon, 2020.

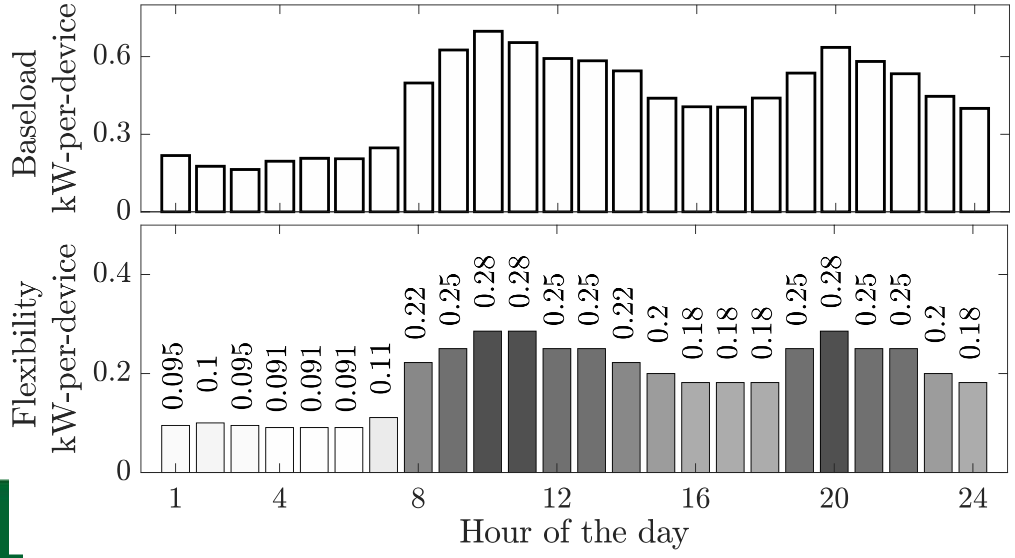
Estimating power capacity/flexibility of VB

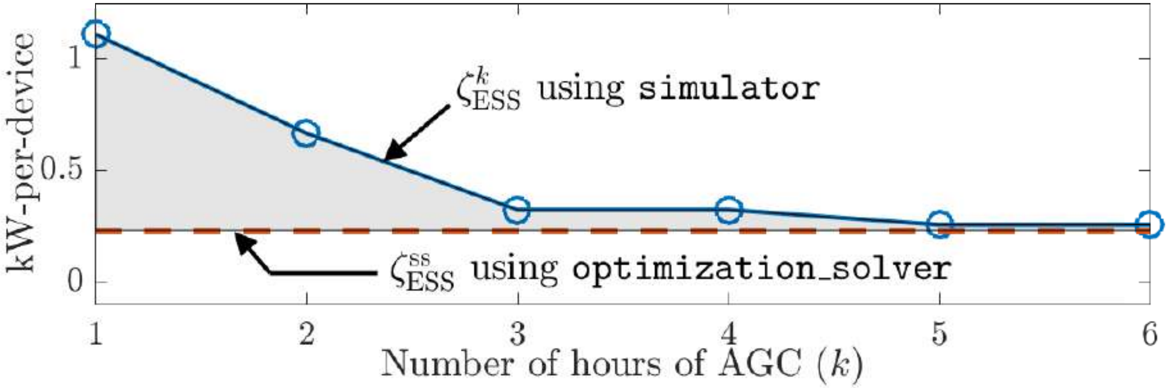
- Data-driven methodology to answer questions:
  - How many devices for 1MW flexibility?
  - What is flexibility (±kW) per device?
- Define flex-kW by fleet's ability to track AGC signal

Batteries



Electric water heaters





Adil Khurram, Luis Duffaut Espinosa, Mads Almassalkhi, *"A Methodology for quantifying flexibility in a fleet of diverse DERs,"* under review (arXiv)