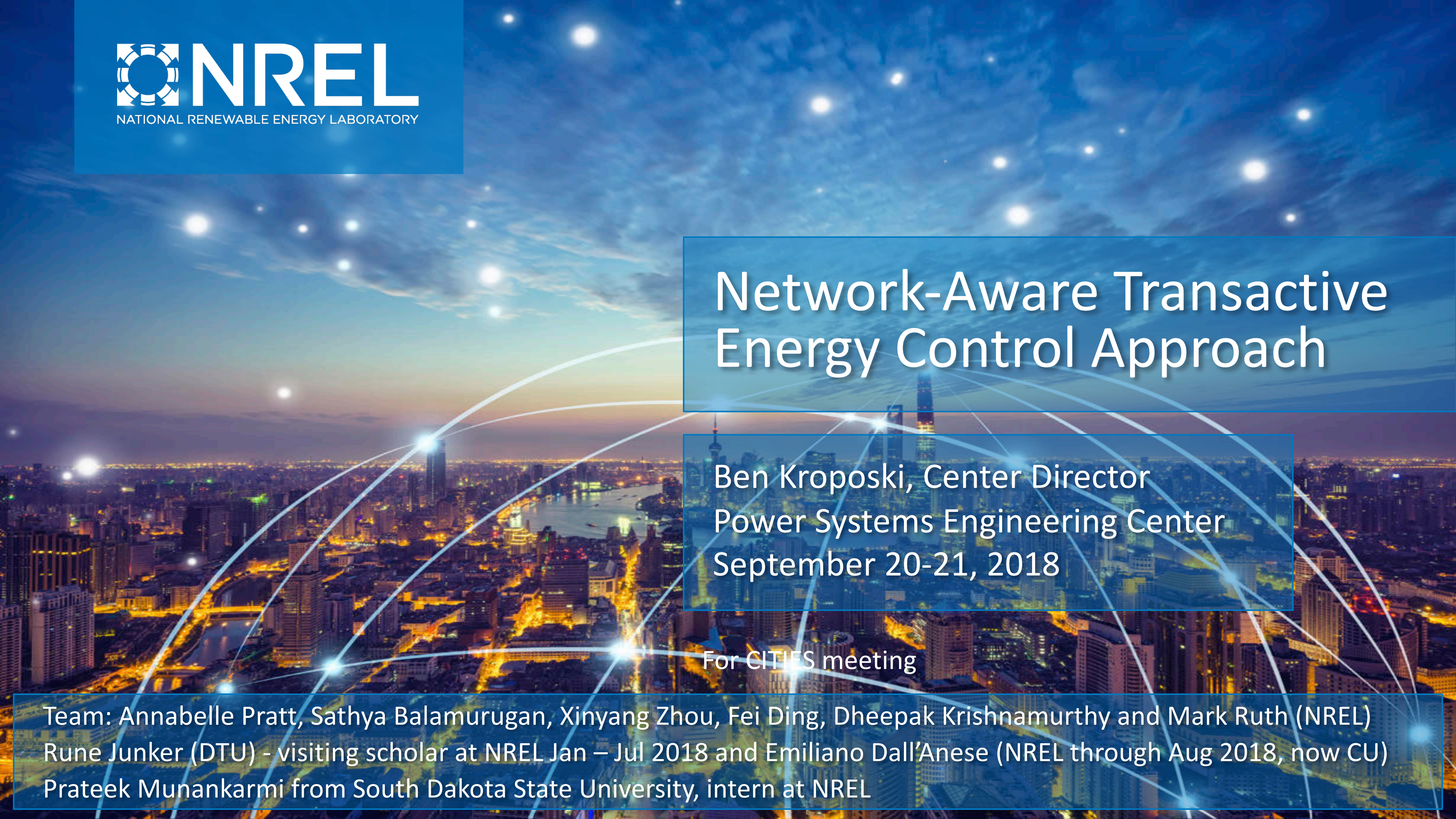

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Network-Aware Transactive Energy Control Approach

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Power Systems Engineering Center
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For CITIES meeting

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Disclaimer

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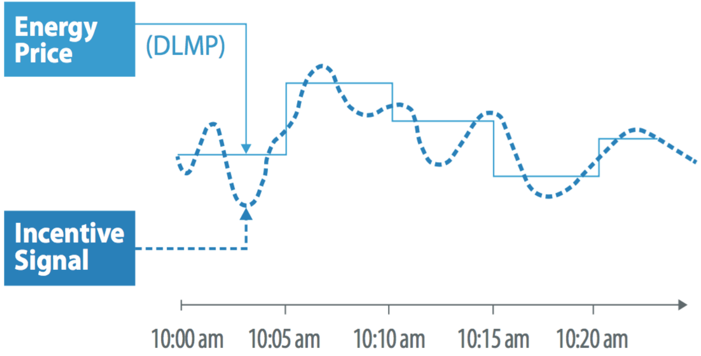
Transactive Energy

- A definition: “a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter”
- Most current transactive control approaches incentivize loads and DERs
  - to dynamically balance supply and demand and to limit real power peaks
  - based on rules of thumb and heuristics, ignoring underlying power flows → may not be stable and might lead to severe voltage swings
  - Without taking into account the effect on voltage regulation —a key responsibility of DSOs
- We propose a ***composite pricing structure*** with
  - an energy price based on wholesale prices and bids by participating DERs (5-15 minutes)
  - incentive signals for fast-timescale grid services (1-10 seconds)



DLMP-based market

- NREL is working on DLMP formulation and application
  - Different components of DLMP[1]
- Collaboration with Kansas State University on DLMP-based day-ahead market[2]
  - Both real and reactive power prices
  - Considers losses, congestion and voltage violations
  - Results from modified IEEE 69-node model
    - PV added, handles uncertainty in market
    - 50% of load considered responsive
- *Will require some foundational work to integrate with online optimization for voltage regulation, focus of rest of talk*

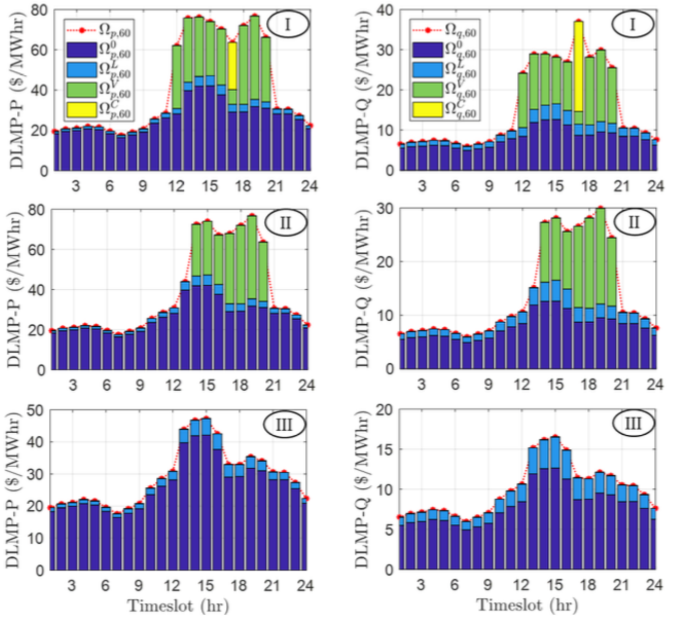


Fig. 5. DLMP-P and DLMP-Q of node 60 and its components (energy $\Omega^0_{p,q}$, loss $\Omega^L_{p,q}$, voltage violation $\Omega^V_{p,q}$, and congestion $\Omega^C_{p,q}$) in Scenarios I-III.

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[1] R. Yang and Y. Zhang, “Three-Phase AC Optimal Power Flow Based Distribution Locational Marginal Price,” *IEEE Innovative Smart Grid Technologies Conference*, Arlington, VA, April 2017.

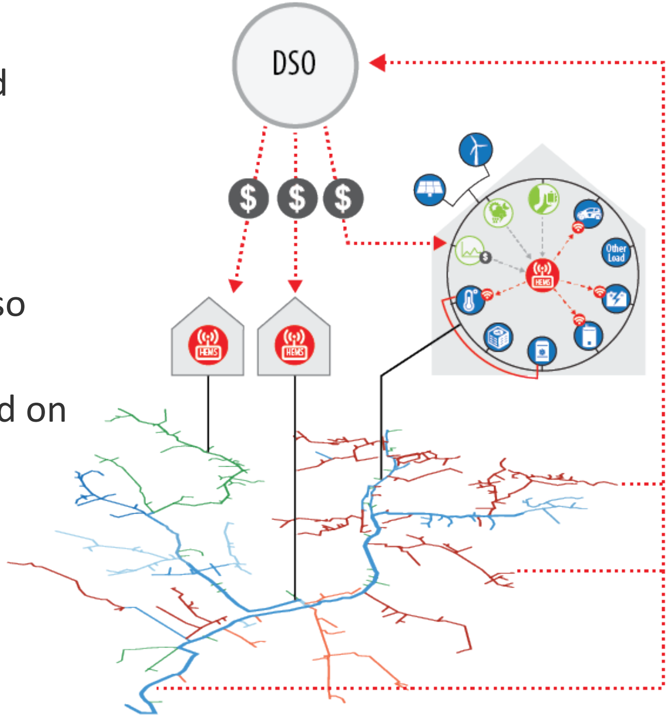
[2] N.N. Faqiry, L. Edmonds, H. Wu, R. Yang, A. Pratt and Y. Zhang, “Distribution LMP-based transactive forward market with variable renewable generation,” submitted to *IEEE Trans Power Systems.*

Network-aware control

- Loads and DERs participate in voltage regulation by responding to incentive signals ***calculated using a power flow model***
  - increasing or decreasing active power consumption and generation and/or reactive power sourcing or sinking

$$\begin{aligned} &\min\ C_i(p_i, q_i) - (\alpha_i \cdot p_i + \beta_i \cdot q_i) \\ &s.t.\ (p_i, q_i) \in Feasible\ Set \end{aligned} \quad (1)$$

- Impact on voltage depends on location within the network, so incentive signals are location-specific
- Incentive signals calculated for active & reactive power based on
  - linearized AC-OPF
  - measured voltages and currents
  - predicted power usage and flexibility of building loads
- Online optimization executed every 1-10 seconds



Network-level controls at DSO

- A social-welfare problem capturing both customer-oriented and network-oriented objectives[1]
- Based on a linearized three-phase power flow model[2]

$$min \sum_{i=1}^{N} C_i(p_i, q_i) \qquad (2)$$

s.t.

$$v = M_P \cdot P + M_Q \cdot Q + m$$
$$|v| = K_P \cdot P + K_Q \cdot Q + \mathrm{k}$$
$$\underline{v} \leq |v| \leq \overline{v}$$

(p_i, q_i) is the optimal solution to (1).

Solve p_i, q_i and α_i, β_i.

- Use convex relaxation and the dual algorithm to solve

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[1] X. Zhou, E. Dall'Anese, L. Chen, and A. Simonetto, "An Incentive-based Online Optimization Framework for Distribution Grids." IEEE Transactions on Automatic Control, October 2017.

[2] A. Bernstein and E. Dall'Anese, "Linear power-flow models in multiphase distribution networks," in the 7th IEEE International Conference on Innovative Smart Grid Technologies, Sep. 2017.

Control theory developments

- This work is an application of a general framework for online optimization of dynamical systems being developed at NREL

Steer the output of the dynamical system...

$$\left.\begin{aligned} \dot{x} &= Ax + Bu + B_w w \\ y &= Cx + D_w w \end{aligned}\right\}$$ Grid dynamics, wind farm etc..

...to the solution of the optimization problem...

$$\left.\begin{aligned} \min_{u} \quad & f(u) + h(y) \\ \text{s.t.} \quad & y \in \mathcal{S} \end{aligned}\right\}$$ OPF - Maximum power output, etc...

... without any knowledge on the disturbance w

Theorem 1

If an LMI of the form

$$\underbrace{\begin{bmatrix} \mathbf{A}^\top\mathbf{P}+\mathbf{PA} & \mathbf{PB} \\ \mathbf{B}^\top\mathbf{P} & 0 \end{bmatrix} + \begin{bmatrix} \mathbf{C}^\top & 0 \\ 0 & I \end{bmatrix} \Xi_\varphi \begin{bmatrix} \mathbf{C} & 0 \\ 0 & I \end{bmatrix} \preceq 0}_{\text{Convex, easy to check}}$$

is feasible.. the primal dual algorithm in feedback with a dynamical system is ***stable*** and ***tracks the optimal solution exponentially fast.***

Theorem 2:

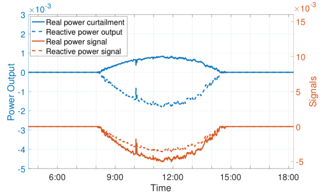
If the primal dual algorithm is ***sufficiently slow*** with respect to the system's dynamics... then the LMI condition above is ***always feasible***.

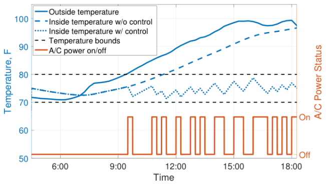
M. Colombino, E. Dall'Anese, and A. Bernstein, "Online Optimization as a Feedback Controller: Stability and Tracking," submitted to the IEEE Transactions on Control of Network Systems.

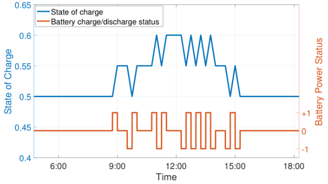
A. Bernstein, E. Dall'Anese, and A. Simonetto, "Online Optimization with Feedback," submitted to the IEEE Transactions on Signal Processing.

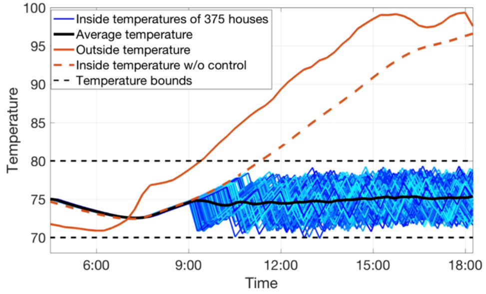
Initial Modeling and Simulation Results

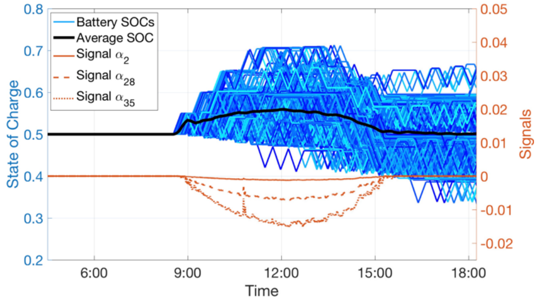
- Phase C of modified IEEE 37-node feeder with measured load data
- 18 PV systems, 375 air conditioners and 375 batteries responding to incentive signal

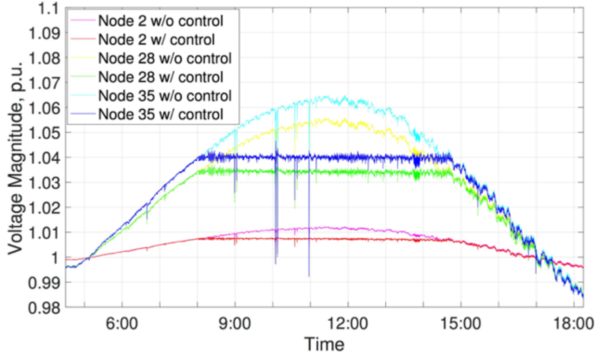












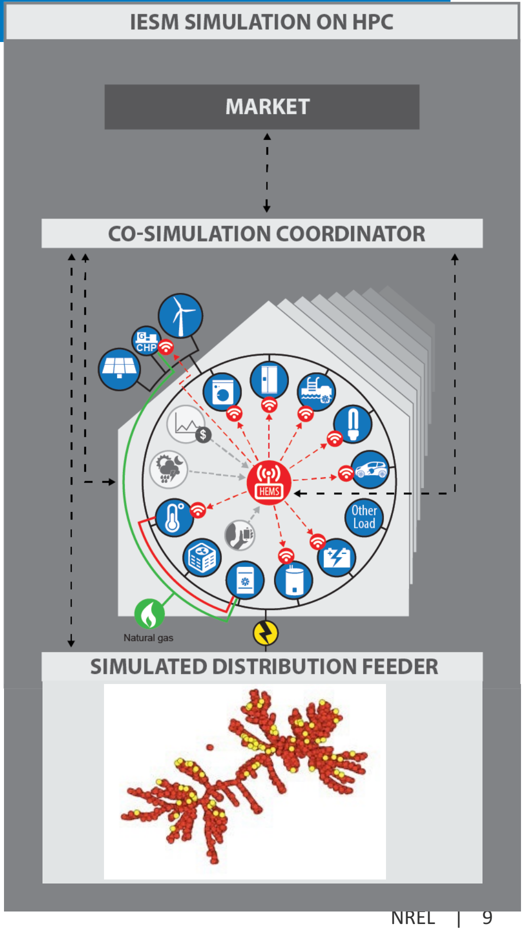
- Left: (up) an arbitrary PV's real and reactive power output w.r.t. incentive signals, (middle) an arbitrary A/C's temperature and its power on/off status, and (down) an arbitrary battery's SOC and charging status.
- Middle: (up) temperatures under control of all 375 A/Cs; (down) SOC pf all 375 batteries.
- Right: voltages w/ and w/o control throughout a day.

X. Zhou, E. Dall'Anese, L. Chen, and A. Simonetto, "An Incentive-based Online Optimization Framework for Distribution Grids." IEEE Transactions on Automatic Control, October 2017.

X. Zhou, E. Dall'Anese, and L. Chen, "Online Stochastic Optimization of Networked Distributed Energy Resources." (Under review) IEEE Transactions on Automatic Control, 2018.

Larger Scale Modeling and Simulation

- Simulated incentive-based online optimization using NREL's IESM cosimulation tool
  - Python-based tool to cosimulate power system, buildings and markets
  - Larger scale & higher fidelity simulations
    - IEEE 8500 node feeder with 1,977 homes, 1,777 with PV[1]
    - Air conditioners and PV inverters respond to incentive prices and a time-of-use (TOU) price
    - DSO determines incentive prices to reduce voltage violations
- Simulated four scenarios, defined by NIST for the TE Challenge[2]:
  - Sunny: day in Arizona, actual weather
  - Cloudy: weather event added, based on actual weather event
  - Price-responsive demand (PRD): A/Cs and PVs respond to a TOU price
  - Transactive energy controls (TEC)



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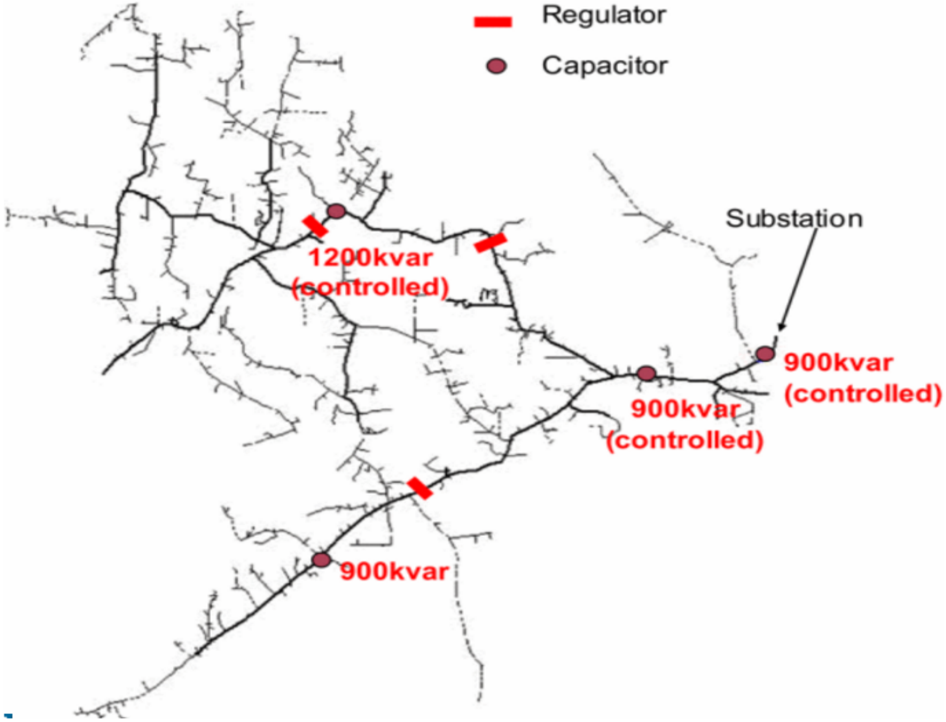
[1] Model prepared by PNNL for the TE Challenge

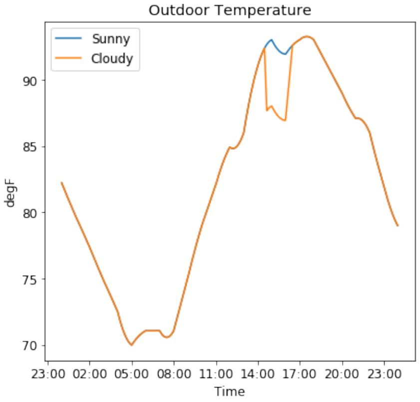
[2] https://www.nist.gov/engineering-laboratory/smart-grid/hot-topics/transactive-energy-modeling-and-simulation-challenge

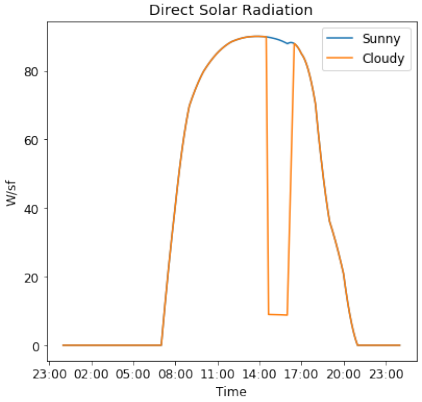
IEEE 8500 grid & scenario



Electric feeder with high penetration of PV.
At 2:30, a storm front overspreads the feeder and PV power production drops from full sun to 10% sun in a period of 10 min.
This is followed by a ramp back up to full sun from 4:00 – 4:30 pm.

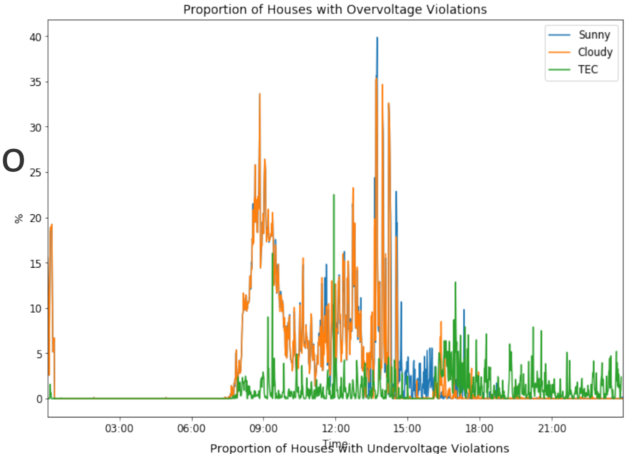
Based on Scenario #3 in [SGIP TE Application Landscape Scenario white paper]

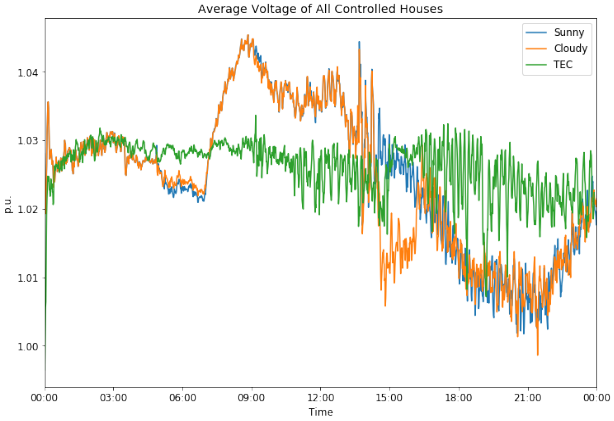




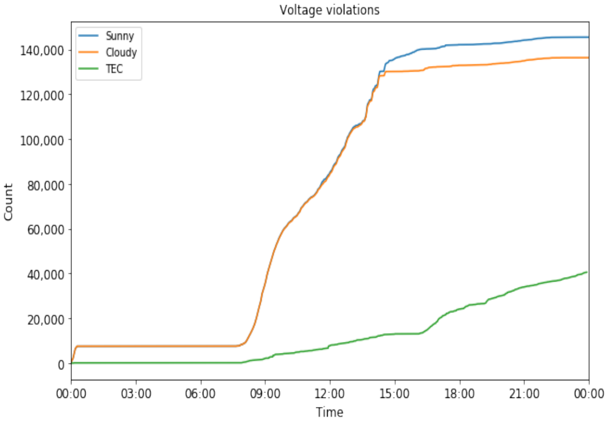
Voltage violations

Voltage violations decreased compared to Cloudy scenario

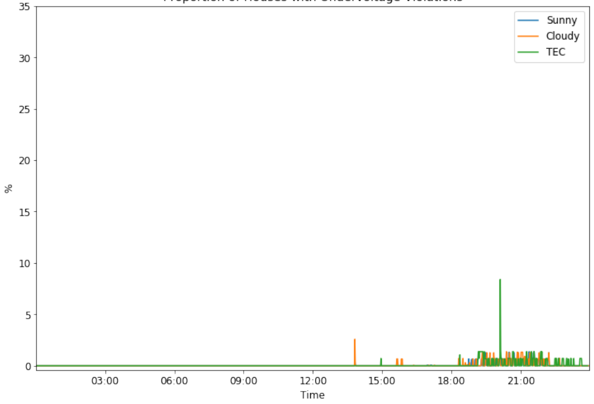




Average voltages across feeder



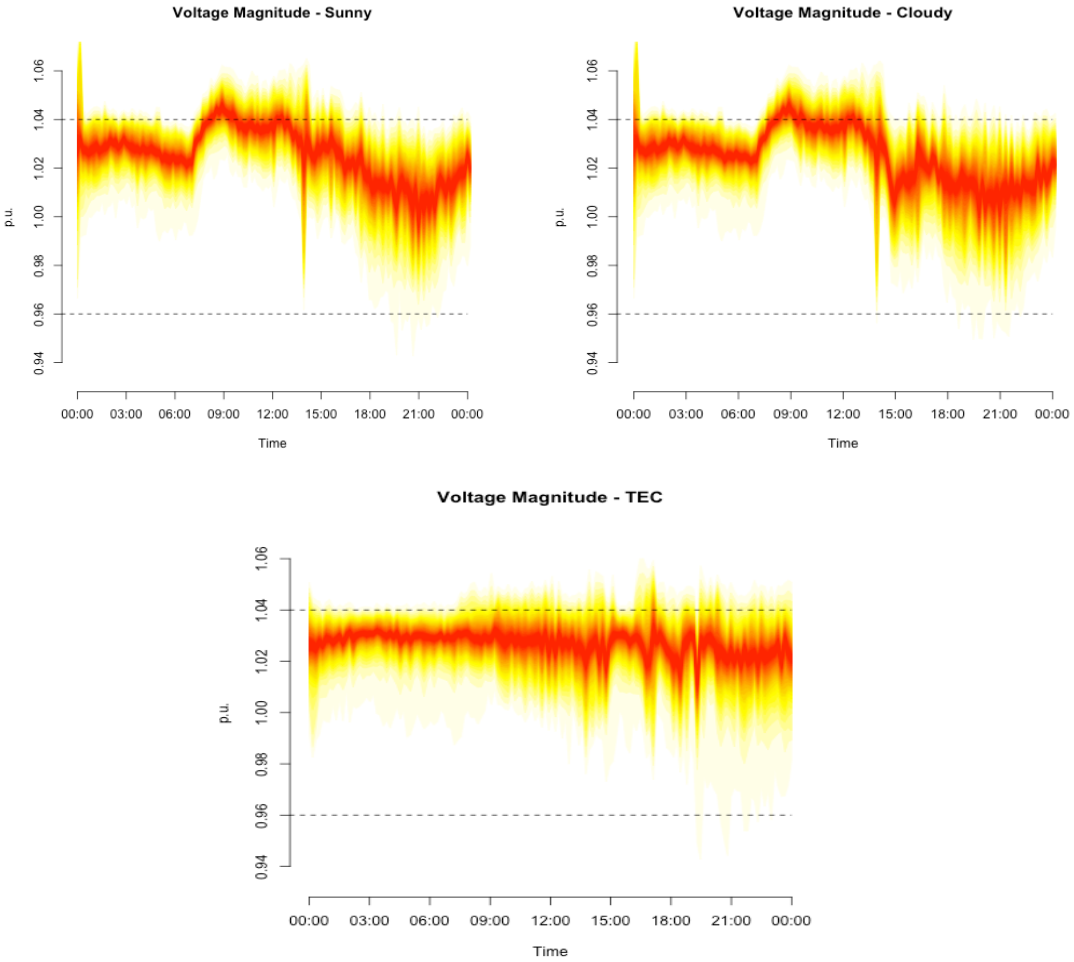
Total number of voltage violations



Proportion of houses with overvoltage and undervoltage violations [%]

Voltage distributions

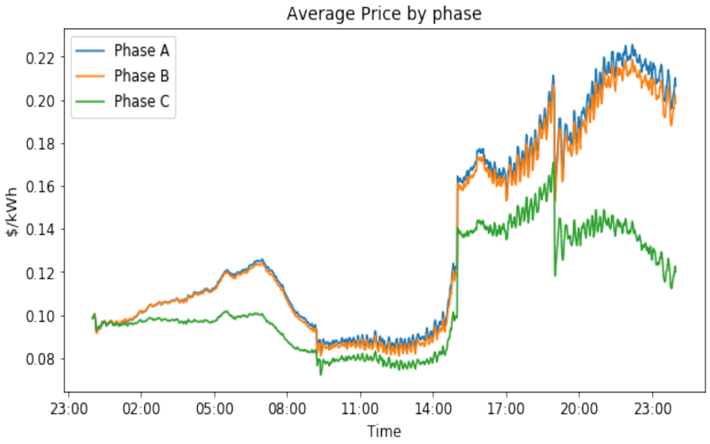
Voltage varies less as under- and over-voltages are reduced

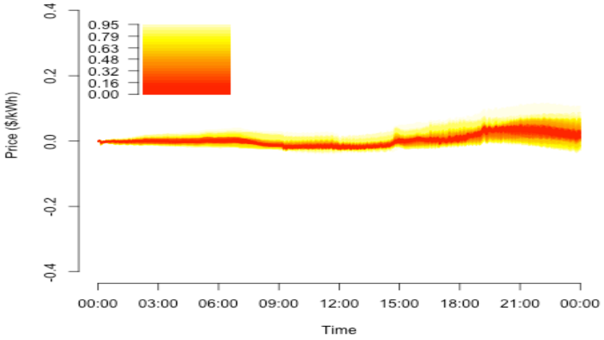


Distribution of voltages for scenarios

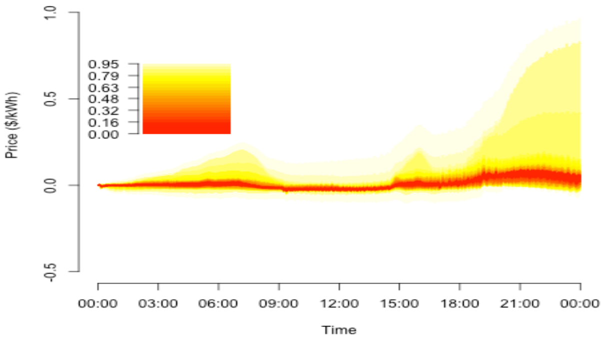
Incentive price signals

Varies by phase in response to voltages





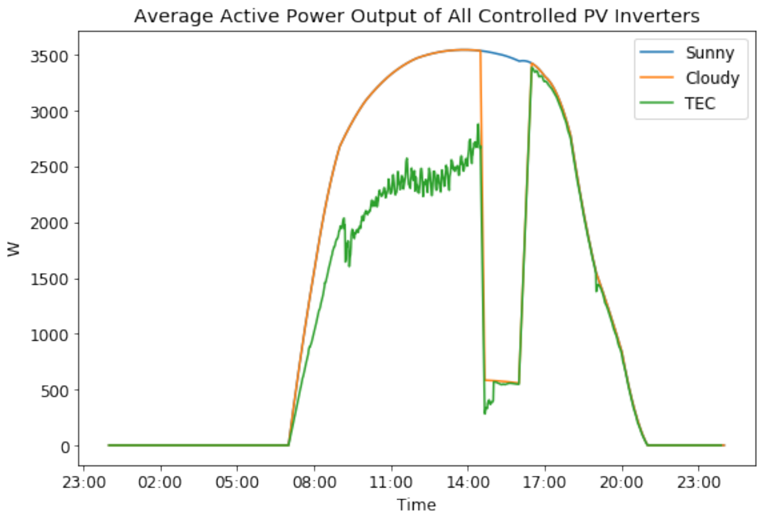
Incentive price signal for reactive power



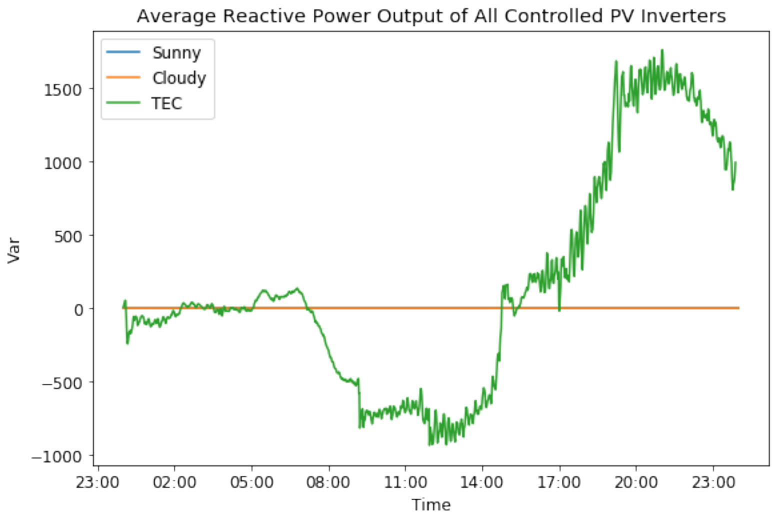
Incentive price signal for active power

PV inverter responses

PV inverters curtailed in the morning and supply reactive power support in the evening

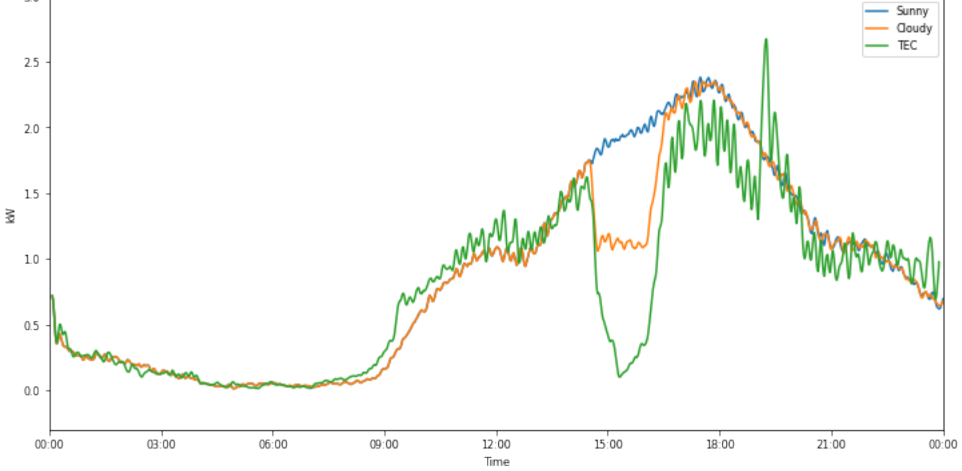


Incentive price signal for reactive power

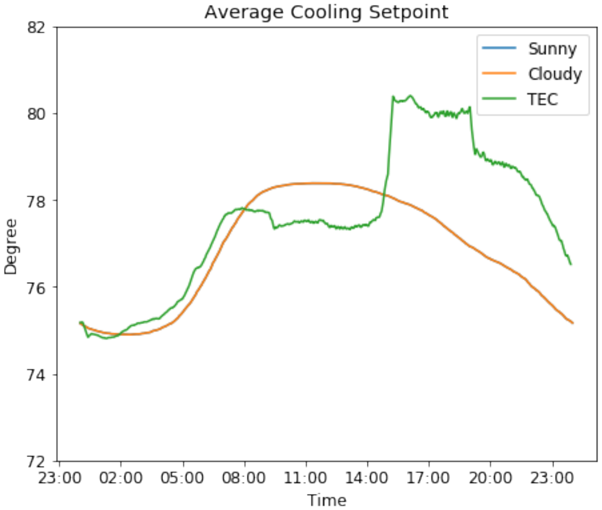


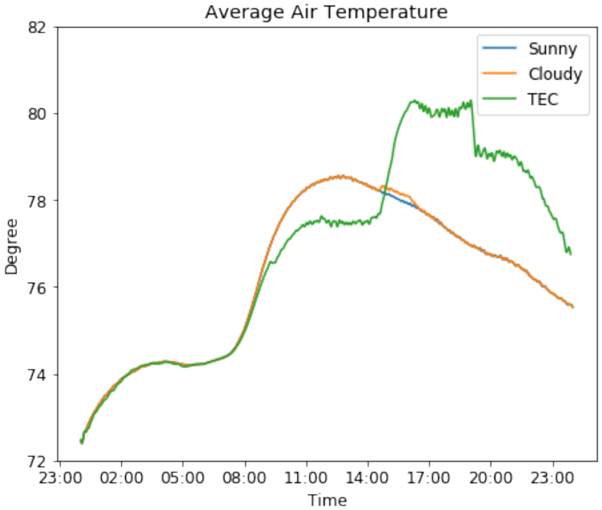
Incentive price signal for active power

A/C responses



Lower setpoint in morning to increase load and higher setpoint during peak TOU price to decrease cost

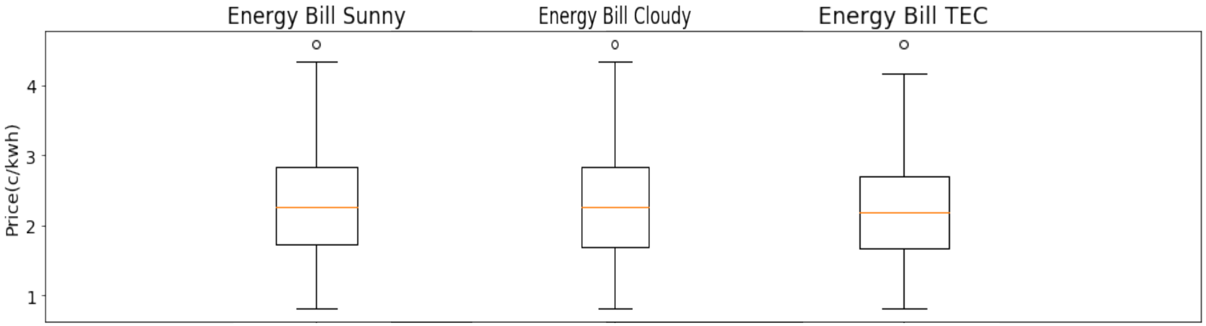




Air temperature responses

Consumer cost impact

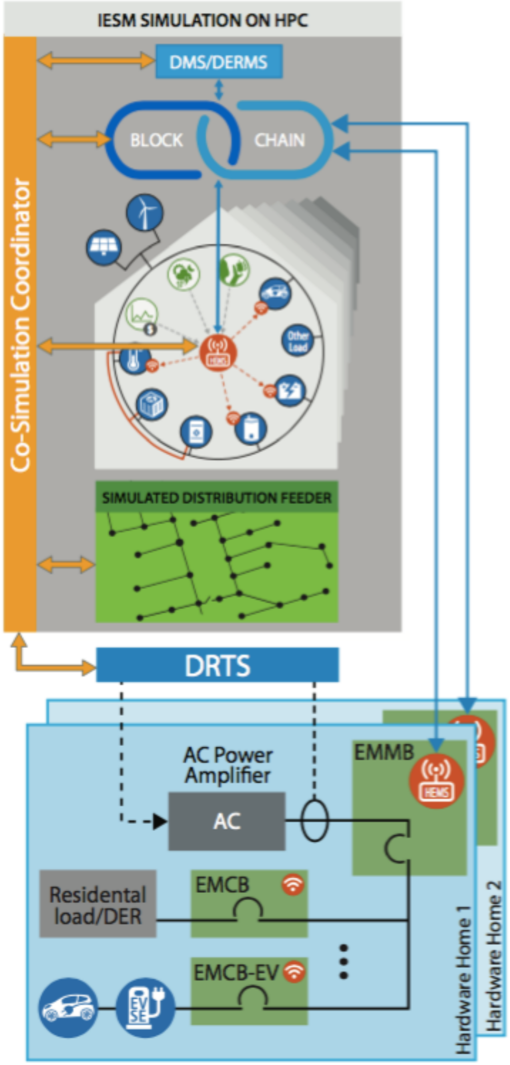
Incentive signal has no significant impact on total electricity cost



Average consumer cost

Future Steps

- Improve performance by tuning of parameters within optimization
- Simulated for longer time periods and more scenarios
- Machine learning approaches to tune parameters
- Include an open-source blockchain to exchange data within simulation
- HIL simulation using NREL’s Systems Performance Lab with real residential loads and DERs



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