



Integrated Energy System Model (IESM)

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Transactive Controls for Buildings to Benefit from Grid Services

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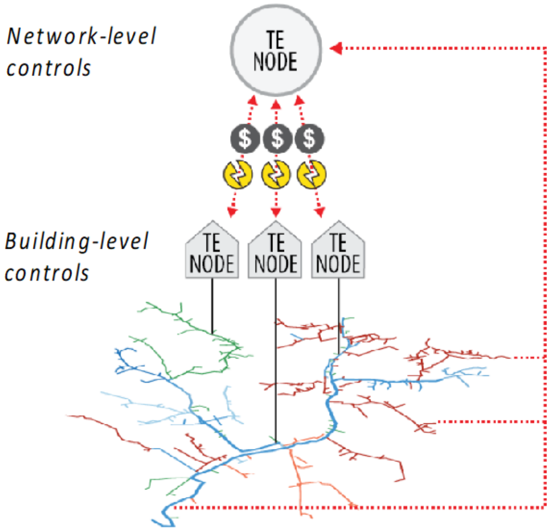
L048-1502

Topic 1

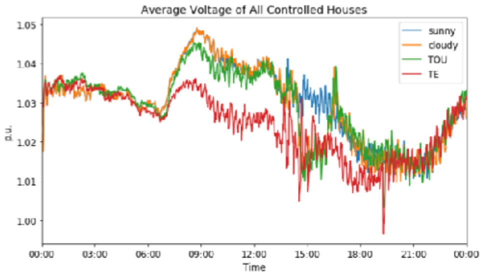
Project Summary

Current transactive control approaches incentivize building loads and distributed energy resources (DERs) to dynamically balance supply and demand and limit real power peaks. This project adds the capability for buildings to support voltage regulation by using a network-aware transactive control approach that involves building-level and network-level controls that interact to ensure robust and stable operation. Network-level controls determine building-specific price signals that include an energy price based on distribution locational marginal pricing (DLMP) and an incentive signal for voltage regulation. Price signals are communicated via an open-source blockchain provided by RMI to ensure private, rapid transactions. Building-level controls balance comfort desires and cost impacts. Viability will be demonstrated through cosimulation using an HCE feeder and hardware-in-the-loop (HIL) experiments that include a pre-commercial prototype of proposed building controls integrated with Eaton's smart circuit breakers.

1. Develop network-aware transactive control algorithms using online optimization.



2. Cosimulate feeder, buildings, and controls to evaluate operational and economic performance.



3. Demonstrate deployment viability through HIL experiments.

Key Personnel/Organization

Annabelle Pratt/NREL, Emiliano Dall'Anese/NREL and University of Colorado, Dane Christensen/NREL, Rui Yang/NREL, Dheepak Krishnamurthy/NREL, Bethany Sparn/NREL, Bryan Hannegan/Holy Cross Energy, Sam Hartnett/Rocky Mountain Institute, Yi Yang/Eaton, Hongyu Wu/Kansas State University, Henrik Madsen/ Technical University of Denmark

Budget and Timeline

Federal funds: $700K/yr   Cost share: $93K/yr   Total: $2,380K

Key Milestones and Deliverables

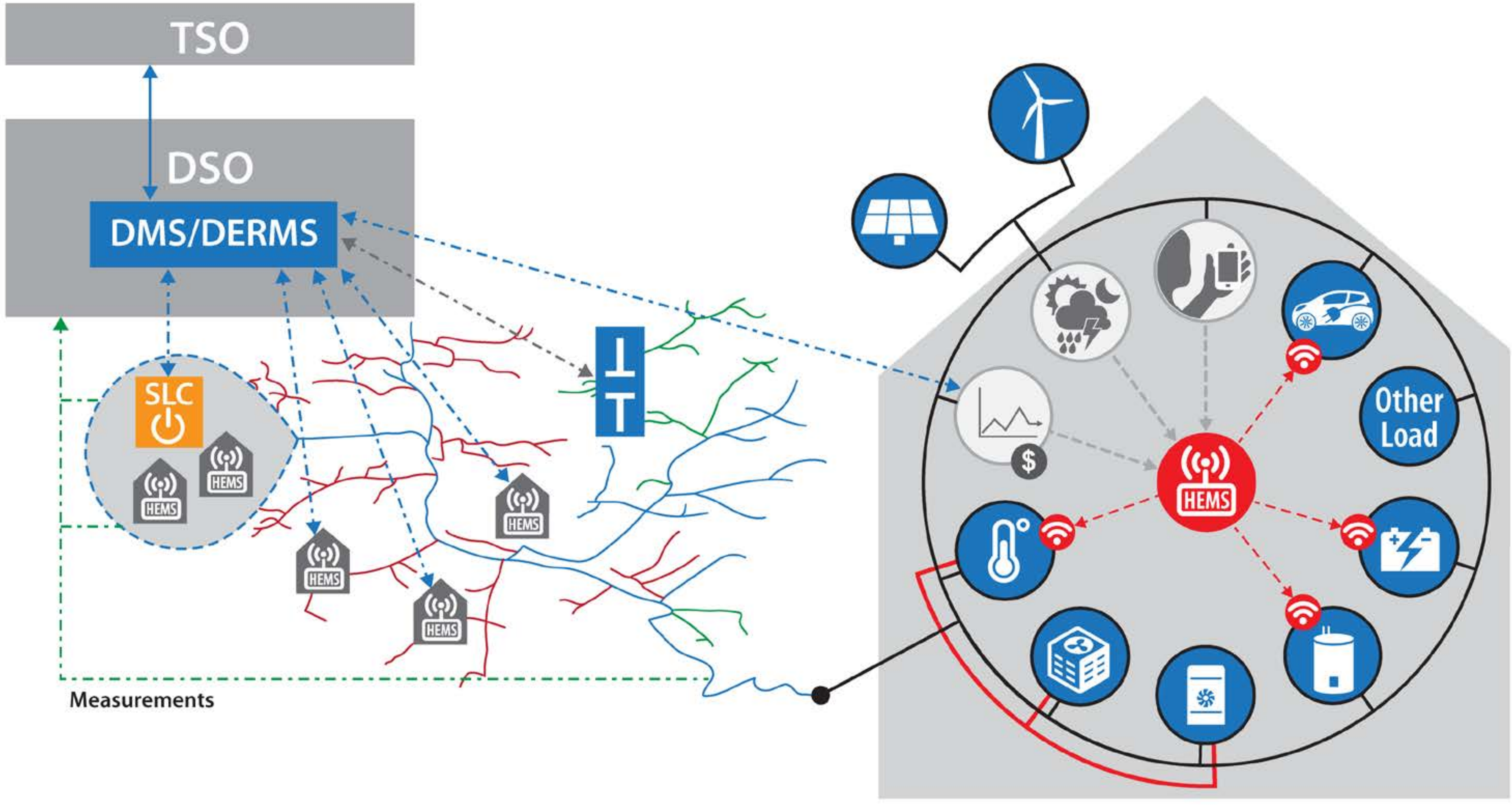
Year 1	Develop architecture for network-aware transactive controls and blockchain integration. Develop and deliver python-based code for building controls.
Year 2	Deliver python-based code for network-level control algorithms. Cosimulate feeder, buildings, and controls. Deliver report and paper on results.
Year 3	Demonstrate deployment viability through HIL experiments. Disseminate results through reports and papers. Complete technology transfer activities.

Project Impact

Building owners will benefit from reduced costs by providing more grid services while maintaining building occupants' comfort expectations. Grid operators will benefit from minimizing investments to reliably serve load and manage voltage variability. A key technical contribution is the addition of voltage regulation services by using a power flow model to calculate the incentive signals. The project will evaluate both the operational and economic impacts of the controls, and this will promote understanding of the value of transactive energy. NREL is uniquely qualified to lead this effort based on prior LDRD investments and GMLC projects involving control theory, online optimization, and cosimulation.

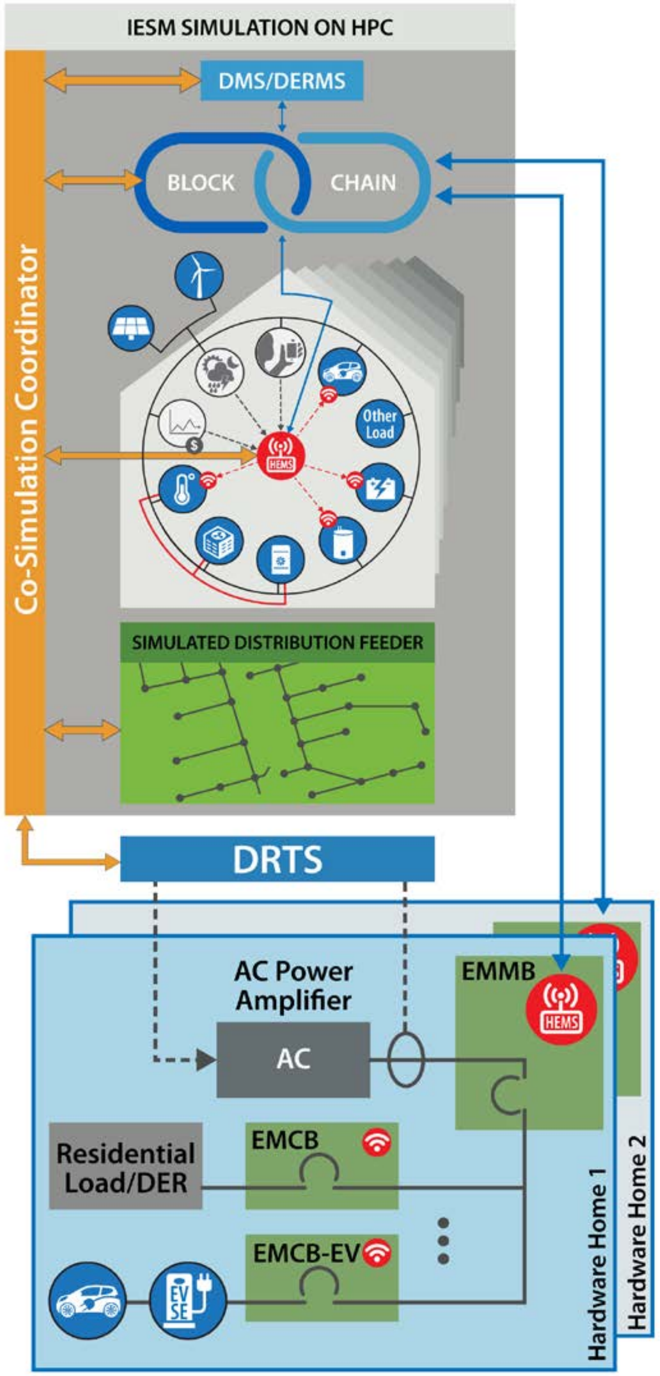
Develop and demonstrate a network-aware transactive control approach for buildings to provide more grid services.

BTO proposal : Network-aware transactive control



BTO proposal – HIL

- Current transactive control approaches incentivize building loads and distributed energy resources to dynamically balance supply and demand and to limit real power peaks.
- This project extends the opportunities for buildings to participate in grid services by voltage regulation services by using a power flow model to calculate the incentive signals. These signals are communicated via an open-source blockchain to ensure private, rapid transactions.
- Viability will be demonstrated through cosimulation and hardware-in-the-loop experiments.
- NREL is uniquely qualified to lead the development of a network-aware transactive controls approach based on prior LDRD investments and Grid Modernization Laboratory Consortium projects involving control theory, online optimization, and cosimulation, as well as their world-class laboratory capabilities in NREL's Energy Systems Integration Facility (ESIF).
- The project will evaluate both the operational and economic impacts of the controls, which will promote understanding of the value of transactive energy.



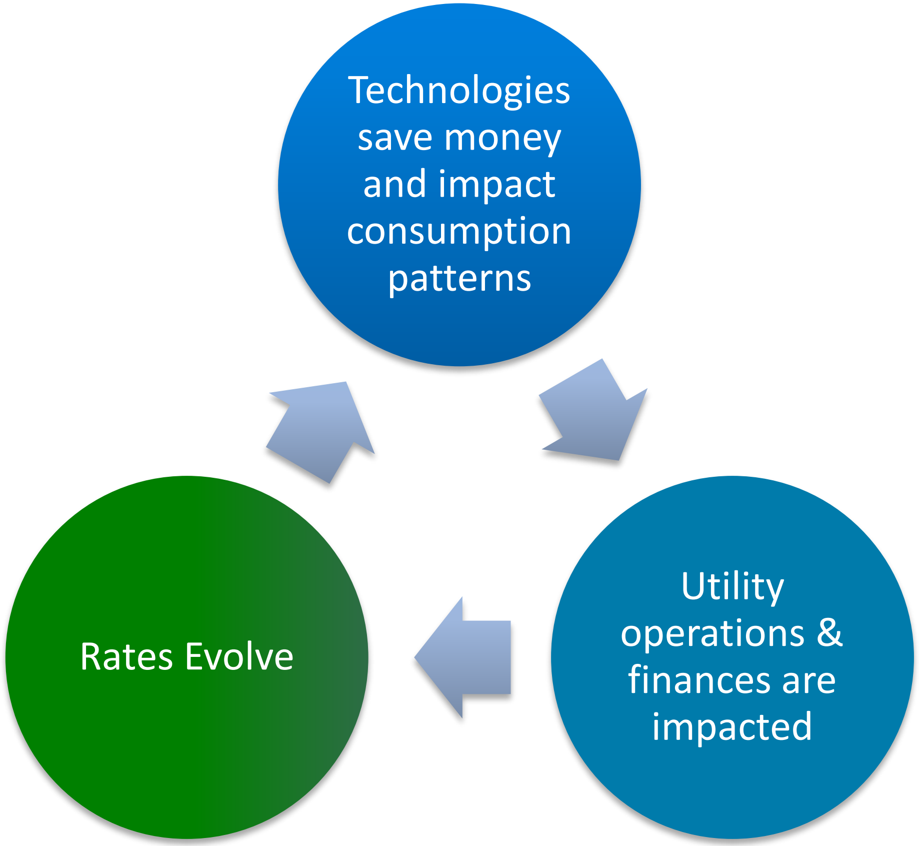
Outline

- Motivation
- Context
- IESM description
- Studies:
  - Air conditioner control by HEMS
  - Electric water heater control
  - Transactive Energy Challenge
  - Highly Distributed Energy Future
- Smart Home HIL

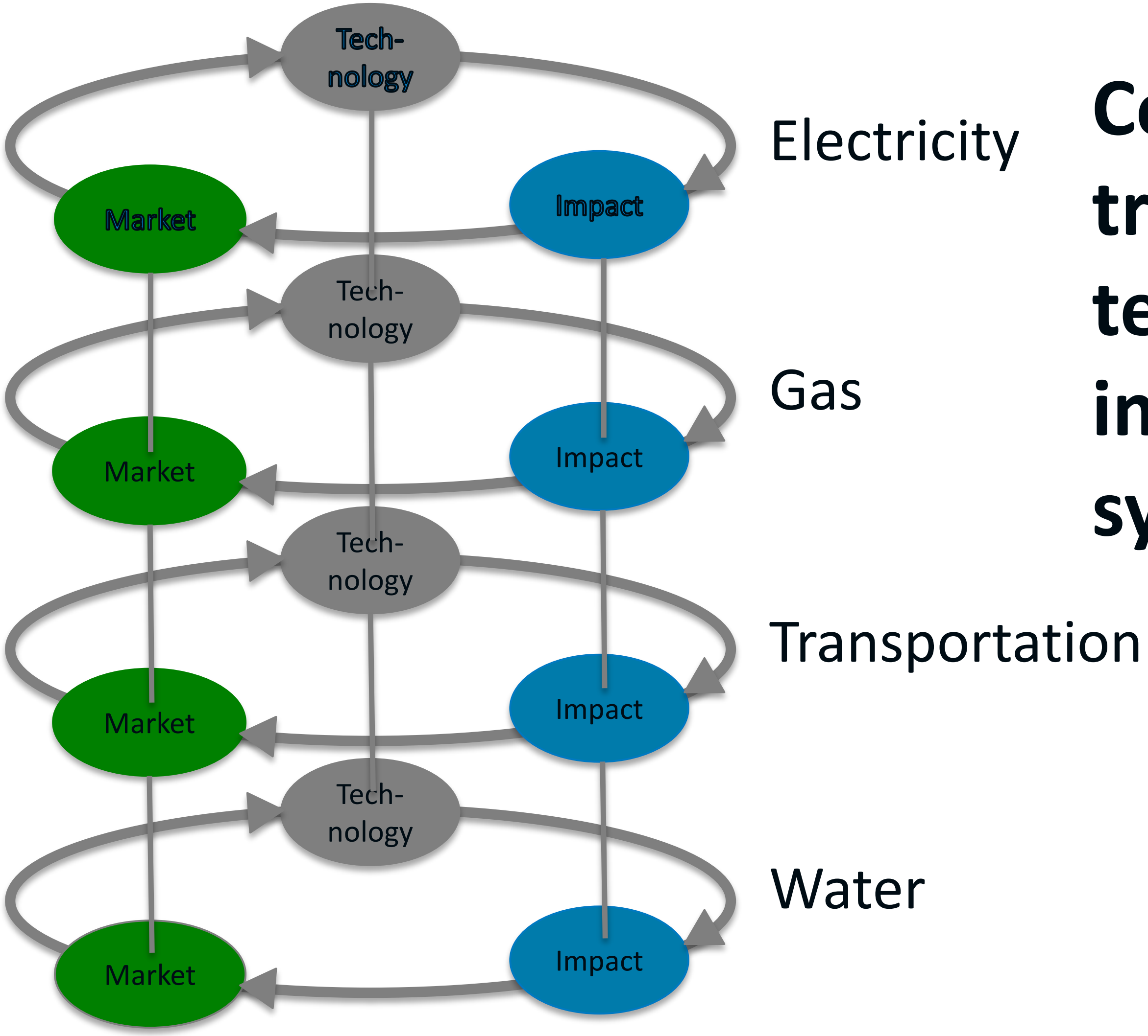
Premise:

Systematic modeling is necessary to identify overall impacts and avoid unintended consequences

Development funded through NREL's LDRD

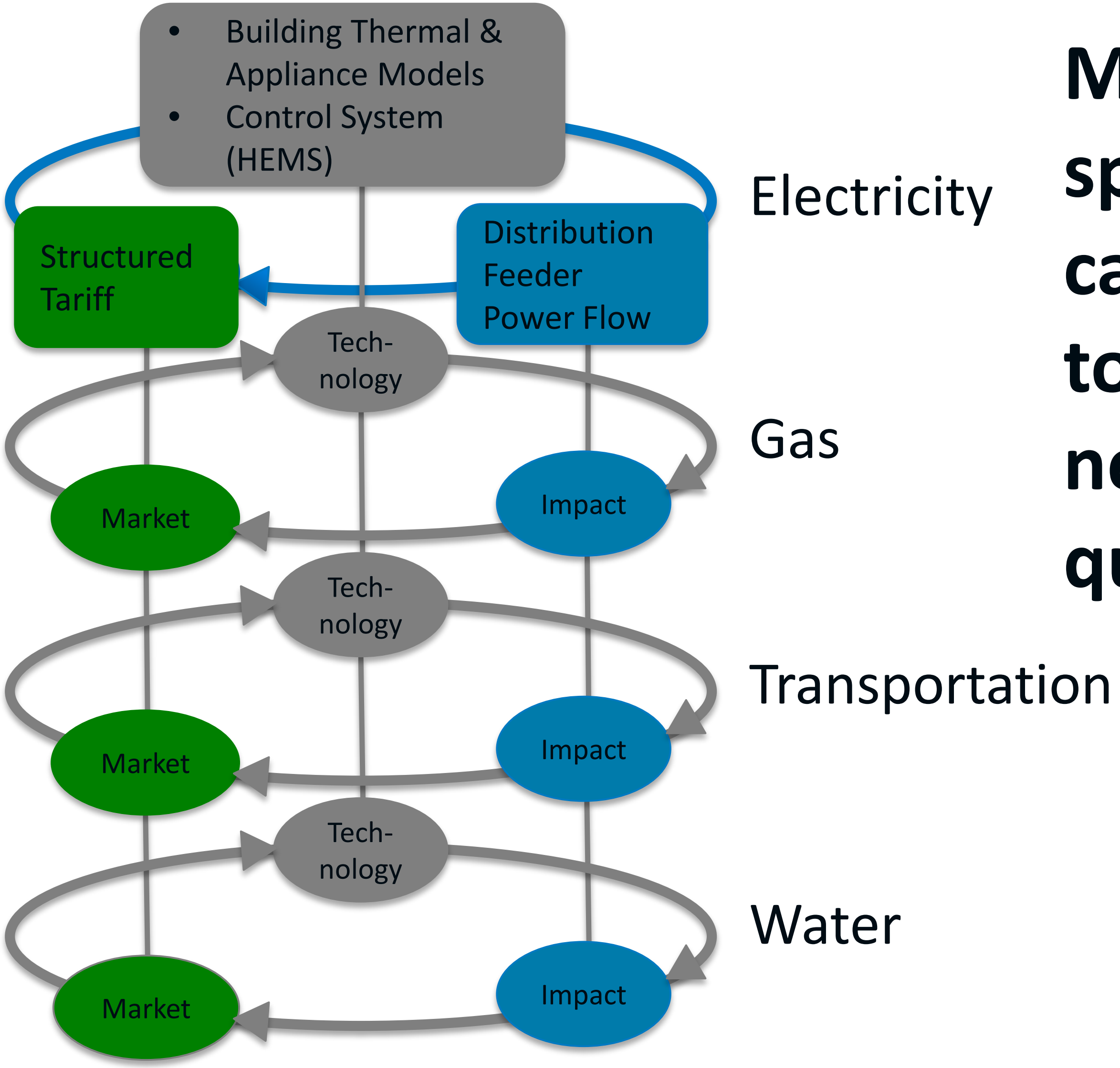


Multiple Energy Systems Are Involved



Consumer tradeoffs between technologies will impact multiple systems

Subsystem Models Exist



Models exist for specific pieces and can be connected to answer the necessary questions

DOE Context

Grid Modernization relies on an
advanced modern grid
planning & analytics platform

Need to model:

"new grid developments including
proliferation of smart
consumer end-use devices
on the customer side of the meter"
and
"**new approaches for distributed control and coordination across local intelligent assets.**"

“Common Platform” for TE simulations

Why do we need a “Common Platform” for TE simulations?

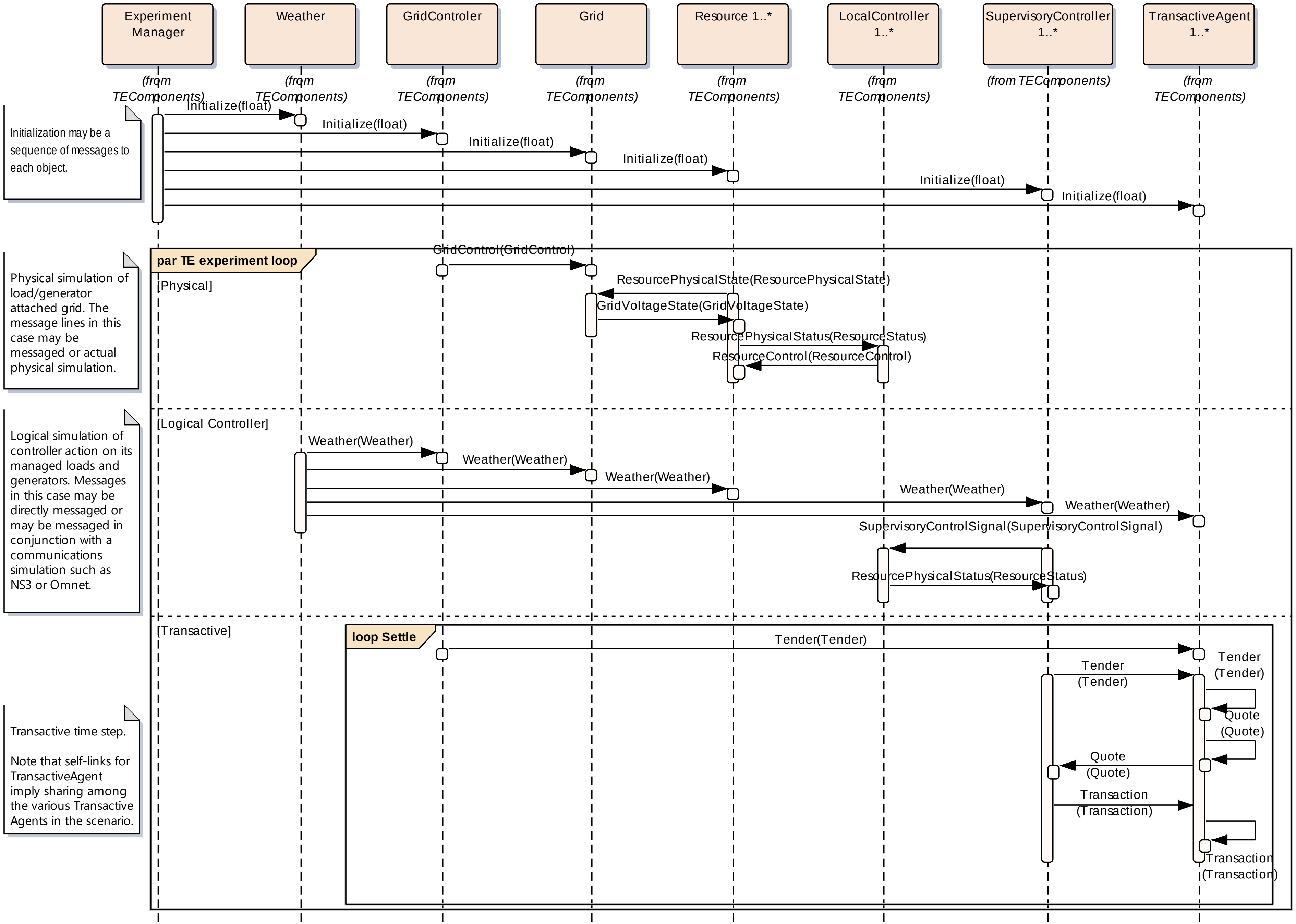
- It enables teams to **share common understanding of TE co-simulation** components and semantics
- In order to understand, evaluate, **compare and validate transactive energy approaches**, grid operations and controls.
- And to enable **potential for connecting library of tools and models** into a larger co-simulation environment for TE evaluations.

6 components in the Common Platform:

- Grid
- Resource (load or generator)
- Resource controller
- Supervisory controller
- Transactive Agent
- Weather

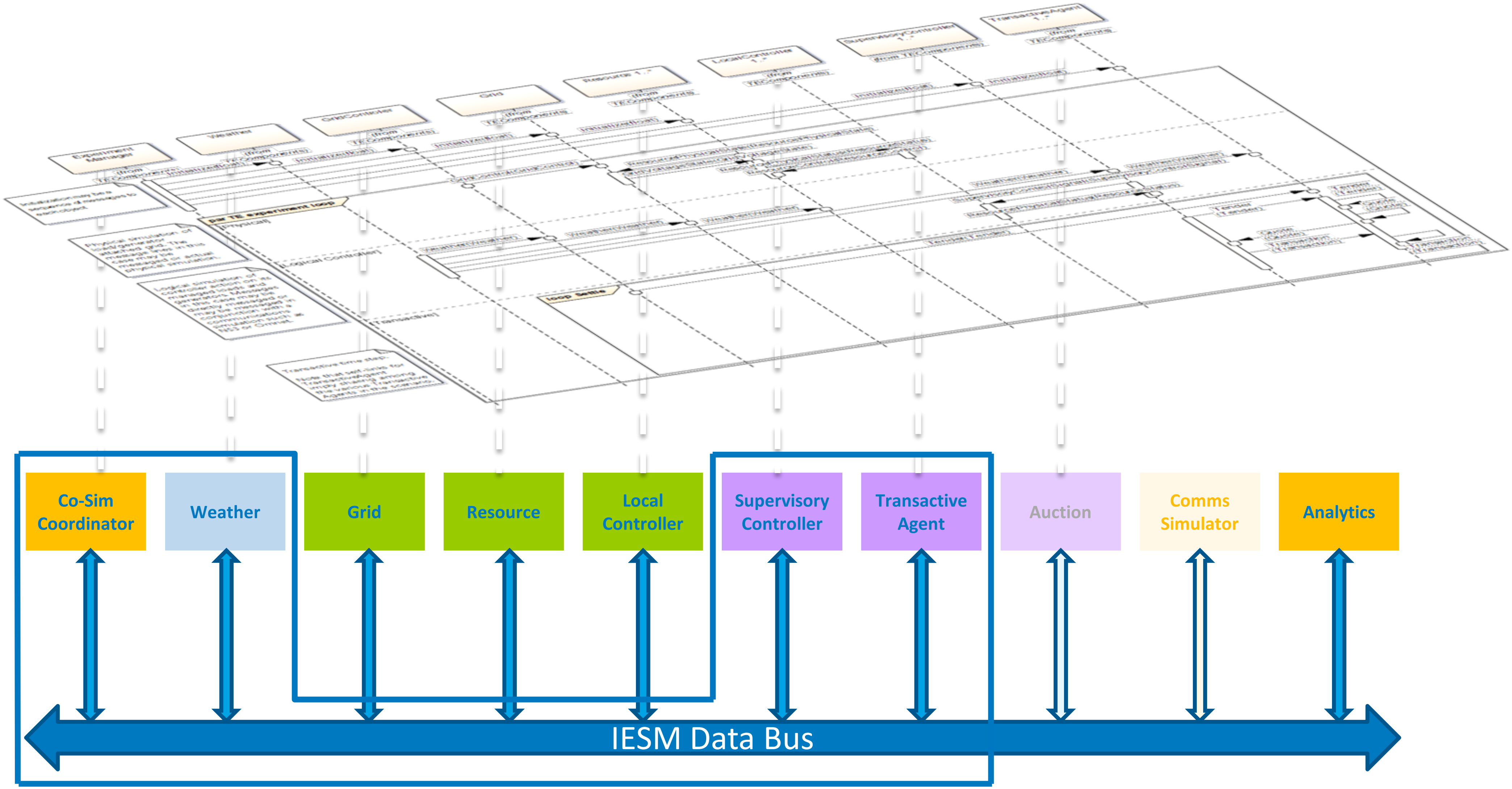
This slide from NIST

Common Platform Canonical Simulation



This slide from NIST

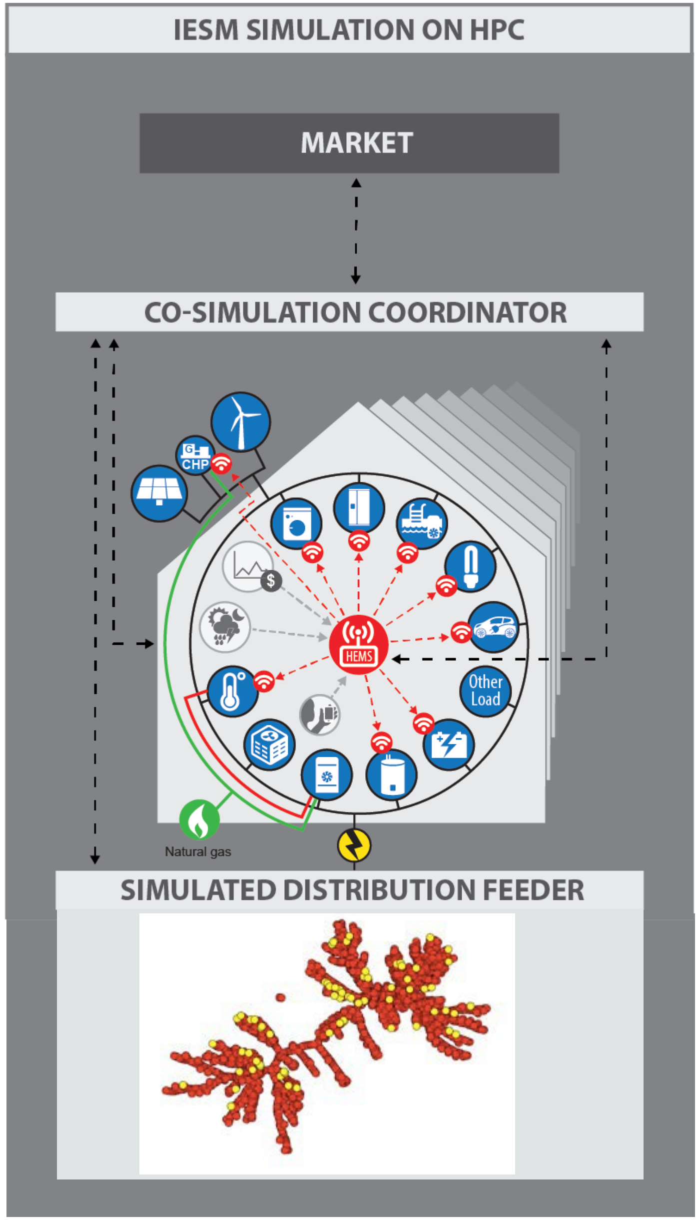
How Simulation Components Get Realized in Simulators



This slide originally from NIST; modified by NREL

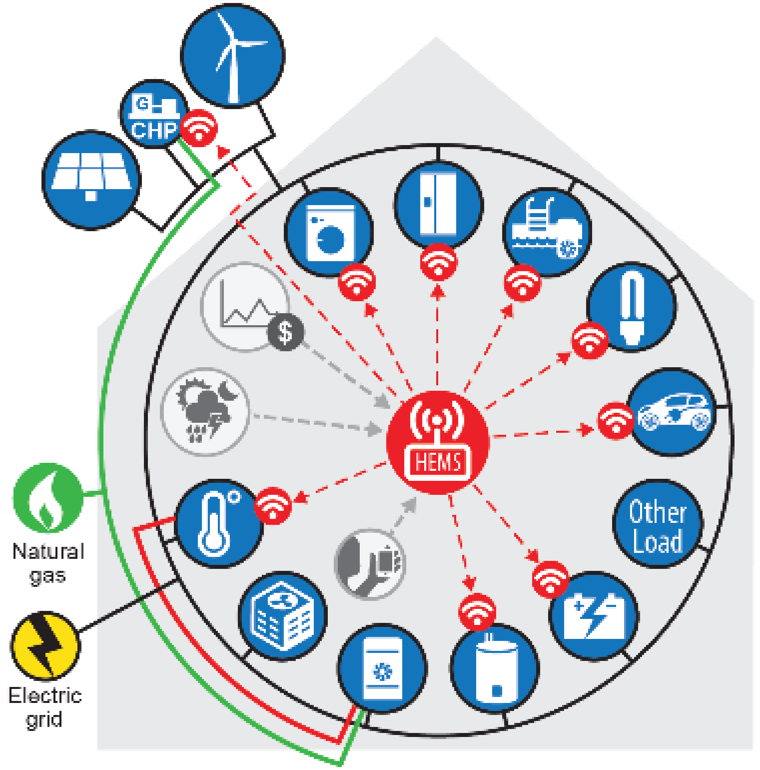
Integrated Energy System Model (IESM) co-simulation platform

- IESM simulates performance of *technologies* within multiple *buildings* under various retail *market* structures
- Co-simulation coordinator integrates feeder & building simulations, home energy management systems (HEMS) & markets
  - Python-based (plan to adopt HELICS)
- HEMS schedules operation of appliances in response to consumer preferences, price, weather, and distributed generation forecasts
  - Multi-objective, stochastic optimization based on model predictive control (MPC)
  - HEMS controls thermostat, EVSE and water heater
  - Runs on HPC to parallellize hundreds of HEMS



Home Energy Management System

- **Schedules operation of appliances and distributed energy resources (DERs)**
  - e.g., thermostat setpoint, electric vehicle charging rate
- **Co-optimizes multiple objectives**
  - e.g., comfort, cost, energy use
- **Based on inputs**
  - *Preferences*: e.g., desired air/water temperature, EV charge completion time
  - *Electricity price & weather forecasts, DR request*
  - *Sensors:* e.g., temperatures, lighting level



Approach:

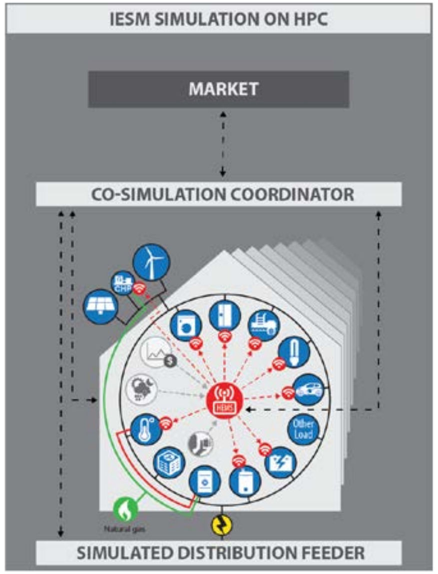
Model Predictive Control (MILP), Stochastic

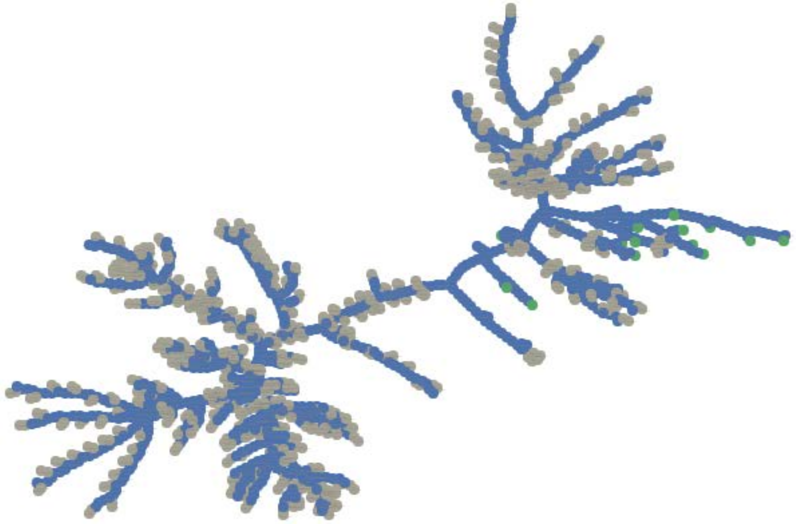
H. Wu, **A. Pratt**, and S. Chakraborty,"Stochastic optimal scheduling of residential appliances with renewable energy sources," *IEEE PES General Meeting*, July 2015

NATIONAL RENEWABLE ENERGY LABORATORY

Studies: IESM with HEMS example

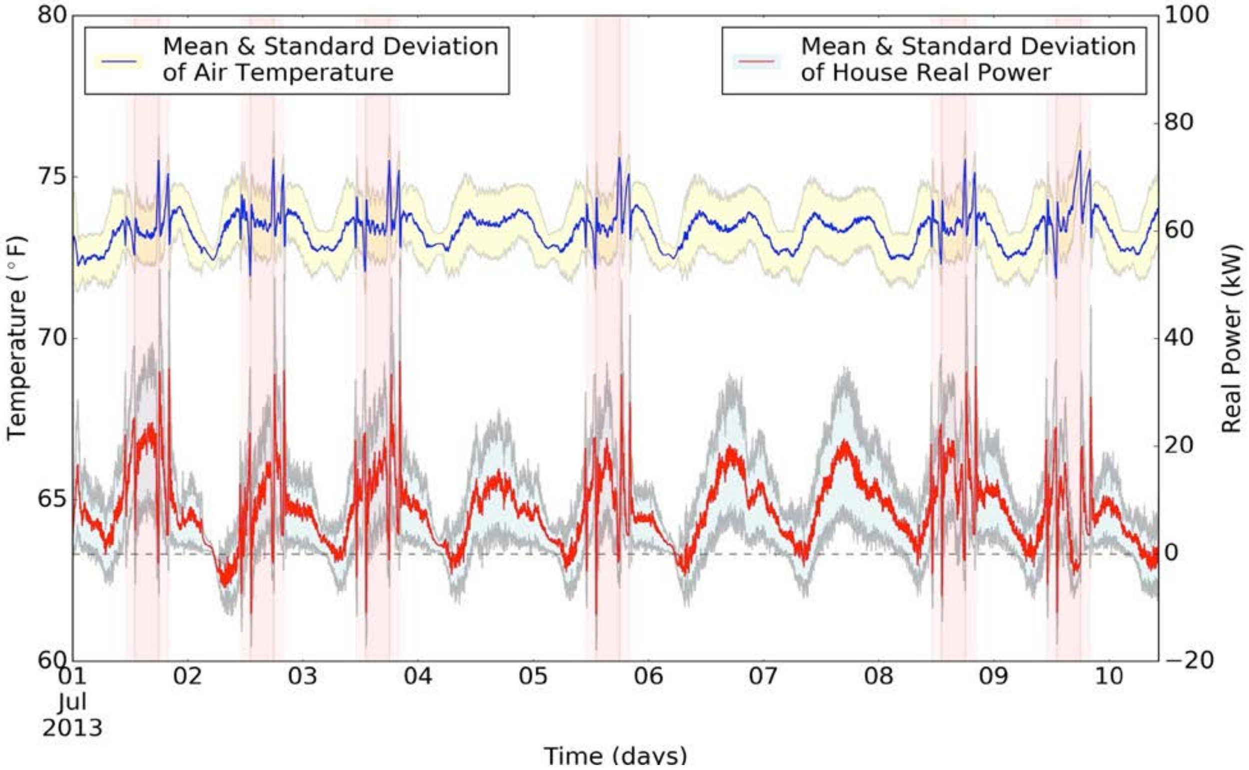
- Representative feeder
  - GridLAB-D taxonomic feeder
  - 12 MW planning load
  - Mostly residential loads (2000 homes)
- Modeled 505 houses on feeder:
  - Four house types utilized, all with PV
  - Varied insulation, air-change rate and thermal mass
- TOU pricing from Duke Energy
- TMY weather for Charlotte, NC
- HEMS optimizes thermostat setpoint
  - Cost and discomfort objectives

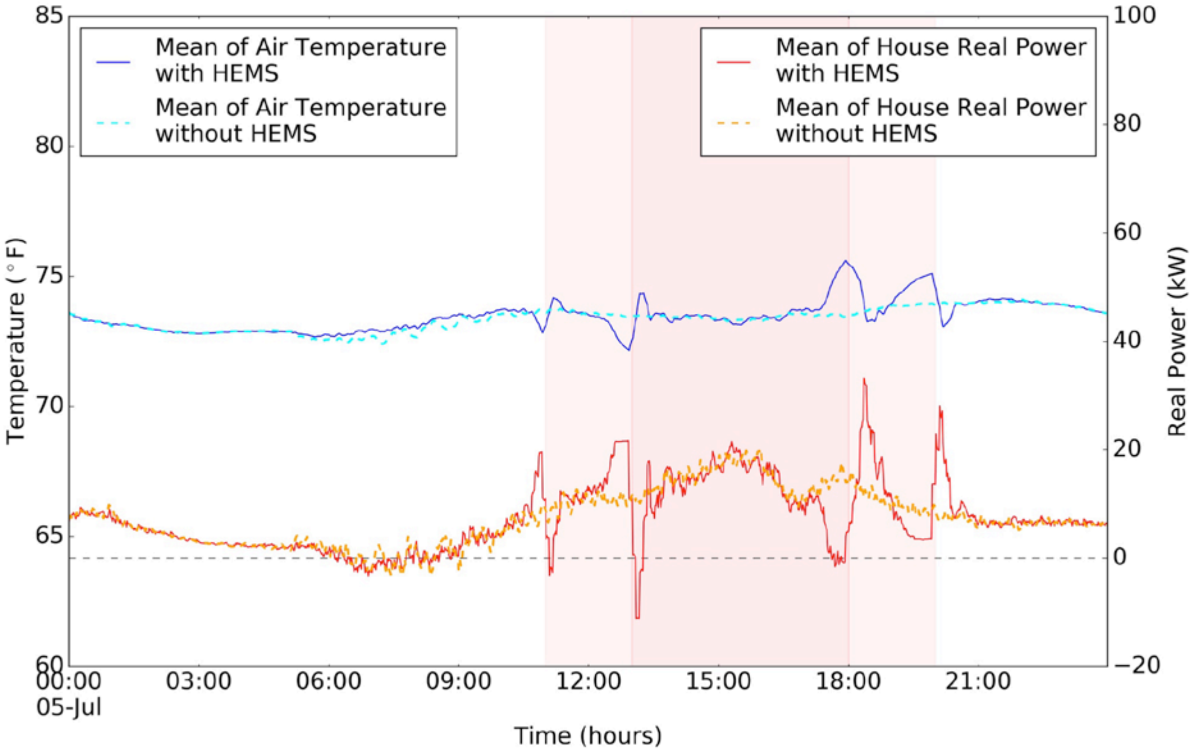




IESM simulation results with high HEMS penetration

- Outcome: HEMS reduce peak loads during high price hours, but shifts it to off-peak and shoulder hours, resulting in a higher peak load

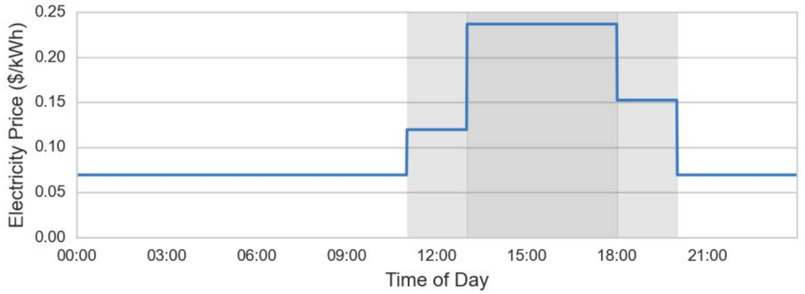


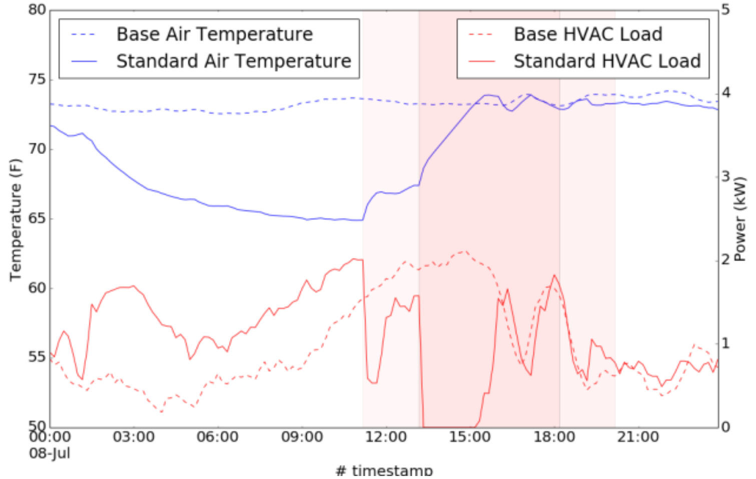


Studies: IESM simulation of different rate structures

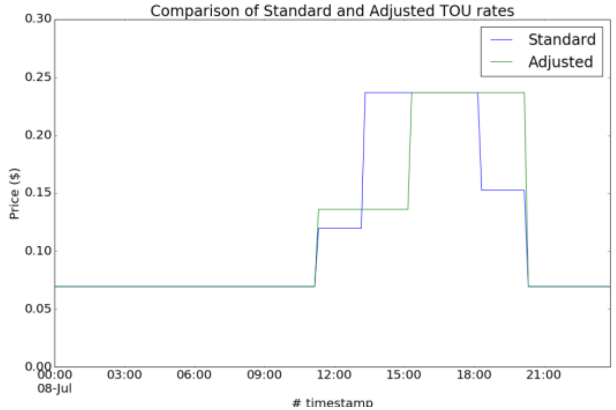
- GMLC Future of Electric Regulation project evaluated three TOU structures
  - o Staggering start times of TOU rates for different “bins” of homes decreases volatility in loads

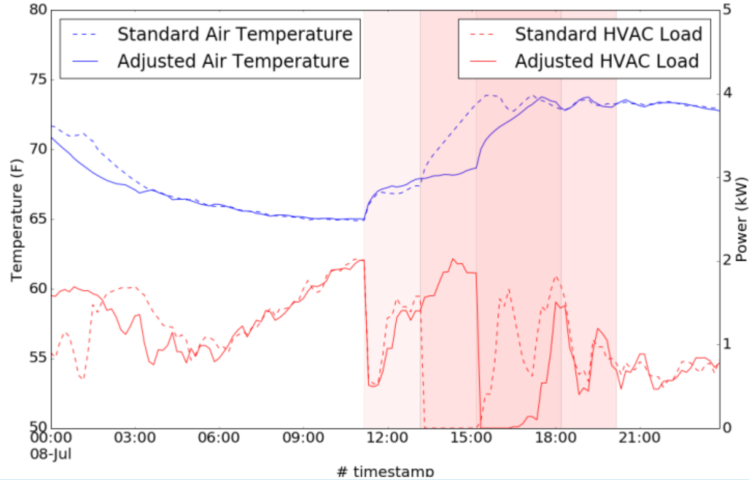
Standard Duke TOU Tariff



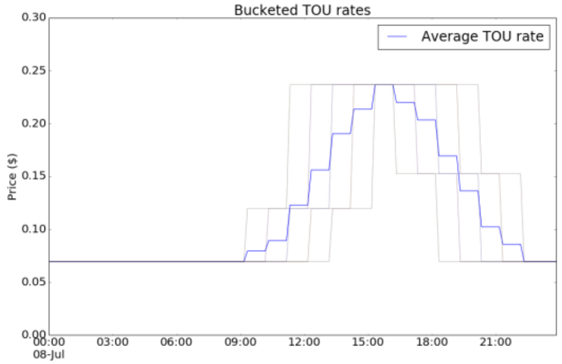


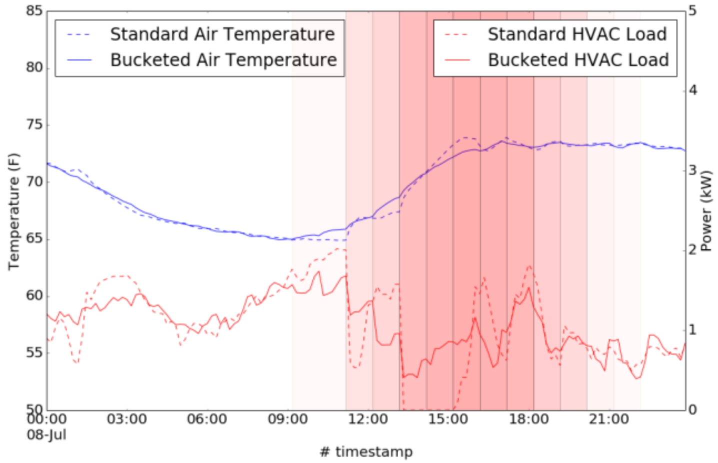
Adjusted TOU: Match Net Loads w/ PV





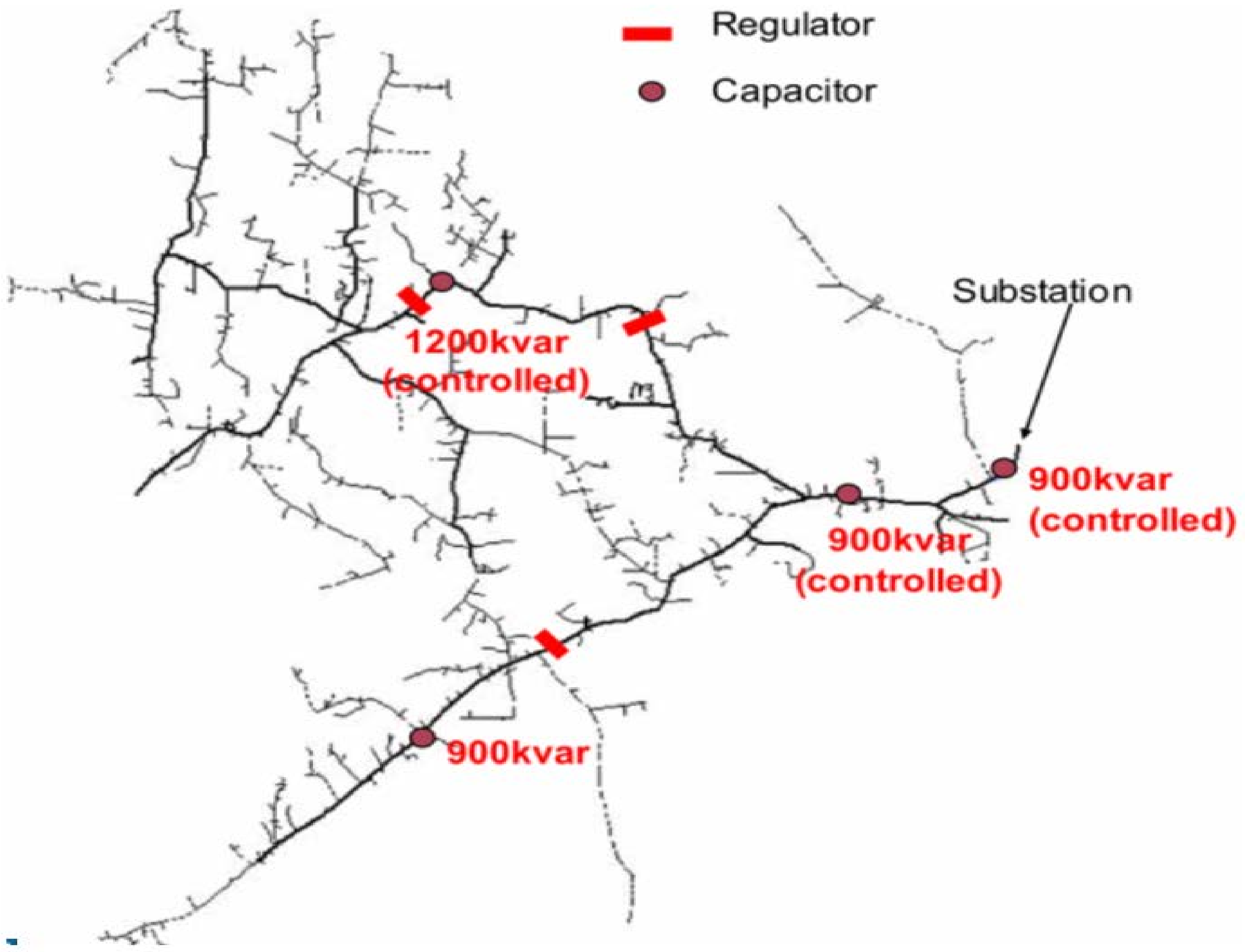
Staggered TOU into 5 bins





- Organized by NIST
- Started July 25, 2017
- Multiple teams, self-funded
- Use own co-simulation platform
- Simulate the same scenario
- Use own transactive approach
- Share results
  - Panel at ISGT in Feb 2018
  - NIST report
  - Joint paper to Nature & Energy

IEEE 8500 grid & scenario



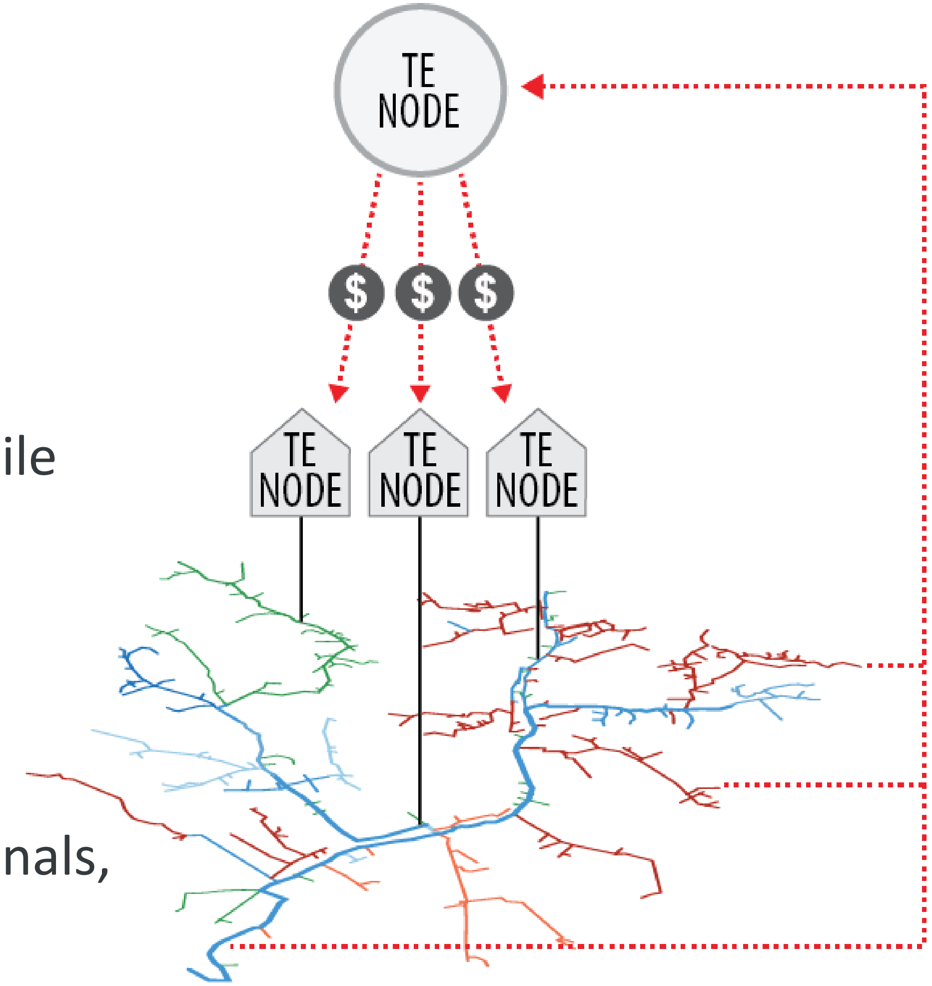
// Nominal peak load = 10773.2 + j2700.0 kVA
// Houses: 1977 from 500.0 to 3500.0 sf, total area 3941782 sf
// Electric water heaters: 1013 totaling 4574.7 kW
// Air conditioners: 1977 totaling 26150.6 kW
// Solar: 1777 totaling 6755.2 kW
// Storage: 857 totaling 4285.0 kW
// Water heater load is resistive
// HVAC load ZIP=0.2,0.0,0.8 with variable power factor as input
// (the fan load ZIP=0.2534,0.7332,0.0135 and pf=0.96)
// Non-responsive ZIP load is input all constant current, pf=0.95

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

Case Studies

- Four scenarios:
  - o Sunny day
  - o Cloudy day
  - o Time-of-use (TOU):
    - – Homes are price-takers
    - – Each house is controlled to satisfy its comfort while considering the impact of TOU
  - o Transactive energy (TE)
    - – Network-level controls coordinates residential appliance behavior to meet feeder level objectives
      - ▪ PV inverter, air conditioner & water heater
    - – Network controller sends additional incentive signals, based on measured voltages and AC-OPF



Xinyang Zhou, Emiliano Dall'Anese, Lijun Chen, and Andrea Simonetto, "An Incentive-based Online Optimization Framework for Distribution Grids." IEEE Transactions on Automatic Control, October 2017.

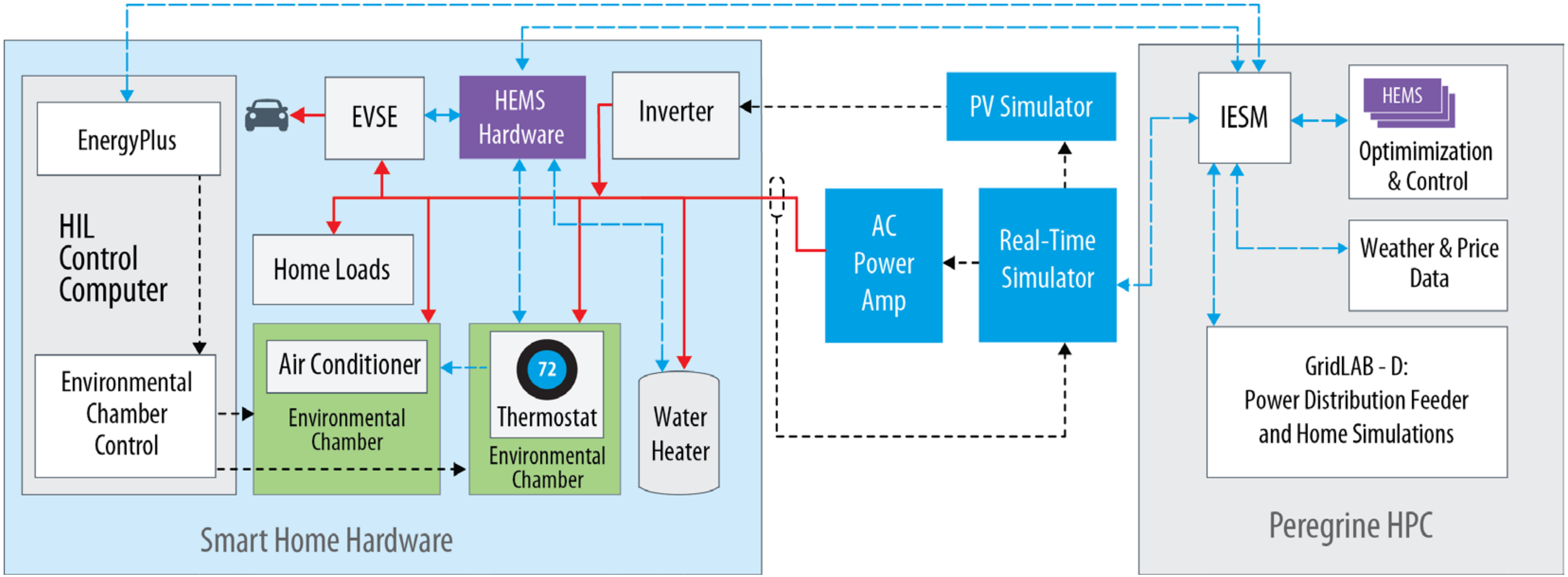
IESM simulation of different rate structures

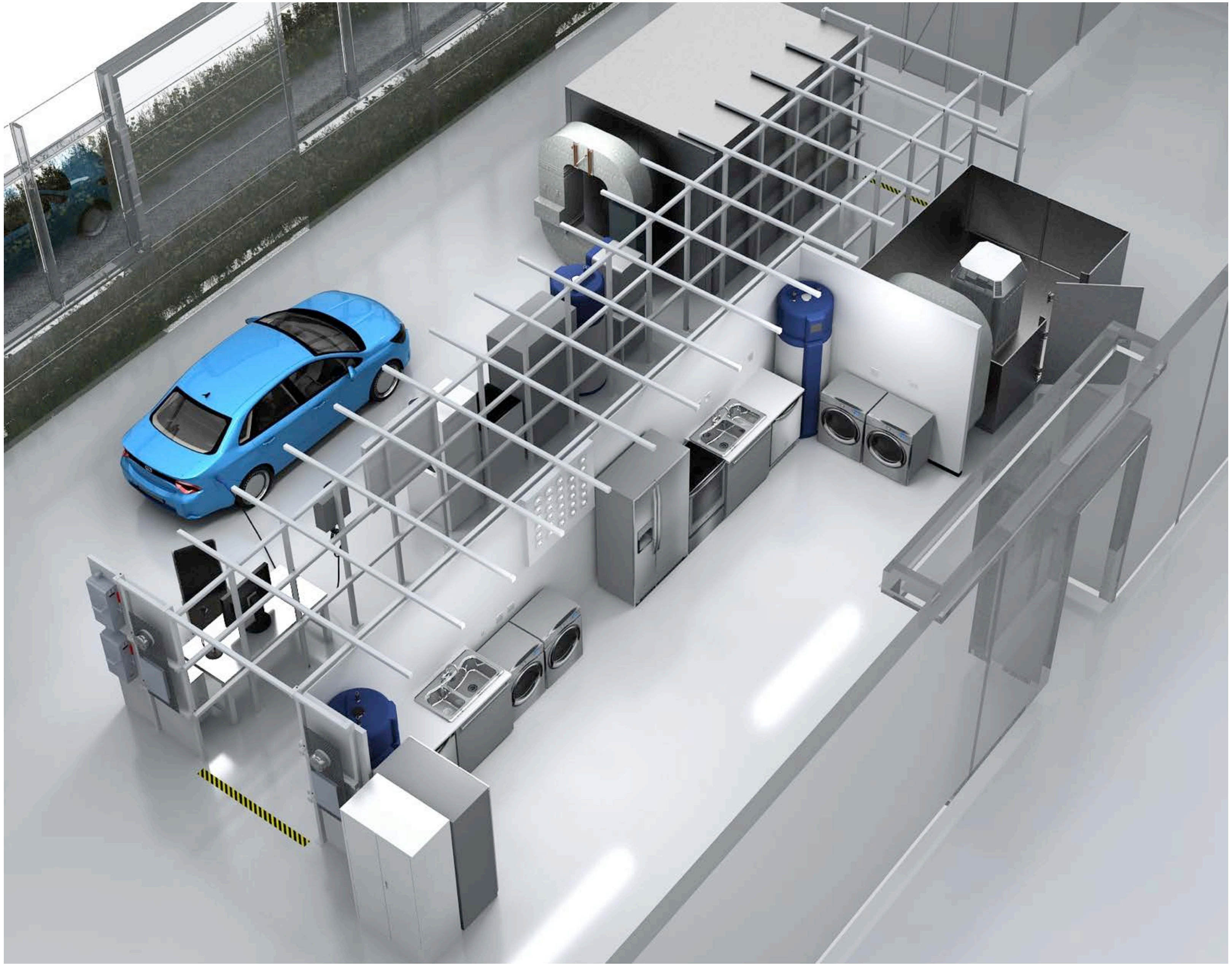
- Potential Impacts of a Highly Distributed Energy Environment project will evaluate the impact of both TOU and 2-way (export) rates
  - 2-way rates implemented in several states and under consideration in others
  - Combining residential batteries and EVs with rooftop solar under HEMS control
  - Funded by EERE's Strategic Priorities and Impact Analysis group
- Use Cases

Use case	PV	BESS	EV	Tariff	HEMS
TOU with high PV and low storage, no HEMS	25%	2%	0%	TOU	0%
TOU with high PV and low storage and HEMS	25%	2%	0%	TOU	20%
CPP with high PV and low storage, no HEMS	25%	2%	0%	2way	0%
CPP with high PV and low storage and HEMS	25%	2%	0%	2way	20%
TOU with high PV and high storage, no HEMS	25%	10%	10%	TOU	0%
TOU with high PV and high storage and HEMS	25%	10%	10%	TOU	20%
CPP with high PV and high storage, no HEMS	25%	10%	10%	2way	0%
CPP with high PV and high storage and HEMS	25%	10%	10%	2way	20%

Smart Home HIL Test Bed

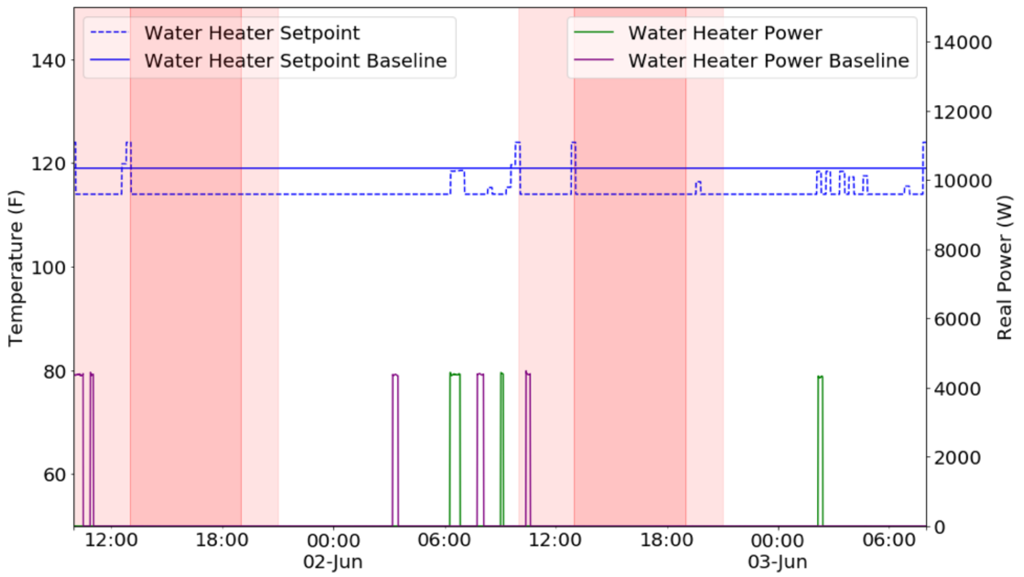
- Extended IESM co-simulation platform to include actual appliances through power HIL
- This will accelerate and reduce cost of testing by combining large-scale software simulation with hardware evaluation of a small set of representative systems

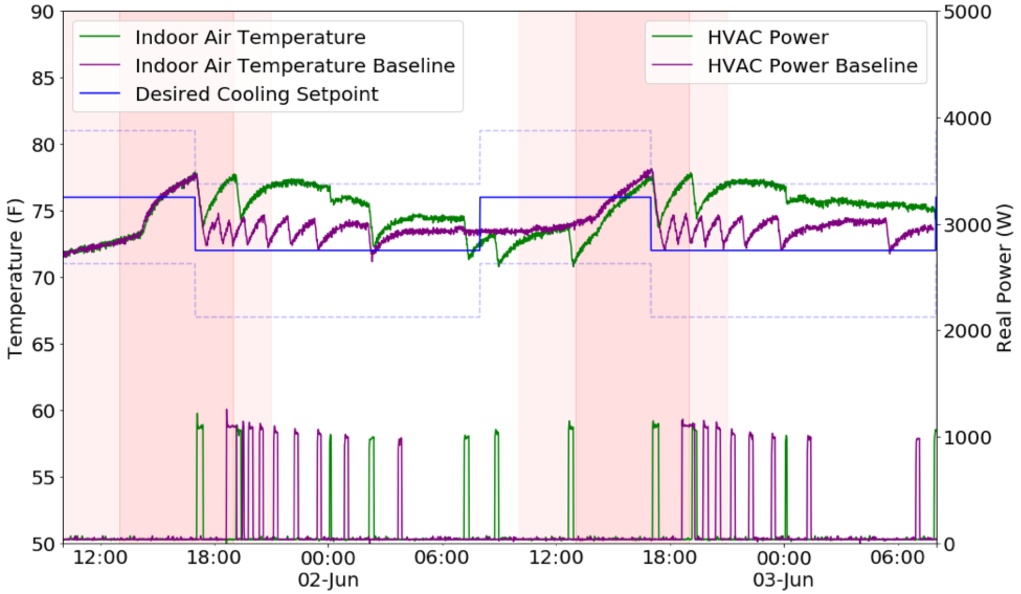


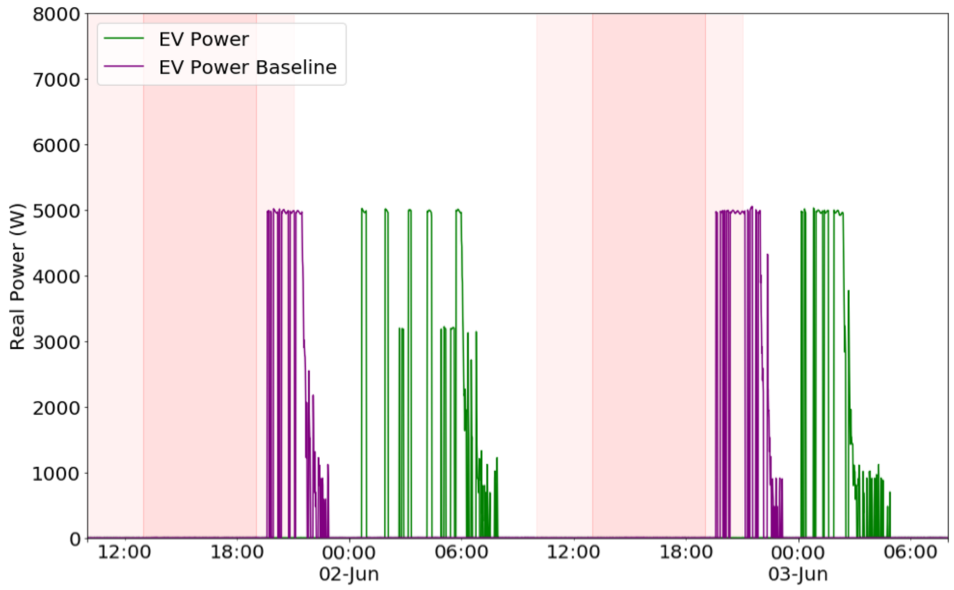


Smart Home HIL Test Bed Results

- Simulation:
  - 13 node IEEE test feeder with 20 homes
  - Time-of-Use rate
  - Air conditioner, water heater and EV under HEMS control







Further reading

Studies:

- A. Pratt, D. Krishnamurthy, M. Ruth, M. Lunacek and P. Vaynshenk, “Transactive Home Energy Management and Distribution Grid Impact,” *IEEE Electrification Magazine* special issue on Smart Buildings and Transactive Energy, Dec 2016.
- M. Ruth, A. Pratt, M. Lunacek, S. Mittal, W. Jones, and H. Wu (2015). “Effects of Home Energy Management Systems on Distribution Utilities and Feeders Under Various Market Structures,” 23rd International Conference on Electricity Distribution (CIRED), June.


By Annabelle Pratt, Dheepak Krishnamurthy, Mark Ruth, Hongyu Wu, Monte Lunacek, and Paul Vaynshenk

Transactive Home Energy Management Systems

The impact of their proliferation on the electric grid.

IESM:

- S. Mittal, M. Ruth, A. Pratt, M. Lunacek, D. Krishnamurthy, and W. Jones (2015). “A System-of-Systems Approach for Integrating Energy Modeling and Simulation,” Summer Computer Simulation Conference, Chicago, IL, July 26-29.

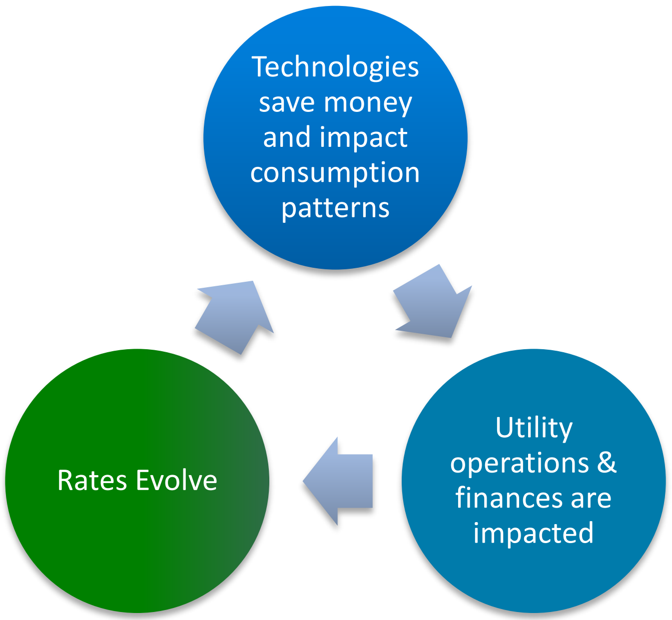
Smart Home HIL:

- A. Pratt, M. Ruth, D. Krishnamurthy, B. Sparn, et al., “Hardware-in-the-Loop Simulation of a Distribution System with Air Conditioners under Model Predictive Control,” *IEEE PES General Meeting*, July 2017.
- B. Sparn, D. Krishnamurthy, A. Pratt, M. Ruth and H. Wu, “Hardware-in-the-Loop (HIL) Simulations for Smart Grid Impact Studies,” to be presented at *IEEE PES General Meeting*, August 2018.

Smart Grid Evaluation – Technology and Market Impacts

CORE EXPERTISE

- Co-simulation and performance analysis of power systems, buildings and controllers under different rate structures
- Optimization of building (residential/commercial) operations based on Model Predictive Control (MPC)
- Hardware-in-the-loop (HIL) simulation



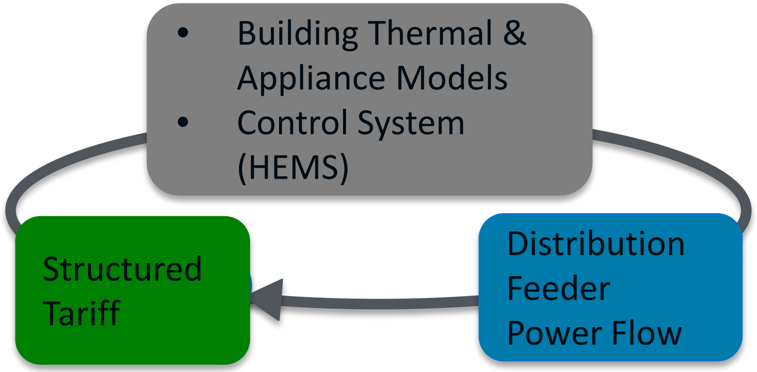
KEY APPLICATIONS:

System evaluation, including power system, buildings and appliances interacting with control systems in the presence of different tariff structures

NREL developed a co-simulation platform (the IESM) to support smart grid evaluations under an LDRD and is applying that to studies of different control and market structures.

NREL developed Home Energy Management System (HEMS) algorithms under an LDRD and is developing an optimal dispatch controller for fuel cell-integrated commercial buildings funded by DOE's Fuel Cell Technology Office (FCTO)

NREL extended the IESM under an LDRD to include actual residential appliances through power HIL (PHIL), creating an HIL test bed for smart homes.



Thank You!!

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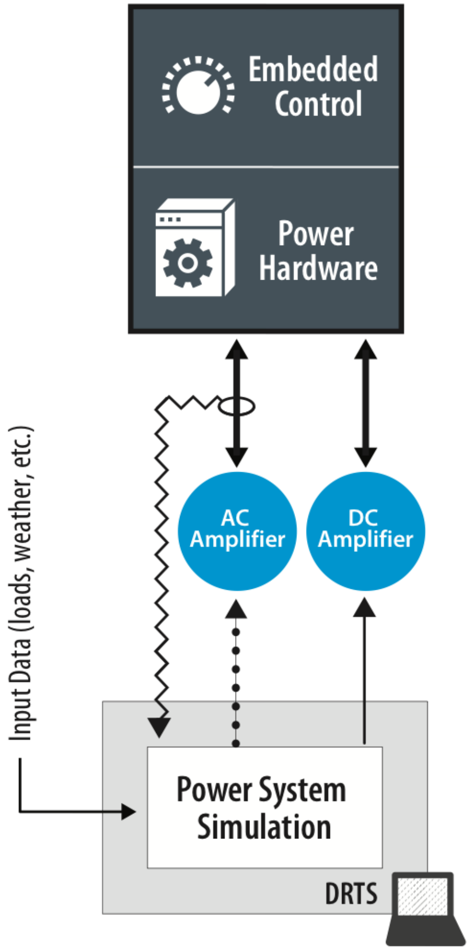
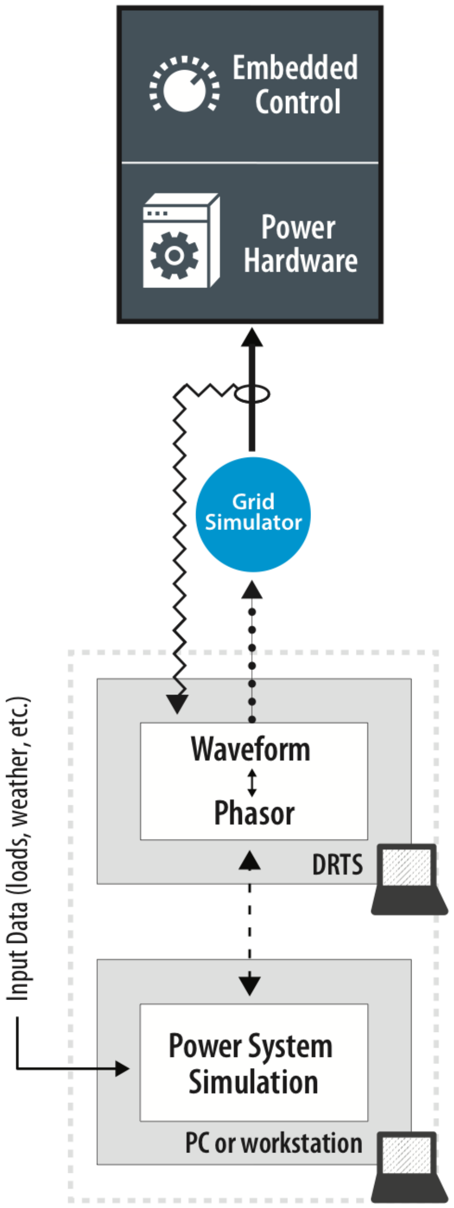
Setting up the Smart Home Hardware-in-the-Loop Test Bed

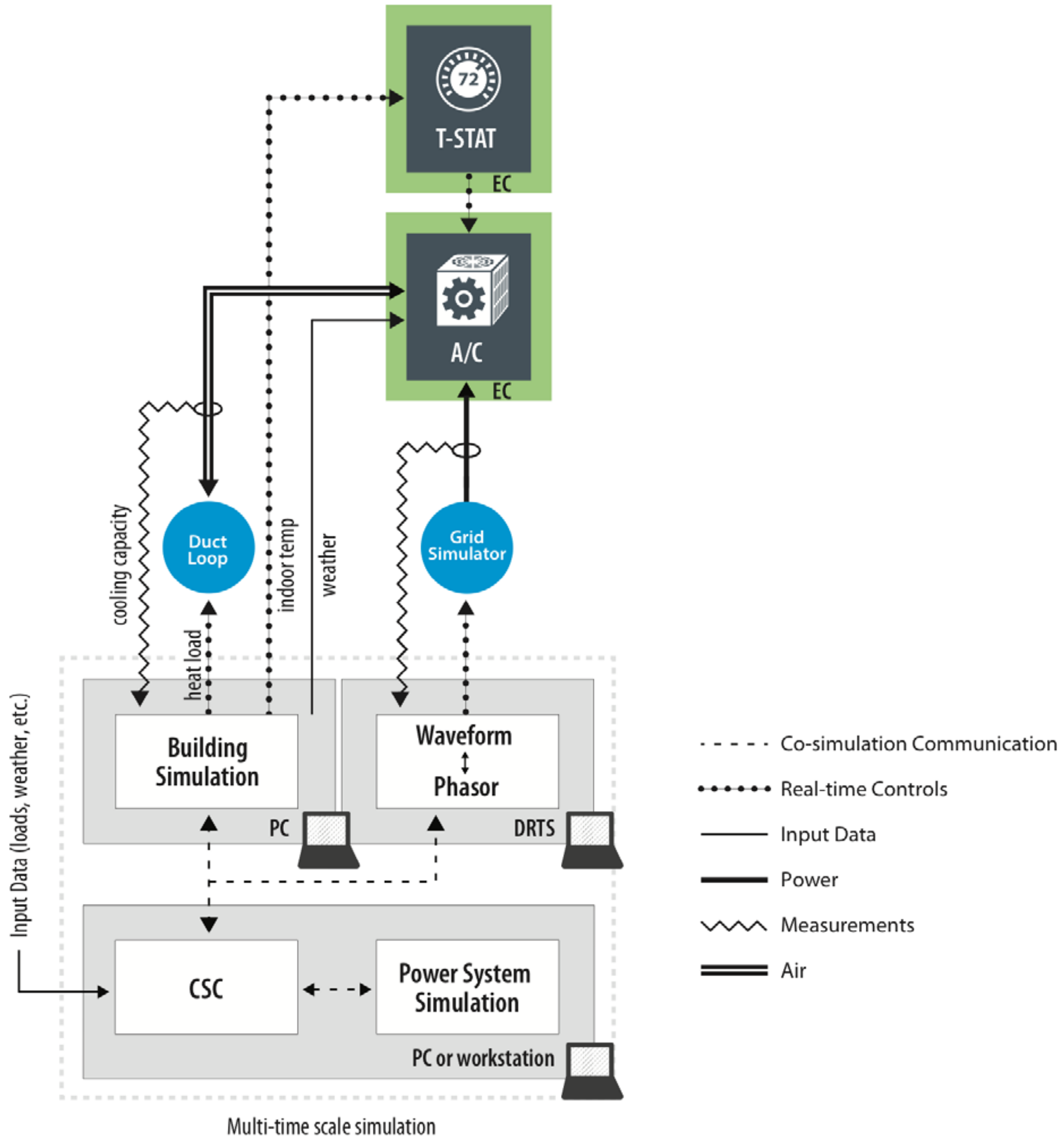
- Builds on prior power HIL and PHIL co-simulation experience
- Photovoltaic (PV) inverter, electric vehicle supply equipment (EVSE), water heater, stove, fridge, washing machine, etc.





Power and Thermal Hardware-in-the-Loop

- Air conditioner (HVAC)
  - Thermostat separate local control
- Building simulation (EnergyPlus)
- Co-simulation coordinator (CSC)
  - feeder
  - building simulation



Smart Home Hardware-in-the-Loop