GMLC RDS Program Review 1.5.4 - Integration of Responsive Residential Loads into Distribution Management Systems

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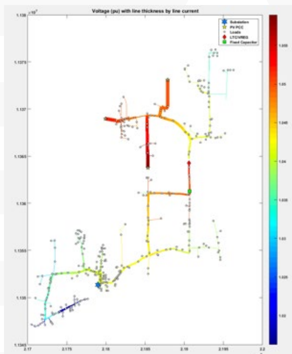
Project Outline

- Introduction to Project
- Utility-level Development
- Building-level Development
- Deployment

Project Outline

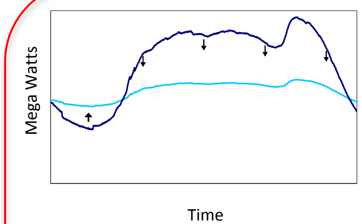
- Introduction to Project
  - *Goal/Concept*
  - *Targeted Challenges*
  - *Scope*
  - *Approach*
  - *Timeline*
- Utility-level Development
- Buildings-Level Development
- Deployment

Goal: Improve Resilience – Engaging Building Loads/DERs

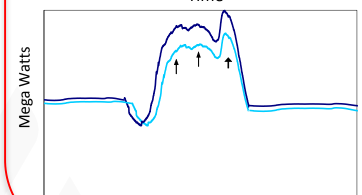


Distribution Reconfiguration

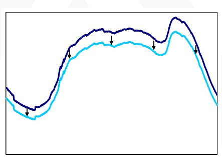
Coordinate Large Number of Building Loads



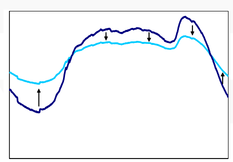
Reduce Energy Intensity and Increase Energy Efficiency



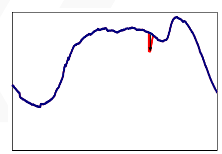
Increase Load Flexibility and Improve Grid Resiliency



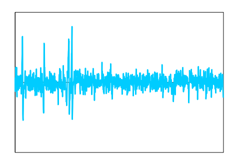
Capacity



Load Shaping



Reliability



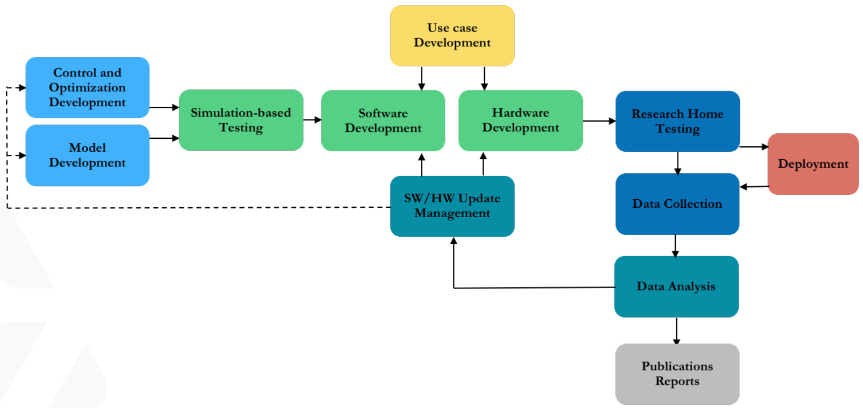
Regulation

Integration of Responsive Residential Loads into Distribution Management Systems

End-to-end system for engaging residential DERs to provide grid resilience services

Project Objectives

- ✓ Develop interoperable home energy management system (HEMS) as an interface to distribution-level integration of Residential loads and DERs to provide distribution resiliency services
- ✓ Develop transactive control system to co-optimize Loads/DER performance to satisfy grid requirements and residential needs
- ✓ Deploy and validate the technology in field with utility partners



Value Proposition

- ✓ Increasing number of smart residential-level assets including controllable loads, rooftop solar, and storage technologies imposing new challenges in distribution operations
- ✓ These assets can be leveraged for enabling resilient rapid reconfiguration of the distribution circuits by managing demand, voltage, and power flows
- ✓ An end-to-end solution establishing interoperability across the meter and coordinated control technology is needed to engage residential loads for grid services
- ✓ The end-to-end system performance and resilience has to be validated in field for adoption

Modeling, Simulation, Controls, Software

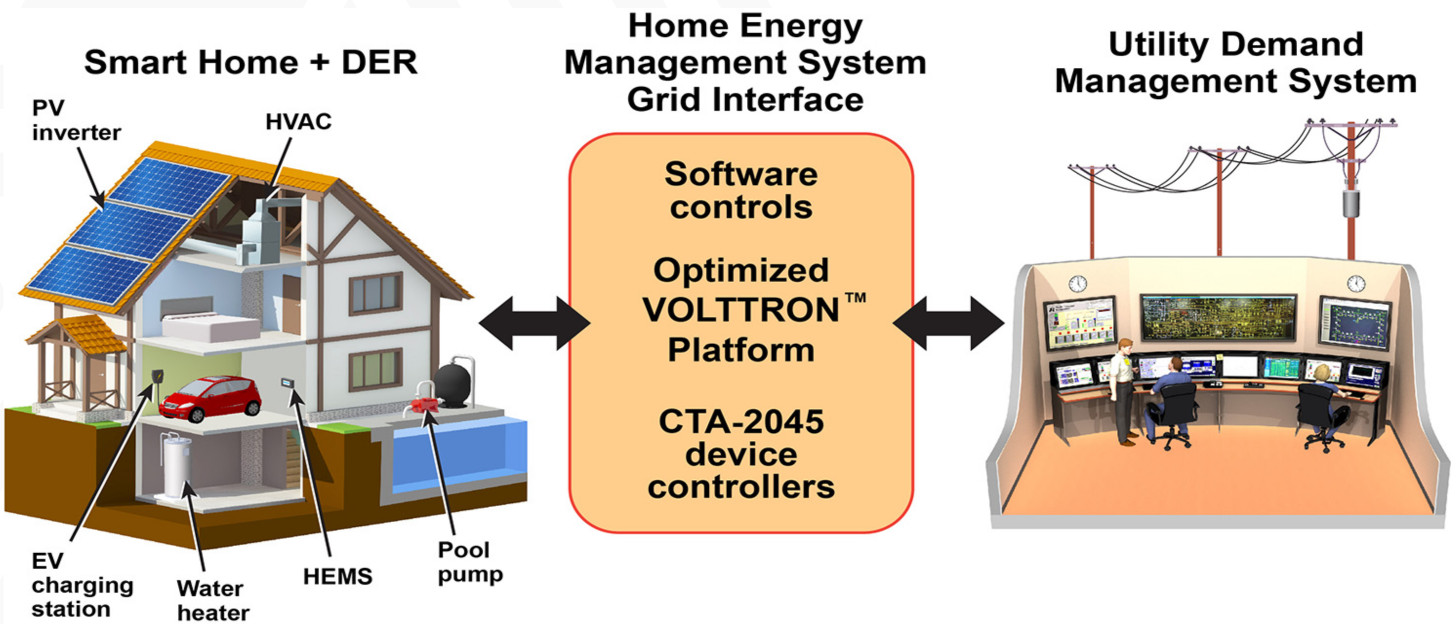
M&V, Software, Analytics

Hardware, Analytics, Deployment

Requirement Definition, Deployment

Project Overview

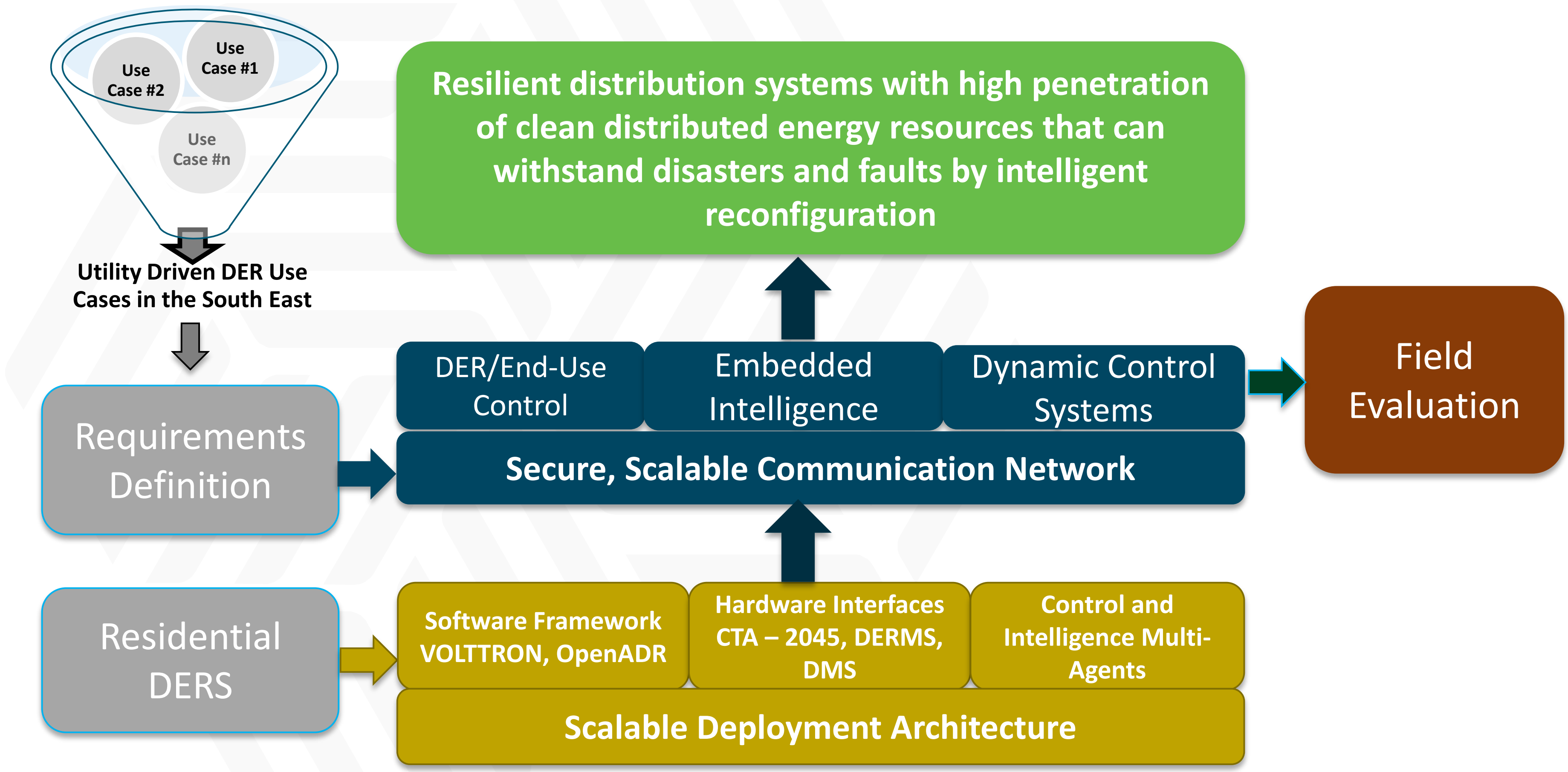
Resilient distribution systems with high penetration of distributed energy resources (DERs) that can withstand disasters and faults by intelligent reconfiguration



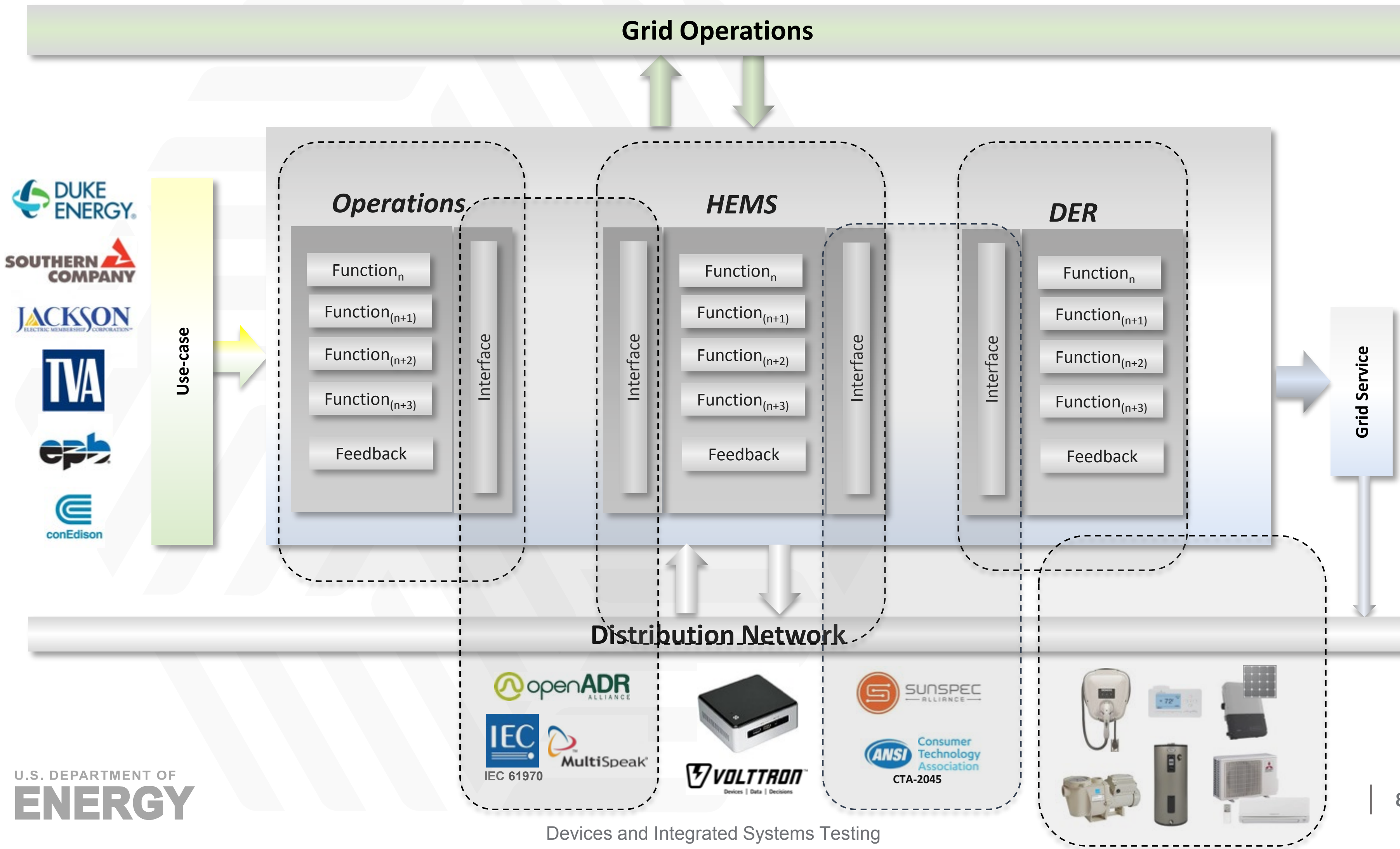
Develop end-to-end interoperable software and hardware system for engaging residential responsive loads and DERs to provide grid services

Final Product

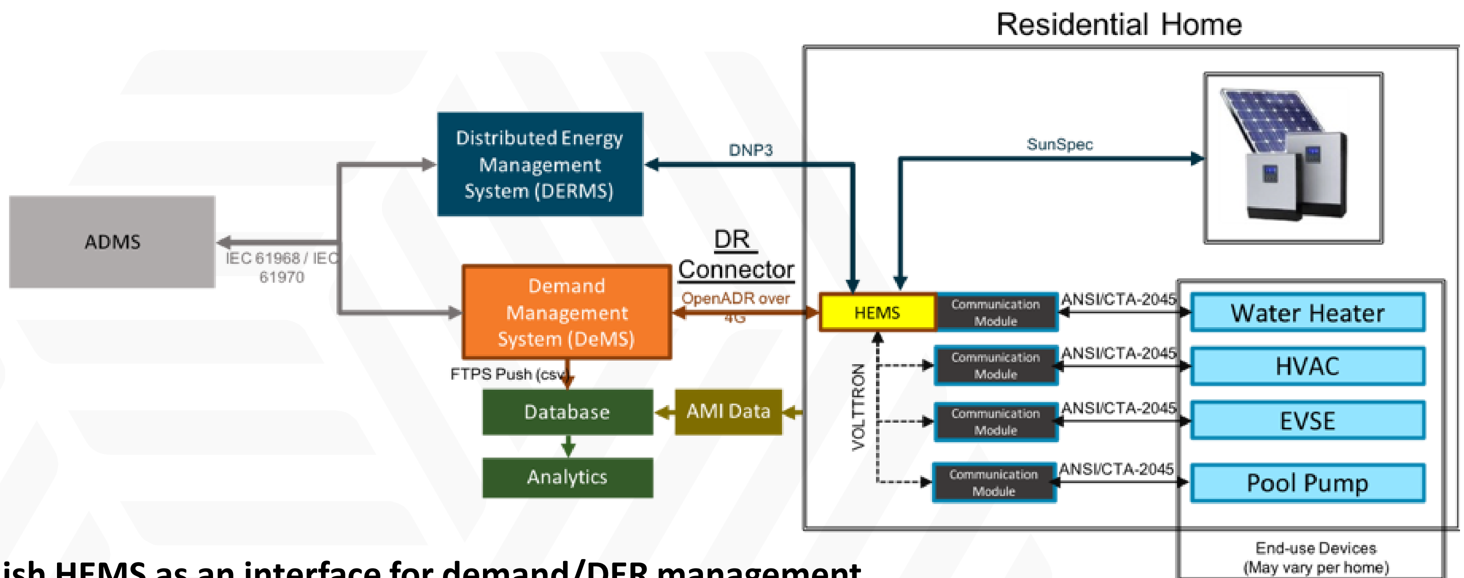
Develop end-to-end system for engaging residential DERs to provide grid services



Addressing the Challenge



Key Outcomes

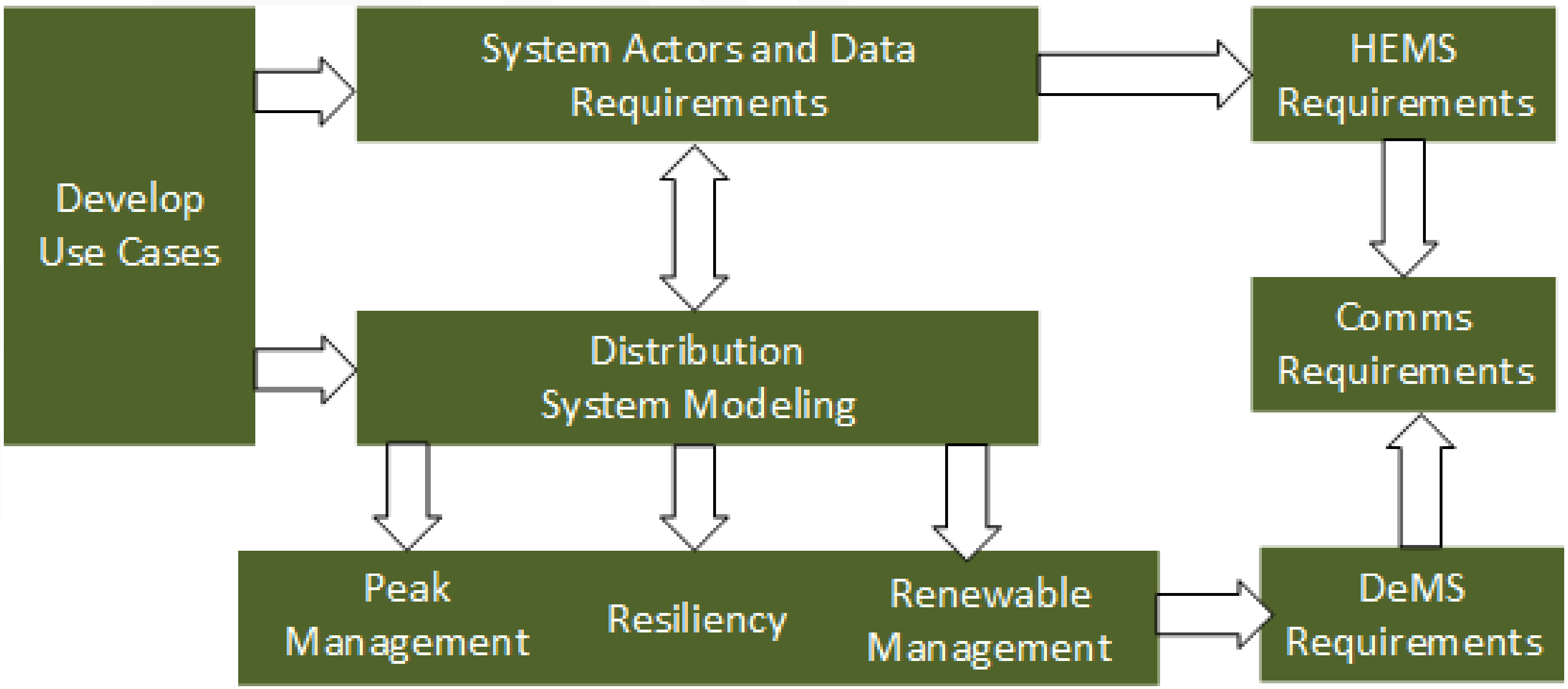


- **Establish HEMS as an interface for demand/DER management**
  - Interoperable interface with DeMS – reliably support data exchange
  - Engage residential loads – control execution and feedback to operations
- **Improve distribution-level grid resilience**
  - Field validation to demonstrate the SW, HW, and Algorithms demonstrate response in time and magnitude
  - Demonstrate this capability to be expandable to multiple deployment architectures
- **Open Source Systems (Reduces Challenges with Deployment and Continued Utility Use)**
  - Leverage Opens Source Execution Platforms, Solvers, and Algorithms
  - Deliver standards base reference specification for HEMS to Utilities

Project Timeline

Year 1	Year 1/Year 2	Year 3
Requirement Definition	**Technology Development**	**Field Evaluation**
Use Case Development	Edge Intelligence	Deployment & Testing
Software Specification	Load Control System	Evaluation Scenarios
Hardware Specification	Software Platform	
	Hardware Platform Interface to Load	

Overall Approach



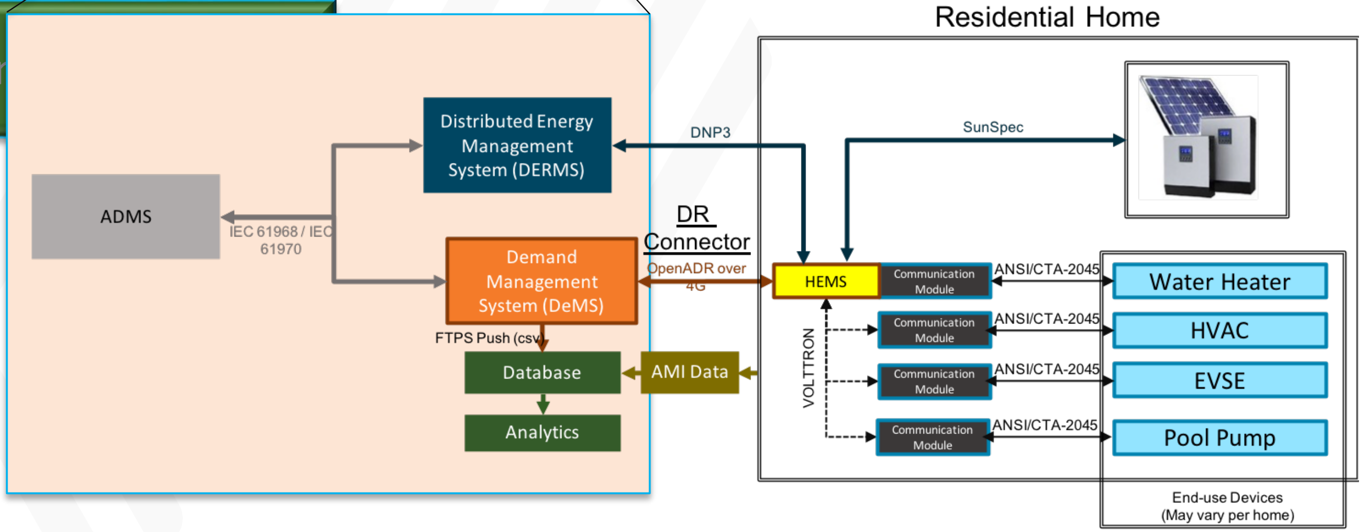
Project Outline

Introduction to Project

Utility-level Development

Building-level Development

Deployment



Use Cases Developed

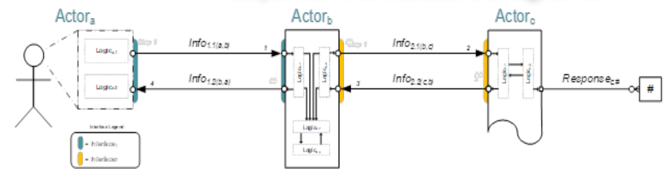
UC #1	• Reduce Critical Peak Load
UC #2	• Improve Disaster Preparedness through Real-time Situational Awareness and Distribution Operations Planning
UC #3	• High Penetration of Renewable Energy in Distribution Systems
UC #4	• Virtual networked microgrids in distribution circuits to enable resilience
UC #5	• Improves Asset Utilization through Locational Pricing
UC #6	• Reduce Outage and Recovery times through intelligent Cold Load Pickup
UC #7	• Residential-level islanding with Assets Sensing a Grid Event
UC #8	• Distribution Feeder-level Battery for Transmission Level Grid Service and Enabling Distribution Resilience
UC #9	• Inverter Control to Prevent Power Generation Curtailment due to Control of Distribution-level Voltage Control Assets (e.g. capacitor banks)
UC #10	• Adaptive control of DERs on a Distribution Radial Line to Stabilize Voltage Sag across a Line
UC #11	• Power flow and Congestion Management
UC #12	• Load Control to Support Frequency Regulation

Method of Design - Systems to Enable Behind-the-Meter Grid Services

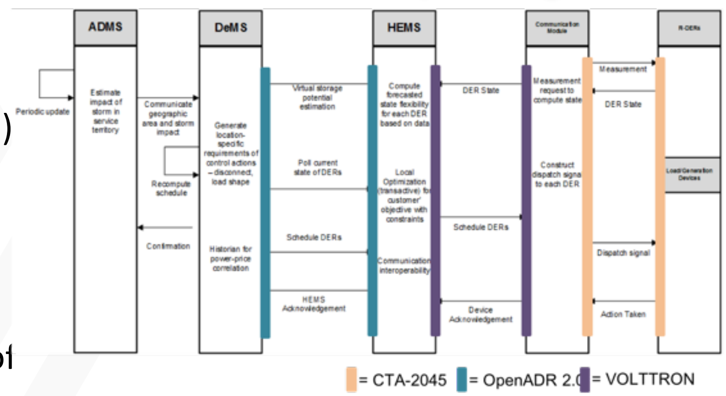
Use case and System Architecture Development

- **Design Templates**
  - Stakeholder Questionnaire
  - Use-case Narrative
  - Actor Specifications
    - Information Exchange and Communication Interfaces
- **Graphical Representations**
  - Layered architectural diagrams (information exchange sequence)
- **Unified Documentation**
  - System Design Package
- **System Architecture**
  - End-to-end system architecture to support hierarchical control of demand side assets to provide unified response
  - Demand management system (DeMS) coordinates the communication with HEMS for transactive control using incentives to drive optimization
  - Local HEMS coordinates device response to grid service request while maintaining customer constraints
  - Interoperability and cybersecurity driven by requirement definition

Layered Architecture Diagrams



Use case Sequence Diagrams

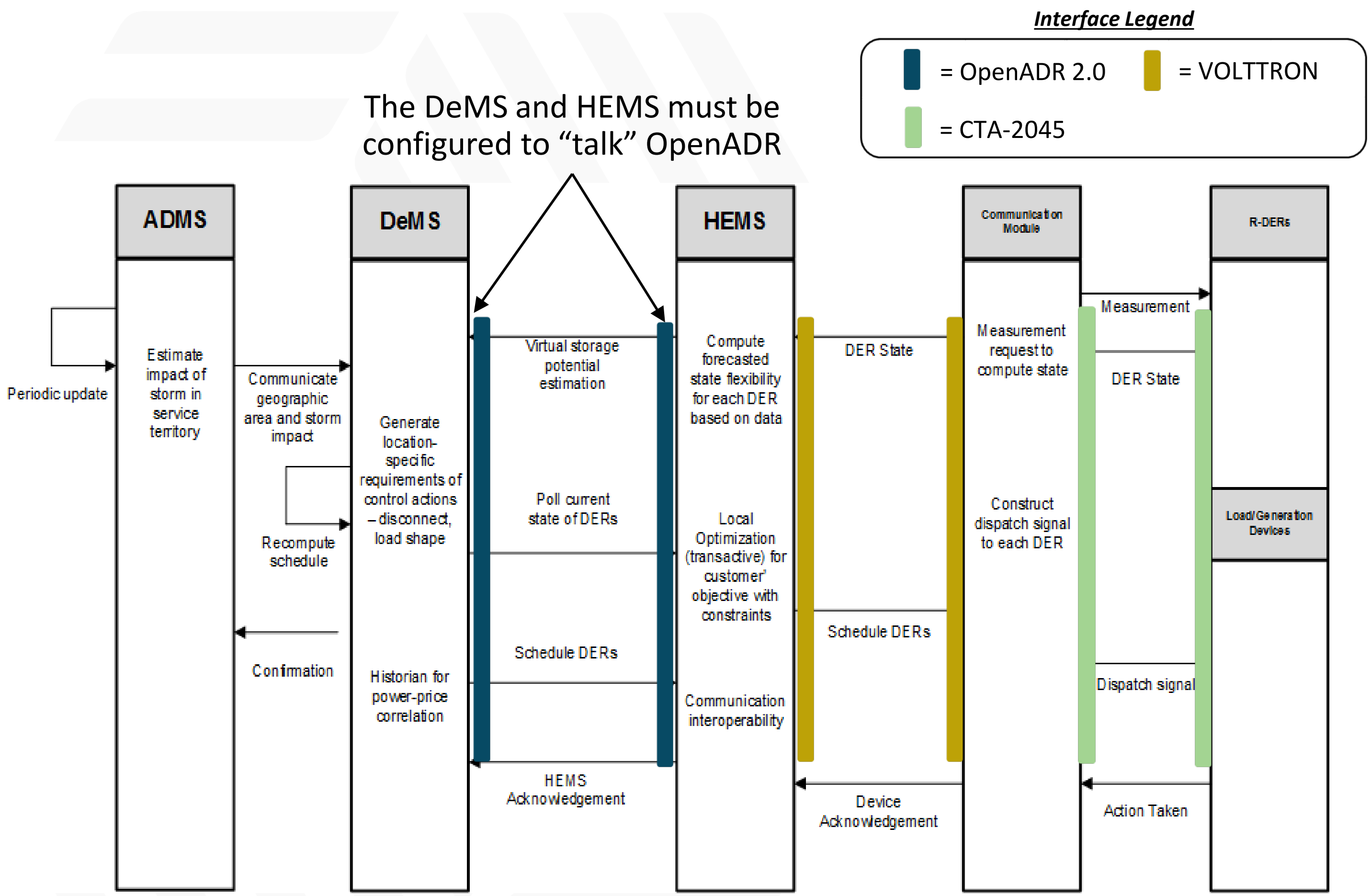


System Design Package

SYSTEM DESIGN DOCUMENTS

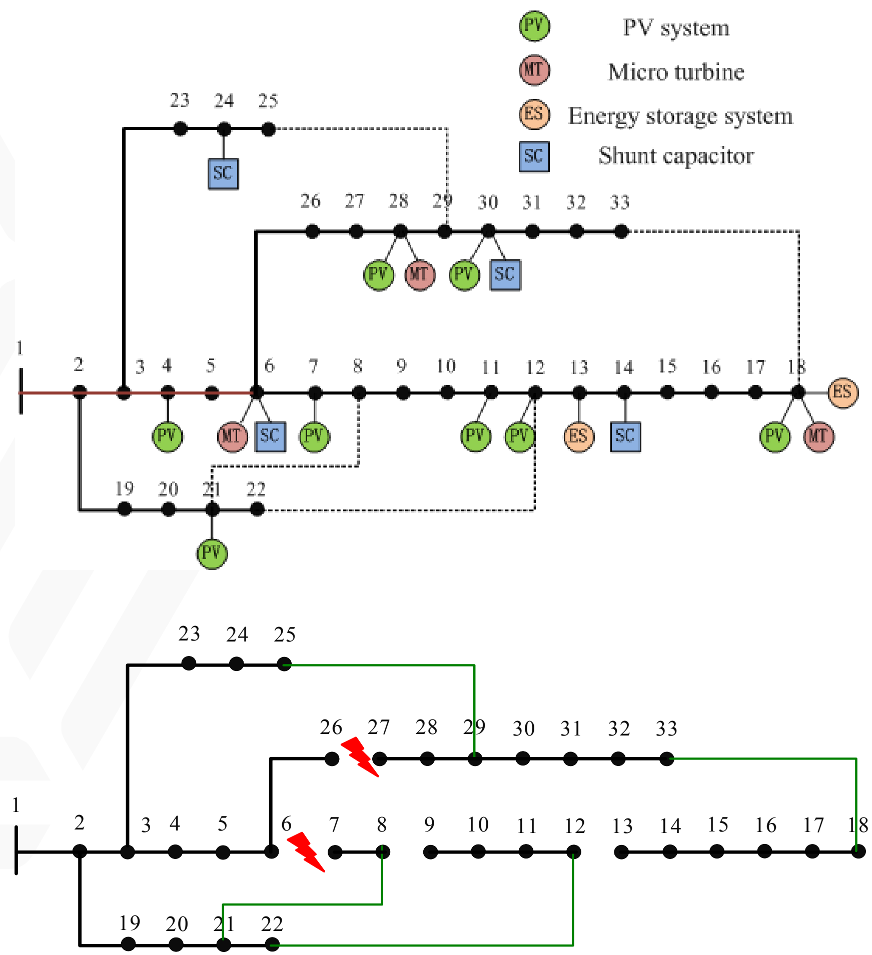
Interface Requirements

(Use Case #2 from "Use Case and Logical Architecture Development" Document)

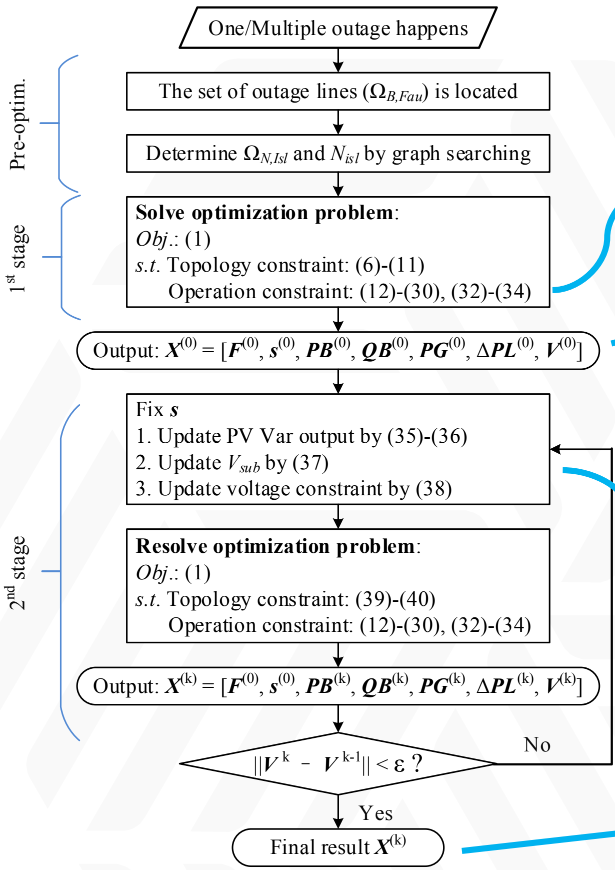


Distribution Reconfiguration

- Optimize system configuration for most resilient distribution system setup considering availability of load flexibility and local generation.
- Optimization approach considers the need to keep a tree structure (in other words radial system).
- Make use of advanced features of reactive power control by generation systems (or potentially HEMS level assets)



Two-stage Optimization Procedure



https://projects.coin-or.org/Cbc

$$V_{sub,t} = 1.02$$

$$-M\left(1-s_{ij}\right)+\frac{r_{ij}P_{ij}+x_{ij}Q_{ij}}{V_0} \le V_i - V_j \le M\left(1-s_{ij}\right)+\frac{r_{ij}P_{ij}+x_{ij}Q_{ij}}{V_0}$$

MILP: Obtain topology and rough result of DER response, voltage profile

$$p_{j,t}^{PV} = \sqrt{\left(p_{j,t}^{PVmp}\right)^2 - \left(q_{j,t}^{PV}\right)^2}$$

$$V_{sub,t} = 0.99 + 0.005\left\lceil \frac{K_{TC}P_{sub,t}}{0.005} \right\rceil$$

$$-M\left(1-s_{ij}\right)+\frac{r_{ij}P_{ij,t}+x_{ij}Q_{ij,t}}{V_{j,t}^{(k-1)}} \le V_{i,t}^{(k)} - V_{j,t}^{(k)} \le M\left(1-s_{ij}\right)+\frac{r_{ij}P_{ij,t}+x_{ij}Q_{ij,t}}{V_{j,t}^{(k-1)}}$$

LP: Use the existing topology and obtain accurate result of DER response, voltage profile

Objective function:

Cost of DG + Economic loss of CL + Cost of IL reward payment

$$min. \sum_{t\in T}\Delta t\left(\sum_{j\in\Omega_G} c^G P_{j,t}^G + \sum_{j\in\Omega_{CL}} c^{CL} P_{j,t}^{CL} + \sum_{j\in\Omega_{IL}} c^{IL} P_{j,t}^{IL}\right)$$

Qingxin Shi, Fangxing Li, Mohammed M. Olama, Jin Dong, *Yaosuo Xue, Michael Starke, Cody Rooks, Wei Feng, Chris Winstead, Teja Kuruganti,* "Enhancing Distribution System Resilience by Linear Topological Constraints and Distributed Energy Resource Scheduling," manuscript submitted to IEEE Transactions on Smart Grid

Project Outline

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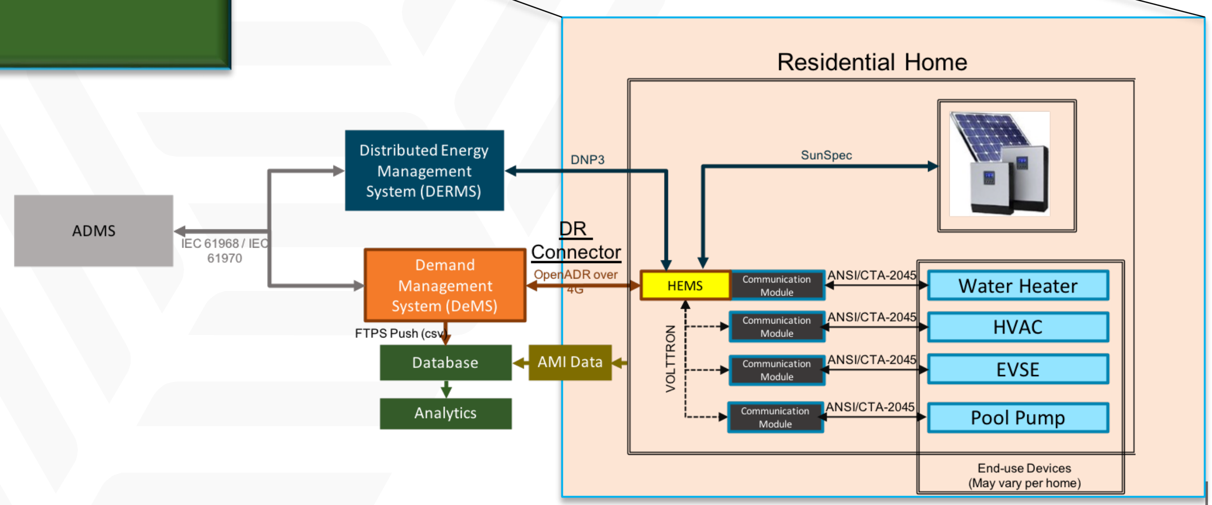
- Utility-level Development
- **Building-level Development**
- Deployment



Project Outline

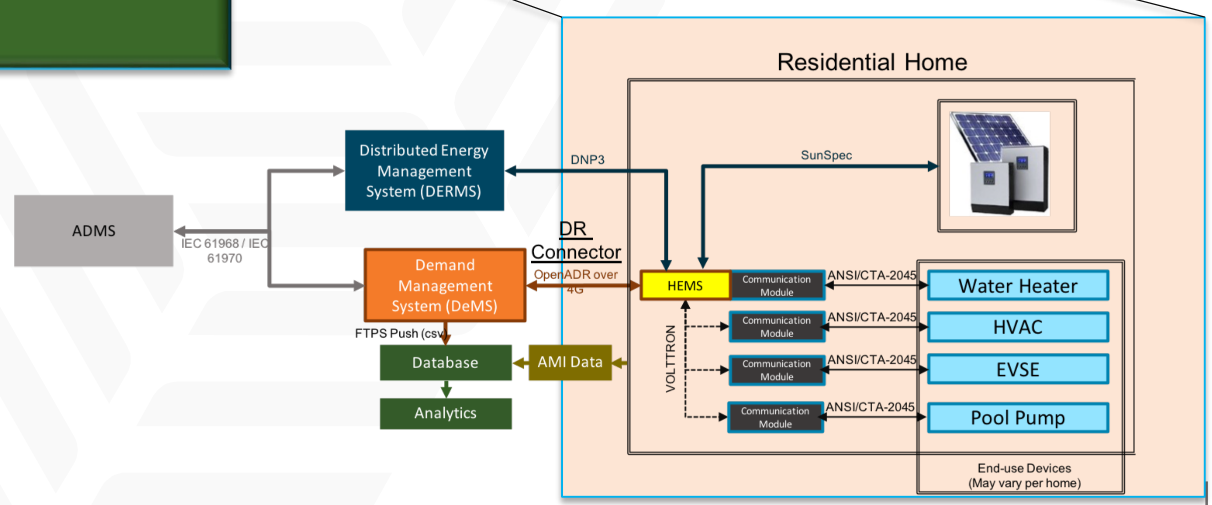
Introduction to Project

Utility-level Development

Building-level Development

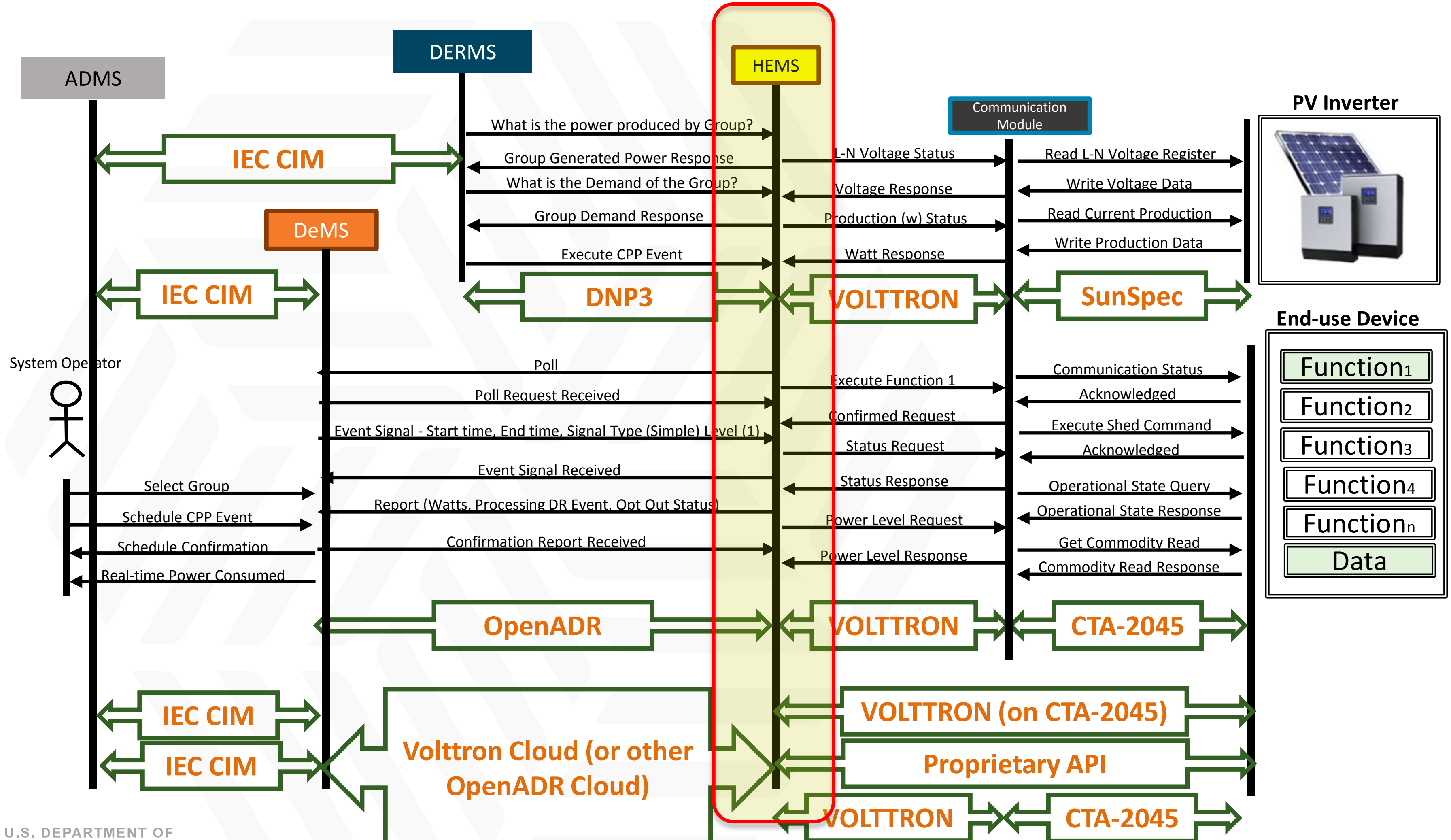
Deployment

General Approach

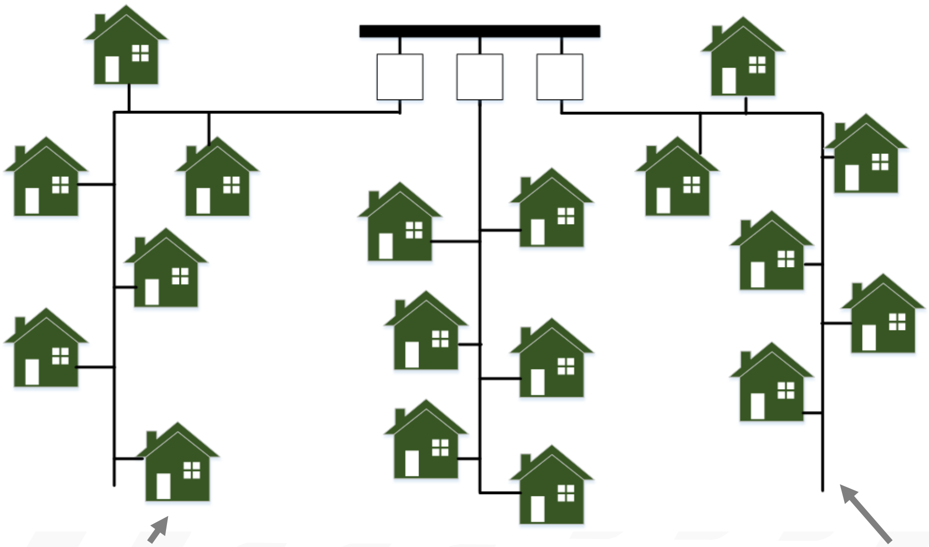


System Architecture - Detail

Enable wide-area responsive residential loads



Decision Making and Optimization



Resource Optimization

- Battery Model
- Non Controlled Load

Electrical Network Constraints

- Real and Reactive Calcs
- Voltage Limits

Goals: 1) Encapsulate Privacy!
2) Simplify data exchange
3) Provide Consistent Figures of Flexibility

DeMS Optimizer Output Considering Resources

Nodal:

- Target P/Q
- System Voltages

Signals

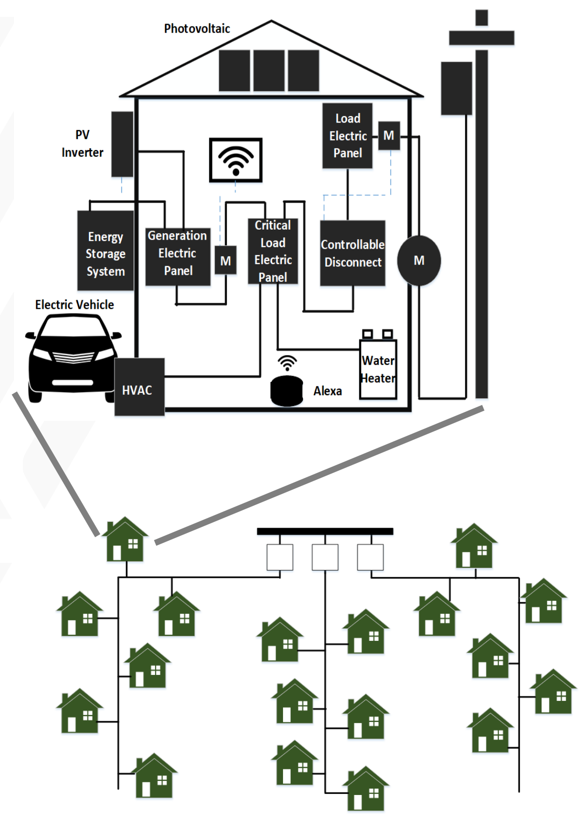
- Electricity Price Signal
- Maximum Power Signal
- Reference Control Signals
- Automatic System Responses

Control Overview

- Utilize Home Energy Management System (HEMS) to control building resources for widescale distribution system management.
- Utilize open communication standards: OpenADR / CTA for demonstration of widescale implementation.

Challenges:
- Aggregation of information to common framework for HEMS
- Limit resource optimization at highest level to reduce computational complexity

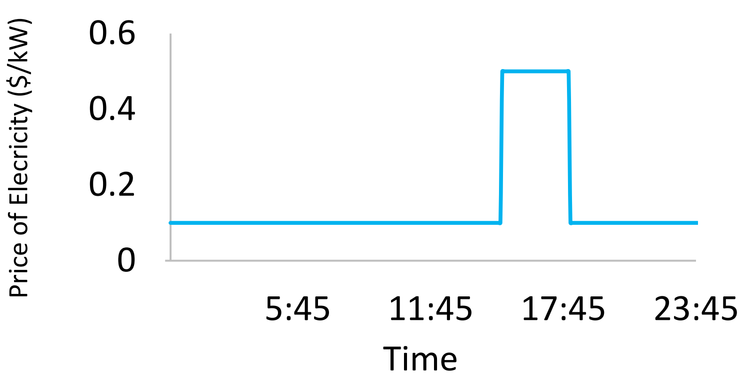
- Optimize resources to
  - Limit distribution voltage within tolerance
  - Limit peak conditions
  - Support Emergency Shedding
  - Enforce Emergency Islanding
- Appropriate Knobs for Control
  - Shift/Shed Load
  - Generating Real Power
  - Generating Reactive Power
  - Islanding

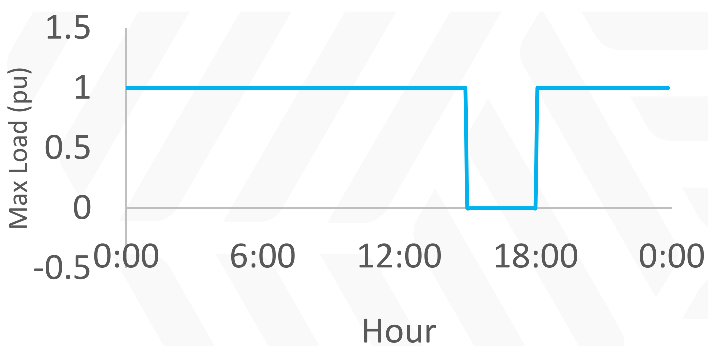


Output from Optimization and Control

TIME BASED OUTPUT REQUESTS

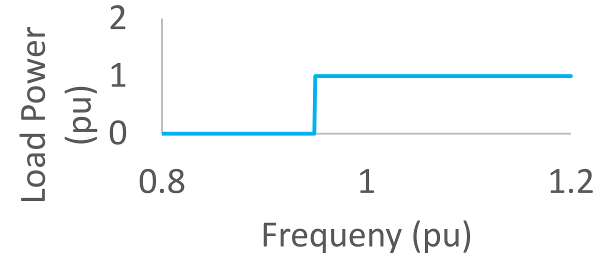
- Incentivize or restrict local control options.

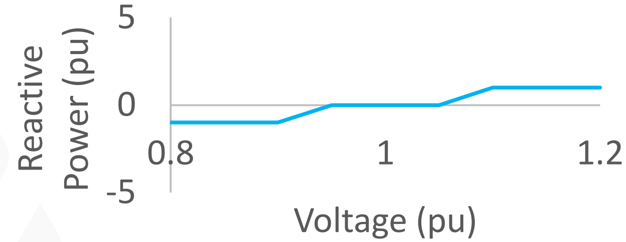


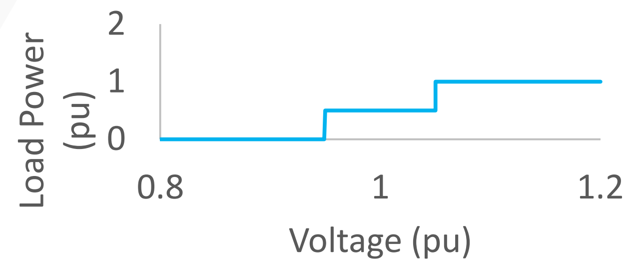


AUTONOMOUS RESPONSE

- Device performs automatic control based on local measurements -







Distributed Optimizer (General Formulation)

Objective Function:

$$\min(W_{PRICE}\sum P_t^{Grid}\varphi_t + W_{COMF}\sum HVAC_t^{SOC} + W_{COMF}\sum WH_t^{SOC} + W_{VIOL}\sum E_t^{SOC} + W_{VIOL}\sum EV_t^{SOC} + W_{VIOL}\sum Pump_t^{SOC})$$

Constraints **For nomenclature: negative is discharge, positive is charge

All Devices Follow Same Format (battery model formulation):

Real Charge: $P_{min}^{bc} b_t^{bpc} \le P_t^{bc} \le P_{max}^{bc} b_t^{bpc}$

Real Discharge: $P_{min}^{bd} b_t^{bpd} \le P_t^{bd} \le P_{max}^{bd} b_t^{bpd}$

Real Power Binary: $b_t^{bpc} + b_t^{bpd} \le 1$

Reactive Charge: $Q_{min}^{bc} b_t^{bqc} \le Q_t^{bc} \le Q_{max}^{bc} b_t^{bqc}$

Reactive Discharge: $Q_{min}^{bd} b_t^{bqd} \le Q_t^{bd} \le Q_{max}^{bd} b_t^{bdq}$

Reactive Power Binary: $b_t^{bqc} + b_t^{bqd} \le 1$

Battery Model: $SOC_{t+1}^b \ge SOC_t^b + \left(P_t^{bc}\eta - \frac{P_t^{bd}}{\eta} - P_t^{bloss}\right)\Delta t / E_t^b$

$X_t^{SOC} \ge SOC_t^x - SOC_t^{Max,x}$

$X_t^{SOC} \ge SOC_t^{Min,x} - SOC_t^x$

$X_t^{SOC} \ge 0$

**All devices should scale actual energy operation to 0 for minimum SOC and 100 for maximum SOC

Net Nodal: $P_t^{Grid} = \sum_{x=1}^{Devices}(P_t^{xbc} - P_t^{xbd})$ $Q_t^{Grid} = \sum_{x=1}^{Devices}(Q_t^{xbc} + Q_t^{xbd})$

Objective considering individual resources as part of the minimization! Leads to a large multi-objective problem

Whole-home as Energy Storage Equivalence

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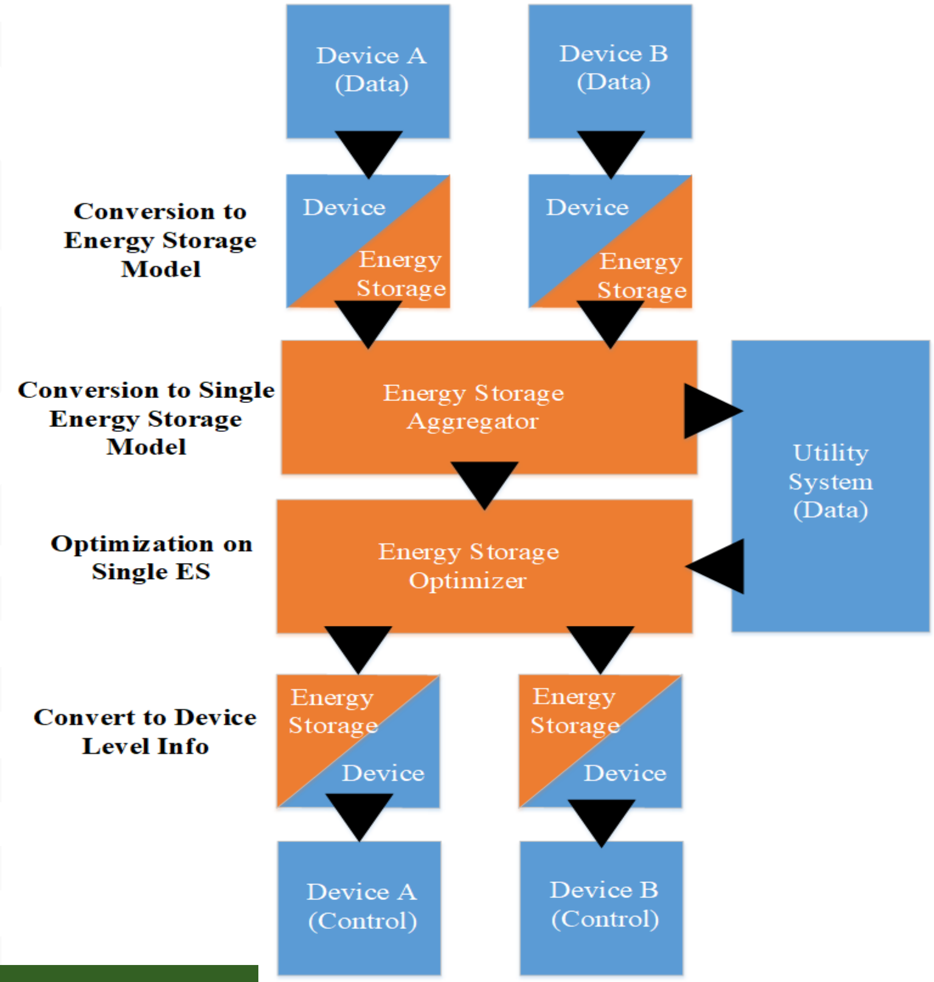
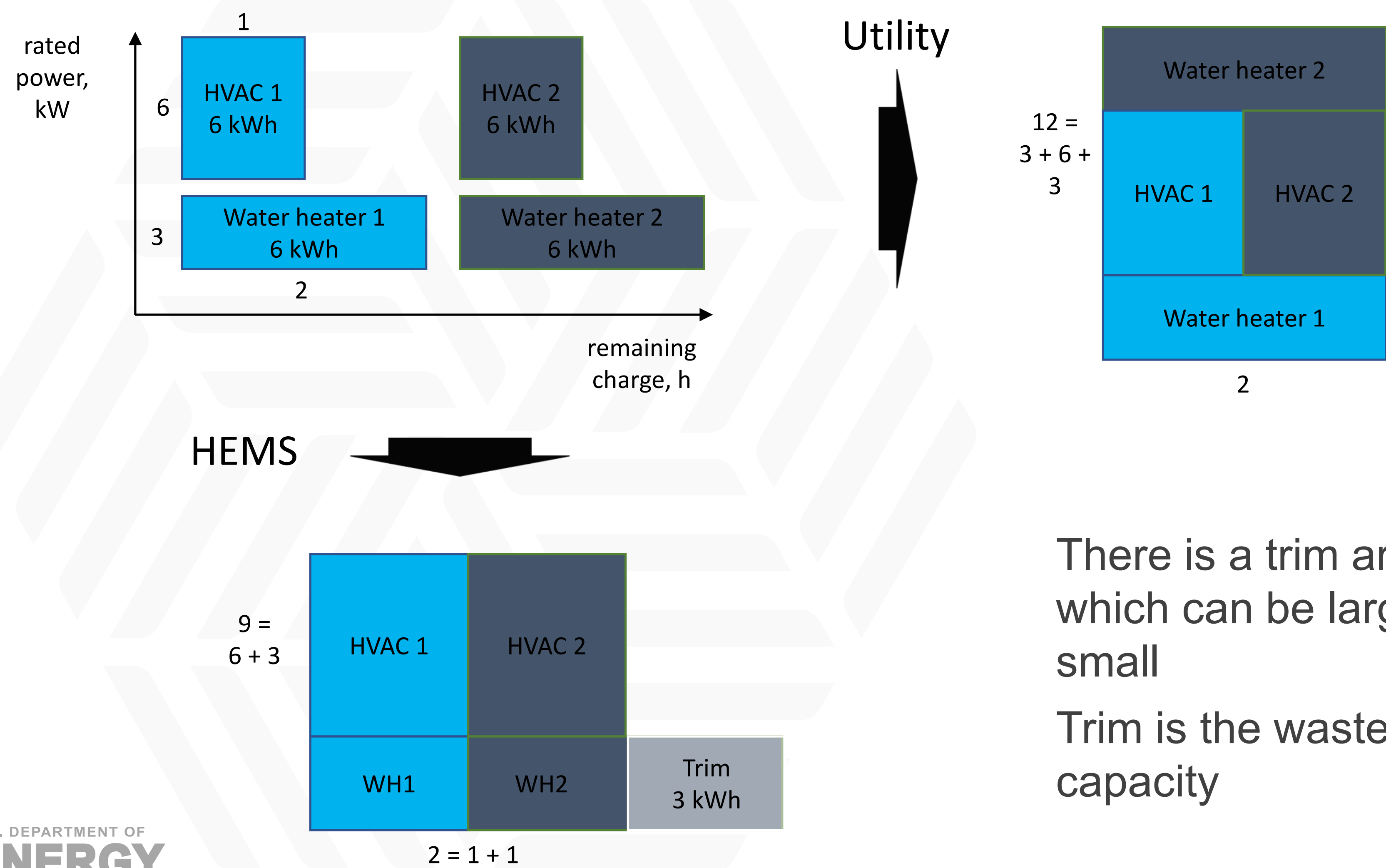
- Devices are converted to energy storage equivalent representation.
- Energy storage elements are aggregated to a single ES device
- Provided to utility for decision making (price estimation).
- Price curve is provided to HEMS for Optimization.
- Devices are separated and returned to original data orientation.



HEMs representing a whole home as an energy storage block.

However, by nature of the approach area of the sum <= the area of parts



There is a trim area which can be large or small

Trim is the wasted capacity

2d bin packing problem with partial sorting

Inputs	Pre-processing	Recursive join	Outputs
Rated power, kW	Initialize appliances	Place the rectangle in a specific position	Rated power of a home, kW
Remaining charge, h	Sort appliances	Find the total area	Remaining charge of a home, h

Minkowski sum has the capacity to handle the optimal aggregation

$$E_j = \sum_i P_i \, charge_i$$

s.t. $P_i = P_{rated\ i};\ charge_i \leq charge_{max\ i}$

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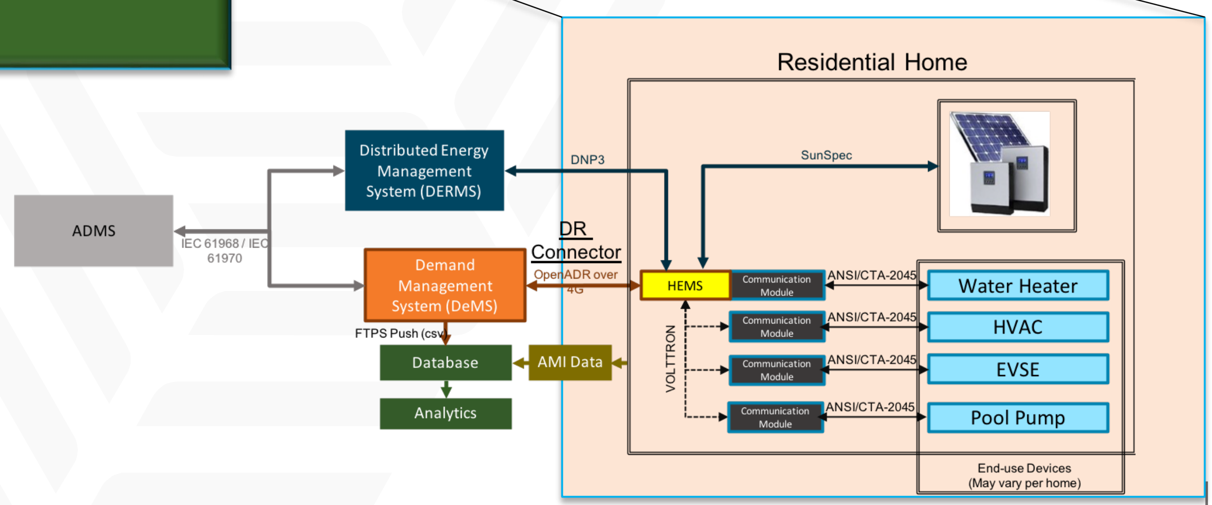

Software Architecture

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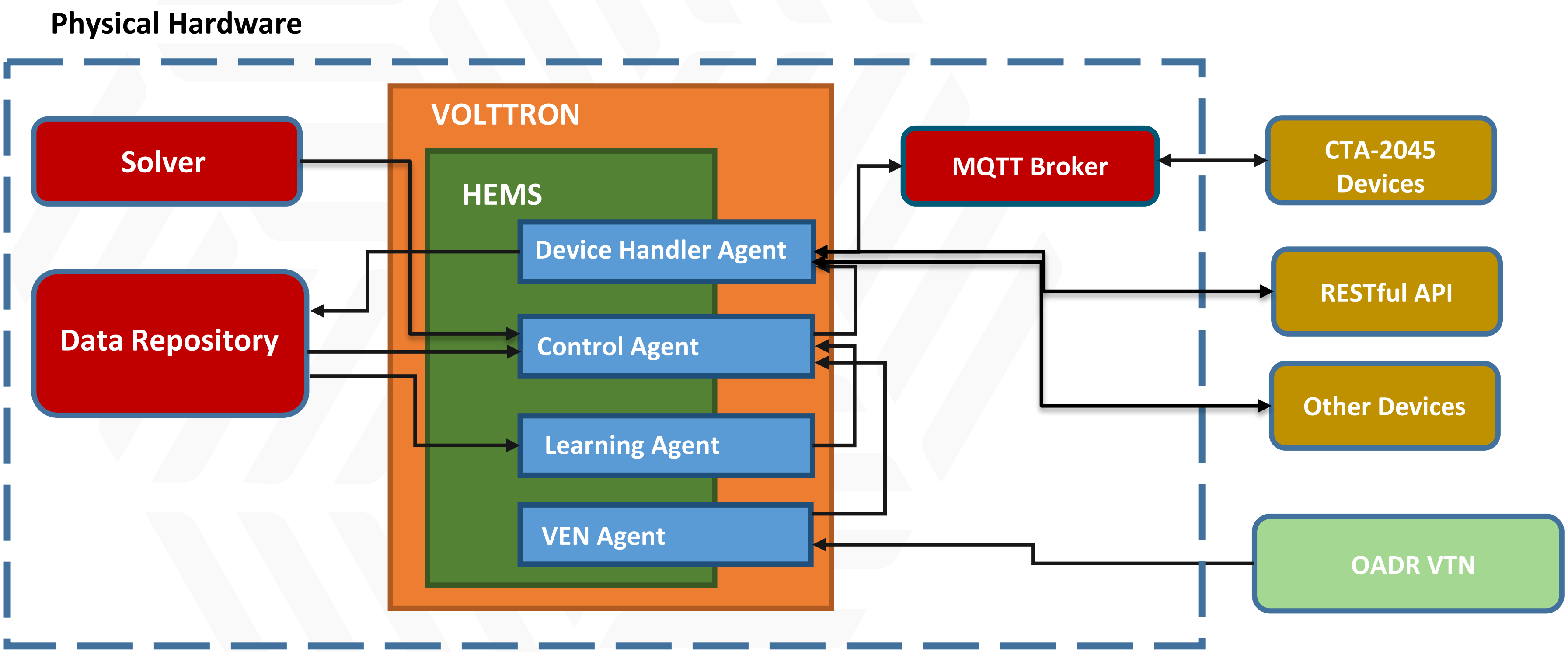
- HEMS is a Python application on the VOLTTRON platform
- Four Volttron agents each with area of responsibility
- 4 components hosted on the hardware: Data Repository, VOLTTRON, MQTT Broker, Solver



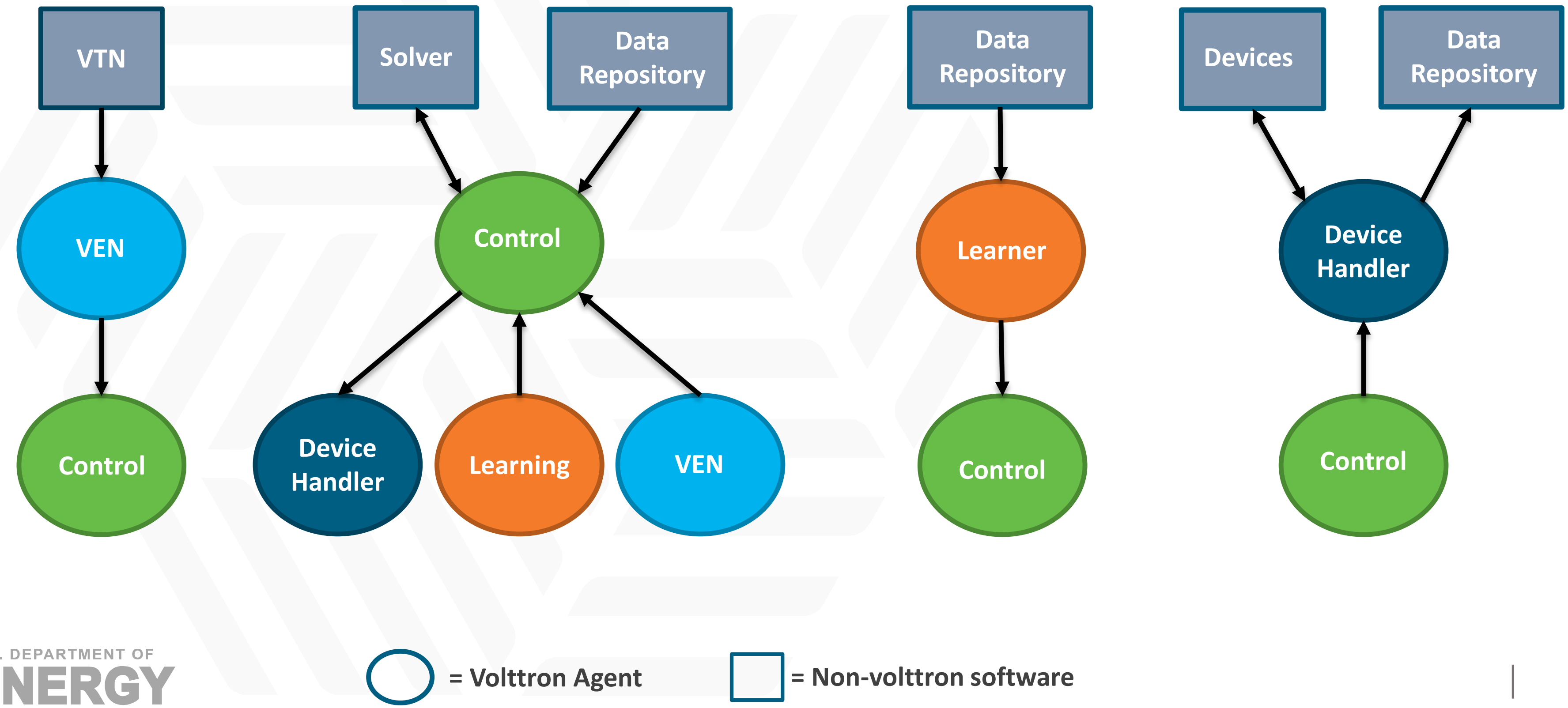
Agent Responsibilities

- Each Agent has a distinct lane of responsibility
- Communication between lanes facilitated by VOLTTRON communications

Talk to the outside world	VEN Agent
Learn the system under control	Learning Agent
Coordinate the optimization	Control Agent
Talk to the home devices	Device Handler Agent

Inter-Agent Communication

- Communication between agents occurs over message bus or through RPC calls between agents
- Communication with VTN is OADR
- Communication with home devices is CTA-2045 or RESTful API



Asynchronous Operation

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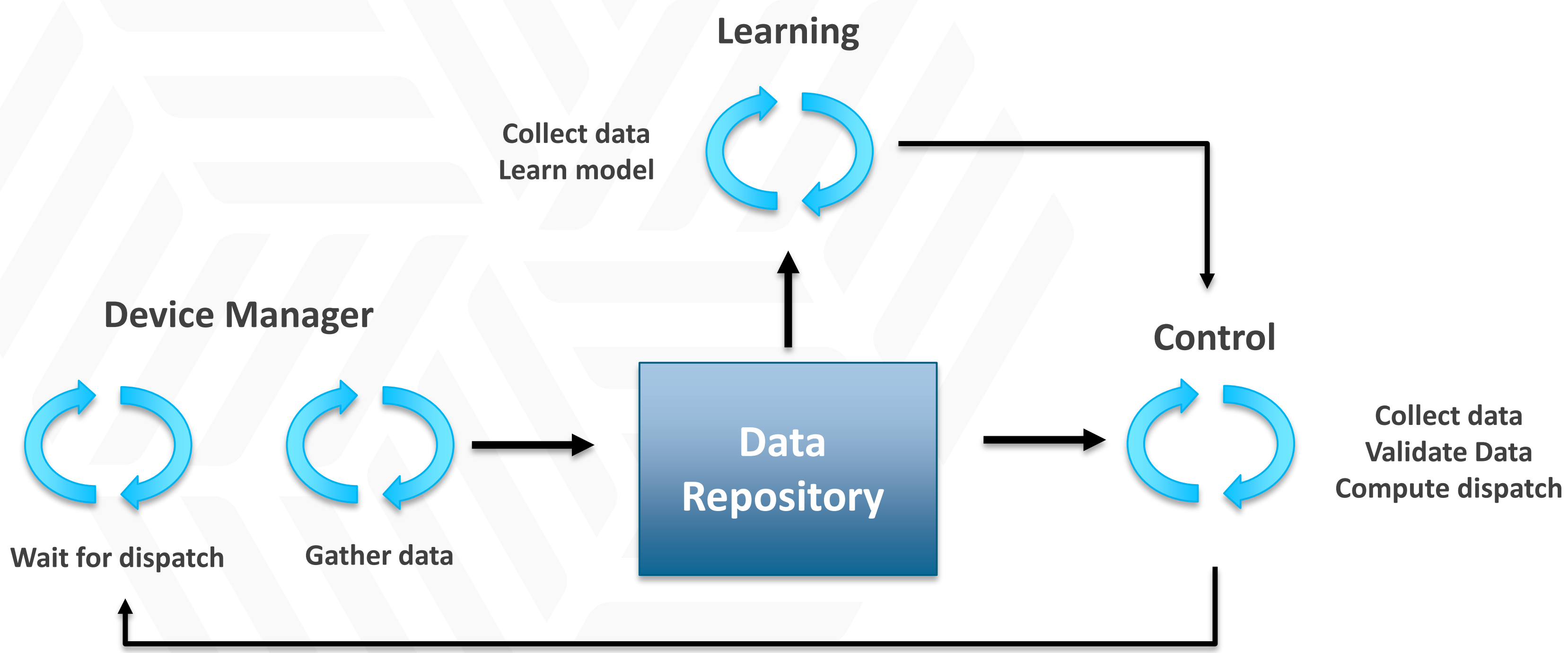
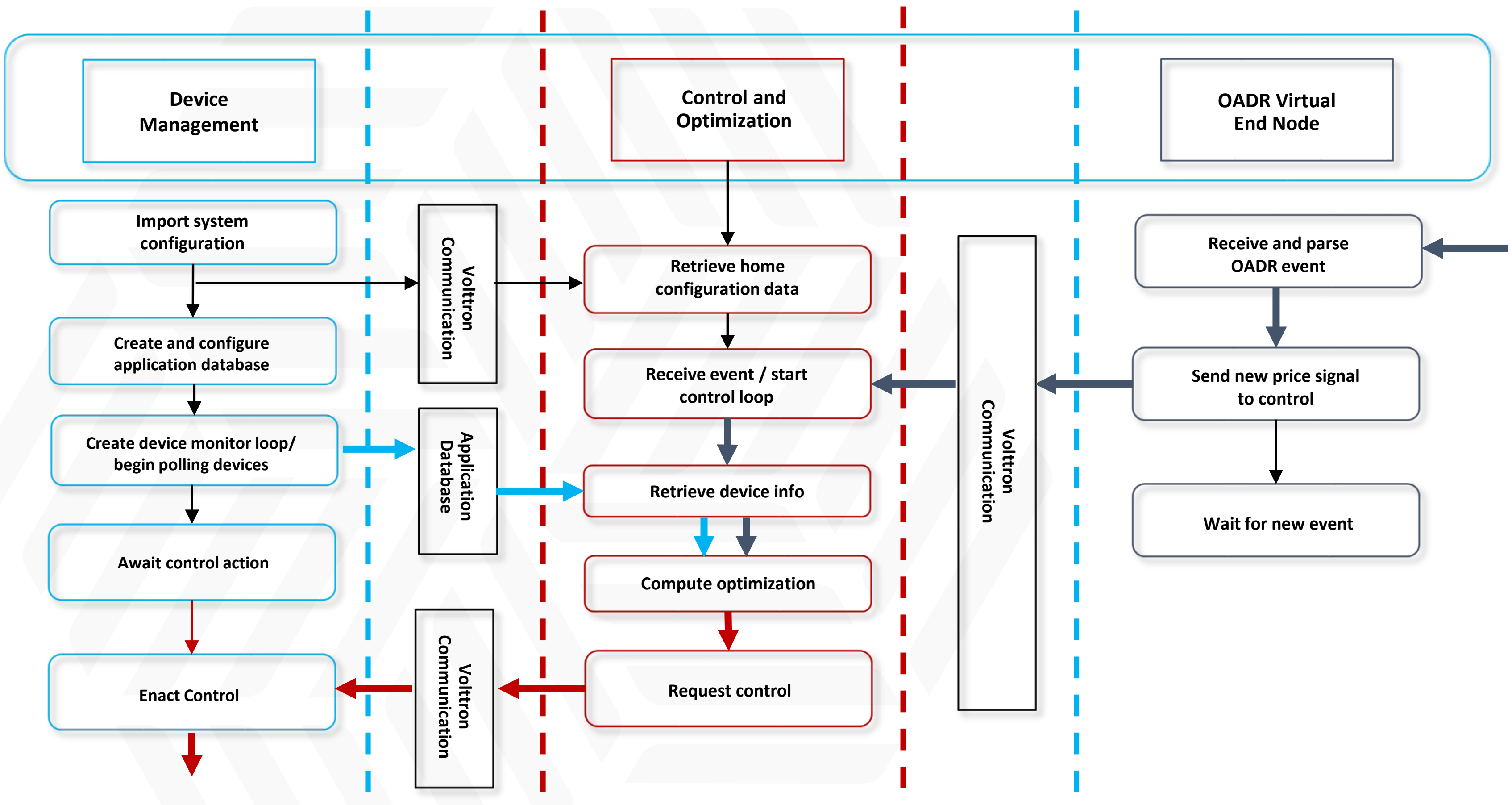
- HEMS designed to operate asynchronously
- Agents operate as separate processes
- Data repository allows separation of data-gathering and control/dispatch
- The HEMS is insulated from any device-side errors

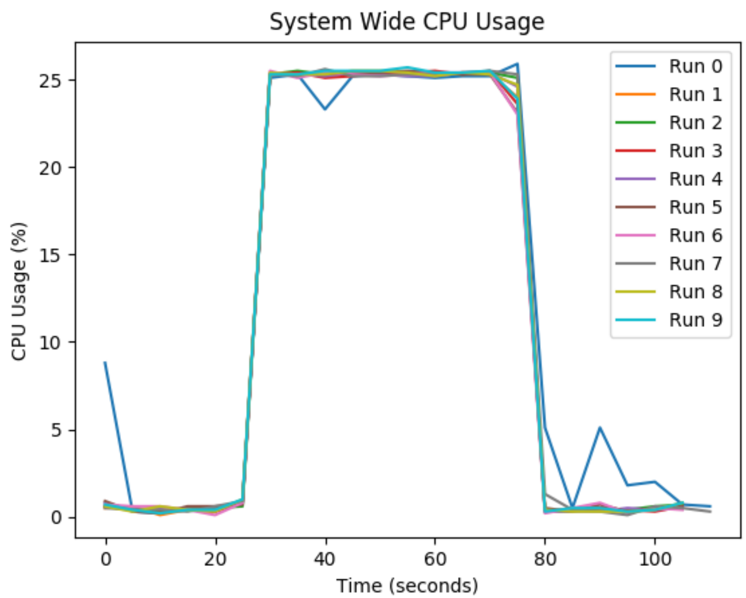


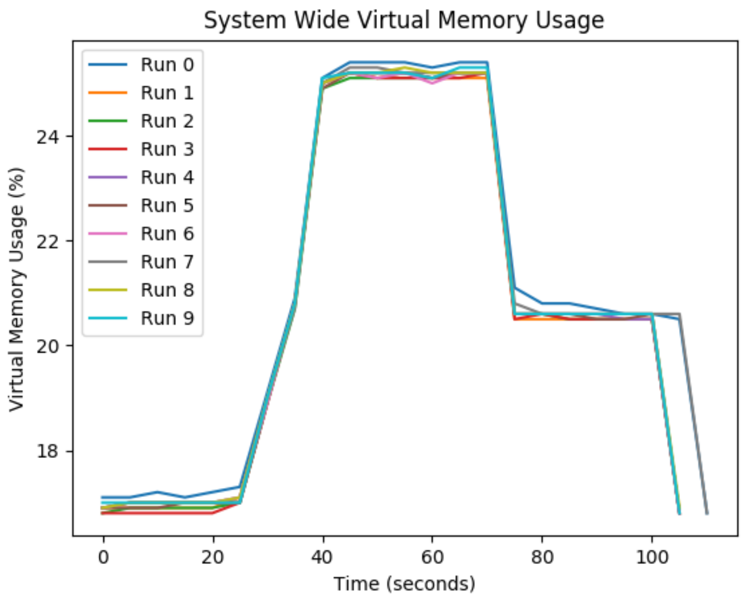
HEMS – Anatomy of a Pricing Event



Hardware Benchmarking

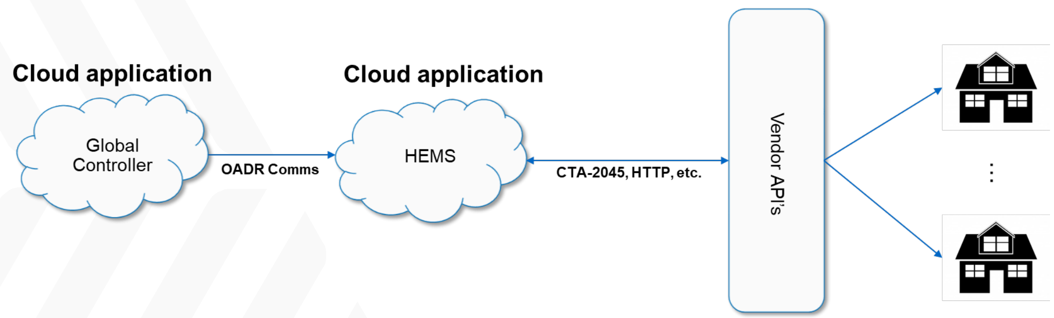
- HEMS will be deployed to Raspberry Pi's inside the home
- Raspberry Pi's must be able to effectively operate against requirements given their computation power
- In benchmarking, the Raspberry Pi 3 model was able to effectively compute a whole-home optimization (4 devices), in adequate time

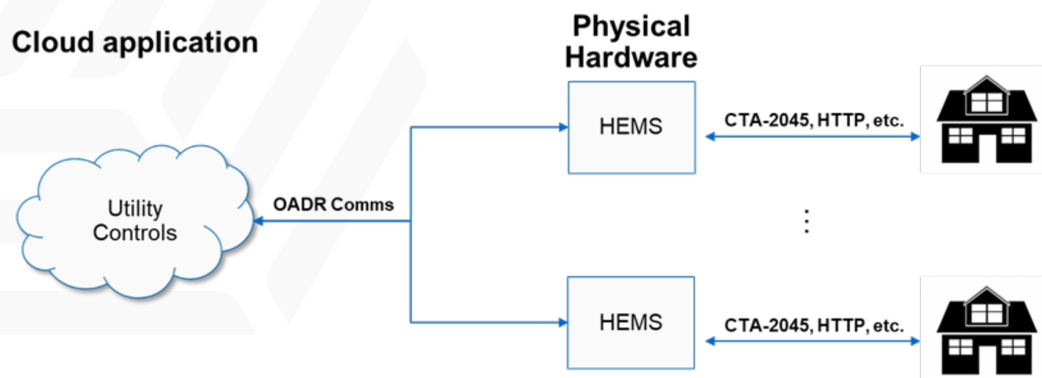


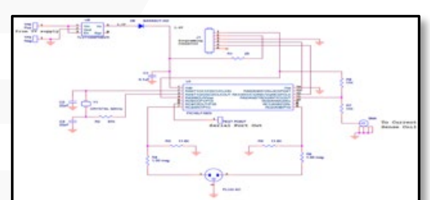


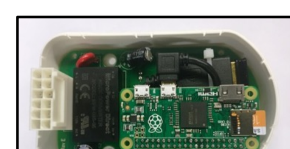
System Deployment Strategy

- Two methods of deployment for neighborhood-scale rollout
- Cloud hosted system
  - One application in cloud
  - Data gathered through vendor API
- Physically hosted system
  - Each home has physical hardware running HEMS
  - Device comms through CTA-2045
  - OADR signals received through cell

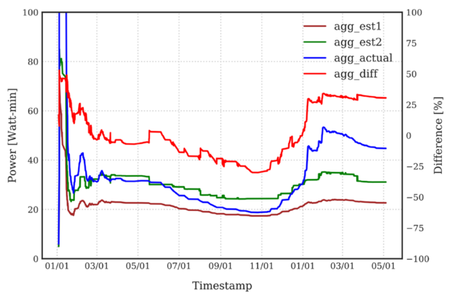


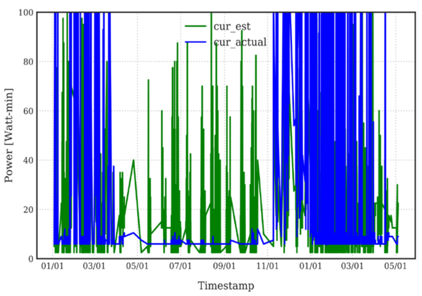



Frequency and Voltage Sensing


CTA-2045 Cellular/Wi-Fi Raspberry PI Zero

- **Test setup at Yarnell Research home**
  - ☐ Setup VOLTTRON-based HEMS with device agents
  - ☐ Instrumentation for evaluating controller performance (device-level submetering)
  - ☐ Accessing device-level API for enabling advanced control functionality
- **Measurement and Verification (M&V)**
  - ☐ Implemented whole home M&V Algorithms
  - ☐ Adjust data resolution 1 min to 15 min
  - ☐ Currently evaluating the performance





Deployment Readiness

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- Infrastructure supporting the full transmission of information from OADR VTN through device transmission is complete
- Currently can send price signal/load profile from off-site top-node, translate into action for devices in test home
- Further use-case specific capabilities and device integration needed before production

Alpha

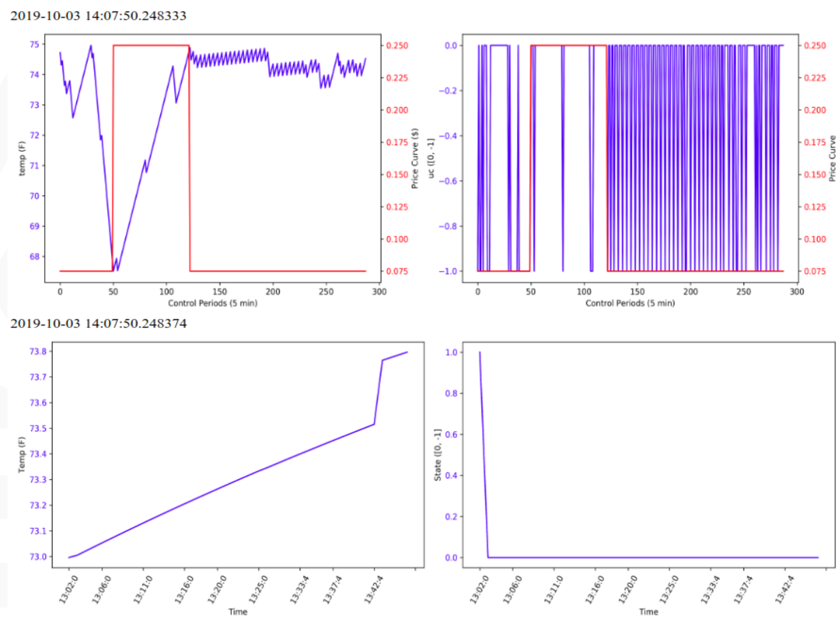
Can we optimize to use case?
Can we talk to devices?
Can we receive/parse OADR messages?

Beta ◀ *We are here*

Can we translate received signal to action?
Can we respond to changed events
Can we run use-case analytics?
Can we respond to fringe events?
Are VOLTTRON Agents robust and resilient?
Can we integrate with full set of devices?
Can we improve optimization formulation?
Can we layer multiple use-cases?

Production

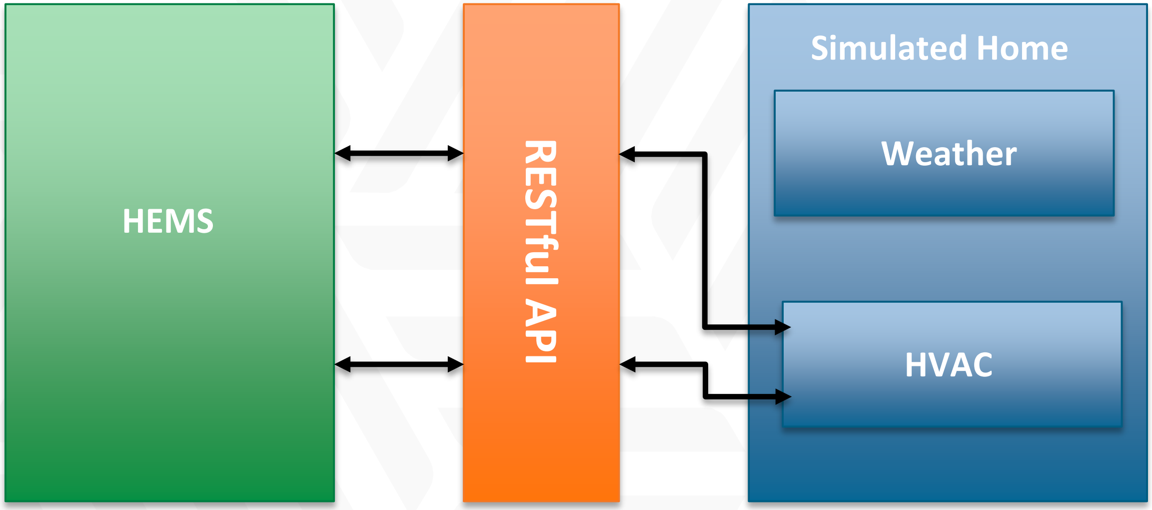
Can we scale?
Can we rapidly deploy?



A forecasted load signal, device action and observed system state in Yarnell test home

Full Stack Test

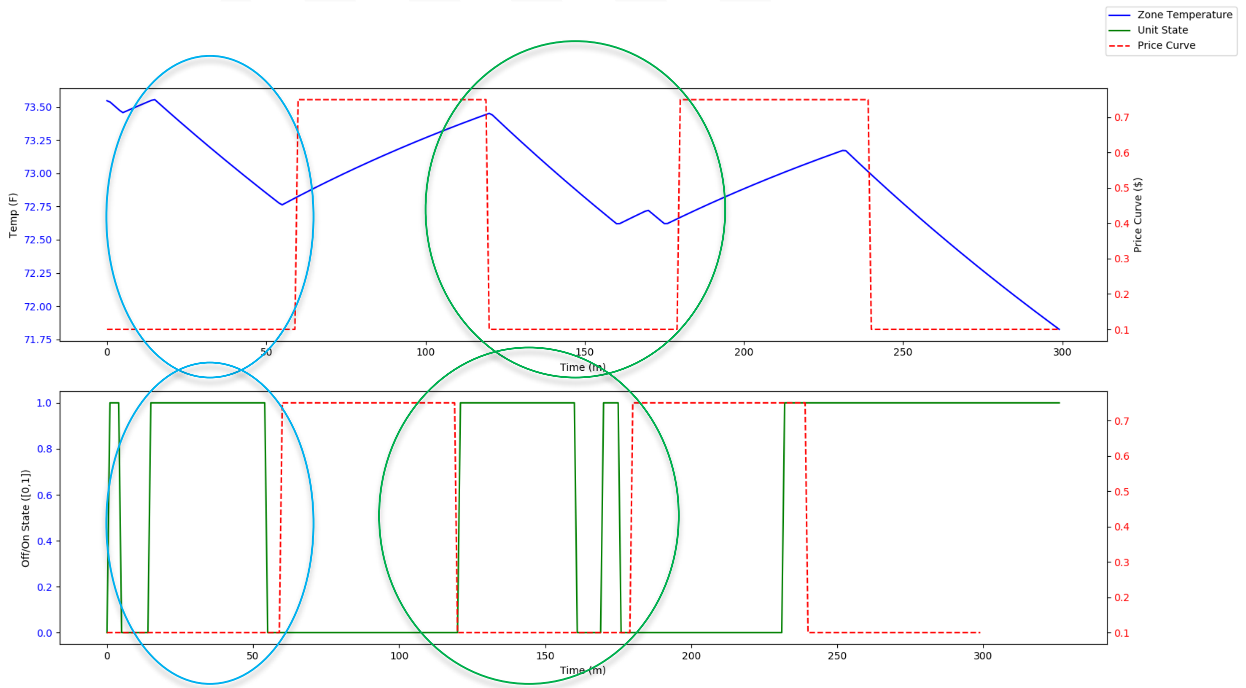
- HEMS was run in software in the loop test – 5 Hour Test
- Full software stack used. Tested against simulated home
- Simulated home sat behind a custom built RESTful API and ran in real-time
- Interface points similar as to commercial thermostat



Software-in-the-loop Full-Stack Test

Full Stack Test– Performance

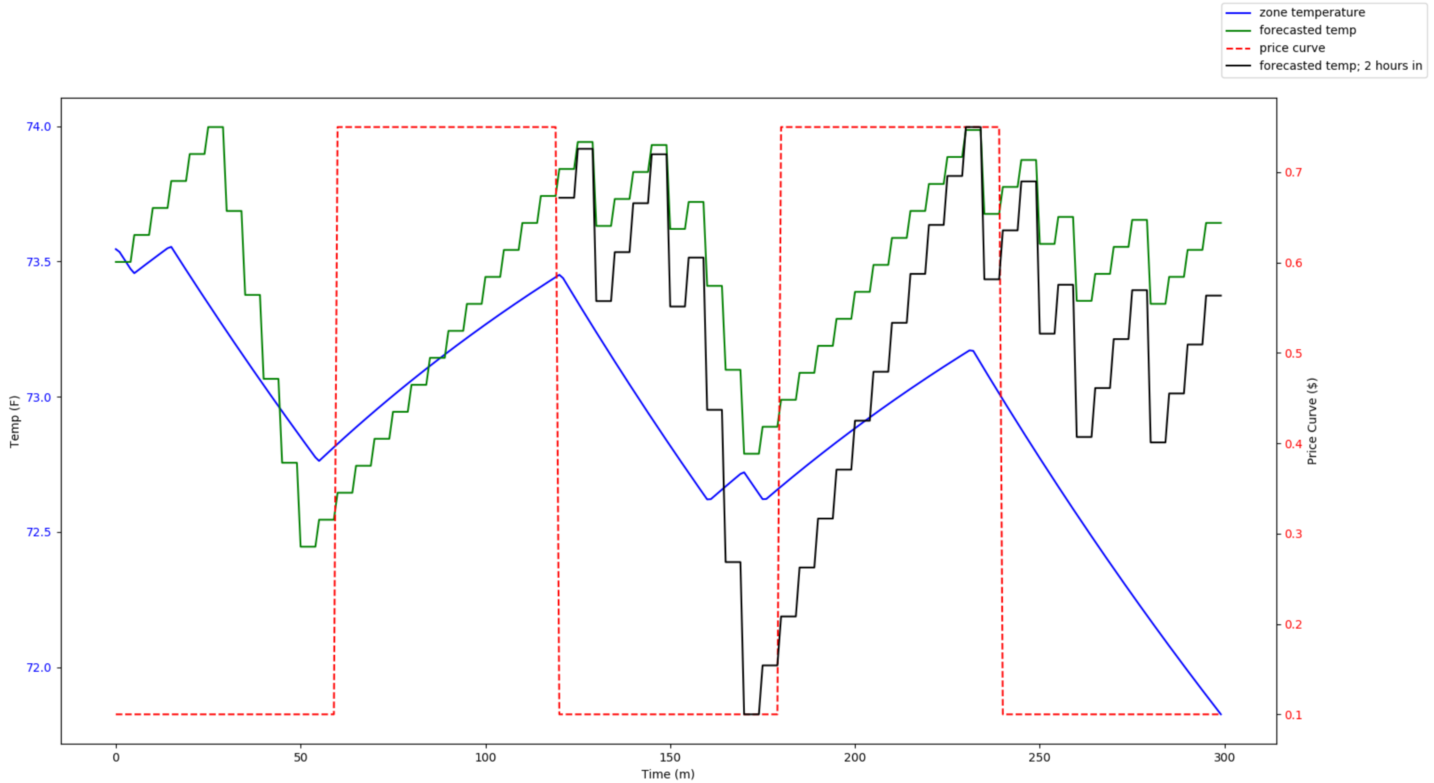
- HEMS optimization utilized battery-storage equivalency optimization
- Goal is to pre-cool in advance of pricing events
- In test, pre-cooling was observed at correct times



HEMS Test – Observed Temperature and State

Full Stack Test– Learning and Forecast

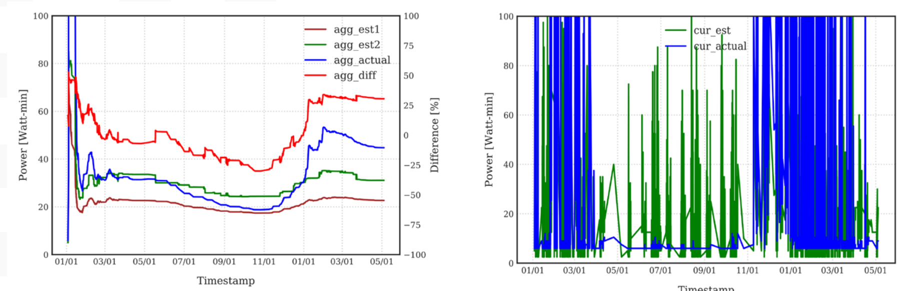
- Forecasting captured trajectory of behavior if not magnitude
- Forecast is updated every control period. Stayed roughly consistent
- Further improvements to system identification and learning in work before production



HEMS Test – Forecasted and Observed Temperature and State

Testing, Measurement, and Verification

- **Test setup at Yarnell Research home**
  - Equipment donated by EPRI
  - Setup VOLTTRON-based HEMS with device agents
  - Instrumentation for evaluating controller performance (device-level submetering)
  - Accessing device-level API for enabling advanced control functionality
- **Measurement and Verification (M&V)**
  - Traditional M&V is for efficiency not load management
    - Calculates kWh not kW – Often uses proxy measurements and statistical analytics



Devices and Integrated Systems Testing

Project Outline

Introduction to Project

Utility Side Development

Building Side Development

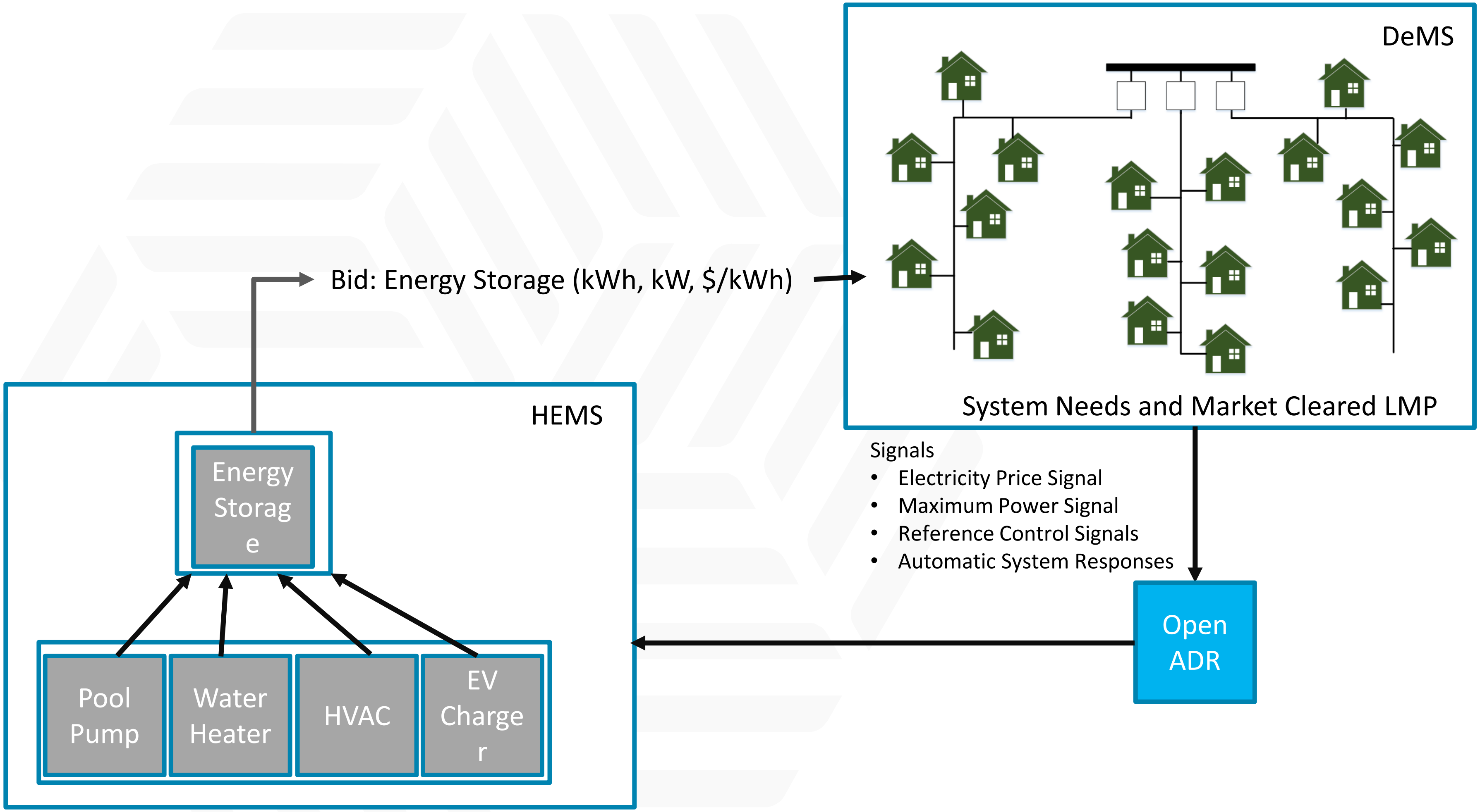
Deployment

Field Test Sites

Duke Energy, Electric Power Board (TVA) and Southern Company

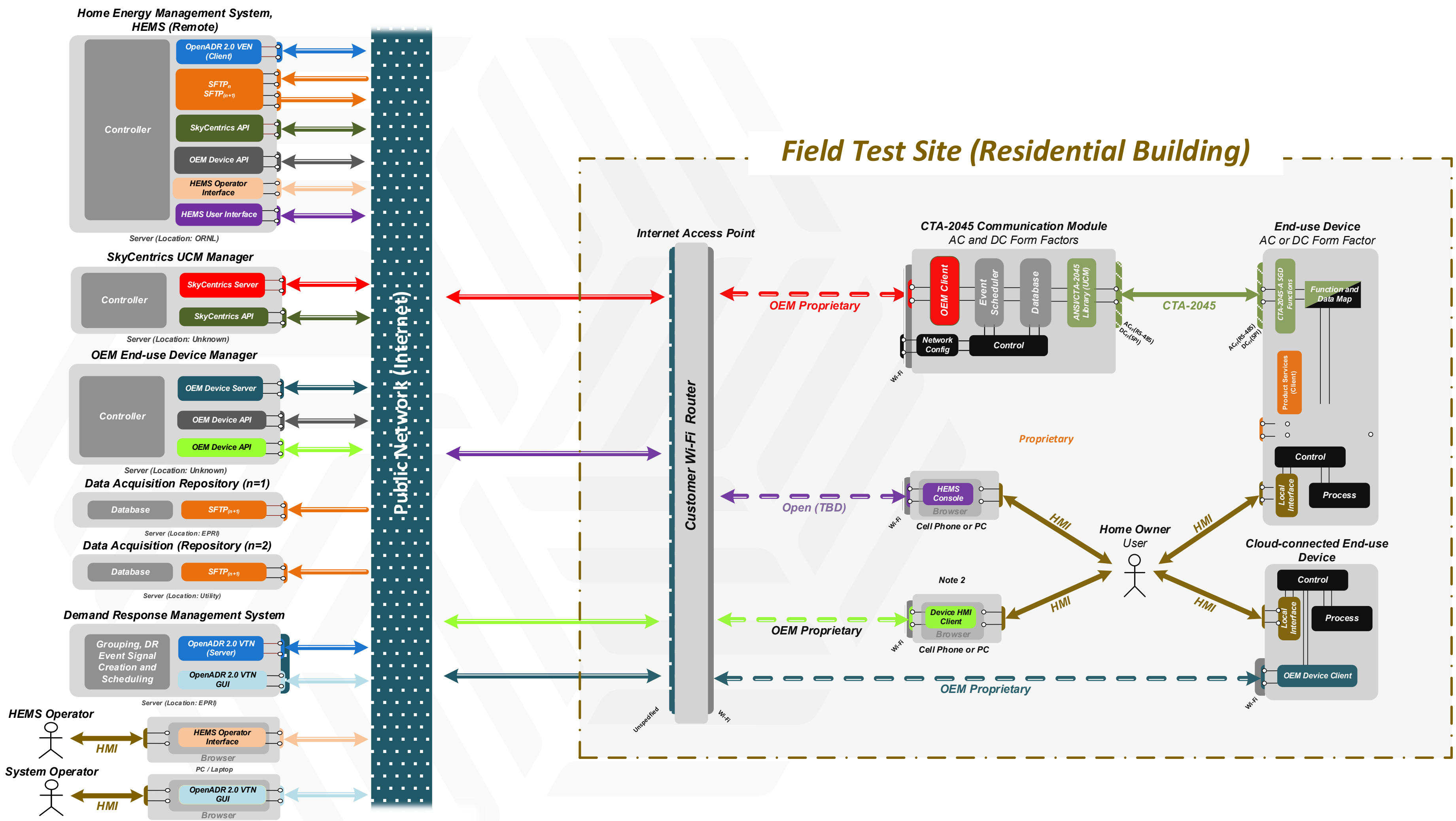
Utility	Deployment	Number of sites	Location	Customer Class	End-use Device Type Distributed Across Test Sites (Min 2 Device types at each site)
Duke Energy	HW	20-40	St Petersburg, FL	Residential	• Resistive Water Heater (50 gal) • Heat Pump Water Heater (50 gal) • Electric Vehicle Supply Equipment (Level 2) • HVAC Thermostat • Variable Speed Pool Pump (3kW)
Southern Company	Cloud	5-10	Atlanta, GA	Residential	• Heat Pump Water Heater (50 gal) • HVAC Thermostat
Electric Power Board (EPB)	Cloud	10	Chattanooga, TN	Residential	• Resistive Water Heater (50 gal) • Electric Vehicle Supply Equipment (Level 2) • HVAC Thermostat • Variable Speed Pool Pump (3kW)

End-to-End Evaluations



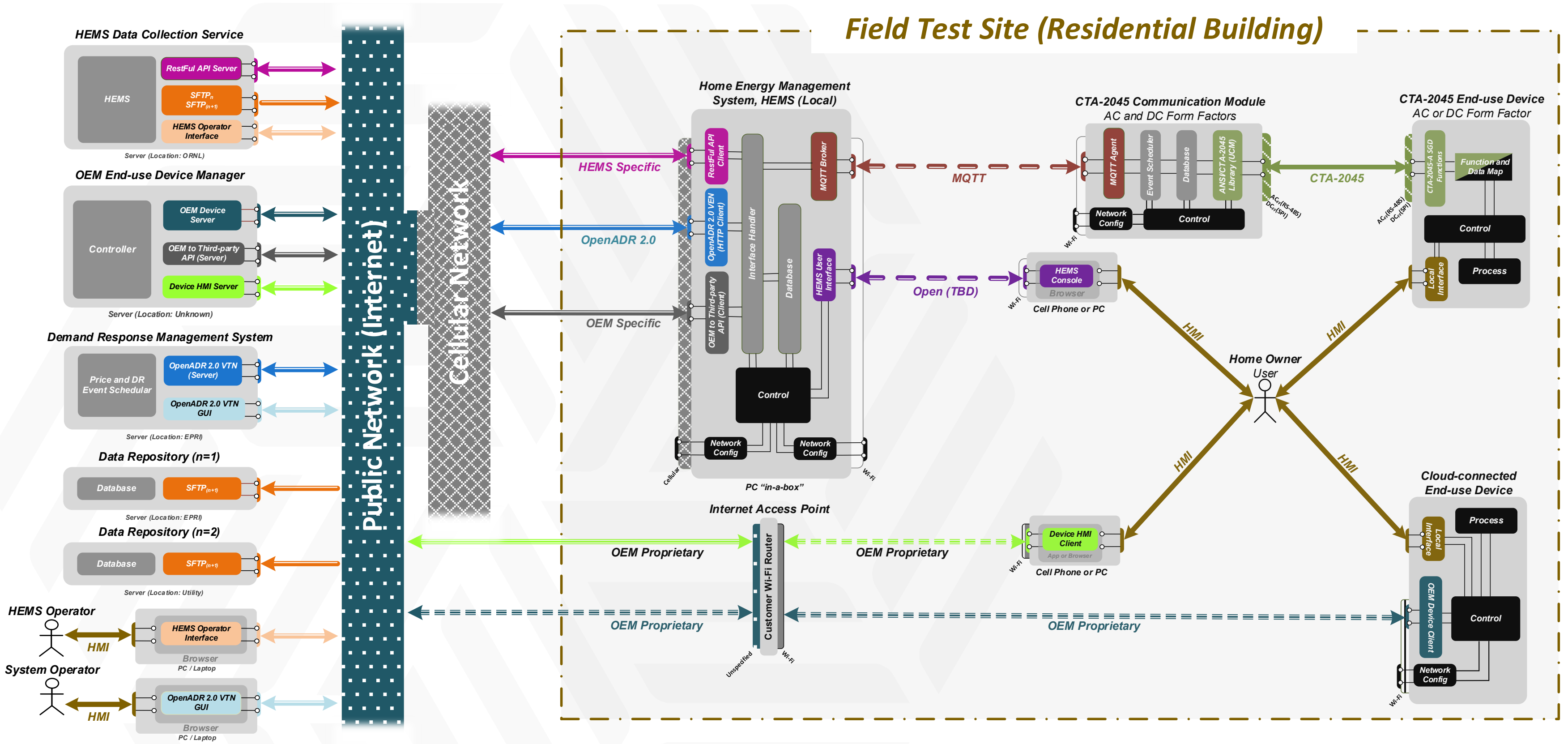
HEMS in the Cloud

Architecture



HEMS on Local Hardware

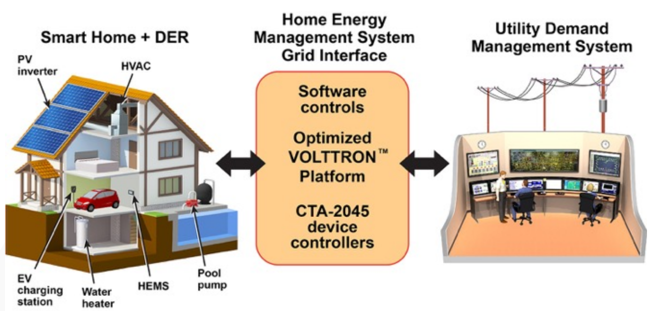
Architecture

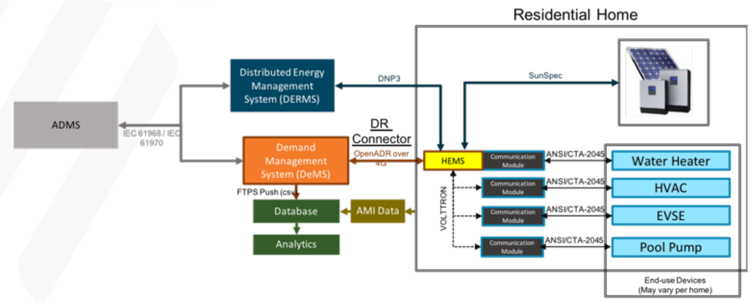


Summary

Enable Resilient distribution systems with high penetration of distributed energy resources (DERs) that can withstand disasters and faults by intelligent reconfiguration

- Developed a low-touch retrofit Home Energy Management System (HEMS) to interact with loads, DERs, and Utility to manage demand for providing grid services and enable resilience
- Developed a method for distribution reconfiguration to improve resilience by engaging demand flexibility
- Engaged with Southeast utilities and identified test deployment sites for technology evaluation
- Developed novel device-level retrofit hardware to enable measurement of grid parameters
- Cloud-based platform for data analytics and situational awareness





Publications/Reports/Meetings

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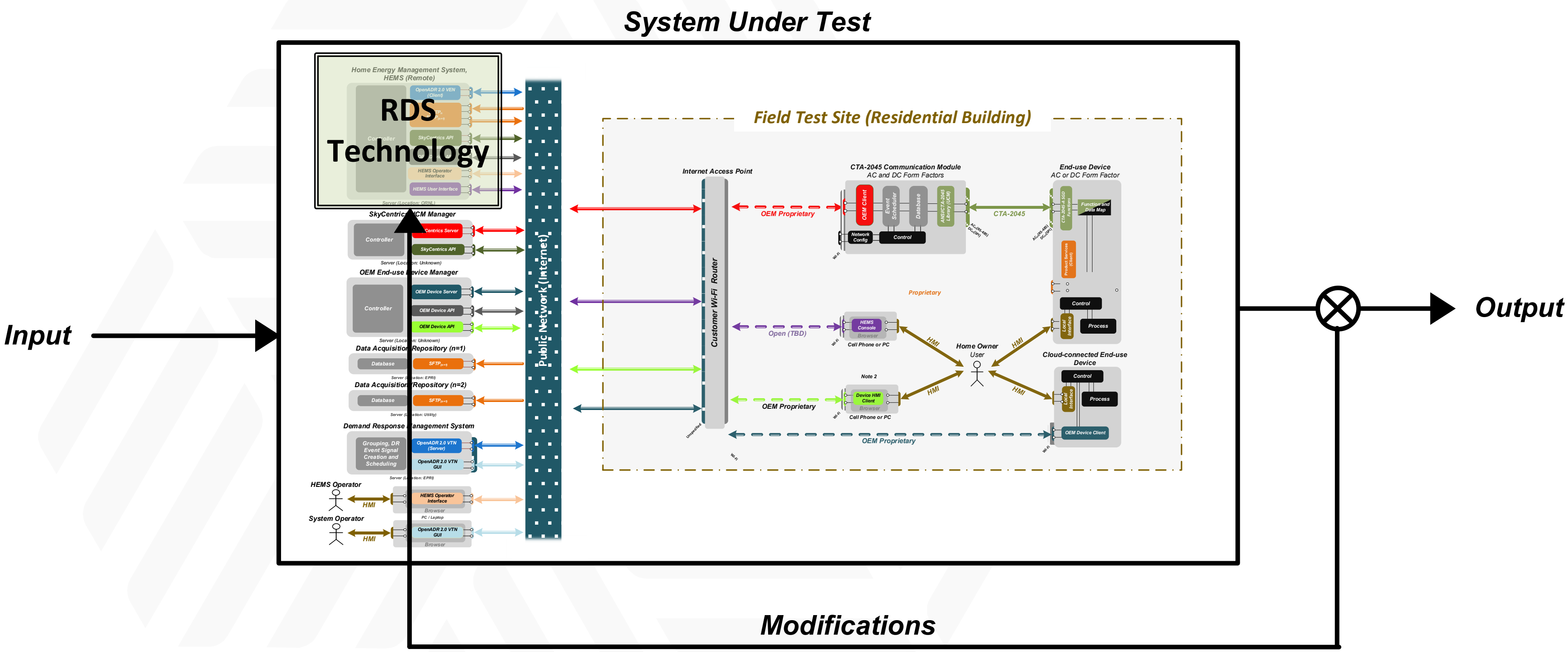
- **Publications/Reports**
  - Michael Starke, Madhu Sudhan Chinthavali, Teja Kuruganti, Christopher Winstead, Sheng Zheng, Rong Zeng, Steven Campbell, Walter Thomas, “Networked Control and Optimization for Widescale Integration of Power Electronic Devices in Residential Homes,” Energy Conversion Congress and Expo, September 2019, Baltimore, MD
  - Borui Cui, Cheng Fan, Jeffrey Munk, Ning Mao, Fu Xiao, Jin Dong, Teja Kuruganti, “A hybrid building thermal modeling approach for predicting temperatures in typical, detached, two-story houses,” Applied Energy, Volume 236, 15 February 2019, Pages 101-116, doi.org/10.1016/j.apenergy.2018.11.077 (112387)
  - Helia Zandi, Michael Starke, Teja Kuruganti, “A General Framework to Transform any Home Energy Management System to a Multi-agent System”, 7th International Building Physics Conference Syracuse, NY, September 23-26, 2018 (Accepted)
  - J. Dong, Y. Xue, T. Kuruganti, M. Olama, J. Nutaro, “Distribution Voltage Control: Current Status and Future Trends,” 9th International Conference on Power Electronics for Distributed Generation Systems (PEDG2018), Charlotte, NC, June 2018
  - Yaosuo Xue, Michael Starke, Jin Dong, Mohammed Olama, Teja Kuruganti, Jeffrey Taft, Mallikarjun Shankar, “On a Future for Smart Inverters with Integrated System Functions” Power Electronics for Distributed Generation Systems (PEDG2018), Charlotte, NC, June 2018
  - M. M. Olama, T. Kuruganti, J. Nutaro, J. Dong, “Coordination and Control of Building HVAC Systems to Provide Frequency Regulation to the Electric Grid,” Energies, 11, 1852, pp. 1-15, July 2018.
  - Teja Kuruganti, Chuck Thomas, George Hernandez et. al., “Use Case Development and Logical Architecture Specification”, Technical Report
  - Mohammed Olama, Helia Zandi et al., “State-of-the-art of Demand Response Management Applications” Technical Report
- **Meetings**
  - Use case definition – webinar/work session – December 5th 2017 – provided project overview
  - Face-to-Face Requirement Definition Meeting with Utilities – San Diego, CA – February 7th 2018 – workshop for use case
  - Transmission Control Center – Generation Operator Interview – FL – July 19th 2018 – understanding operational processes
  - Monthly phone calls with Utility partners – Providing direct feedback
- **LVAT, Cybersecurity, and Interoperability**
  - Completed Metrics selection for Resiliency, Reliability, Security, Flexibility, Security, Sustainability, and Affordability
  - Selected Cybersecurity technology for implementation – Beholder (malware detection for applinaces), and Reviewing secure multi-speak protocol for ADMS and DeMS communication

Discussion

System-in-the-Loop Test Setup

Cloud-based HEMS



System-in-the-Loop Test Setup

Hardware-based HEMS