U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Home Battery System

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Project Summary

Timeline

Start date: May, 2016
Planned end date: Sept, 2018

Key Milestones

1. Demonstrated automated, self-learned control of simulated loads. **9/20/2016**
2. Demonstrated improved efficiency, resource predictions, and laboratory readiness for scenario experiments. **7/20/2017**
3. Document laboratory findings. Release open source software modules to enable industry adoption. **9/30/2018**

Budget

Total project, to date: $2.64M

- DOE: $684k
- Cost Share: $1.96M ($1.20M BPA, $760k Bosch)

Total project: $2.83M

- DOE: $750k
- Cost Share: $2.08M ($1.25M BPA, $830k Bosch)

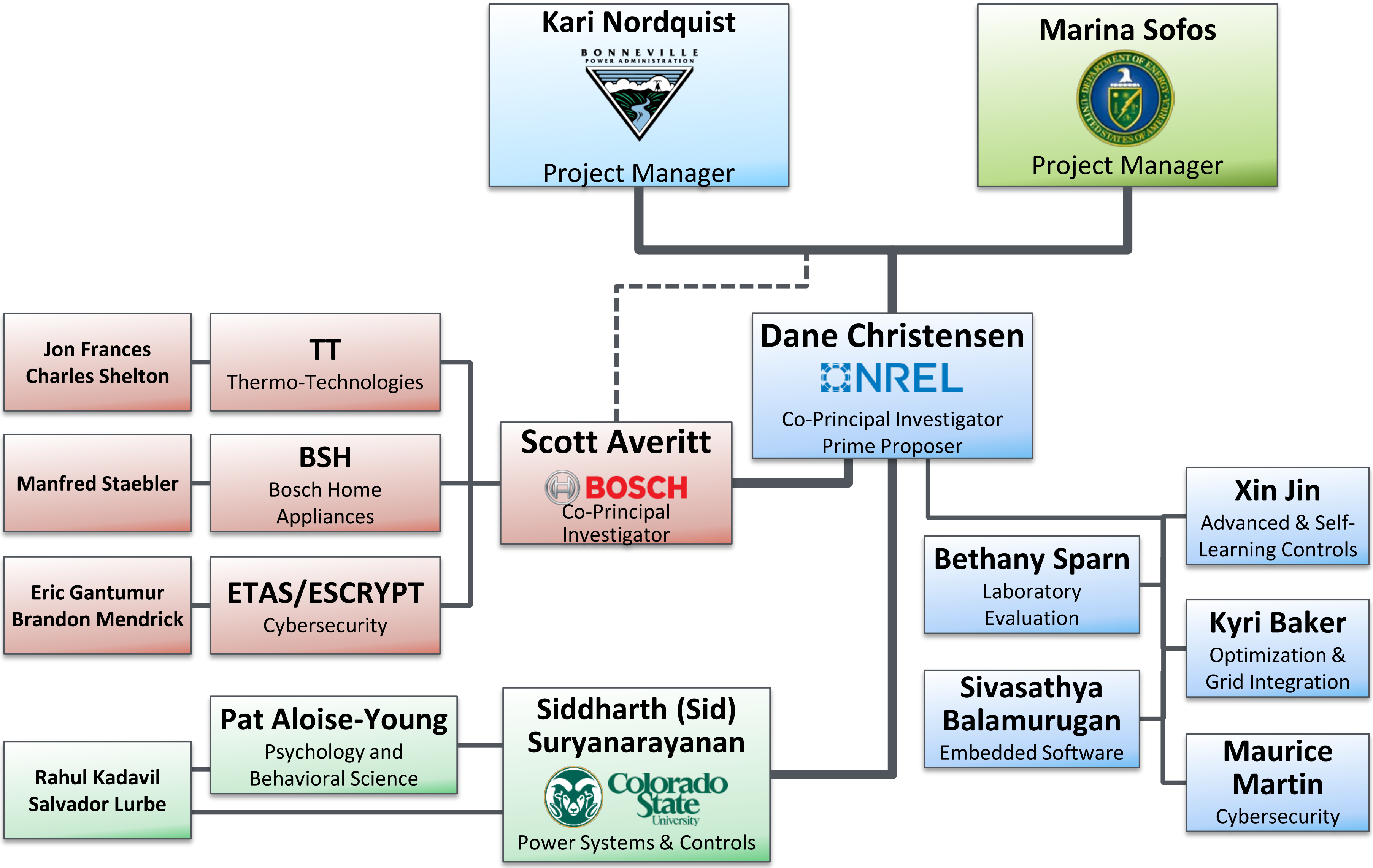
Key Partners:

Project Outcomes

Foundational automation strategies enable future product solutions to deliver win-win grid-interactive efficiency for homeowners, utilities, and energy service aggregators.

Increase residential sector energy efficiency (goal: 5% savings per home, or ~1 Quad potential) and demand response participation (goal: >2 kW firm resource per home), by easing consumer adoption of integrated solutions, towards enabling >10% active devices to provide flexibility by 2035.

Team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Psychology and Behavioral Science
Rahul Kadavil
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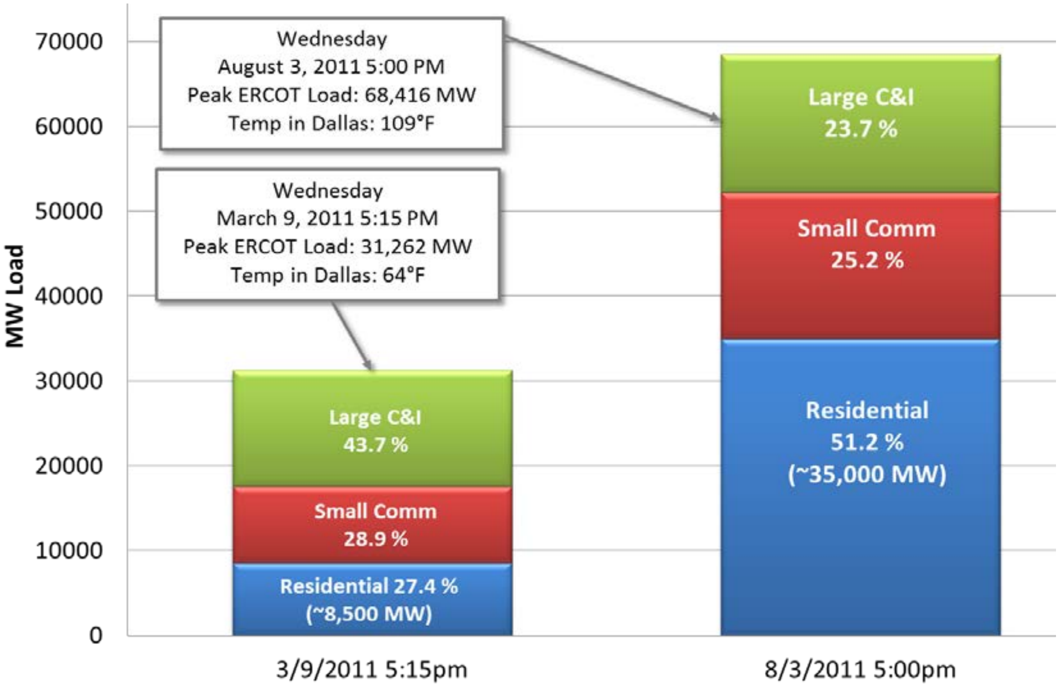
Colorado State University
Power Systems & Controls

Challenge

- Residential electricity consumption is larger than any other sector, and dominates utility peak load
- But…
  - *Residential buildings are* ***96% of utility customers***
  - *There is high occupant and building diversity*
  - ***Decisions are less financially-motivated***
  - *Awareness of grid issues is lacking*
  - ***Internet of Things*** *creates dozens of new cybersecurity risks per home*
  - ***Rapid growth in rooftop PV*** *challenges existing grid control and business models*

ERCOT Peak Loads



How can we leverage connected residential products to generate more EE and DR, while avoiding occupant intervention & discomfort?
Are there Win-Win solutions?

Approach

The Home Battery System project expects to achieve the following **technical objectives**:

1. Guaranteed comfort and improved energy savings for homeowners
2. Optimal operation of home based on user preferences and grid signals
3. Cybersecure demand response (DR) compliant with critical infrastructure protection (CIP)
4. Delivery of highly-available (more than 90%) DR capacity, >2 kW/home, from individual homes
5. Reliable DR capacity prediction from individual homes across multiple look-ahead time frames

Approach

1. Interface for homeowner engagement, preferences
2. Multi-criterion decision making control algorithms
3. Cybersecurity layer for privacy, grid security
4. Develop & install hardware
5. Validate under realistic lab use cases

Year 1	Year 2	Year 3
Develop fundamental methods and architecture	Integrate software to improve control and reduce uncertainty. Prepare laboratory	Conduct laboratory experiments to study dynamic operation and validate outcomes from simulation.

Impact

- Demonstrates feasibility of fundamental methods and algorithms for a residential automation serving homeowners, utilities, and energy service aggregators.
- Demonstrates 5% annual energy savings and >2 kW firm resource per home from demand response participation without sacrificing occupant comfort or requiring user intervention.
- Laboratory experiment results will establish technical feasibility, leading to:
  - Market-driven solutions contributing to >10% of active devices providing grid flexibility by 2035, and
  - Informed field experiments in the future.

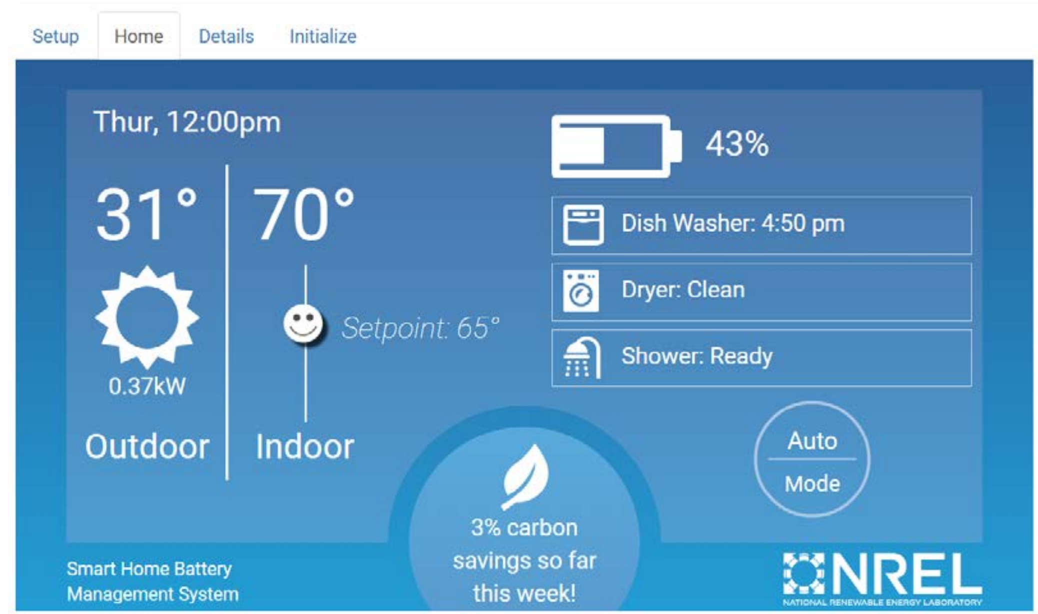
Progress: User Preference Elicitation

- Three method evaluated; 1,000 respondents each
- Follow-up survey, 250 each, to assess predictiveness

amazon mechanical turk

Method	Correct Predictions
AHP	49.0%
DCM	68.0%
SMARTER	**72.2%**

SMARTER selected as the initialization method for **foresee**

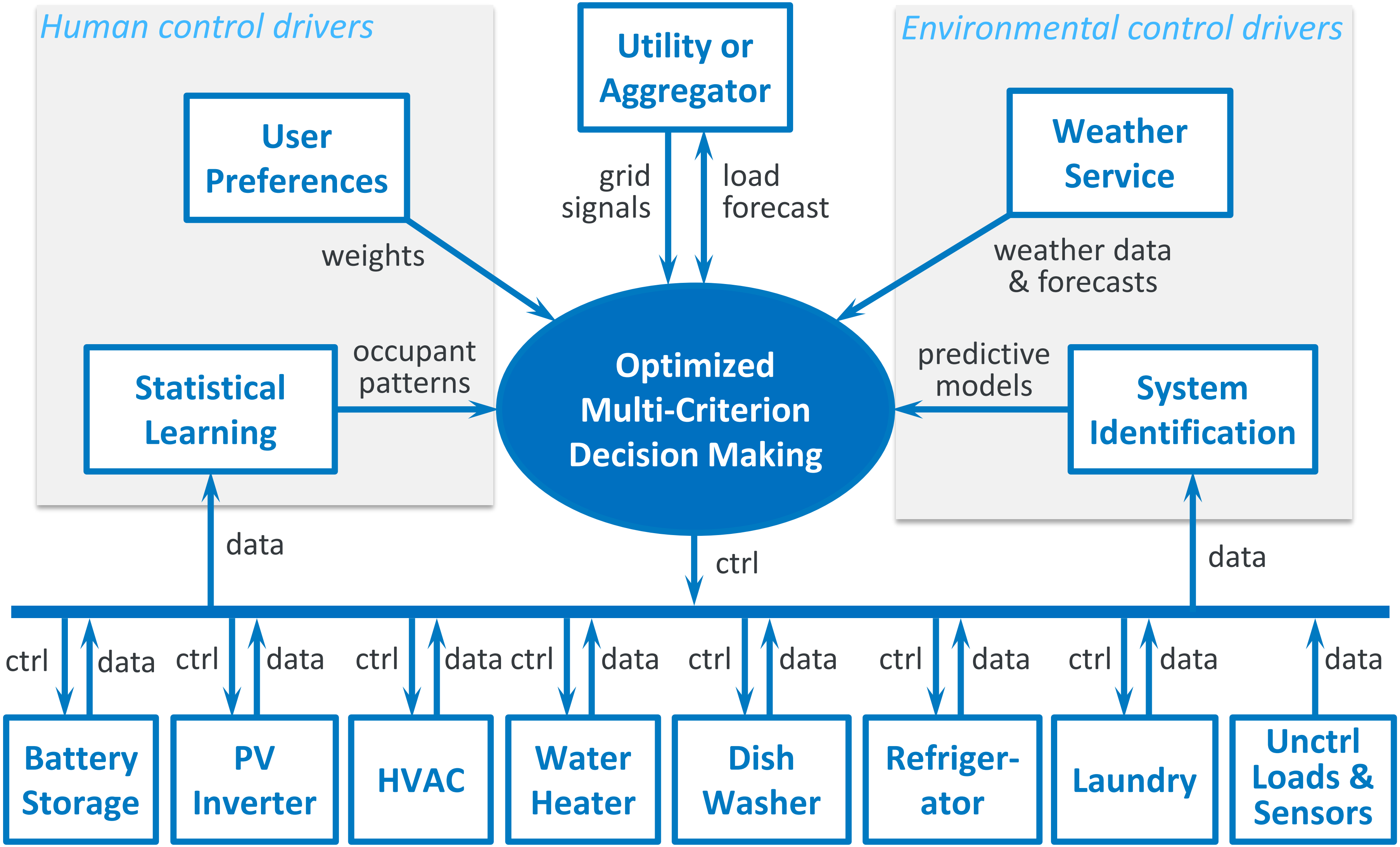


Money, Dishes, Shower length, Asym. term

$$U_i = \beta_{i,m}M + \beta_{i,c}C + \beta_{i,d}D + \beta_{i,l}L + \beta_{i,sl}S_l + \beta_{i,t}A_t^2 + \beta_{i,tn}\, I_{A_t<0}A_t^2 + \epsilon_i$$

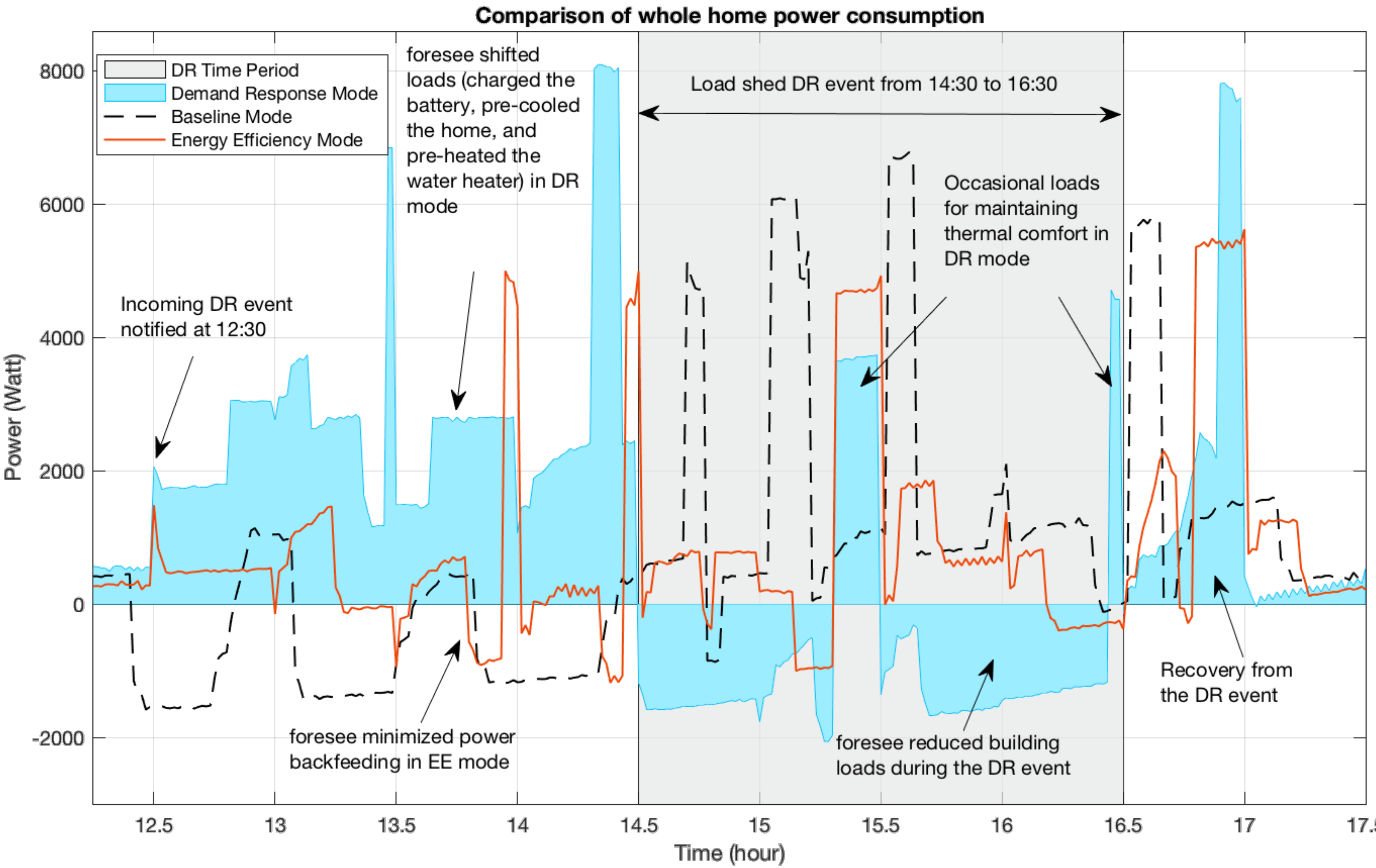
Source energy, Laundry, Air temperature, Error

Progress: Control Architecture

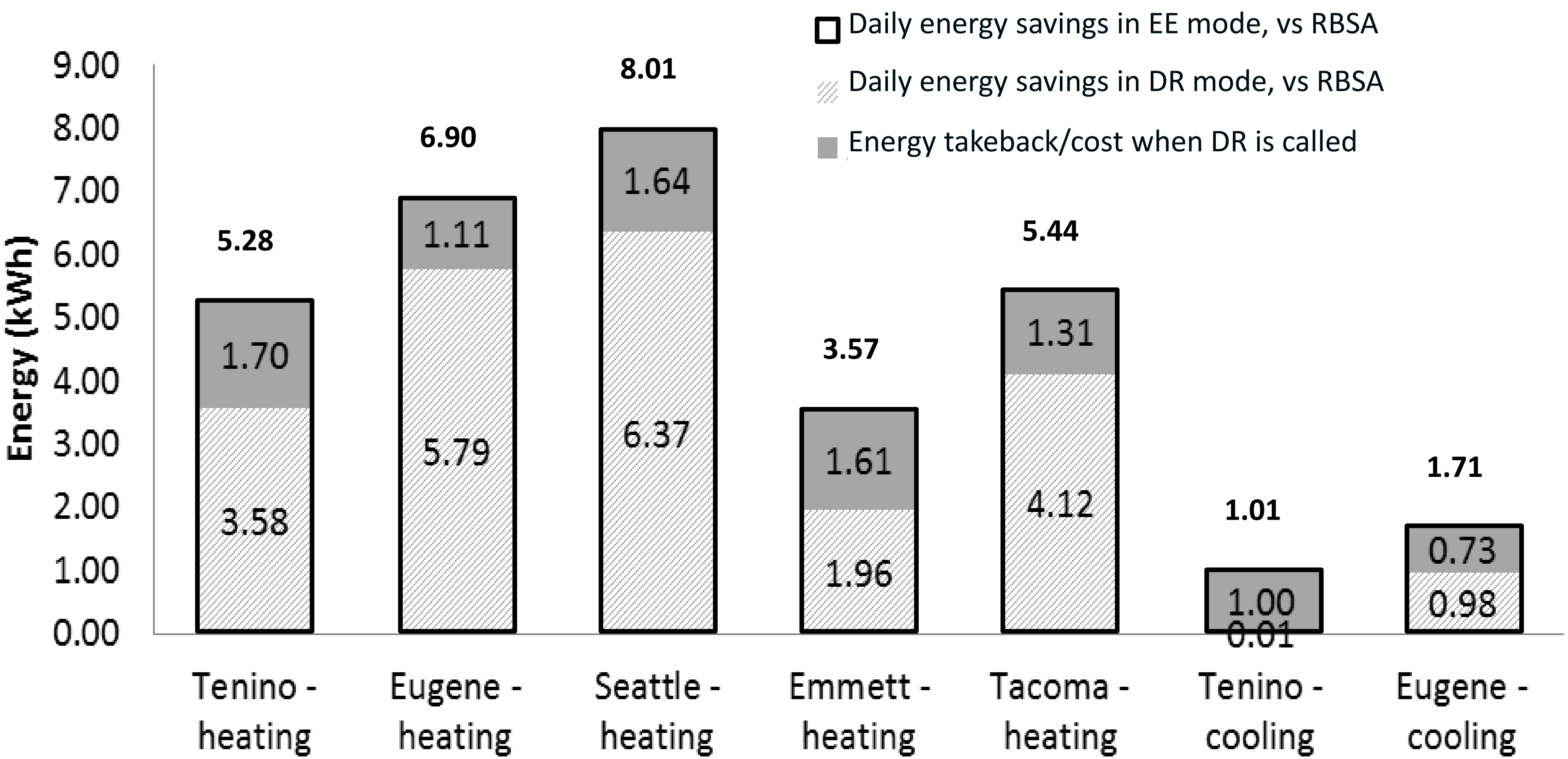


Progress: ESIF Experimental Testbed

Progress: Demand Response Use Case

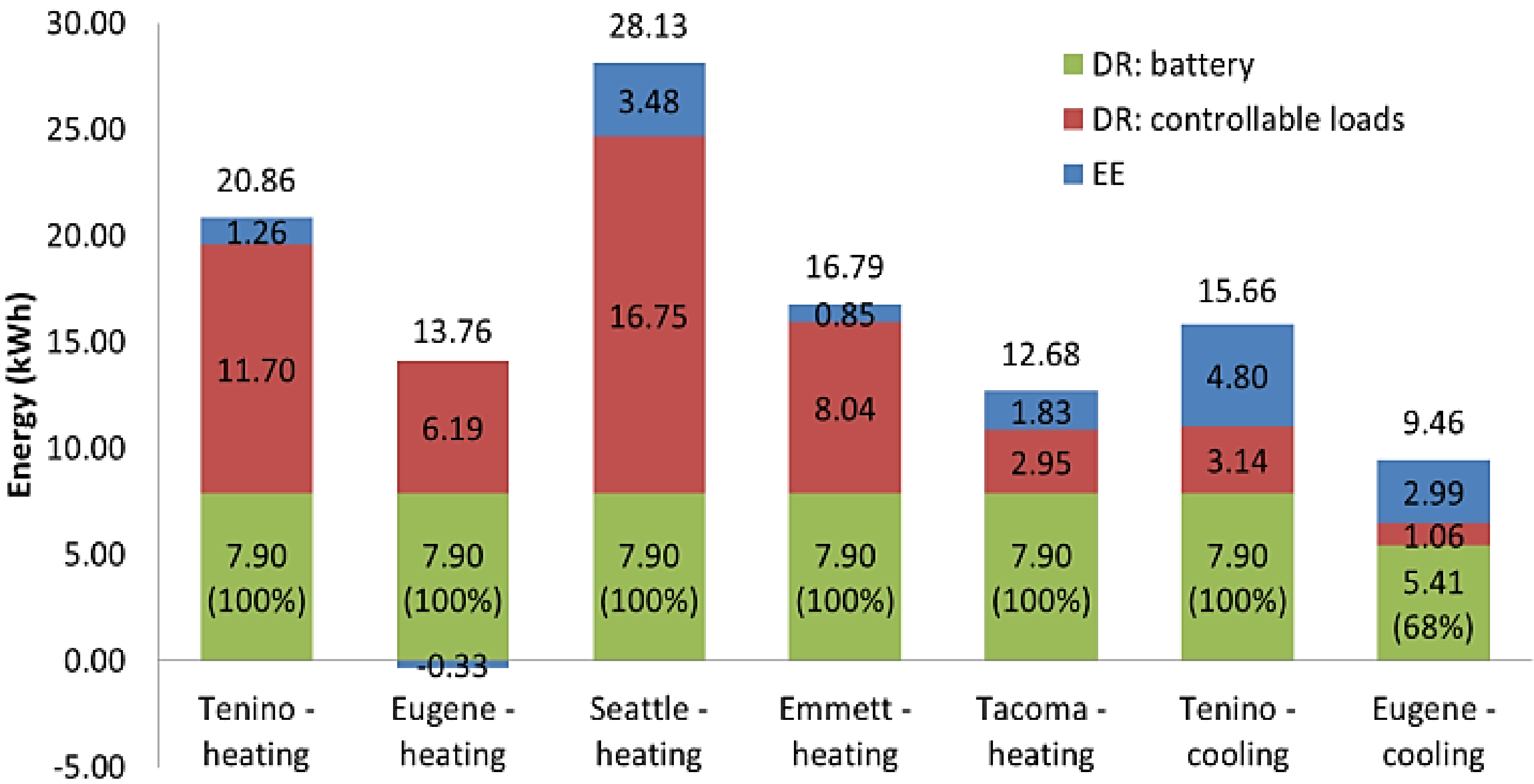


Progress: Daily Energy Savings Breakdown



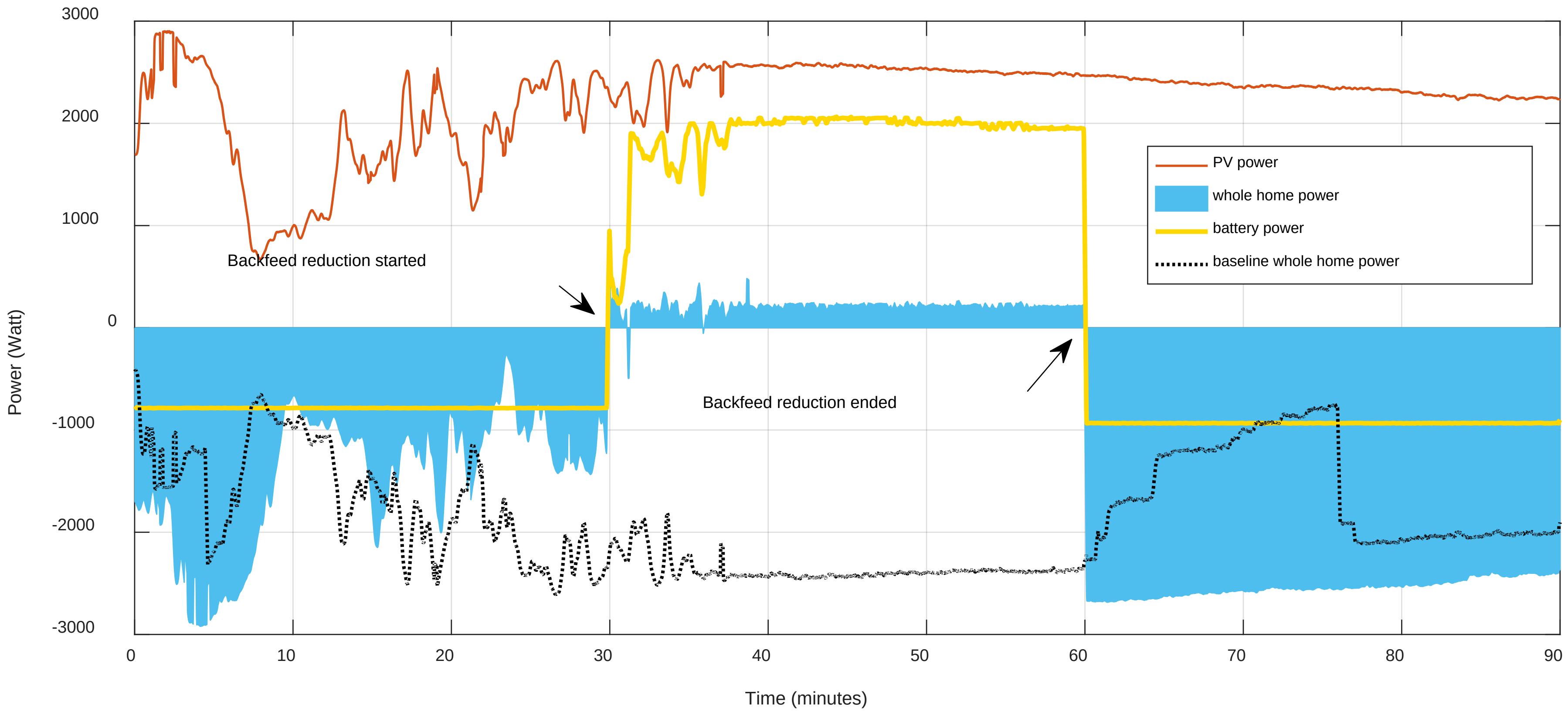
(4-hour load-shed event)

Progress: DR Demand Reduction Breakdown



(4-hour load-shed event)

Progress: Solar Firming Use Case



Progress: Cybersecurity Layer

- ✓ Documented rigorous risk assessment
- ✓ Created an implementation plan to address risks in software, hardware
- ✓ Developed the cybersecurity layer based on the implementation plan
- ✓ Developed a security test plan and CIP compliance document
- ✓ Assessed platform hardening and documented best practices
- ➢ Penetration testing underway

Stakeholder Engagement: Advisory & Outreach

- Industry advisory board on sizing batteries for a smart home, using multi-criterion model predictive control

- Laboratory demonstrations for eight major utilities and industry stakeholders.

- Active industry discussions to resolve real-world issues via field experiments/ pilots.

2 Journal papers, 3 in development
5 Conference papers, 5 in dev.
9 Conference presentations, to date
2 Published presentations/webinars
1 Copyrighted open-source software

Remaining Project Work

1. Perform laboratory experiments to evaluate Technical Objectives per approved Scenario Test Plan
   - *Automated satisfaction of three different archetype homeowners' preferences*
   - *"Business as usual" baseline in three climates*
   - *EE operation under TOU rates in three climates*
   - *Locationally-relevant DR in three climates*
   - ***24 physical performance scenarios***
   - ***11 different cybersecurity scenarios***
2. Perform simulations to evaluate aggregated impacts
3. Document and close out project – end of FY 2018
4. Complete in-process publications, including:
   - *Application of NERC CIP Standard requirements to aggregated end-use loads & building energy management systems*
   - *Preference elicitation methodology comparison for multi-criterion control of residential equipment*

Thank You!

The Home Battery System Team

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REFERENCE SLIDES

Stakeholder Engagement: Publications

- X. Jin, K. Baker, S. Isley, and D. Christensen. "User-Preference-Driven Multi-Objective Model Predictive Control of Residential Building Loads and Battery Storage for Demand Response." Proceedings of the 2017 American Control Conference. https://www.nrel.gov/docs/fy17osti/67809.pdf
- E. Raszmann, K. Baker, D. Christensen and Y. Shi, "Modeling Stationary Lithium-ion Batteries for Optimization and Predictive Control." IEEE Power and Energy Conference at Illinois (PECI) 2017. (Best Paper Award) https://www.nrel.gov/docs/fy17osti/67809.pdf
- D. Christensen, S. Isley, K. Baker, X. Jin, P. Aloise-Young, R. Kadavil and S. Suryanarayanan, "Homeowner Preference Elicitation: A Multi-Method Comparison," ACM BuildSys '16, Stanford, CA, Nov. 2016.
- R. Langner and D. Christensen, "Navigating Cybersecurity Implications of Smart Outlets." *Accepted*, ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 12-17, 2018.
- P. Aloise-Young, S. Isley, R. Kadavil, S. Suryanarayanan and D. Christensen, "Preferences for Demand Response Behavioral Sacrifices." ACEEE Behavior Energy & Climate Change conference, Sacramento, CA, Oct. 15-18, 2017.
- Webinar on Battery Sizing for the Smart Home, driven by **foresee**, was delivered.*(paper in development)* Slides: https://www.nrel.gov/docs/fy18osti/70684.pdf & recording: https://attendee.gotowebinar.com/register/7159243851961563905

Most Impactful Publications:

X. Jin, K. Baker, D. Christensen, and S. Isley, "*foresee: A user-centric home energy management system for energy efficiency and demand response*." Applied Energy, 205,1 November 2017, pp. 1583-1595. https://doi.org/10.1016/j.apenergy.2017.08.166

K. Garifi, K. Baker, B. Touri, and D. Christensen, "*Stochastic Model Predictive Control for Demand Response in a Home Energy Management System*." *Accepted*, IEEE Power & Energy Society General Meeting, August 5-9, 2018.


Stochastic Model Predictive Control for Demand Response in a Home Energy Management System

R. Kadavil, S. Lurbe, S. Suryanarayanan, P. Aloise-Young, Steven Isley, and D. Christensen, "*An Application of the Analytic Hierarchy Process for Prioritizing User Preferences in the Design of a Home Energy Management System*." *Accepted*, Sustainable Energy, Grids and Networks.

Project Budget

Project Budget:

($k)	DOE	BPA	Bosch	Total
FY16	250	500	312	**1,062**
FY17	250	500	435	**1,185**
FY18, to date	186	200	13	**399**
FY18, remaining	64	50	70	**184**
Total	**750**	**1,250**	**830**	**2,830**

Variances: No significant variances. Bosch delivered all expected effort at slightly lower accrued cost share than initially expected.

Cost to date: $2,640k

Additional funding: non-BTO DOE **Extension to enhance project impact, $250k**

Budget History					
FY 2016 – FY 2017 (past)		FY 2018 (current)		FY 2019 *Project Concluded*	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$ 500k	$ 1,760k	$ 250k	$ 320k	N/A	N/A

Project Plan and Schedule

Planned start date: 10/1/2015
Actual start date: 5/1/2016
- Delayed start due to contracting
- Increased effort/spending & met Year 1 Go/No Go Milestone on time
- Met Year 2 Go/No Go Milestone on time

Project end date: 9/31/2018

Current work
- Laboratory scenario experiments underway
- Cyber penetration testing is underway

Next major milestone: Project completion

Task	Task Name	FY16				FY17				FY18			
		1	2	3	4	1	2	3	4	1	2	3	4
1	**Control Platform**												
1.1	Control Architecture												
1.2	Data Model												
1.3	Equipment Drivers												
2	**User Preference**												
2.1	Input Methodology												
2.2	Preferences to Control Inputs												
2.3	Demo User Interface												
3	**Advanced Controls**												
3.1	Reduced-Order Equipment Models												
3.2	MPC for each equipment model												
3.3	Self-learning algorithms												
3.4	Supervisory MCDM												
4	**Hardware Development**												
4.1	Battery Selection & Integration												
4.2	Bosch Connected Appliances												
4.3	Demonstrate Integration in ESIF												
5	**Performance Test & Validation**												
5.1	Develop test use cases												
5.2	Install equipment in ESIF												
5.3	Scenario Experiments												
5.4	Comfort Evaluation												
5.5	Final Demonstration												
6	**Cybersecurity (CIP)**												
6.1	Security Risk Analysis												
6.2	Security design and Specification												
6.3	Implement & deploy demo CIP												
6.4	Acceptance testing												
6.5	Penetration testing