NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Economic Sizing of Batteries for the Smart Home

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Presenter Introductions

Dane Christensen

Ph.D., Mechanical Engineering,
University of California, Berkeley
B.S., Mechanical Engineering, Rice
University

12 years of research and development experience in:

- *Zero energy homes,*
- *Advanced controls,*
- *Internet of things, and*
- *Laboratory evaluation of system performance.*

Co-principal investigator: Home Battery System for Cybersecure EE and DR:

- *Developing and demonstrating holistic, homeowner-friendly control of smart appliances and energy storage for solar-integrated homes*
- *Partnership with Bosch, with supported from Colorado State University*
- *Jointly funded by Bonneville Power Administration and US DOE*

Over 35 peer-reviewed publications, 3 patents and multiple software copyrights, patents pending, etc.

Xin Jin

Ph.D., Mechanical Engineering, Penn State University
M.S., Mechanical Engineering, Penn State University
M.S., Electrical Engineering, Penn State University
B.S., Mechanical Engineering and Automation,
Shanghai Jiao Tong University

10 years of research and development experience in:

- *Model-predictive control,*
- *Machine learning*
- *Building-grid integration,*
- *Grid interactive appliances, and*
- *Building diagnostics.*

Technical leader in:

- *Non-intrusive load monitoring,*
- *Machine learning,*
- *Sensors and controls, and*
- *Algorithm and prototype development of building energy management systems*

Over 30 peer-reviewed publications, numerous patents, software copyrights, patents pending, etc.

Sizing & Selection of Building-Integrated Batteries

Analytical Tools:

- EPRI StorageVET www.storagevet.com
- NREL ReOPT reopt.nrel.gov
- Several commercial offerings

Rules of thumb

Recent body of literature on design considering flexible loads. Examples include:

- Molderink, A., et al., *Management and Control of Domestic Smart Grid Technology.* IEEE Transactions on Smart Grid, 2010. 1(2): p. 109-119.
- Castillo-Cagigal, M., et al., *PV self-consumption optimization with storage and active DSM for the residential sector.* Solar Energy, 2011. 85: p. 2338-2348.
- Cao, S., A. Hasan, and K. Sirén, *Analysis and solution for renewable energy load matching for a single-family house.* Energy and Buildings, 2013. 65: p. 398-411.
- Masa-Bote, D., et al., *Improving photovoltaics grid integration through short time forecasting and self-consumption.* Applied Energy, 2014. 125: p. 103-113.
- Widén, J., *Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings.* Applied Energy, 2014. 126: p. 199-212.
- Jin, X., et al, *Foresee: A User-Centric Home Energy Management System for Energy Efficiency and Demand Response.* Applied Energy, 2017. 205, pp. 1583-1595.

Image sources: https://blog.pickmysolar.com/home-battery-backup-comparison-lg-sonnen
https://cleantechnica.com/2016/01/08/tesla-starts-off-2016-producing-delivering-powerwall/
https://sustainablerace.com/lg-chem-and-eguana-announce-premium-home-battery-system-for-north-america/31558/

Solar+Storage is a major market opportunity

Solar + batteries prepping to take over 10GW of US natural gas peaker power plant market

John Fitzgerald Weaver - Dec. 13th 2017 12:28 pm ET @SolarInMASS

https://electrek.co/2017/12/13/solar-batteries-to-take-10gw-natural-gas/

Solar+Storage can hit breakeven cost with existing technology

Energy Storage Paired with Solar More Cost Effective in MN Today

July 11, 2017

Energy Storage Paired with Solar Found to Be More Cost Effective in Minnesota Today than Natural Gas Peaking Plants

As federal policy on renewable energy is being rolled back, a new UMN-led report finds that when environmental benefits are considered combined energy storage and solar arrays can be a more cost-effective alternative in

https://twin-cities.umn.edu/news-events/energy-storage-paired-solar-more-cost-effective-mn-today

Home Battery System: Advanced HEMS and Battery Sizing

Description

Develop cyber-secure Home Battery System (HBS) controls that deliver high-reliability demand response while avoiding negative homeowner impacts.

Technologies

Energy storage, connected home appliances, rooftop PV, grid. Designed to also work with EVs and wind.

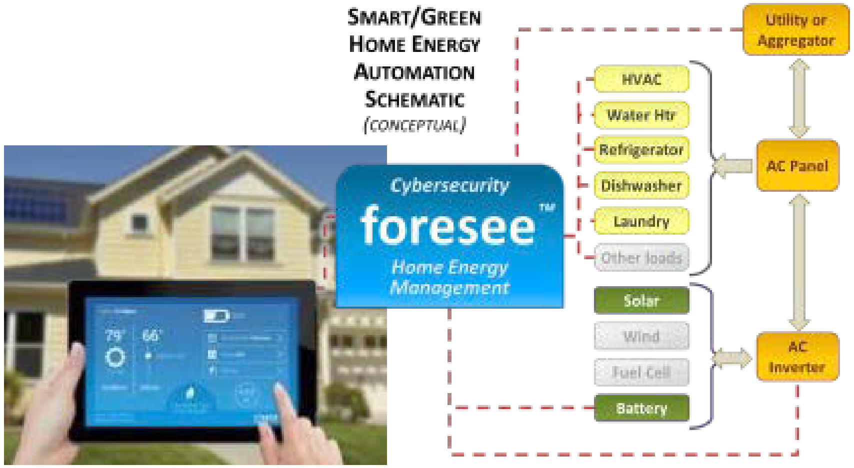
FY17 Notable Outcome

Develop first draft of methodology for Home Battery Sizing. NREL will develop an initial methodology for battery sizing (power and capacity) for application in “smart homes” with varying levels of control.

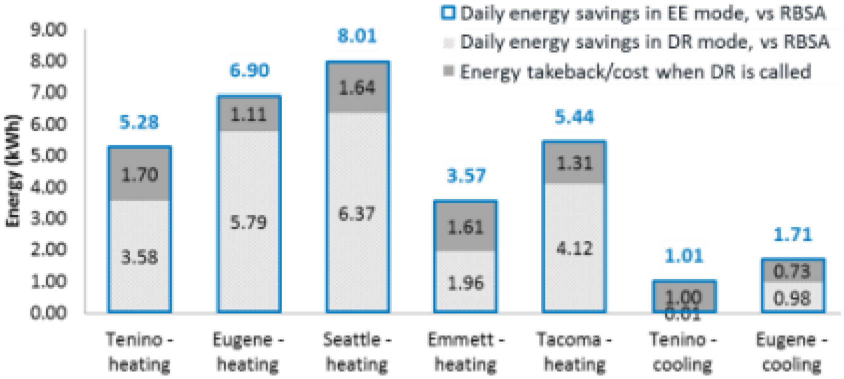
Impact

Enables standards for right-sizing home battery systems that is applicable to developers, appliance manufacturers, regulators and utilities nationwide as home automation is adopted.

Partners



Daily Energy Savings in EE & DR modes



Home Battery Sizing Research Questions

- How does a home battery benefit home owners?
- How does a home battery benefit electric utilities?
- How does smart appliances change how a home battery will be used?
- How do a home battery’s upfront cost and the associated benefit of a home battery compare to smart appliances alone?

Topics that are NOT considered in our preliminary study:

- Ancillary services – near future research
- Battery life modeling – near future research
- Islanded operation – future research

Findings of Preliminary Research

- **Smart appliances** may be necessary to ensure batteries are economically viable under many utility tariffs
- **Cost-Effectiveness** is dominated by two factors:
  - *Application type (new construction vs. retrofit solution)*
  - *Utility tariffs (flat rate vs. TOU, net metering vs. feed-in tariff)*
- **For homeowners**: Smaller batteries have shorter payback time periods
- **For Utilities**: Grid benefit increases with larger batteries
- **Location** has minor influences on operating cost savings and payback periods when smart appliances are considered

Comparative Evaluation: Baseline, HB & HEMS

A model-based dynamic approach for parametrically exploring the sensitivities of battery sizes to pertinent variables

Baseline Case

No battery, no smart appliances, no home energy management system (HEMS)

- Solar and traditional appliances (deadband-controlled) only

Home Battery (HB)

Battery is controlled by model-predictive controls to minimize energy cost and battery degradation

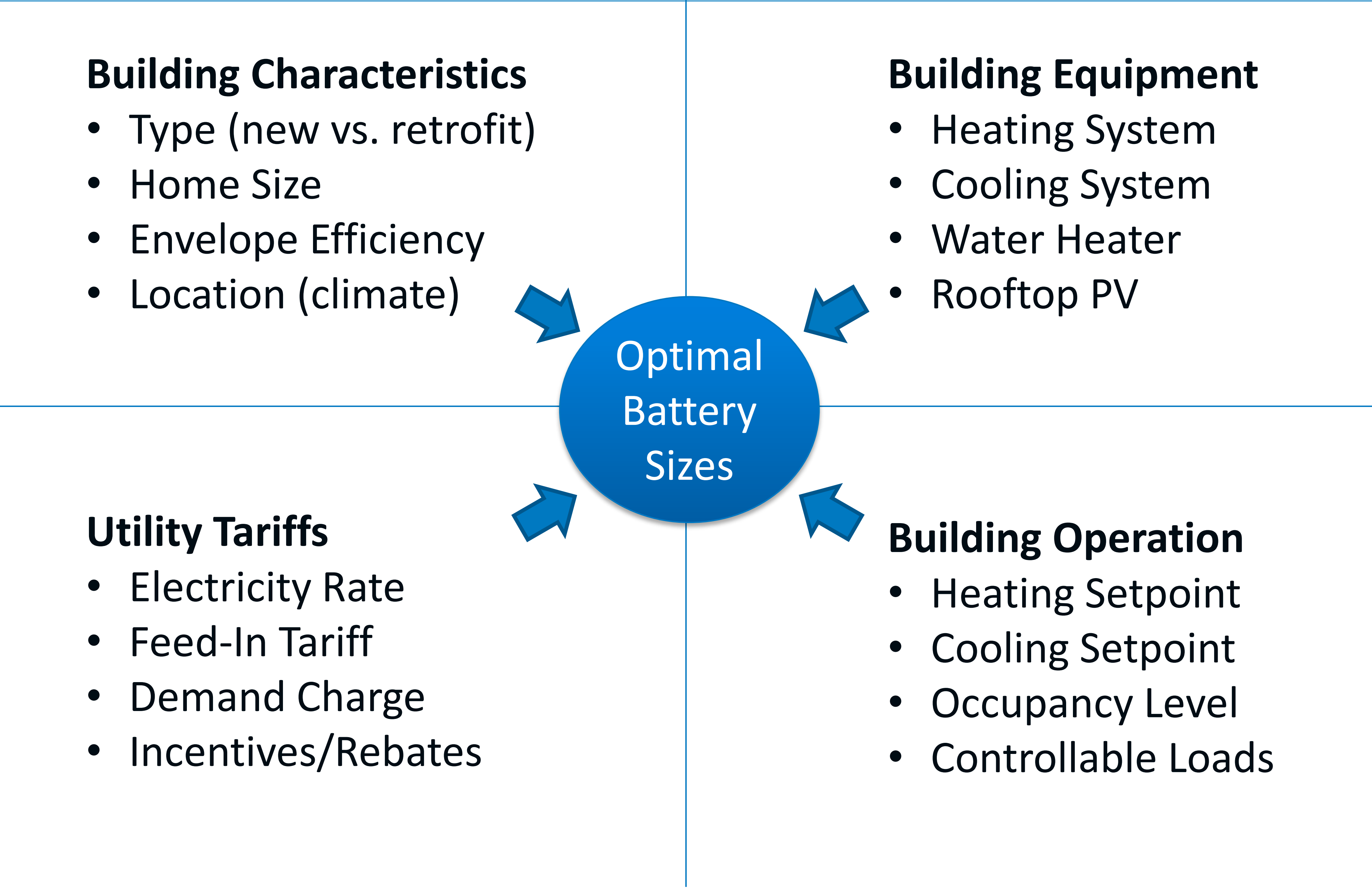
HEMS

Smart appliances including HVAC and water heater are controlled by model-predictive controls to minimize energy cost and thermal discomfort

HB + HEMS

Battery and smart appliances are controlled by model-predictive controls to minimize energy cost and thermal discomfort, as well as minimize battery degradation

Pertinent Parameters for Battery Sizing



Building Characteristics
- Type (new vs. retrofit)
- Home Size
- Envelope Efficiency
- Location (climate)

Building Equipment
- Heating System
- Cooling System
- Water Heater
- Rooftop PV

Optimal Battery Sizes

Utility Tariffs
- Electricity Rate
- Feed-In Tariff
- Demand Charge
- Incentives/Rebates

Building Operation
- Heating Setpoint
- Cooling Setpoint
- Occupancy Level
- Controllable Loads

Detailed List of Pertinent Parameters

Category	Parameter	# Levels	Levels
Battery Size	Battery Size	6	**0, 3, 6, 9**, 12, 15 kWh
Building Characteristics	Application Type	2	**New Construction, Retrofit**
	Home Size	5	1000, **2000**, 3000, 4000, 5860
	Envelope Efficiency	1	IECC 2009
	Location	6	BA Climate Zones (**2 in this study**)
Building Equipment	Heating System	2	**Electric Resistance**, ASHP
	Cooling System	2	**Central AC**, ASHP
	Water Heater	2	**Electric Resistance**, HPWH
	PV System	4	**0, 3, 6**, 9 kW
Building Operation	Heating SP Temp	3	67, **71**, 75
	Cooling SP Temp	3	72, **76**, 80
	Occupancy Levels	3	Low, **Medium**, High
	Controllable Loads	4	**None**, HVAC, Water Heater, **Both**
Utility Tariffs	Electricity Rate	2	**Flat, TOU**
	Feed-In Tariff	2	**Net Metering, FIT**
	Demand Charge	2	Yes, **No**

- Exhaustive parametric study would require millions simulations
- 132 scenarios in initial study

Our Approach: Model-based Parametric Analysis

Procedures for the parametric simulation:

1. Generate building models and validate against EnergyPlus, a high-fidelity whole building energy simulation program.
2. Load different combinations of parameters and perform annual simulations for every parameter combination
3. Post-process results using various metrics

Building Locations	Model	Water Heating Load (kWh)	HVAC Load (kWh)	Total Controllable Loads (kWh)
Phoenix	EnergyPlus	2099	9404	11503
	Our Models	1950	9932	11882
	Difference	-7.10%	5.61%	3.29%
Chicago	EnergyPlus	3676	21494	25170
	Our Models	3623	21426	25049
	Difference	-1.44%	-0.32%	-0.48%

Benefits of Home Battery Systems

- **Homeowner's Perspective**:
  - Internal Rate of Return
  - Operating Cost Savings
  - Payback Period
  - Battery Degradation
- **Utility's Perspective**:
  - Backfeed Reduction

Potential benefits of residential battery systems:

- **Cost**: economic benefit under certain utility tariffs
- **PV**: PV curtailment mitigation in high-penetration areas
- **Externalities:** reduce consumption of natural resources, improve air quality, etc.
- **Resilience**: backup power supply for emergency events
- **Grid**: reduction of power backfeed/reverse power flow

Parametric Details: HEMS Cost

Smart Home/HEMS

- Assumes whole-home model predictive control, with this study's objective to minimize costs and thermal discomfort
- Controlled appliances are HVAC, water heater & battery

- HEMS Hardware Cost
    - *HEMS: $100*
    - *Sensors: $250*
    - *Smart thermostat: $250*
    - *Smart water heater: $575 (water heater)* [a] *+ $40* [b] *(controller)*

  Total HEMS hardware cost: $1215

- HEMS Hardware Incentives
    - *HEMS: $0*
    - *Smart thermostat: $75*[c]
    - *Grid-connected water heater: $0*

  HEMS cost after incentives: $1140

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[a] A.O. Smith EnergySmart 50 Gal. Electric Water Heater. https://www.aosmithatlowes.com/products/electric-water-heaters/es12-50h55dv/

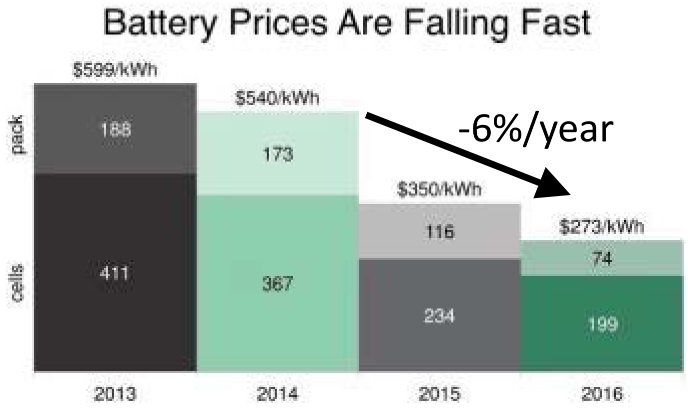
[b] EnergySmart Electric Water Heater Controller. https://www.lowes.com/pd/EnergySmart-Electric-Water-Heater-Controller/50292493

[c] Xcel Smart Thermostat Rebate. https://www.xcelenergy.com/programs_and_rebates

Parametric Details: Home Battery Cost & Utility Tariffs

Home Battery Systems

- Upfront Installed Cost
  - Retrofit Solution[a]
    - Inverter: $1,271/kW
    - Battery: $1,060/kWh
  - New Construction (Builders)[b]
    - Inverter: $630/kW
    - Battery: $338/kWh
    - Base Cost: $500
- Incentives[c]
  - SCE, SCG & PG&E: $400/kWh
  - SDGE: $350/kWh
- Annual Operational & Maintenance
  - $0 for residential HBS



Source: Bloomberg New Energy Finance

Utility Tariffs [d] *($/kWh)*

- Flat rate: 0.16
- Feed-In Tariff (FIT): 0.03
- Time Of Use (TOU):
  - Winter: 0.13 (off-peak), 0.27 (mid-peak), & 0.34 (on-peak)
  - Summer: 0.13 (off-peak), 0.28 (mid-peak), & 0.45 (on-peak)
  - Weekends: On-peak is at mid-peak costs

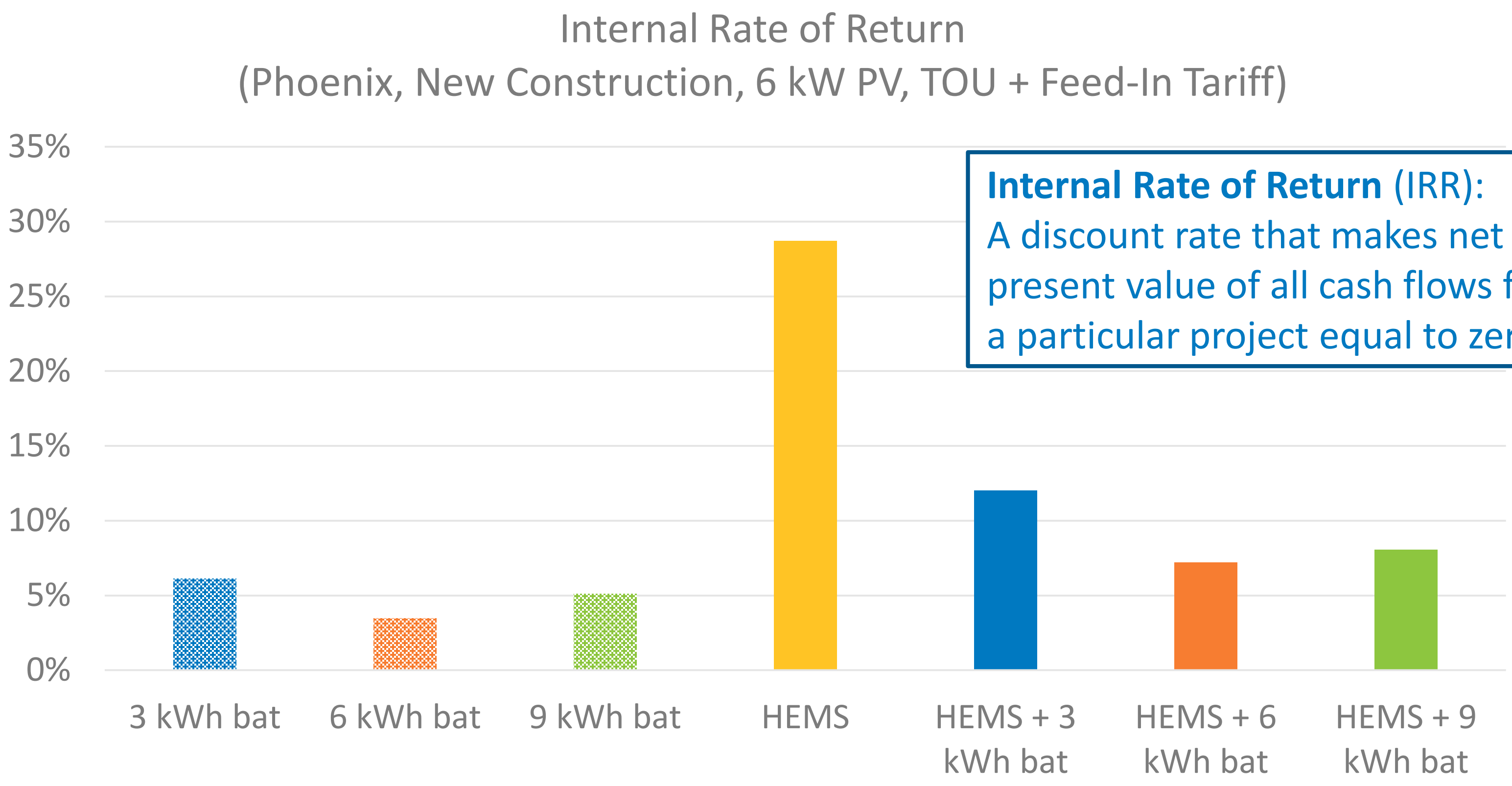
[a] O'Shaughnessy et al. Solar Plus: A Holistic Approach to Distributed Solar PV. NREL/TP-6A20-68371.

[b] Based on the price quote from a battery manufacturer plus $500 builder installation cost

[c] Self-Generation Incentive Program. https://www.selfgenca.com/home/program_metrics/

[d] Based on Southern California Edison rates (TOU-D-A). https://www.sce.com/wps/portal/home/residential/rates/Time-Of-Use-Residential-Rate-Plans

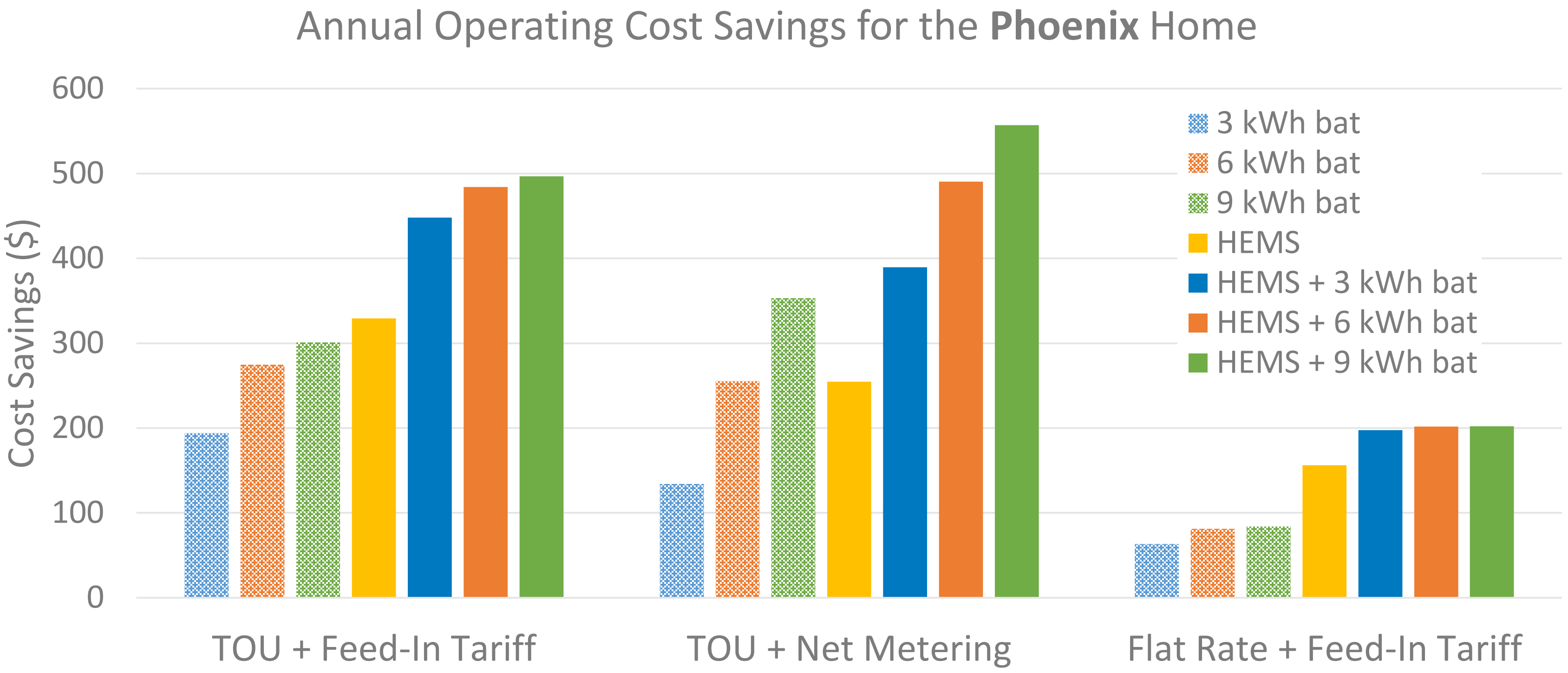
Homeowner's Perspective – Internal Rate of Return



Internal Rate of Return (IRR):
A discount rate that makes net present value of all cash flows from a particular project equal to zero

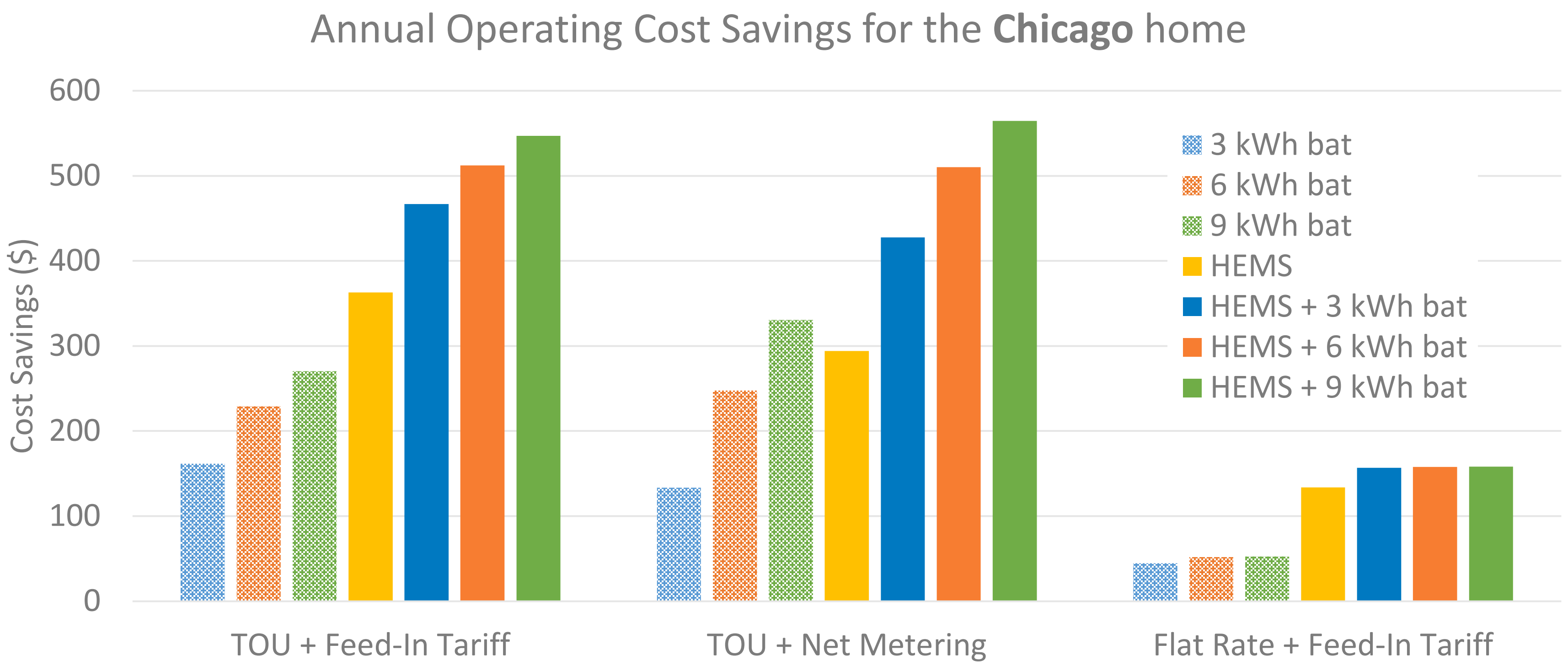
- HEMS-only solution has highest IRR whereas battery-only solution has lowest IRRs
- In general, larger batteries have lower IRRs due to the incremental hardware cost
- Combining battery with HEMS significantly increases the IRRs compared to the battery-only cases

Homeowner’s Perspective – Annual Operating Cost Savings



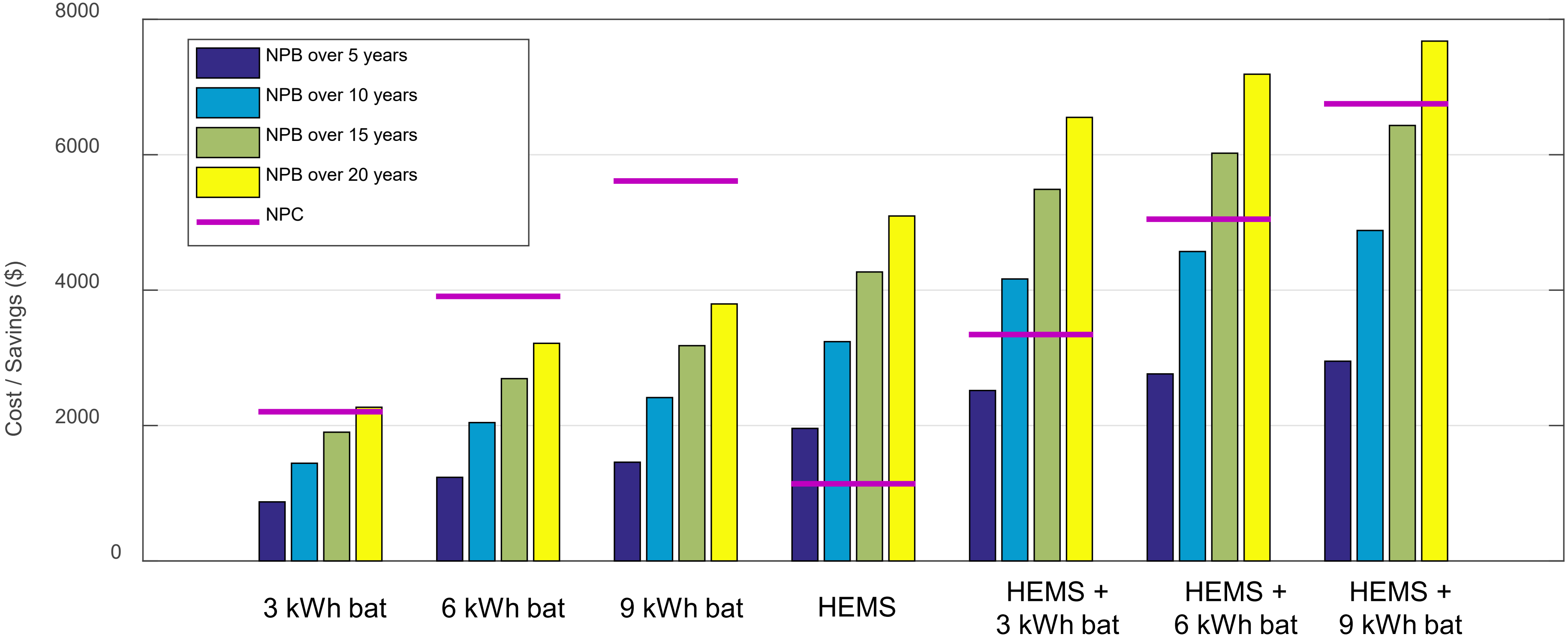
- **For homes with batteries only**, increasing the battery size does not significantly improve the annual operating cost savings in the presence of feed-in tariff
- **For homes with HEMS**, adding a small battery improves annual operating cost savings, but adding larger batteries is less cost-effective without net metering
- **Utility tariffs** have significant impact on annual operating cost savings. The same solution has more cost savings under TOU and little cost savings under flat rate.

Homeowner's Perspective – Annual Operating Cost Savings



- Location has **minor influences** on the annual operating cost savings. The results are very similar to the ones of the Phoenix home.
- Compared to the Phoenix home, the Chicago home has slightly more cost savings under TOU + Feed-In Tariff and less cost savings under Flat Rate + Feed-In Tariff.

Homeowner’s Perspective – Payback Period (TOU + FIT)

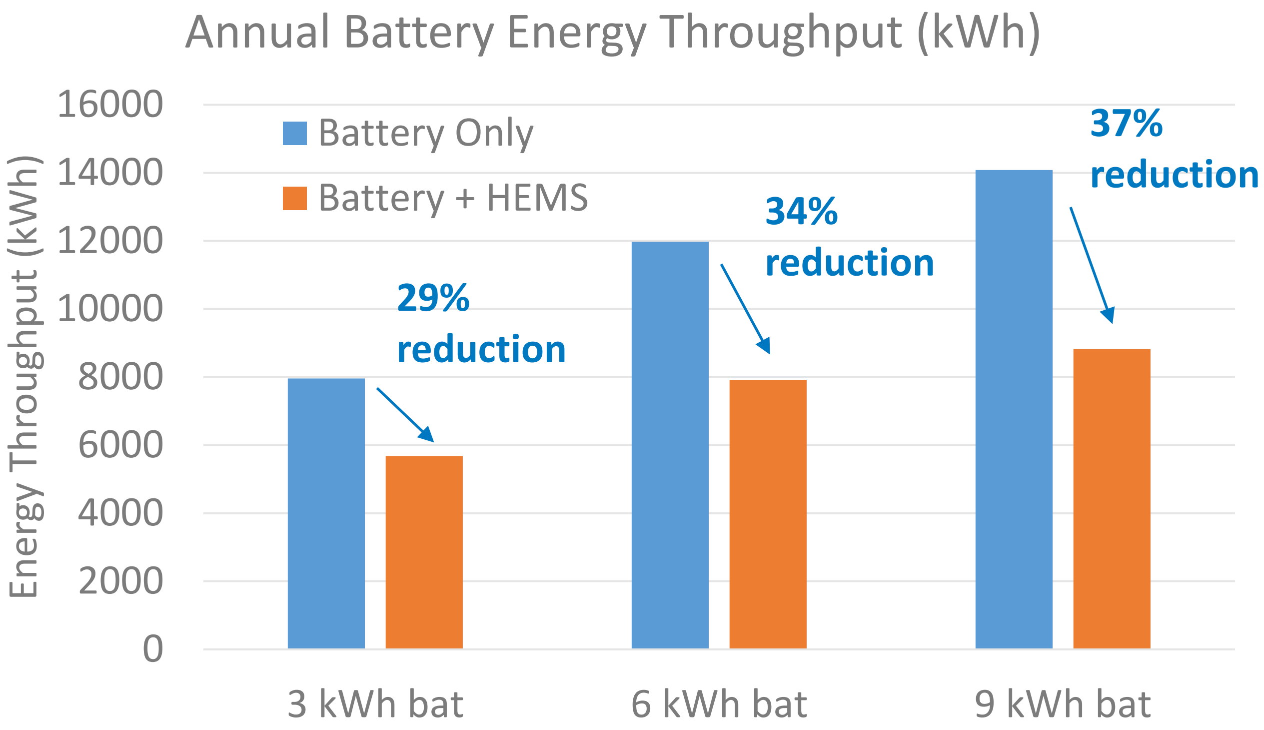


Net Present Benefit (**NPB**): Discounted cumulative benefits of reduced electricity bills over the evaluated period

Net Present Cost (**NPC**): Cumulative discounted cost of the system, including initial cost, incentives, and O&M

- Without incentives, **HEMS-only** solution becomes cost-effective in less than 5 years whereas **battery-only** solutions are not cost-effective even over 20 years
- **HEMS + 3 kWh bat** breaks even between 5-10 years, **HEMS + 6 kWh bat** breaks even between 10 and 15 years, and **HEMS + 9 kWh bat** breaks even right after 15 years

Homeowner’s Perspective – Battery Degradation (TOU + FIT)

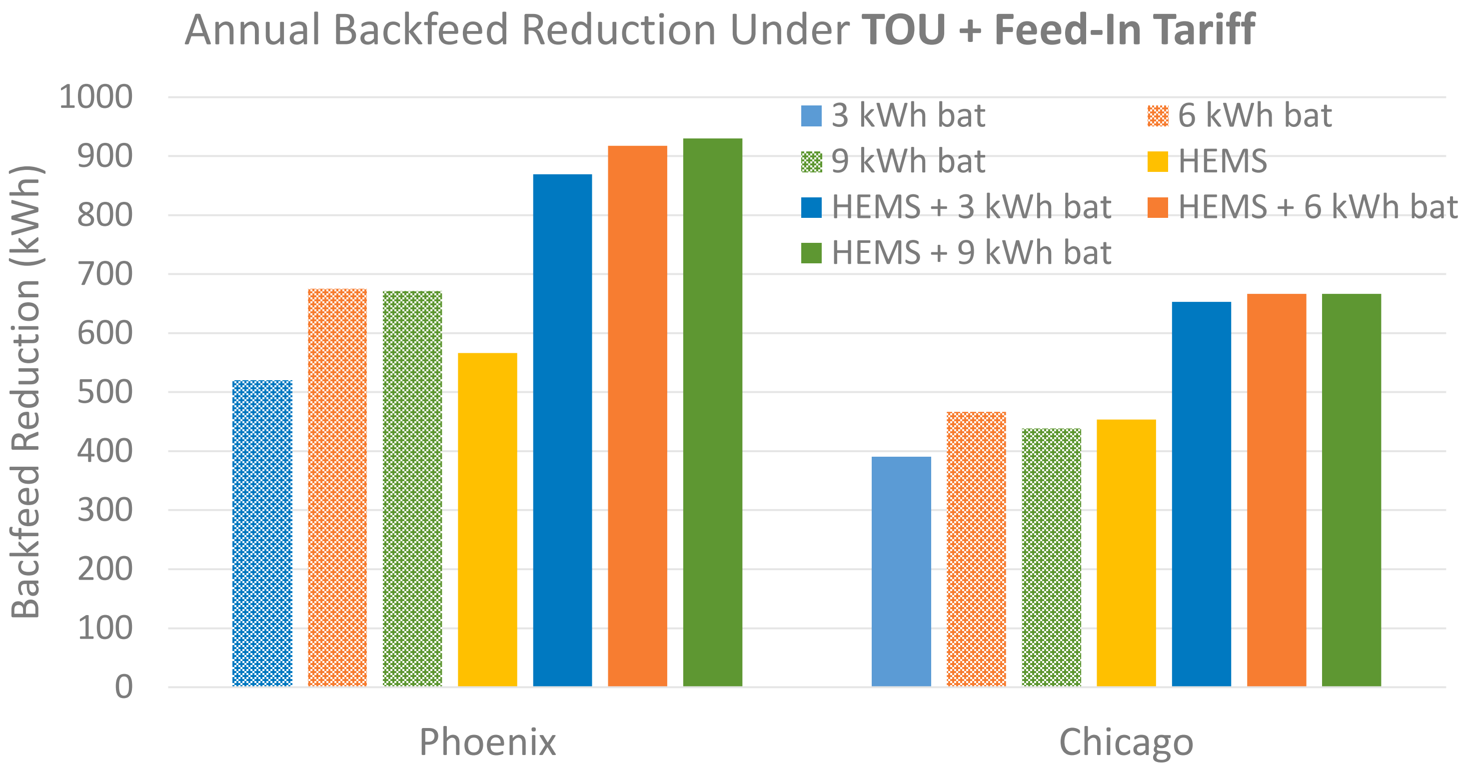


Other contributing factors of battery degradation:

- Temperature
- Depth of discharge
- Resting SOC
- C-rates

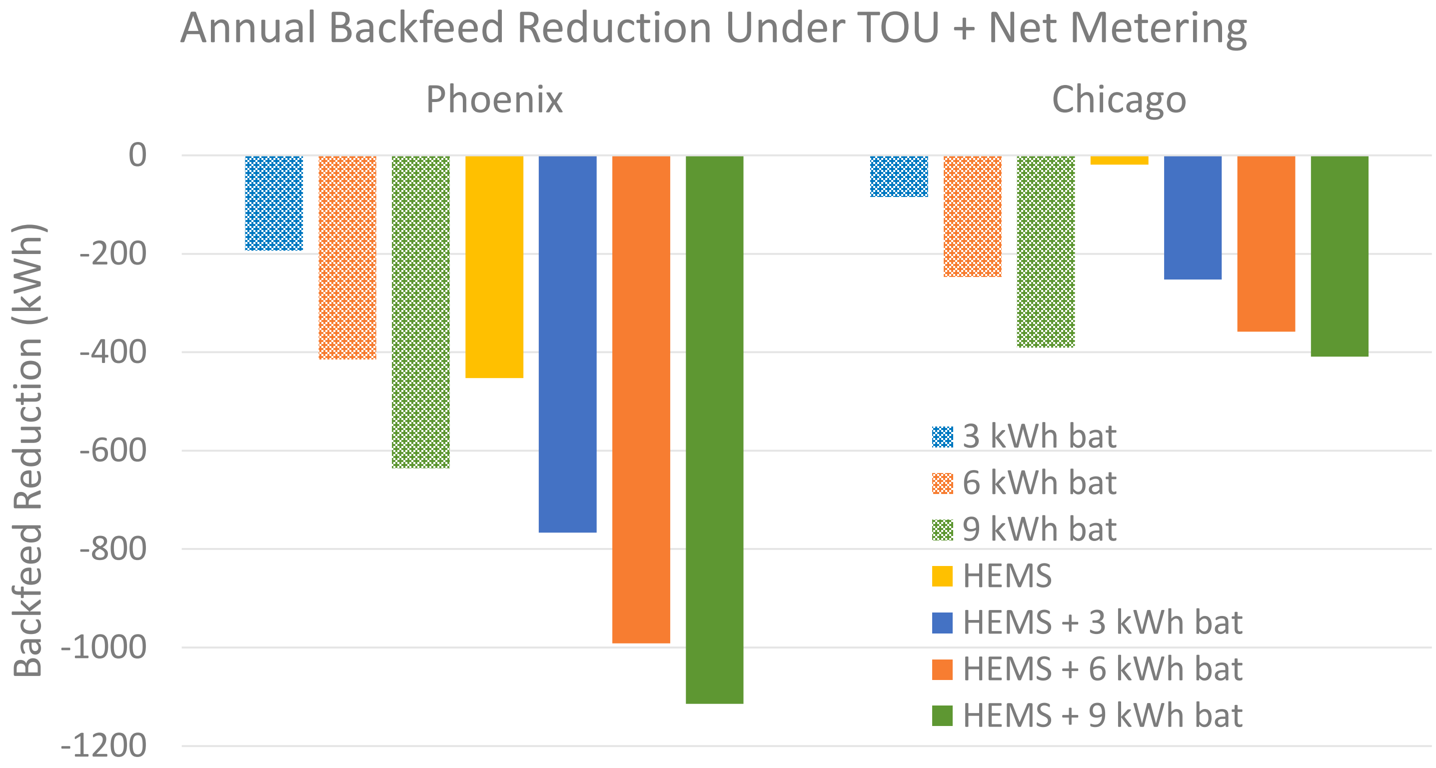
- Combining battery with HEMS significantly reduces the battery cycling fade in terms of energy throughput and extends the battery lifetime
- Larger battery has higher percentage reduction of energy throughput
- Future research includes incorporating battery life model to quantify the battery degradation in terms of capacity loss

Utility's Perspective - Annual Backfeed Reduction



- Large batteries have little incremental contribution to backfeed reduction
- 3 kWh battery, HEMS, and their combinations are the most cost-effective solutions for backfeed reduction
- The Phoenix home has more backfeed reduction because Phoenix has better solar resources than Chicago and thus higher probabilities of backfeed

Utility’s Perspective - Annual Backfeed Reduction

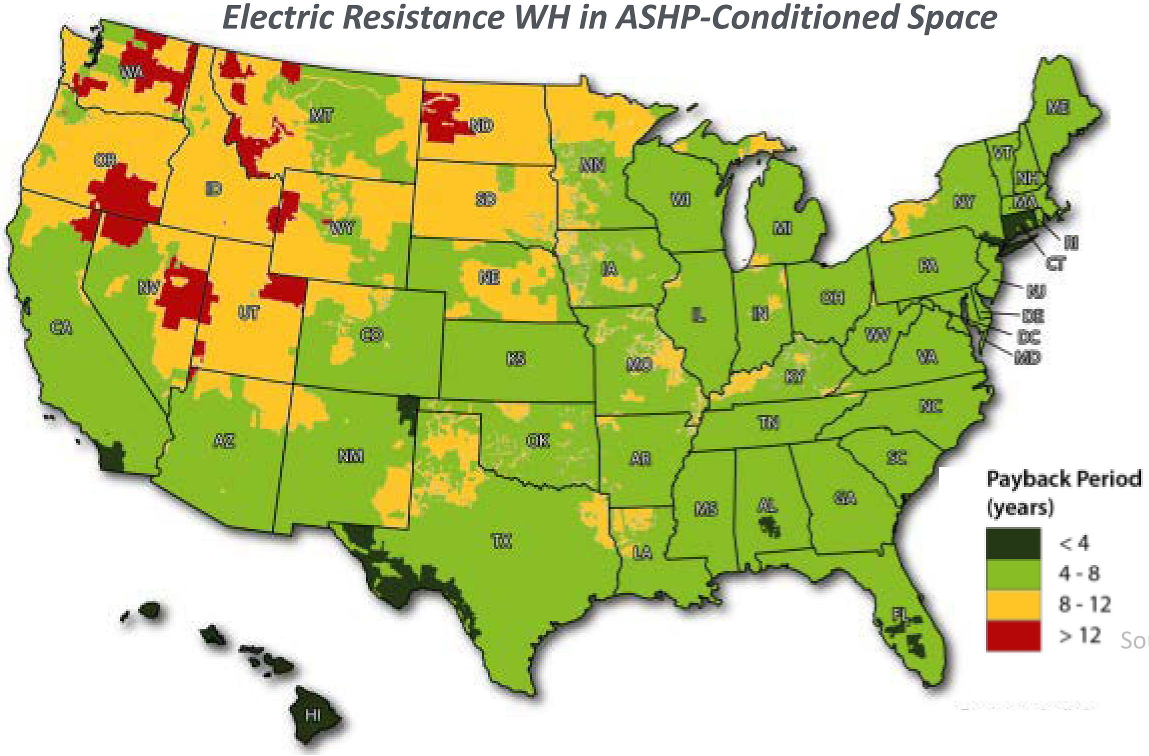


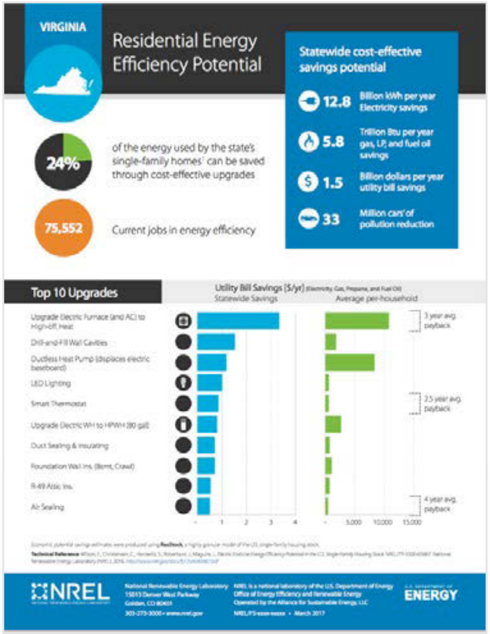
- Feed-in tariffs reduce power backfeed whereas net metering encourages backfeed.
- Under TOU and net metering rate structure, all solutions perform energy arbitrage for the economic gain, thus losing backfeed reduction benefits.
- Backfeed reduction is more location dependent than other metrics

Next Steps

- Conduct parametric study that expands the parameter space
- Further refine sizing method
- Apply methodology to U.S. housing market opportunity space
- Develop public materials & stakeholder collateral, similar to other NREL products:

Estimated GE 50-gal HPWH payback, when replacing Electric Resistance WH in ASHP-Conditioned Space




VIRGINIA

Residential Energy Efficiency Potential

24% of the energy used by the state's single-family homes¹ can be saved through cost-effective upgrades

75,552 Current jobs in energy efficiency

Statewide cost-effective savings potential

12.8 Billion kWh per year Electricity savings

5.8 Trillion Btu per year gas, LP, and fuel oil savings

1.5 Billion dollars per year utility bill savings

33 Million cars² of pollution reduction

Top 10 Upgrades

Utility Bill Savings ($/yr) (Electricity, Gas, Propane, and Fuel Oil)

Statewide Savings | Average per-household

- Upgrade Electric Furnace (and AC) to High-Eff. Heat
- Drill-and-Fill Wall Cavities
- Ductless Heat Pump (displaces electric baseboard)
- LED Lighting
- Smart Thermostat
- Upgrade Electric WH to HPWH (80 gal)
- Duct Sealing & Insulating
- Foundation Wall Ins. (Bsmt, Crawl)
- R-49 Attic Ins.
- Air Sealing

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Sources: "Heat Pump Water Heater Technology Assessment Based on Laboratory Research and Energy Simulation Models." NREL Report No. CP-5500-51433. Map by Billy Roberts, NREL. Draft (unpublished) state-level residential energy efficiency potential fact sheet, based on NREL ResStock.

Findings of Preliminary Research

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Thank you!

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