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Demand Response Capability of Heat Pump Water Heaters

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Sarah Widder
Research Engineer
Pacific Northwest National Laboratory

Outline

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- Background on Demand Response and Water Heating
- Background on Heat Pump Water Heaters
- Issues Related to Heat Pump Water Heaters Providing Demand Response Services
- Summary and Conclusions

Types of Demand Response Services

Duration

- Load Shifting
  - 3 – 6 hour reductions or deferments in load to help handle peak or capacity constraints
- Load Balancing
  - 1 – 2 hour modulations in load to help accommodate variable energy resources
- Regulation/ancillary services
  - 4 sec – 2 minute modulation of loads in response to voltage, frequency, or Area Control Error (ACE) deviations

Direction

- INC
  - Too much demand; need to *increase* generation or decrease load
- DEC
  - Too much generation; need to *decrease* generation or increase load

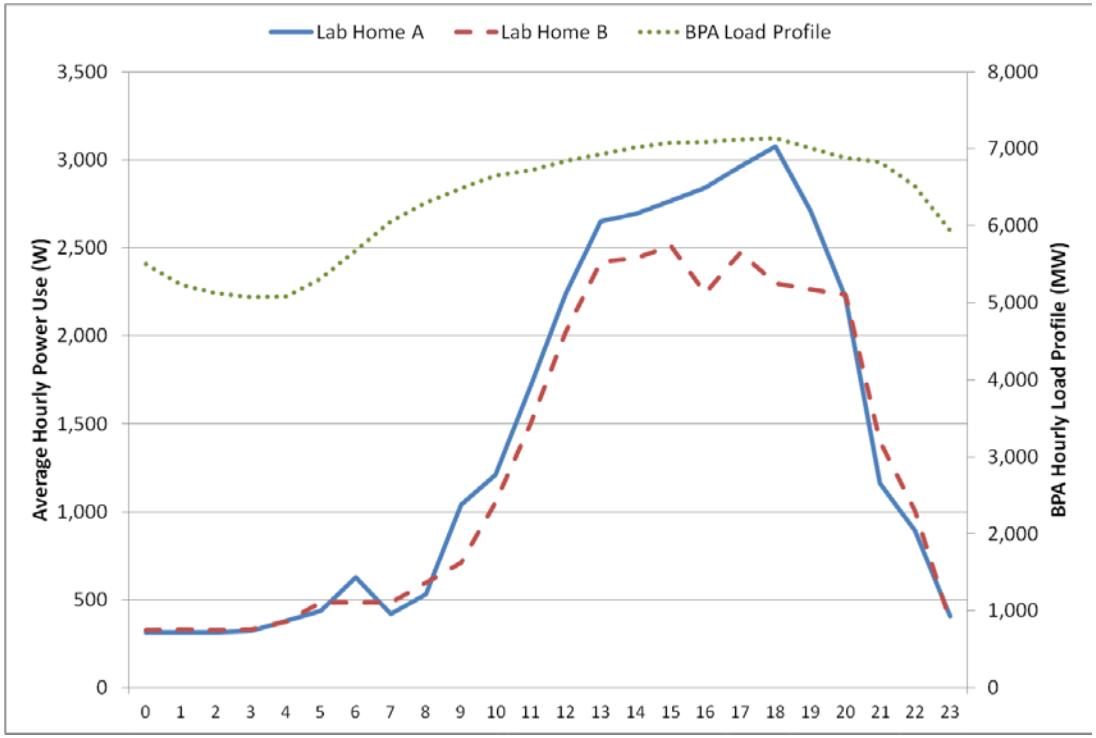
Load Shifting

- Also known as “peak shaving,” “peak load reduction,” “peak curtailment,” “electric thermal storage”

- Reduction or deferment of noncritical loads for a period of 4–6 hours during the time when power use is highest and the strain on the grid is greatest.

- Can decrease use of inefficient, fossil fuel-fired “peaking plants” that exist solely to generate electricity during the peak 4–6 hour period and are otherwise turned down or off.

- Can utilize excess capacity when demand is low



Load Balancing

- Also know as “balancing reserves” or “load following”
- Responds to hourly or sub-hourly changes in generation capacity either due to inherent variability in the generation resource or large disturbances in the grid (e.g., transmission fault).
- As increasing amounts of wind and solar are introduced on the grid, the need for balancing to respond to fluctuations in wind speed or solar insolation will be needed.
- Using DR for balancing reserves can also increase overall grid efficiency and decrease stress on mechanical generators from frequent ramping.

Load Balancing

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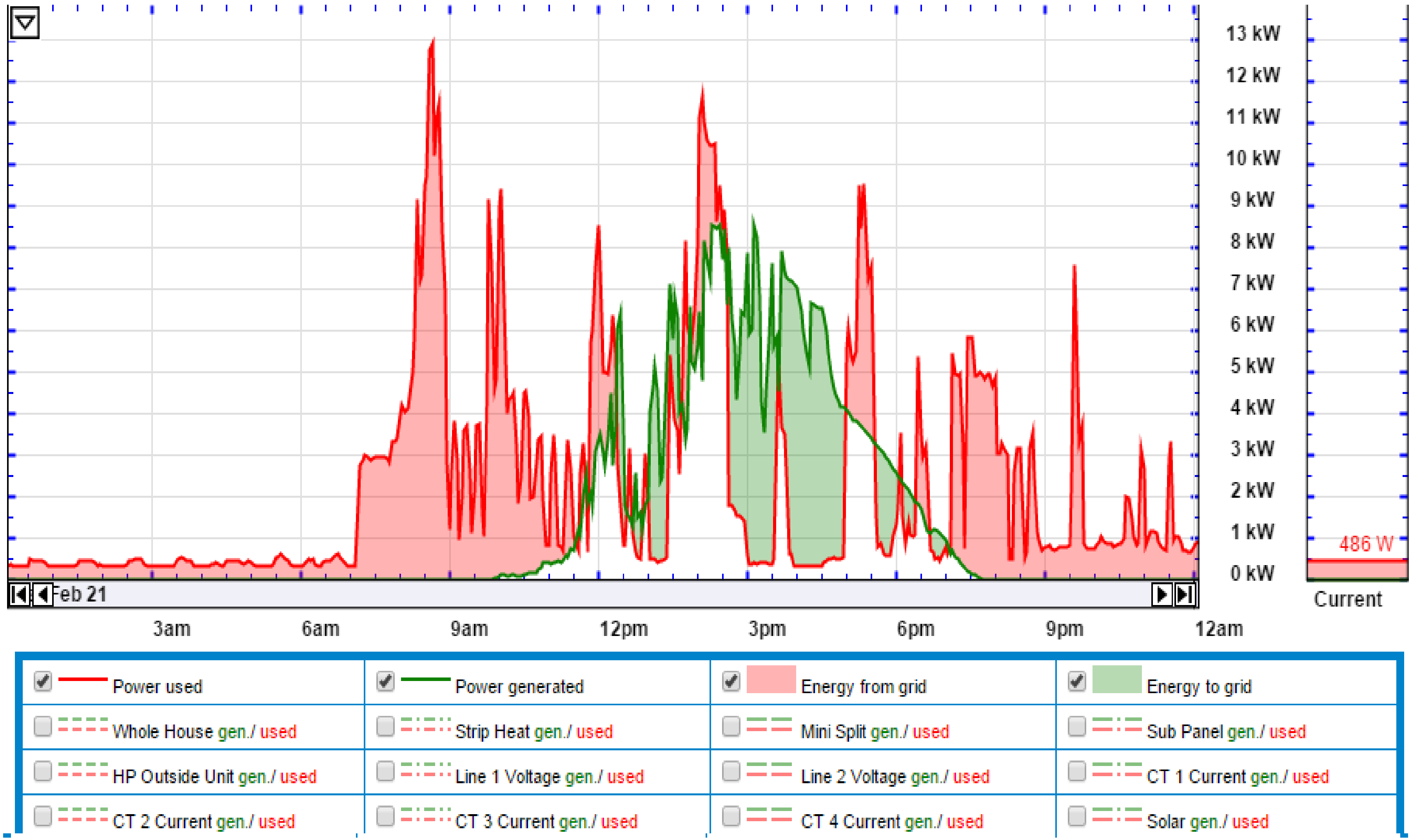

Regulation

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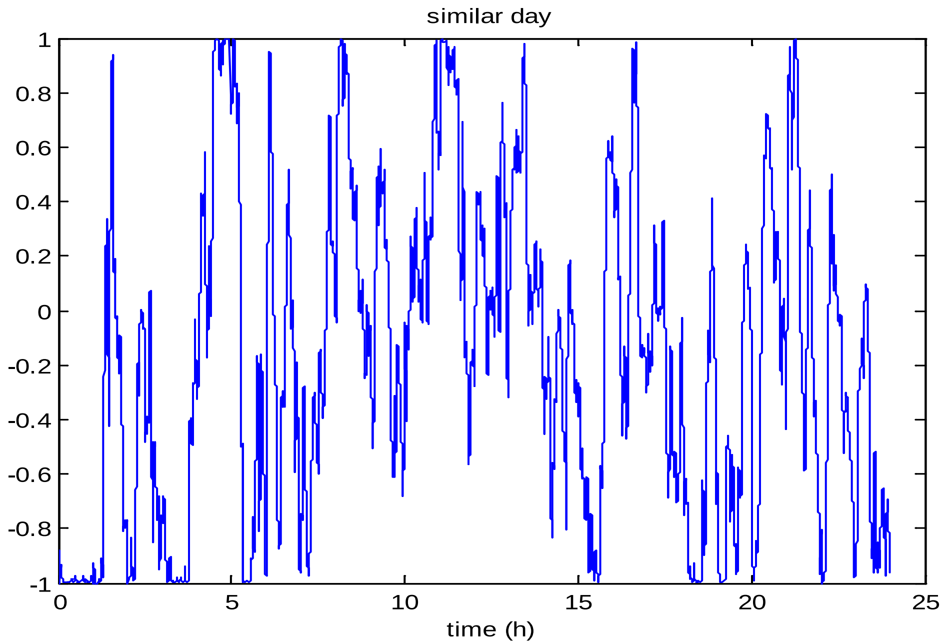
- Also known as "ancillary services" or "regulation support"
- Consists of adapting to sub-minute fluctuations in voltage or frequency to maintain consistent electricity service and distribution.
- Can be described in terms of "area control error" (ACE)
  - Consists of both voltage and frequency bias
  - Sent in 4-second to 1- to 2-minute timeframe
  - INC and DEC

Typical "Area Control Error" (ACE) Regulation Signal
From the PJM Regulation Signal Sent to the MidAtlantic Control Zone in 2009



Water Heaters and Demand Response

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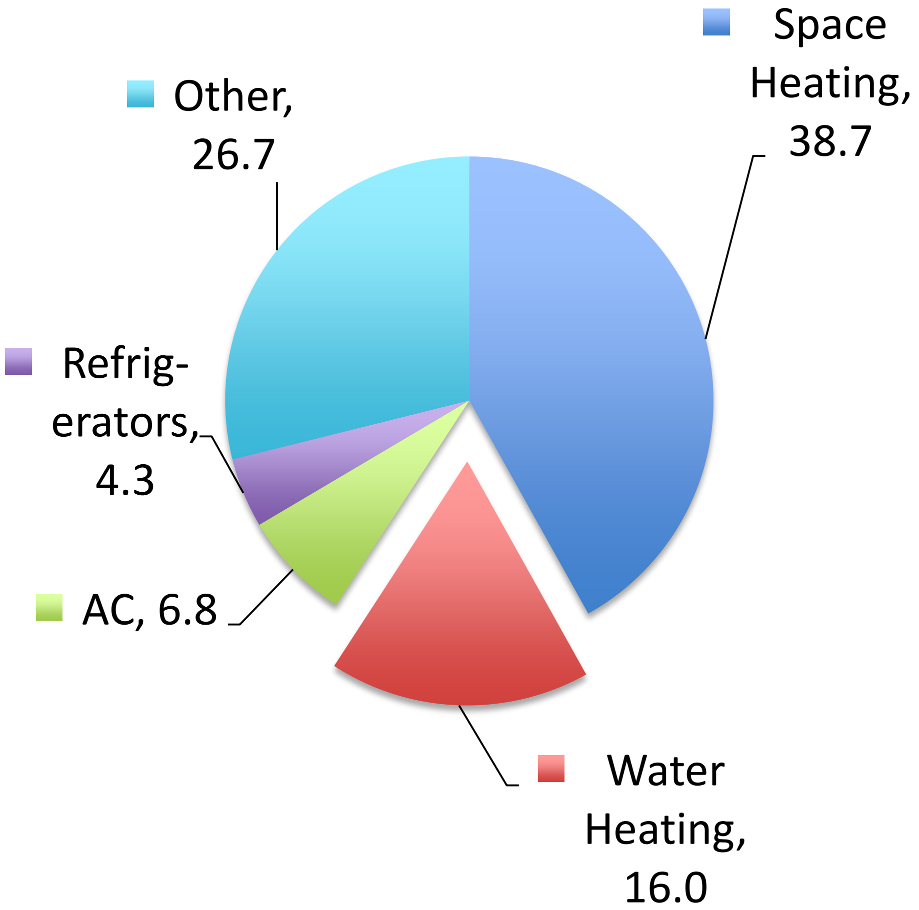
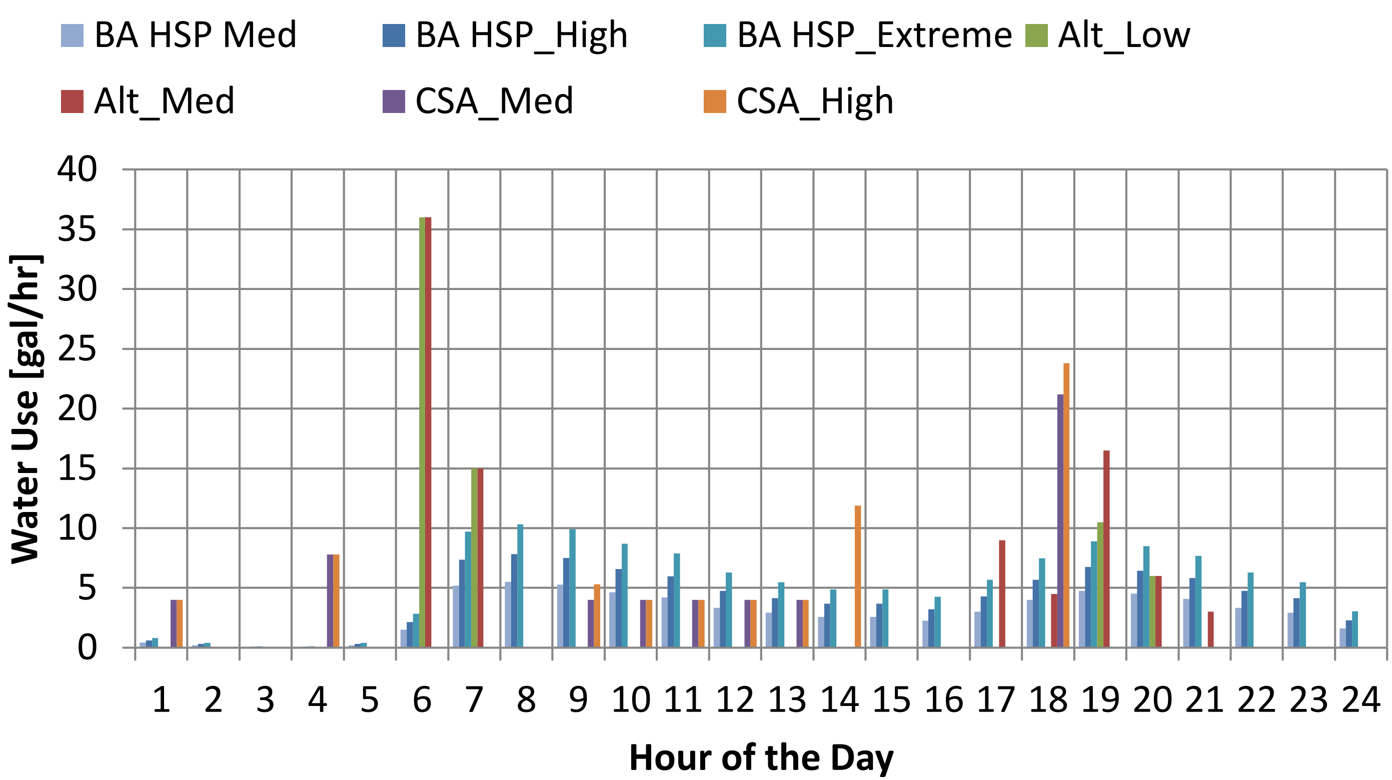
- Water heaters are ideal for providing demand response services because:
  - they have a large amount of thermal storage so their electrical energy input can be changed with minimal impact on the utility of the appliance
  - they contribute a significant amount of the residential load
  - they have relatively high power consumption and a large installed base
  - they follow a consistent load pattern that is often coincident with utility peak power periods

Average Site Energy Consumption (million Btu per household)
RECS, 2009



Hot Water Draw Profile



Profile	Daily Hot Water Use *[gal/day]*
BA HSP Med	69
BA HSP High	98
BA HSP Extreme	130
Alt Low	68
Alt Medium	81
CSA Med	53
CSA High	69

Existing Water Heating Demand Response Programs

- Utilities currently use ERWH in demand response programs to, primarily, manage peak load and shift load of off-peak periods.
  - ~2.0 million controlled ERWHs in US
    - Vast majority of tanks installed for peak-shaving
      - Storage programs are emerging, but make up small share of controlled WH population currently
    - Mostly in South and Midwest
      - 50% in investor-owned utility programs
      - 40% in rural electric co-ops
      - 10% public power
    - Rural co-ops are the most active utility type on per customer basis

Electric Thermal Storage Programs and Tank Size

- Utilities currently utilize a mix of tank sizes in these programs
  - An estimated 80% of utility-controlled tanks are *less than* 55 gallons currently
- However larger storage tanks provide additional storage capacity:
  - ensure that participating customers have sufficient hot water during the peak period when electricity is not provided and no water heating can occur
  - provide increased thermal capacity to absorb excess energy at off-peak times

Benefits of Demand Response

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- Reduces costs of operating and increases efficiency of operating the power grid and providing electricity through:
  - deferred investment in additional capacity
  - save on whole-sale power costs with off-peak energy use
  - reduction in operating of peaking plants
- Decreases carbon intensity of power grid through:
  - reduction in operating of peaking plants
  - increased ease of integrating variable renewable resources
- Improves reliability of service and may reduce outages through:
  - faster and more localized response to generation outages or transmission failures

Heat Pump Water Heaters

- HPWH can provide up to 62% energy savings over ERWH.[1]
  - Field data have demonstrated an average of approximately 50% water heating energy savings, depending on occupancy, control strategy, climate, and install location
- Increasing market penetration of HPWHs
  - New efficiency standards require 55-gal or larger water heaters to be HPWHs beginning on April 16, 2015. 75 FR 20112 (April 16, 2010)
  - A waiver process for large tank ERWHs has been proposed, but is not yet final. 78 FR 12969 (Feb. 26, 2013).
- Currently, market adoption and utility program incentives of HPWHs are limited due to lack of understanding and field data regarding:
  - Impact on space conditioning energy consumption and occupant comfort
  - Impact on demand response programs

[1] Based on the DOE test procedure and comparison of an electric tank water heater (EF=0.90) versus a heat pump hot water heater (EF=2.35)

Frequently Cited Issues Associated with HPWHs and DR

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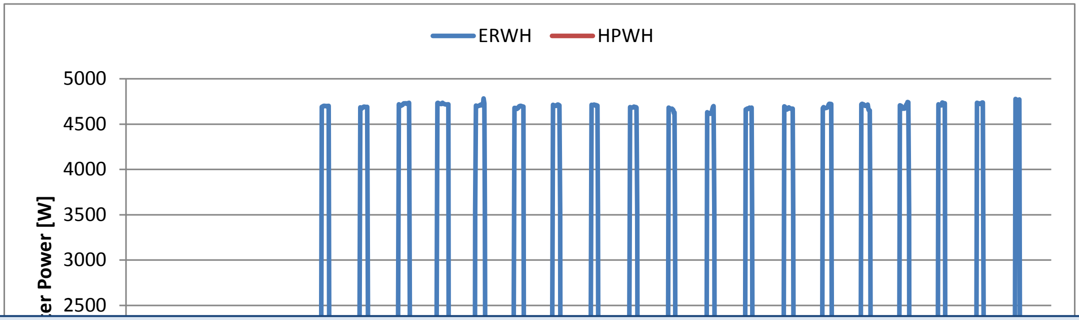
Issue #	Summary of Issue
Issue # 1: "Dispatchable Power"	HPWHs cannot provide similar levels of peak-load reduction services as ERWHs
Issue #2: Hot Water Availability	HPWHs require longer time than ERWHs to recover water temperature, which leads to low water delivery temperatures
Issue #3: Lifetime	Using HPWHs for DR will negatively impact the product's service life due to excessive compressor cycling
Issue #4: Thermal Comfort	HPWHs vent cold air into conditioned space and require large amounts of space to operate effectively
Issue #5: Tank Temperature	HPWHs are limited in their storage capacity because their storage temperature is limited
Issue #6: Cost	HPWHs will increase cost of DR programs

Issue # 1: “Despatchable Power”

HPWHs have reduced “dispatchable power” availability

- “Dispatchable power” = *f*(power, availability)

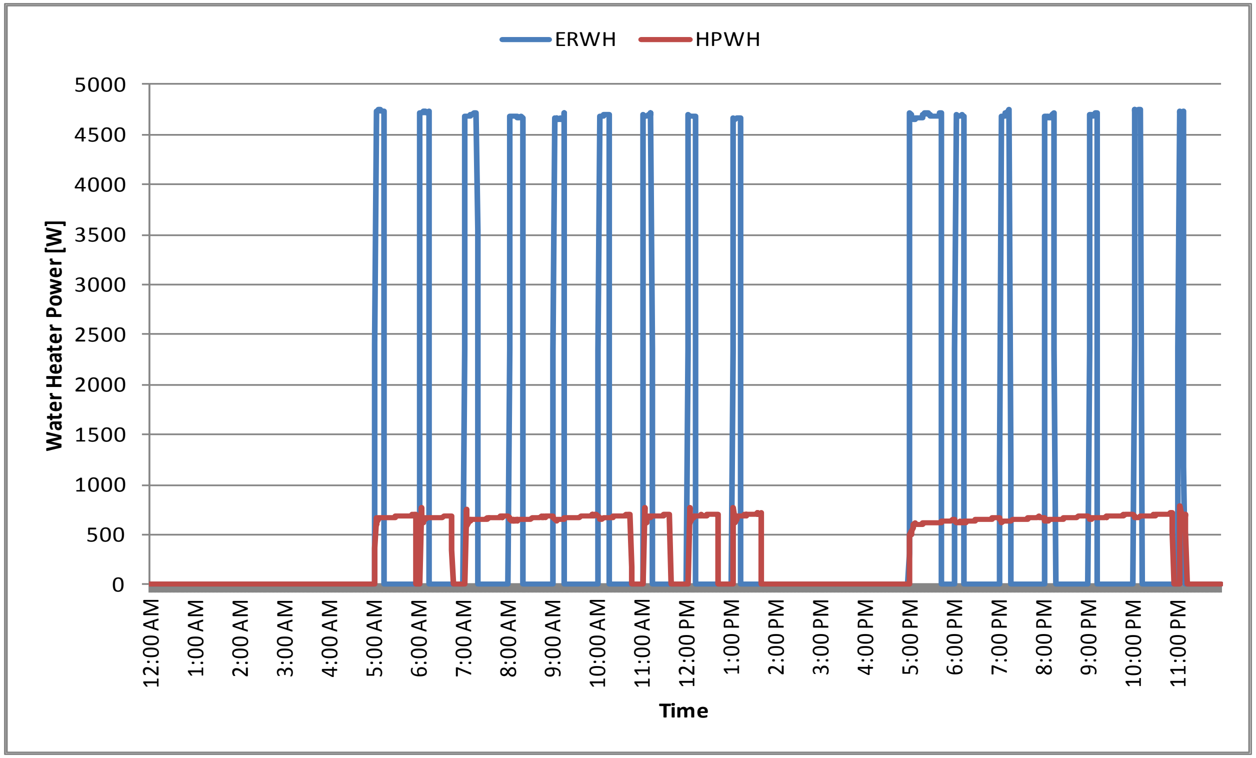
- Power is fixed for a given water heater
  - E.g. -> ERWH = 4,650W;   HPWH = 587W



$$\boldsymbol{Theoretical\ Number\ Equivalent\ HPWH} = \frac{ERWH\ Power\ Use\ [W]}{HPWH\ Power\ Use\ [W]} = \frac{4{,}650\ W}{587\ W} = 7.9$$

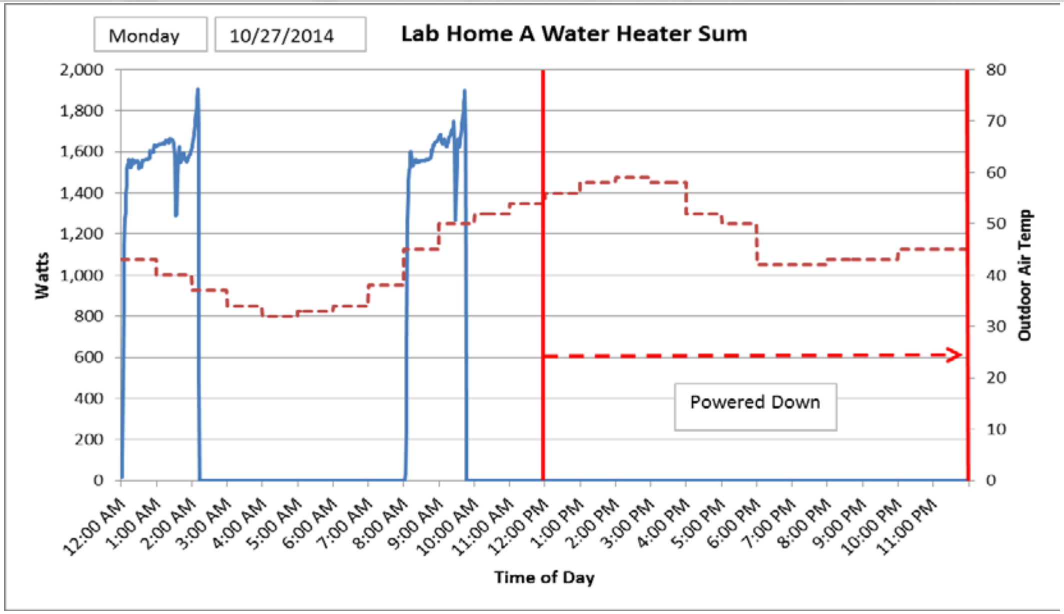
$$\rightarrow 8\ HPWH/ERWH$$

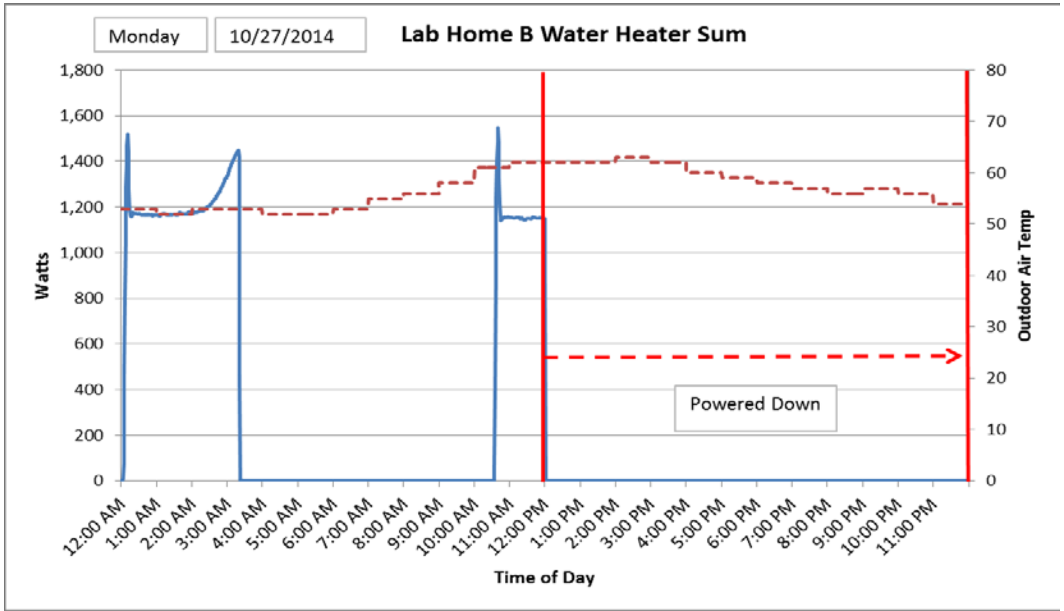
HPWH Power Consumption



- However, HPWH operates much more than ERWH
  - ERWH = 18% of 3 hr event
  - HPWH = 54% of 3 hr event
- Availability:
  - Function of how often the water heater is “on” or “off” and available to respond
  - Inversely related to power input for a given load

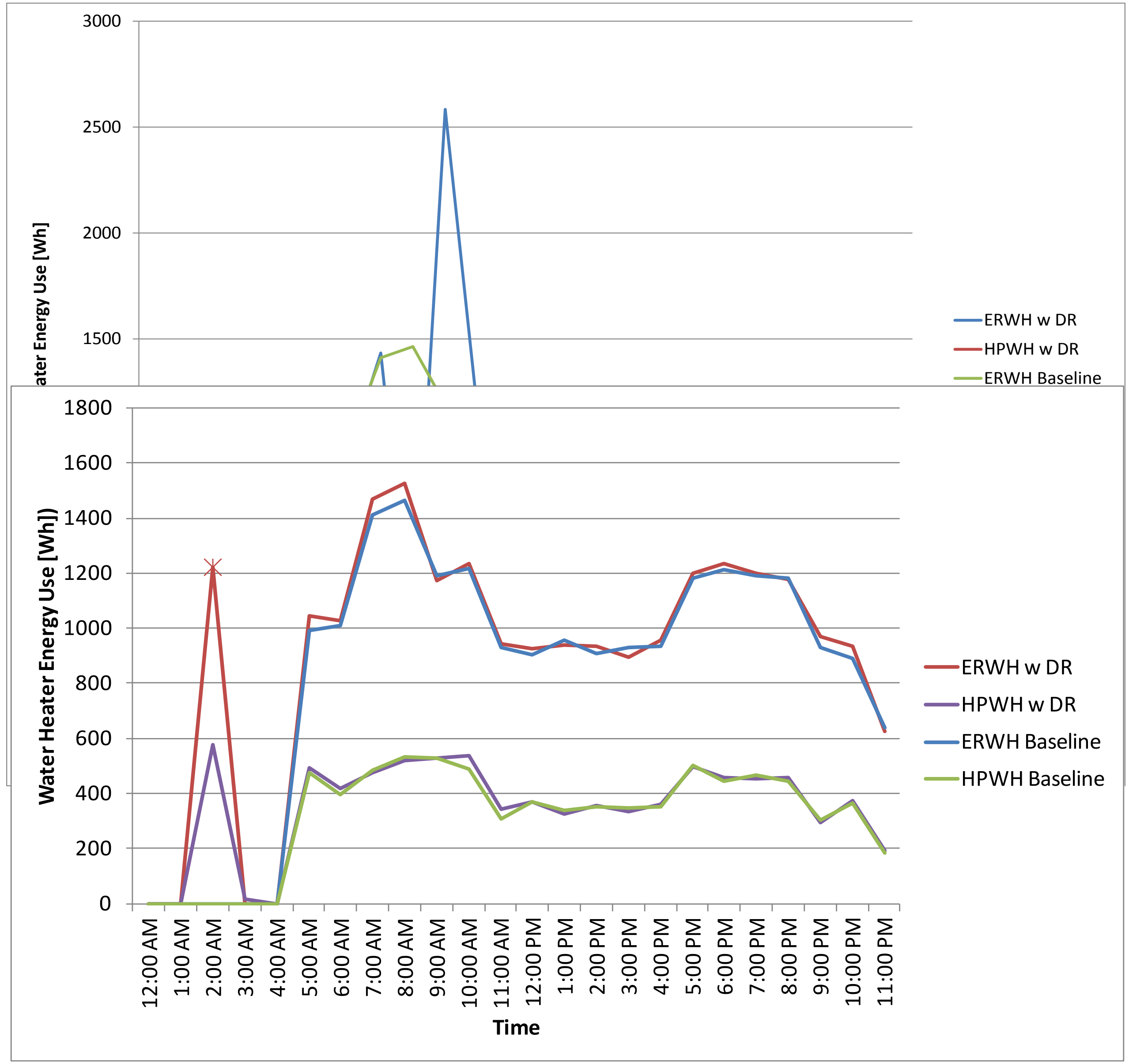
Example with CO_2 HPWHs



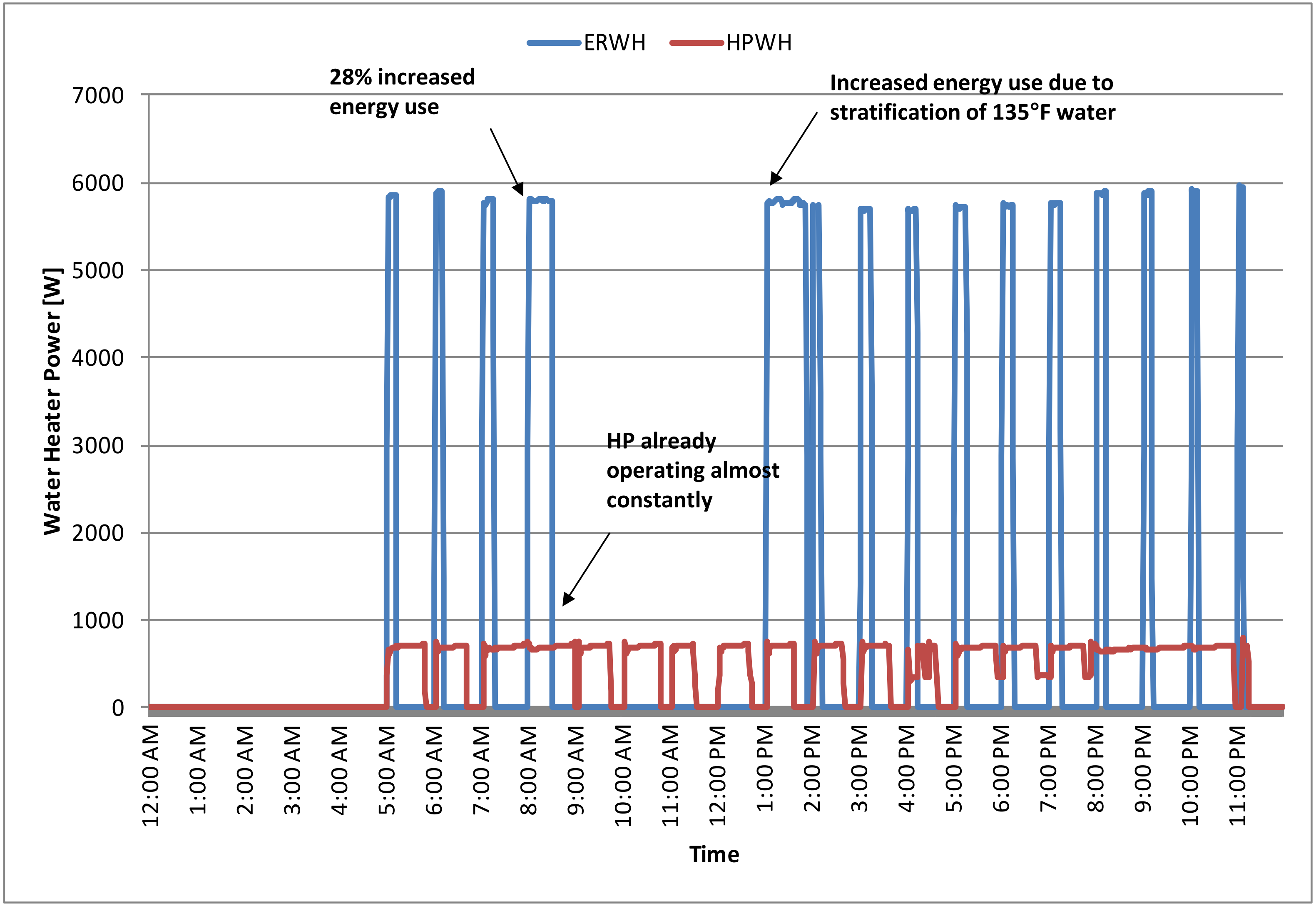


Availability Different for INC and DEC Events

- Ability of water heater to respond based on operating time in baseline (no DR) operation
  - No Late night INC Balance due to no load at that time
  - Both ERWH and HPWH effectively provide DEC balancing event in the late night hours



Availability also Dependent on Draw Profile



“Equivalent HPWHs/ERWHs”

$$\boldsymbol{Theoretical\ Number\ Equivalent\ HPWH} = \frac{ERWH\ Power\ Use\ [W]}{HPWH\ Power\ Use\ [W]} = \frac{4{,}650\ W}{587\ W} = 7.9 \rightarrow 8\ HPWH/ERWH$$

$$\boldsymbol{Number\ Equivalent\ HPWH} = \frac{ERWH\ Power\ Use\ [W] * Fraction\ of\ Hour\ On/Off}{HPWH\ Power\ Use\ [W] * Fraction\ of\ Hour\ On/Off}$$

Experiment	Duration	Water Heater Mode	Average Power Draw Impact (W)	Average Energy Impact During DR Event (W·h)	Average Daily Energy Impact (W·h/day)	Number Equivalent HPWH/ ERWH
Peak Curtailment	3 hours	HP	−439	−1,285	−498	2.64
		ER	−1,158	−3,320	258	
INC Balancing*	1 hour	HP	−442	−442	−159	2.67
		ER	−1,185	−1,185	86	
DEC Balancing	1 hour	HP	220	220	−158	17.1**
		ER	1,174	1,174	1,543	

* = does not include 2 a.m. INC balancing event, for which both water heaters had zero load.

** = ranges from 2.12 for 2 a.m. event to 50.6 for 8 a.m. DEC event, when HPWH ramping capability is significantly decreased.

Issue # 2: Hot Water Availability

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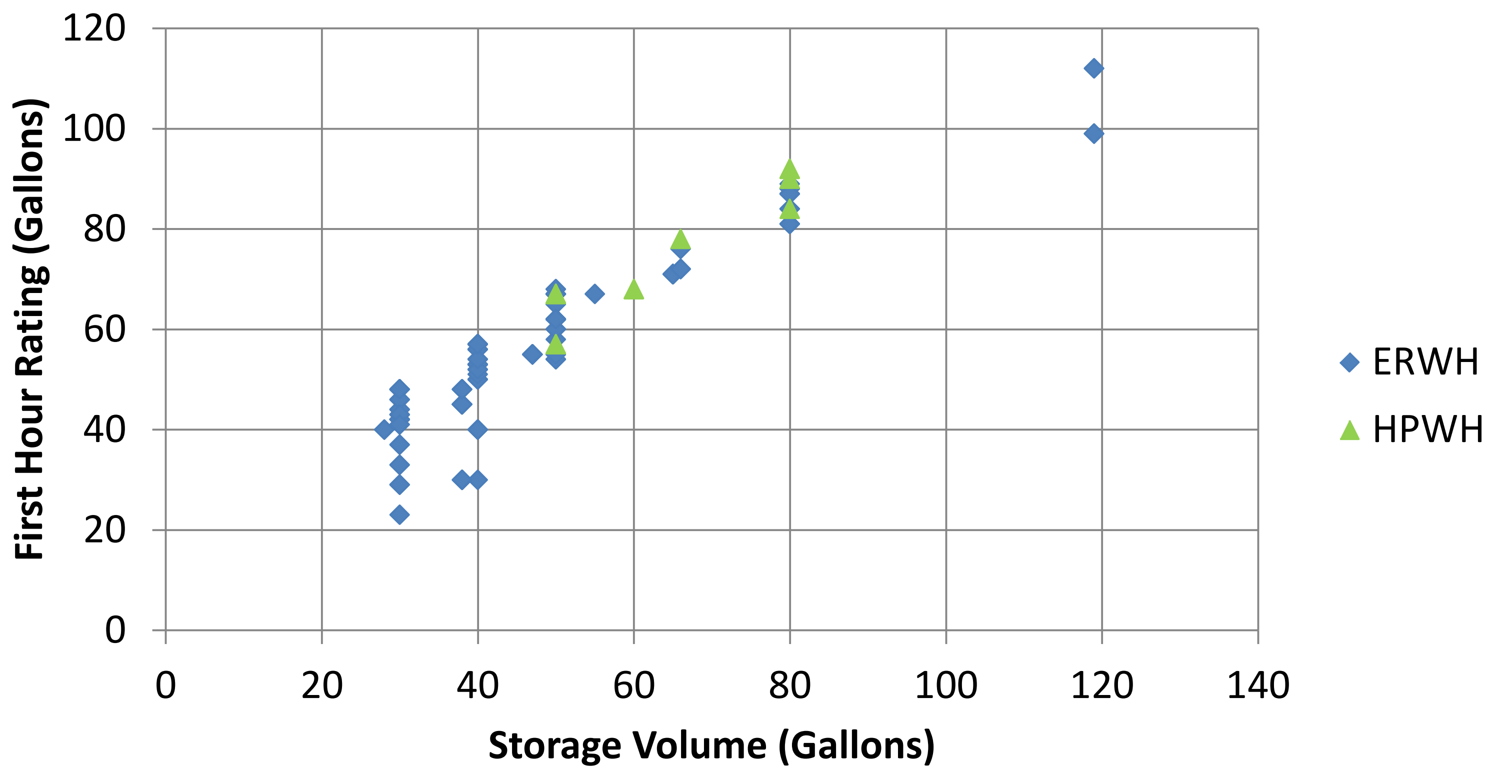
HPWHs have lower capacity than ERWHs and thus, require longer recovery times and may impact hot water availability

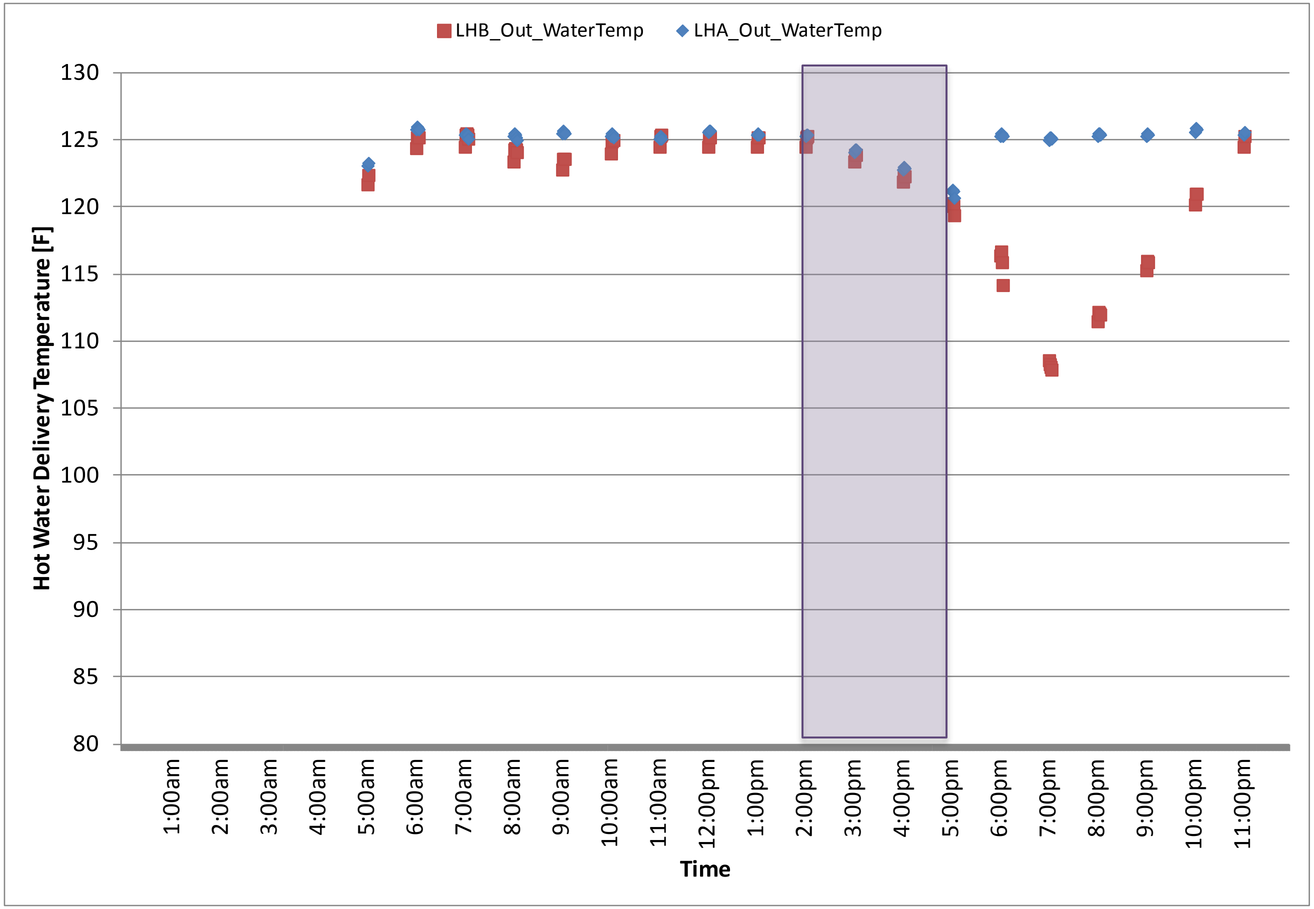
- More related to tank size than capacity



Data from **DOE CCMS Residential Water Heater Database**, Downloaded Feb 2015.

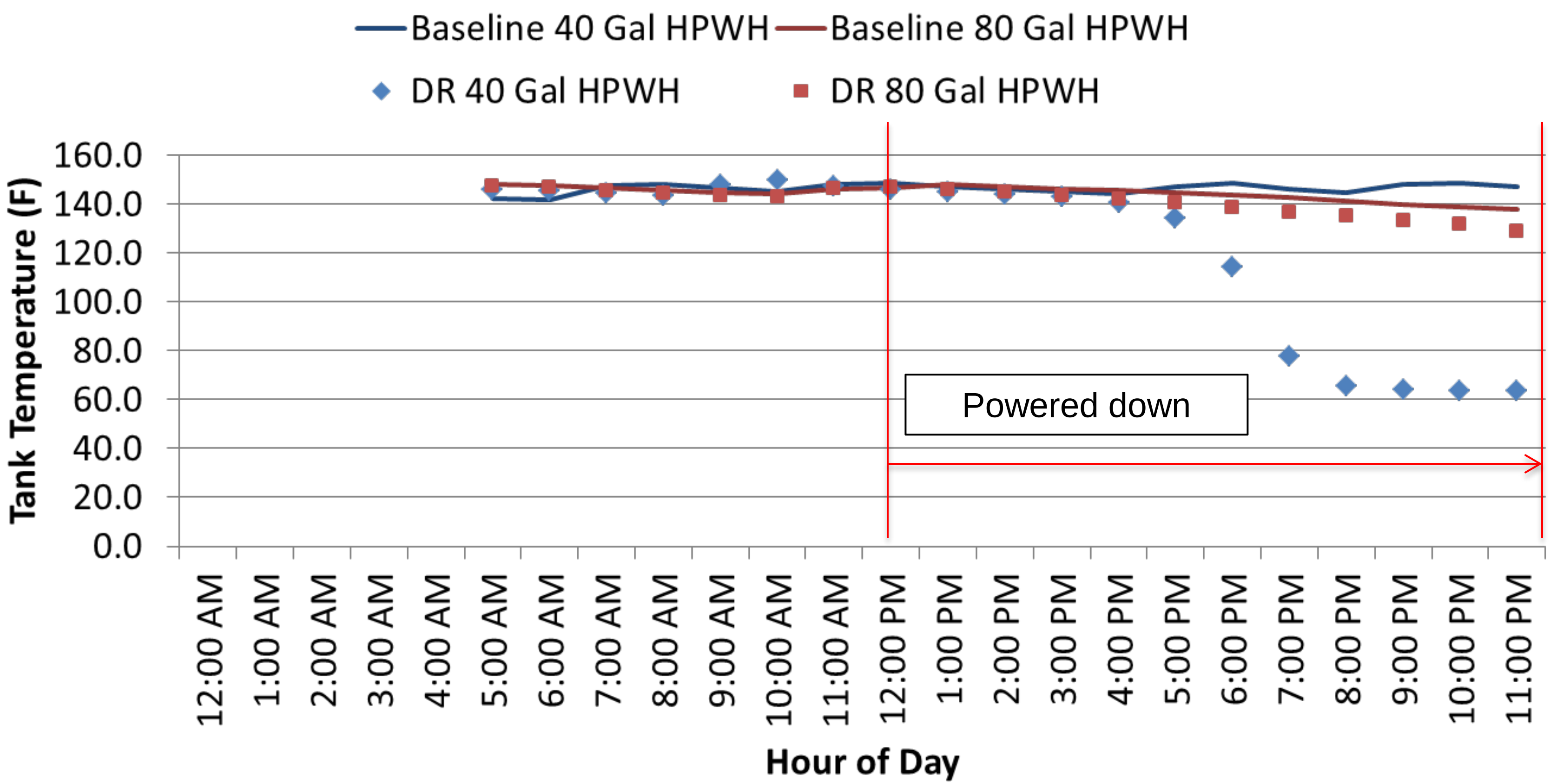
Temperature Impacts

- Slight reduction in delivered water temperature observed during extreme draw events
  - 130 gallons/day
  - 14 gallons between 2 and 5 PM
  - 30.5 gallons between 5 and 9 PM
  - Except in extreme cases HPWH will likely provide sufficient capacity and recovery



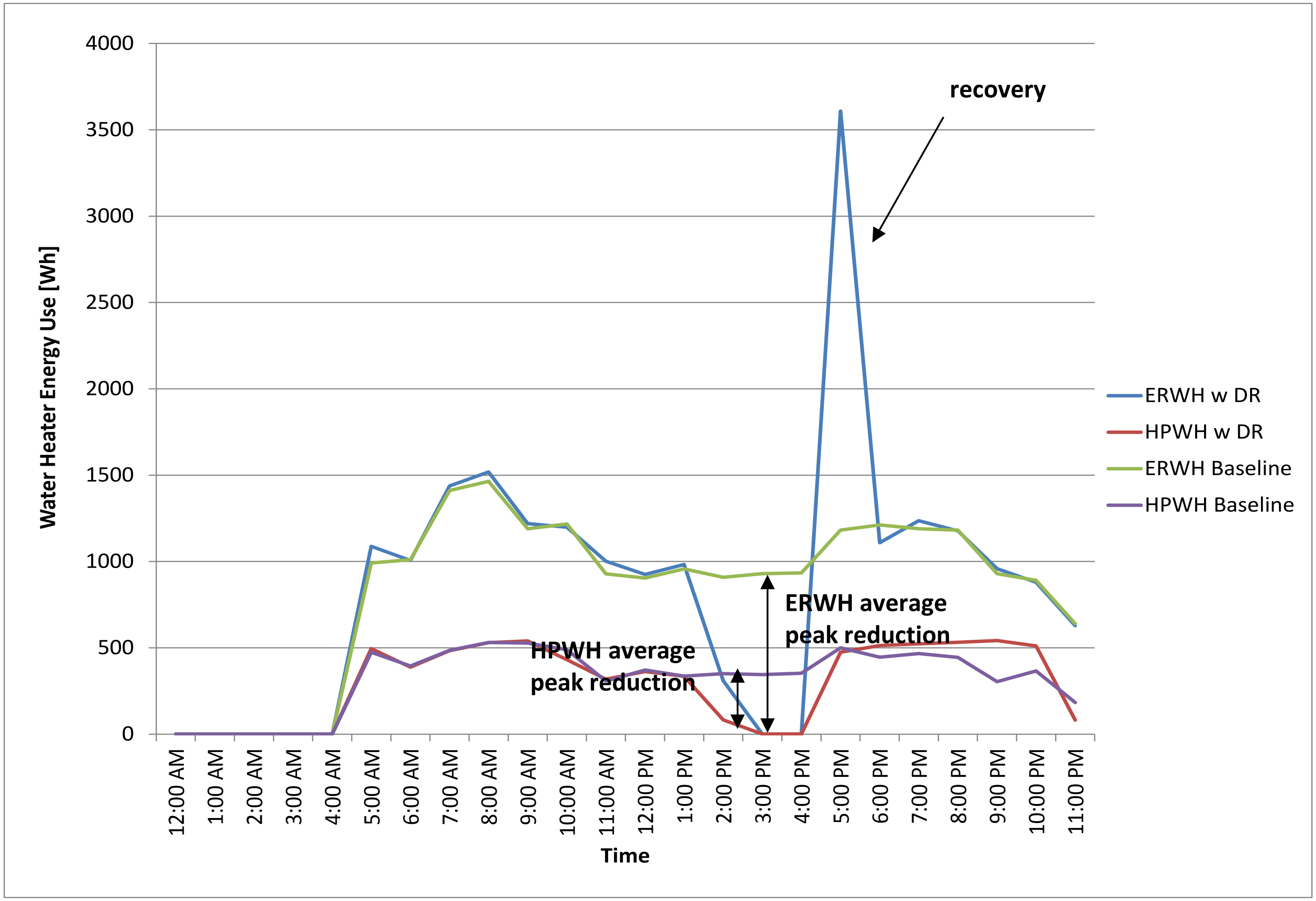
Sanden HPWHs

- For relatively similar HPWHs (similar power draw), ability to provide water based on tank size…



Power Impacts of Recovery

- With Hybrid HPWH or ERWH, must be careful about period after DR event and potential for power “rebound”



Issue #3: Lifetime

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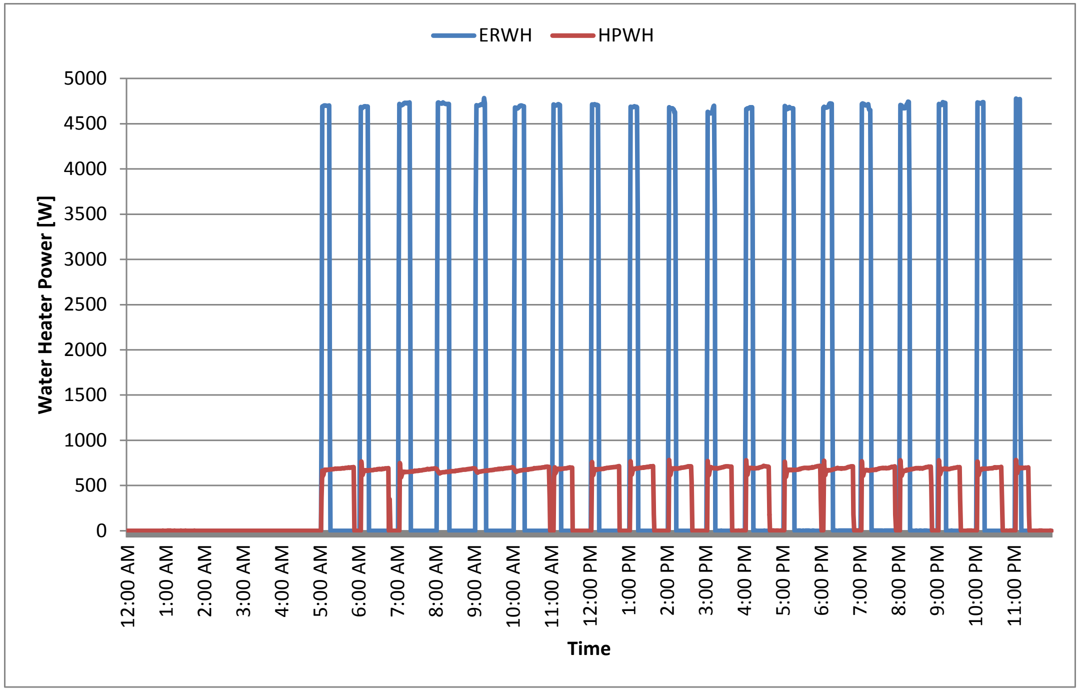
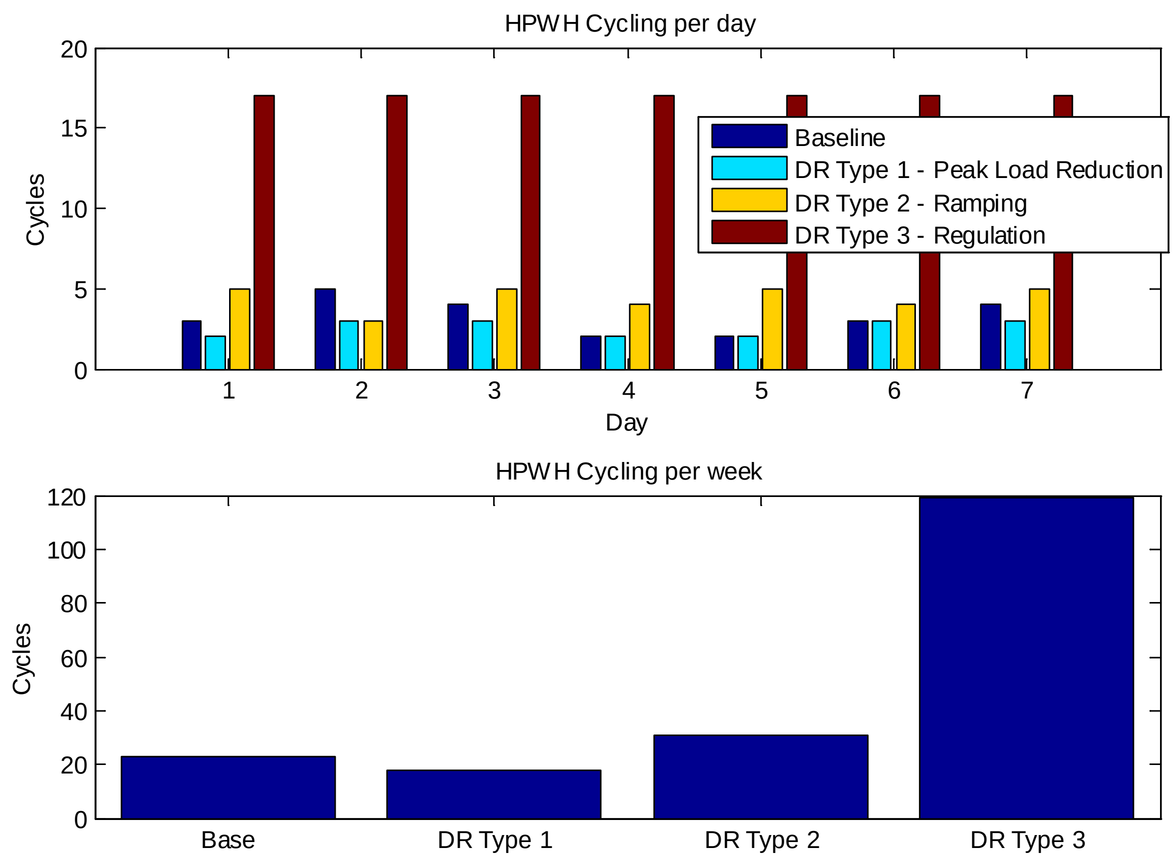
Demand response may cause increased compressor cycling, which would negatively impact the product's service life

- Depends, primarily on frequency of calls on HPWH for DR
- For peak curtailment and load balancing, DR has no impact on compressor cycling
  - In some cases decreases compressor cycling due to increased length of cycle
  - Many HPWHs have built in controls to limit cycling and protect compressor



Compressor Cycling and Different DR Modes

- Impact of DR on compressor cycling is a function of DR mode timeframe
  - If change in DR signal is more frequent than typical compressor on time, increased compressor cycling will occur when serving the same load



Issue #4: Thermal Comfort

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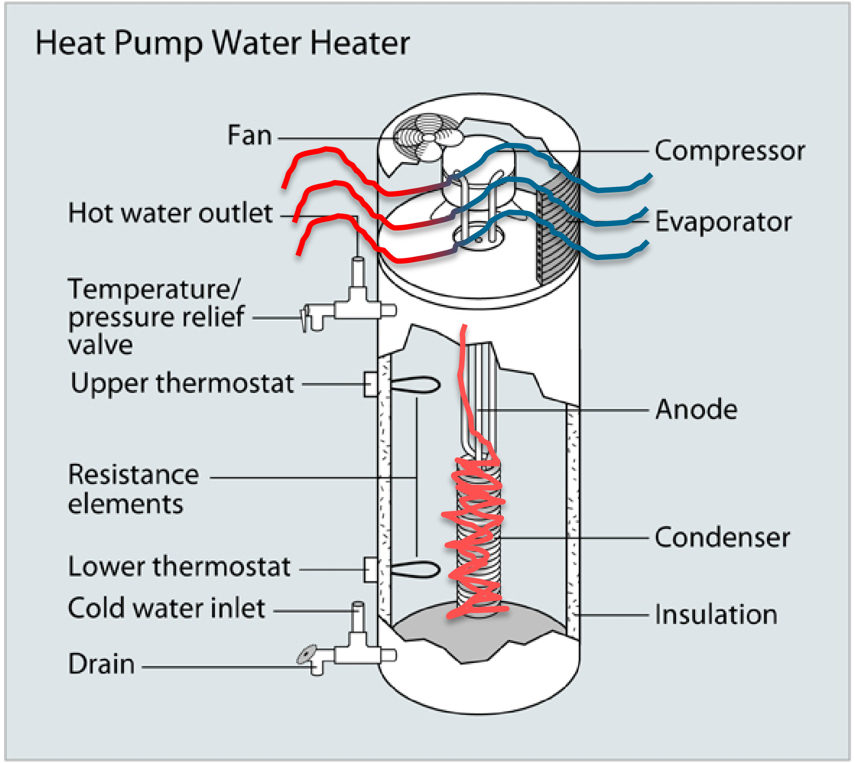
HPWHs vent cold air into conditioned space (a problem for colder climates) and require more space to operate effectively

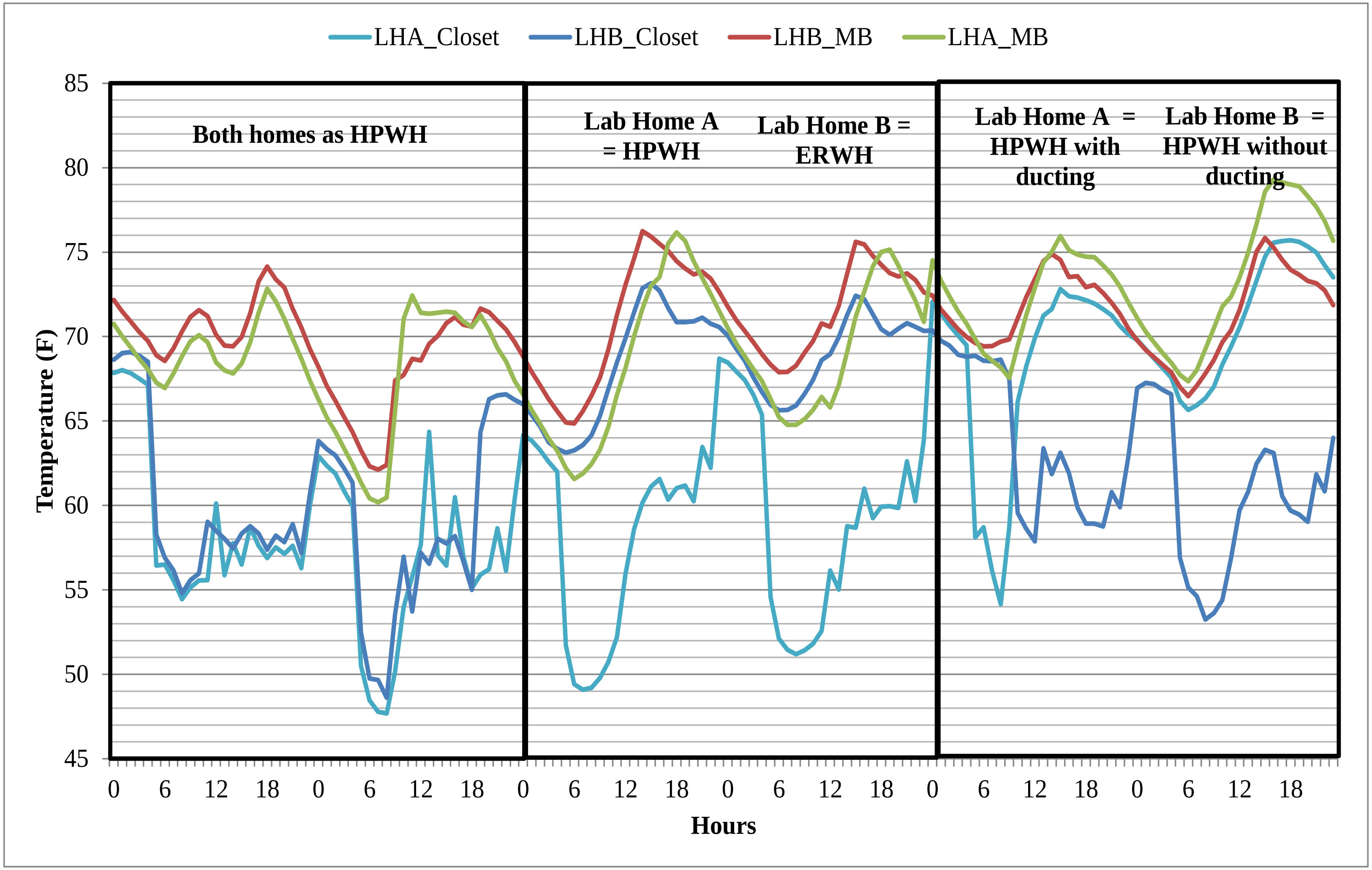
- Integrated HPWHs operate by removing heat from the inlet air stream and exhuasting cool air
  - Split systems to not interact with space conditioning



Source: U.S. DOE; energysavers.gov

Localized Cooling

- Impact of ducting can also impact localized cooling



HPWH Impacts on Thermal Comfort

- Presence of ducting did not significantly impact interior temperatures in the main body of the house

	Exhaust-Only Ducted Comparison			Fully Ducted Comparison		
Cooling Season	Exhaust-Only	Unducted	Difference	Fully Ducted	Unducted	Difference
Average Interior Temperature (° F)	75.9 ± 2.1	75.5 ± 2.3	0.3 ± 3.1	74.7 ± 0.4	74.9 ± 0.6	-0.2 ± 0.7
Heating Season	Exhaust-Only	Unducted	Difference	Fully Ducted	Unducted	Difference
Average Interior Temperature (° F)	71.6 ± 1.6	71.8 ± 1.5	-0.2 ± 2.2	71.3 ± 1.5	71.7 ± 1.5	-0.4 ± 2.1

Heating Season Interior Temperatures with Exhaust-only (Top) and Full (Bottom) Ducting

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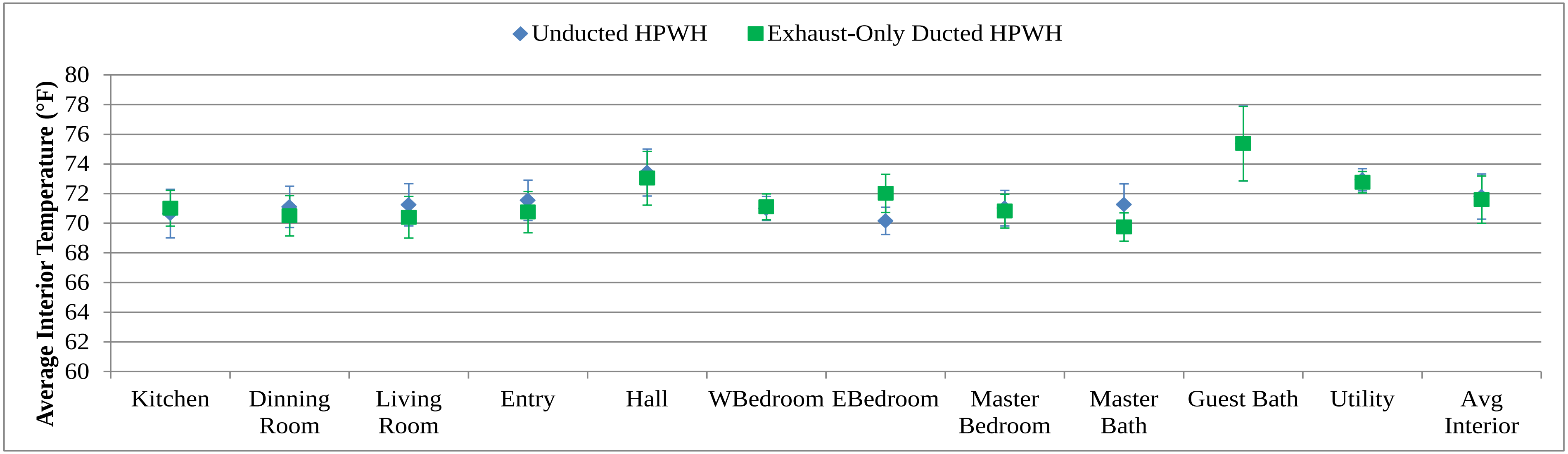

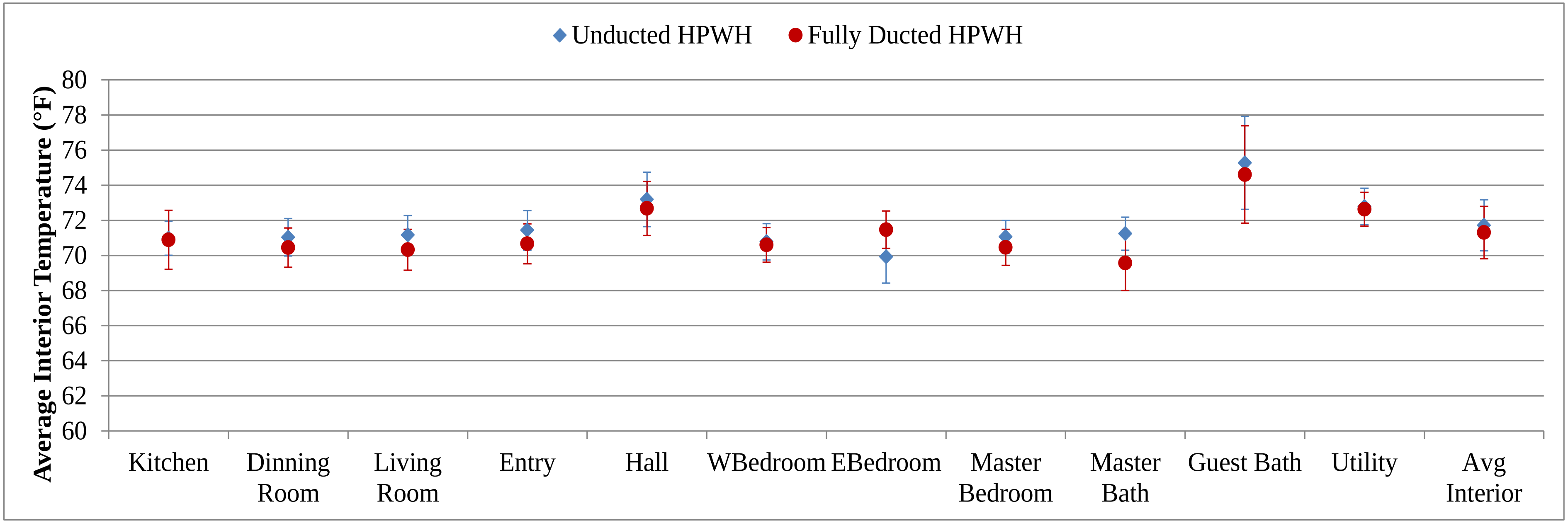

Issue #5: Tank Temperature

The HPWH storage temperature is limited compared to ERWH, which may limit the types of DR services a HPWH can provide

- Both ERWH and HPWH are capable of reaching temperatures of 170 °F with modified controls and minimal hardware
  - Increased energy use of 5,550 Wh per event
  - ERWH = 71 minutes of constant operation at 4,650 W (with no water draws)
  - HPWH = 4 hours of constant operation at 587 W (with no water draws)

Issue #6: Cost

HPWHs may impact the cost of running DR programs because HPWHs:

- cost more than similar ERWHs (installation and equipment costs)
- may decrease the capacity of the DR programs, which
  - may reduce the amount of off-peak heating that can occur
  - may limit the amount of new generation that can be deferred
  - may increase the cost of new renewable integration
- Different costs and benefits for utility versus consumer

	Pros	Cons
Utility	Lower peak Lower consumption overall*	May require higher incentive May require more water heaters to participate Lower consumption overall*
Consumer	Reduced energy costs and lifecycle costs	Increased purchase price and installation cost

- Existing programs extremely variable, making impacts difficult to generalize

Concerns/Findings on Feasibility of HPWH for Demand Response

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Issue #	Summary of Issue	Finding
Issue # 1: "Dispatchable Power"	HPWHs cannot provide similar levels of DR services as ERWHs	ERWHs can respond more dynamically, but are less available (e.g., they are 'on' for less time)
Issue #2: Hot Water Availability	HPWHs require longer time than ERWHs to recover water temperature, which leads to low water delivery temperatures	Hot water availability more related to tank size than heating mode; Very small impact on water delivery temperature for similar tank sizes
Issue #3: Lifetime	Using HPWHs for DR will negatively impact the product's service life due to excessive compressor cycling	Insignificant impact on cycling , except for with extremely frequent DR calls (which may be mitigated with effective population control).
Issue #4: Thermal Comfort	HPWHs vent cold air into conditioned space and require large amounts of space to operate effectively	Insignificant impact thermal comfort; localized cooling may be mitigated by ducting or split system; Installation may be a concern (not related to DR).
Issue #5: Tank Temperature	HPWHs are limited in their storage capacity because their storage temperature is limited	Both HPWHs and ERWHs can reach tank temps of 170 °F; HPWHs take longer to heat tanks
Issue #6: Cost	HPWHs will increase cost of DR programs	Different costs and benefits for utility vs. consumer; Existing programs extremely variable, making impacts difficult to generalize

Future Work

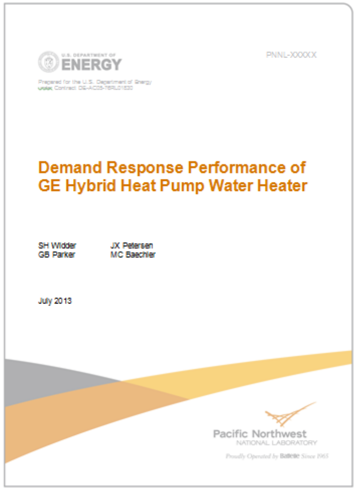
- HPWHs are technically capable of providing DR services to the grid, but response characteristics and costs are different than ERWHs

- Further research may by beneficial, including:
  - Extrapolate experimental results from individual water heaters to populations of water heaters to determine the feasibility of HPWHs for performing DR functions at the program level using population models, such as PNNL's GridLAB-D (www.gridlabd.org)
    - Account for inherent "peak load" reduction
    - Determine effect of variable hot water draw profiles and control strategies on the results
    - Consider diversity of loads responding (not just water heaters)

  - Further explore cost impacts under a variety of different program types and utility constraints
    - Capacity constrained
    - Transmission constrained

Projects & Deliverables

Project	Project Team	Funder(s)	Status
Demand Respond Performance of GE Hybrid Heat Pump Water Heater	PNNL (w/ NEW, GE, and Efficiency Solutions)	DOE Building America & BPA	Complete; Report available at labhomes.pnnl.gov
TIP 302 Demand Response Potential of Heat Pump Water Heaters	WSU, PNNL, Ecotope, Efficiency Solutions	BPA & DOE EERE	In Progress


ENERGY
PNNL-XXXXX

Demand Response Performance of GE Hybrid Heat Pump Water Heater

SH Widder   JK Petersen
GB Parker   MC Baechler

July 2013

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  - Greg Sullivan, Efficiency Solutions

Thank you!

Questions?