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Demand Response: Heat Pump Water Heater vs. Electric Resistance

Demonstration of 2nd Generation Ducted GE "Brillion" Hybrid Water Heater in the PNNL Lab Homes

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Project Participants

- Project Sponsors: DOE Building America Program/Bonneville Power Administration
- Contractor: PNNL
- Principal Investigators: Graham Parker/Sarah Widder, PNNL
- Other Project Stakeholders: Northwest Energy Works (NEW)**; GE Appliances; Regional Technical Forum (RTF); Regional/National Utilities & Efficiency Advocates; PNW Manufactured Homes Industry; Appliance, Plumbing, HVAC Industry; Residential Customers

***Cost sharing partners.*

Project Synopsis

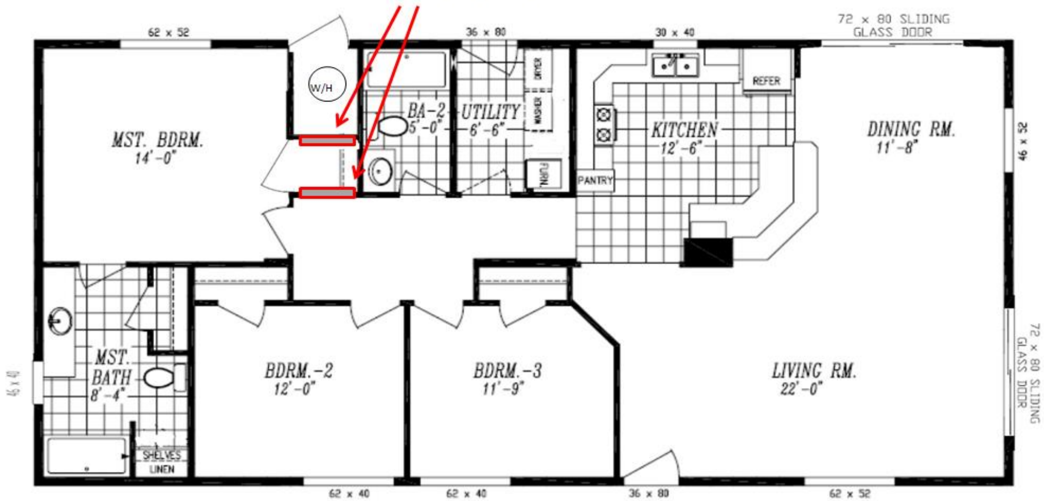
- Evaluate the performance and demand response (DR) of the Gen II GE GeoSpring™ HPWH under a number of operating configurations in Lab Homes.
  - Exhaust ducted HPWH vs. standard WH & unducted HPWH (winter/summer).
  - Exhaust & supply ducted HPWH vs. unducted HPWH (winter/summer).
  - DR characteristics of unducted 50 gal HPWH vs. electric resistance 50 gal WH.
- Experiments conducted with controlled & measured variables under identical simulated occupancy in each home.

HPWH DR Project Background

- Previous modeling efforts at PNNL and elsewhere have demonstrated the potential of electric resistance water heaters to provide a variety of grid services (peak curtailment, regulation, and voltage/frequency response) in the PNW and nationwide (Lu et al, 2011; Diao et al 2012)
- The demand response characteristics of HPWH are not currently well understood
- There is concern for some utilities (and recognition by DOE) that HPWH may conflict with DR program goals

HPWH Experimental Design

- Two side-by-side GE Brillion-enabled HPWH
  - One operated in Heat Pump mode with no ducting or back-up electric resistance elements
  - One operated in Standard mode with electric resistance elements only
- Installed in Lab Homes conditioned space



Types of DR Services

Duration

- Peak Curtailment
  - 3 – 6 hour reductions 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
  - <1 minute modulation of loads in response to voltage, frequency, or Area Control Error (ACE) diviations

Direction

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

HPWH DR Project Specifics

Experiment	Experiment Description	Time	Duration	Purpose of Experiment
A.M. Peak Curtailment	Turn off heating elements	7:00 a.m.	3 hours	Evaluate HPWH load shedding potential (dispatchable kW and thermal capacity) as compared to electric resistance baseline to manage peak load
P.M. Peak Curtailment	Turn off heating elements	2:00 p.m.	3 hours	Evaluate HPWH load shedding potential (dispatchable kW and thermal capacity) as compared to electric resistance baseline to manage peak load
EVE Peak Curtailment	Turn off heating elements	6:00 p.m.	3 hours	Evaluate HPWH load shedding potential (dispatchable kW and thermal capacity) as compared to electric resistance baseline to manage peak load
INC Balancing	Turn off heating elements	2:00 a.m. 8:00 a.m. 2:00 p.m. 8:00 p.m.	1 hour	Evaluate HPWH potential to provide balancing reserves for dispatchable kW as compared to electric resistance baseline
DEC Balancing	Set tank temp to 135°F	2:00 a.m. 8:00 a.m. 2:00 p.m. 8:00 p.m.	1 hour	Evaluate thermal capacity of HPWH, as compared to ERWH, when temperature set point is increased to 135°F

Baseline Performance

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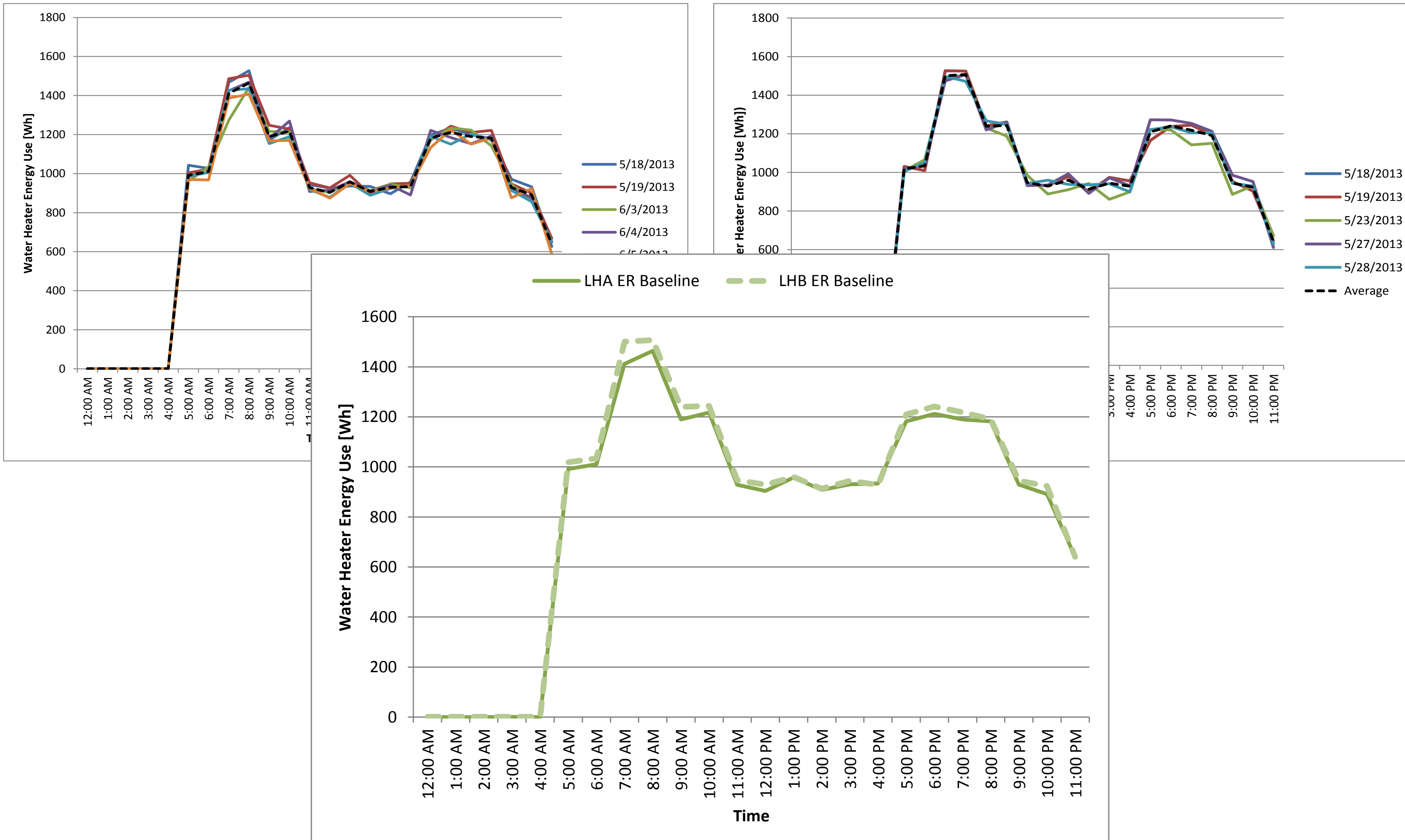
- **ER**: Lab Home A Lab Home B



Baseline Performance

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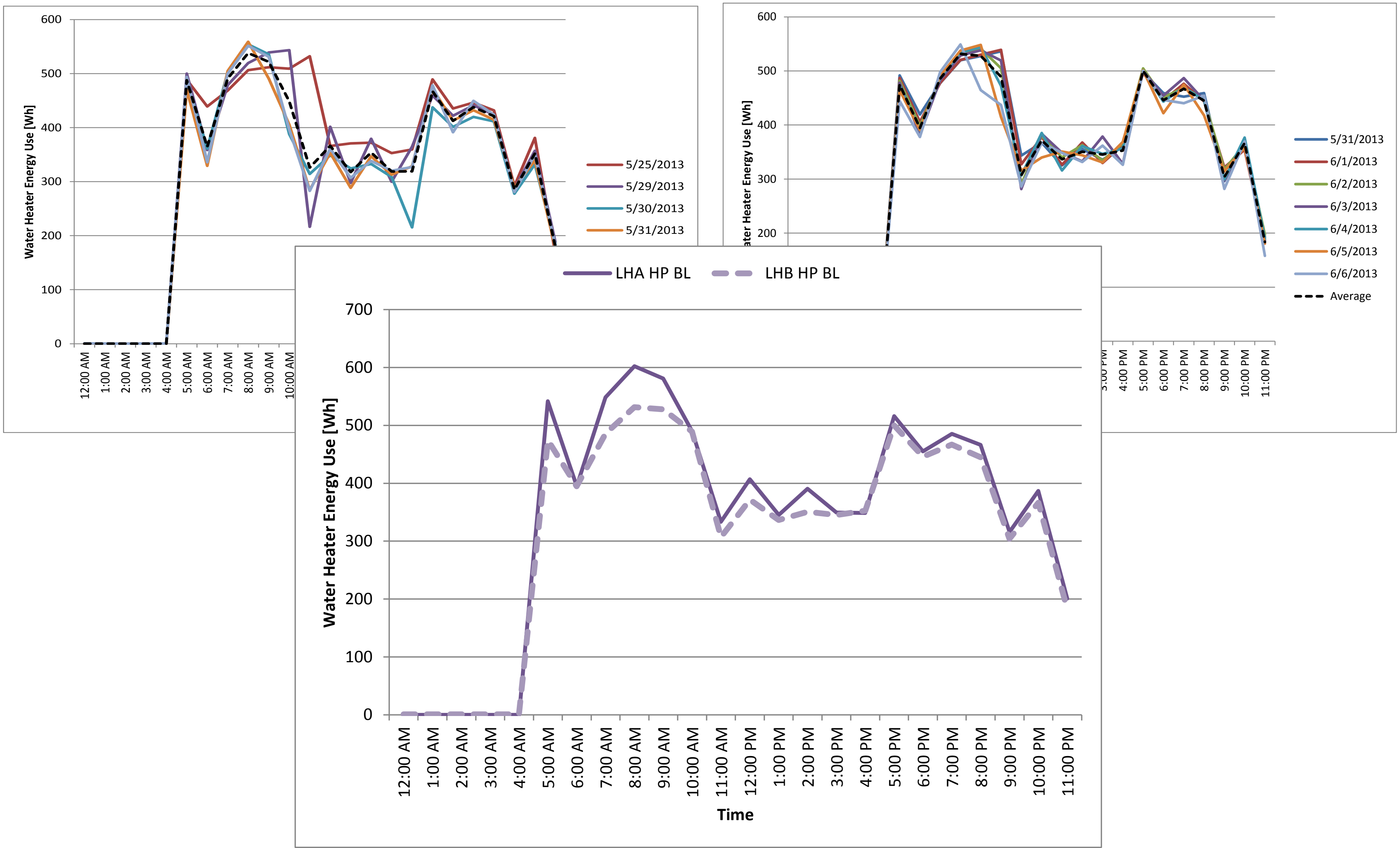
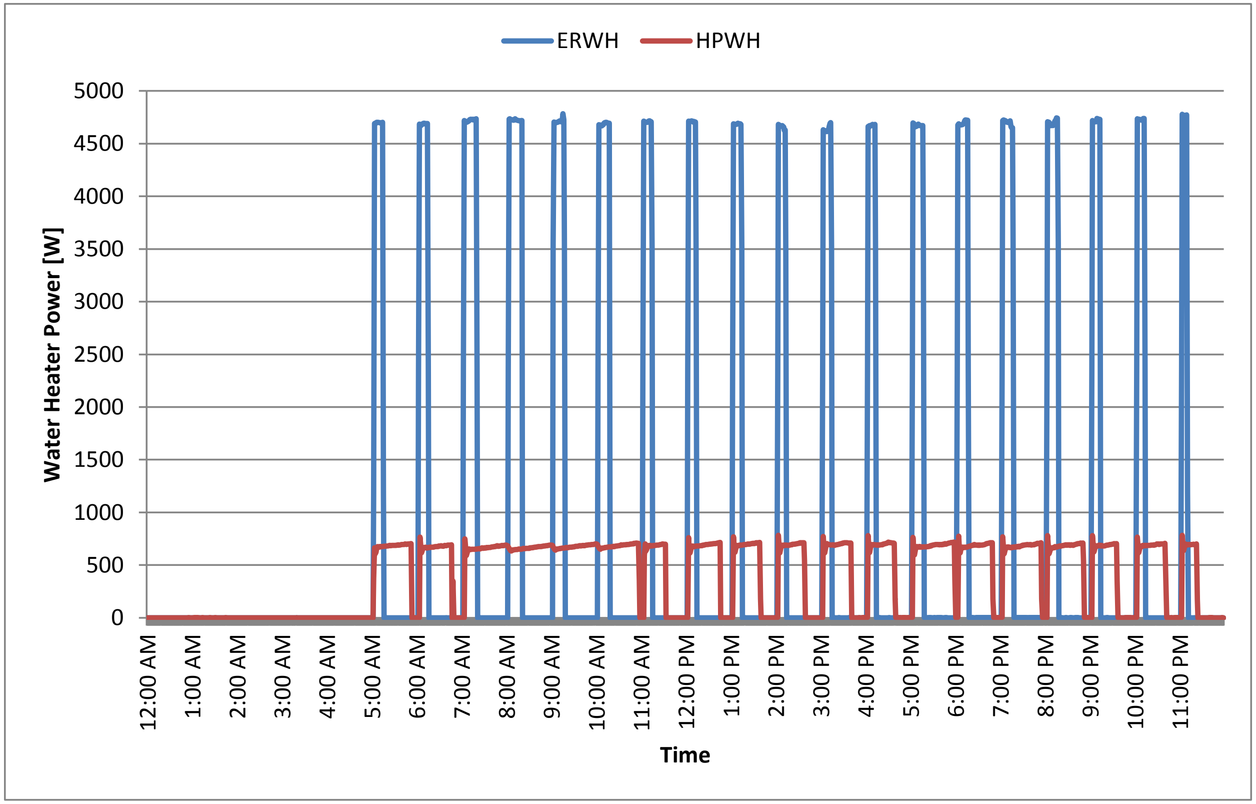
- **HP**: Lab Home A Lab Home B



HPWH Efficiency Evaluation

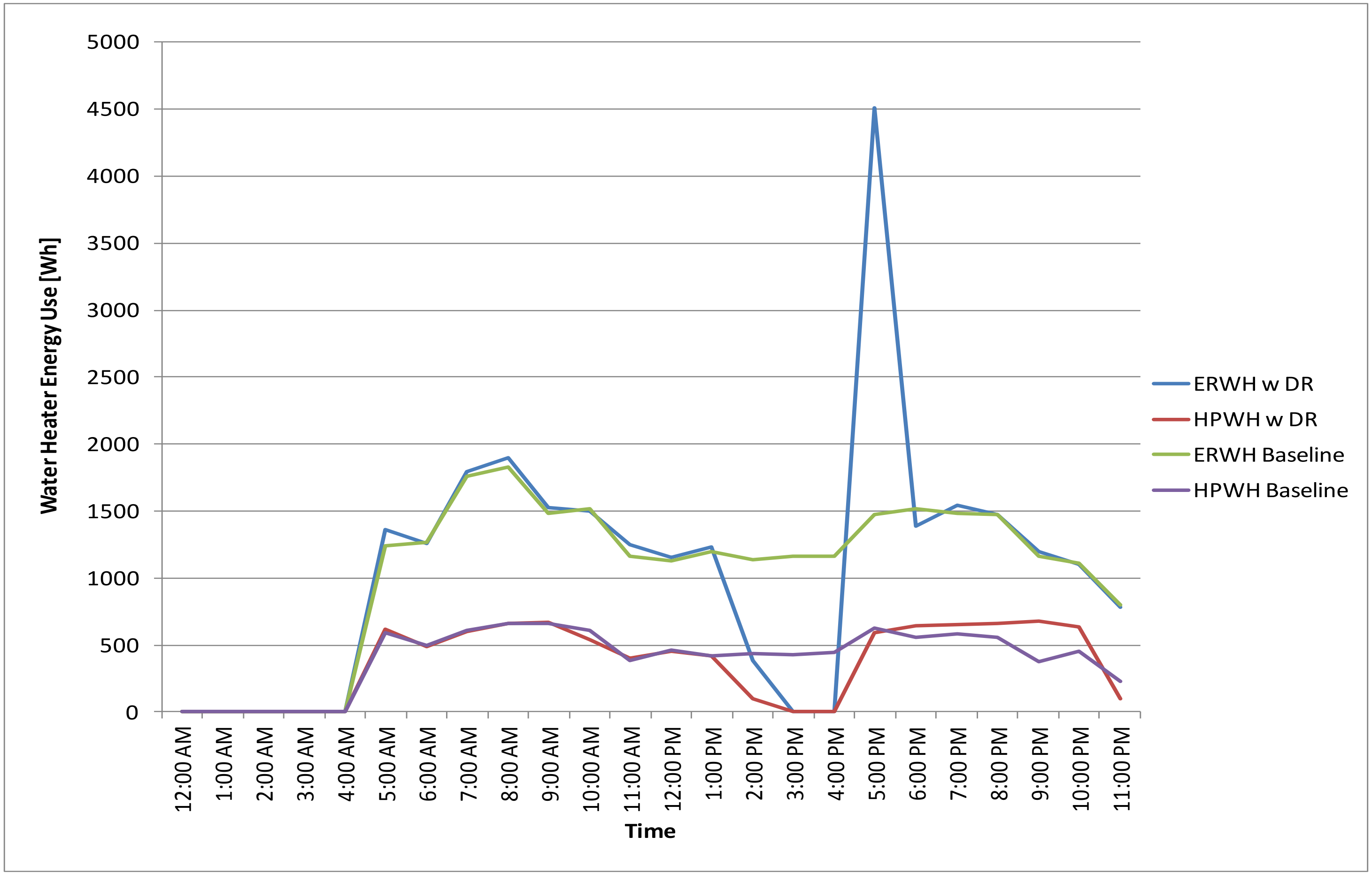
- 61.7 ± 1.7% energy savings from HPWH as compared to ERWH
- Also note:
  - Power draw relatively fixed for HPWH and ERWH for individual unit
  - HPWH operates much more than ERWH



Water Heater Type	Baseline Daily Energy Use (W·h/day)
ERWH	20,073 ± 348
HPWH	7,684 ± 119

Extrapolating to Population Performance

- Operating time each hour defines DR performance
  - Can be extrapolated to population of water heaters due to average load shape



PM Peak Curtailment

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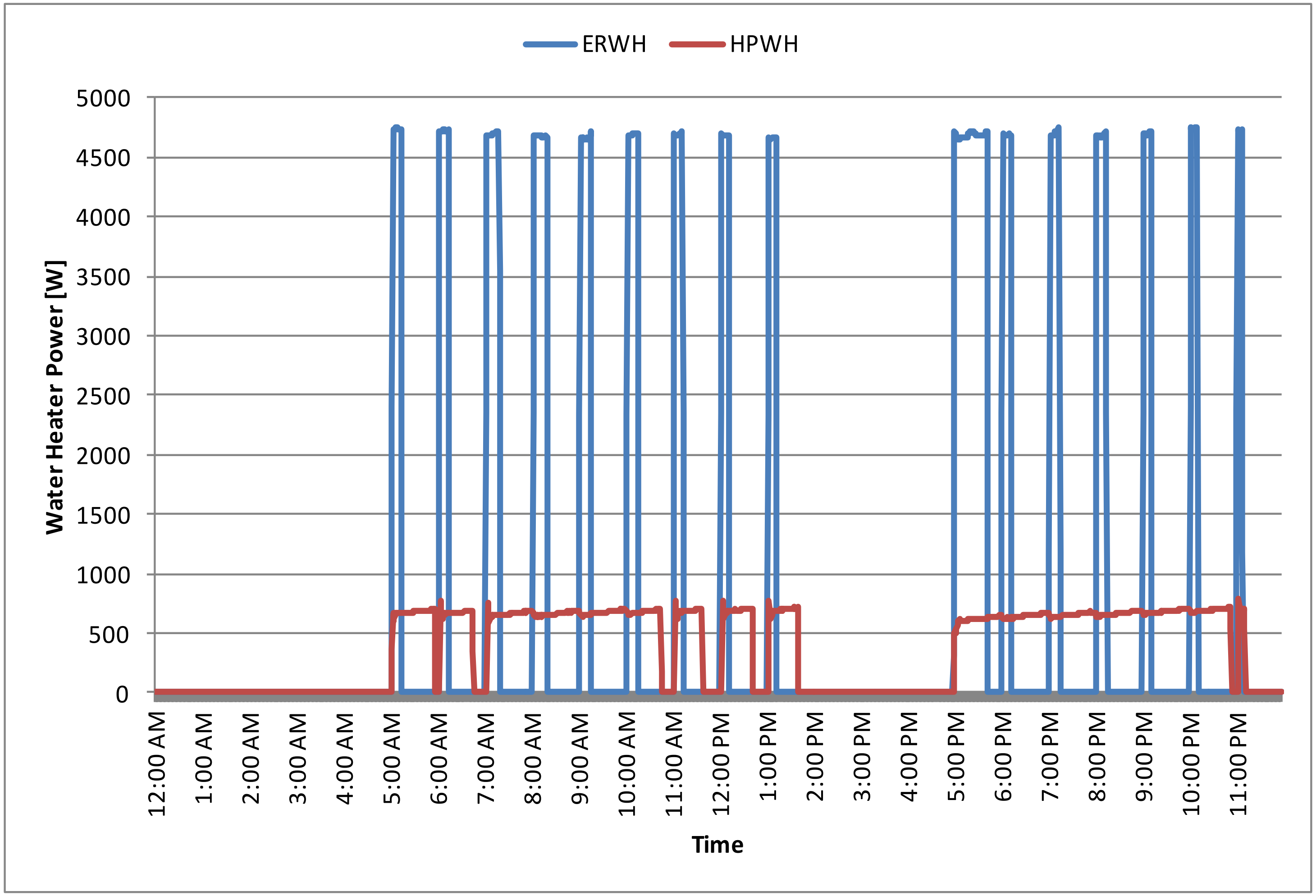
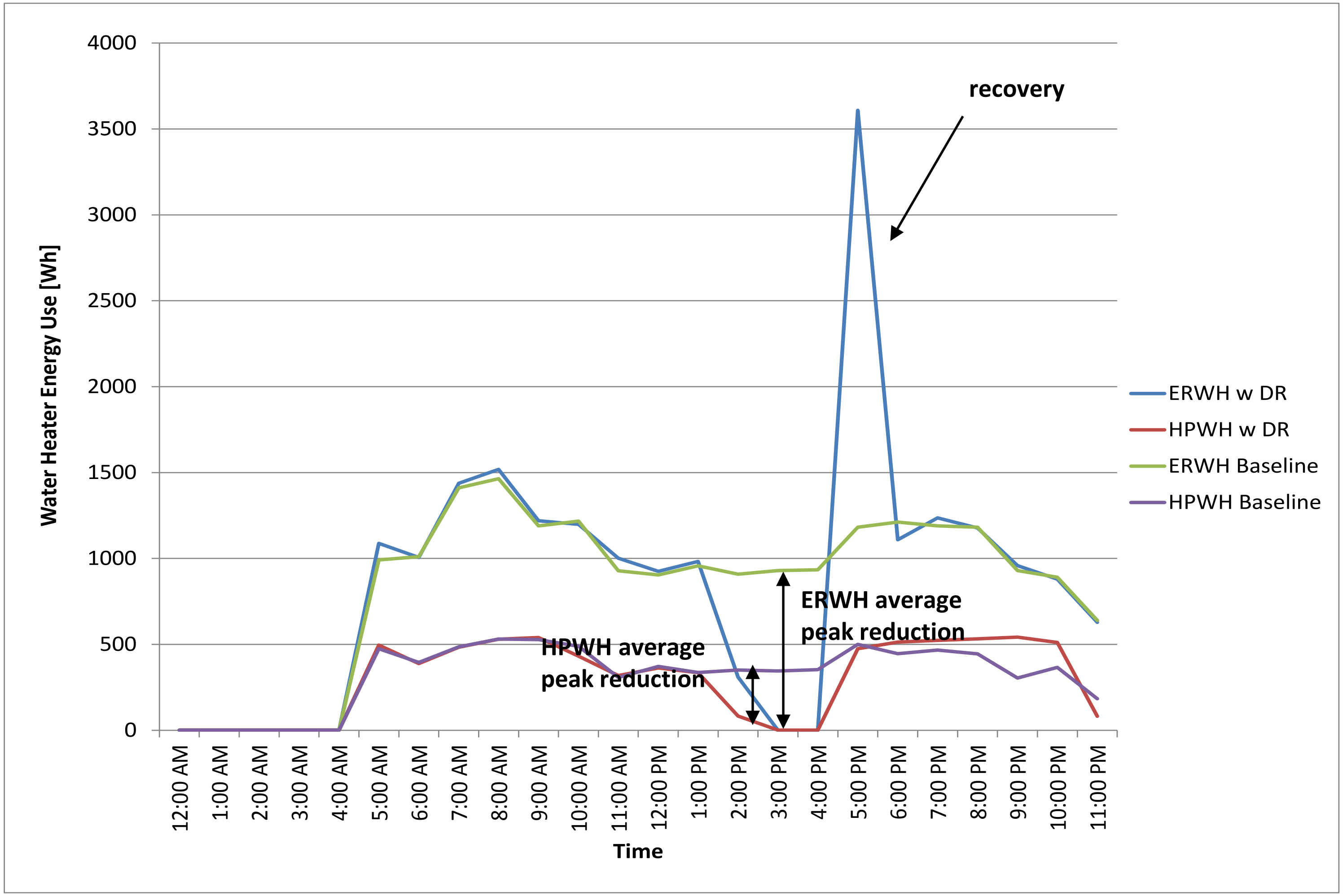
- Peak impact (W) commensurate with peak draw
  - ERWH = 4,650W; HPWH = 587W



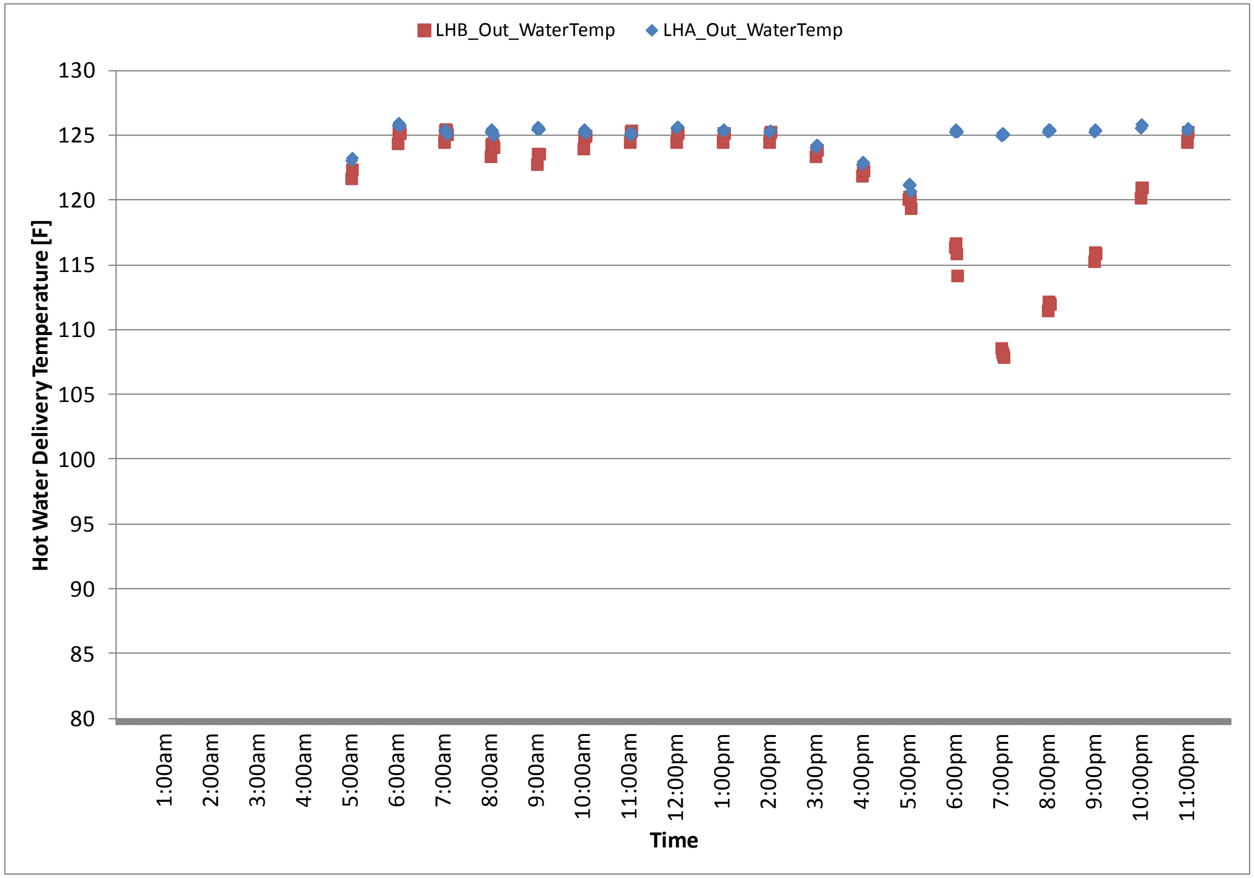
PM Peak Curtailment

- However, duration of draw impacts “average power draw” over the DR event
  - ERWH = 18% of 3 hr event
  - HPWH = 54% of 3 hr event



PM Peak Curtailment

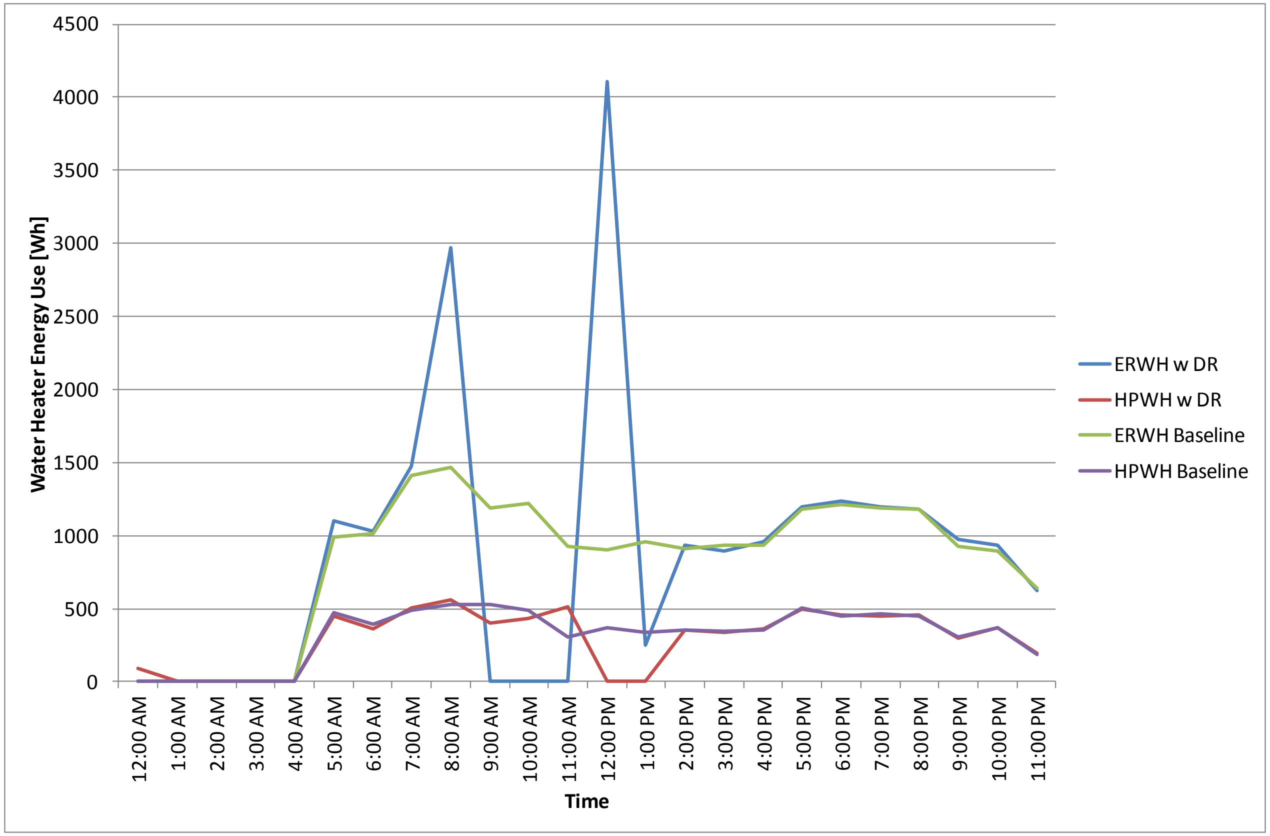
- Energy use reduced related to decrease in tank temperature experienced in HPWH
- Recovery of ER tank temperature associated with recovery spike in energy use in hour following DR event



Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
P.M. Peak Curtailment	HP	3 hours	−350	−965	−533
	ER	3 hours	−924	−2,463	213

DEC Balancing Events

- Ability of water heater to respond based on operating time in baseline (no DR) operation
  - HP = 91% operating
  - ER = 31% operating
- 1-hr DEC balancing events exhibit rebound following DR event
  - Based on control logic of GE water heater



Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
Morning DEC Balancing Event	HP	1 hour	26	26	−689
	ER	1 hour	1,305	1,305	1,309

DEC Balancing Event Rebound Response

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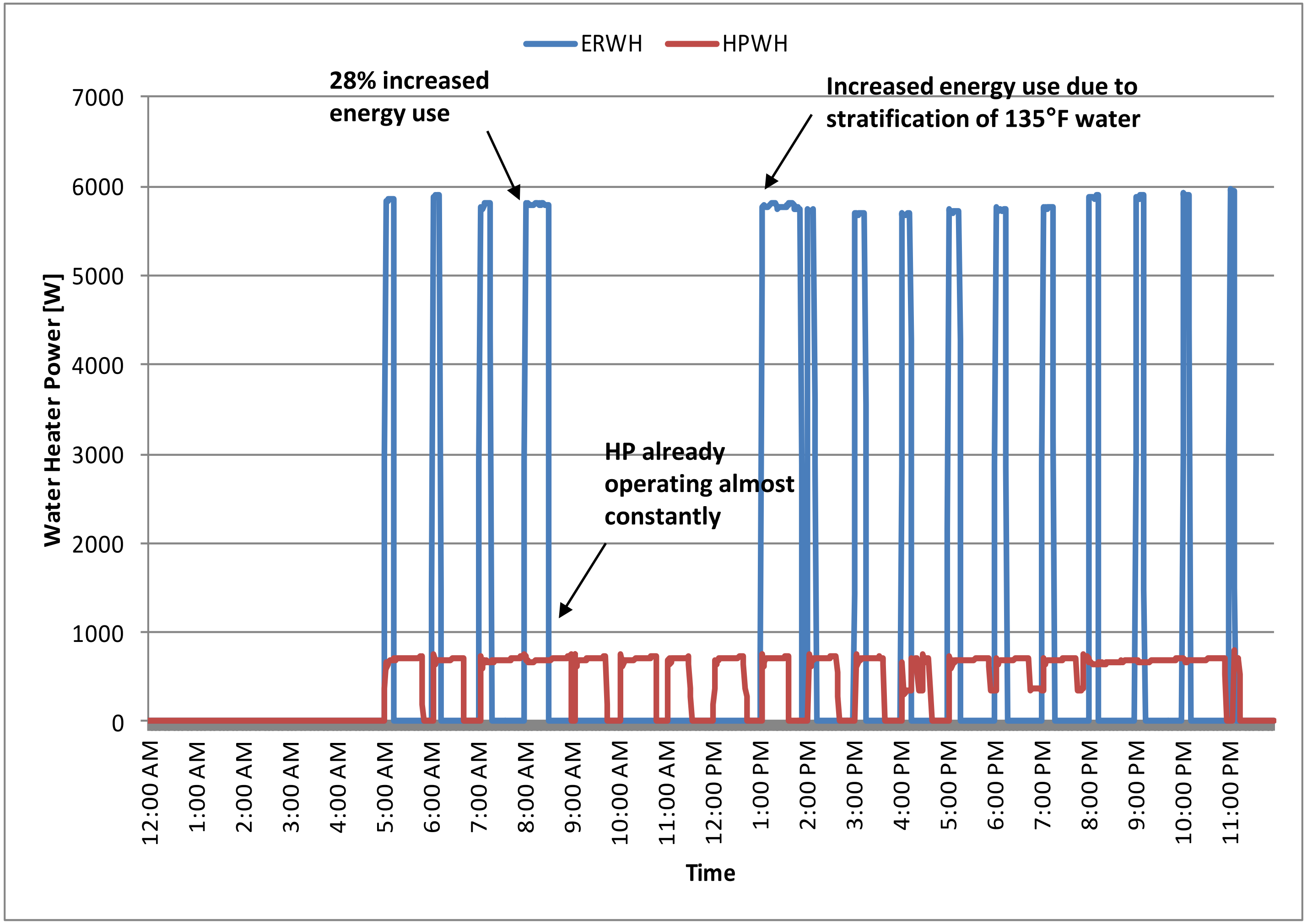
- GE control strategy references one thermocouple (near top element)
- Stratification of temperature causes unusual “coast” and “rebound” behavior



Increased Tank Temperatures

- 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)

Key Findings:
Peak Curtailment and INC Balancing Events

- In general, HPWH provides 38% of the peak reduction or INC balancing response capability of ERWH
- Both HPWH and ERWH can effectively perform peak curtailment services in the morning, afternoon, and evening periods
  - HPWH has lower power draw but operates (on average) 2.68 times as often at the ERWH for the water hot water load
  - Decreased energy use observed for HPWH due to lower tank temps, however this may not be noticeable for most homeowners
  - ERWH exhibited significant rebound following DR event, which may be problematic (this would also apply to HPWH operating in Hybrid mode)
  - This analysis does not account for inherent peak load reduction from increased efficiency of HPWH (61.7%)
- INC balancing results very similar

Key Findings: DEC Balancing Events

- Ability to respond very dependent on draw profile
  - ERWH had significantly better dynamic ramping capability to increase load (baseline operation = ~25% of hour)
  - HPWH already operating for a majority of each hour when a DEC event was initiated
- Response varies based on time of day
  - Morning ERWH has 50 times the response capability of HPWH because HPWH is already operating constantly to meet 10 gallon draw
  - Afternoon and evening ERWH has 6 to 8 times the response capability of the HPWH due to reduced loads
  - Late night ERWH has only 2.12 times the response capability of the HPWH because ERWH satisfies the increase in tank temperature to 135 °F in 16 minutes, whereas the HPHW takes the entire hour
- Higher tank temperatures could increase the response from both HPWH and ERWH

DR Results Summary

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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	

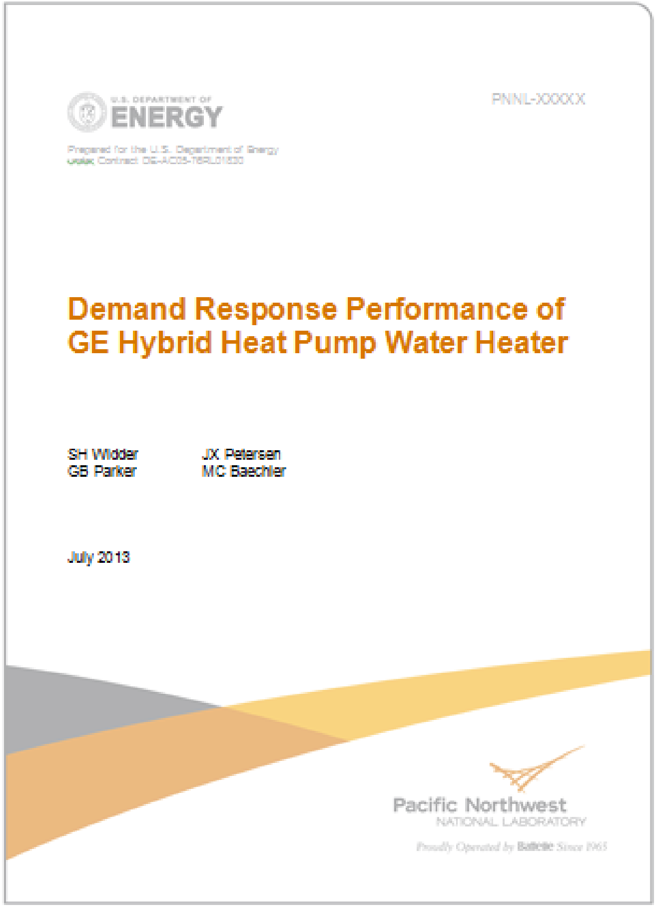
* = does not include 2 a.m. INC balancing event, for which both water heaters had zero load.
** = ranges from 2.12 for 2 a.m. event to 50.6 for 8 a.m. DEC event, when HPWH ramping capability is significantly decreased.

Future Experiments

- These experiments are only a initial indication of the relative response of HPWHs as compared to ERWHs under a given, high hot water draw profile with GE GeoSpring Hybrid HPWH
- Further research is required, including:
  - Explore ERWH response to DEC balancing events where the events are more spread out and with a standard ERWH to better characterize "coast and rebound" effect
  - Characterize the DEC response of ERWH and HPHW with elevated temperatures more fully
  - Determine effect of different hot water draw profiles on the results
  - 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)

Project Deliverables

Deliverable	Status
Report Summarizing DR Findings (includes descriptive graphs & tabulated summary data)	Complete
Clean 1-min data of WH kW, kVA, water flow, and inlet & outlet temps for all experiments	In Progress


U.S. DEPARTMENT OF ENERGY

PNNL-XXXXX

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Demand Response Performance of GE Hybrid Heat Pump Water Heater

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Questions?

Back Up Slides

The PNNL Lab Homes

LAB HOMES

Demonstrating tomorrow's efficient and smart technologies.

- Goal is to demonstrate an intelligent, energy efficient, and grid responsive home retrofit over a period of five to seven years which achieves 50% whole house energy savings.

PNNL Project Team

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PNNL

- Graham Parker Staff Engineer, Project Manager
- Sarah Widder, Engineer, Principal Investigator
- Viraj Shrivastava, Engineer, DR Lead
- Bora Akoyl, Senior Engineer, DR Engineer
- Vrushali Mendon, Engineer, Energy Modeling
- Nathan Bauman, Engineer, Metering
- Erica Johnson, Energy Modeling

NEW

- Brady Peeks, Engineer/Manufactured Homes

GE Appliances

- Jonathan Smith/Scot Shaffer, Engineers/Software & Hardware

Efficiency Solutions (subcontractor)

- Greg Sullivan, Principal/Metering & Analysis

Monitoring Approach

Monitored Parameter	Monitoring Method/Points	Monitored Variables	Data Application	Existing or New?
Electrical Power Measurements				
Whole House Electrical Power and Circuit Level Power HPWH Electrical Power Electric Power for HPWH Fan Power for Electric Heaters	1 Campbell data acquisition system with 42 current transducers at electrical power mains and panel	kW, amps, volts	Comparison and difference calculations between homes of • power profiles • time-series energy use • differences and savings	Existing
Temperature Measurements				
Inlet Water Temperature	Insertion thermocouple	Temp.,°F	Characterize impact of incoming water temperature on HPWH performance	New
Outlet Water Temperature	Insertion thermocouple	Temp.,°F	Monitor outlet water temperature as proxy for tank temperature	New
Flow Rate Measurements				
Outlet Water Flow Rate	Turbine flow meter, in line with hot water outlet prior to mixing valve	Flow rate, gallons per minute (gpm)	Verify water draws are in accordance with specified profile	New

Hot Water Draw Profile

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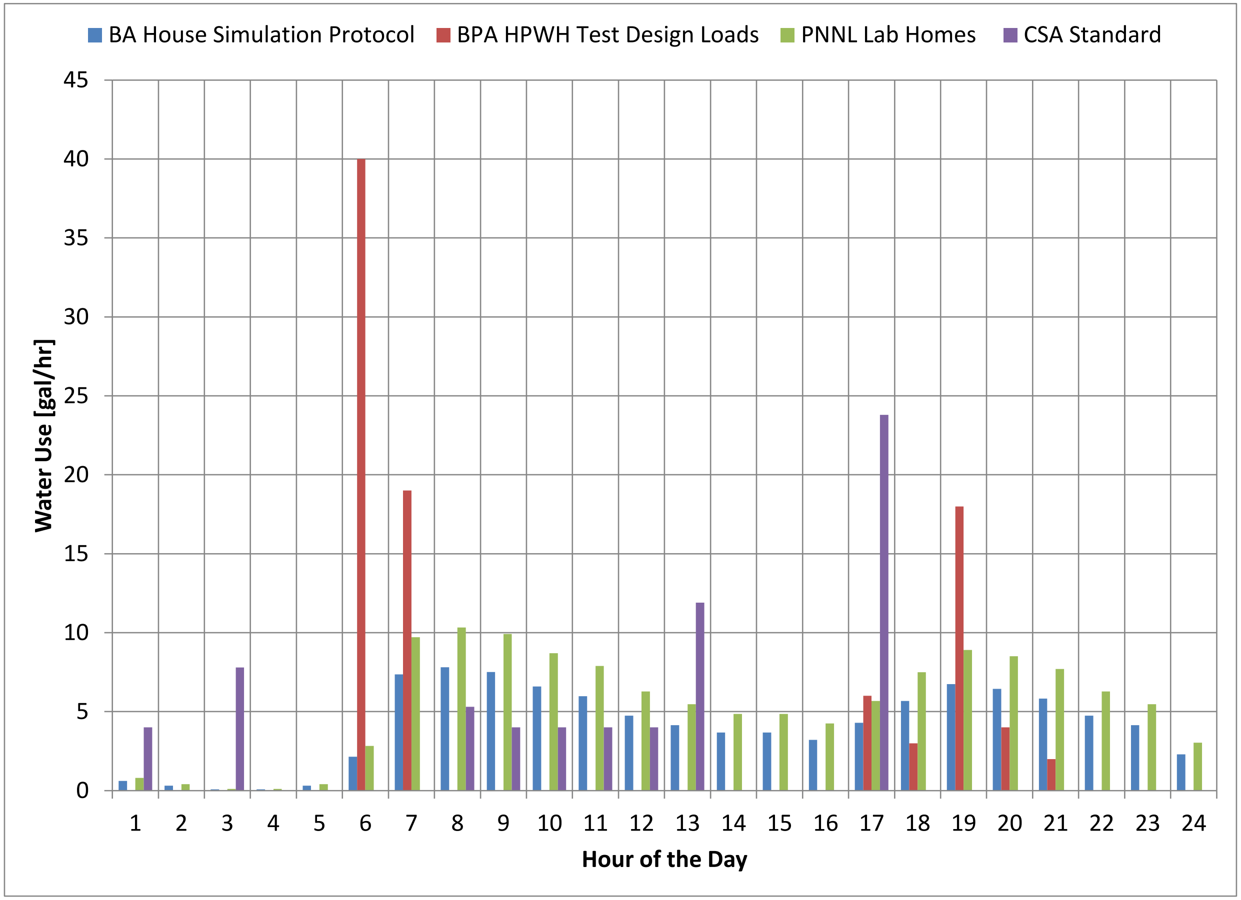
- **Performance *very* dependent on hot water draw profile**
- Draw profile PNNL selected representative of typical daily draw pattern for group of homes
  - Based on Building America House Simulation Protocol
- 125 ^{o}F set point
  - Based on LBNL Meta-Analysis recently performed by Lutz and Melody (2012)
- Fixed 1.5 gpm flow rates
  - Tank water heater performance more dependent on volume of draw than frequency of draws
  - Consistent with LBNL study of typical flow rates (1 to 1.5 gpm) and duration (1 to 4 minutes in length)
- Selected high draw volume to explore "worst-case scenario" impacts on tank temperature and maximum availability of DR resources
  - Initially simulated 97 gal/day, consistent with LBNL study's "high" daily draw volume (98.04 gal/day)
  - Had to increase flow rates to 2 gpm to achieve consistent performance home to home, increasing draw volume to 130 gal/day

Hot Water Draw Profile



Profile	Daily Hot Water Use (gal/day)
Building America House Simulation Protocol	97 (6 people)
BPA HPWH Evaluation	90 (4 people)
Canadian Test Standard	68.8 (“high usage”)
PNNL Lab Homes	130

Building America House Simulation Protocol

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End Use	End Use Water Temperature	Water Use	Sensible Heat Gain	Latent Heat Gain
Clothes washer	water heater setpoint	$2.35 + 0.78 \times N_{br}$ gal/day (hot only)	0*	0*
Common laundry	water heater setpoint	2.47 gal/day/housing unit (hot only)	0*	0*
Dishwasher	water heater setpoint	$2.26 + 0.75 \times N_{br}$ gal/day (hot only)	0*	0*
Shower	110°F	$14.0 + 4.67 \times N_{br}$ gal/day (hot and cold)	$741 + 247 \times N_{br}$ Btu/day	$703 + 235 \times N_{br}$ Btu/day ($0.70 + 0.23 \times N_{br}$ pints/day)
Bath	110°F	$3.5 + 1.17 \times N_{br}$ gal/day (hot and cold)	$185 + 62 \times N_{br}$ Btu/day	0**
Sinks	110°F	$12.5 + 4.16 \times N_{br}$ gal/day (hot and cold)	$310 + 103 \times N_{br}$ Btu/day	$140 + 47 \times N_{br}$ Btu/day ($0.14 + 0.05 \times N_{br}$ pints/day)
Office/public sink	110°F	$0.028 \times N_{units}$ gal/day (hot and cold)	$0.69 \times N_{units}$ Btu/day	$0.314 \times N_{units}$ Btu/day ($3.14 \times 10^{-4} \times N_{units}$ pints/day)

* Sensible and latent heat gains from appliances are included in the section titled, "Appliances and Miscellaneous Electric Loads."
** Negligible compared to showers and sinks.

Source: Hendron and Engebrecht 2010.

Canadian Standards Association Hot Water Draw Profile

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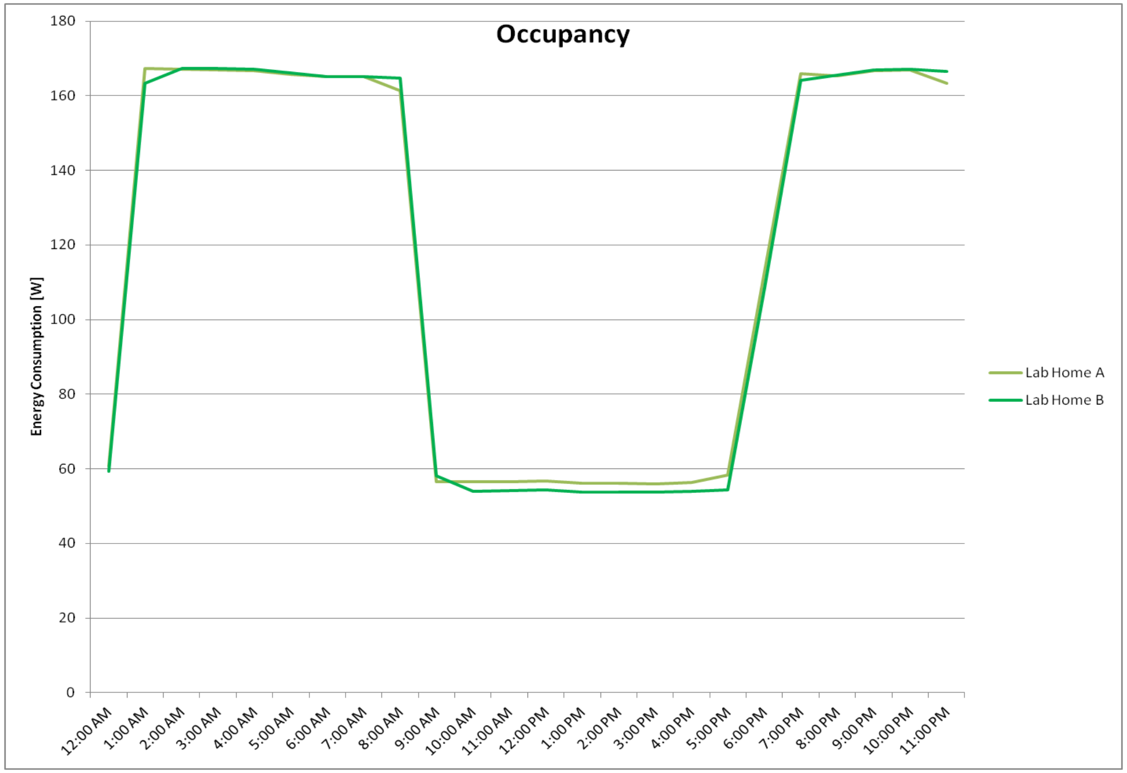
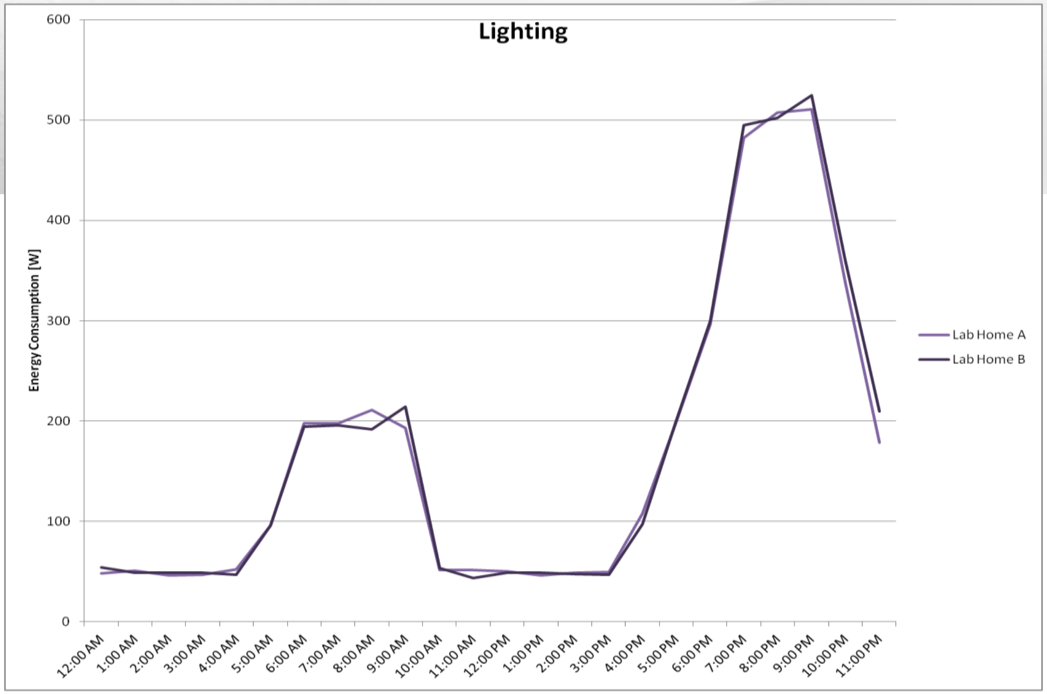
		WATER HEATER CLASSIFICATION					
		LOW USAGE		MEDIUM USAGE		HIGH USAGE	
Draw No.	TIME OF DAY (HH:MM:SS)	VOLUME DRAWN (gal)	FLOWRATE (gal / Min)	VOLUME DRAWN (gal)	FLOWRATE (gal / Min)	VOLUME DRAWN (gal)	FLOWRATE (gal / Min)
1	00:00:00	2.6	1.0	4	1.0	4.0	1.0
2	3:00:00	2.6	1.0	2.6	1.0	2.6	1.0
3	3:07:38	2.6	1.0	2.6	1.0	2.6	1.0
4	3:13:17	2.6	1.0	2.6	1.0	2.6	1.0
5	8:00:00	--	--	4	1.0	5.3	1.0
6	9:00:00	1.3	1.0	4	1.0	4.0	1.0
7	10:00:00	1.3	1.0	2.6	1.0	4.0	1.0
8	11:00:00	1.3	1.0	2.6	1.0	4.0	1.0
9	12:00:00	--	--	2.6	1.0	4.0	1.0
10	13:00:00	--	--	--	--	11.9	3.0
11	17:00:00	4.0	3.0	9.2	3	9.2	1.0
12	17:06:19		1.0	--	--	--	--
13	17:08:05	--	--	4.0	1.0	--	--
14	17:13:16	4.0	1.0	--	--	--	--
15	17:14:14	--	--	--	--	5.3	1.0
16	17:15:02	--	--	4.0	1.0	--	--
17	17:21:13	4.0	1.0	--	--	--	--
18	17:21:59	--	--	4.0	1.0	--	--
19	17:22:41	--	--	--	--	5.3	1.0
20	17:30:58	--	--	--	--	4.0	1.0
*	18:15:00	End Test					

Occupancy Simulation: Occupancy



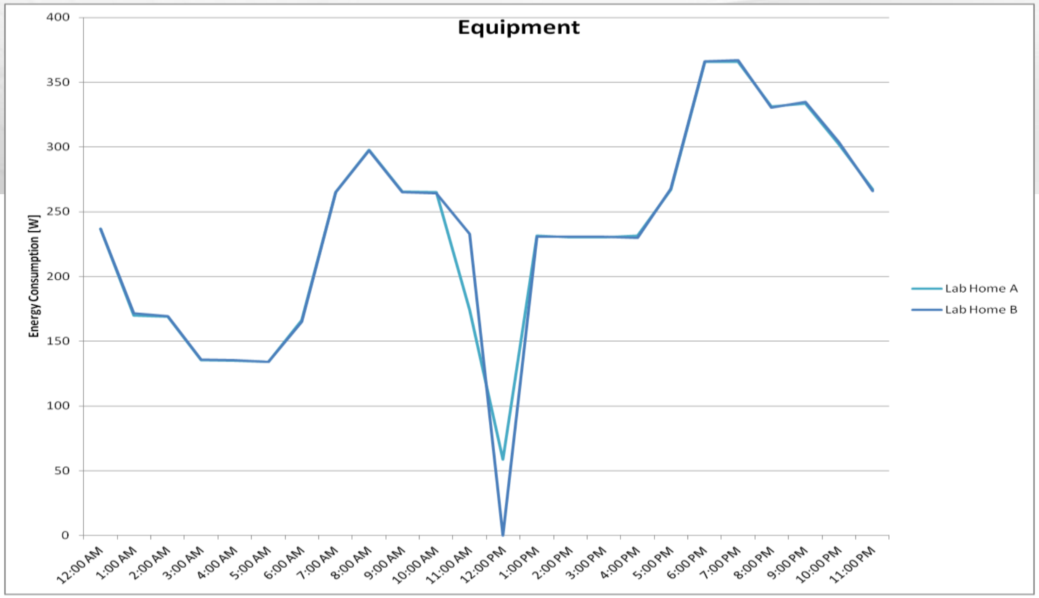
Hours of Day	Simulation Strategy	Simulated Watts	Load Locations
1 a.m. – 7 a.m.	3 60-Watt table lamps	180	Lamps in master and each bedroom
7 a.m. – 8 a.m.	3 60-Watt table lamps	180	Lamps in master and each bedroom
8 a.m. – 9 a.m.	1 60-Watt table lamp	60	Lamp in master bedroom
9 a.m. – 4 p.m.	1 60-Watt table lamp	60	Lamp in master bedroom
4 p.m. – 5 p.m.	1 60-Watt table lamp	60	Lamp in master bedroom
5 p.m. – 6 p.m.	2 60-Watt table lamps	120	Lamps in master and East bedroom
6 p.m. – 9 p.m.	3 60-Watt table lamps	180	Lamps in master and each bedroom
9 p.m. – 12 p.m.	3 60-Watt table lamps	180	Lamps in master and each bedroom
Wattage Totals		3180	

Occupancy Simulation: Lighting



Hours of Day	Simulation Strategy	Simulated Watts	Load Locations
1 a.m. – 4 a.m.	Ceiling fixture, 1 60-Watt lamp	60	Hall fixture
4 a.m. – 5 a.m.	Ceiling fixture, 2 60-Watt lamps	120	Entry and living room fixtures
5 a.m. – 6 a.m.	2 ceiling fixtures, 2 60-Watt lamps each	240	Kitchen fixtures
6 a.m. – 7 a.m.	2 ceiling fixtures, 2 60-Watt lamps each	240	Kitchen fixtures
7 a.m. – 8 a.m.	2 ceiling fixtures, 2 60-Watt lamps each	240	Kitchen fixtures
8 a.m. – 9 a.m.	Ceiling fixture, 2 60-Watt lamps	120	Kitchen fixtures
9 a.m. – 3 p.m.	Ceiling fixture, 1 60-Watt lamp	60	Hall fixture
3 p.m. – 4 p.m.	Ceiling fixture, 2 60-Watt lamps	120	Entry and living room fixtures
4 p.m. – 5 p.m.	2 ceiling fixtures, 2 60-Watt lamps each	240	Kitchen fixtures
5 p.m. – 6 p.m.	3 ceiling fixtures, 2 60-Watt lamps each	360	Kitchen and entry fixtures
6 p.m. – 7 p.m.	5 ceiling fixtures, 2 60-Watt lamps each	600	Master, kitchen, and 2 bedroom fixtures
7 p.m. – 8 p.m.	5 ceiling fixtures, 2 60-Watt lamps each	600	Master, kitchen, and 2 bedroom fixtures
8 p.m. – 9 p.m.	5 ceiling fixtures, 2 60-Watt lamps each	600	Master, kitchen, and 2 bedroom fixtures
9 p.m. – 10 p.m.	4 ceiling fixtures, 3 60-Watt lamps each	420	Master, kitchen and hall fixtures
10 p.m. – 11 p.m.	2 ceiling fixtures, 2 60-Watt lamps each	240	Kitchen fixtures
11 p.m. – 12 p.m.	Ceiling fixture, 1 60-Watt lamp	60	Hall fixture
Wattage Totals		4800	

Occupancy Simulation: Equipment



Hours of Day	Simulation Strategy	Duration of Load (Minutes)	Simulated Watts	Load Locations
1 a.m. – 2 a.m.	One 500 W & one 1,500 W wall heater	5	170	Living/dining room
2 a.m. – 3 a.m.	One 500 W & one 1,500 W wall heater	5	157	Living/dining room
3 a.m. – 4 a.m.	One 500 W & one 1,500 W wall heater	4	149	Living/dining room
4 a.m. – 5 a.m.	One 500 W & one 1,500 W wall heater	4	148	Living/dining room
5 a.m. – 6 a.m.	One 500 W & one 1,500 W wall heater	4	147	Living/dining room
6 a.m. – 7 a.m.	One 500 W & one 1,500 W wall heater	5	181	Living/dining room
7 a.m. – 8 a.m.	One 500 W & one 1,500 W wall heater	8	258	Living/dining room
8 a.m. – 9 a.m.	One 500 W & one 1,500 W wall heater	9	284	Living/dining room
9 a.m. – 3 p.m.	One 500 W & one 1,500 W wall heater	8	268	Living/dining room
3 p.m. – 4 p.m.	One 500 W & one 1,500 W wall heater	8	250	Living/dining room
4 p.m. – 5 p.m.	One 500 W & one 1,500 W wall heater	7	243	Living/dining room
5 p.m. – 6 p.m.	One 500 W & one 1,500 W wall heater	7	236	Living/dining room
6 p.m. – 7 p.m.	One 500 W & one 1,500 W wall heater	7	229	Living/dining room
7 p.m. – 8 p.m.	One 500 W & one 1,500 W wall heater	7	222	Living/dining room
8 p.m. – 9 p.m.	One 500 W & one 1,500 W wall heater	7	235	Living/dining room
9 p.m. – 10 p.m.	One 500 W & one 1,500 W wall heater	7	220	Living/dining room
10 p.m. – 11 p.m.	One 500 W & one 1,500 W wall heater	8	282	Living/dining room
11 p.m. – 12 p.m.	One 500 W & one 1,500 W wall heater	11	356	Living/dining room
Wattage Totals			5,875	

WH Baseline Performance

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AM Peak Curtailment

- Unable to collect data due to internet connectivity issues and connection with GE servers
- Theoretical calculation yields:

Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
A.M. Peak Curtailment	HP	3 hours	−515	−1,545	N/A
	ER	3 hours	−1,355	−4,065	N/A

EVE Peak Curtailment

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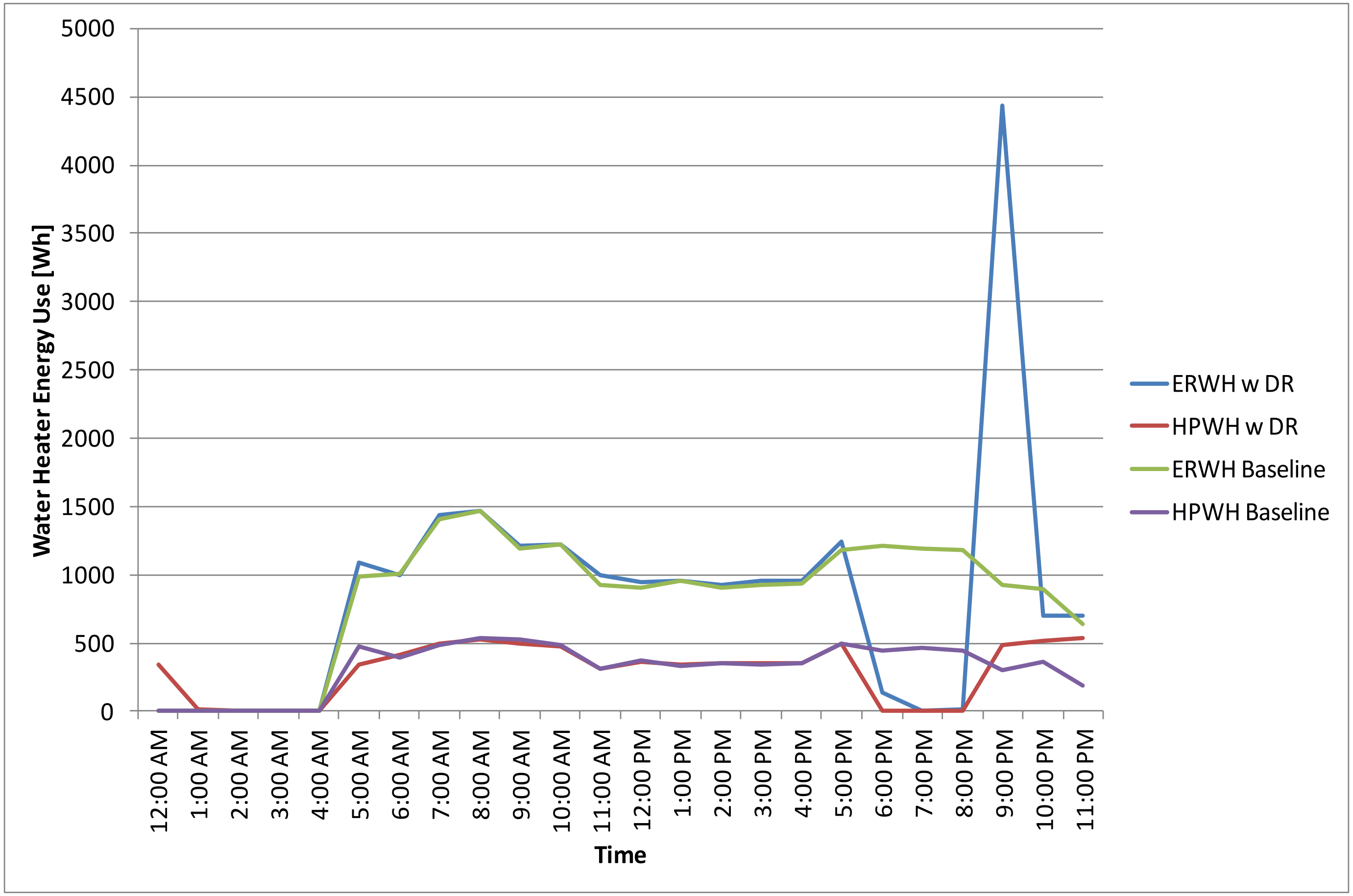
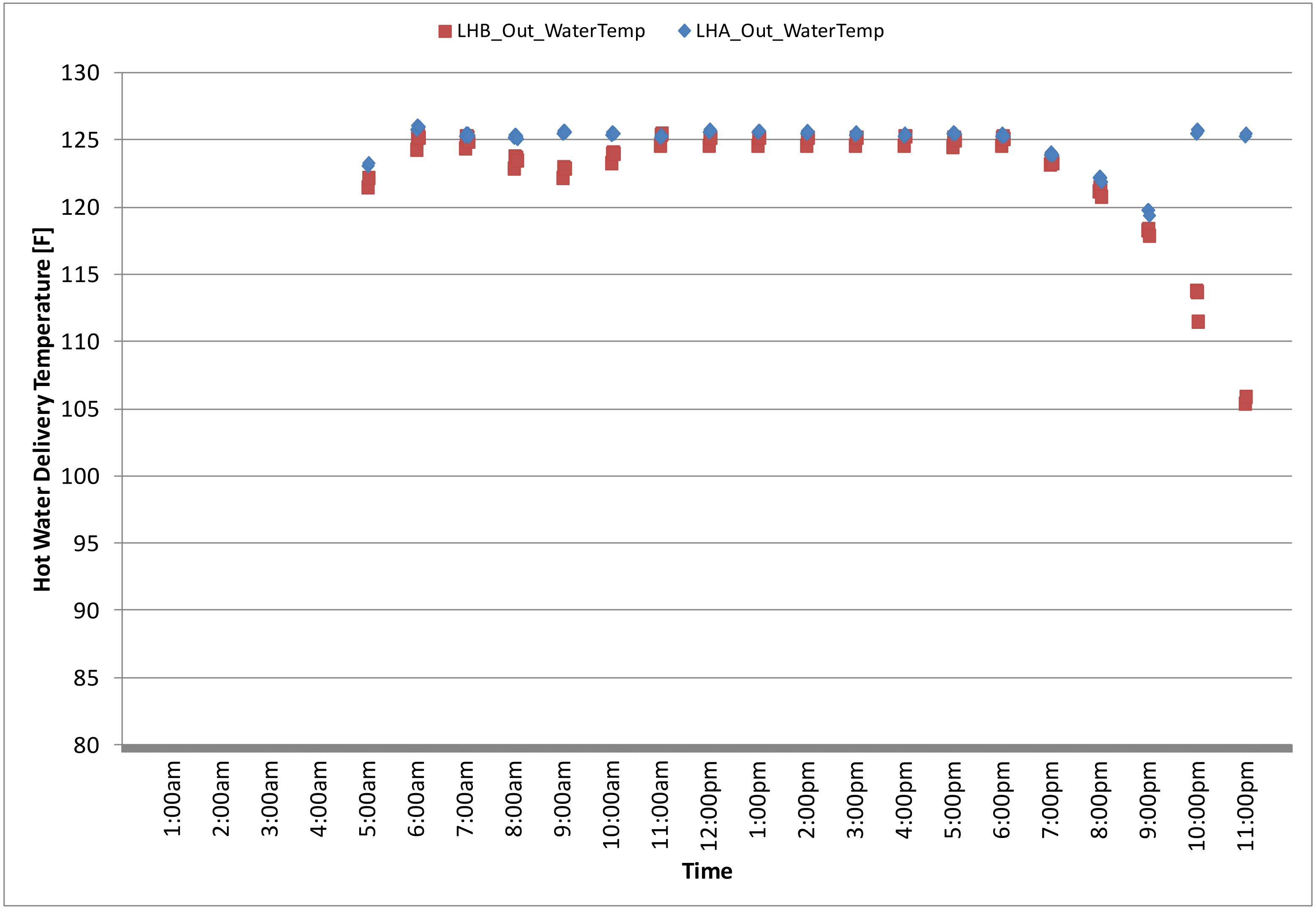
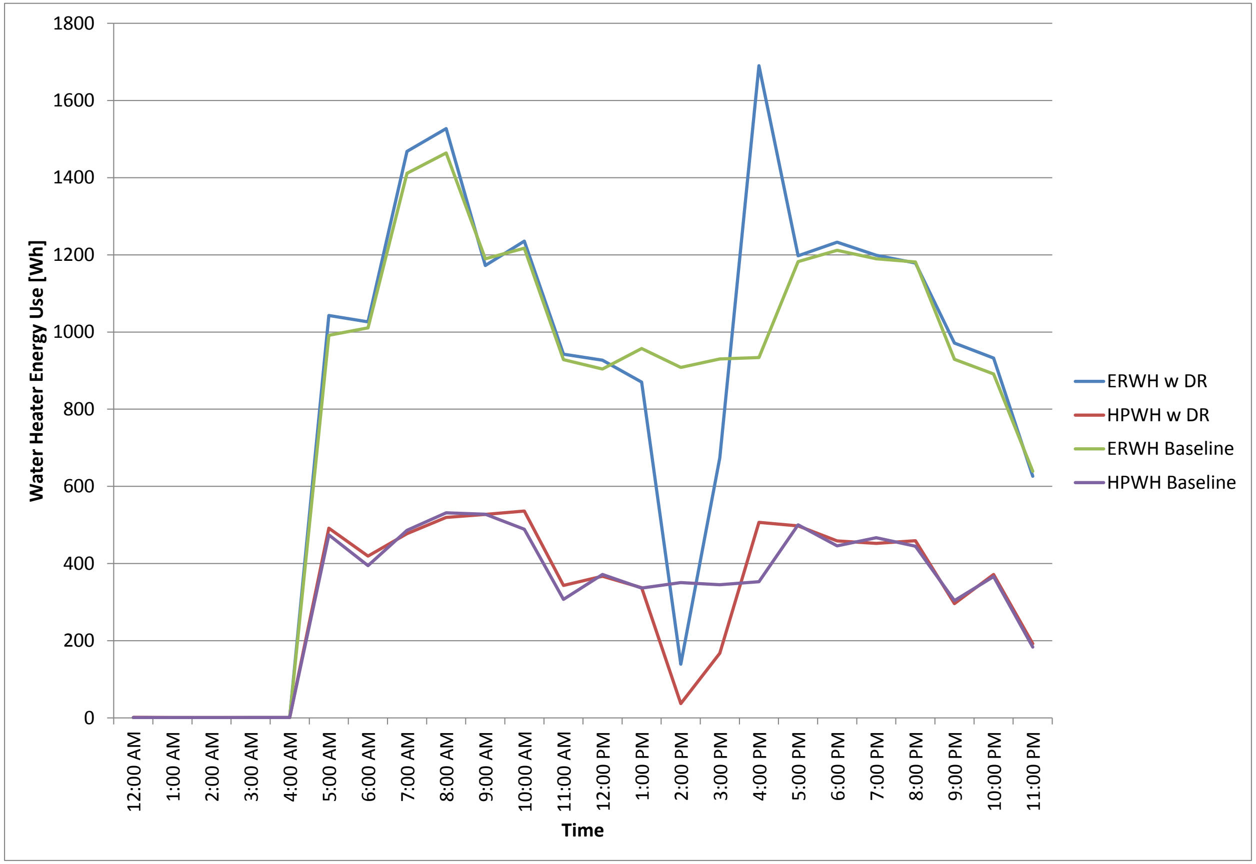
Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
EVE Peak Curtailment	HP	3 hours	−453	−1,345	−463
	ER	3 hours	−1,194	−3,433	303



EVE Peak Curtailment Tank Temperature



PM INC Balancing Event



Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
Afternoon INC Balancing Event	HP	1 hour	−351	−351	−218
	ER	1 hour	−908	−908	−15

PM INC Balancing Event Tank Temperature

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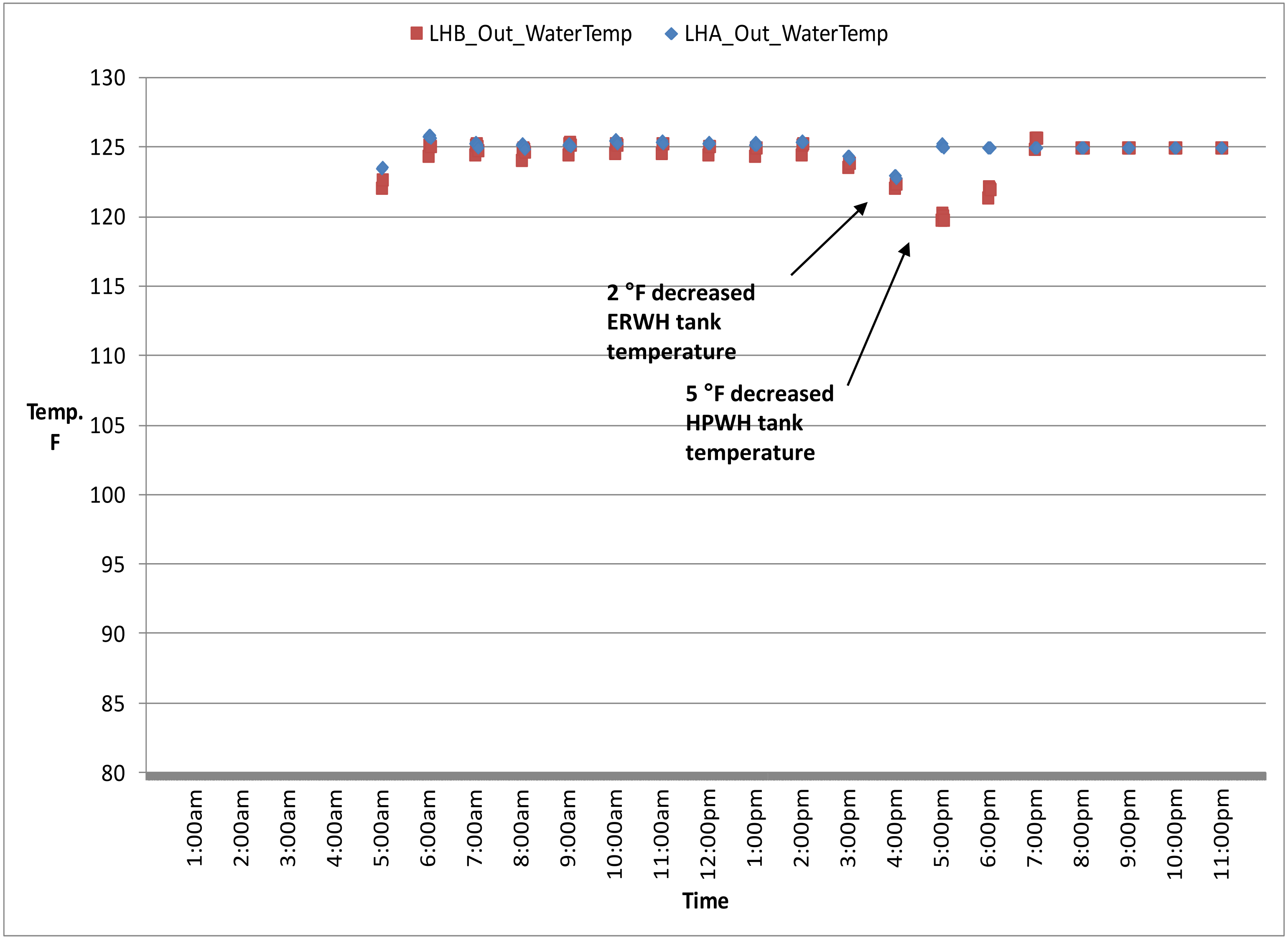
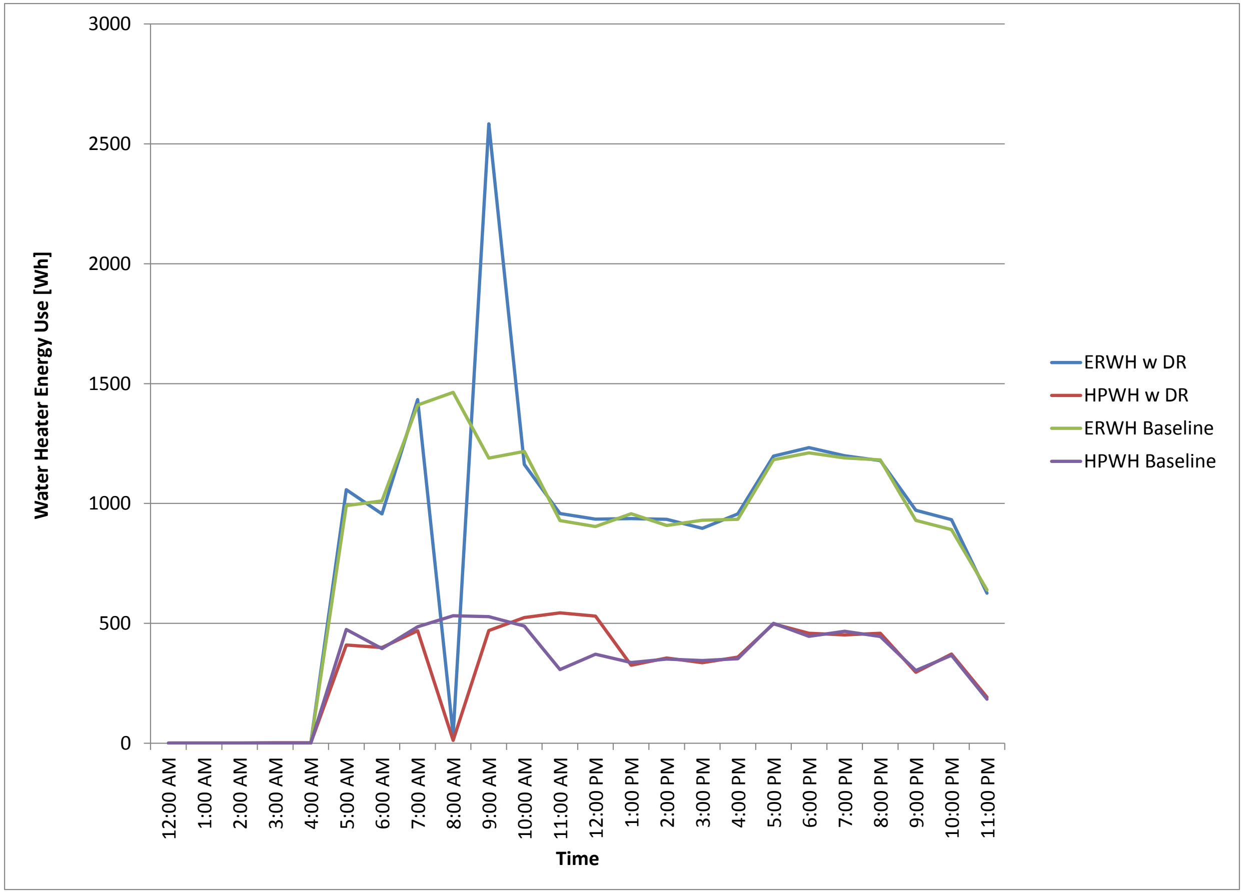


INC Balancing Events

- Decreased power (W) AND energy (Wh) use commensurate with operating time
- AM, PM, and EVE all show expected performance
- No Late night INC Balance due to no load at that time



Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
Morning INC Balancing Event	HP	1 hour	−532	−532	−216
	ER	1 hour	−1,464	−1,464	118

INC Balancing Event Tank Temperature

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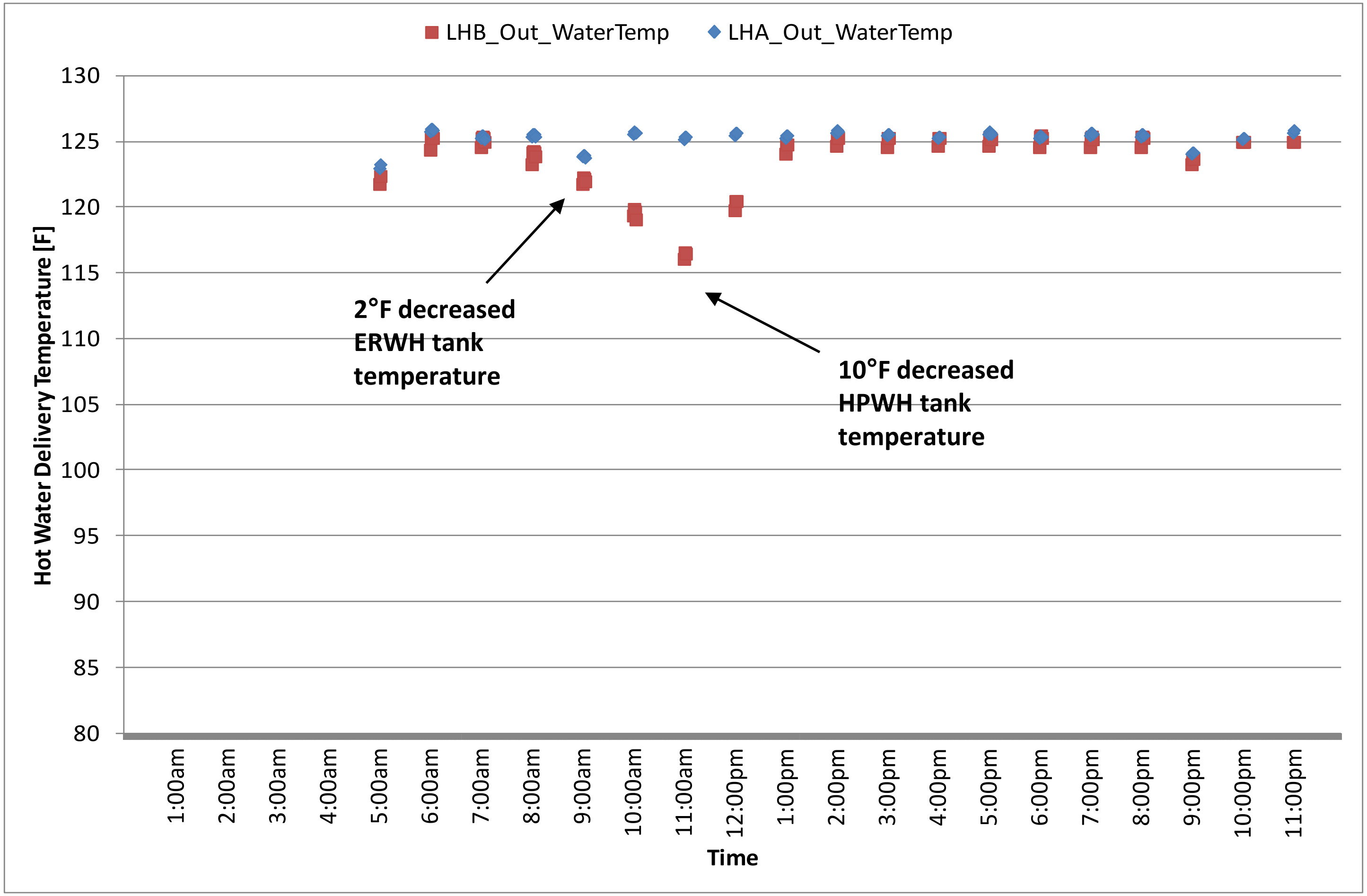
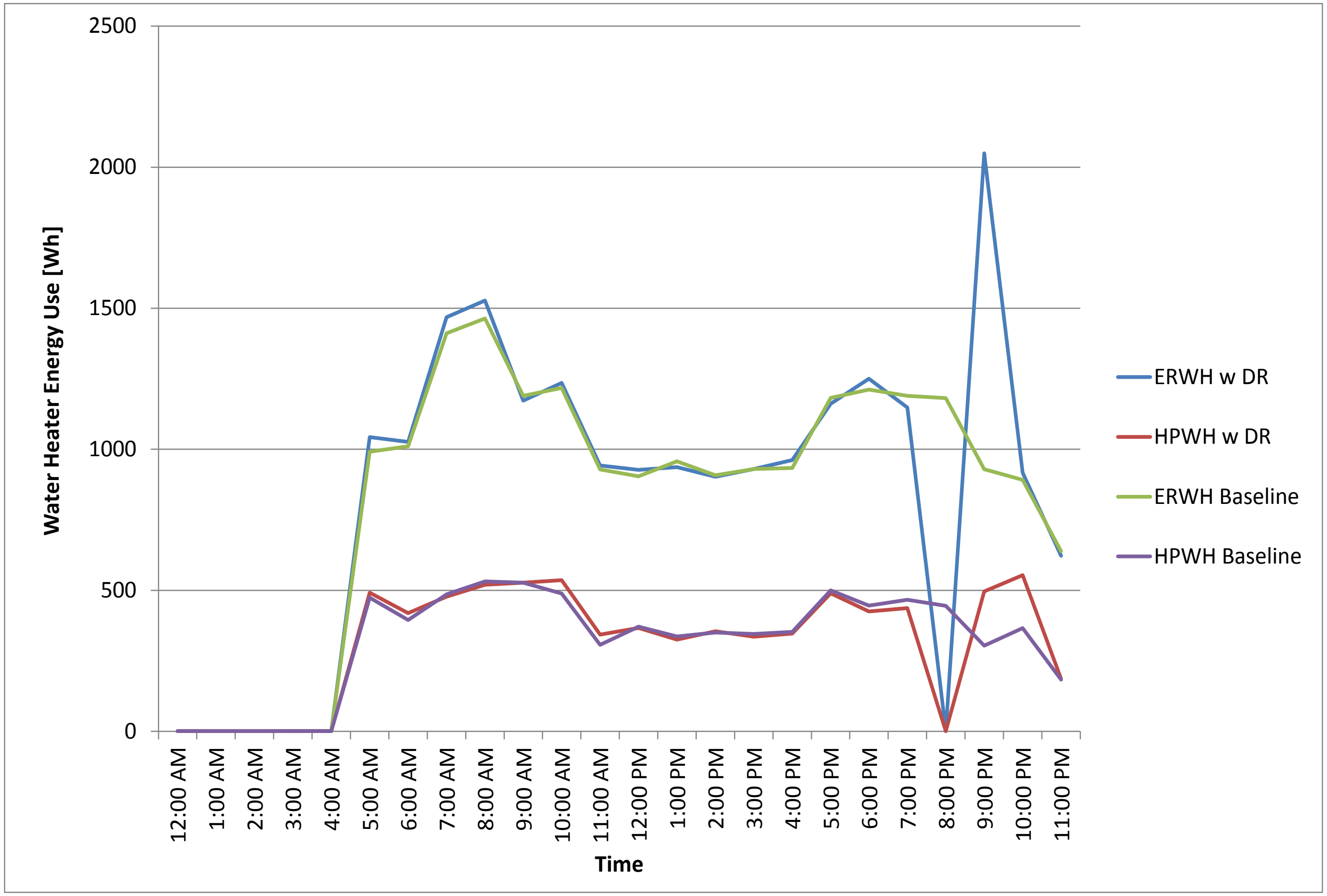
- Reduced energy use in HPWH significant due to reduced tank temperature
- May not be experienced by most occupants



EVE INC Balancing Event



Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
Evening INC Balancing Event	HP	1 hour	−445	−445	−42
	ER	1 hour	−1,182	−1,182	155

EVE INC Balancing Event Tank Temperature

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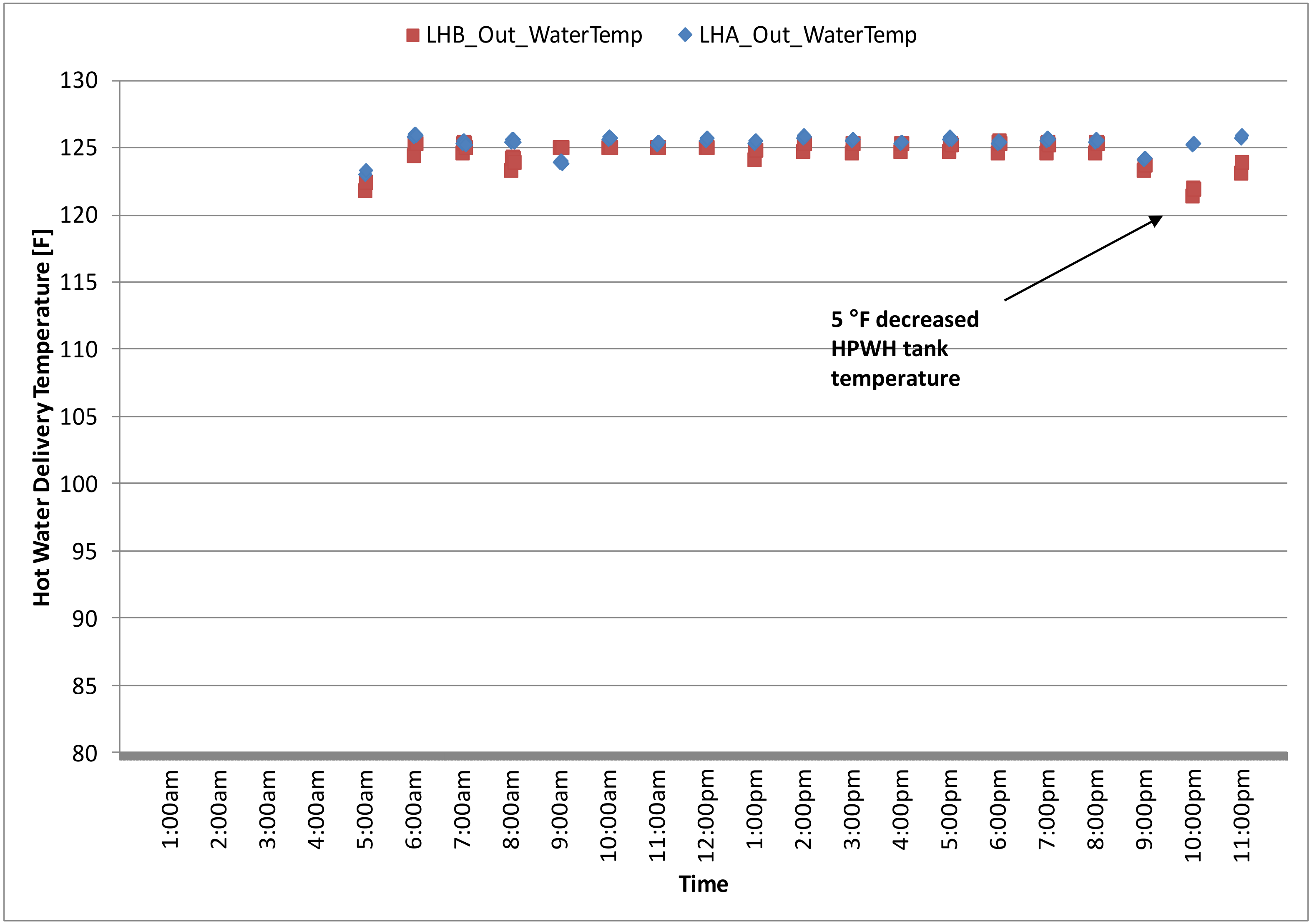
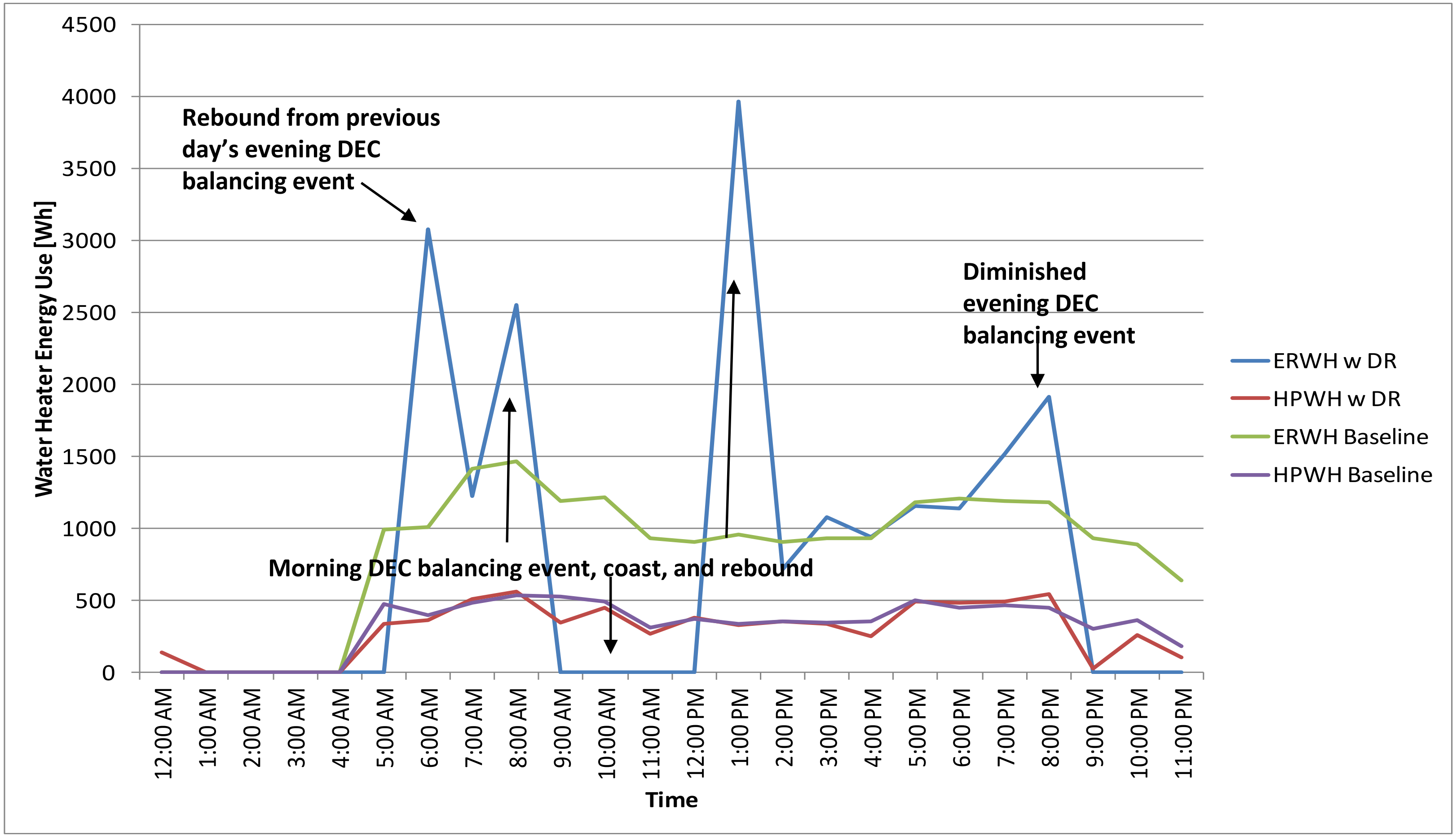


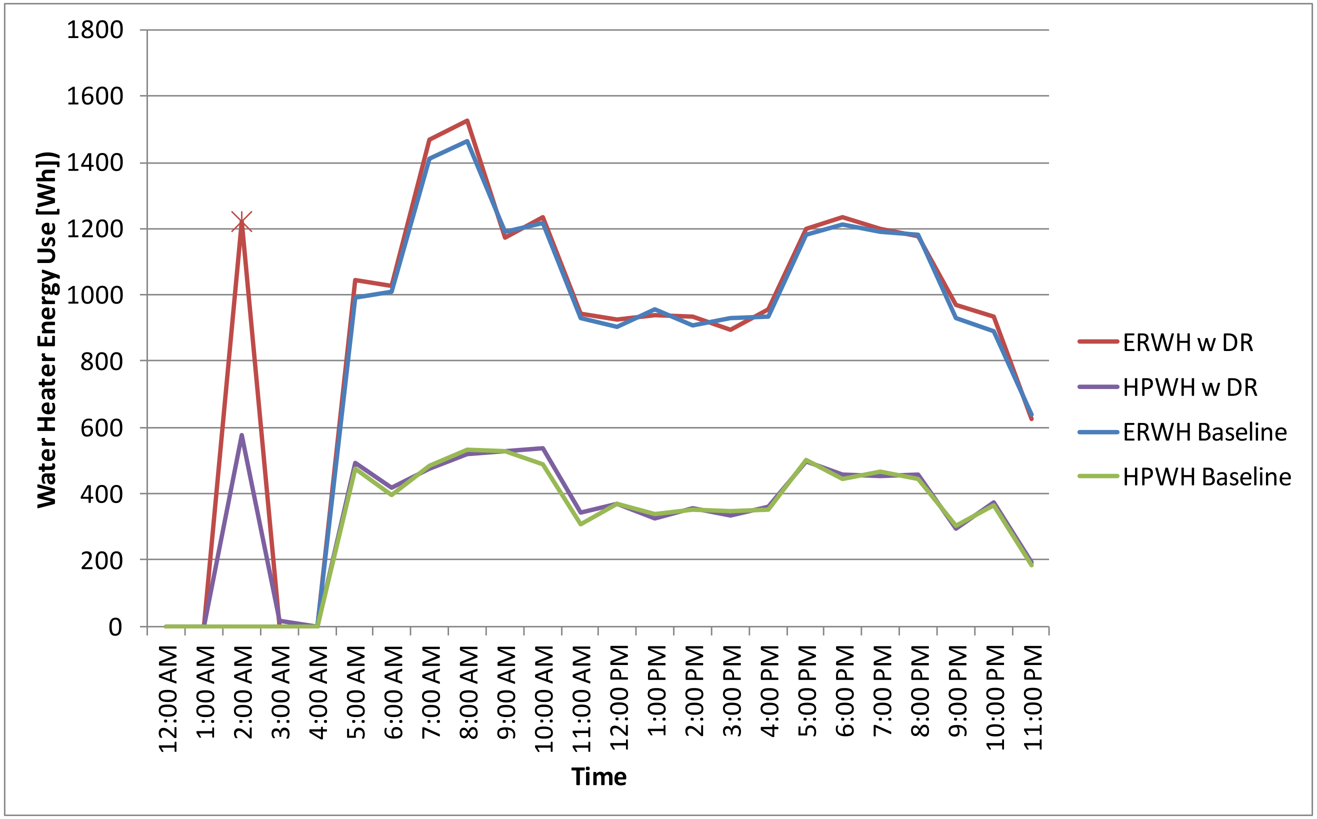
EVE DEC Balance Event Confounded by Coast and Rebound Effect



Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
Morning DEC Balancing Event	HP	1 hour	98	98	−347
	ER	1 hour	787 (1,222*)	787 (1,222*)	Unable to calculate
	* = data point is estimated based on theoretical calculation				

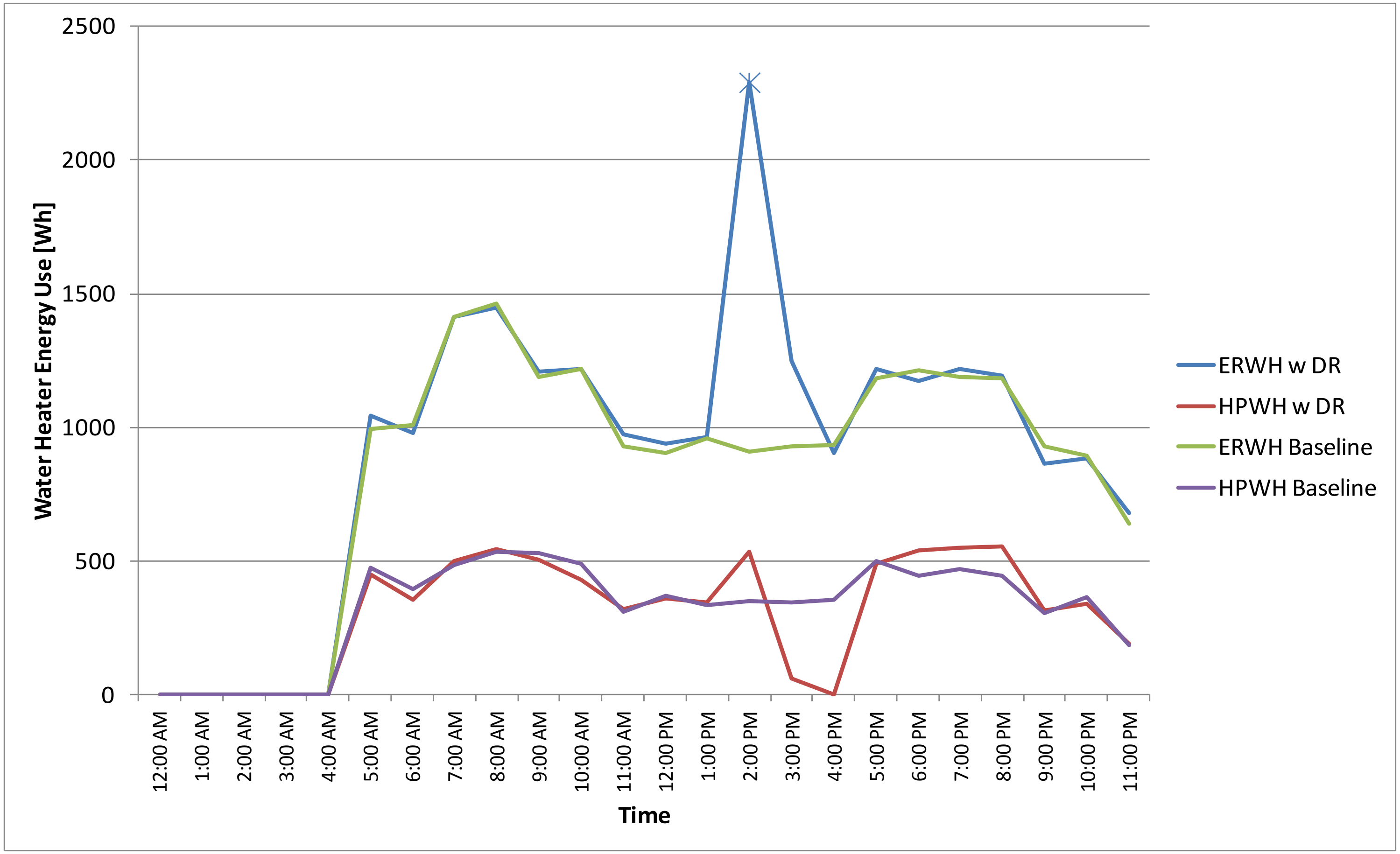
Late Night DEC Balancing Event

- Both ERWH and HPWH effectively provide DEC balancing event in the late night hours



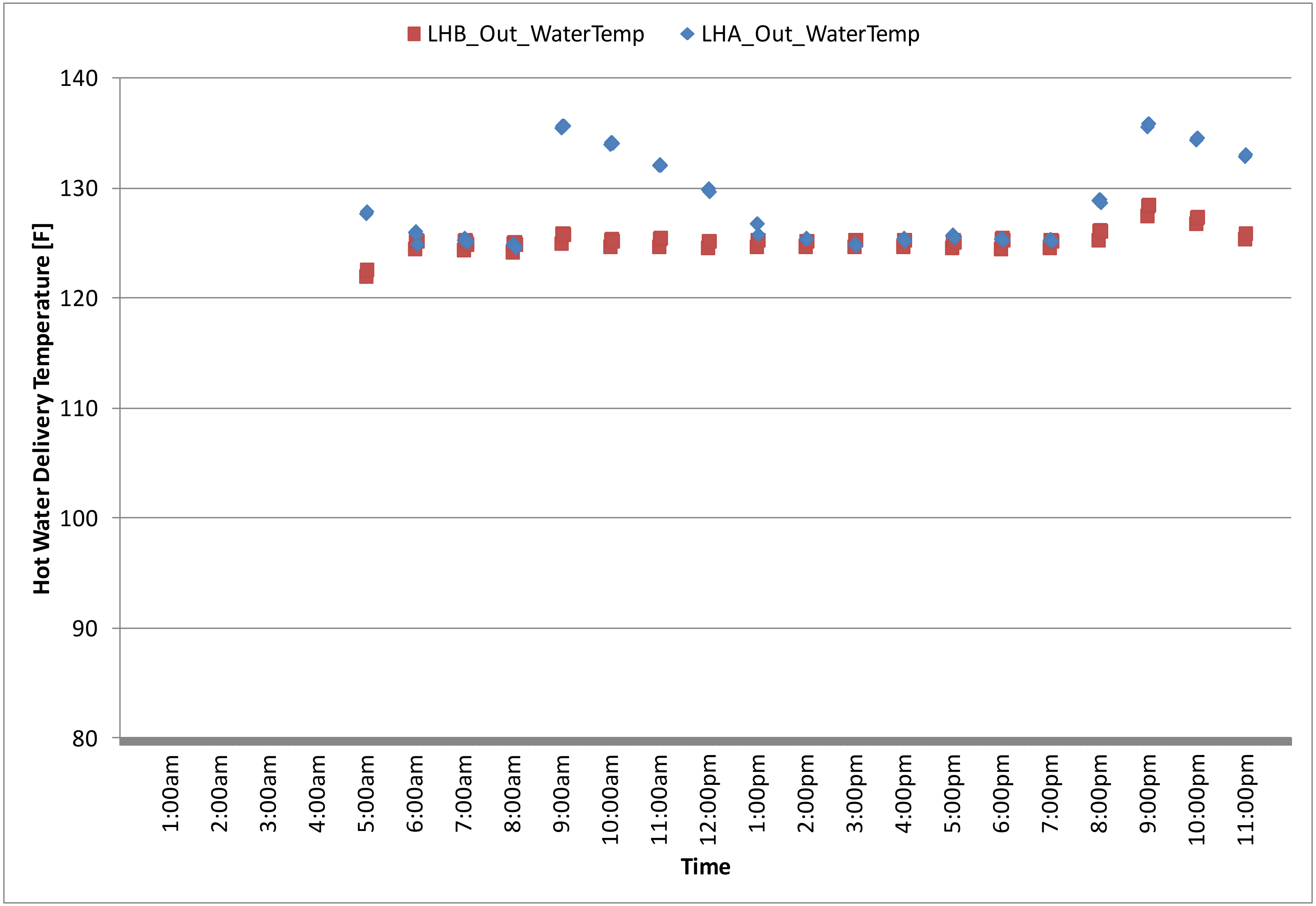
Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
Late Night DEC Balancing Event	HP	1 hour	577	577	700
	ER	1 hour	1,222*	1,222*	Unable to calculate
	* = data point is estimated based on theoretical calculation				

PM DEC Balancing Event



Experiment	WH Mode	Duration	Average Power Draw Impact (W)	Average Energy Impact during DR Event (W·h)	Average Daily Energy Impact (W·h/day)
Afternoon DEC Balancing	HP	1 hour	182	182	−297
	ER	1 hour	1,381*	1,381*	1,776*
	* = data point is estimated based on theoretical calculation				

DEC Balancing Event Tank Temperature



Calculation of Theoretical Hourly Demand

$$Q = m \times C_p \times (T_{setpoint} - T_o) \times 0.293\, {}^{Wh}/_{Btu}$$

where:

Q = energy in Wh

m = mass of water in pounds

C_p = specific heat capacity of water ($1\, {}^{Btu}/_{lb \times °F}$)

$T_{setpoint}$ = the desired set point of the water heater tank in °F

T_o = the initial temperature of the water (i.e., the previous tank set point) in °F

If there are draws during the hour, then use:

$$Q = [m_{tank} \times C_p \times (T_{setpoint} - T_o) + m_{draw} \times C_p \times (T_{setpoint} - T_{in})] \times 0.293\, {}^{Wh}/_{Btu}$$

where:

T_{in} = the incoming water temperature in °F

and other variables are as described previously.

Calculation of Theoretical Number of HPWHs Required to Provide the Same DR Potential as a Single ERWH

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