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Demand-Response Performance of Electric Resistance and CO_2 Refrigerant Heat Pump Water Heater

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Background

- Water heating is a large load
  - Represents ~19% of residential energy consumption, amounting to 1.803 Quads annually
  - 41% of homes currently use electric resistance water heaters (ERWH)
- HPWHs can save energy!

Source	Savings	Source	Notes
DOE Test Procedure	≥63%	10 CFR 430	Specific test conditions
NREL COP measurements	18-72%	Sparn et al, 2014	Dependent on temperature and draw profile
PNNL Lab Homes	61.7 ± 1.7%	Widder et al, 2013	Heat pump only mode
NEEA HPWH Model Validation Study	38-58%	Larson et al, 2015	Field measurements

CO_2 (R-744) Water Heaters

- Beneficial for a variety of reasons:
  - Wider operating temperature
    - High efficiency, even at low temps
  - Low GWP

Refrigerant	GWP	Avg COP @ 19.4 °C (67 °F)	Low operating temp	Source
R-134a	1,302	~2.5	1.7°C (35°F)	GE Gen2 GeoSpring[1]
R-410a	2,000	~2.9	2.8°C (37°F)	Rheem HB50RH[2]
R-744	1	~4.0	-8.3°C (17°F)	Sanden[3]

[1] http://neea.org/docs/default-source/lab-test-reports/hpwh-lab-report_ge_gen2_09-28-2012.pdf?sfvrsn=2
[2] http://neea.org/docs/default-source/lab-test-reports/hpwh-lab-report_rheem_hb50_06-28-2013.pdf?sfvrsn=2
[3] http://neea.org/docs/default-source/lab-test-reports/hpwh-lab-report_sanden_ges_hpwh_11-06-2013.pdf?sfvrsn=2

HPWHs and Demand Response

- DR programs are an important tool to enable widespread integration of variable renewable energy and enable other grid benefits
- Utilities often use electric resistance water heaters to conduct DR
  - Significant thermal storage (volume of hot water).
  - Contribute the second largest residential load, behind heating equipment.
  - Relatively high power consumption and a large installed base.
  - Follow a consistent load pattern that is often coincident with utility peak power periods
- HPWHs may change how utilities offer and manage DR programs
  - HPWHs offer inherent peak load reduction benefits due to their increased energy efficiency
  - Preliminary research on traditional, integrated HPWHs demonstrated that HPWHs offer a smaller "controllable load" but are more "available" since they are more likely to be on during the event due to longer compressor run times (Widder et al, 2013)

Study Overview

- **Previous studies** have:
  - Evaluated DR performance of HPWHs (e.g., Widder et al, 2013; Mayhorn et al, 2015; etc)
  - Evaluated the energy efficiency performance of CO_2 HPWHs (Larson et al, 2013; Eklund and Banks, 2014; etc)
- **This study** compares DR performance of two electric water heaters:
  - Emerging HPWH technology employing a remote compressor design (i.e., split-system) using CO_2 as the refrigerant
  - 190 liter (50 gal) electric resistance water heater (ERWH) reference case
    - Represents standard practice in DR programs today (Cooke et al, 2015)

	ERWH	HPWH
Tank Size (liter)	190	315
Set point (°C)	48.9	65.6
Energy Factor (d'less)	0.93	3.35*
COP (d'less)	1	2.1-5.0; depending on outdoor air temperature [4]
Compressor location	NA	Outside conditioned space
Refrigerant	NA	R-744 (CO_2)

* Larson et al, 2015

Study Conducted in the PNNL Lab Homes

Side-by-side baseline and experimental home to compare ERWH to HPWH.

Split-System CO_2 HPWH

DR Project Details

- Two primary types of Demand Response evaluated:
  - **Peak Shifting** = shifting load out of the peak demand period into hours when there is low demand, and possible excess generation.
  - **Balancing** = response to hourly or sub-hourly changes in generation capacity because due to variability in generation resources or large disturbances in the grid.
    - Just looked at INC Balancing (decreasing load) in this study

- Different schedules were used for ERWH and CO_2 HPWH due to different experimental objectives of the DR studies, but provide comparable findings regarding *ability* and *characteristics* of ERWH and HPWHs providing these two services.

DR Schedules

Peak Shifting

ERWH

Day	Start Time	End Time	DR Event Duration
1	7:00 AM	10:00 AM	3 hours
2	2:00 PM	5:00 PM	3 hours
3	6:00 PM	7:00 PM	1 hours

CO2 HPWH

Day	Start Time	End Time	DR Event Duration
1	6:00 PM	12:00 AM	6 hours
2	5:00 PM	12:00 AM	7 hours
3	4:00 PM	12:00 AM	8 hours
4	3:00 PM	12:00 AM	9 hours
5	2:00 PM	12:00 AM	10 hours
6	1:00 PM	12:00 AM	11 hours
7	12:00 PM	12:00 AM	12 hours

Balancing

ERWH

Day	Start Time	End Time	Balancing INC Event Duration
1	8:00 AM 8:00 PM	9:00 AM 9:00 PM	1 hour 1 hour
2	2:00 PM 2:00 AM	3:00 PM 3:00 AM	1 hour 1 hour

CO2 HPWH

Day	Start Time	End Time	Balancing INC Event Duration
1	2:00 PM	3:00 PM	1 hour
2	2:00 PM	3:00 PM	1 hour
3	2:00 PM	3:00 PM	1 hour
4	8:00 AM 2:00 PM 8:00 PM	9:00 AM 3:00 PM 9:00 PM	1 hour 1 hour 1 hour
5	8:00 AM 2:00 PM 8:00 PM	9:00 AM 3:00 PM 9:00 PM	1 hour 1 hour 1 hour
6	8:00 AM 2:00 PM 8:00 PM	9:00 AM 3:00 PM 9:00 PM	1 hour 1 hour 1 hour

Hot Water Draw Profile

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- **Performance is *very* dependent on hot water draw profile**
  - ERWH draw profile was representative of typical daily draw pattern for group of homes
  - 120 ºF set point
  - Fixed 1.5 gpm flow rates
- **Selected high draw volume to explore "worst-case scenario" impacts on tank temperature and maximum availability of DR resources for CO2 HPWH**
  - Simulated 492 liter/day (130 gal/day) draw profile
  - Ensures that the results are conservative and representative of the worst-case customer impact, where many homeowners will be impacted much less than the experiments demonstrate
  - Allows for easier extrapolation to more representative draws

Baseline Performance

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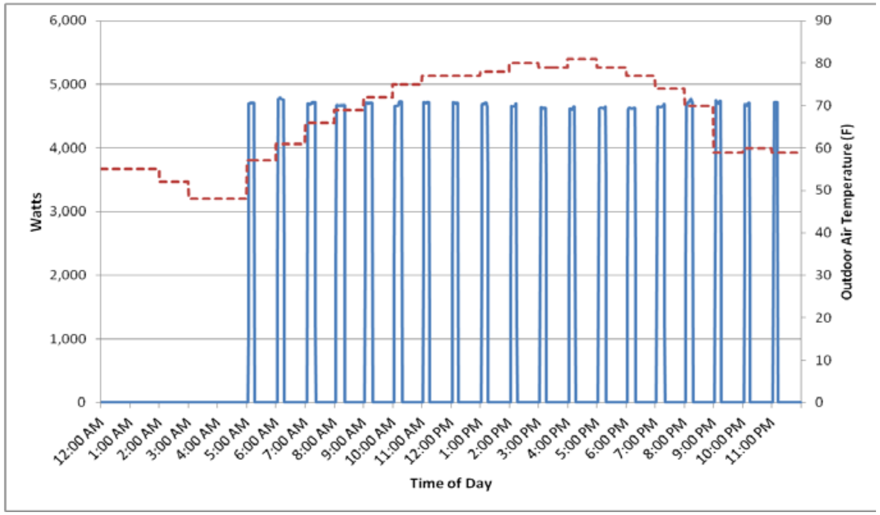
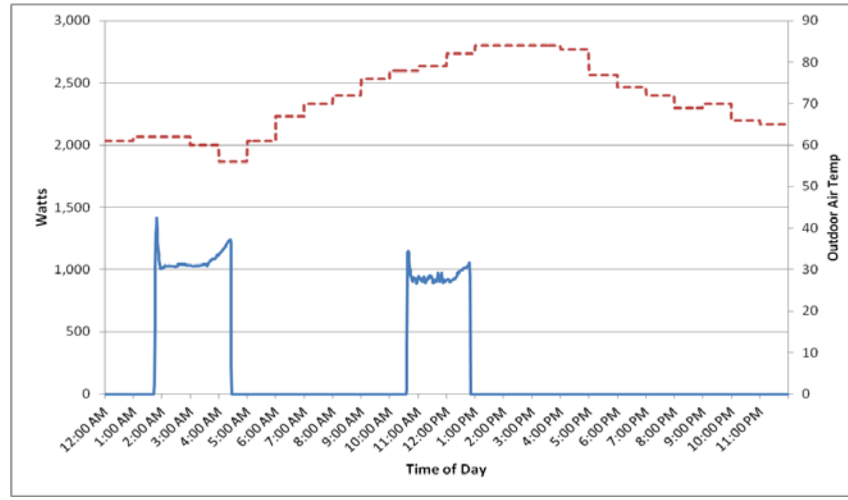
ERWH



ERWH Baseline Power Profile, June 3, 2013

CO2 HPWH



Split-System HPWH Baseline Power Profile, August 22, 2014

Experiment	ERWH	HPWH
Baseline Period	20.2 ±0. 348 kWh/day	4.99 ±0. 992 kWh/day
% reduction over ERWH	0%	75%

- CO2 HPWH demonstrated:
  - Lower power consumption (1kW compared to 4.5 kW)
  - Longer, more sporadic draws due to increased tank thermal capacity
  - 75% reduction in energy consumption

Peak Shifting Performance

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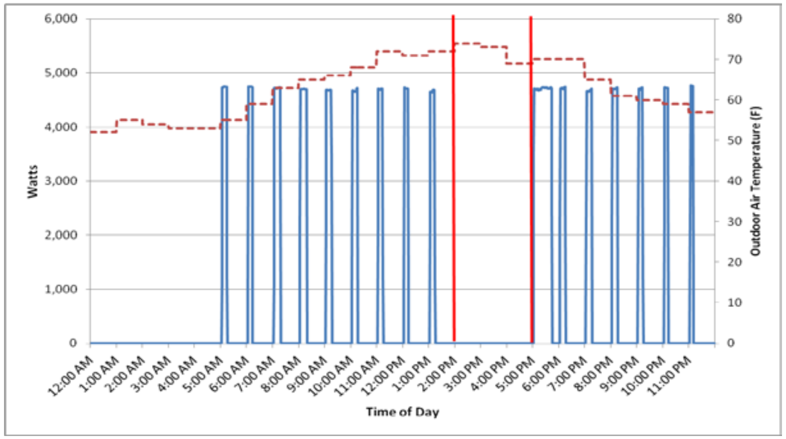
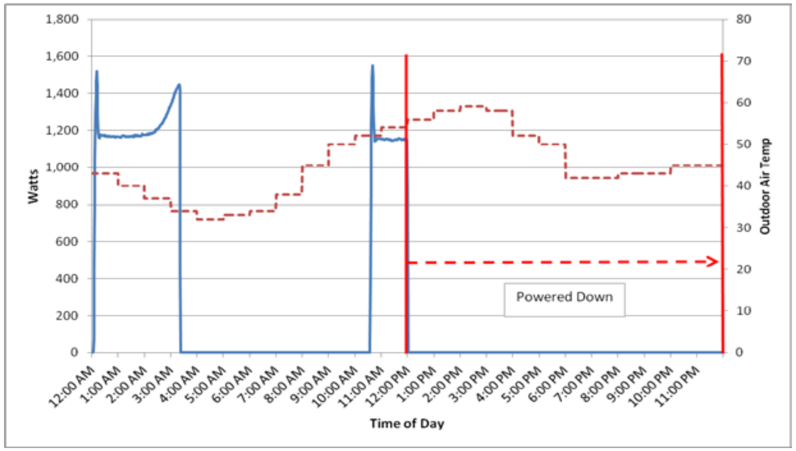
ERWH



ERWH Peak Shift Power Profile: 2:00 PM to 5:00 PM Powered-Down Protocol, 6-13-13

CO2 HPWH



Split-System Peak Shift Power Profile: Longest DR Event (12 hours powered down), 10-27-14

Experiment Metric	ERWH	HPWH
Dispatchable Watts (kW)	4.6	1.2
Recovery Energy Shift (kWh)[1]	2.69	2.95
Peak Shift Duration (hours)	3	6
Maximum Off Period While Delivered Water Temperature Met (hours)	3	12
Daily Energy Consumption (kWh)	8.87	5.90[2]

[1] The Recovery Energy Shift is the water heater energy use at the conclusion of the Peak Shift period.
[2] Dependent on outdoor air and supply water temperature

- CO2 HPWH demonstrated:
  - Decreased Dispatchable Watts
  - Max shift of up to 12 hrs while maintaining HW delivery temp (compared to 3 hrs for 190 L ERWH). Important for shifting peak into low-demand through periods.

Balancing INC Performance

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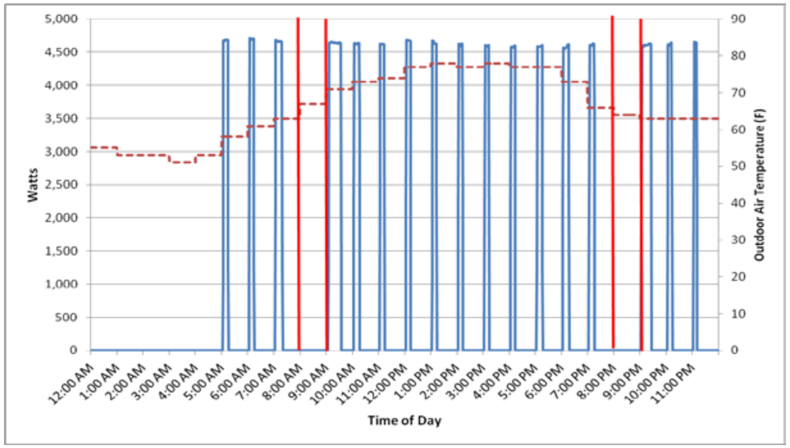
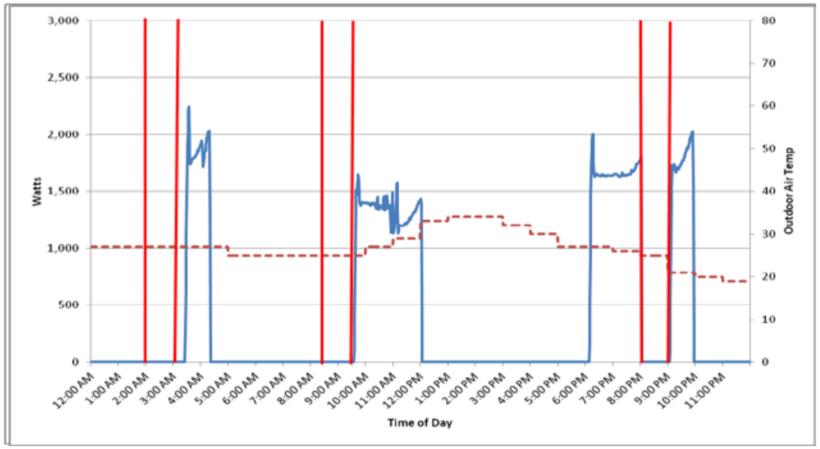
ERWH



ERWH Balancing INC Power Profile 8:00 AM and 8:00 PM (1 hour powered down), 6-23-13

CO2 HPWH



Split-System Balancing INC Power Profile: 2:00 AM, 8:00 AM, and 8:00 PM (1 hour powered-down protocol), 11-14-14

Experiment Metric	ERWH	HPWH
Dispatchable Watts (kW)[1]	4.6	1.6
Recovery Energy Shift (kWh)[2]	0.86	1.6
Daily Energy Consumption (kWh)	21.1	10.1[3]

[1] The increase in HPWH Dispatchable Watts for the Balancing INC experiments results from the cooler source air and supply water during this period.
[2] The Balancing INC Recovery Energy Shift is reported assuming the protocol period aligns with a water heater activation event. Assuming alignment and the 1-hour event, the values listed are the maximum energy shifts.
[3] Larger energy consumption compared to the baseline period due to decreased outdoor air and supply water temperatures.

- CO2 HPWH demonstrated an increased ability to shift load *if* the DR event aligns with period HPWH is on

Key Findings: Peak Curtailment and INC Balancing Events

- In general, 315 L HPWH demonstrated (compared to 190L ERWH):
  - 75% reduction in energy consumption
    - Dependent on outdoor air and supply water temps
  - Reduced Dispatchable Watts
    - Due to increased efficiency
  - Increased availability (i.e. likelihood water heater is on during event)
    - Due to lower input capacity of compressor compared to draw profile
  - Significant increase in duration of peak shifting
    - Due to increased thermal capacity of HPWH tank
  - Increased response during Balancing INC, but decreased availability

Due to HPWH technology

Due to tank size

Water Heater	ERWH	Split System HPWH
Dispatchable Watts	4.6kW	1.2-1.6kW*
Total Off Period While Delivered Water Temperature Met	3 Hours	12 Hours
Baseline Average Daily Minutes of Operation	4.51 Hours	4.96 Hours
* Dependent on outdoor air and supply water temperature		

Conclusions

- HPWH can provide similar DR services as an ERWH, but more efficiently
- Characteristics of HPWH response are different (e.g., lower Dispatchable Watts, increased availability in some hours), so utility programs should be designed with these characteristics in mind
- Thermal capacity and size of the storage tank (for either HPWH or ERWH) need to be matched to the specific DR event to ensure adequate operation and implementation of the event

Thank you!

Questions?

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