Space Conditioning Interactions with Heat Pump Water Heaters: A Test in the PNNL Side-by-Side Lab Homes

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BACKGROUND
Definition: Interaction Factor

- \( (HC_f) = \text{Thermal Coupling as percent of the total theoretical HPWH thermal load that impacts space conditioning load} \)

- In English: How much energy does the space conditioning system have to make up when a HPWH is in a home?
Motivation

- **November 2014**, the Regional Technical Forum (RTF) accepted a preliminary interaction factor \( (HC_f) = 65\% \) based on preliminary data from the PNNL Lab Homes.\(^1\)

- The RTF also directed staff to develop a research plan to study the HVAC interaction effect induced by heat pump water heaters (HPWHs), which was accepted in **April 2015**.

- Research plan consists of two primary components:
  1. Theoretical analysis (Ecotope) to describe basis for \( HC_f \)
  2. Experimental study in the PNNL Lab Homes to determine/validate range of expected field \( HC_f \) values

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1. Some of the heat from the space is latent heat \( Q_{\text{HPWH,latent}} \), which will not affect the ambient dry bulb temperature of the space.

2. Localized cooling may decrease the heat transfer from the space as compared to the pre-retrofit case \( U_A \Delta T_{\text{HPWH}} < U_A \Delta T_{\text{no HPWH}} \).

3. Some of the heat imparted to the water heater from the space may be “free heat” from solar gains that would also decrease the total heat transfer from the space if the house drifts above set point.

4. HPWH near a thermostat may artificially call for more heat than necessary for thermostat to maintain set point.
Lab Homes show localized cooling in water heater closet of ~8.4 °F (~4.7 °C)

NRCan shows localized cooling in basement of ~3.6 °F (~2 °C)
TEST PLAN
Research Strategy: PNNL Lab Homes

► Research Goal
  ■ Observe the space conditioning energy interaction that results from the installation of a HPWH in interior spaces

► Data Collection
  ■ PNNL Lab Home Study: Test four install locations throughout home
    • Use a HPWH on a dolly operating on a known “high” load profile compared to a ERWH operating in the baseline home

► Analysis
  ■ Compute change in space heating requirement, change in latent heat across the coil, and any impact on localized cooling to compute HVAC interaction factor for each location
  ■ Observe range of results
# Experimental Plan

<table>
<thead>
<tr>
<th>Test Case Description</th>
<th>Test Location</th>
<th>Reason to Include Test Case</th>
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<tbody>
<tr>
<td>Master Bath, Door Closed</td>
<td>A</td>
<td>Most disconnected to thermostat, but still in conditioned space</td>
</tr>
<tr>
<td>Utility Closet</td>
<td>B</td>
<td>Most connected to the return duct</td>
</tr>
<tr>
<td>Living Room</td>
<td>C</td>
<td>Most connected to the thermostat</td>
</tr>
<tr>
<td>Water Heater Closet</td>
<td>D</td>
<td>Represents semi-conditioned space</td>
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EXPERIMENTAL SETUP
Side-By-Side Homes Are Fully Equipped

- Energy metering
  - 42 individually monitored breakers with ½ controllable
- Temperature and relative humidity
  - 15 interior room temperature thermocouples
- Water and environment
  - Controllable water flows at fixtures
  - On-site weather station
- Data collection via 2 Campbell Scientific data loggers/home
  - 1 minute data, sometimes averaged over longer periods

Per Home!
Monitored Data Around Water Heater

*Note: Picture demonstrates monitored values only. Location of sensors is not necessarily accurate.
Fully Mobile Water Heaters

- Air Flow Sensor Bracket
- Flexible Hoses for Water Inlet and Outlet
- Solar shielded “ambient” T/RH sensor
- Tipping Bucket
- Rolling Platform
- Plywood False Floor
Two T/RH Sensors (Campbell Scientific HC2S3, 75ft cable, ±0.1°0.8% RH). Top arrow points to supply T/RH measurement, bottom arrow points to exhaust T/RH measurement.

Condensate Drain

Tipping Bucket (Rainwise Inc., Rainew 111 Single Counter. 0.01 inches per tip. 2% accuracy at 1.5 inches per hour)
Utility Room Setup
INITIAL RESULTS
General Observations

- Previously mentioned studies could be considered semi-conditioned space (garage, basement, water heater closet). In current experiment, water heaters are truly interacting with the thermostat in conditioned space.

- Water draw profile is high (84 gallons per day) compared to national or regional averages in order to capture the high end of a realistic signal.

- Heat pump only mode so no input energy coming from resistance elements. All input energy from either the air or the compressor motor.

- Thermostat set at 71°F, water heater set at 125°F
Whole House Energy Use During Calibration (1/15/17)

March 6, 2017
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Difference in Daily Water Heater Energy: (Baseline minus Experimental Home)

[Graph showing energy consumption and outdoor temperature for different areas of a home.]
Difference in Daily HVAC Energy: 
(Experimental minus Baseline Home)

DIAGRAM: 
- Axis X: Average Outdoor Temp (°F) 
- Axis Y: Energy (Wh)
- Baseline (ER) 
- WH in Mstr Ba 
- WH in Liv Rm 
- WH in Utl Rm

Symbols:
- Red Diamond: Δ Daily Heating Loads (Wh) 
- Black Circle: Average Outdoor Temp (°F)

Note: ER = Electric Resistance Mode
Experimental Home - Hall Temperatures in the Experimental Home

Thermostat doing a good job at keeping the hall temperatures fairly constant so we can compare results.
Local Cooling Effect in Small Spaces

Local cooling is about 17-20°F in small spaces

Master Bathroom Temperatures

Utility Room Temperatures
Increased space temperatures in master bedroom - potentially due to local cooling around thermostat

Solar gains because master bedroom on south side
General Observations

- Theoretical interaction factors assume a single, well-mixed zone miss most of the relevant processes.
- Energy use in home with HPWH increases as HPWH is closer to the thermostat and/or return grille.
- Local cooling effect is more than double of previous experiments in small spaces. Conditioned space, not ducted to the outside.
- As expected, indoor winter conditions are dry so no condensate measured.
  - HVAC load due to HPWH interaction is exaggerated in this instance.
Future Work

- Flip flop homes. Put water heater in HPWH mode in “baseline” home and in ER mode in “experimental” home. Compare results to previous experiments.

- Additional experiment still needs to take place in the water heater closet. Results can be compared with previous experiments in the water heater closet.

- Determine if stratification is occurring in each room, and contributing to elevated temperatures

- RTF contract analysts have requested a space heating experiment using similar approach, but with space heaters instead of HPWHs. This may shed light on sensible heating interaction vs. sensible cooling interaction

- Report all results in HCf