New Construction
Hybrid-Ductless Heat Pump Study
(Resistance is Futile)

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What is a Ductless Heat Pump (DHP)?

1. Fan coil (indoor)
2. Compressor (outdoor)
3. Remote
DHP Performance

- Unlike central heat pumps, DHPs have outstanding cold weather performance, requiring no supplemental heat.

- They also maintain COPs above 2 even at extreme cold temperatures.

Winkler, J, NREL, 2011
Hybrid DHP/Electric Resistance Systems

• A DHP fan coil located in the main living area in combination with electric resistance zone heaters located in the perimeter rooms.

• The DHP carries the bulk of the home’s heating/cooling load while the zone heaters provide supplemental heat.
How DHP Hybrid Displacement Works

• Ideal alternative to electric resistance zonal heated homes

• Reduces heating bills by displacing a large share of zonal electric heat

• DHP installed in the main living area
New Construction Hybrid DHP/ER Study

- **February 2011** – Habitat for Humanity (HFH) seeks help for new housing project from Tacoma Power using DHPs.
- **Fall 2012** - Tacoma Power recruits BPA, SnoPUD, and Cowlitz PUD for new construction hybrid DHP study.
- **Spring 2012** – HFH breaks ground.
- **Spring 2013** – HFH starts construction, first five homes take shape.
- **Late fall 2013** – All co-funder agreements in place. Monitoring begins on first homes, weather station erected onsite.
- **2014/15** – Construction continues, additional 7 homes completed and added to study. Monitoring continues on all homes. One-year data collected on first 7 homes.
- **2015/17** – Neighborhood built out (30 homes). Monitoring continues.
Research Team

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HFH Sustainable Community

- Community of single-family, zonal electric-heated homes
- 30 planned, 12 built to date
- 5 distinct designs (950 to 2,200 ft²)
- Homes comply with NWESH v2 5% more efficient than 2012 code
- No chimneys for wood stoves/natural gas
New HFH Homes

Specifications

• Continuous R-15 underslab insulation
• R-21 + R5 exterior walls
• R-49 ceiling
• U-.28 windows
• ENERGY STAR-certified lighting
• Continuous heat recovery ventilation
• Hybrid ductless heat pump-electric resistance heating (DHP-ER)
Homeowner Orientation

Operating and maintaining your heating system

- Clean ductless heat pump filters every three months

Let the DHP “heat” the house

- DHP thermostat
  - Set the ductless heat pump thermostat to maintain a comfortable temperature in the main living area

- Bedroom thermostats
  - Set the bedroom thermostat to 62° or where you are comfortable
  - Remember, the DHP should help heat the bedrooms as well

Maintaining your heat recovery ventilator

- Remove and wash HRV filters monthly

Heating system schedule

Heating systems switch weekly

- WEEK 1
  - DUCTLESS HP
  - WEEK 2
  - ZONE HEAT

System electronics

- Do not open these panels
Key Research Questions

1. What are the performance characteristics of a hybrid DHP/ER heating system compared to an all-ER heating system in new construction single-family homes in a marine climate in the Pacific Northwest?

2. What are the average annual electricity savings of the hybrid DHP system over an all-ER system?

3. What are the total and incremental installed costs of this system?

4. What are the average expected life cycle impacts of such a system?

5. What are the occupant perceptions of a hybrid system? Does a hybrid system produce the same comfort levels as an all-ER system?
Study Design of Energy Use

- Compare electrical use of hybrid DHP/ER heat vs. all-ER heat in new construction
- Common area contains both DHP and ER heat switched between the two weekly
  - The switching schedule is staggered between homes
- Each home to act as its own control over a range of temperatures
- Temperature and relative humidity (RH) captured
- Homeowners given choice at end of study of which heating system they would like to keep
Technical Implementation

Data Captured

- Total Electric Service
- Site Weather Data
- Domestic Hot Water
- DHP Vapor Line Temp
- Common Area
- All Other Zone Heat
- Common area - Bedroom Temp/RH
Project Equipment - Installed

- U30-Data logger with cellular communications allows us to monitor data hourly and provides instant error notification
- Relay
- Time Clock
- Watt Nodes used to convert energy consumption pulse data from the current transducers
- Pulse Input Adapter tracks pulses
- Current Transducers (CTs) connected to electrical circuits to measure current
Web Based Hourly Monitoring
Research Question #1

What are the average annual electricity savings of the hybrid DHP system over an all-ER system at The Woods?

• A multivariable regression to control for differences in weather, study periods, and house characteristics estimated savings of 2,640 kWh/year/house for the hybrid DHP-ER heating system for 2014-15 site weather.

• A variable degree day regression analysis for each house estimated weather normalized savings for Western Washington ranging from 1,787 KWh/year to 3,254 kWh/year with an average of 2,410 kWh/year.

• Using a 2016 weighted average state residential electric rate of $0.0853/kWh, average annual bill savings are $239 (2806 kWh/year) for a typical 1280 ft2 new home. Site-specific savings at the Woods ranged from a low of 2,019 kWh to just over 4,289 kWh. The savings estimates are based on TPU polynomial regression analysis utilized in the life cycle cost analysis (adjusted for cooling).
Observations

Energy Use in all-ER Heating Mode

Observed from case study

Daily kWh/ft² vs. Daily Average Temperature

- All-ER
- Poly. (All-ER)

R² = 0.7166
Observations

Energy Use in Hybrid DHP-ER Heating Mode

Observed from case study

- Daily kWh/ft^2 vs. Daily Average Temperature
- Hybrid DHP-ER
- Poly. (Hybrid DHP-ER)
- $R^2 = 0.7161$
Savings Analysis (Heating)

Comparison of All-ER vs Hybrid DHP-ER

Observed from case study

Diagram showing the comparison between Daily kWh/ft² and Daily Average Temperature for All-ER and Hybrid DHP-ER systems.
# Hybrid DHP System Savings Estimates - TPU

<table>
<thead>
<tr>
<th>Energy Used (kWh/ft²)</th>
<th>Hybrid DHP-ER</th>
<th>All-ER</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Season</td>
<td>2.47</td>
<td>4.71</td>
<td>2.24</td>
</tr>
<tr>
<td>Cooling Season (Jul &amp; Aug)</td>
<td>0.04</td>
<td>-</td>
<td>-0.04</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.52</strong></td>
<td><strong>4.71</strong></td>
<td><strong>2.19</strong></td>
</tr>
</tbody>
</table>

- 47% savings over all-ER system
- 1280 ft² (typical) x 2.19 = 2806 kWh/year
- 2806 kWh/year x $0.0853/kWh = $239/year
Peak Heating Season – 7 homes

Total Heating Load Profile

- ER-Max
- ER-StdH
- ER-Avg
- ER-StdL
- ER-Min
- DHP-Max
- DHP-StdH
- DHP-Avg
- DHP-StdL
- DHP-Min
Adjusting for Cooling

Adjusted savings accordingly to account for DHP cooling

No information for cooling in ER mode:
- Common areas placed in DHP mode Jul 11-Sep 19, 2014
- Don’t know what equipment would have been bought in absence of DHP

Apply daily average observed in data (0.00067 kWh/ft²) to Jul & Aug in our “normal” year for DHP energy estimate:
- Assume no cooling in all-ER system

Assumed conservative estimate of DHP savings because:
- Study year was warmer than normal
- No accounting for alternate cooling equipment in ER mode
## Summer Period DHP Energy Use
(7/11 – 9/14, 2014)

<table>
<thead>
<tr>
<th>House</th>
<th>Energy Use (kWh)</th>
<th>Survey Cooling Use</th>
<th>Average OAT (°F)</th>
<th>Maximum OAT (°F)</th>
<th>Cooling Degree Days (base 70°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>48</td>
<td>Sometimes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larch</td>
<td>18</td>
<td>Never</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fir</td>
<td>115</td>
<td>Often</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemlock</td>
<td>76</td>
<td>Often</td>
<td>66</td>
<td>95</td>
<td>143</td>
</tr>
<tr>
<td>Alder</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oak</td>
<td>30</td>
<td>Sometimes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cedar</td>
<td>31</td>
<td>Often</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Research Question #2

What are the total and incremental installed costs of this system?

• The average hybrid DHP-ER heating system cost for a buyer of a new HFH home is $2,746.

• Average cost for an all-ER heating system is $321.

• These costs result in an incremental cost of $2,451 per home.
Research Question #3

What are the expected life-cycle impacts and monthly cash flow?

• On average, these homes have a 2015 present value positive benefit of $3,690 with a hybrid DHP-ER heating system when compared to an all-ER heating system. Assumes 2800 kWh/year savings for a typical 1280 ft² home.

• On average, the monthly cash flow is positive:
  - $8.96-$23.26/month with HFH financing with 30 years, 0% interest loan vs. $8
  - $2.39 - $16.69/month with 15 years, 5% interest loan.
Life Cycle Impacts

- Economic analysis run using Washington State Office of Financial Management (OFM) economic analysis tool
- Hybrid DHP-ER heating system’s life-cycle present value benefit = $3,690
- Cash flow positive w/HFH loan (30-year, 0% interest)
- Cash flow positive w/loan at (15-year, 5% interest)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Baseline All-ER Zonal System</th>
<th>Alternative Hybrid DHP-ER System</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Construction Costs</td>
<td>$318</td>
<td>$2,722</td>
<td>2,403</td>
</tr>
<tr>
<td>PV of Capital Costs</td>
<td>$503</td>
<td>$6,700</td>
<td>6,198</td>
</tr>
<tr>
<td>PV of maintenance Costs</td>
<td>$-</td>
<td>$473</td>
<td>473</td>
</tr>
<tr>
<td>PV of Utility Costs</td>
<td>$22,254</td>
<td>$11,893</td>
<td>-10,361</td>
</tr>
<tr>
<td>Total Life Cycle Cost (LCC)</td>
<td>$22,757</td>
<td>$19,067</td>
<td>-3,690</td>
</tr>
</tbody>
</table>
Research Question 4a

What are the occupant perceptions of a hybrid system?

Six of the seven household picked the DHP over ER due to:

- Availability of cooling
- Better heating performance
- More furniture placement options
- Safety concerns about the ER heat

One household wants more information: savings, maintenance and replacement costs
Occupant Survey Perceptions

On performance: “How did [system] perform in heating your common living area to a comfortable temperature?”

- 6 homeowners gave the DHP a higher rating than ER
- 4 homeowners rated them the same
- Only 1 homeowner rated the ER higher

When asked “Which system they would choose at end of study?”

- 10 out of 11 have already decided to keep DHP
- 1 preferred DHP but wants to see energy savings first

Many reasons why DHP is preferred, including:

- Heating performance, cooling function, furniture placement & curtain use, fire hazard & child safety concerns with baseboards

(*) Of the 11 households surveyed, 7 homes were the subject of this report.
Research Question 4b

Does a DHP/hybrid provide the same comfort levels as an all-ER system?

- Indoor temp and RH monitoring maintained comfort conditions with both systems.

- One household said DHP was worse than the ER system. They had the largest drop in average living area indoor temperature in DHP mode, but home was still around 70°F

- Two households behaved differently in DHP mode, lowering the bedroom T-stats and keeping bedroom doors open to allow the DHP to displace a larger portion of the ER heating load. The % energy savings were the highest, suggesting behavior contributed to savings.
Monitored Temperature Differences
Living Room Temp in ER and DHP Heating Modes
Monitored Temperature Differences
Master Bedroom Temp in ER and DHP Heating Modes
Monitored Temperature Differences

Second Bedroom Temp in ER and DHP Heating Modes
# Monitored RH Differences

Living Room RH in ER and DHP Heating Modes

<table>
<thead>
<tr>
<th>House</th>
<th>Period</th>
<th>Mode</th>
<th>Days</th>
<th>Maximum (%)</th>
<th>+1 Std. Dev. (%)</th>
<th>Average (%)</th>
<th>-1 Std. Dev. (%)</th>
<th>Minimum (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>9/27/2013 to 1/22/2015</td>
<td>ER</td>
<td>178</td>
<td>80.1</td>
<td>61.4</td>
<td>52.2</td>
<td>43.0</td>
<td>32.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHP</td>
<td>199</td>
<td>81.3</td>
<td>62.0</td>
<td>53.0</td>
<td>44.1</td>
<td>27.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-12%</td>
<td></td>
<td>0.8</td>
<td>1.1</td>
<td>-4.7</td>
</tr>
<tr>
<td>Larch</td>
<td>12/13/2013 to 1/22/2015</td>
<td>ER</td>
<td>168</td>
<td>83.9</td>
<td>59.9</td>
<td>48.2</td>
<td>36.6</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHP</td>
<td>170</td>
<td>88.4</td>
<td>61.8</td>
<td>50.1</td>
<td>38.4</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1%</td>
<td></td>
<td>1.9</td>
<td>1.8</td>
<td>-6.8</td>
</tr>
<tr>
<td>Fir</td>
<td>11/26/2013 to 1/22/2015</td>
<td>ER</td>
<td>204</td>
<td>85.2</td>
<td>57.5</td>
<td>49.2</td>
<td>41.0</td>
<td>25.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHP</td>
<td>151</td>
<td>75.5</td>
<td>58.6</td>
<td>48.4</td>
<td>38.2</td>
<td>20.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26%</td>
<td></td>
<td>-0.8</td>
<td>-2.8</td>
<td>-5.1</td>
</tr>
<tr>
<td>Hemlock</td>
<td>4/15/2014 to 1/22/2015</td>
<td>ER</td>
<td>111</td>
<td>71.1</td>
<td>58.7</td>
<td>49.8</td>
<td>40.9</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHP</td>
<td>105</td>
<td>73.0</td>
<td>59.2</td>
<td>49.3</td>
<td>39.3</td>
<td>23.8</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td></td>
<td>-0.5</td>
<td>-1.6</td>
<td>7.3</td>
</tr>
<tr>
<td>Alder</td>
<td>11/19/2014 to 1/22/2015</td>
<td>ER</td>
<td>29</td>
<td>56.8</td>
<td>43.2</td>
<td>36.2</td>
<td>29.1</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHP</td>
<td>35</td>
<td>55.0</td>
<td>43.5</td>
<td>37.8</td>
<td>32.1</td>
<td>19.5</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>-21%</td>
<td></td>
<td>1.6</td>
<td>3.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Oak</td>
<td>12/12/2013 to 1/22/2015</td>
<td>ER</td>
<td>170</td>
<td>80.1</td>
<td>63.6</td>
<td>52.4</td>
<td>41.2</td>
<td>21.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHP</td>
<td>169</td>
<td>75.1</td>
<td>62.5</td>
<td>50.1</td>
<td>37.6</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1%</td>
<td></td>
<td>-2.3</td>
<td>-3.6</td>
<td>-6.5</td>
</tr>
<tr>
<td>Cedar</td>
<td>3/2/2014 to 1/22/2015</td>
<td>ER</td>
<td>134</td>
<td>68.8</td>
<td>55.7</td>
<td>47.7</td>
<td>39.7</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHP</td>
<td>126</td>
<td>69.3</td>
<td>57.9</td>
<td>48.2</td>
<td>38.6</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6%</td>
<td></td>
<td>0.6</td>
<td>-1.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>
## BEOPT vs. Measured

<table>
<thead>
<tr>
<th></th>
<th>Space Heat Site Energy (kWh/yr.)</th>
<th>Pine</th>
<th>Larch</th>
<th>Fir</th>
<th>Hem</th>
<th>Alder</th>
<th>Cedar</th>
<th>Oak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case A:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100% ER (heat kWh)</td>
<td></td>
<td>5,111</td>
<td>4,666</td>
<td>3,722</td>
<td>5,484</td>
<td>4,637</td>
<td>4,660</td>
<td>1,964</td>
</tr>
<tr>
<td><strong>Measured ER</strong></td>
<td></td>
<td>7,294</td>
<td>8,565</td>
<td>6,520</td>
<td>6,544</td>
<td>NA</td>
<td>7,440</td>
<td>5,131</td>
</tr>
<tr>
<td><strong>Case B:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100% DHP (heat kWh)</td>
<td></td>
<td>1,043</td>
<td>1,061</td>
<td>923</td>
<td>1,172</td>
<td>953</td>
<td>982</td>
<td>378</td>
</tr>
<tr>
<td><strong>Case A-B (heat kWh)</strong></td>
<td></td>
<td>4,068</td>
<td>3,605</td>
<td>2,799</td>
<td>4,312</td>
<td>3,684</td>
<td>3,678</td>
<td>1,596</td>
</tr>
<tr>
<td><strong>Measured Savings</strong></td>
<td></td>
<td>2,218</td>
<td>4,116</td>
<td>3,334</td>
<td>3,201</td>
<td>NA</td>
<td>4,230</td>
<td>2,759</td>
</tr>
<tr>
<td><strong>Estimated ER Displacement</strong></td>
<td></td>
<td>70%</td>
<td>67%</td>
<td>86%</td>
<td>86%</td>
<td>81%</td>
<td>76%</td>
<td>77%</td>
</tr>
<tr>
<td><strong>Modeled Savings Estimate</strong></td>
<td></td>
<td>2,862</td>
<td>2,418</td>
<td>2,405</td>
<td>3,722</td>
<td>2,998</td>
<td>2,809</td>
<td>1,230</td>
</tr>
</tbody>
</table>

To estimate modeled energy savings, the estimated ER displacement by the DHP (from measured data) was multiplied by the case A-B savings (100% ER-100% DHP). This approach assumes a linear relationship between 100% ER and 100% DHP energy use.
BEOPT vs. Measured

• A single zone model cannot model DHP heat in the living area and ER heat in the bedrooms. It can only model 100% DHP.

• Measured energy use is higher than modeled use in all cases.

• In general, modeled energy savings for each house do not match the measured savings very well.

• The average (7 house) modeled savings estimate is 2,636 kWh/year/house, while the average (6 house) measured savings estimate is 3,310 kWh/year/house.

To estimate modeled energy savings, the estimated ER displacement by the DHP (from measured data) was multiplied by the case A-B savings (100% ER-100% DHP). This approach assumes a linear relationship between 100% ER and 100% DHP energy use. Assumes; TMY McChord AFB and Variable Degree Day Regression Analysis.

The displacement calculation assumes 100% displacement in the living room plus any displacement or increase in bedroom ER use in DHP mode. The calculation is basically 100% minus the proportion of total ER mode heating load in the bedroom during DHP mode. Displacement = 1 – Bedroom ER use in DHP mode/total heating use in ER mode.
For More Information

• **Case Study: Testing Ductless Heat Pumps in High-Performance Affordable Housing, The Woods at Golden Given – Tacoma, WA**

• Contact Mike Lubliner for more information on the WSU/Tacoma Power research report(s).
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