CO2 Heat Pump Water and Space Heating
- Combi System
- Field Test Preliminary Results

Presenters:
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Funded collaboratively by BPA and NEEA
NEEA Product Council

Charter

• Identify technology and market opportunities
• Review and disposition of unsolicited proposals and other new ideas
• Prioritize NEEA's scanning / development work and share priorities and findings
• Recommend concepts for advancement into NEEA's program portfolio
• Identify high-lights of emerging technology work to share broadly

Frequency: Weekly, Tuesdays 10:30-12:00 Pacific

Style: Informal, clarifying questions welcomed
Today’s Discussion

- CO2 Heat Pump Technology
- NW CO2 Heat Pump Research History
- Eco Runo Field Test Design
  - Site Locations
  - System Design
- Preliminary Findings & Analysis
- Lessons Learned
NW Projects on Advanced Heat Pump

BPA Funded Projects (NEEA provided metering, monitoring and installation maintenance)

• TIP 292 Performance as a Water Heater
  2012-2016

• TIP 302 Demand/Response Potential of Split and Unitary Systems
  2013-2015

• TIP 326 Combined Space and Water Heating in New, High Efficiency Homes
  2014-2016

• TIP 338 Combined Space and Water Heating in Existing Homes
  2015-2018

NEEA Co-Funded Project

• EcoRuno CO2 HPWH used for Space and Water Heating
EcoRuno Project Objectives

Test CO2 heat pump designed for space heating

- Does it do a better job than the GAU unit that was designed for domestic water heating?
- What are the design issues we might face with combi-systems?
- What are the installation issues we might face with combi-system?
CO2 Heat Pump Technology

Split System
CO2 Refrigerant - GWP = 1
Variable Speed Inverter Driven
No Electric Element
158F output Temp (single pass)
Excellent low ambient performance

Sanden Eco Runo
27kBtu/h
Dedicated space heater

Sanden (GAU unit)
15kBtu/h
Dedicated water heater
How $CO_2$ Heating Works (& Is Defeated)

Warm Water to Gas Cooler

Heat transfer to water via gas cooler.

Compressor does work and adds energy to cycle.

Heat absorbed from air.
**Eco Runo System**

**Lab Test results**
- 8 kW output (2.2 tons) (actual is up to 2.8 tons)
- COP = 2.5
- 3 output temperature settings = 113°F, 131°F, 158°F

**Integrated variable speed circ pump**

**Two-stage CO2 heat pump**

**Combined space and water heating concept:**
- Flexible heating type—radiant slab, furnace
- Hot water—indirect tank
- Locate in cold climates, larger load houses
- Possible forced air furnace replacement
Example System (Tacoma)
3 Loop System Design

Space Heating Types
- Force Air Furnace
- Hydronic radiant
- Hydronic baseboard

Space Heating (closed loop)

Domestic Hot Water (closed loop)

Heat Pump (glycol loop)
# Project Sites

<table>
<thead>
<tr>
<th>Site Location</th>
<th>ft²</th>
<th>Year built</th>
<th>House Description</th>
<th>Distribution System</th>
<th>Monitoring Start</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland – 1</td>
<td>2,700</td>
<td>1951</td>
<td>1-story home, well insulated, PV roof system</td>
<td>Radiant Slab / AHU</td>
<td>4/2017</td>
<td>Missing Data</td>
</tr>
<tr>
<td>Portland – 2</td>
<td>1,450</td>
<td>1979</td>
<td>2-story home. Moderately insulated. Double pane windows with metal frames</td>
<td>Forced Air Furnace</td>
<td>11/2017</td>
<td>Complete</td>
</tr>
<tr>
<td>Stevensville</td>
<td>2,400</td>
<td>2017</td>
<td>1-story, super-insulated and insulated crawl space</td>
<td>Radiant Slab</td>
<td>11/2017</td>
<td>Complete</td>
</tr>
<tr>
<td>Salem</td>
<td>1,100</td>
<td>1995</td>
<td>2-story home built into 17° slope with post and pier foundation with daylit basement. Exposed exterior floor.</td>
<td>Hydronic Baseboard</td>
<td>12/2017</td>
<td>Complete</td>
</tr>
<tr>
<td>Spirit Lake</td>
<td>1,308</td>
<td>2015</td>
<td>Marlette manufactured home, efficient</td>
<td>Forced Air Furnace</td>
<td>5/2018</td>
<td>Q1 2020</td>
</tr>
</tbody>
</table>
Preliminary Findings

Equipment & Design
- System Manufacturer no longer has plans for North American market
- Each system was custom designed and built
- Default programming did not work

Performance
- Best performance from sites with high heating needs
- Parasitic losses significantly impacted system COP (aka Field Efficiency Factor)
- CO2 heat pump performance is less dependent on ambient temperature and more dependent on return loop temperature than conventional R-410a refrigerant systems

Challenges
- Cost and overall system complexity
- Lack of equipment availability and service support
  - No English language manuals
  - Not UL listed
- Lack of contractor experience
Field Test Data & Analysis

One Minute Interval Data
- Water flow rate, Air Temperatures, Water Temperatures, electricity uses

Calculated Results
- Data aggregated into daily averages to reduce transient errors
- Space heating load, $Q_{\text{supply}}$
- Building Heat Loss Rate & Balance Point
- Heat pump water heater COP
- Field Efficiency Factor (aka the total system COP)

2 System Modes Analyzed:
- “Combi-mode” – Days with both space heating and DHW provided
- “DHW-only mode” – Days with only DHW provided, primarily in summer
Monitoring Issues

Murphy works overtime in field research

- Installing monitoring requires many sensor installations and connections and all have to be perfect for collection of complete data
- Internet connections should not be relied on for continuous data collection
- Flow meters must be calibrated to collect accurate data
- Whoops! Plumber moved the sensor. Monitoring is impacted by changes in design, plumbing and wiring

Occupancy Changes

- Some systems not used as expected
- Some homes were rentals
System Performance Metrics

Field measured COP
  • Quantifies efficiency of the EcoRuno unit

Field Energy Factor (FEF)
  • Quantifies total system performance including standby losses and auxiliary heating requirements
Using Daily Averages Removes Non-Coincident Energy Flow Caused Scatter

Daily averages smooth out these events, reduce scatter without significantly changing regression results.
Heat Loss Rate and Balance Points from Measured Data

Plotting space heating load versus daily average OAT

Regression used to determine the slope and the x-intercept

- Slope is heat loss rate (of house and system)
- x-intercept is the balance point

UA and Balance Point

**Salem**

UA-value = 972.0 Btu/h/F
Balance Point = 58.5F

**Montana**

UA-value = 109 Btu/h/F
Balance Point = 48.9 F
Correction Factor Assumptions

Space Heating Loop Flow Rate
- Some sites had poor/inaccurate flow meter readings
- Applied a calibration factor so that heat lost measured was the same as the heat loss rate calculated (UA based on insulation and infiltration)

Glycol Heating Loop Flow Rate
- Most sites looked good – and could be adjusted with correction factor
  - McCall1 was not reconcilable
- We used the glycol loop losses from similar systems to approximate a correction factor
<table>
<thead>
<tr>
<th>System Type</th>
<th>Annual Heat Transfer to Main Glycol Loop ($Q_{eco}$)</th>
<th>Auxiliary Hot Water Heating</th>
<th>Annual Space Heating Load ($Q_{supply}$)</th>
<th>Annual Domestic Hot Water Heating Load ($Q_{dhw}$)</th>
<th>Calculated Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kWh/year</td>
<td>kWh/year</td>
<td>kWh/year</td>
<td>kWh/year</td>
<td>kWh/yr %</td>
</tr>
<tr>
<td>McCall-2</td>
<td>RS</td>
<td>17,186</td>
<td>13</td>
<td>9,724</td>
<td>409</td>
</tr>
<tr>
<td>Portland-2</td>
<td>FAF</td>
<td>20,217</td>
<td>0</td>
<td>10,724</td>
<td>2,322</td>
</tr>
<tr>
<td>Salem</td>
<td>Hydronic Baseboard</td>
<td>31,256</td>
<td>0</td>
<td>19,770</td>
<td>1,464</td>
</tr>
<tr>
<td>Montana</td>
<td>Hydronic Zoned</td>
<td>7,562</td>
<td>-</td>
<td>2,598</td>
<td>2,284</td>
</tr>
<tr>
<td>Tacoma</td>
<td>FAF (totals over 7 months)</td>
<td>6,001</td>
<td>0</td>
<td>1,921</td>
<td>2,122</td>
</tr>
</tbody>
</table>

*Italics* indicates remediated data – data adjusted
Parasitic Losses

• ~35% of total load occupied homes
• More than just storage tank losses - lots of piping, pumping and circulation of warm fluids

Interior Piping Not Always Insulated

• Sites with piping insulation were in garages
  o Tacoma
  o Portland-2
• Salem system installed in a closet with an exterior wall
• Portland-1 system installed in unconditioned basement
Heat Pump COP and System FEF

COPs measuring performance are very good at all homes HZ1

• Daily average Combi-Mode COP ranged from 2-6
• Daily average DHW-Mode COP ranged from 3-5

FEF values, which account for system losses, were significantly lower

○ We are not sure why this is – this is still under investigation

<table>
<thead>
<tr>
<th>Site</th>
<th>System Type</th>
<th>FEF</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Annual Median Daily</td>
<td>Annual Median Daily</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Combi DHW Combi DHW</td>
<td>Combi DHW Combi DHW</td>
</tr>
<tr>
<td>McCall-1</td>
<td>RS</td>
<td>1.14 1.15 0.04</td>
<td>2.72 2.79 1.88</td>
</tr>
<tr>
<td>McCall-2</td>
<td>RS</td>
<td>1.72 1.75</td>
<td>3.04 3.16</td>
</tr>
<tr>
<td>Portland-1</td>
<td>RS</td>
<td></td>
<td>4.46 4.44 4.54 4.44</td>
</tr>
<tr>
<td>Portland-2</td>
<td>FAF</td>
<td>2.20 1.34 2.16 1.29</td>
<td>3.62 3.17 3.63 3.09</td>
</tr>
<tr>
<td>Salem</td>
<td>RHZ</td>
<td>2.03 0.89 1.79 0.92</td>
<td>3.04 3.65 3.46 3.93</td>
</tr>
<tr>
<td>Montana</td>
<td>RS</td>
<td>1.31 1.24 1.28 1.23</td>
<td>2.03 1.67 1.93 1.71</td>
</tr>
<tr>
<td>Tacoma</td>
<td>FAF</td>
<td>2.37 1.58 2.40 1.67</td>
<td>3.20 3.47 3.36 3.63</td>
</tr>
</tbody>
</table>
Observations & Notes

- COPs and FEF tend to decline below about 20 kWh per day heat output
- Salem’s FEF performance appeared bimodal – more on this later
- Partial Data years for
  - Portland-1
  - Tacoma
- Space heating loop at Portland-1 was not monitored, so we don’t have FEF
- McCall-1 had questionable flow meter (not in graph)
Performance vs Load: DHW-only Mode

DHW-only mostly occurs in summer
- Below heat output of about 10 kWh per day, the COP and FEF is poor
- Same pattern observed in combi-mode

No DHW-only for McCall homes
- Different configuration – “sidearm” heater
- Did not function well in DHW-only mode – ran constantly
Performance vs Ambient: DHW-only Mode

COP increases slightly with increasing OAT, as expected

Observations:
- Montana has a wider range of temperatures with DHW-only operation because of a low balance point
- Montana and Portland-2 have unexpected lower performance
- Low-load impacts performance
Performance vs Ambient: Combi-Mode

COP Increases with Increasing Ambient Air Temperature

Factors may Influence low COP

- Montana home had low heating needs due to super-insulation and passive design (lower UA-values)
- Limited data from Tacoma and Portland-1 (partial year)
Lessons Learned*

Overall

• EcoRuno system appears to operate well as a space heater when the load is significant
• Combi complexity does not appear to provide additional performance or cost savings
• Lack of cooling limits applicability of Combi system

Performance

• CO2 HPWH is better suited for sites with high heating needs
  o Heating load should be large relative to standby losses
  o COP declined significantly with unit heat outputs less than 10-20 kWh/day.
  o Homes with low heating requirements were not good candidates:
• Storage tank and circulation loop standby losses are significant
• Standby losses increased with uninsulated pipes – weatherize pipes

*Preliminary Findings – final report due Q2 – 2020
Future Recommendations

Installation Recommendations

• Provide contractor training in advanced of design and installation
• Provide contractors with a list of recommended components
• Request basic training from manufacturer on heat pump and occupant controller
• Provide occupant education on the project, comfort expectations and system operation
• Provide appropriate materials to homeowner and contractor – in English please!

Design Recommendations

• Existing forced air distribution system should be carefully considered and may require substantial duct size increases to handle lower delivered air temperatures.
• Not recommended in homes with very low loads – this system is overkill.

*Preliminary Findings – final report due Q2 – 2020
Questions?

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Backup Slides
Summary of Homes

Homes located in all three RTF heating zones with HDD65 ranging from 4,241 to 7,502 Btu/oF/day
Measured UA-values ranged from 55 Btu/h/ft2/oF for a small super-insulated passive home to 972 Btu/h/ft2/oF for a larger code-built home (1995) with a large window area and exposed floor.

<table>
<thead>
<tr>
<th>Site Location</th>
<th>McCall-1</th>
<th>McCall-2</th>
<th>Portland-1</th>
<th>Portland-2</th>
<th>Salem</th>
<th>Montana</th>
<th>Tacoma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution system</td>
<td>Radiant Slab</td>
<td>Radiant Slab</td>
<td>Radiant Hydronic</td>
<td>Forced Air Furnace</td>
<td>Radiant Baseboard</td>
<td>Radiant Slab</td>
<td>Forced Air Furnace</td>
</tr>
<tr>
<td>Conditioned Floor Area (ft²)</td>
<td>2,812</td>
<td>1,533</td>
<td>1,450</td>
<td>2,400</td>
<td>1,100</td>
<td>1,314</td>
<td></td>
</tr>
<tr>
<td>Measured Balance Point (°F)</td>
<td>52</td>
<td>58</td>
<td>NA</td>
<td>60</td>
<td>59</td>
<td>49</td>
<td>58</td>
</tr>
<tr>
<td>Measured Overall UA-Value (Btu/h/ft²/°F)</td>
<td>354</td>
<td>295</td>
<td>NA</td>
<td>499</td>
<td>972</td>
<td>109</td>
<td>740</td>
</tr>
<tr>
<td>Calculated UA-Value:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Envelope</td>
<td>368</td>
<td>262</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>108</td>
<td>373</td>
</tr>
<tr>
<td>Envelope &amp; Air Flow</td>
<td>422</td>
<td>299</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>116</td>
<td>647</td>
</tr>
<tr>
<td>Measured UA-Value per Floor Area (Btu/h/ft²/°F per ft²)*</td>
<td>0.031</td>
<td>0.105</td>
<td>NA</td>
<td>0.344</td>
<td>0.405</td>
<td>0.023</td>
<td>0.564</td>
</tr>
<tr>
<td>Occupants</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The overall efficiency of the combi system under site conditions is quantified using the “field energy factor”, FEF

\[ FEF = \frac{Q_{\text{dhw}} + Q_{\text{supply}}}{E_{\text{input}}} \]

where \( E_{\text{input}} \) (kWh) is the sum of electricity inputs to the HPWH (HP), auxiliary heat (HA), heat exchanger block (HX), and heat tape (HT).

Space heating load \( Q_{\text{supply}} \) (kWh) and water heating load \( Q_{\text{dhw}} \) (kWh) are calculated as:

\[
Q_{\text{supply}} = m_{\text{supply}} \times C_p \times (T_{\text{supply}} - T_{\text{return}}) \\
Q_{\text{dhw}} = m_{\text{inlet}} \times C_p \times (T_{\text{dhw}} - T_{\text{inlet}})
\]

Regressions were performed to examine the relationship of FEF with other factors:

- Average daily outside air temperature, OAT
- Average daily DHW Use, as determined by inlet water flow
- Heating load

Equations
The performance of the EcoRuno unit is quantified using the field measured coefficient of performance, COP

\[
COP = \frac{Q_{eco}}{(E_{input, \text{HPWH}} + E_{input, \text{pumps & controls}})}
\]

where \( Q_{eco} \) (kWh) is the heat transferred to the main glycol loop as determined by flow and entering and leaving temperatures. \( E_{input, \text{HPWH}} \) and \( E_{input, \text{pumps & controls}} \) are electricity inputs to the EcoRuno compressor and to the pumps and controls.

\( Q_{eco} \) is calculated as:

\[
Q_{eco} = m_{eco} \times C_p \times (T_{\text{glycol, supply}} - T_{\text{glycol, return}})
\]
Balance Point and UA-Value

“Balance point” - the outdoor temperature above which space heating is not required

“Overall UA-Value” or UAo characterizes the home’s heat transfer losses as a function of outside air temperature

- Neglecting thermal mass and solar gains: \( Q = U Ao \times (T_{\text{indoor}} - T_{\text{outdoor}}) \)
- U Ao is determined in two ways:
  - Summing the UA analysis of the building
  - By plotting utility billing data or meter data as a function of daily average temperature.

In this figure, the slope of the blue line is the overall UA value (usually converted to Btu/h/F). The temperature where the red line and blue line intersect is the balance point.

Reference: http://courses.washington.edu/me341/oct24.htm
Seasonality of COP at Salem home

Distinct Seasonal Pattern

• Highest COP occurred in mild Spring and Fall weather in combi-mode
• Low COP occurred in winters of 2017 and 2019
• Fairly constant COP around 4 in DHW-only mode in the summer
**FEF and COP versus Daily DHW Use**

**DHW-only Mode**

- COP is relatively flat for individual sites with increasing DHW use
- FEF goes to zero as DHW use goes to zero by definition
  - \( \text{FEF} = \frac{\text{Useful loads}}{\text{Energy Inputs}} \)
  - Zero when \( Q_{\text{dhw}} \) and \( Q_{\text{supply}} \) are zero
- FEF flattens out above about 50 gallons per day
**FEF and COP versus Return Temperature**

**Combi Mode**

- XX
FEF and COP versus Daily DHW Use

Combi-Mode

- FEF and COP were not found to be strongly related to daily average DHW use
Performance vs Load

Observations & Notes

• The Salem, Tacoma and Portland homes in HZ1 all have higher COP than the homes in Idaho HZ3 and Montana HZ2

• COPs and FEF tend to decline below about 20 kWh per day heat output

• McCall-1 is very low, presumably due to low occupancy
  o System operates to keep storage tank hot despite many days of low or zero heating needs

• Salem’s FEF performance was particularly varied
  o Average COP is similar to Tacoma and Portland-2
  o Performance varied by season and year
  o Will look at this in more detail in later slide

• Portland-1 data is for partial year from March to November 2019
  o Space heating loop at Portland-1 was not monitored, so we don’t have FEF