REHAU MONTANA ECOSMART HOUSE PROJECT
Bozeman, MT
RMEH 09 Test Report

Energy Usage of Radiant Floor Heating:
Boiler vs. Ground-Source Heat Pump

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Executive Summary

A test was run at the REHAU Montana Ecosmart House in Bozeman, MT to compare energy usage to heat the house with an electrically powered ground source heat pump (GSHP) and a natural gas fired boiler. The GSHP used 75% less energy per heating degree-day (HDD) than the boiler; moreover, it produced 46% less greenhouse gas (GHG) emissions, and in terms of cost of energy, it was 2% cheaper.

Experiment Description

The purpose of this experiment was to compare energy usage to maintain the house at 68°F room setpoint using radiant heating distribution with boiler versus ground-source heat pump (GSHP). Both heat sources were set up in optimal configuration. Outdoor reset schedules were in place for both scenarios. The 6-ton GSHP has two 2.8-ton modulating digital scroll compressors and was set up with two 300-feet vertical 2U-bend geothermal boreholes. Boiler is a high efficient condensing unit with modulating capacity up to 154 MBTU heat output (DOE rating). The amount of energy consumed by each type of system (natural gas and electric power) was recorded. Each test scenario was run over a three-day time period.

Results

In scenario 1, the boiler used 832 standard cubic feet (SCF) of natural gas, equivalent to 8.5 therms at the BTU factor provided by the utility company (see Calculations). There was 75.5 Fahrenheit heating degree-day (°F-HDD) during the test period. That is 11.2 MBTU/°F-HDD. HDD were calculated with a base of 65°F. In scenario 2, the GSHP consumed 110.7 kWh, equivalent to 3.8 therms delivered energy. There was 132°F-HDD during the test scenario. That means the GSHP used only 2.9 MBTU/°F-HDD, 75% less than the boiler.

In monetary terms, an estimated cost ratio was calculated from the owner's utility bills, resulting in $0.84/therm of natural gas and $0.11/kWh of electricity. Net cost of energy was then $7.1 for scenario 1 (boiler) and $12.2 for scenario 2 (GSHP). But if the cost is prorated per °F-HDD to account for the severity of the weather during each test scenario, the result is $0.094/HDD with boiler and $0.092/HDD with GSHP. That is a reduction of 2% in cost of energy by using the GSHP.

Finally, in respect of environmental concerns, a greenhouse gases (GHG) emission analysis was carried out. According to EPA eGRID [1], the carbon dioxide equivalent (CO_2e) indirect emissions from power generation in the Northwestern region of the US is 112.6 kg/MMBTU (0.846 lb/kWh). Direct emissions from burning natural gas are 11.7 lb/therm. Applying this values to the energy consumption relative to the amount of HDD resulted in 1.32 pounds of CO_2e per HDD with boiler versus 0.71 pounds of CO_2e per HDD with the GSHP. That is a 46% reduction of greenhouse gas emissions by using the GSHP, equivalent to 4854 pounds (2.2 metric tons) of CO_2 saved to the atmosphere per year in a city like Bozeman, with approximately 8000 HDD/year [2].

These results are summarized on Table 1.

Table 1. Energy Usage, Estimated Cost, and GHG Emissions Analysis

Test Scenario	OA Average (°F)	°F HHD 3-day period	Energy Usage	Energy per HDD (MBTU/°F-HDD)	Net Cost ($)	Cost per HDD ($/°F-HDD)	GHG Emissions (lb)	GHG Emissions per HDD (lb/°F-HDD)
1 – Boiler	36.2	75.5	8.5 therms	**11.2**	7.1	**0.094**	99.3	**1.32**
2 – GSHP	20.4	132.0	110.7 kWh	**2.9**	12.2	**0.092**	93.6	**0.71**

Maintaining Setpoint Temperature

The ability of each system to maintain the setpoint was similar, due to the fact that both the boiler and the GSHP worked to maintain a setpoint on the buffer tank that is set up by the control system to be 10°F greater than the setpoint required for supply temperature to the radiant loops. This temperature is dictated by the reset schedule in place and it was the same for both test scenarios (Figure 1 and Figure 2). It was noticeably colder during the GSHP test, with an average outdoor temperature of 20.4°F. This is particularly interesting because it enhances the virtues of a ground source heat pump compared to a traditional air cooled heat pump especially in severe weathers.

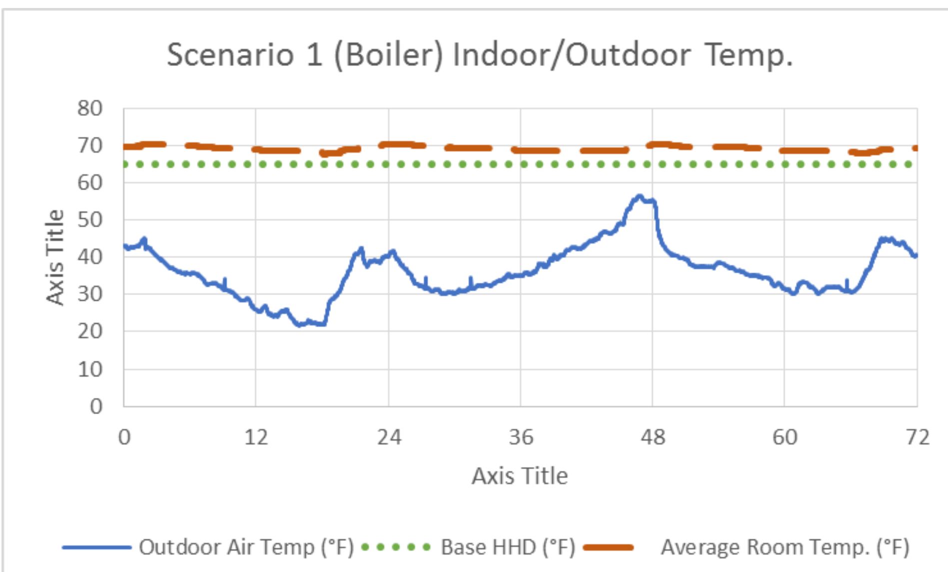

Figure 1. Space Temperature vs. Time

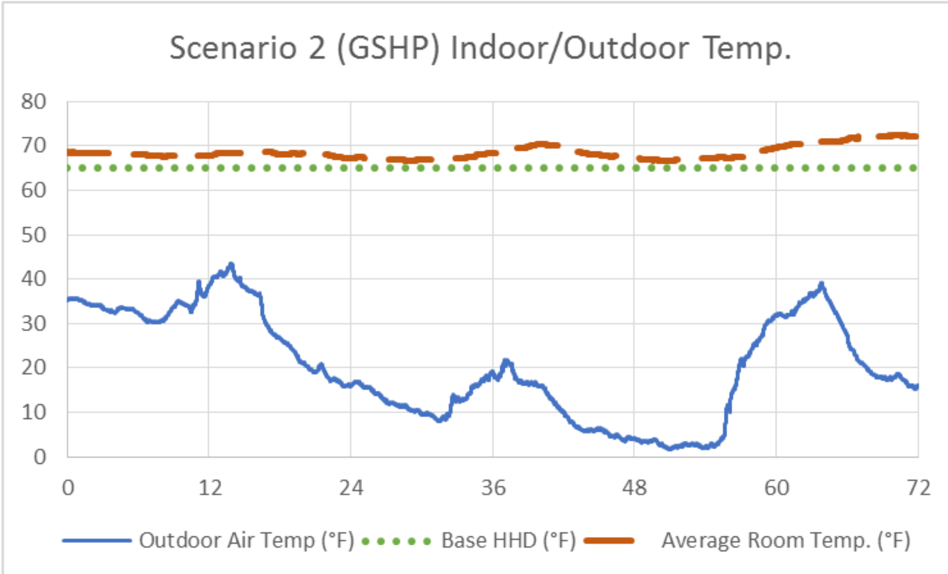

Figure 2. Space Temperature vs. Time

Degree of Uncertainty

The main difficulty in this report was the fact that the gas meter accounted for the total gas consumption, including domestic hot water (DHW) preparation, which is done exclusively with the boiler. Note that at the time of this test, the Ecosmart House was already occupied by the owners. In addition, it was observed that a small amount of heat was able to divert to the buffer tank during the DHW heating cycles. This was unavoidable due to the complex piping configuration at the mechanical room. All this added up to some degree of uncertainty as for the real amount of energy used for heating on each scenario. However, it is still very clear that overall, the use of a ground source heat pump resulted in important savings in energy and greenhouse gas emissions.

Calculations

***Original data sets will be provided upon request.

Energy of Natural Gas

In order to calculate the energy used by the boiler, the volume of gas was recorded by the Data Acquisition System (DAQ). The gas meter installed for such purpose is calibrated to measure Standard Cubic Feet per Hour (SCFH) of natural gas (Figure 3), thus it is already accounting for the pressure conversion factor for the altitude of Bozeman, MT (approximately 4800 ft). In addition, the utility company states the BTU factor in their billing information, resulting in 1.0205 therms/CCF (CCF = 100 Cubic Feet) during the time of the experiment. So,

$$Energy\ Input\ (therms) = \frac{Gas\ usage\ (SCF) \cdot BTUFactor}{100}$$

In this case, the boiler used 832 SCF during the test period, then:

$$Energy\ Input = \frac{832\ SCF \cdot 1.0205}{100} = 8.5\ therms$$

Figure 3. Gas Meter with Data Bus connected to DAQ and Webcam for Remote Reading

Electric Power

The electric power was calculated thanks to a power transducer located in the main line of the GSHP connected to the DAQ system. Instant power readings (in kW) were taken every second and averaged and logged every ten seconds. Accumulated power consumption (in kWh) was easily integrated along the test time period with the aid of a spreadsheet.

Heating Degree-Days

Heating Degree Days were calculated using the following equation [3]:

$$HDD = T_{base} - T_{ave}$$

Where

T_{base} = Selected base temperature, in this case 65°F
T_{ave} = Daily average temperature (°F), the arithmetic mean between the high and low temperature for a 24-hour period

HDD was computed daily and summed for each 3-day test period.

Sample Calculation

Table 2. Sample Calculation of HDD (T_{base} = 65°F)

<table>
<tr><th colspan="2">Date</th><th>RSC Outdoor Temperature (°F)</th><th>Observations</th></tr>
<tr><td colspan="2">1/19/2015 14:13:00</td><td>40.55</td><td rowspan="9">This section is a sample of the outside air sensor values acquired by RSC</td></tr>
<tr><td colspan="2">1/19/2015 14:13:30</td><td>40.44</td></tr>
<tr><td colspan="2">1/19/2015 14:14:00</td><td>40.48</td></tr>
<tr><td colspan="2">1/19/2015 14:14:30</td><td>40.64</td></tr>
<tr><td colspan="2">1/19/2015 14:15:00</td><td>40.47</td></tr>
<tr><td colspan="2">1/19/2015 14:15:30</td><td>40.60</td></tr>
<tr><td colspan="2">1/19/2015 14:16:00</td><td>40.52</td></tr>
<tr><td colspan="2">1/19/2015 14:16:30</td><td>40.47</td></tr>
<tr><td colspan="2">1/19/2015 14:17:00</td><td>40.49</td></tr>
<tr><td rowspan="3">Day 1</td><td>T_{min}</td><td>21.70</td><td>Minimum Temperature Day 1</td></tr>
<tr><td>T_{max}</td><td>45.41</td><td>Maximum Temperature Day 1</td></tr>
<tr><td>HDD</td><td>31.44</td><td>HHD Day 1</td></tr>
<tr><td rowspan="3">Day 2</td><td>T_{min}</td><td>29.96</td><td>Minimum Temperature Day 2</td></tr>
<tr><td>T_{max}</td><td>56.62</td><td>Maximum Temperature Day 2</td></tr>
<tr><td>HDD</td><td>21.71</td><td>HHD Day 2</td></tr>
<tr><td rowspan="3">Day 3</td><td>T_{min}</td><td>29.99</td><td>Minimum Temperature Day 3</td></tr>
<tr><td>T_{max}</td><td>55.37</td><td>Maximum Temperature Day 3</td></tr>
<tr><td>HDD</td><td>22.32</td><td>HHD Day 3</td></tr>
<tr><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="2">3-Day Total HDD</td><td>75.47 (≈ 75)</td><td>Cumulative HDD Days 1-3</td></tr>
</table>

Appendix A. Test Schedule Sheet

System Performance
Data Collection

REHAU ECOSMART HOUSE
Bozeman, MT

lee2289

Test Number:	RMEH 09-001
Description:	Compare energy usage to maintain house at 68F setpoint using radiant heating distribution with boiler in optimal configuration (outdoor reset) compared with energy usage with heat pump in ideal configuaration
Objectives:	**1** Run house at 68F steady state using radiant heatingwith boiler **2** Run house at 68F steady state using radiant heating with heat pump **3** Measure energy consumption for each scenario **4** **5**

Data Collection Parameters:

	Description	Source
1	OA Temp	RSC
2	Zone Set Point Temp	RSC
3	Zone Actual Temp	RSC
4	Slab Sensor Temp	RSC
5	Slab Set Point Temp	RSC
6	HDD	MSU
7	Boiler Gas Usage	MSU
8	Buffer Tank Temp	RSC
9	Boiler HWS Temp	RSC
10	RFH HWS Temp	RSC
11	RFH HWR Temp	RSC
12	Borehole Temps	MSU
13	Geo Field Flow Rate	MSU
14	Heat Pump Flow Rate	MSU
15	Heat Pump Energy Usage	MSU
16		
17		
18		

Test Duration:

Length 3 day for each scenario
Start Date ____
End Date ____

Deliverables:

1 Measure RFH energy usage with boiler
2 Measure RFH energy usage with heat pump
3
4
5

Notes:

MSU Notes: ***Testing in March 2014*** Based on heat pump rework.

Appendix B. Experiment Notes

Data for experiment RMEH 09 was collected during the following dates:

- Scenario 1 – Boiler: 16-Jan-15 – 19-Jan-15
- Scenario 2 – GSHP: 24-Feb-15 – 27-Feb-15

Appendix C. Data Collection Parameters

REHAU Smart Controls (RSC), National Instruments (NI), Agilent Benchlink and eGauge data acquisition systems were used to collect data for this experiment. Data was collected for the following points:

RSC Data Points

- Outdoor Air Temperature
- Zone Setpoint Temperature
- Zone Temperature
- Slab Temperature
- Slab Setpoint Temperature
- Buffer Tank Temperature
- Radiant Floor and Ceiling Cooling HWS/HWR Temperature

NI Data Points

- Relative Humidity

Agilent Data Points

- Air (space) Temperature
- Wall Temperature
- Window Temperature

eGauge Data Points

- Ground-source Heat Pump Energy Usage

Appendix D. References

1. EPA (2014). Portfolio Manager Technical Reference: Greenhouse Gas Emissions. Energy Star® Program of the Environmental Protection Agency. Retrieved from http://www.energystar.gov/buildings/tools-and-resources/portfolio-manager-technical-reference-greenhouse-gas-emissions

2. James Owenby, Richard Heim, Jr., Michael Burgin, Devoyd Ezell (2009). Maps of Annual 1961-1990 Normal Temperature, Precipitation and Degree Days. *CLIMATOGRAPHY OF THE U.S.* No. 81 - Supplement # 3. National Oceanic and Atmospheric Administration (NOAA). Retrieved from http://www.ncdc.noaa.gov/oa/documentlibrary/clim81supp3/clim81.html

3. ASHRAE (2009). *2009 ASHRAE Handbook – Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Chapter 9.

4. Wujek, J.B. and Dagostino F. R. (2010). Mechanical and Electrical Systems in Architecture, Engineering and Construction. 5th Edition. Upper Saddle River, New Jersey: Pearson.