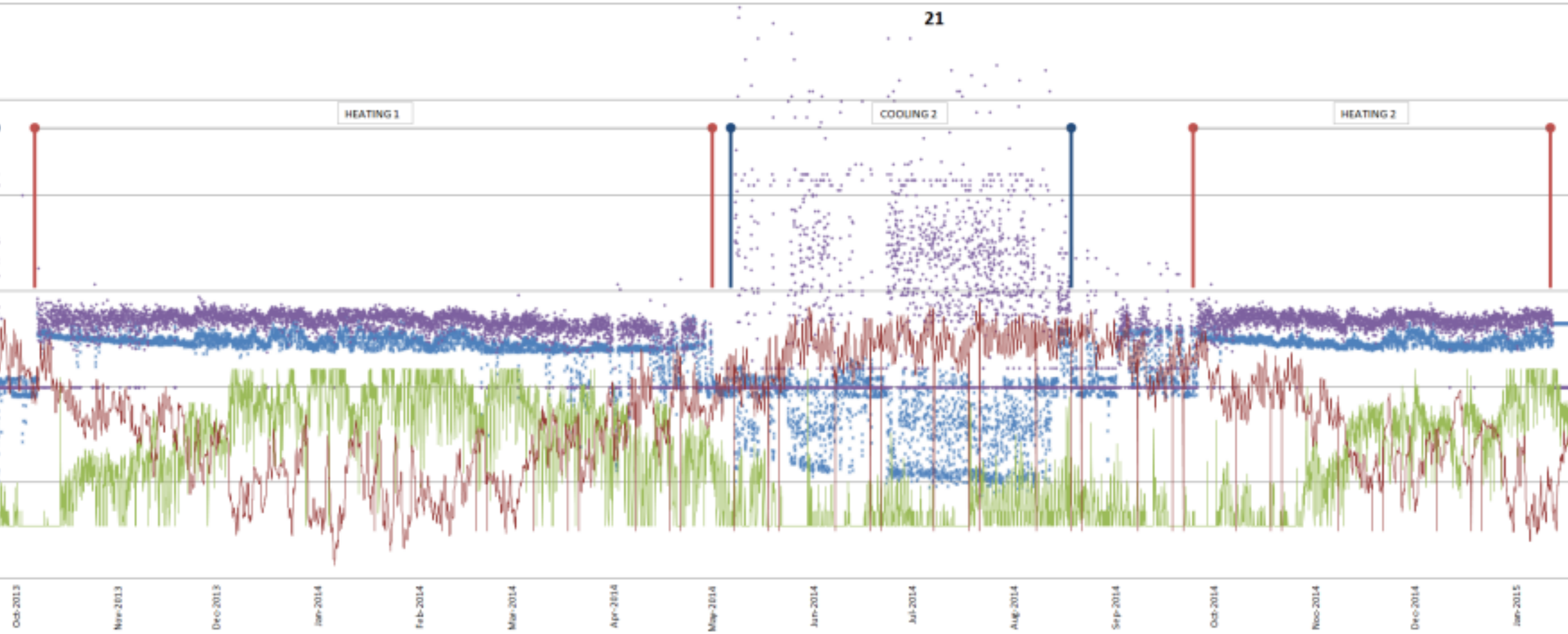
GSHPs and ASHPs

Real Performance Results in Cold Climates



University of Minnesota Cold Climate Housing Program

Center for Sustainable Building Research (CSBR)

Center for Energy and Environment (CEE)

Outline

1) Ground source heat pump monitoring project
   i. Background
   ii. Monitoring
   iii. Modeling

2) Air source heat pump monitoring project
   i. Background
   ii. Monitoring Results

3) Discussion, comparison, & implications for Passive House

GSHP - background

Prior research:

Michaels Engineering Report for MN Department of Commerce (2008)

1) Found negative life cycle savings and increased CO_2 emissions for residential installations.
2) Widely criticized by the GSHP industry for using modeled energy results based on assumed GSHP efficiency levels.
3) Assumed 3.3 heating COP, 4.1 cooling COP for the energy modeling study


Michaels engineering

Performance, Emissions, Economic Analysis of Minnesota Geothermal Heat Pumps

Final Report

Minnesota Department of Commerce
St. Paul, MN

April, 2008

Michaels No.: MJ807AAN

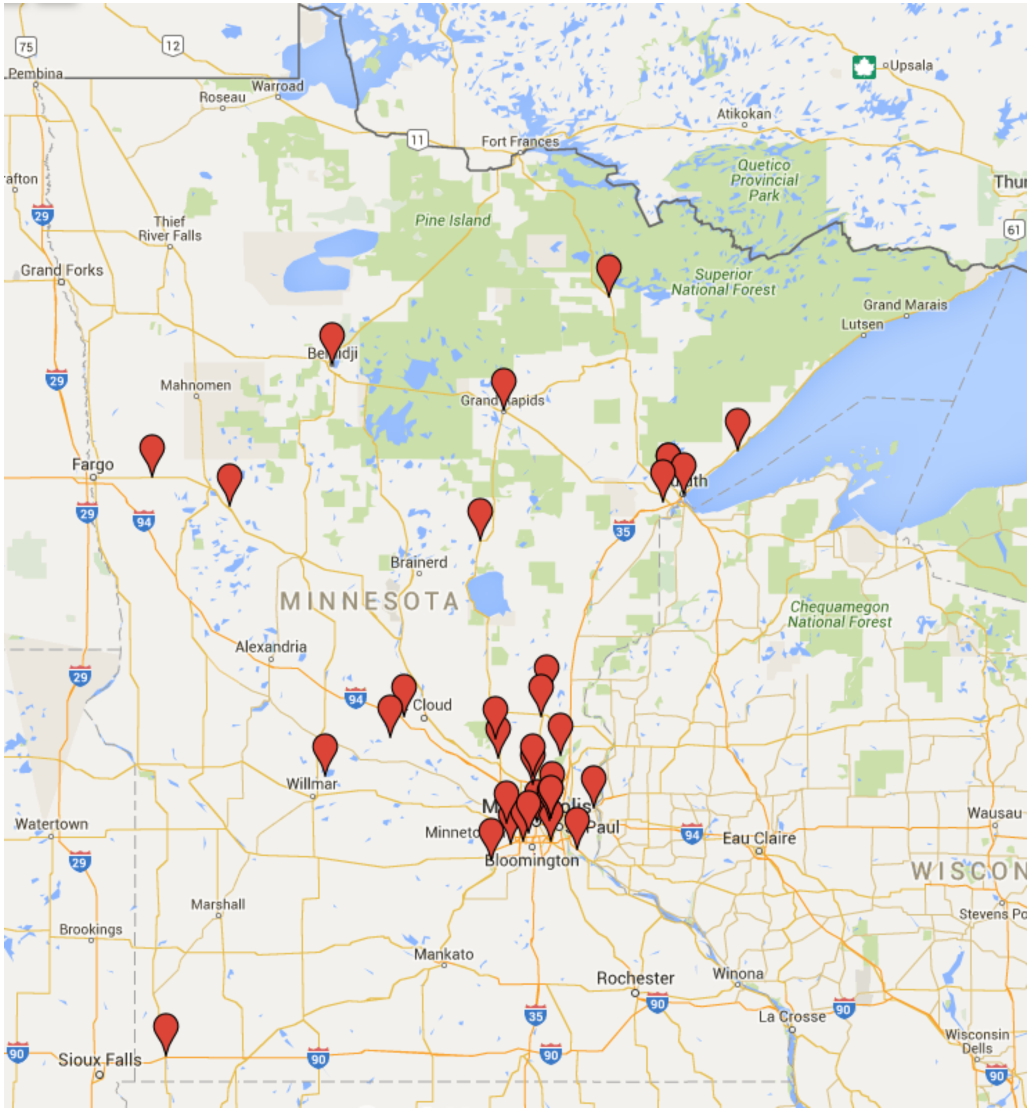
811 Monitor Street, Suite 100
La Crosse, Wisconsin 54603-3101
Phone 608-785-1900 Fax 608-784-2270
www.MichaelsEngineering.com

GSHP - background

University of Minnesota's Cold Climate Housing Program proposed revised research approach:

1) Multi-year in-situ monitoring of GSHP systems
2) Energy modeling comparison to standard GFA systems using COP results from monitoring
3) Broader environmental and policy assessment of GSHP technology, including an LCA study

GSHP - monitoring



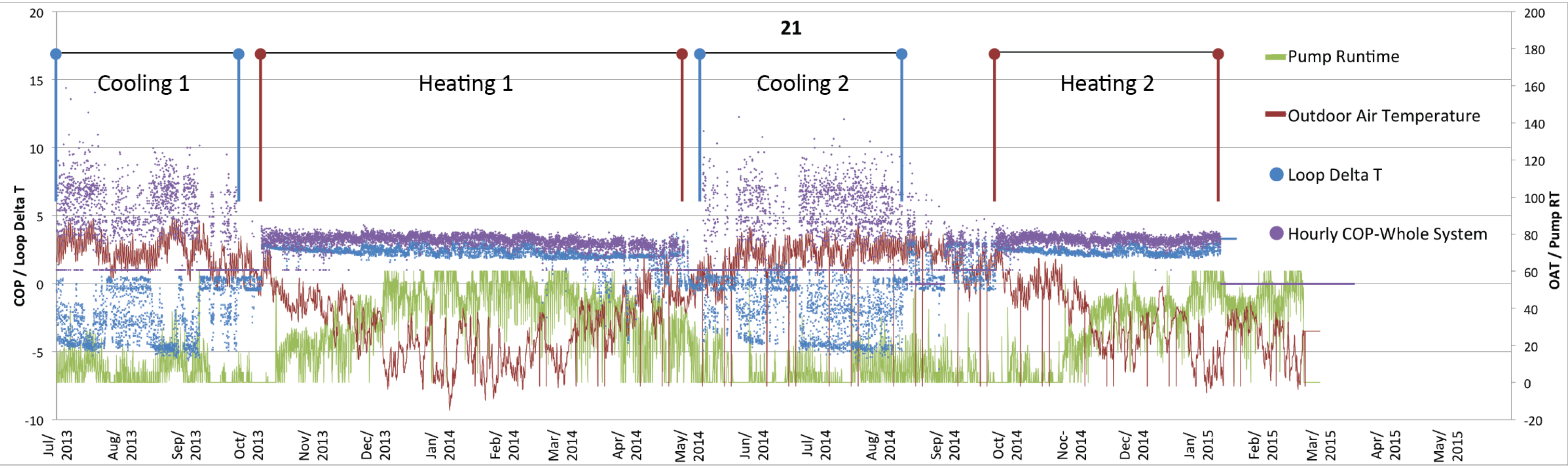
Original goal:
50 monitored systems in various climate zones

After drop-outs, equipment failures and data issues, 37 systems were used for the report.

Monitoring system design and installation provided by Mike LeBeau, CR Building Performance Specialists.

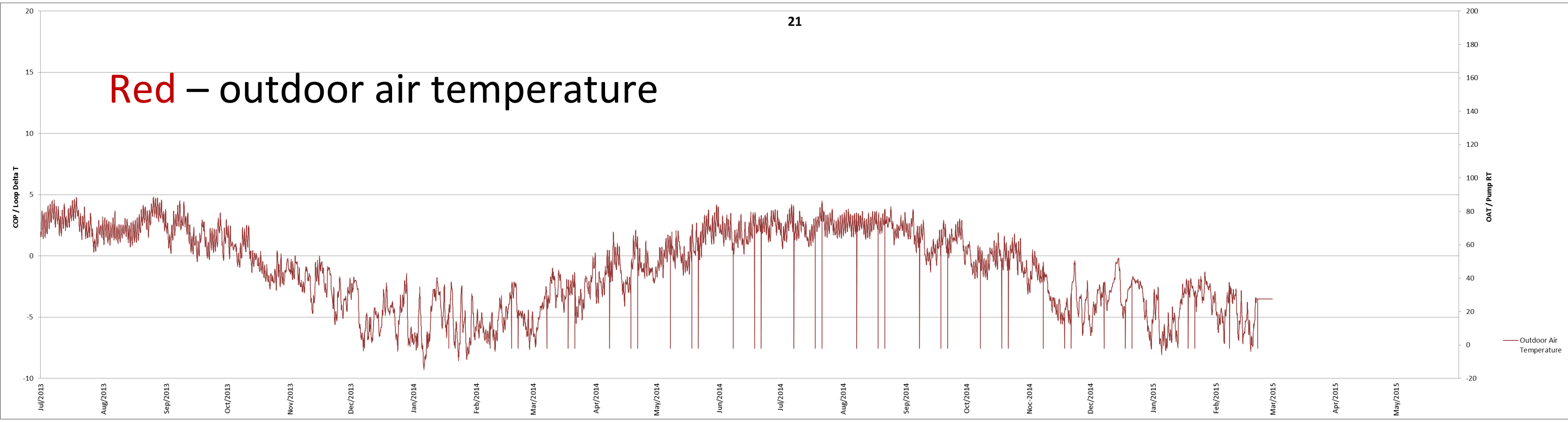

15 minute data for 40+
systems for 2+ years

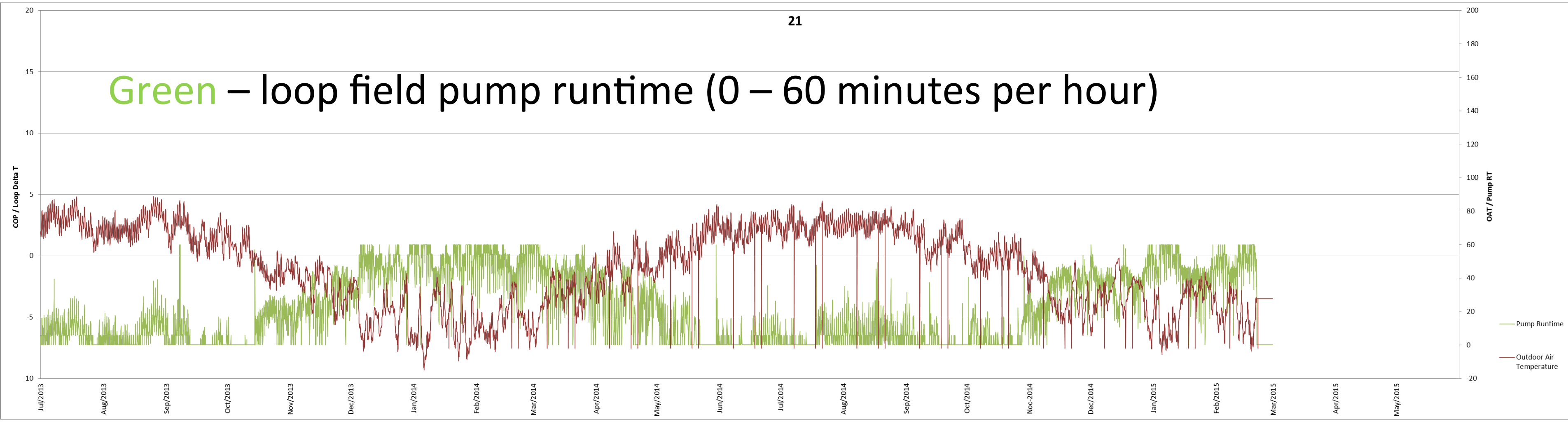
GSHP - monitoring



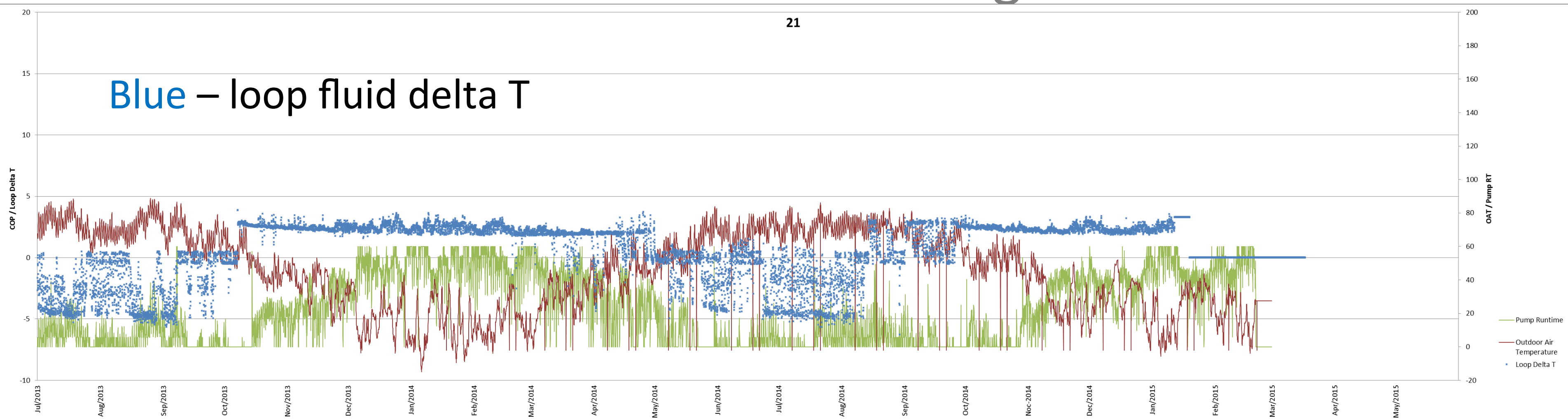
4-variable graphs used to identify heating and cooling seasons

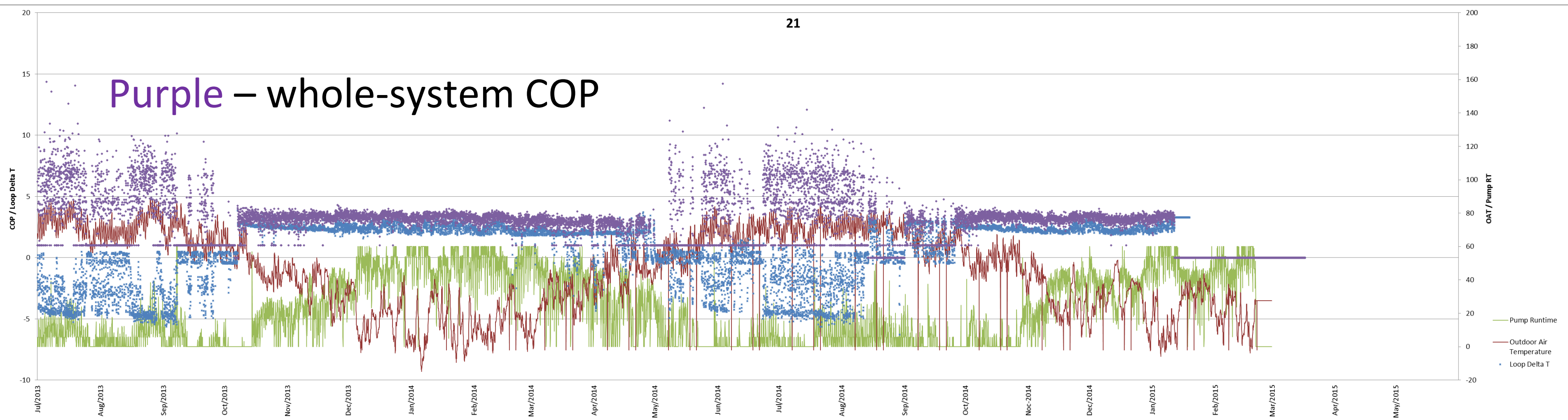
GSHP - monitoring



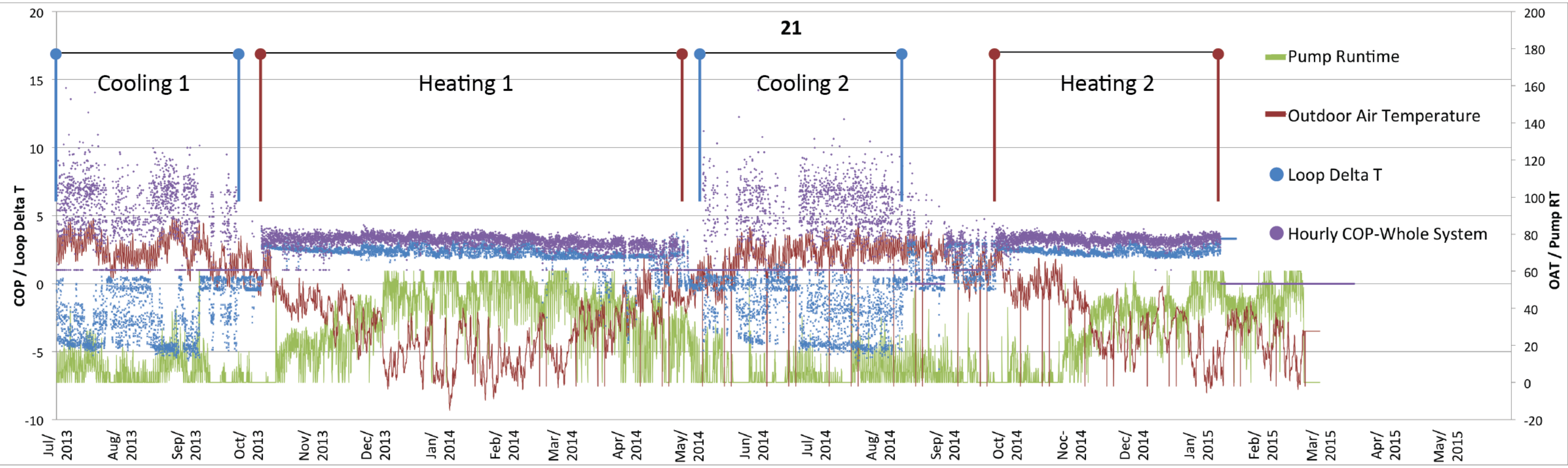


GSHP - monitoring





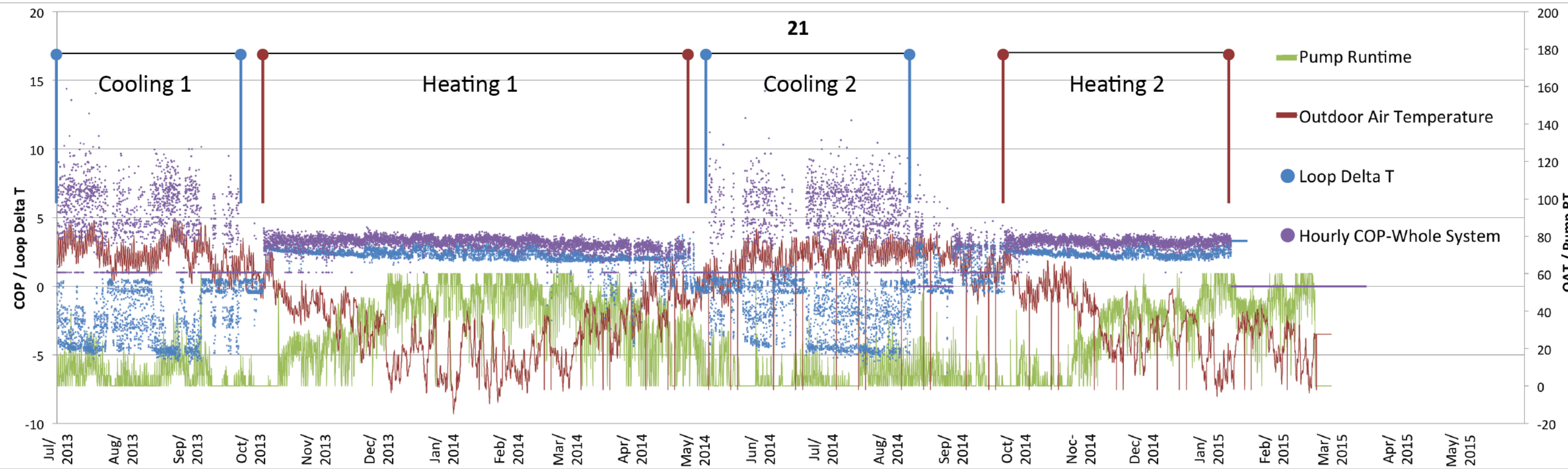
GSHP - monitoring



COP (heating) = (Energy Delivered + Energy Consumed) / Energy Consumed

COP (cooling) = (Energy Extracted – Energy Consumed) / Energy Consumed

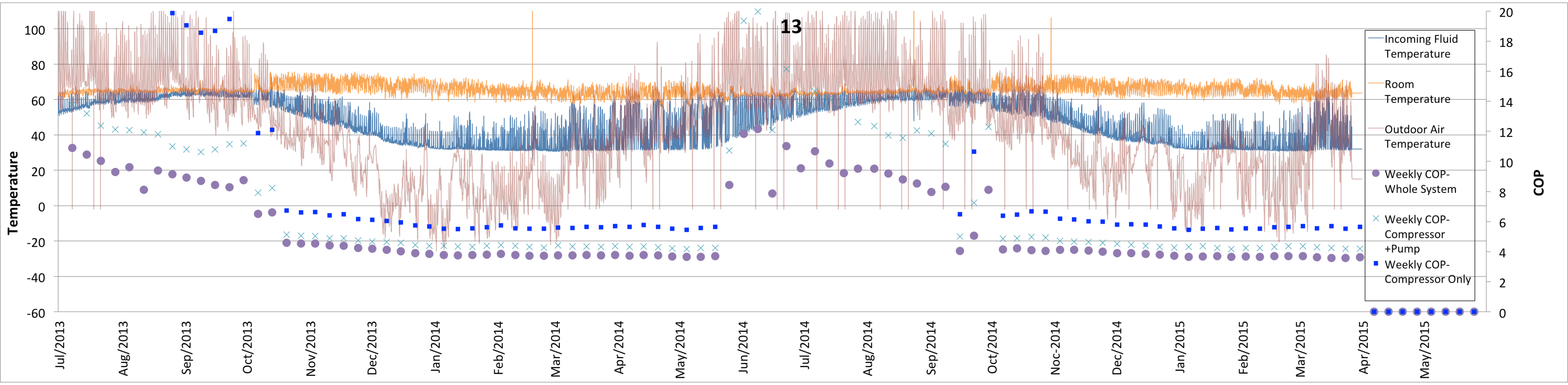
GSHP - monitoring



Take-aways:

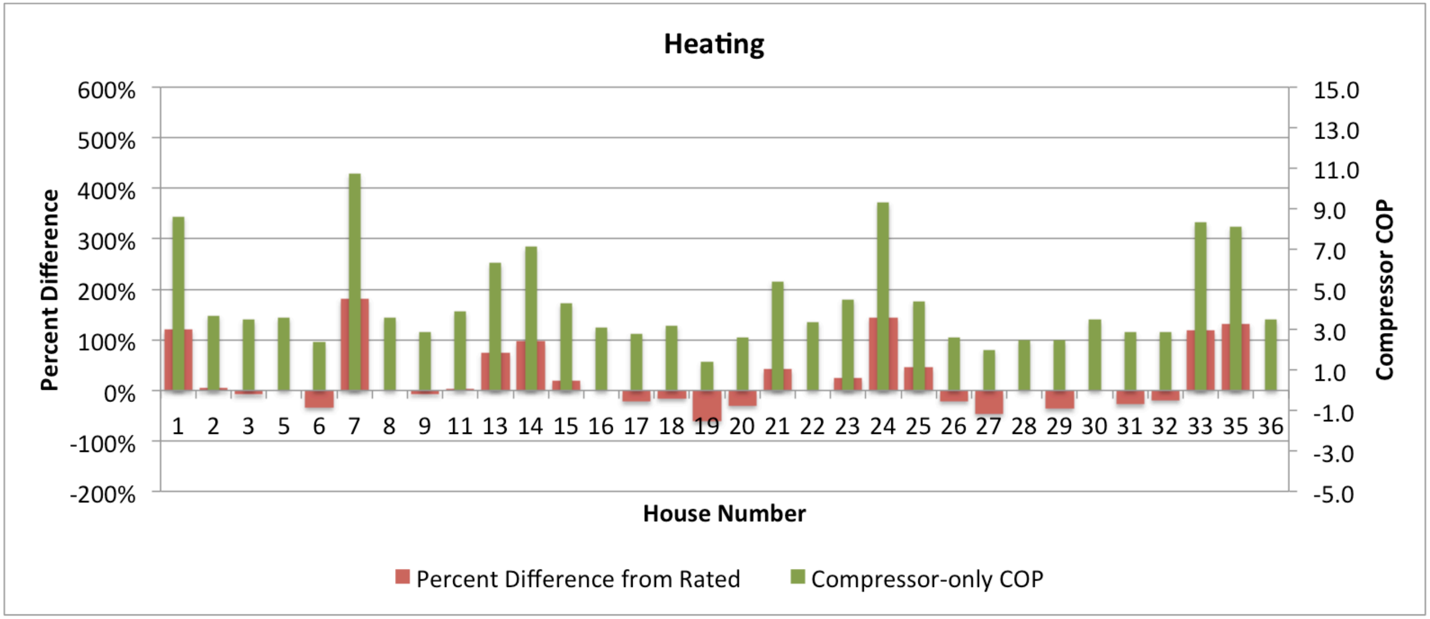
1. Cooling season is short and run time is highly irregular
2. Greater loop fluid delta T corresponds to higher COPs
3. This system is probably undersized (as are most GSHPs to save install cost)

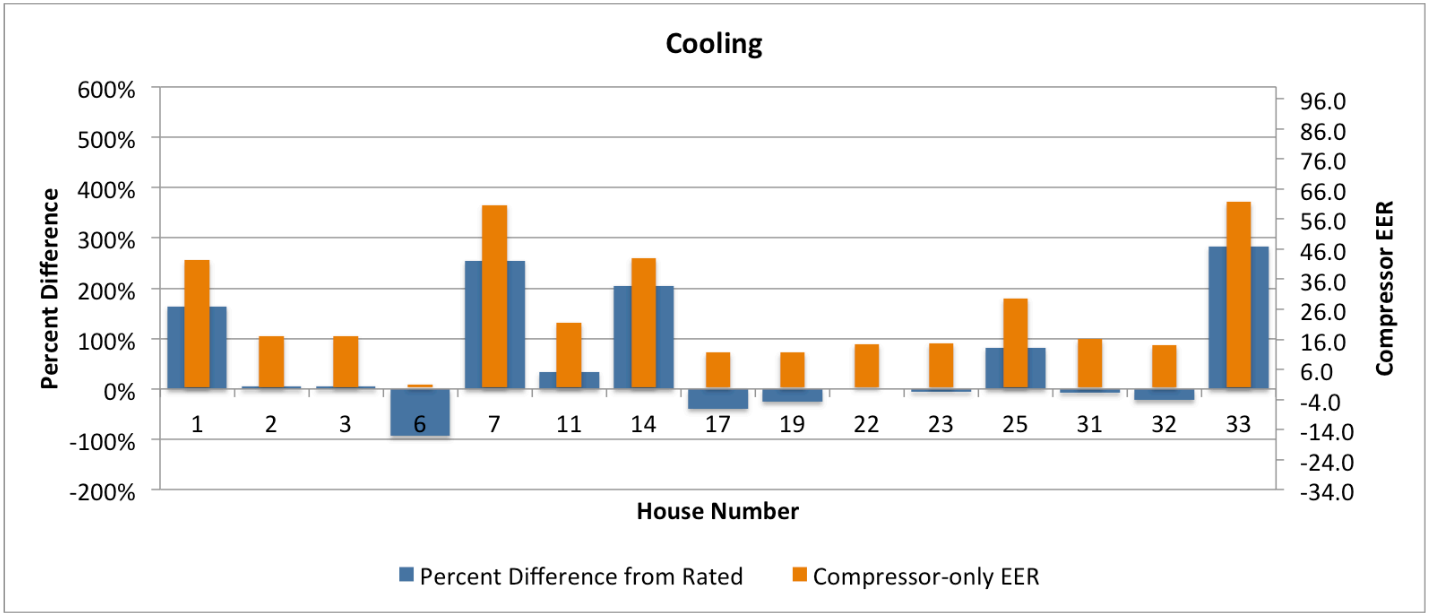
GSHP - monitoring



Take-aways:

1. Noticeable decline in COP during the course of a heating or cooling season
   i. Heating whole system COP – 4.5 down to 3.8
   ii. Cooling whole system COP – 10 down to 8
2. Addition of loop field pump energy drops heating COP by close to 2 (roughly 6 to 4, for this high-performing system)
3. Loop field temperature bottoming out near 32F, peaking at 60F

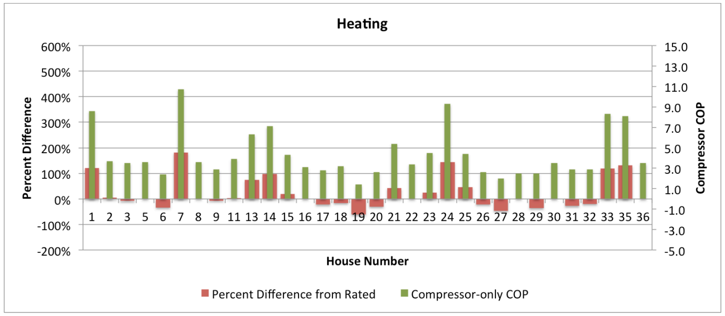

Heating
600%
500%
400%
300%
200%
100%
0%
-100%
-200%
Percent Difference
15.0
13.0
11.0
9.0
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
Compressor COP
1 2 3 5 6 7 8 9 11 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 35 36
House Number
Percent Difference from Rated
Compressor-only COP

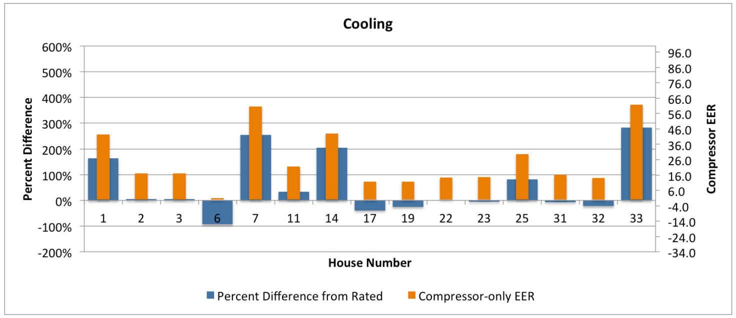

Cooling
600%
500%
400%
300%
200%
100%
0%
-100%
-200%
Percent Difference
96.0
86.0
76.0
66.0
56.0
46.0
36.0
26.0
16.0
6.0
-4.0
-14.0
-24.0
-34.0
Compressor EER
1 2 3 6 7 11 14 17 19 22 23 25 31 32 33
House Number
Percent Difference from Rated
Compressor-only EER

GSHP - monitoring

Large variability in compressor performance, especially on cooling side.

i. Variation from each other
ii. Variation from expected



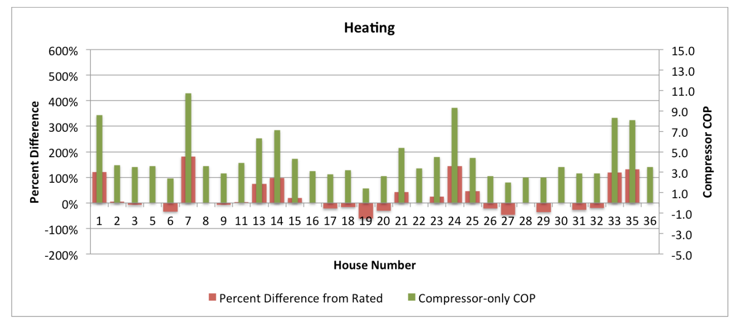


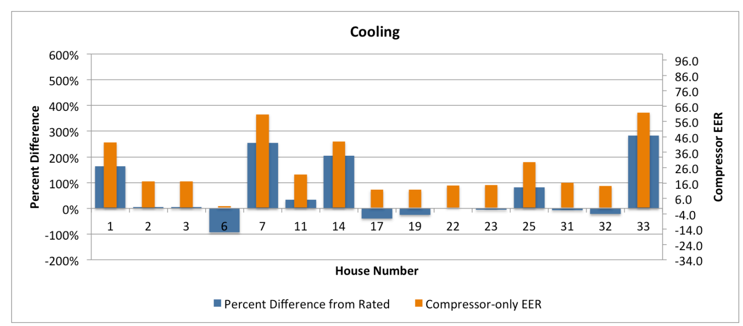
GSHP - monitoring

Large variability in compressor performance, especially on cooling side.

i. Variation from each other
ii. Variation from expected

Is the homeowner going to get what they paid for???





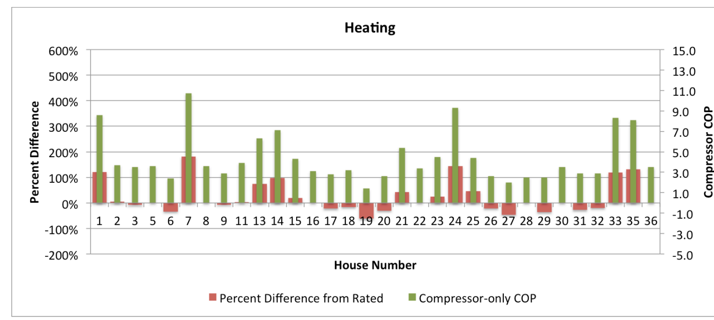
GSHP - monitoring

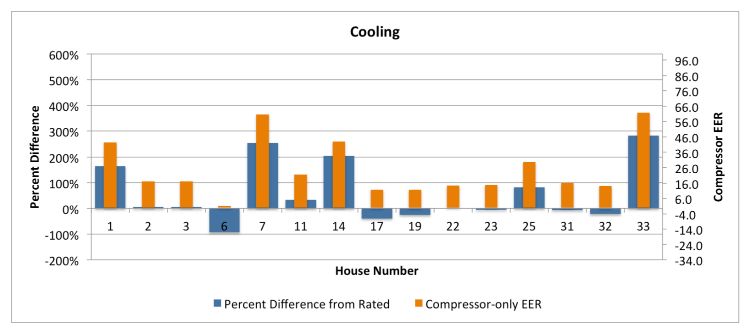
Large variability in compressor performance, especially on cooling side.

i. Variation from each other

ii. Variation from expected

Welcome to the high-stakes table!





GSHP - monitoring

Final measured heating and cooling COPs (compressor + loop pump)

	Heating COP	**Cooling COP**
Minimum Value	1.51	0.23
25th Percentile	2.88	3.91
Median	3.19	5.20
75th Percentile	3.75	10.13
Maximum Value	7.19	23.44

GSHP - monitoring

Final measured heating and cooling COPs (compressor + loop pump)

		Heating COP	Cooling COP
	Minimum Value	1.51	0.23
“low” COP	25th Percentile	2.88	3.91
“mid” COP	Median	3.19	5.20
“high” COP	75th Percentile	3.75	10.13
	Maximum Value	7.19	23.44

Values used for energy modeling

Michaels Engineering report assumptions: heating COP 3.3, cooling COP 4.1

GSHP - modeling

9 base cases used to determine GSHP savings in a wide variety of possible installation scenarios

		Home Energy Efficiency		
		Low	Medium	High
		Pre-energy code	1980's MN energy code	2015 MN energy code
Home Size	2000 sf (small)	1	4	7
	3000 sf (medium)	2	5	8
	4000 sf (large)	3	6	9

GSHP - modeling

9 cases x 3 efficiency levels = 27 GSHP models

+

9 base cases w fuel-fired GFA

+

9 GSHP models w desuperheaters

=

45 models total

GSHP - modeling

Complications:

1) Different supply air temperatures meant that fan airflows and therefore fan energy would be different for each system at a given heat load. And REM Rate does not do a good job with fan energy.

2) GFA systems are oversized, whereas GSHP systems rely on backup heat systems – How much backup? How much oversizing?

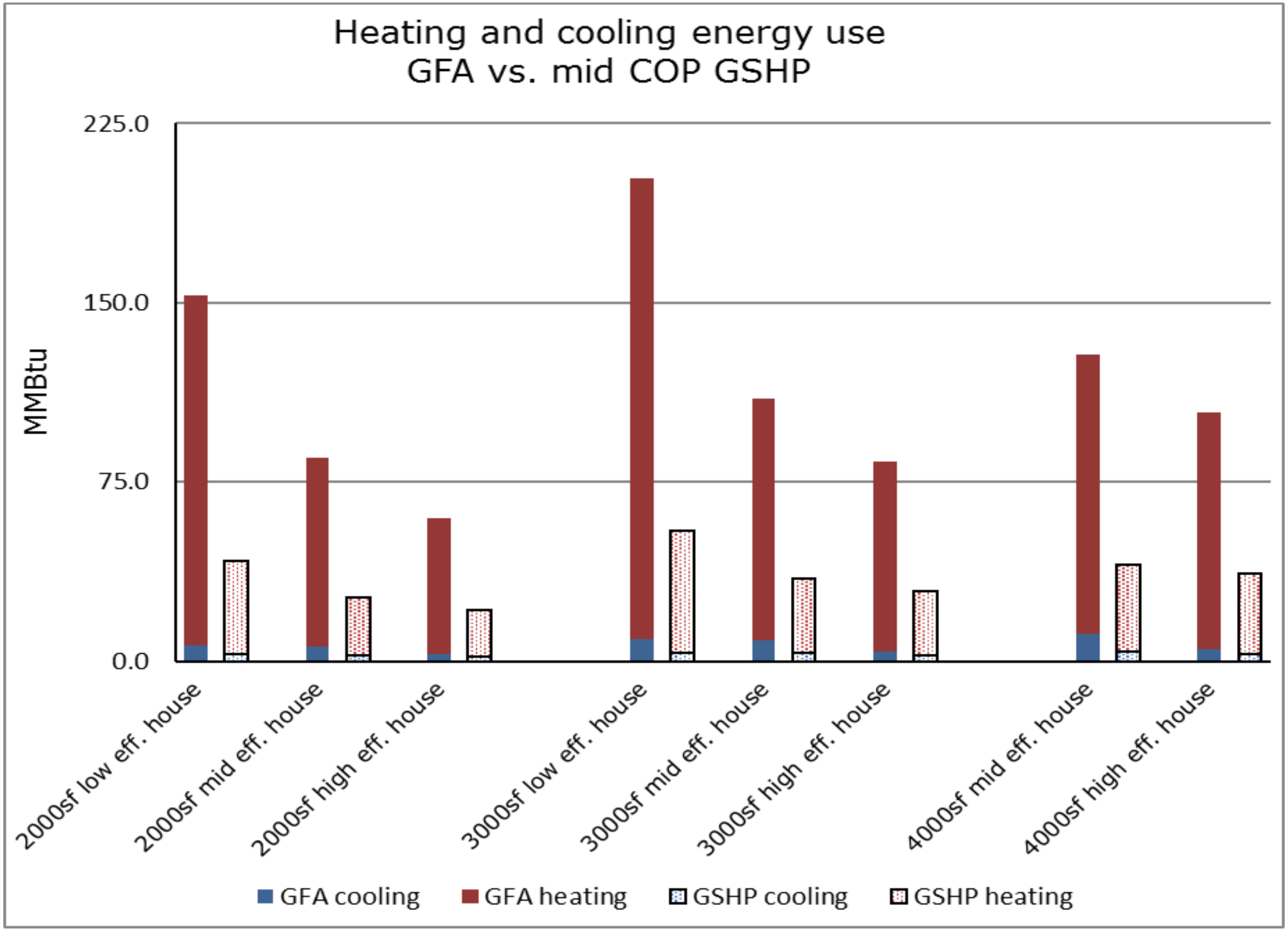
3) GSHP systems can provide hot water savings with the use of a desuperheater

GSHP - modeling

Fan airflows and energy use based on supply air temperature

Heating equipment	Assumed Supply Air Temp	Source	Resulting fan energy factor
70 AFUE GFA	140ºF	CEE, PARR (upper end of range)	0.86
80 AFUE GFA	130ºF	CEE, PARR (lower end of range)	1.0 (base case)
90 AFUE GFA	115ºF	CEE, PARR (lower end of range)	1.32
GSHP (high, med, low COPs)	95ºF	Field data, average heating supply air temp	2.3

GSHP - modeling

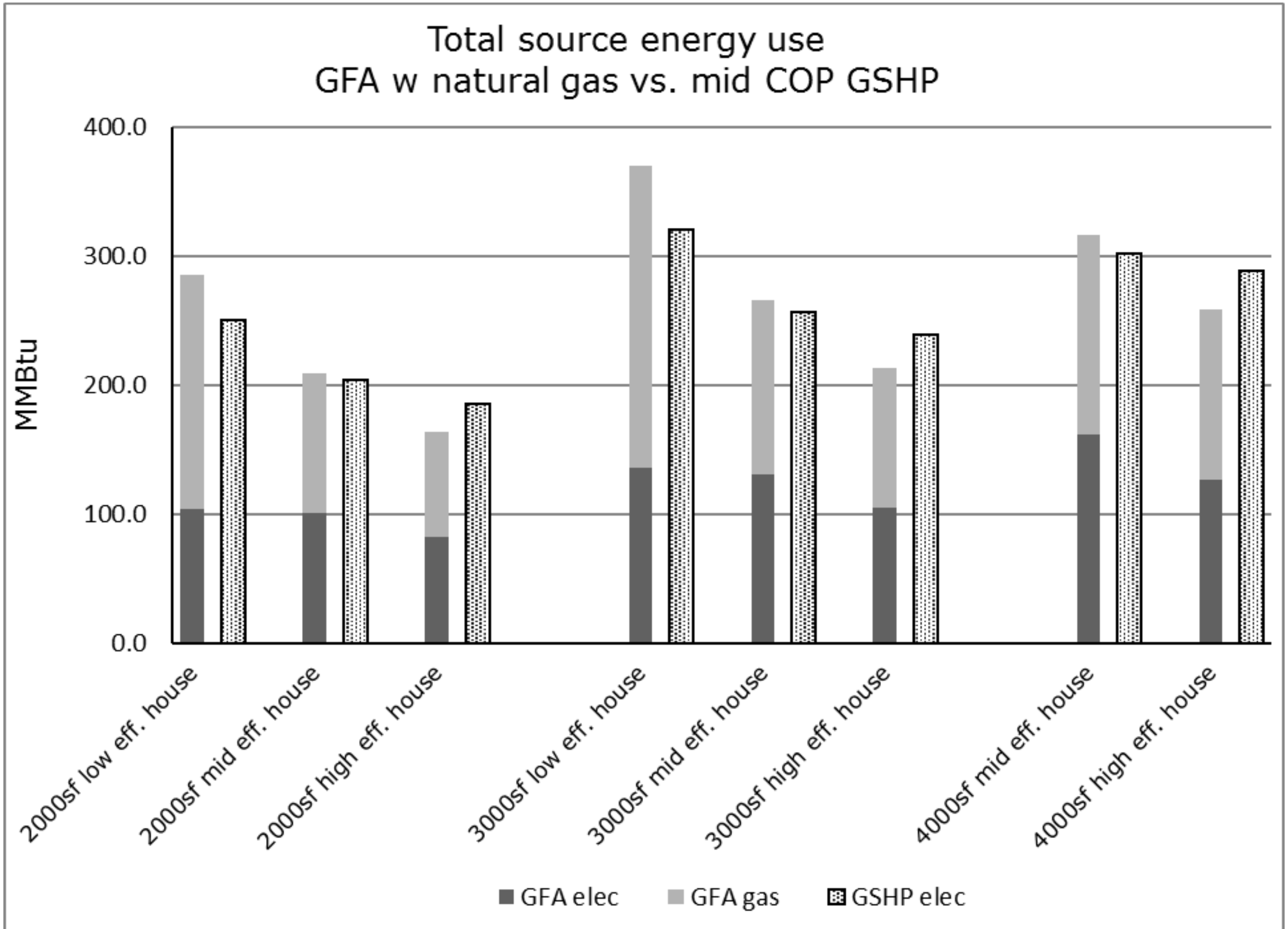


GSHP - modeling

Translate site to source energy…

Source energy factors		referenced source
grid electricity	3.15	ANSI Std. 105-2014 (national avg.)
natural gas burned in combustion appliance	1.09	ANSI Std. 105-2014 (national avg.)
LP burned in combustion appliance	1.15	ANSI Std. 105-2014 (national avg.)

GSHP - modeling

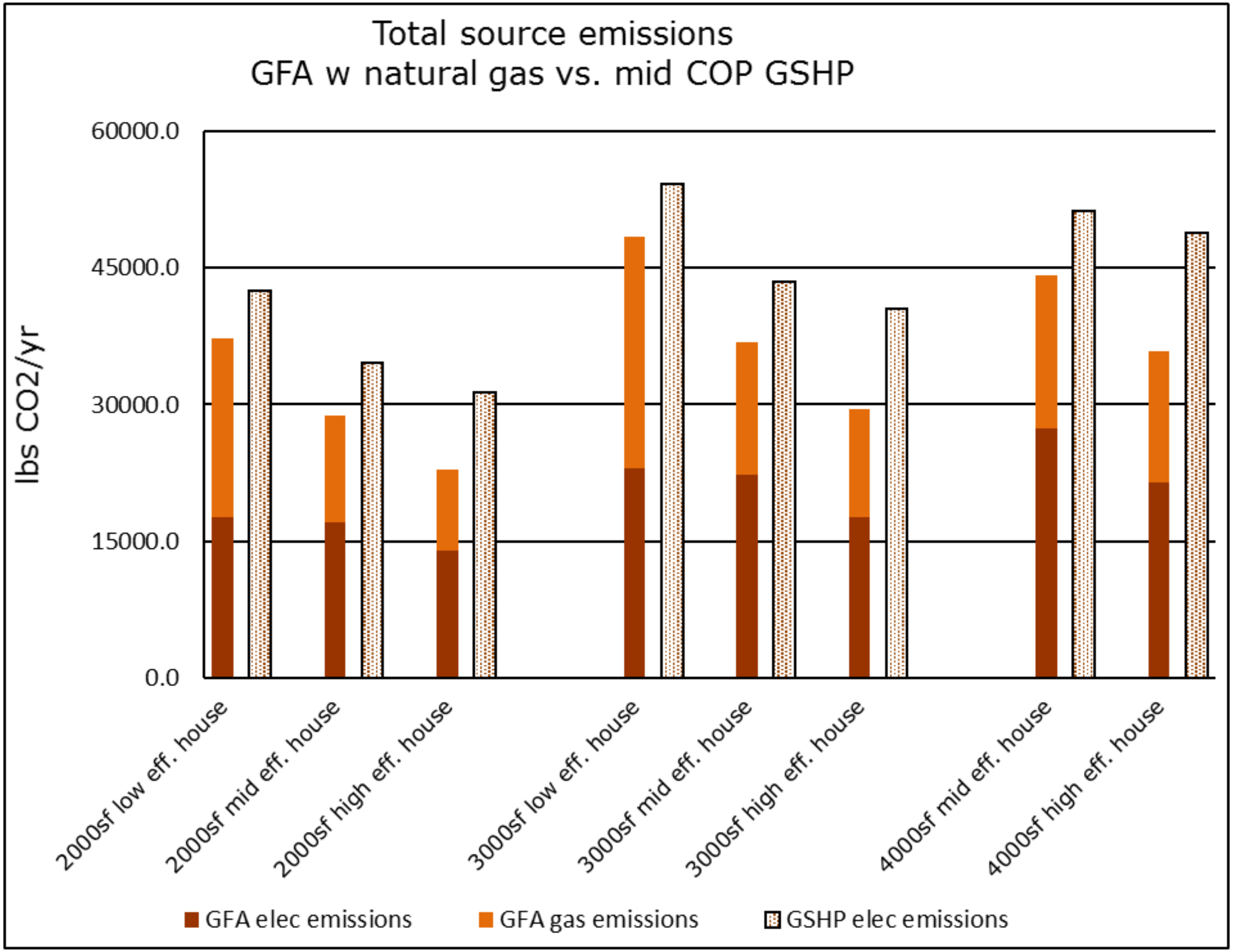


GSHP - modeling

Translate site energy to CO2 emissions…

Energy Type	Rate	Units	Source	lbs CO2/MMBtu
electricity	1.82	lbs CO2/kWh	MN PCA	533.4
natural gas	11.79	lbs CO2/therm	US EIA Form EIA-1605 Instructions "Voluntary Reporting of Greenhouse Gases", 2010	117.9
propane	12.55	lbs CO2/gallon	US EIA Form EIA-1605 Instructions "Voluntary Reporting of Greenhouse Gases", 2010	137.4

GSHP - modeling



GSHP - modeling

Translate to energy costs…

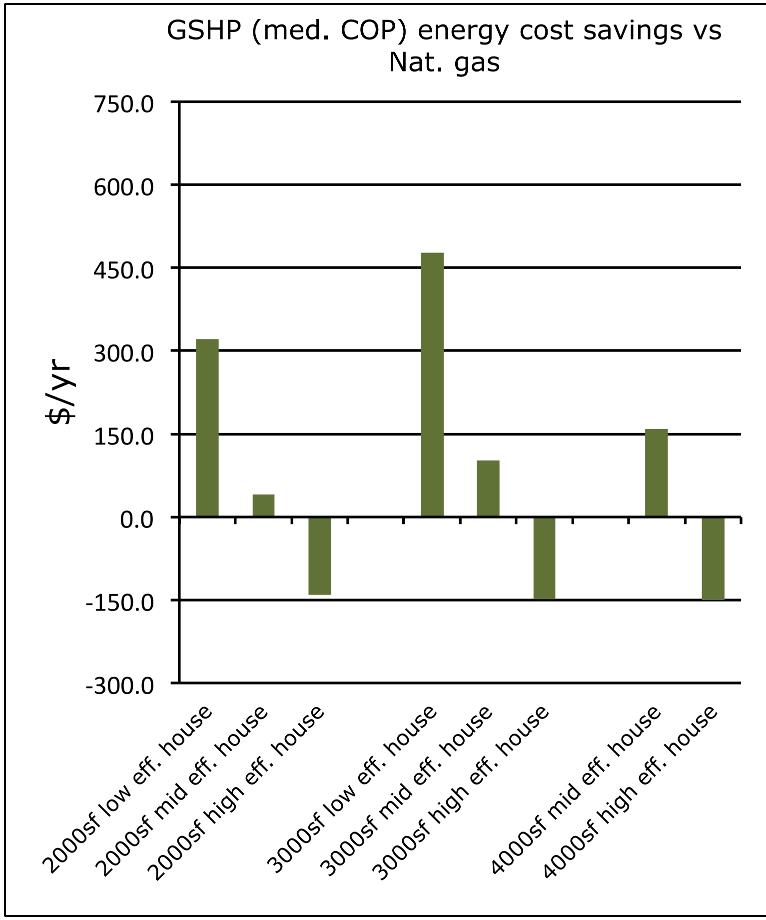
Rate assumptions for base case GFA systems (natural gas/propane)

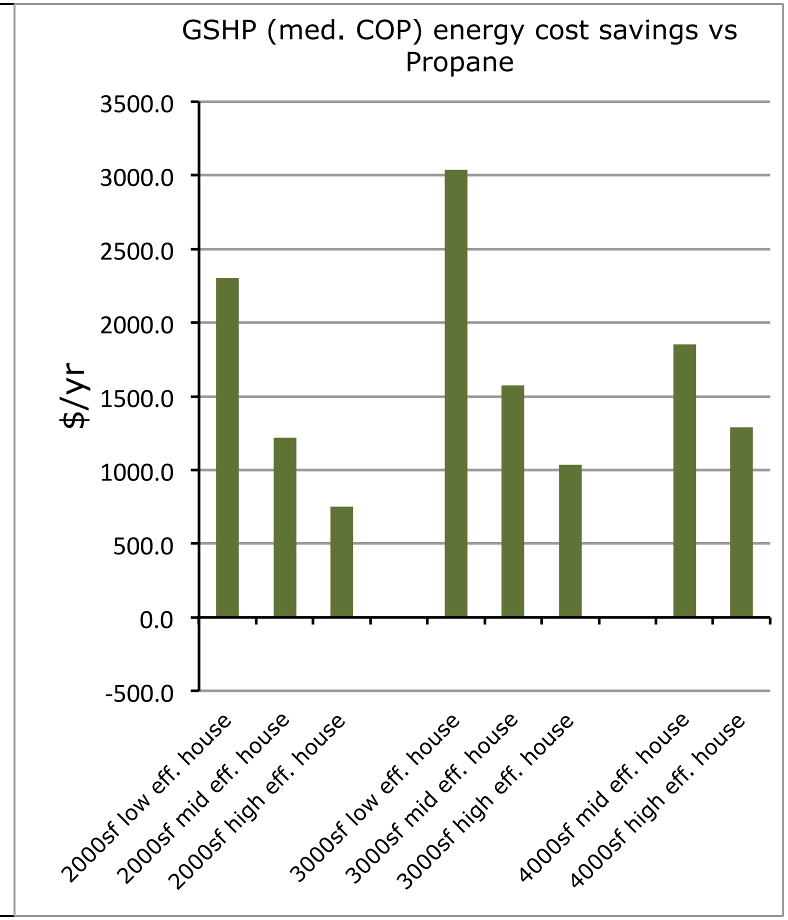
Energy Type	Rate	Units	Time of Year	Source	$/MMBtu
cooling energy charge	0.15	$/kWh	June - Sep	2015 MN utility avg. (inc. surcharges)	$43.96
heating fan energy charge	0.14	$/kWh	Oct - May	2015 MN utility avg. (inc. surcharges)	$41.03
nat. gas (water/space heat)	1.00	($/therm)	whole year	EIA 5yr avg for MN ('10-'15)	$10.00
propane (water/space heat)	2.00	($/gallon)	whole year	EIA 5yr avg for MN ('10-'15)	$21.90

Rate assumptions for GSHP systems (all electric)

Energy Type	Rate	Units	Time of Year	Source	$/MMBtu
cooling energy charge	0.15	$/kWh	June - Sep	2015 MN utility avg. (inc. surcharges)	$43.96
heating energy charge	0.10	$/kWh	Oct - May	2015 MN utility avg. (inc. surcharges)	$29.31
water heating	0.117	$/kWh	whole year	(weighted avg. of above)	$34.19

GSHP - modeling





GSHP - modeling

Assuming a respectable level of performance (which might be a big if) GSHP can provide certain benefits in cold climates:

1) Reduced site energy use for all homes
2) Reduced site and source energy use for old, inefficient homes
3) For outstate areas, reduced site energy, source energy, CO_2 emissions, and energy costs *compared to electric-resistance based systems*
4) For outstate areas, reduced and stabilized energy costs *for propane homes*

However, for most new homes in MN, GSHP systems increase source energy use, CO_2 emissions, and energy costs.

In mixed-humid climates, results would be substantially different.

ASHP - background

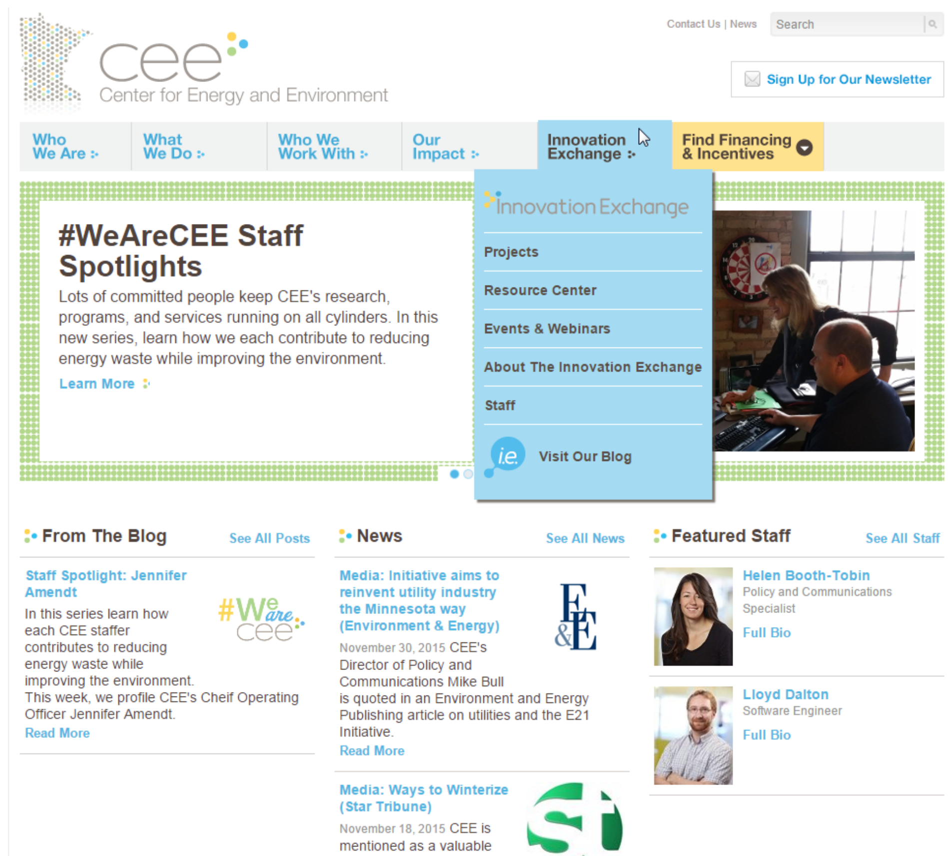
Field research currently underway by Center for Energy and Environment:

Cold Climate Air Source
Heat Pump Field Assessment

Team members:
Nicole Kessler
Josh Quinnell
Ben Schoenbauer

Will install and monitor performance of 6-8 air source heat pumps in a variety of installation conditions
www.mncee.org/heat_pumps

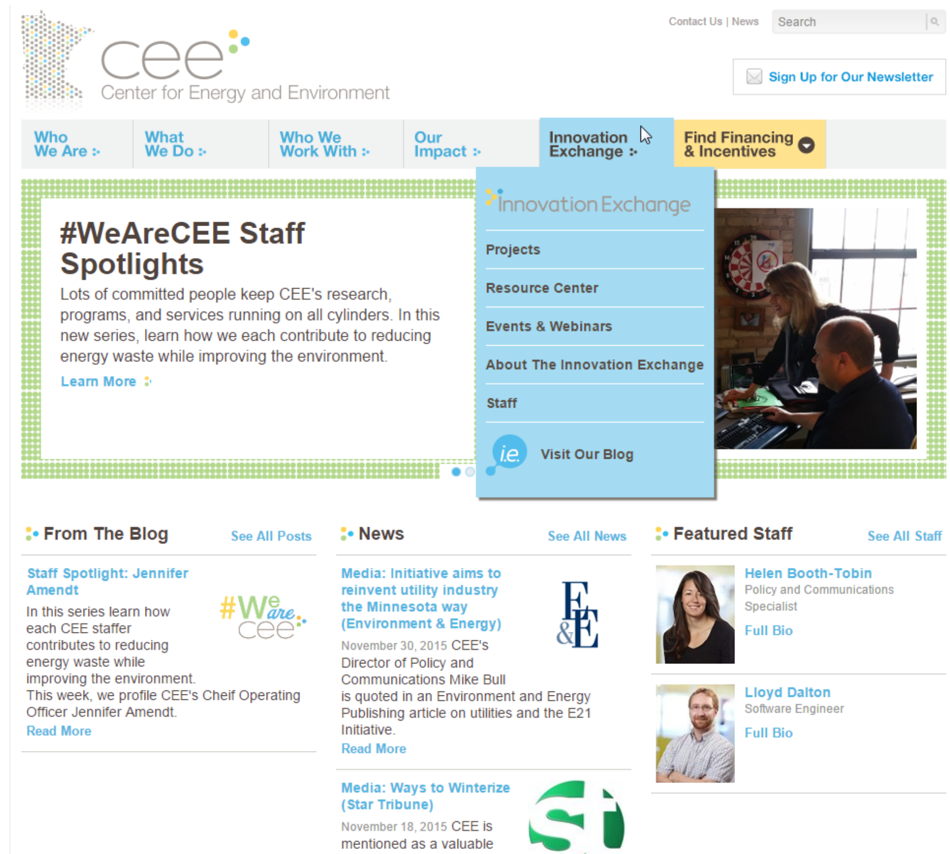
2 ductless models, 6 ducted



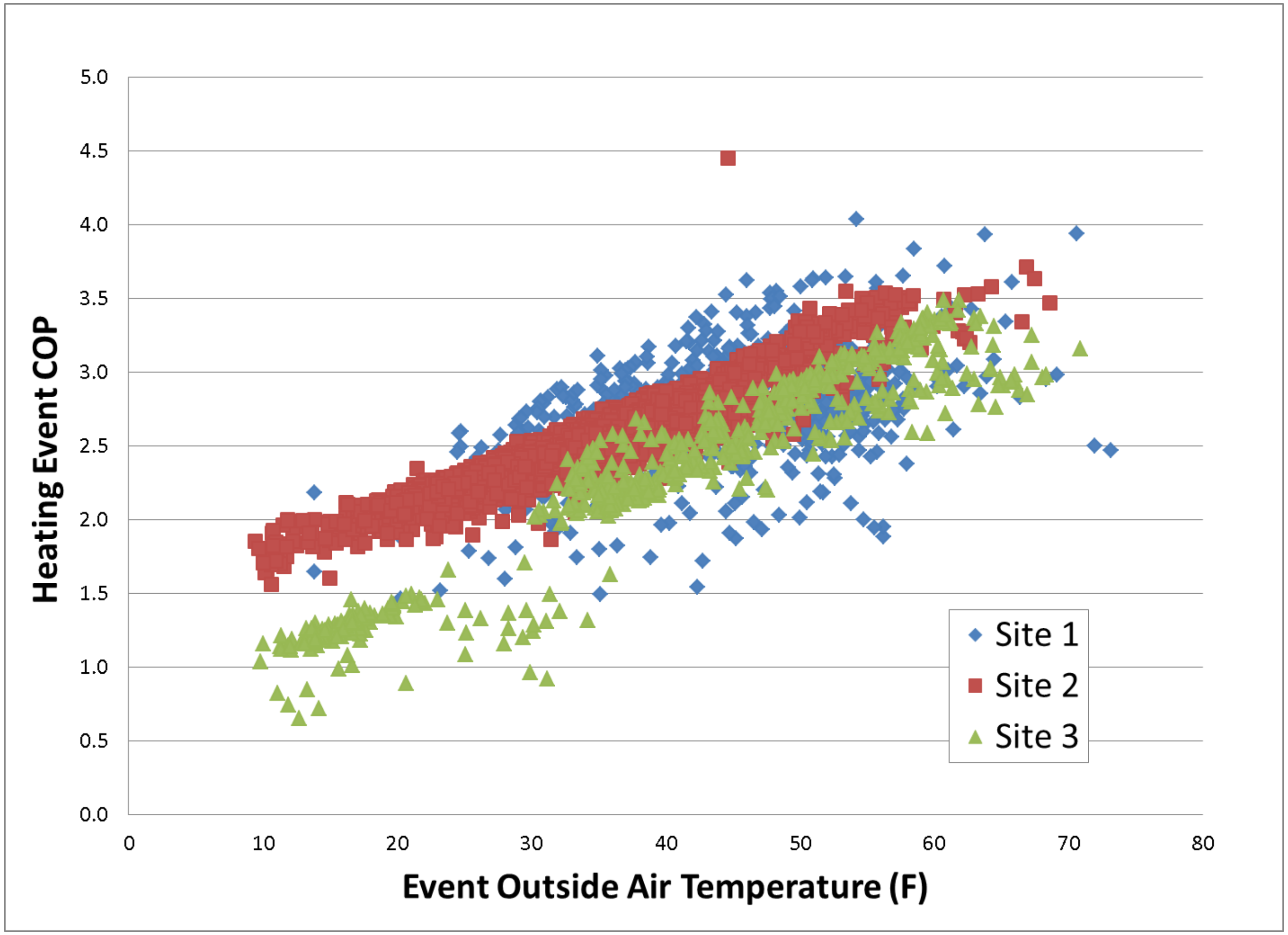
ASHP - background

Several complicating factors with ASHP efficiency:

1. COP varies considerably with temperature
2. In cold climates, COP impacted by backup heat
3. And defrost cycles



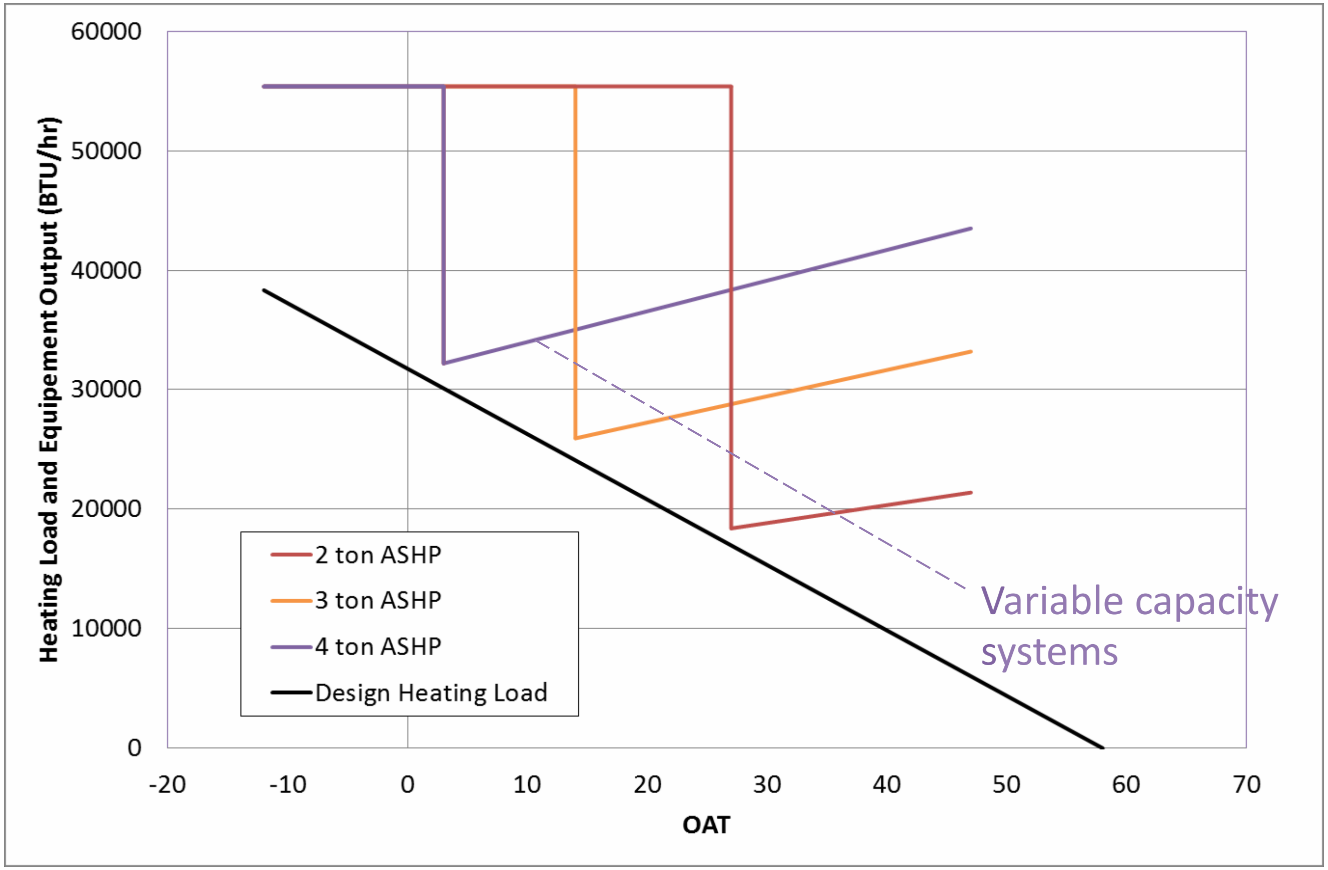
ASHP Performance – Preliminary Data



- Rated COPs of 3.0-3.5 at 47 F
- COP observed
  - 1.5-3.5 (site 1 & 2)
  - 1-3.5 (site 3)
- 2015-2016 heating season
- Results shown with no backup, no frost-protection

Center for Energy and Environment

Sizing



The OAT for the systems to switch to back up:

4ton ~3 F,

3ton ~14 F,

2 ton ~27F

Percentage of heating load meet by ASHP:

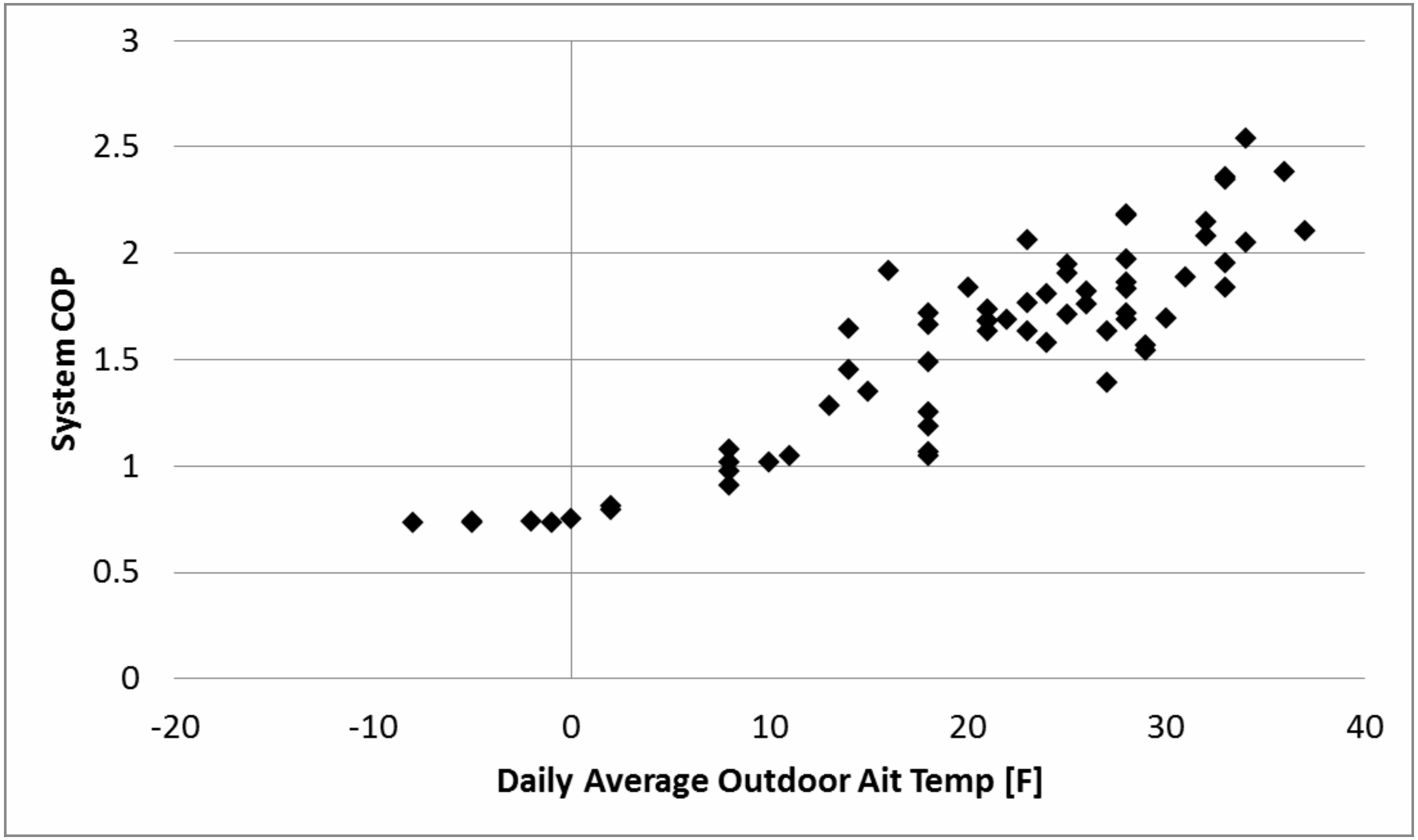
4ton ~ 86%,

3ton ~ 74%

2 ton ~ 40%

cee Center for Energy and Environment

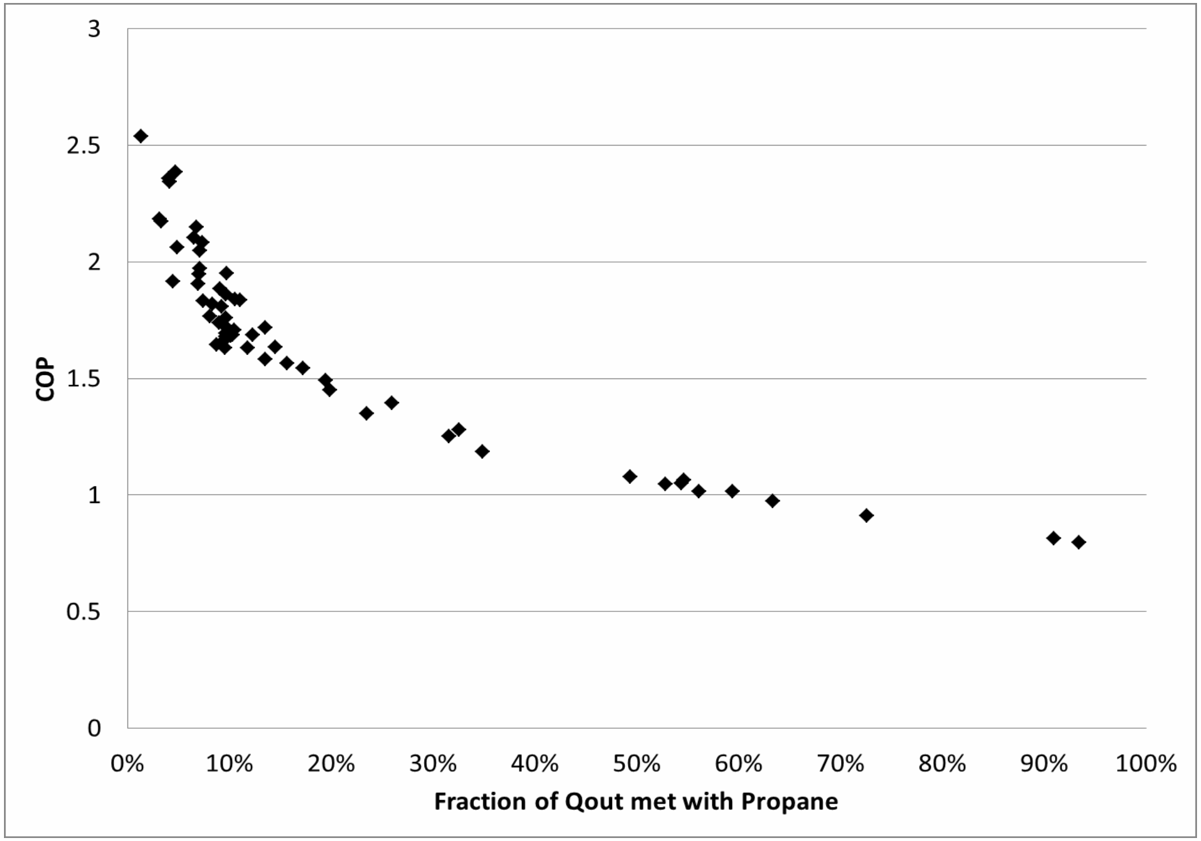
Preliminary Results



Center for Energy and Environment

Including impact of backup heat reduces the combined COP

Preliminary Results



cee
Center for Energy and Environment

Eventually, COP approaches furnace efficiency

Energy Use and Costs

- Assumptions:
  - 40,000 Btu/hr design heating load
  - Minneapolis TMY3
  - Equipment specifications

			LP Use	Electric Use	Annual Cost
	Avg COP	%ASHP	therms/yr	kWh/yr	$/yr
Propane Furnace	0.80	0%	876	0	$1,732
Propane Furnace	0.95	0%	735	0	$1,453
ASHP w/30°F Change-over	1.18	27%	528	1,898	$1,272
ASHP w/10°F Change-over	1.81	79%	152	6,859	$1,124
ASHP w/0°F Change-over	1.97	89%	84	7,958	$1,120

Energy Use and Costs

- Assumptions:
  - 40,000 Btu/hr design heating load
  - Minneapolis TMY3
  - Equipment specifications

			LP Use	Electric Use	Annual Cost	
	Avg COP	%ASHP	therms/yr	kWh/yr	$/yr	ASHP COP:
Propane Furnace	0.80	0%	876	0	$1,732	
Propane Furnace	0.95	0%	735	0	$1,453	
ASHP w/30°F Change-over	1.18	27%	528	1,898	$1,272	3.42
ASHP w/10°F Change-over	1.81	79%	152	6,859	$1,124	2.38
ASHP w/0°F Change-over	1.97	89%	84	7,958	$1,120	2.27

ASHP w/0°F, electric backup	2.17	89%	0	2590 + 7958	$1,266	2.27

ASHP COP declines as it spends more time operating at cold temperatures, but… Avg. COP of total system goes up as backup use goes down.

Comparison and Discussion

How do GSHP and ASHP systems compare, and what are their implications for code houses and Passive Houses? Assume GFA-based code house is "base case"

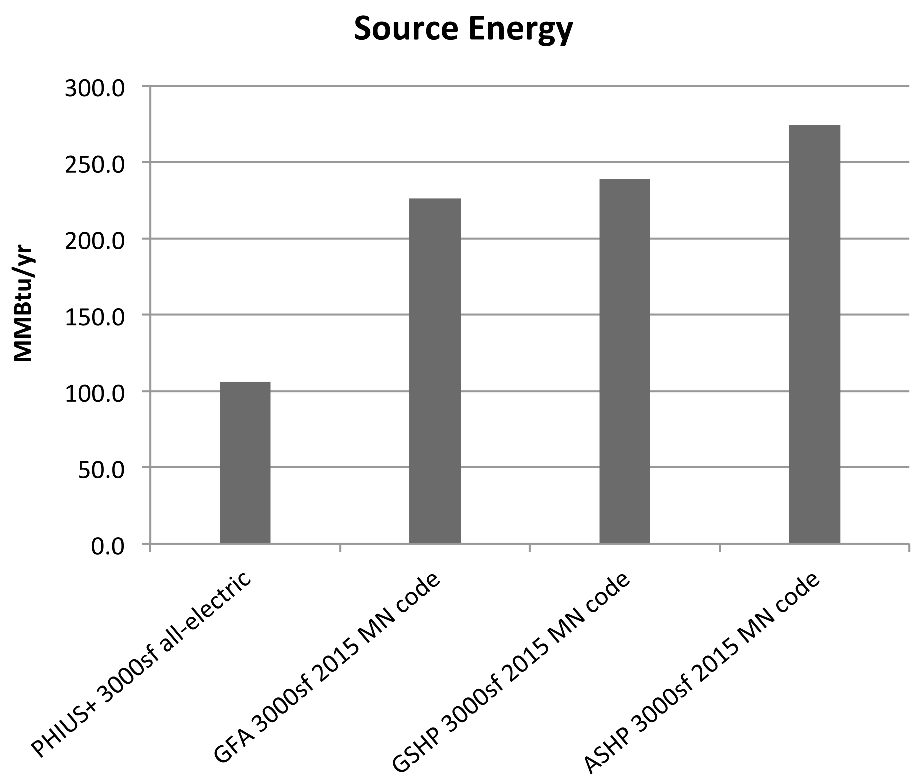
1. GSHP definitely provides highest efficiency
2. Both ASHP and GSHP will reduce *site* energy substantially

	heating COP	cooling COP
GFA (base case)	0.90	3.4
GSHP (mid efficiency)	3.2	5.2
ASHP (ducted, w resistance backup and 0°F switchover)	2.2	4

Comparison and Discussion

How do GSHP and ASHP systems compare, and what are their implications for code houses and Passive Houses? Assume GFA-based code house is "base case"

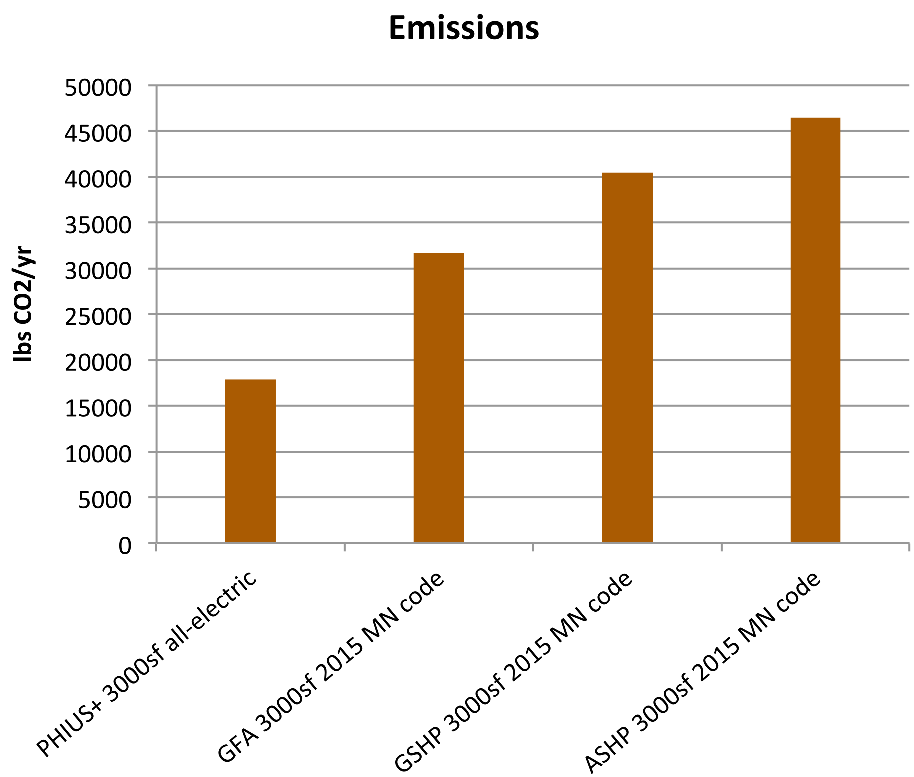
1. Compared to base case, GSHP and ASHP increase source energy slightly.
2. Compared to base case, PHIUS+ saves roughly 55% (6200 kWh x (bed + 1))



Comparison and Discussion

How do GSHP and ASHP systems compare, and what are their implications for code houses and Passive Houses? Assume GFA-based code house is "base case"

1. Compared to base case, GSHP and ASHP increase emissions significantly.
2. Compared to base case, PHIUS+ saves 45% (assuming all site energy is electric, which is worst case)



Implications for Passive House

We know the primary energy requirement is very tight. Maybe be the toughest requirement to hit without resorting to renewables. How do these systems stack up in terms of primary energy use?

Annual load x PE factor/efficiency = primary energy

Base case:
GFA system with 95AFUE, PE factor 1.09
1.09/0.95 = **1.15**

This is the ratio to beat. A lower number saves primary energy.

Implications for Passive House

We know the primary energy requirement is very tight. Maybe be the toughest requirement to hit without resorting to renewables. How do these systems stack up in terms of primary energy use?

Annual load x PE factor/efficiency = primary energy

GSHP system:
Heating COP 3.2, PE factor 3.16
3.16/3.2 = **0.99**

GSHP system will help reduce primary energy use for space heating.

Implications for Passive House

We know the primary energy requirement is very tight. Maybe be the toughest requirement to hit without resorting to renewables. How do these systems stack up in terms of primary energy use?

Annual load x PE factor/efficiency = primary energy

Ducted ASHP system:
Heating COP 2.2 (w 10% electric resistance backup), PE factor 3.16
3.16/2.2 = **1.44**

ASHP system in very cold climates will increase primary energy use for space heating.

Implications for Passive House

We know the primary energy requirement is very tight. Maybe be the toughest requirement to hit without resorting to renewables. How do these systems stack up in terms of primary energy use?

Annual load x PE factor/efficiency = primary energy

Ducted ASHP system:
Heating COP 2.8 (w 10% electric resistance backup), PE factor 3.16
3.16/2.8 = **1.13**

ASHP systems must achieve COP of 2.8 (including backup heating) to reduce primary energy use for space heating.

Implications for Passive House

We know the primary energy requirement is very tight. Maybe be the toughest requirement to hit without resorting to renewables. How do these systems stack up in terms of primary energy use?

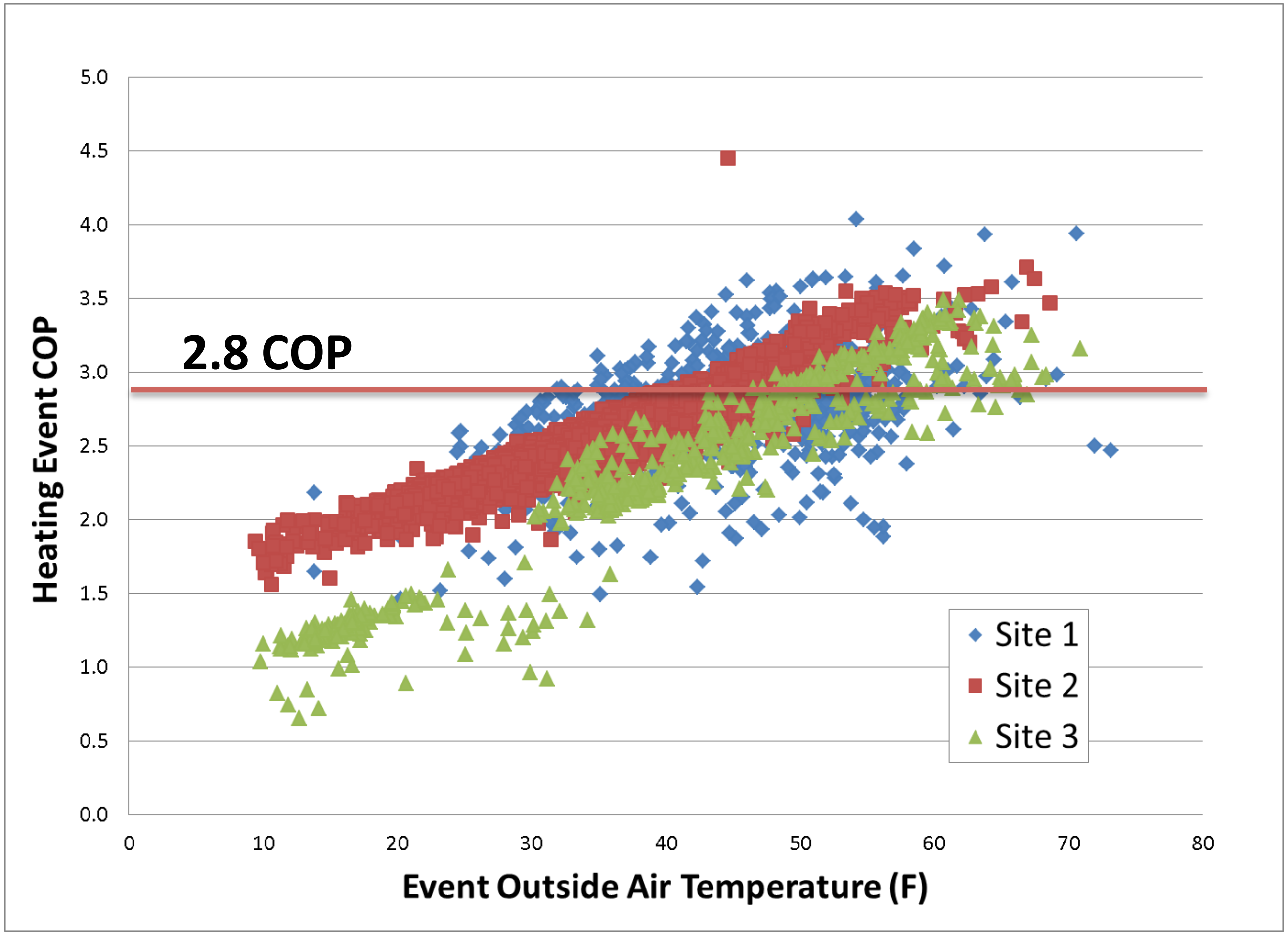
Annual load x PE factor/efficiency = primary energy

Ducted ASHP system:
Heating COP 2.8 (w 10% electric resistance backup), PE factor 3.16
3.16/2.8 = **1.13**

ASHP systems must achieve COP of 2.8 (including backup heating) to reduce primary energy compared to base case.

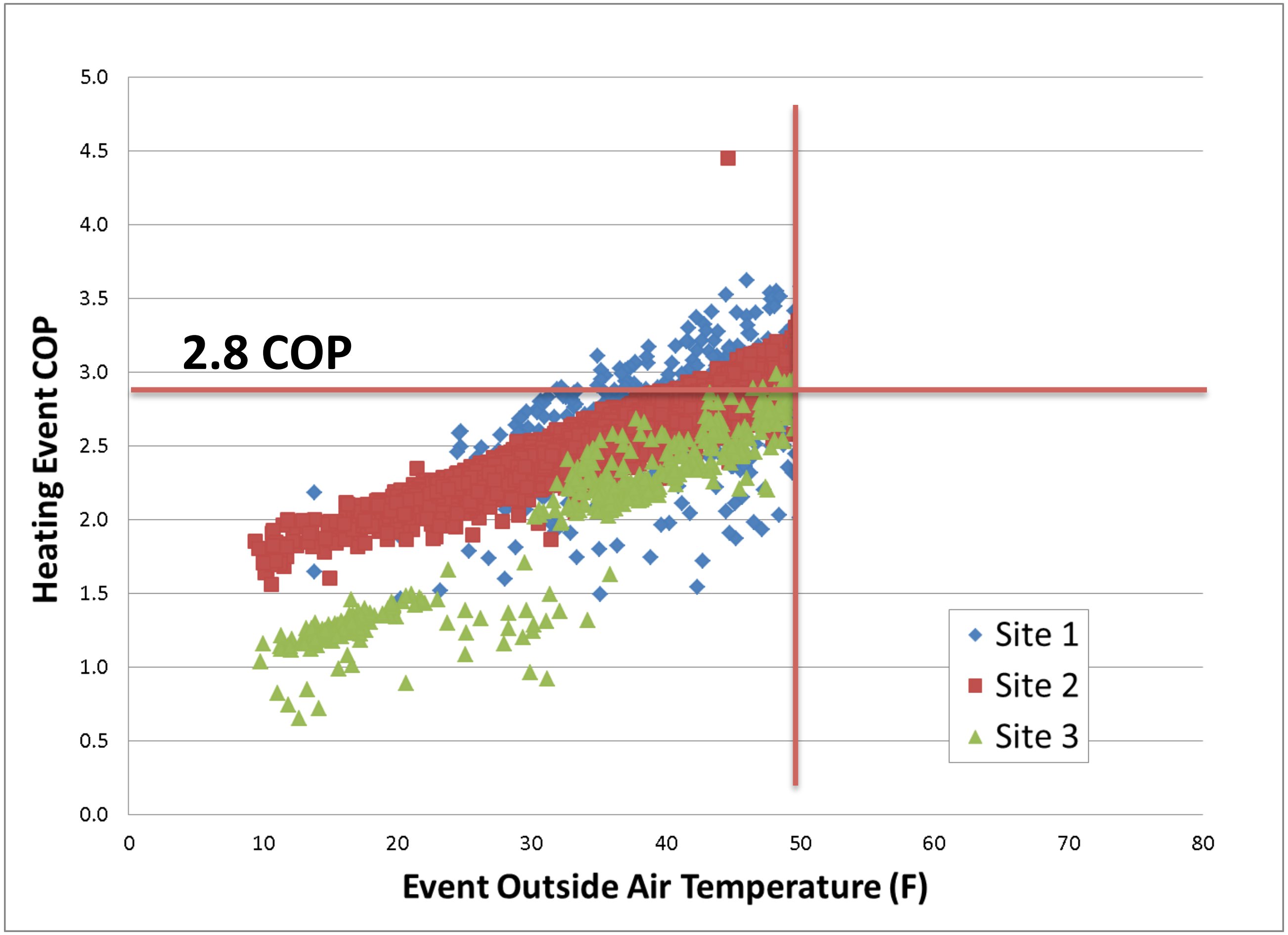
Data from CEE's monitoring on ducted cold climate ASHP suggests this may not be possible (yet) in Minnesota, or similar climate zone 6

ASHP Performance – Preliminary Data



- Rated COPs of 3.0-3.5 at 47 F
- COP observed
  - 1.5-3.5 (site 1 & 2)
  - 1-3.5 (site 3)
- 2015-2016 heating season
- Results shown with no backup, no frost-protection

ASHP Performance – Preliminary Data



- Rated COPs of 3.0-3.5 at 47 F
- COP observed
  - 1.5-3.5 (site 1 & 2)
  - 1-3.5 (site 3)
- 2015-2016 heating season
- Results shown with no backup, no frost-protection

cee

And remember that with a Passive House, the balance point is shifted lower. The vast majority of heating load will be at temperatures below 50F

GSHP - modeling

3 home sizes

2000 sf house	3000 sf house	4000 sf house
26' x 26'	31.5' x 31.5'	36.5' x 36.5'
3-bed, 2-story with conditioned basement	4-bed, 2-story with conditioned basement	5-bed, 2-story with conditioned basement
0.15 window to floor area ratio 300 sf window area equally distributed	0.15 window to floor area ratio 450 sf window area equally distributed	0.15 window to floor area ratio 600 sf window area equally distributed

GSHP - modeling

High efficiency (2015 MN Energy Code)	Values	Notes
Ceiling R-value	50.0	2015 MN Energy Code
Wall R-value	21.0	2015 MN Energy Code
Rim joist R-value	21.0	same as wall
Basement Wall R-value	15.0	2015 MN Energy Code
Slab R-value	10.0	2015 MN Energy Code
Fenestration U-factor (area-weighted avg.)	0.32	2015 MN Energy Code
Fenestration SHGC (area-weighted avg.)	0.26	approx. industry average
Airtightness (ACH@50Pa)	3.0	2015 MN Energy Code
Window-to-Floor Area Ratio	0.15	2012 IECC max
Furnace AFUE	90	2012 IECC
Air Conditioner SEER	13.0	2012 IECC
DHW ER	0.62	2012 IECC, 2015 NAECA
Ventilation Rate (cfm, continuous)	55/75/95	2015 MN Energy Code (2000/3000/4000sf)
Sensible Recovery Efficiency (%)	60.0	HRV (w separate kitchen fan)
Duct location		conditioned space
Lighting CFL percentage	80%	

3 home efficiency levels

"High efficiency" =
2015 MN energy code

GSHP - modeling

Med. efficiency (1980's MN Energy Code)	Values	Notes
Ceiling R-value	38.0	
Wall R-value	19.0	
Rim joist R-value	13.0	
Basement Wall R-value	10.0	
Slab R-value	10.0	
Fenestration U-factor (area-weighted avg.)	0.46	double clear vinyl (REM Rate library)
Fenestration SHGC (area-weighted avg.)	0.57	double clear vinyl (REM Rate library)
Airtightness (ACH@50Pa)	5,4,3	(est. rates 2000sf, 3000sf, 4000sf)
Window-to-Floor Area Ratio	0.15	
Furnace AFUE	80	
Air Conditioner SEER	10.0	
DHW ER	0.56	
Ventilation Rate (cfm, runtime)	50, 3/4/5hr	exhaust only (2000/3000/4000sf)
Sensible Recovery Efficiency (%)	0.0	no recovery
Duct location		conditioned space
Lighting CFL percentage	50%	

3 home efficiency levels

"Med. efficiency" = 1980's MN energy code

GSHP - modeling

Low efficiency (Pre-Energy Code)	Values	Notes
Ceiling R-value	24.0	7 inches cellulose
Wall R-value	11.0	insulated 2x4 wall
Rim joist R-value	11.0	same as wall
Basement Wall R-value	5.0	1 inch interior foam board
Slab R-value	0.0	carpeted slab
Fenestration U-factor (area-weighted avg.)	0.67	single wood frame w storm (REM Rate lib.)
Fenestration SHGC (area-weighted avg.)	0.65	single wood frame w storm (REM Rate lib.)
Airtightness (ACH@50Pa)	7,6,5	(est. rates 2000sf, 3000sf, 4000sf)
Window-to-Floor Area Ratio	0.15	same as other models
Furnace AFUE	70	Gas Furn Pre 1987 (REM Rate library)
Air Conditioner SEER	9.0	Cent AC Pre 1987 (REM Rate library)
DHW ER	0.55	Gas Stor 1984-87 (REM Rate library)
Ventilation Rate (cfm, runtime)	50, 3/4/5hr	exhaust only (2000/3000/4000sf)
Sensible Recovery Efficiency (%)	0.0	no recovery
Duct location		conditioned space
Lighting CFL percentage	50%	

3 home efficiency levels

"Low efficiency" = Pre-energy code with some insulation retrofit