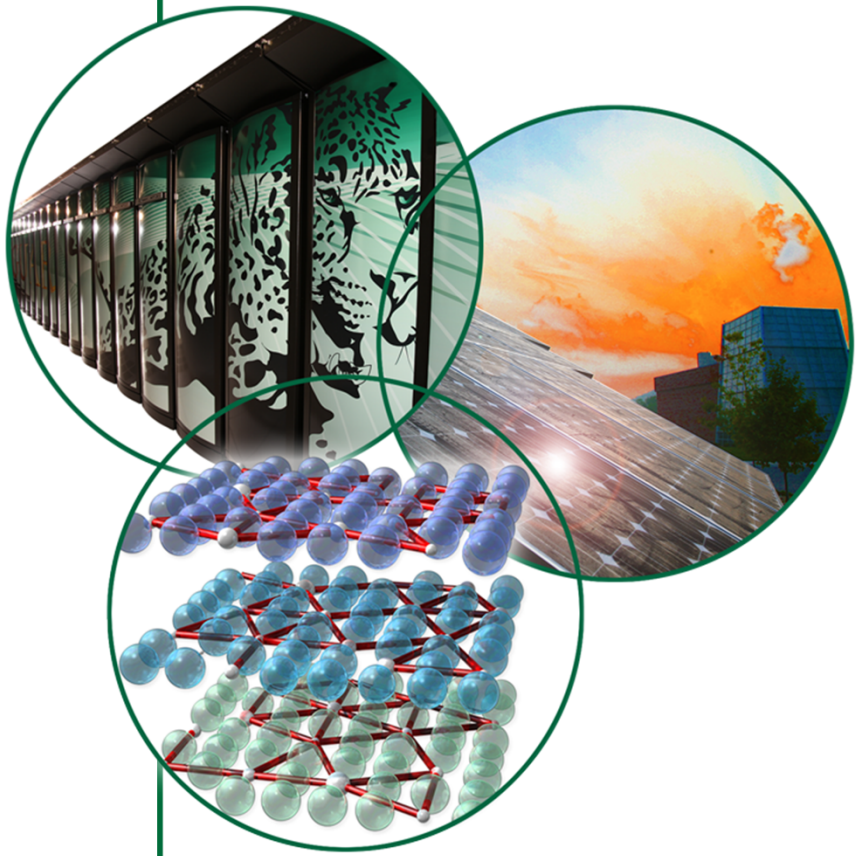
Performance Analysis of Air-Source Variable Speed Heat Pumps and Various Electric Water Heating Options

Jeffrey Munk

Oak Ridge National Laboratory



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Overview

- Electric Water Heating Options
  - Conventional Electric Water Heaters
  - Heat Pump Water Heaters
    - Air-Source
    - Ground-Source
  - Solar Thermal Water Heater
- Variable Speed Heat Pumps
  - Energy Use Analysis
  - Measured Performance
  - Operational Characteristics

Water Heating Options

- Conventional Electric Water Heaters
  - 2 simulated occupancy
- Heat Pump Water Heaters
  - 5 air-source (2 simulated occupancy, 3 real occupancy)
  - 3 ground-source (simulated occupancy)
- Solar Thermal
  - 1 system (simulated occupancy)

Water Draws for Simulated Occupancy

- Discretized version of Building America Research Benchmark 2008

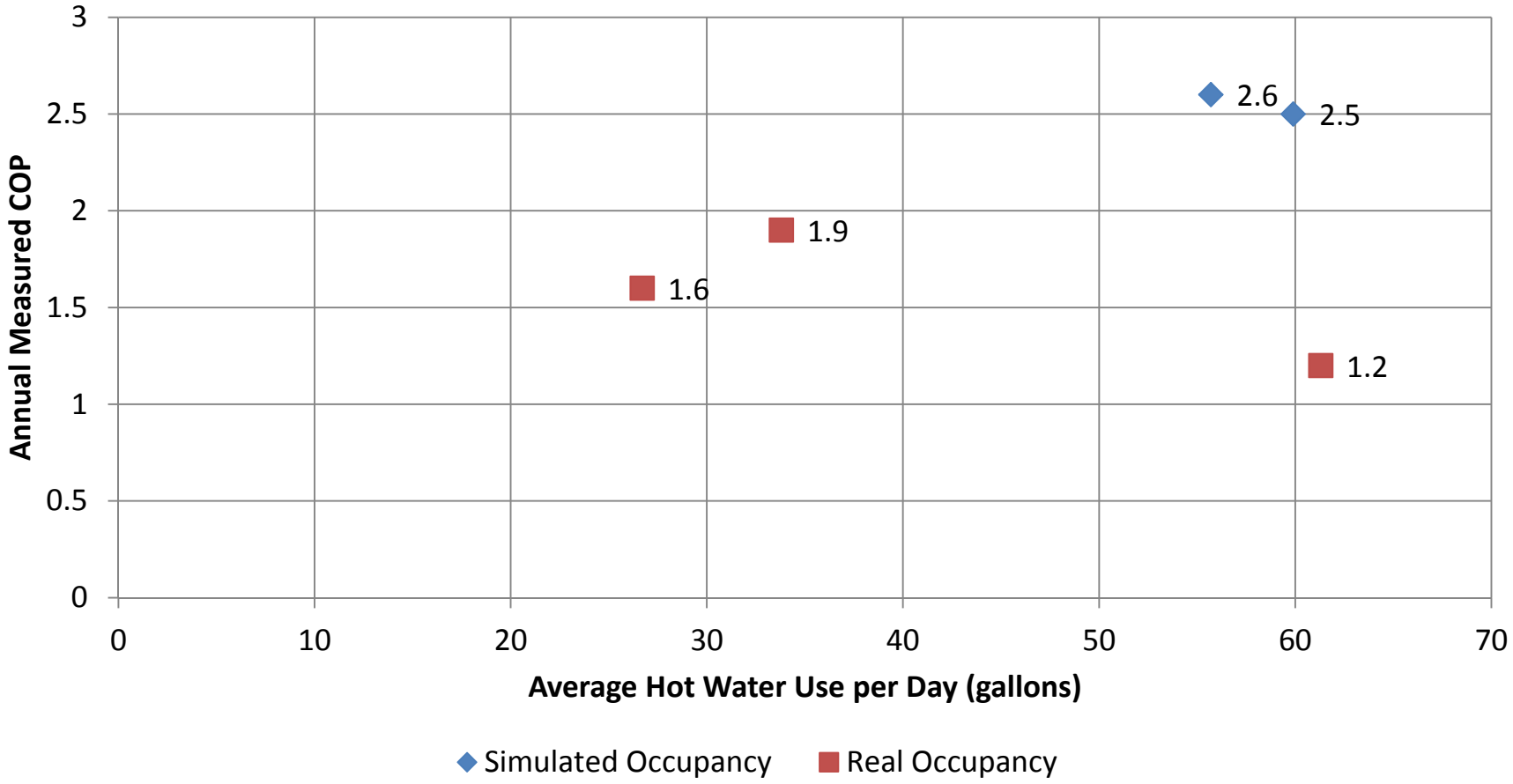
Time	Daily Shower (Mixed @105°F)	Clothes Washer	Dishwasher
7:00	20 gal	Wednesday	
8:00		Saturday and Sunday	
8:30	5 gal		
10:00		Saturday and Sunday	
12:00	5 gal		
17:00	10 gal	Wednesday	
19:30			Sunday-Friday
21:00	20 gal		

Conventional Electric Water Heaters

- Simulated Occupancy
  - WC4 HPWH in resistance mode
    - Installed inside conditioned space
    - 50 gallon tank
    - Annual COP = 0.86
  - CC1 Conventional Electric WH
    - Installed in garage
    - 50 gallon tank
    - Annual COP = 0.86

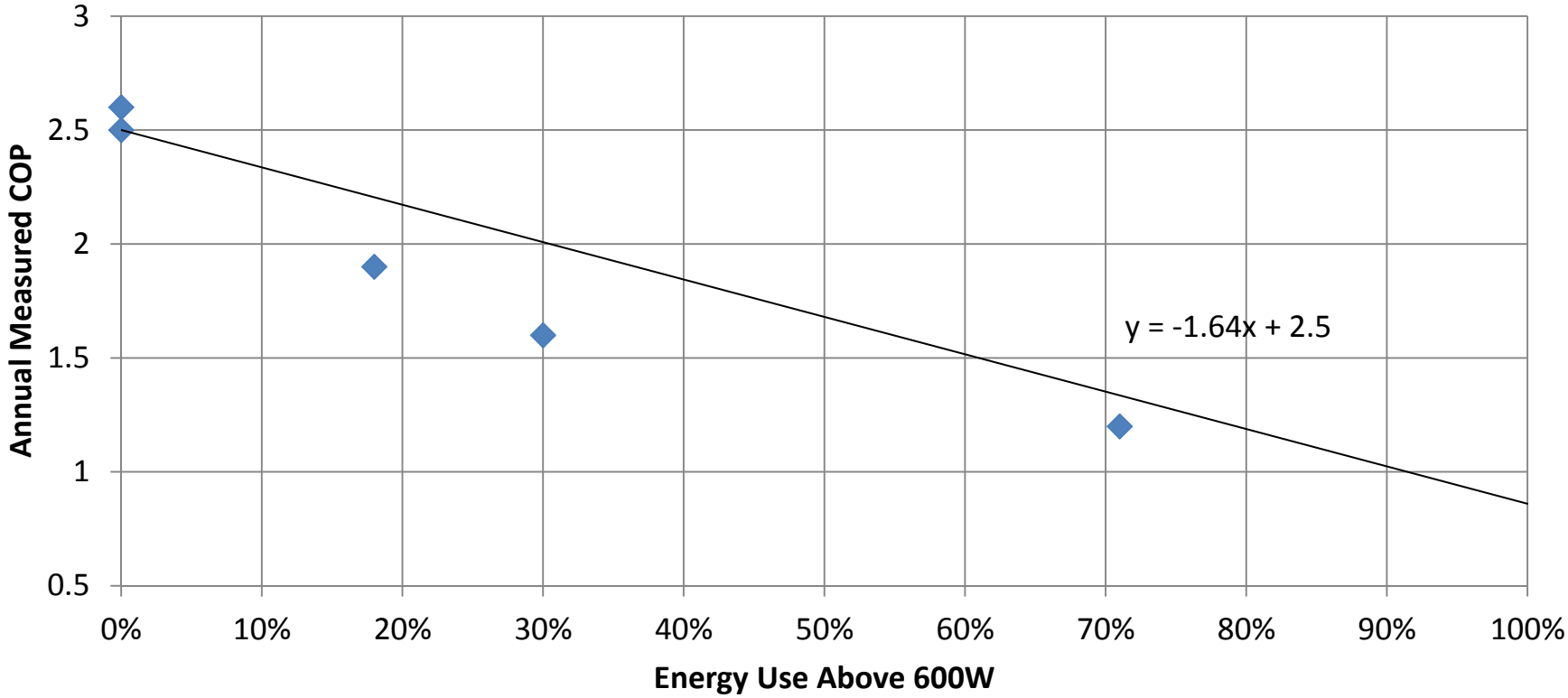
Heat Pump Water Heaters

- All the same model, at factory set point of 120°F



Heat Pump Water Heaters (cont.)

- What is driving the difference in COP?
  - Resistance Heat Use



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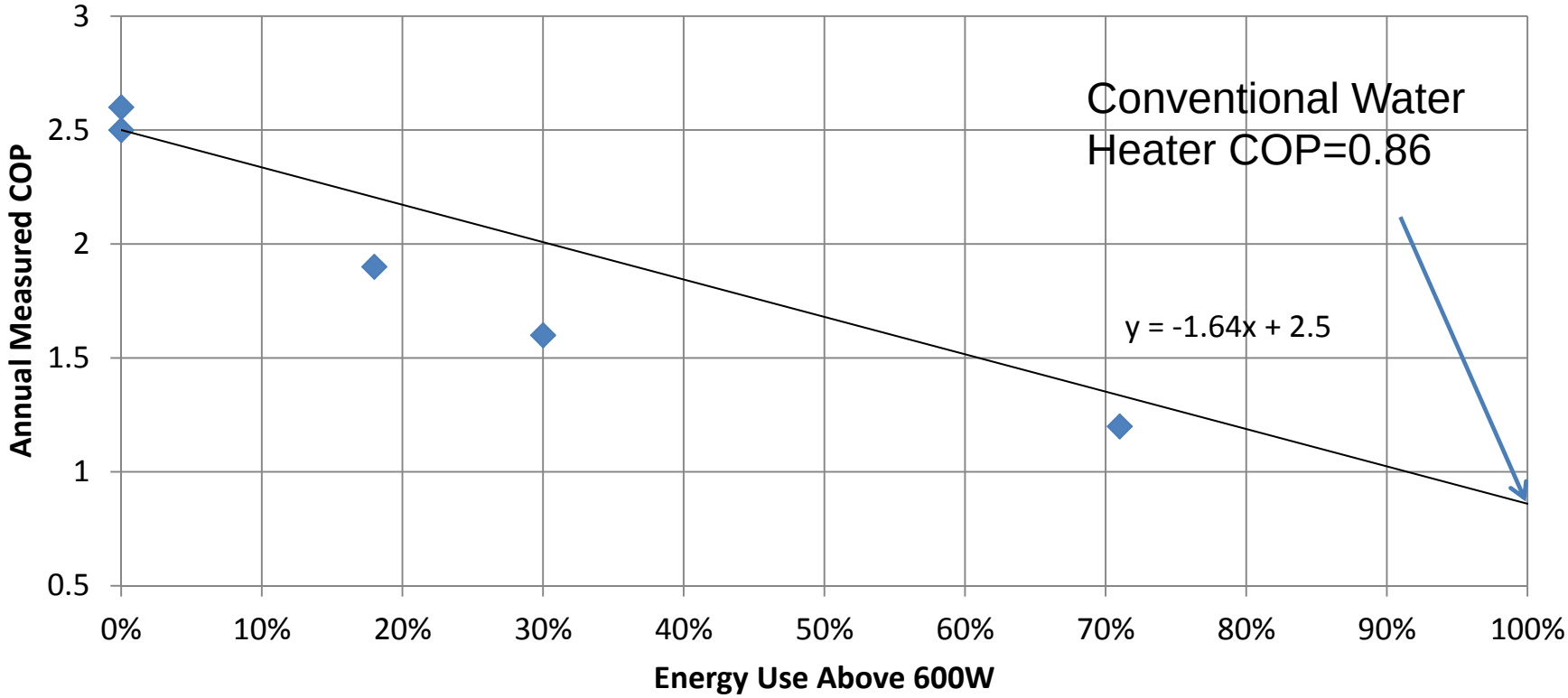

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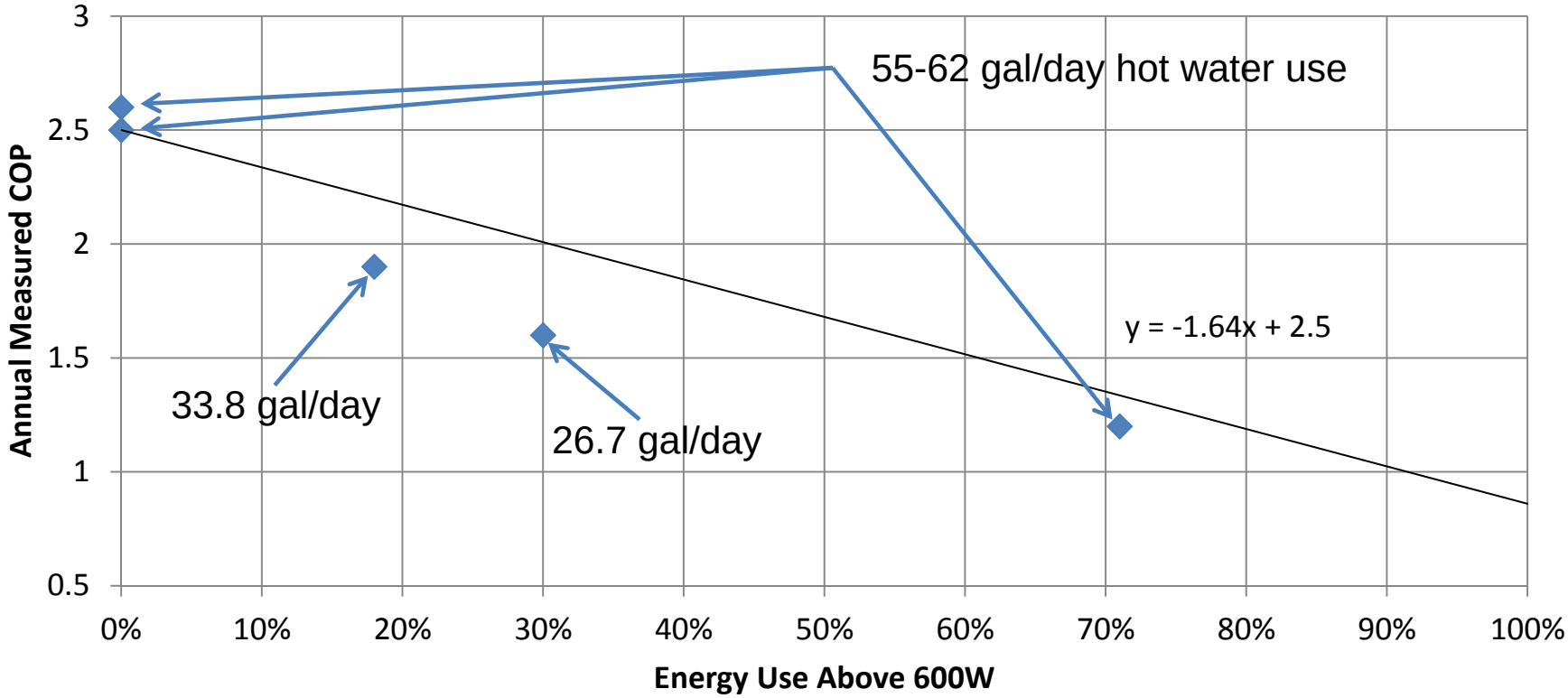
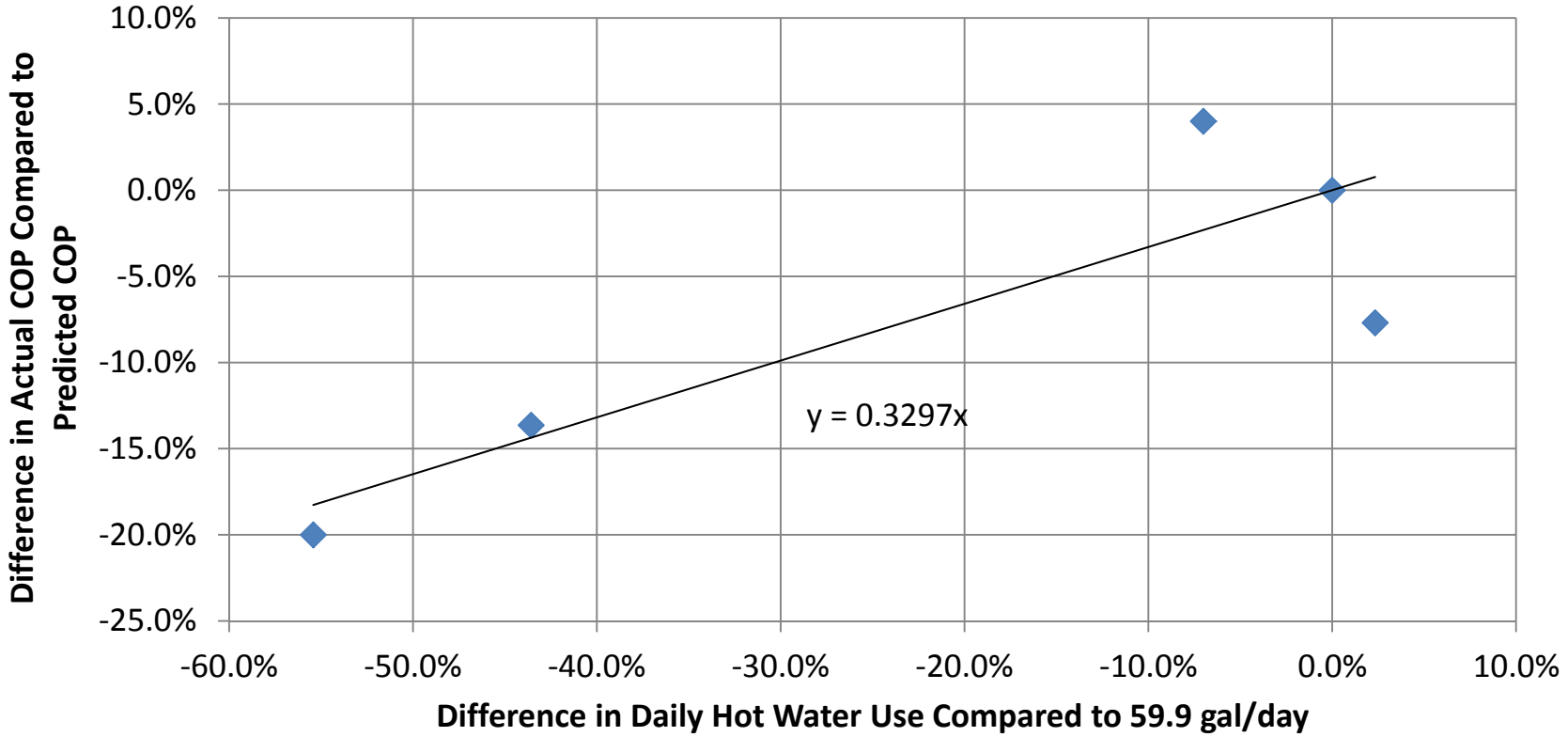


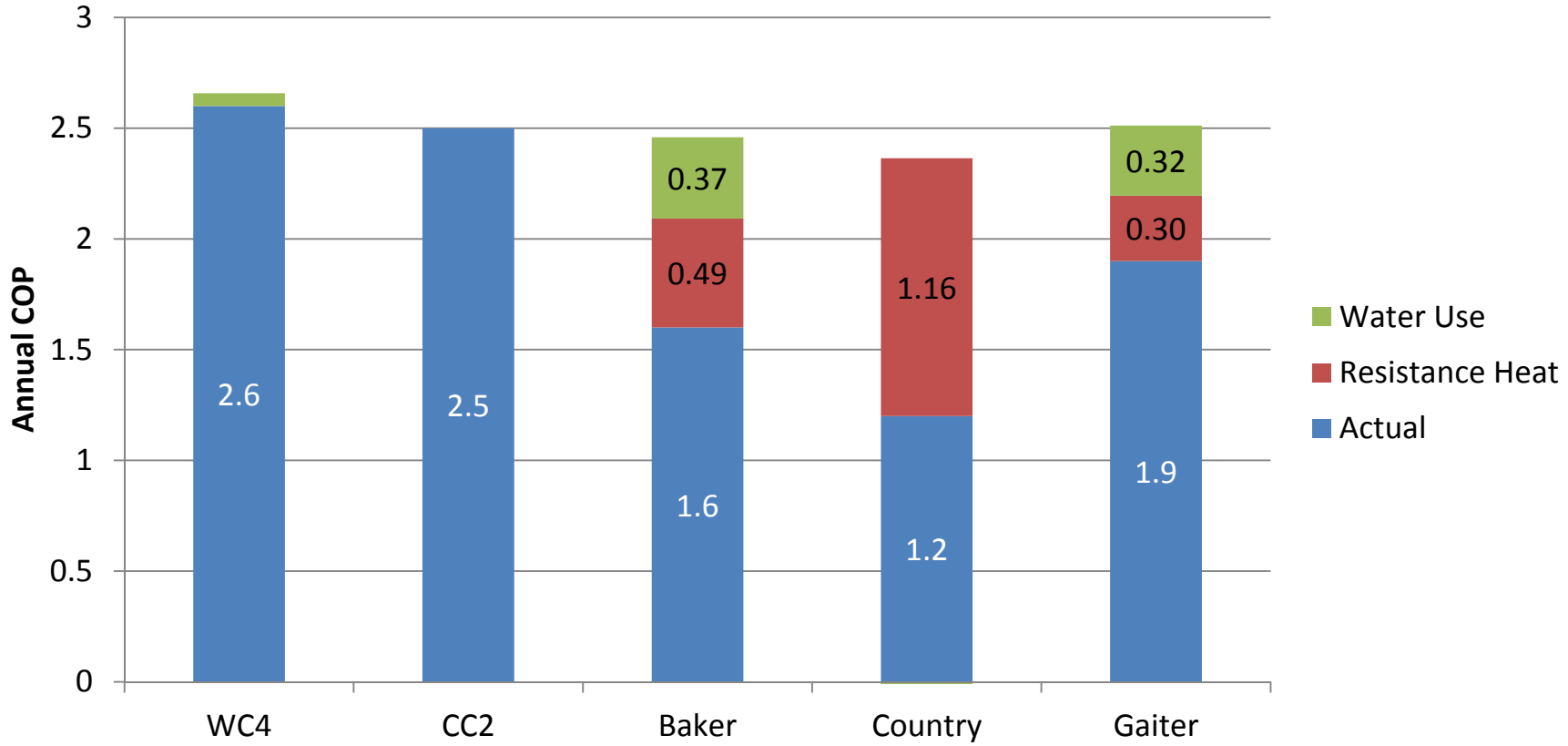
Heat Pump Water Heaters (cont.)

- What is driving the difference in COP?
  - Hot Water Use



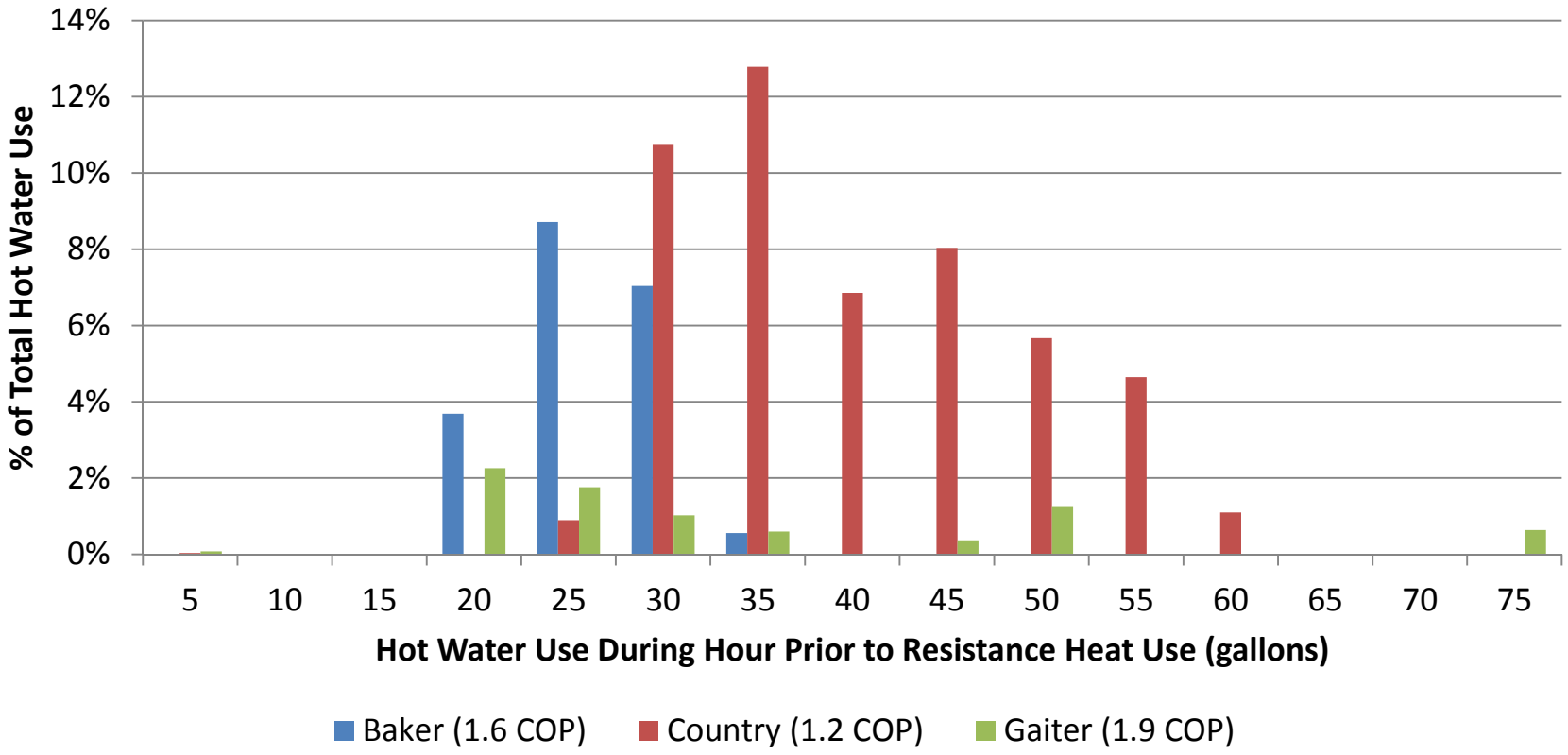
Heat Pump Water Heaters (cont.)

- What is driving the difference in COP?



Heat Pump Water Heaters (cont.)

- How much hot water needs to be drawn to trigger the resistance heat?



Heat Pump Water Heater (cont.)

- Hot Water Quality

House	Percentage of Hot Water Drawn @ less than 110°F	Percentage of Hot Water Drawn @ less than 105°F	Annual Measured COP	Avg Gallons of Hot Water Used/day
WC4	0.3%	0.1%	2.6	55.7
CC2	2.3%	1.3%	2.5	59.9
Baker	8.2%	4.2%	1.6	26.7
Country	30.1%	18.7%	1.2	61.3
Gaiter	6.2%	3.7%	1.9	33.8

Heat Pump Water Heaters

- Impact on Temperature in Surrounding Area

House	Location	Average Temp in Installed Location while Heating (°F)	Average Temp in Installed Location while Off (°F)	Annual Measured COP
WC4	Conditioned Utility Room	66.5	72.5	2.6
CC2	Unconditioned Garage	66.4	68.6	2.5
Baker (only 10 months of data)	Conditioned Basement	69.3	69.9	1.6
Country	Conditioned Basement	65.3	65.7	1.2
Gaiter	Unconditioned Basement	61.7	65.6	1.9

Ground-Source Water-to-Water HPs

House	Loop	Avg Gallons of Hot Water Used (gal/day)	Avg Entering Water Temperature (°F)	Annual Equipment COP	Annual System COP
WC1	Horizontal	56.7	59.8	3.1	2.3
WC2	Horizontal	54.4	57.7	2.6	2.0
WC3	Vertical	56.6	58.7	2.9	2.1

- Equipment COP = $m*c_p*(T_{out} - T_{in})_{Equipment}$/Runtime Energy
- System COP = $m*c_p*(T_{out} - T_{in})_{Tank}$/Total Energy
  - Includes standby energy use ~15W or 350 Wh/day, ~10-15%
  - Includes tank losses, ~10%
  - Includes piping losses between tank and unit, ~2%

Solar Water Heaters

House	Occupancy	Water Heater Type	Annual Measured COP	Avg Gallons of Hot Water Used/day	Monthly Solar Fraction (Solar Heating/Total Heating)		
					Avg	Min	Max
CC3 (Lower Element Turned Down)	Simulated	56 ft^2 Flat Panel Collector	2.3	55.6	0.72	0.37	0.99
CC3 (Lower Element Set to Heat to 120°F)	Simulated	56 ft^2 Flat Panel Collector	1.5	55.6	0.50	0.15	0.93

Solar Water Heaters (cont.)

House	Percentage of Water Drawn @ less than 110°F	Percentage of Water Drawn @ less than 105°F	Annual Measured COP	Avg Gallons of Hot Water Used/day
CC3 (Lower Element Turned Down)	23.1%	10.4%	2.3	55
CC3 (Lower Element Set to Heat to 120°F)	0.6%	0.4%	1.5	55

Equipment Cost and Performance

Equipment	Approximate Installed Cost	COP Range for Knoxville, TN
Standard Electric	$600	0.86
Heat Pump Water Heater (air-source)	$1400	1.3-2.6
Heat Pump Water Heater (ground-source)	$2,500 + ground loop	2.0-2.3
Solar Thermal	$10,000	1.5-2.3

- Despite relatively wide variations in efficiency, the air-source HPWHs had the best “bang for the buck” of the equipment tested.

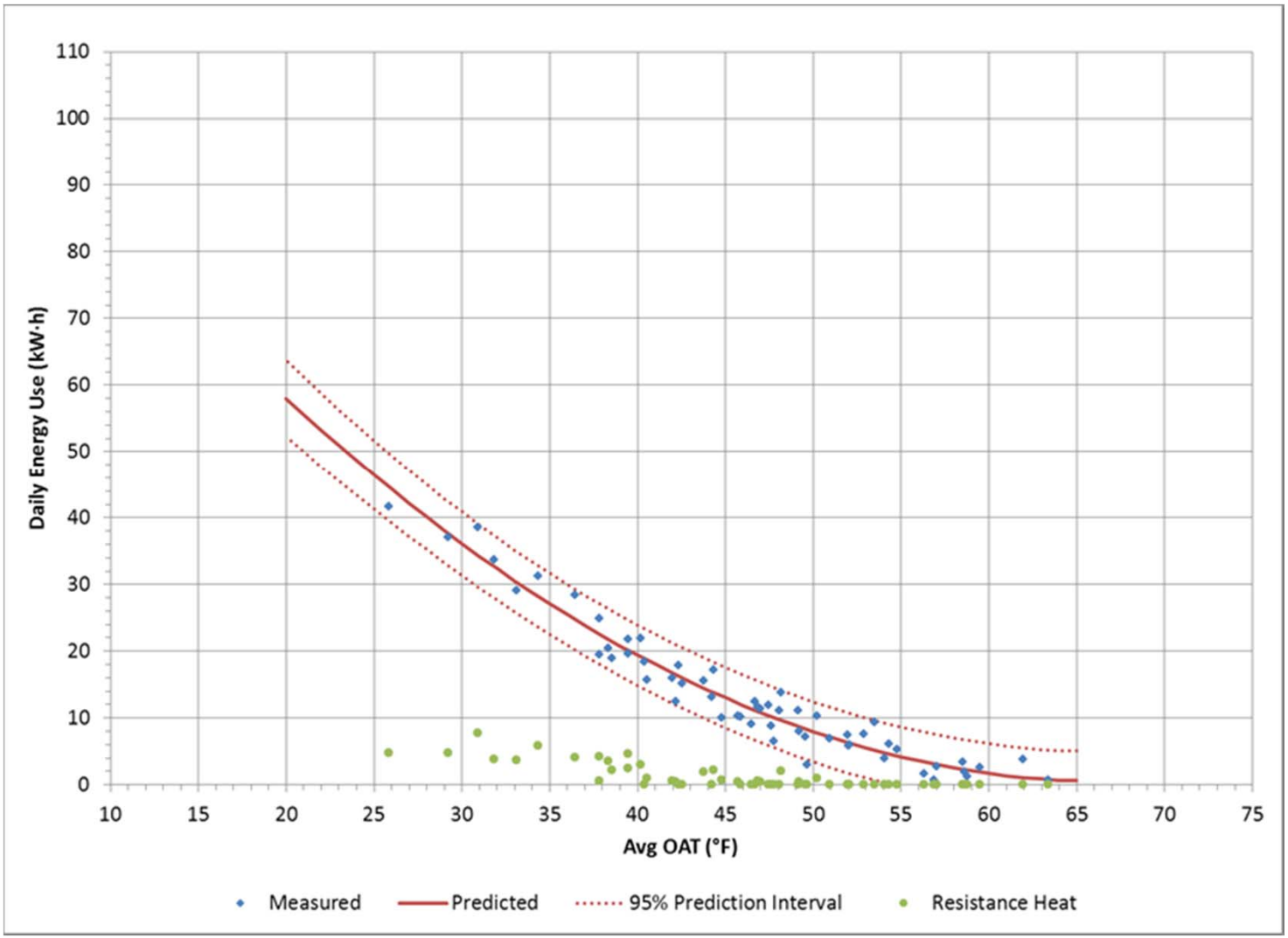
Variable Speed Heat Pumps

- 4 systems evaluated from two different manufacturers
- 2 identical systems from Manufacturer A. One installed in an occupied house (Green) and the other in an unoccupied house (CC2)
- 2 identical systems from Manufacturer B. One installed in an occupied house (Lake) and the other in an unoccupied house (CC3)

System	High Heating Capacity (Btu/h)	Region IV HSPF	Nominal Cooling Capacity (Btu/h)	Region IV SEER
Manufacturer A	33400	13.0	35000	20.5
Manufacturer B	27000	8.9	24000	18.0

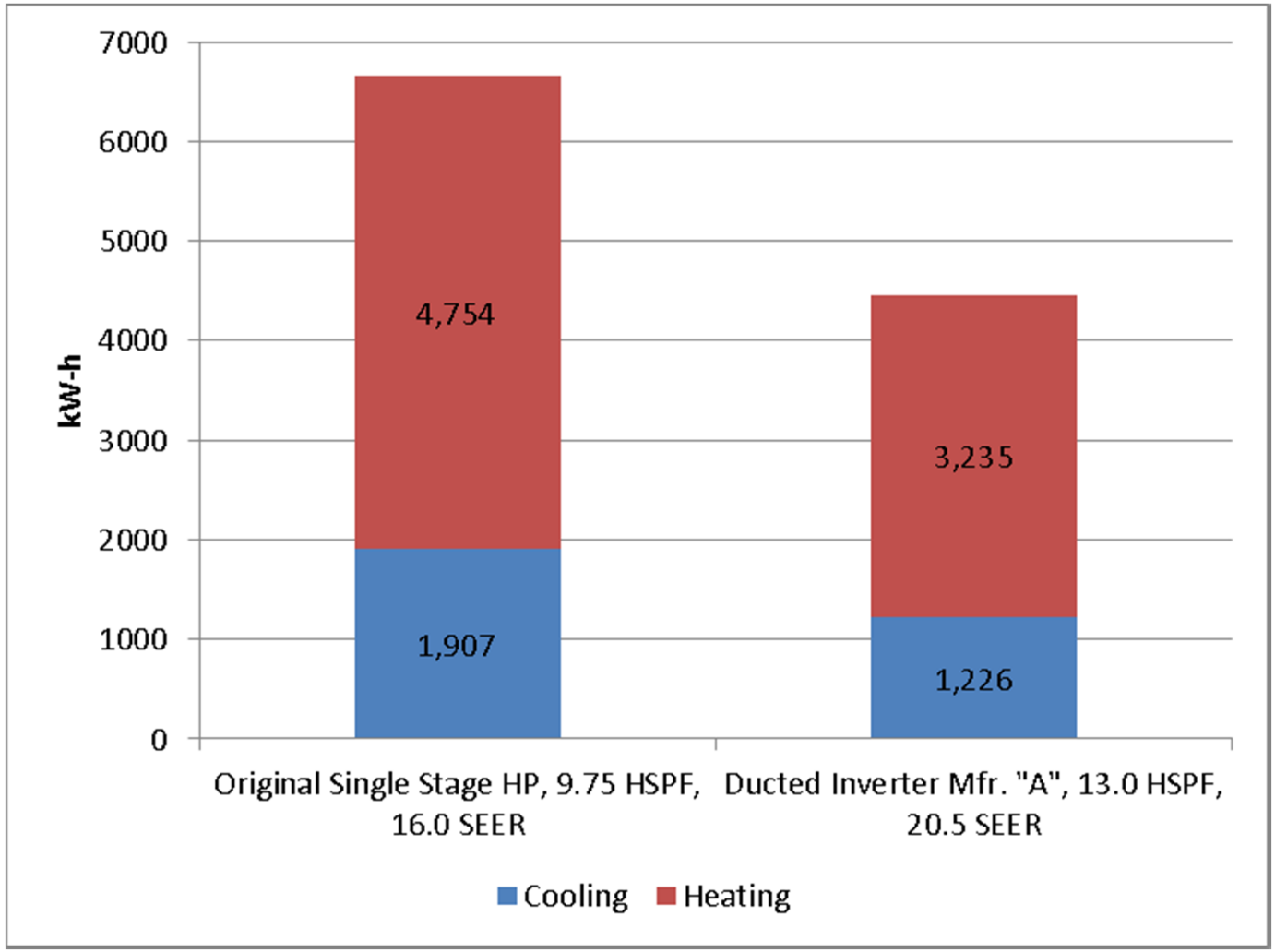
Energy Use Comparison

- Manufacturer A Heating Season



Energy Use Comparison (cont.)

- Manufacturer A TMY Energy Use Comparison



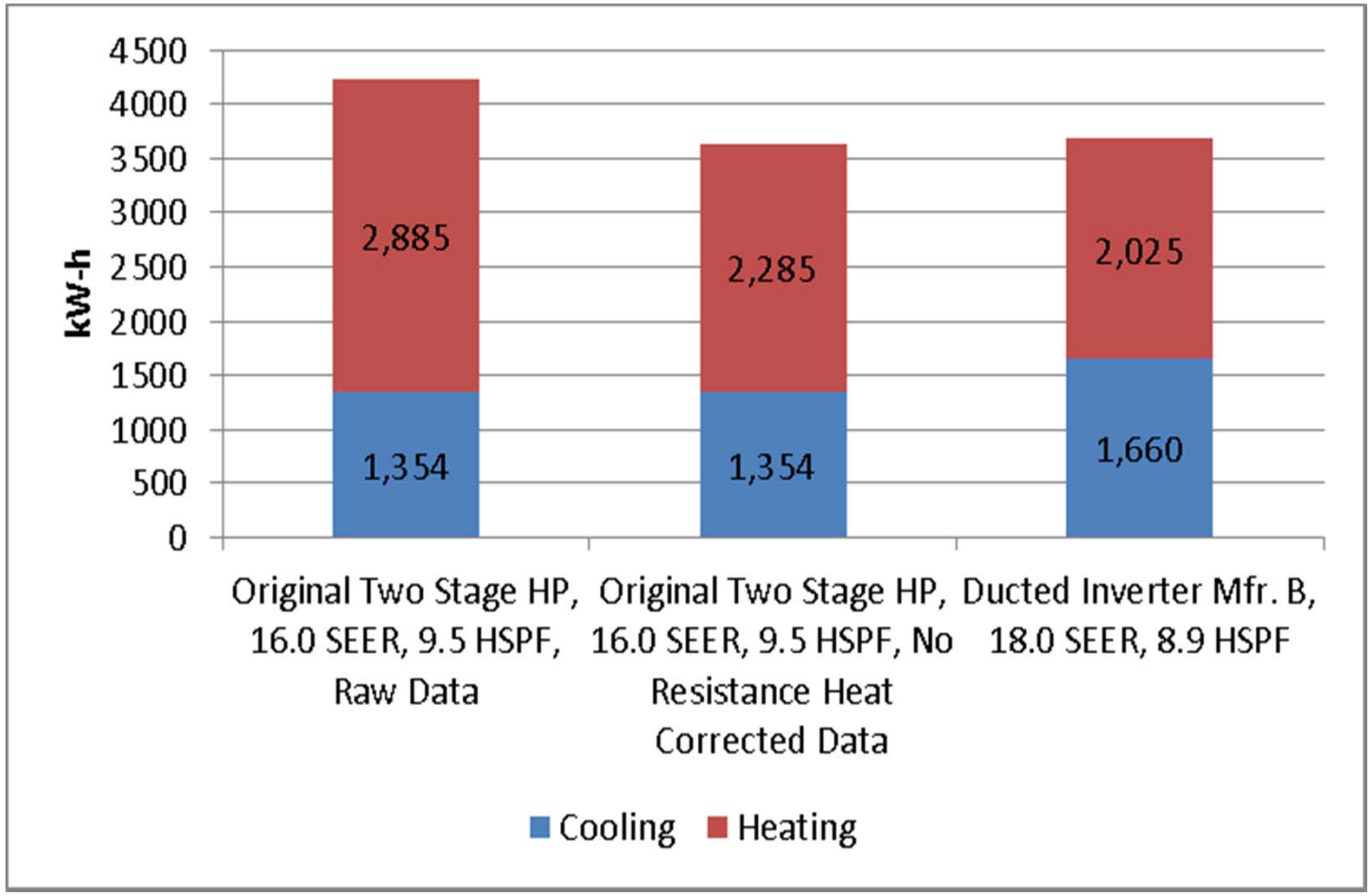
Cooling Savings
681 kWh or 36%

Heating Savings
1519 kWh or 32%

Annual Savings
2200 kWh or 33%

Energy Used Comparison (cont.)

- Manufacturer B TMY Energy Use Comparison



Cooling Penalty
306 kWh or 23%

Heating Savings
Minimum
260 kWh or 11%

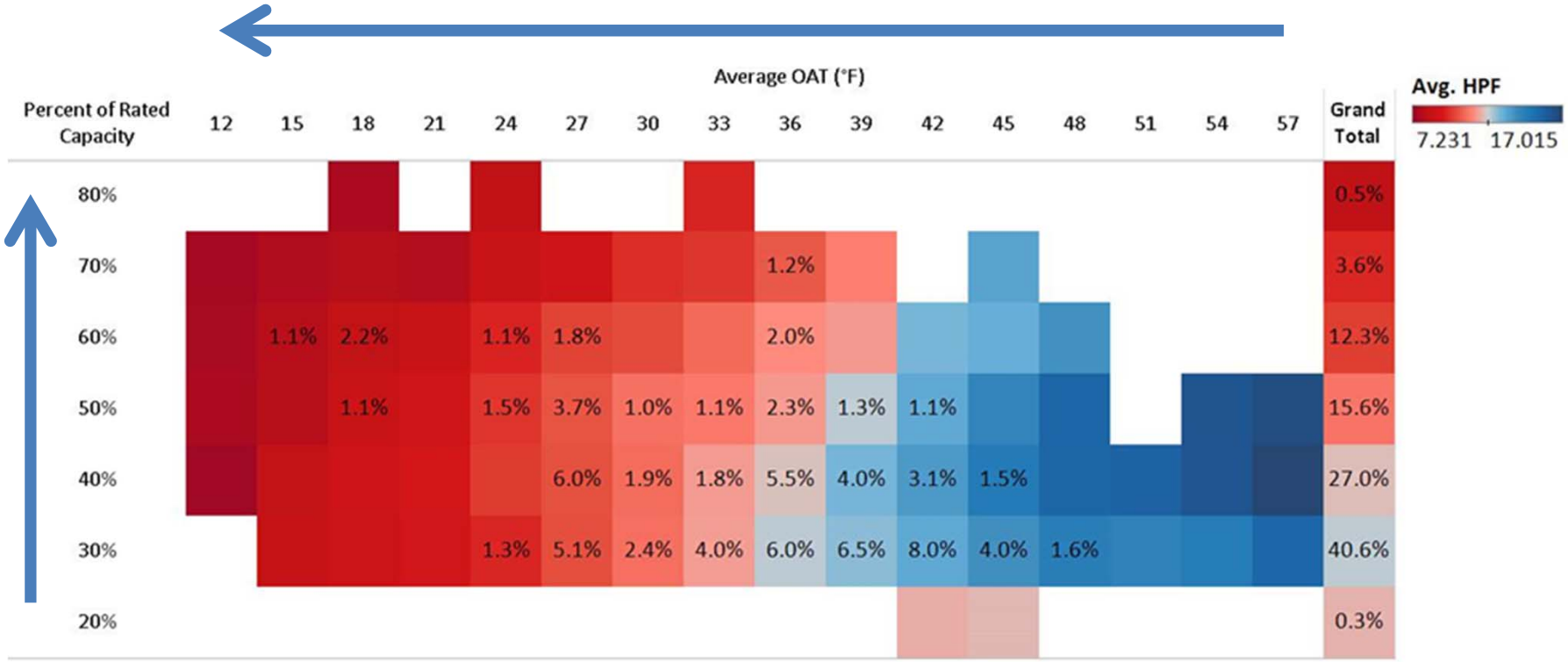
Heating Savings
Maximum
860 kWh or 30%

Heating Season Measured Efficiency

Heat Pump	Published HSPF	Average HSPF From Test Data	OAT Normalized HSPF From Test Data	% Difference of Normalized HSPF from Published HSPF	Average OAT during runtime
CC2 (Ducted Inverter A)	13.0	9.5±1.6	8.3	-36%	36.8
Green (Ducted Inverter A)	13.0	11.2	N/A	N/A	45.1

Operational Characteristics

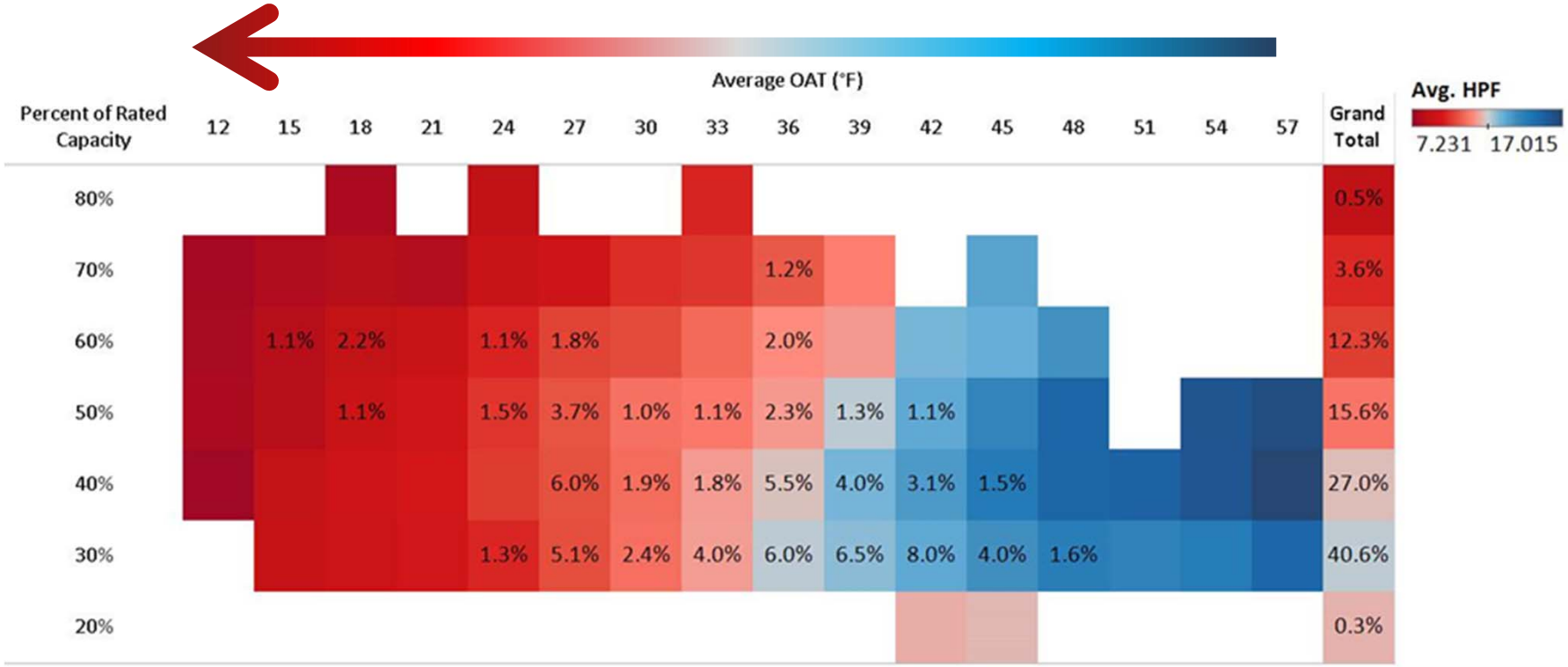
- Manufacturer A (CC2) Heating Season
  - Average capacity increases as average OAT decreases



Percent of Total Runtime in Minutes broken down by Average OAT (°F) vs. Percent of Rated Capacity. Color shows average of HPF (Btu/Wh). The marks are labeled by Percent of Total Runtime.

Operational Characteristics

- Manufacturer A (CC2) Heating Season
  - Average capacity increases as average OAT decreases
  - Efficiency decreases as OAT decreases



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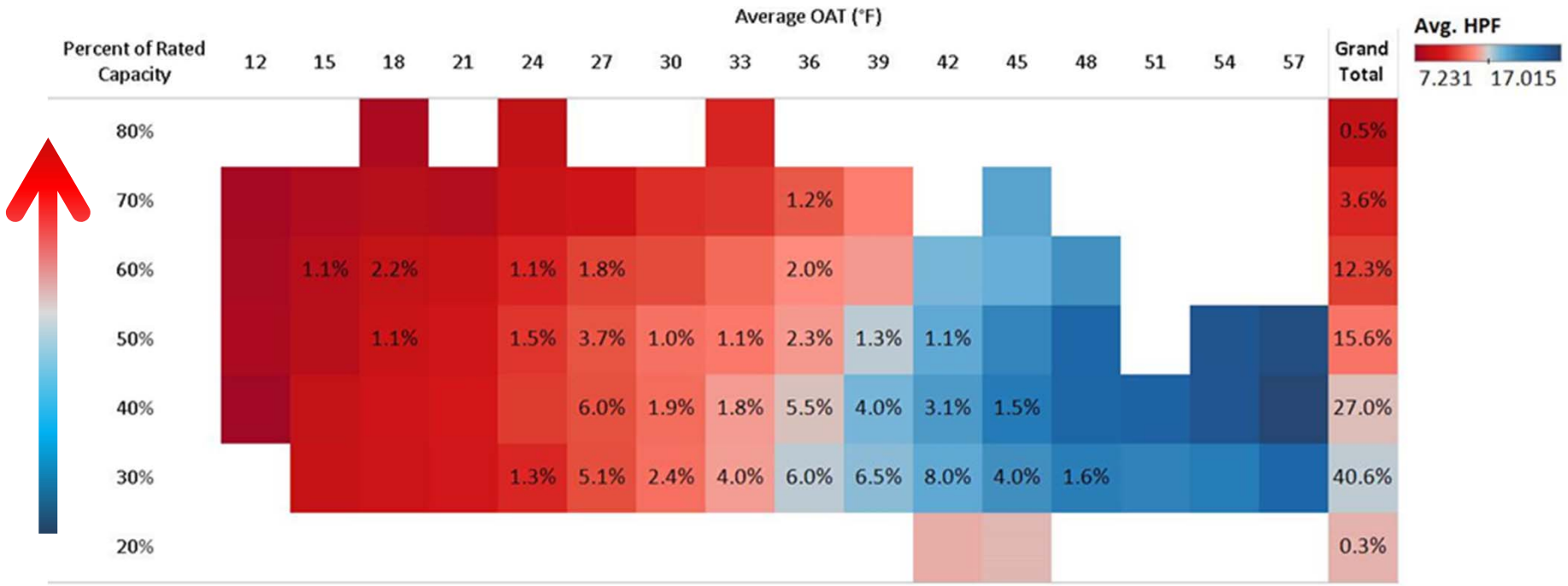
Operational Characteristics

- Manufacturer A (CC2) Heating Season
  - Average capacity increases as average OAT decreases
  - Efficiency decreases as OAT decreases
  - Efficiency decreases as capacity increases



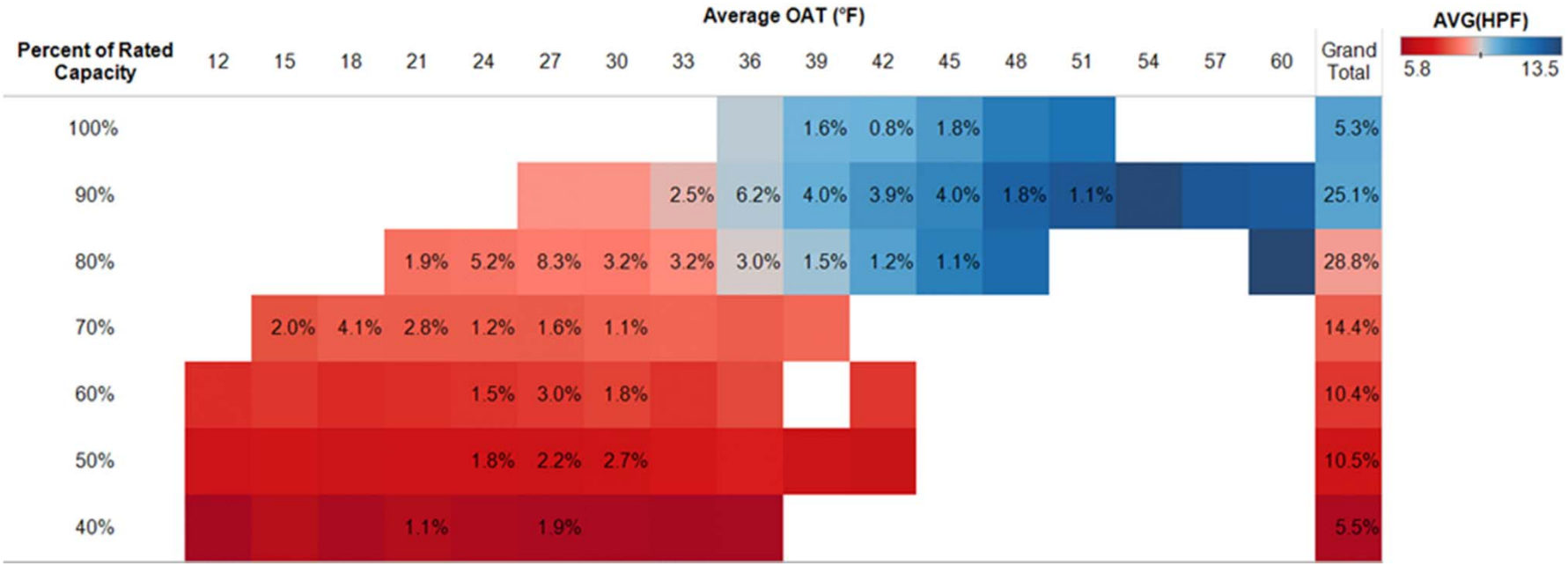
Percent of Total Runtime in Minutes broken down by Average OAT (°F) vs. Percent of Rated Capacity. Color shows average of HPF (Btu/Wh). The marks are labeled by Percent of Total Runtime.

Heating Season Measured Efficiency

Heat Pump	Published HSPF	Average HSPF From Available Test Data	OAT Normalized HSPF From Test Data	% Difference of Normalized HSPF from Published HSPF	Average OAT during runtime
CC3 (Ducted Inverter B)	8.9	8.1±1.3	7.9	-11%	33.6
Lake (Ducted Inverter B)	8.9	7.8	7.5	-16%	43.9

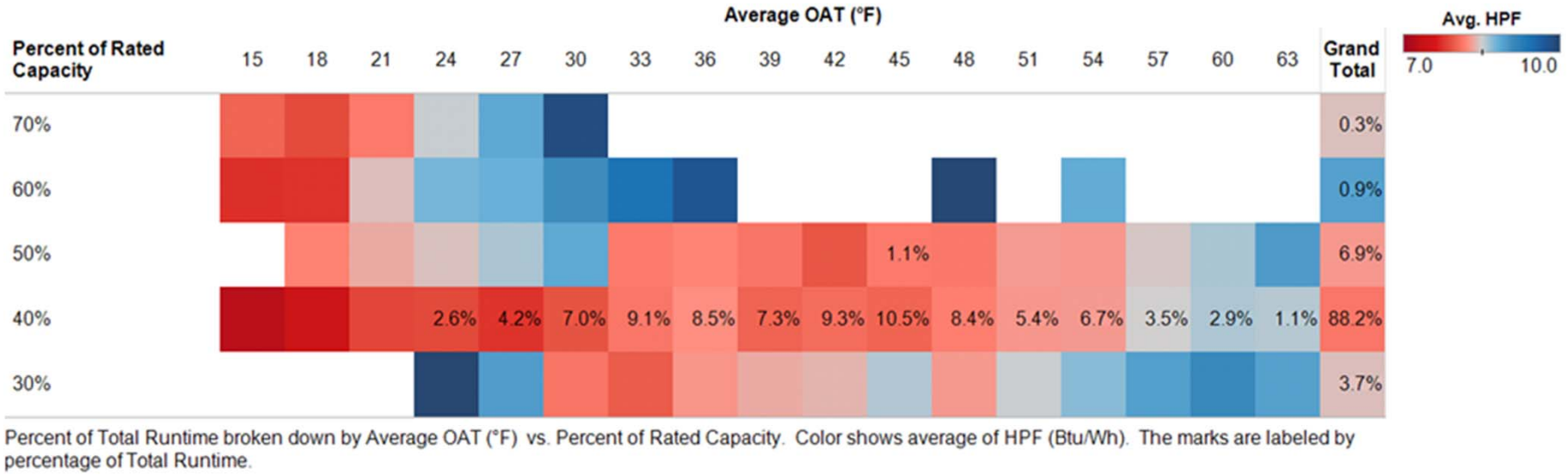
Operational Characteristics

- Manufacturer B (CC3) Heating Season
  - Average capacity decreases with OAT
  - Not as clearly
    - Efficiency decreases with OAT
    - Efficiency decreases with decreased capacity



Operational Characteristics

- Manufacturer B (Lake) Heating Season
  - Trends not as clear
  - Majority of runtime at low capacity



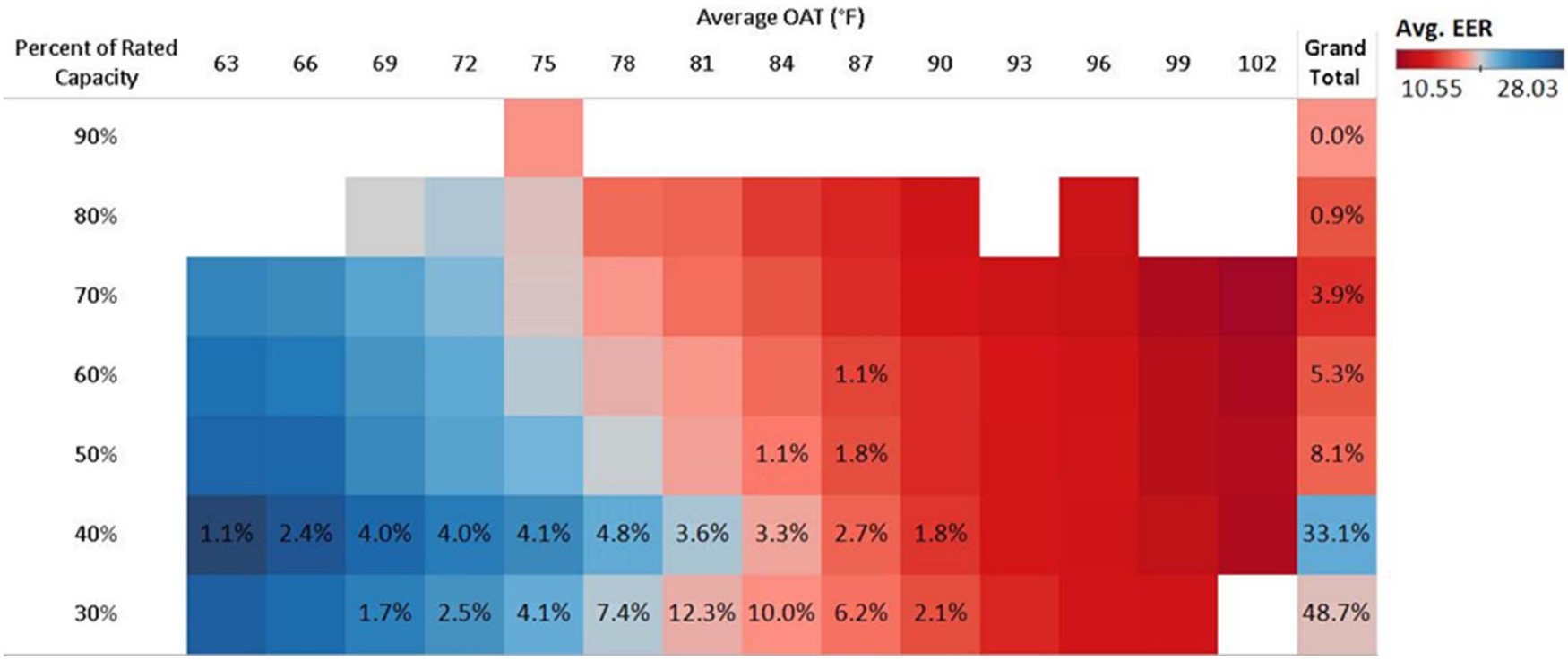
Percent of Total Runtime broken down by Average OAT (°F) vs. Percent of Rated Capacity. Color shows average of HPF (Btu/Wh). The marks are labeled by percentage of Total Runtime.

Cooling Season Measured Efficiency

Model	Published SEER	SEER Estimated From Available Test Data	OAT Normalized SEER	Diff Between Normalized SEER and Published	Average OAT while unit was cooling	Average Return Air Temp ±2σ	Average Return Air Humidity ±2σ
	(Btu/Wh)	(Btu/Wh)	(Btu/Wh)		°F	°F	%RH
CC2 (Ducted Inverter A) Overall		18.0±4.2	17.5	N/A	80.5	75.9±1.6	50%±7.7
CC2 Without RH Control	20.50	20.2±4.7	18.7	-9%	78.5	75.8±1.9	54%±3.8
CC2 With RH Control		17.2±4.0	17.2	N/A	81.3	76.0±1.5	48%±4.9
Green (Ducted Inverter A)	20.50	17.3	16.8	-18%	79.3	73.6±7.1	51%±7.7

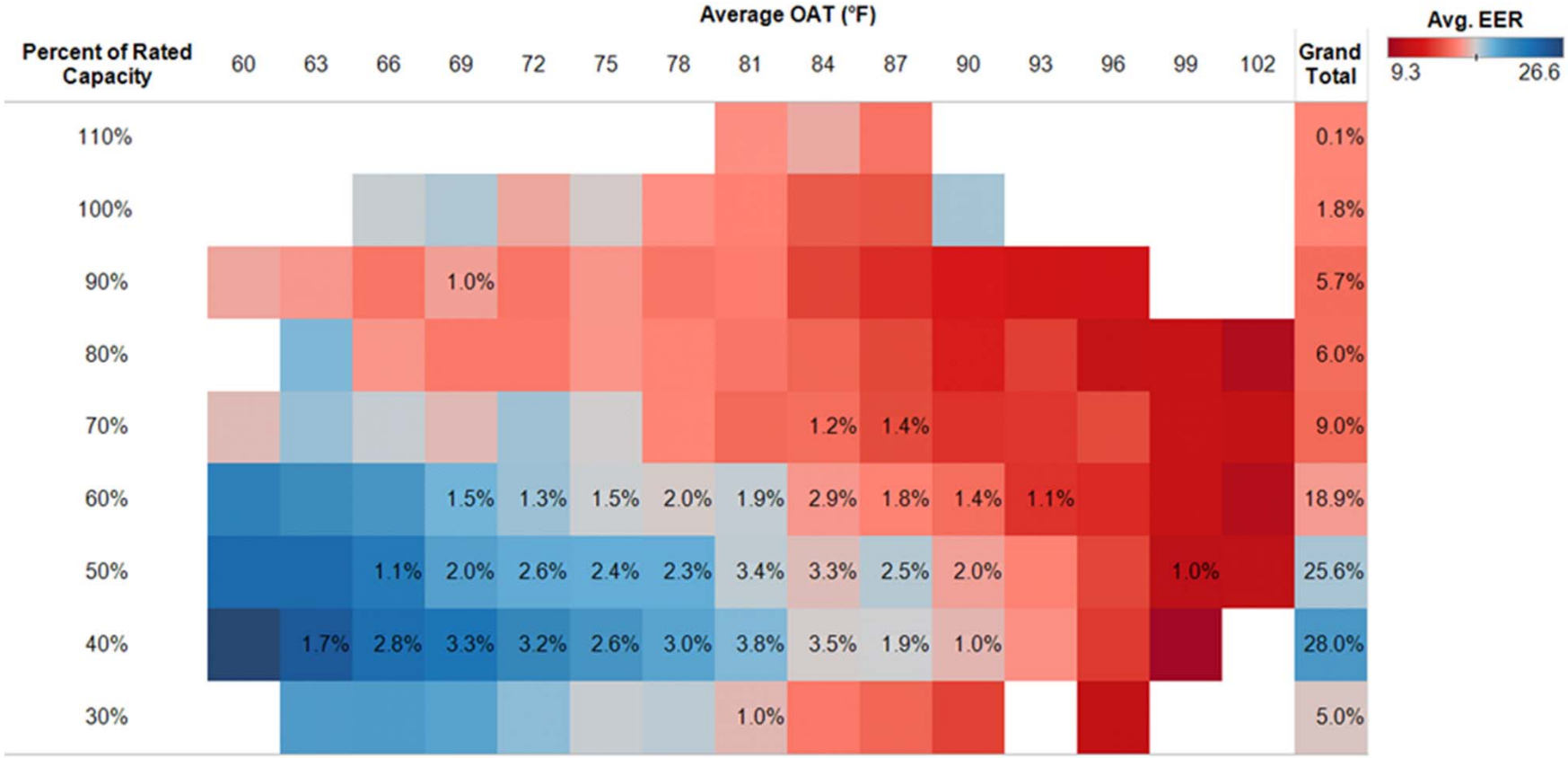
Operational Characteristics

- Manufacturer A (CC2) Cooling Season
  - Efficiency decreases as OAT increases
  - Efficiency decreases as capacity increases
  - Majority of runtime at low capacity



Operational Characteristics

- Manufacturer A (Green) Cooling Season
  - Efficiency decreases as OAT increases
  - Efficiency decreases as capacity increases



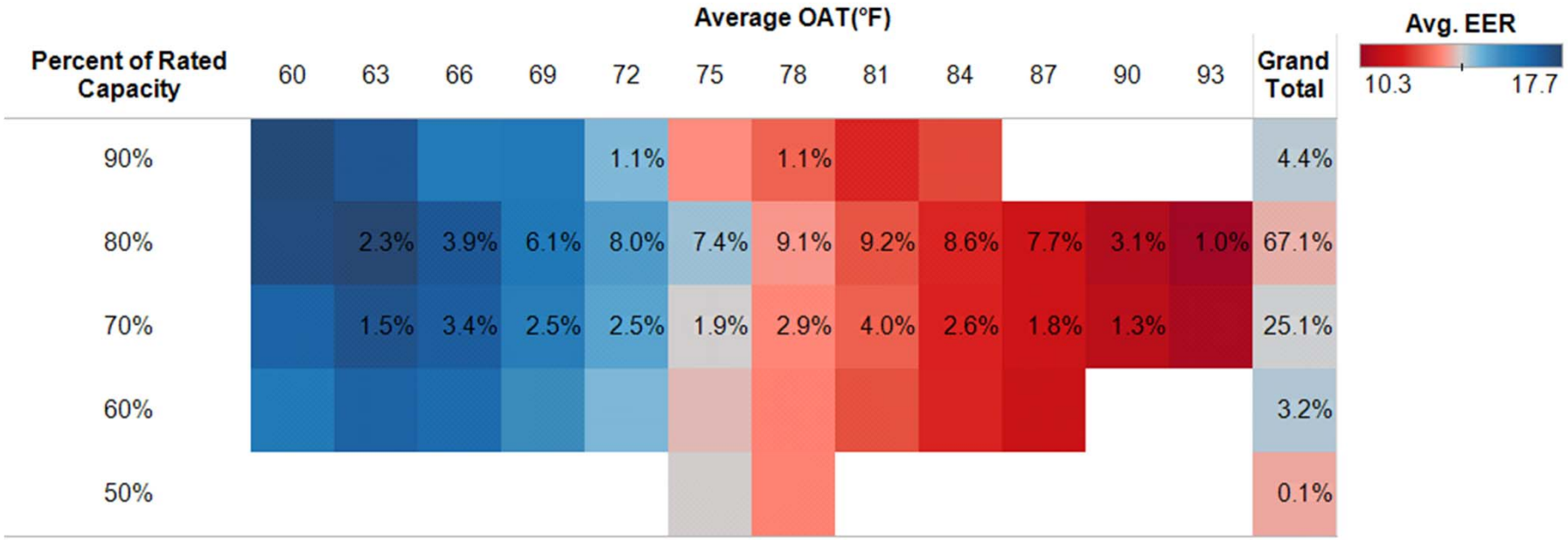
Percent of Total Runtime broken down by Average OAT (°F) vs. Percent of Rated Capacity. Color shows average of EER. The marks are labeled by % of Total Runtime.

Cooling Season Measured Efficiency

Model	Published SEER	SEER Measured From Test Data	OAT Normalized SEER	Diff Between Normalized SEER and Published	Average OAT while unit was cooling	Average Return Air Temp ±2σ	Average Return Air Humidity ±2σ
	(Btu/Wh)	(Btu/Wh)	(Btu/Wh)		°F	°F	%RH
CC3 (Ducted Inverter B)	18.00	12.0±2.6	11.4	-37%	80.0	73.9±2.1	47%±6.9
Lake (Ducted Inverter B)	18.00	16.2	15.3	-15%	80.0	74.2±4.0	57%±10.5

Operational Characteristics

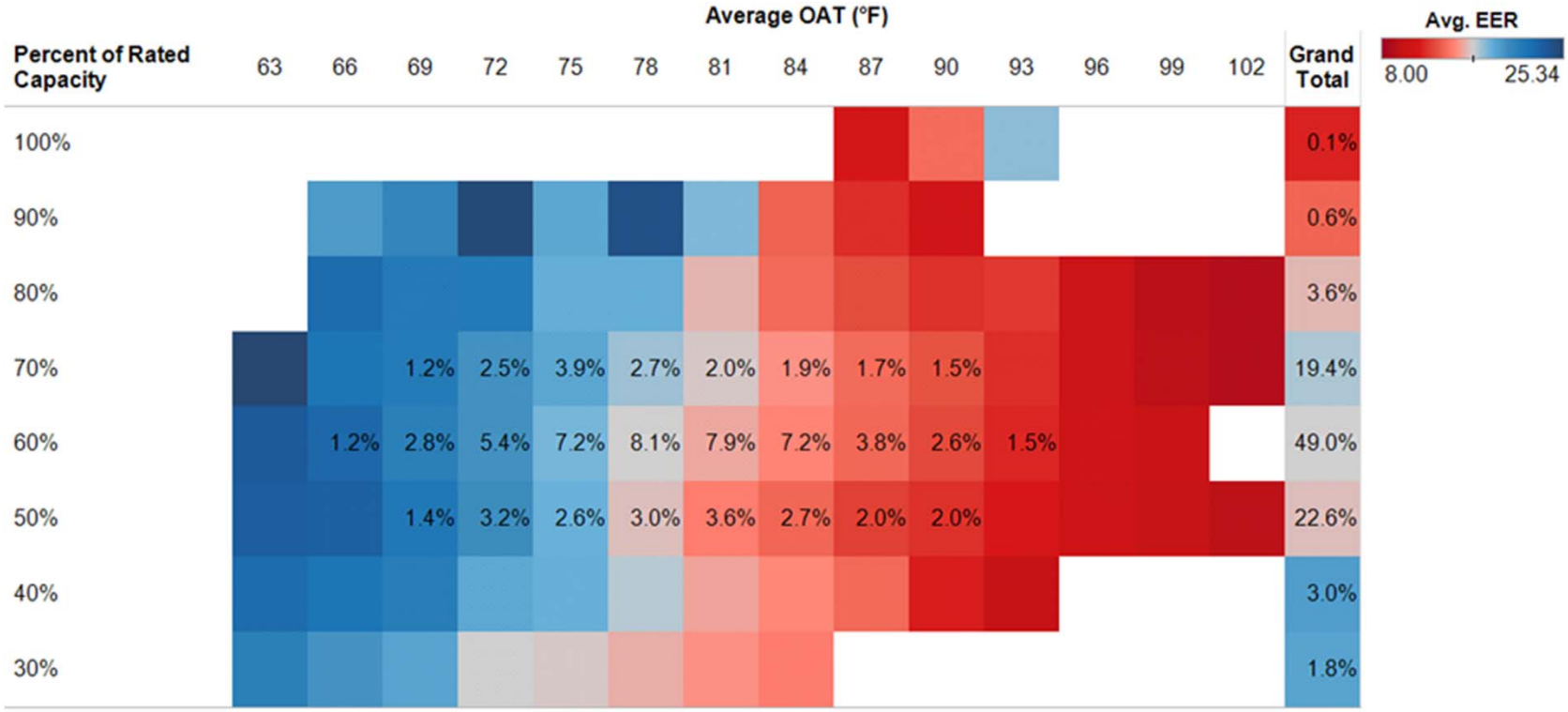
- Manufacturer B (CC3) Cooling Season
  - Efficiency decreases as OAT increases
  - Efficiency decreases as capacity decreases
  - Mostly higher capacity range runtime



Percent of Total Runtime broken down by Average OAT(°F) vs. Percent of Rated Capacity. Color shows average of EER. The marks are labeled by percentage of Total Runtime.

Operational Characteristics

- Manufacturer B (Lake) Cooling Season
  - Efficiency decreases as OAT increases
  - At OAT < 84, appears that efficiency increases as capacity increases



Percent of Total Runtime broken down by Average OAT (°F) vs. Percent of Rated Capacity. Color shows average of EER(Btu/Wh). The marks are labeled by percentage of Total Runtime.

Manufacturer A Summary

- Performed as expected for a variable speed unit
- OAT normalized HSPF was 36% lower than published, but still showed expected or better performance when compared to single speed units.
- Essentially eliminated supplemental resistance heat use in this climate
- Cooling performance was very good, nearly meeting rated SEER.
- RH control performed as expected with a modest (8%) performance penalty

Manufacturer B Summary

- Units ran defrost cycles frequently (~ every 45 min) even at relatively mild OAT (low 50's). Could be why higher capacity data with lower runtime show better efficiency.
- Efficiency trend with capacity was not always clear and sometimes opposite of expectations.
- Poor cooling performance at CC3 is believed to be due to an equipment issue causing the unit not to modulate its speed as expected.
- Unit at the Lake house showed good heating and cooling performance, within 16% of the rated SEER and HSPF

Conclusions

- Variable speed heat pumps are typically not a feasible option based purely on the economics
- Ability to significantly reduce or completely eliminate the use of resistance heat
- Some units allow homeowners more control over indoor humidity providing better comfort
- Current study is looking at the performance of variable speed heat pumps that are significantly oversized for either heating or cooling.

Questions?

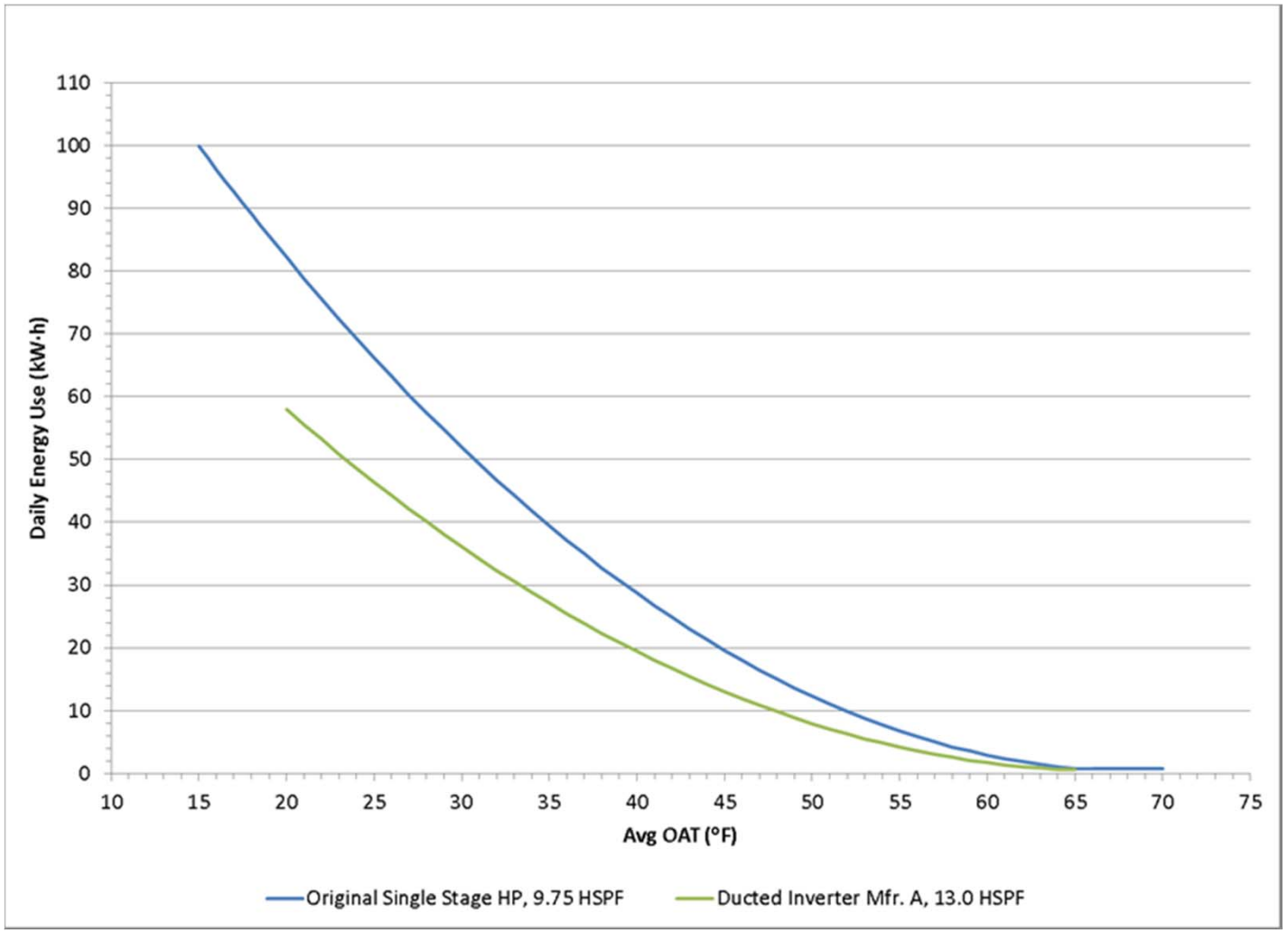
Supporting Slides

Heat Pump	Published HSPF	Average HSPF From Available Test Data	OAT Normalized HSPF From Test Data	% Difference of Normalized HSPF from Published HSPF	Average OAT during runtime	Average Return Air Temperature ±2σ	Date Range
CC1 HP1	7.7	5.6±1.0	5.1	-33%	35.9	68.4±1.8	11/1/2011 to 3/15/2012
CC1 HP2	7.7	5.9±1.0	5.4	-30%	34.7	70.3±3.2	11/1/2011 to 3/15/2012
CC2 (Ducted Inverter A)	13.0	9.5±1.6	8.3	-36%	36.8	72.0±3.0	2/6/2012 to 3/13/2012
Green (Ducted Inverter A)	13.0	11.2	N/A	N/A	45.1	68.5±3.2	3/8/2012 to 4/22/2012
CC3 (Ducted Inverter B)	8.9	8.1±1.3	7.9	-11%	33.6	71.1±2.9	1/18/2012 to 3/11/2012
Lake (Ducted Inverter B)	8.9	7.8	7.5	-16%	43.9	72.8±3.2	1/10/2012 to 3/13/2012

Model	Published SEER	SEER Estimated From Available Test Data	OAT Normalized SEER	Diff Between Normalized SEER and Published	Average OAT while unit was cooling	Average Return Air Temp ±2σ	Average Return Air Humidity ±2σ	Date Range
	(Btu/Wh)	(Btu/Wh)	(Btu/Wh)		°F	°F	%RH	
CC1 HP1	13.0	7.2±2.4	7.1	-45%	80.6	74.9±1.5	52%±5.1	5/1/2012 to 8/31/2012
CC1 HP2	13.0	8.5±2.1	8.4	-35%	78.5	77.2±2.1	46%±6.1	5/1/2012 to 8/31/2012
CC2 (Ducted Inverter A) Overall		18.0±4.2	17.5	N/A	80.5	75.9±1.6	50%±7.7	5/1/2012 to 8/31/2012
CC2 Without RH Control	20.50	20.2±4.7	18.7	-9%	78.5	75.8±1.9	54%±3.8	5/1/2012 to 6/8/2012
CC2 With RH Control		17.2±4.0	17.2	N/A	81.3	76.0±1.5	48%±4.9	6/8/2012 to 8/31/2012
Green (Ducted Inverter A)	20.50	17.3	16.8	-18%	79.3	73.6±7.1	51%±7.7	5/1/2012 to 8/31/2012
CC3 (Ducted Inverter B)	18.00	12.0±2.6	11.4	-37%	80.0	73.9±2.1	47%±6.9	4/1/2012 to 8/31/2012
Lake (Ducted Inverter B)	18.00	16.2	15.3	-15%	80.0	74.2±4.0	57%±10.5	4/8/2012 to 10/9/2012

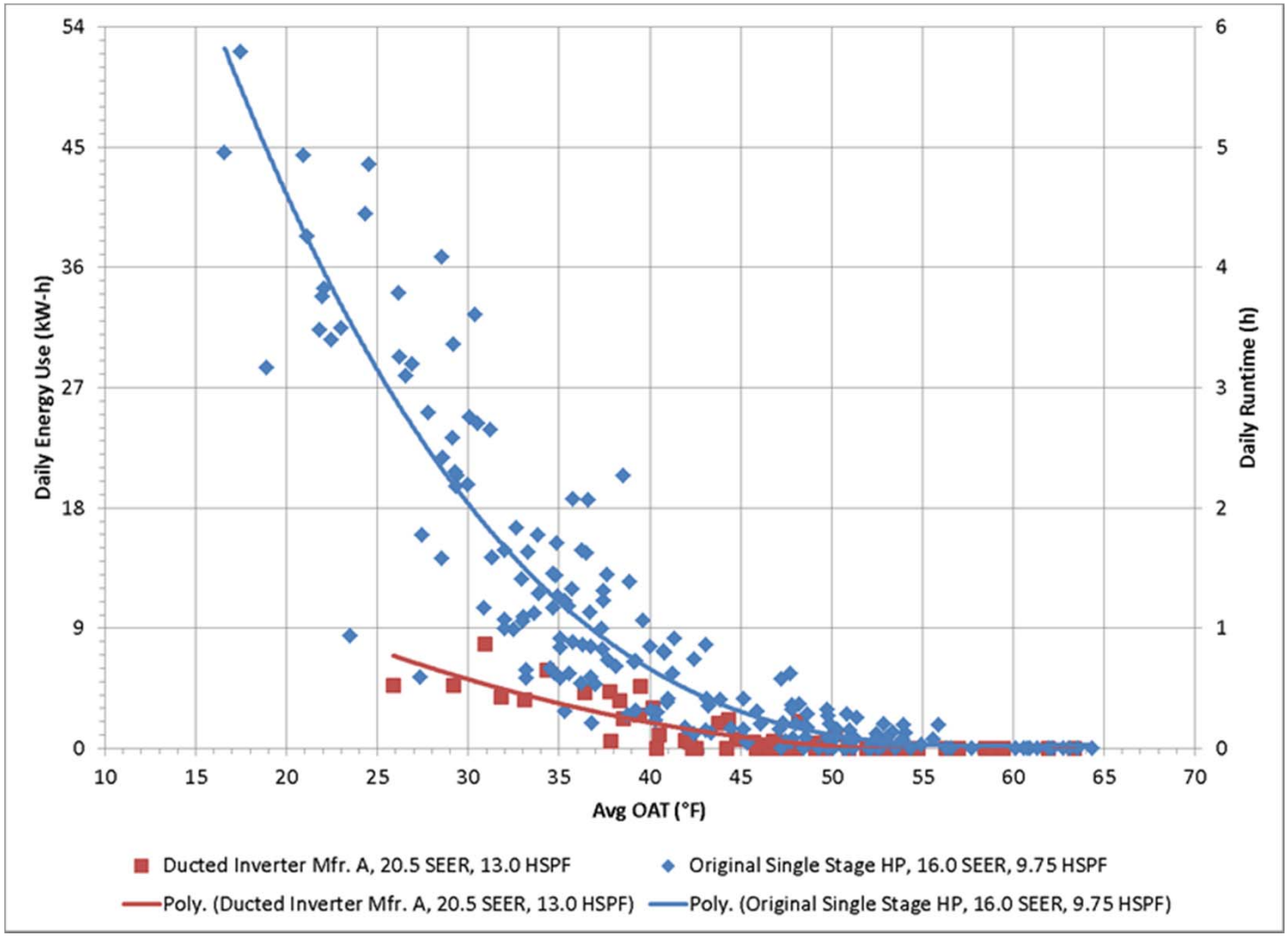
Energy Use Comparison (cont.)

- Manufacturer A Heating Season



Energy Use Comparison (cont.)

- Manufacturer A Heating Season Resistance Heat Use



Energy Use Comparison (cont.)

- Manufacturer A Cooling Season