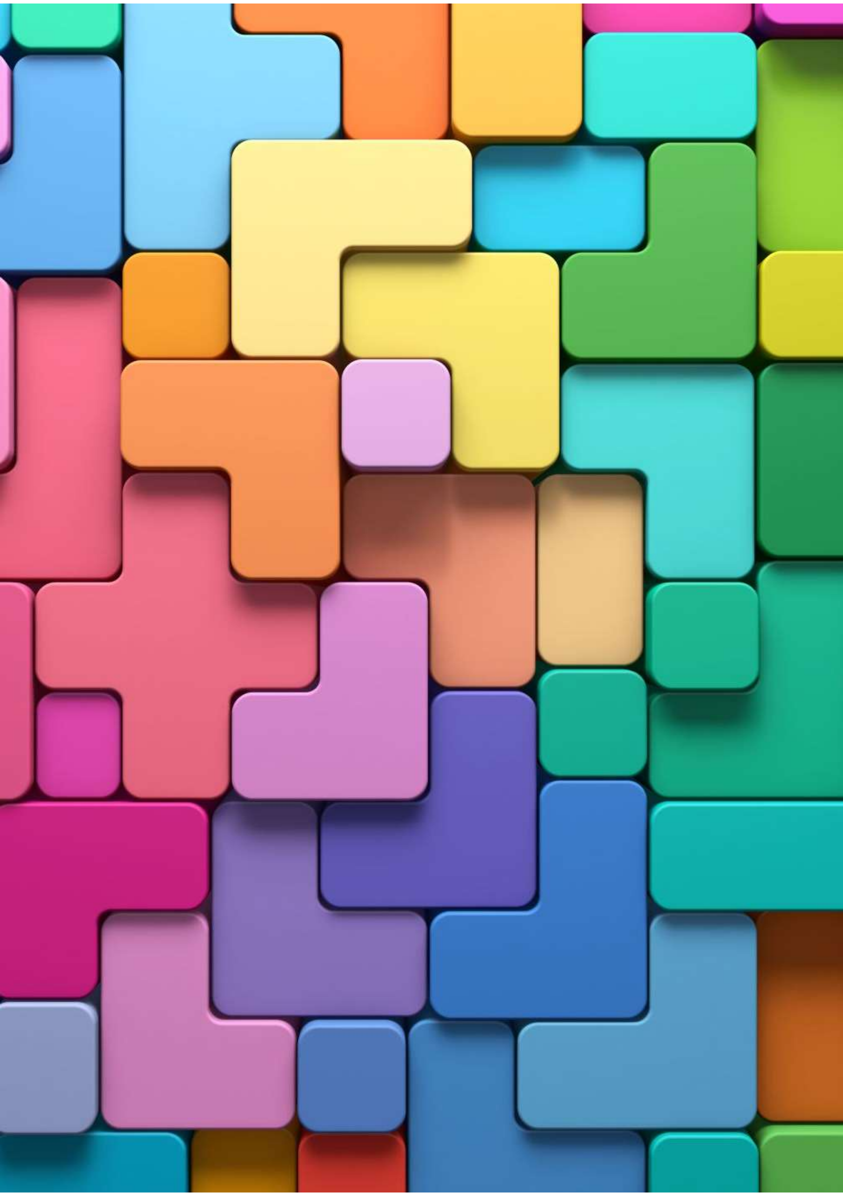

ADVANCED HEAT PUMP SAVINGS RATE MODELING

Presented by:

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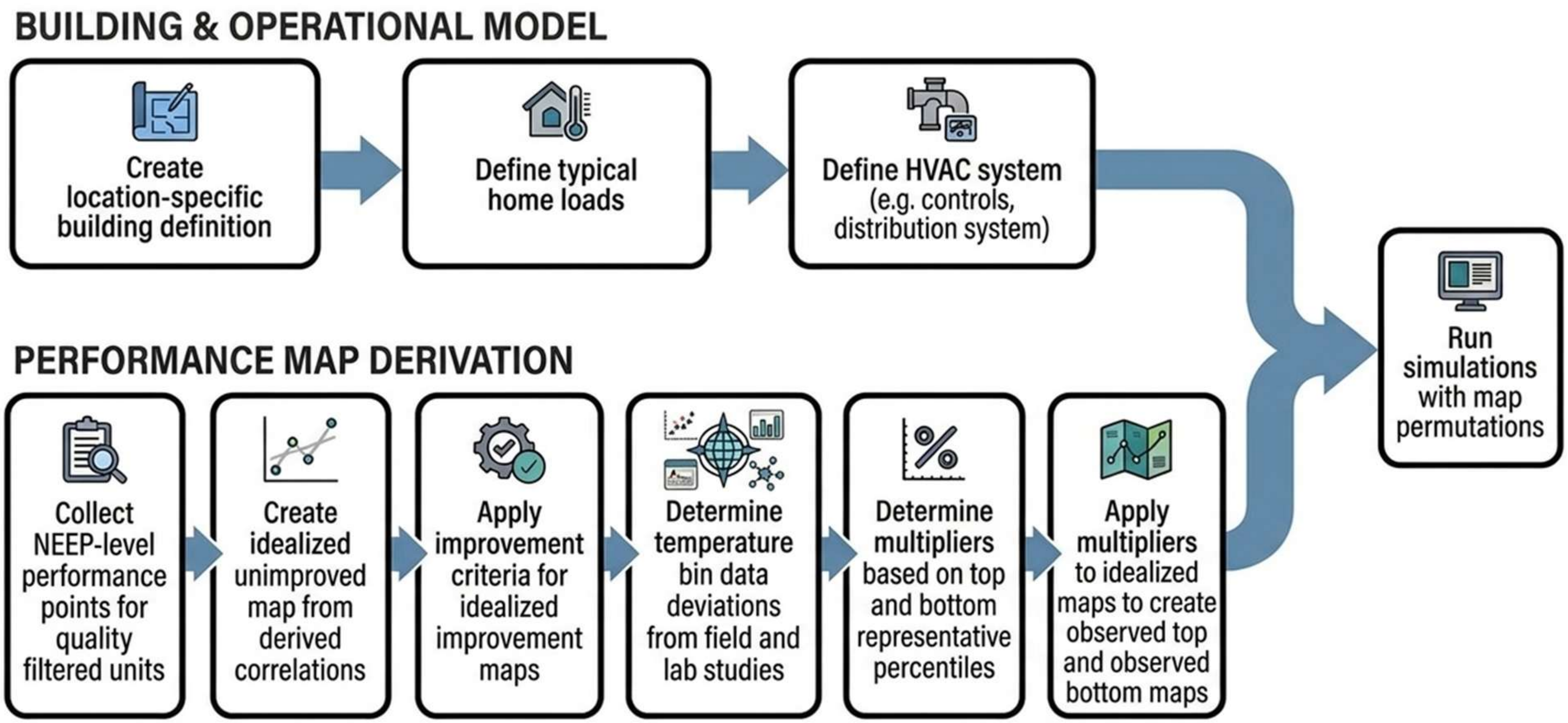
PROJECT WORKFLOW



COHORTS

- Low Load Efficient (LLE)
  - Optimized for efficiency at mild ambient conditions (=low load)
  - Minimum threshold for heating is COP >4.5 @ 47°F min cap

- Cold Climate Capable (CCC)
  - Optimized for providing compressor heating at low temperature conditions
  - Harder to extract heating when the ambient temperature drops
  - Minimum threshold is to provide at 5°F, 80% capacity possible at 47°F

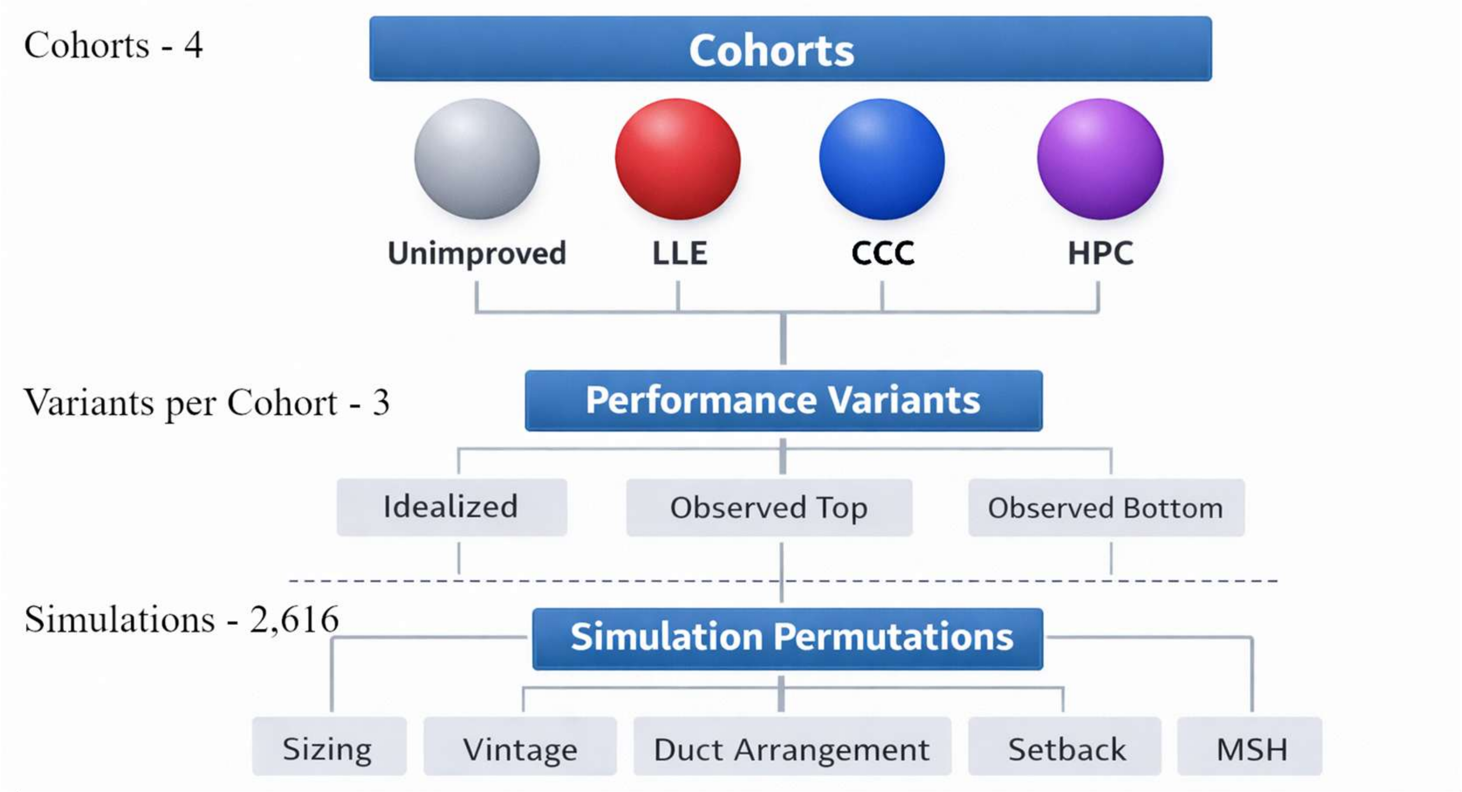
- High Performance High Capacity (HPHC)
  - Has the characteristics of LLE and CCC
  - Results in highest overall rated efficiency

- Unimproved
  - Variable capacity heat pump that doesn't meet the improvement thresholds

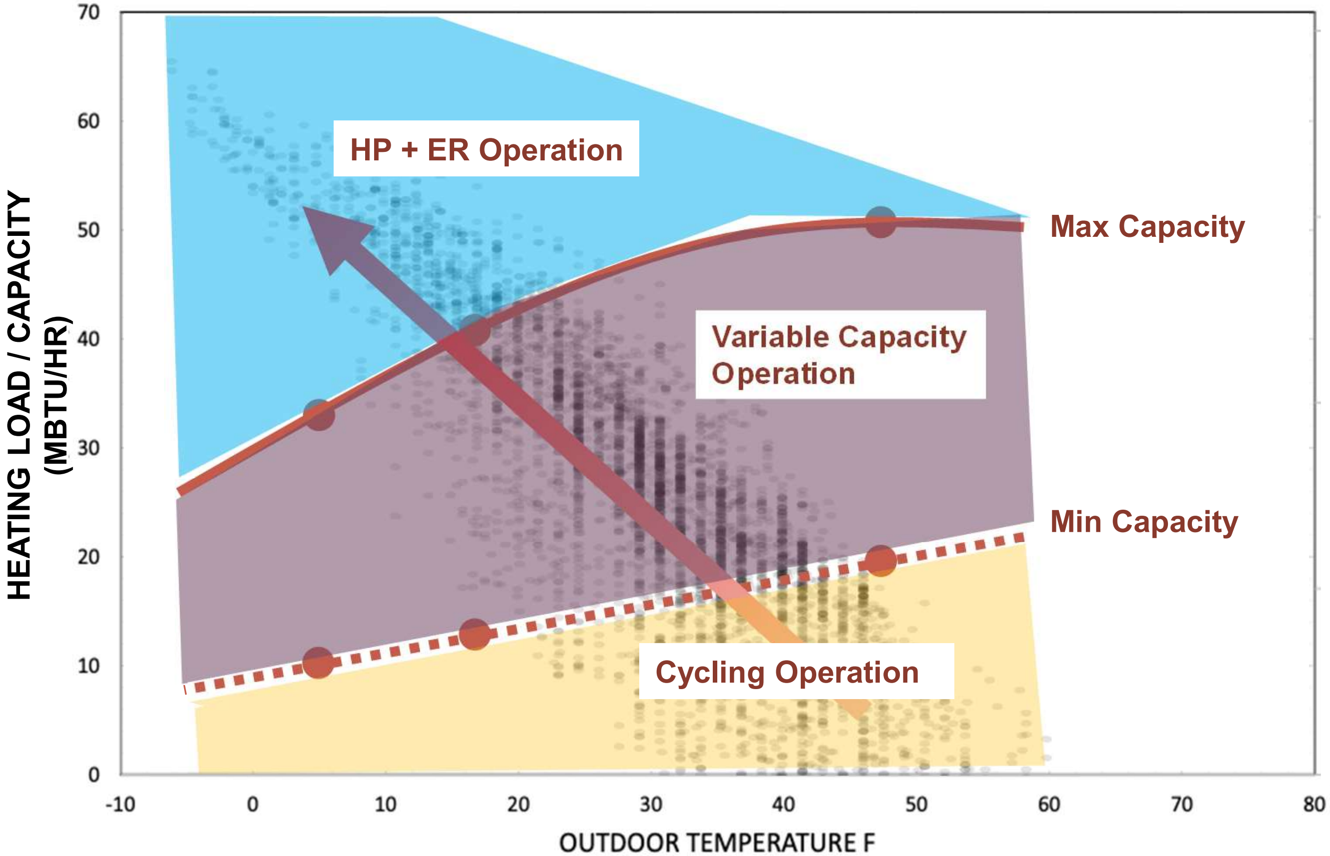
HEAT PUMPS AND PERMUTATIONS

Performance Map	Description
Idealized	Aggregated performance map derived from manufacturer published data and normalized to meet criteria near the federal tax credit threshold 8.5 HSPF2.
Observed Top	Performance map calibrated to observed lab and field data. Statistical multipliers weighted to the 75th percentile of deviations from manufacturer published within discrete temperature bins were applied to the idealized map. Represents the top performing observed heat pumps.
Observed Bottom	Performance map calibrated to observed lab and field data. Statistical multipliers weighted to the 25th percentile of deviations from manufacturer published within discrete temperature bins were applied to the idealized map. Represents the bottom performing observed heat pumps.

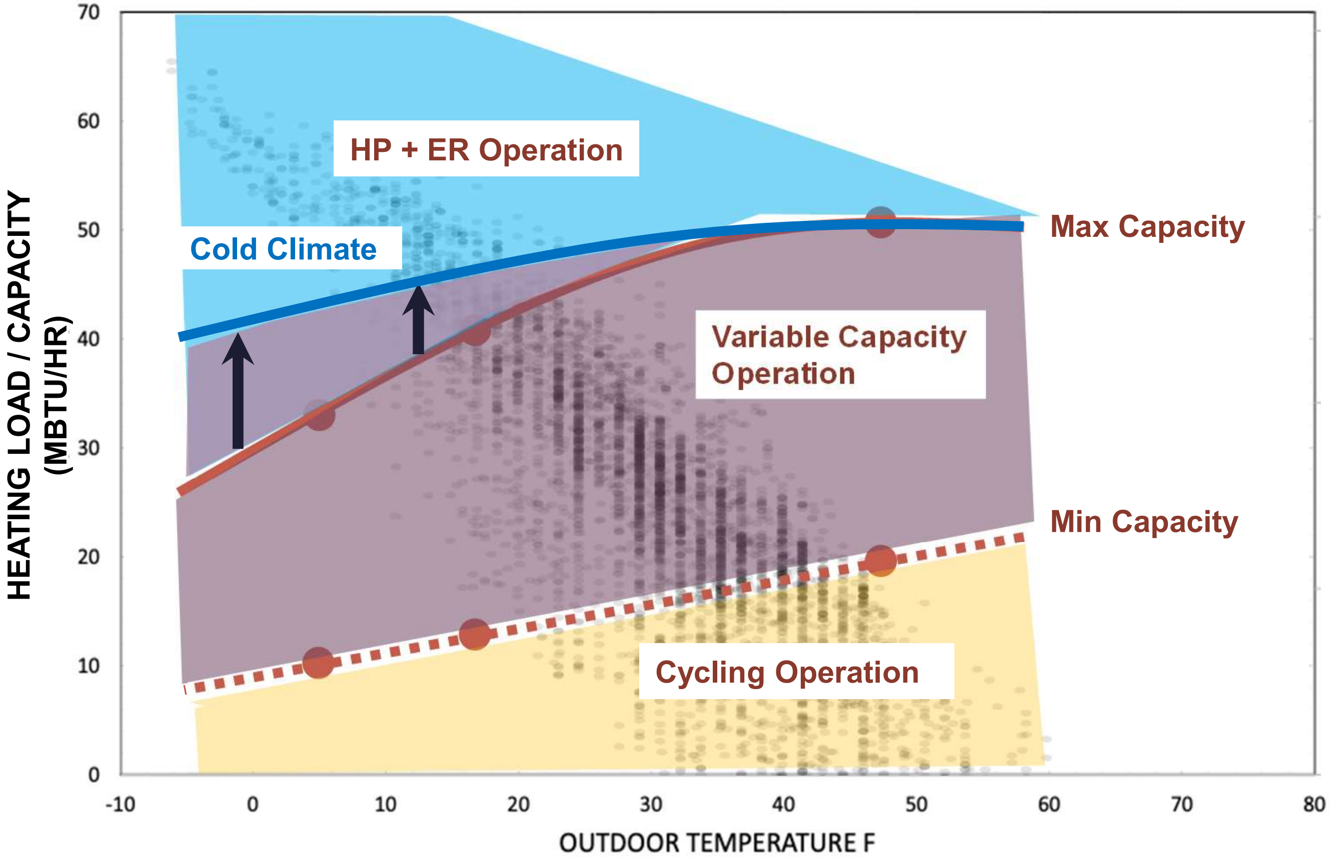
HEAT PUMPS AND PERMUTATIONS



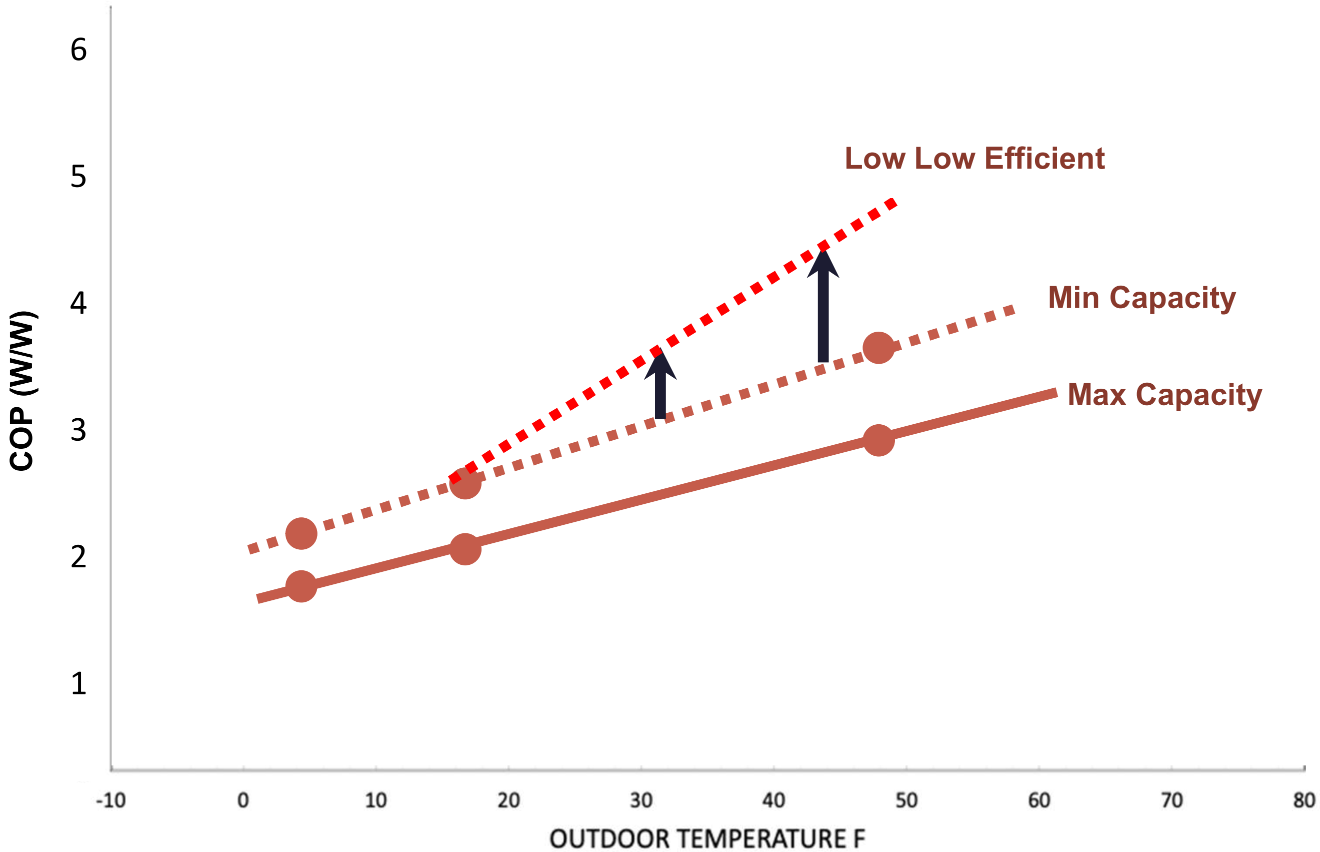
MAP DEVELOPMENT



MAP DEVELOPMENT



MAP DEVELOPMENT



DATA SOURCES

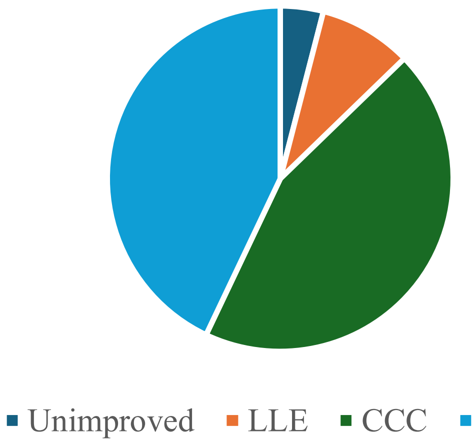
Source	Useable
Cadmus ccc Heat Pump Study	Yes, report only
PG&E ATS lab data	Yes
US DOE Building America / NREL CCHP field testing	Yes
NEEA RBSA Field Data	Yes
NEEA LLE Lab Study	**Yes**
Bonneville Power Administration (BPA) high performance high capacity heat pump (HPHCHP) field testing project	Yes
Ridgeline Analytics	**Yes**
NEEA Home Energy Metering Study (HEMS)	**Yes**
UC Davis Western Cooling Efficiency Center Heat Pump Research	No
Variable Speed Heat Pumps as Air Conditioner Replacement	No
New York (funded by NYSERDA, analyzed by PSD)	No
TechClean California	No
Frontier Energy Modeling Study of ccVCHPs in California	No
Tennessee Valley Authority Field Study	No
COE Cold Climate Heat Pump Challenge Field Validation (PNNL) – Prototype models, not commercial	No
PSD data	No
California Central Valley Research House “Test” House Study	?
Unlocking Heat Pump Performance (Georgia Power and Illume)	?
Rating Representativeness Project	

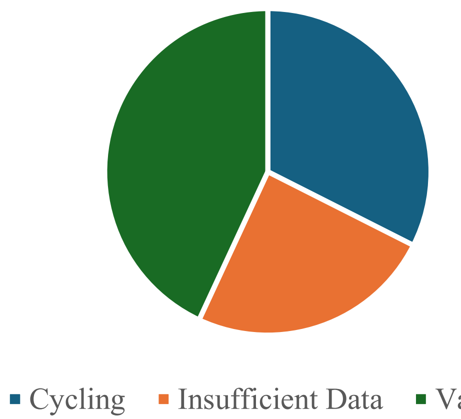
CALIBRATION METHODOLOGY

- Look at units within each non and improvement category
- A lot of disparate units with different ratings
- Focus on deltas of key rating points, %
- If available, form "why" bins, especially for installed units measured
  - Cycling because oversized, de-emphasize trends
  - Trends specific to ducted units represented in ducted maps
  - Emphasize units in our market transformation efficiency range

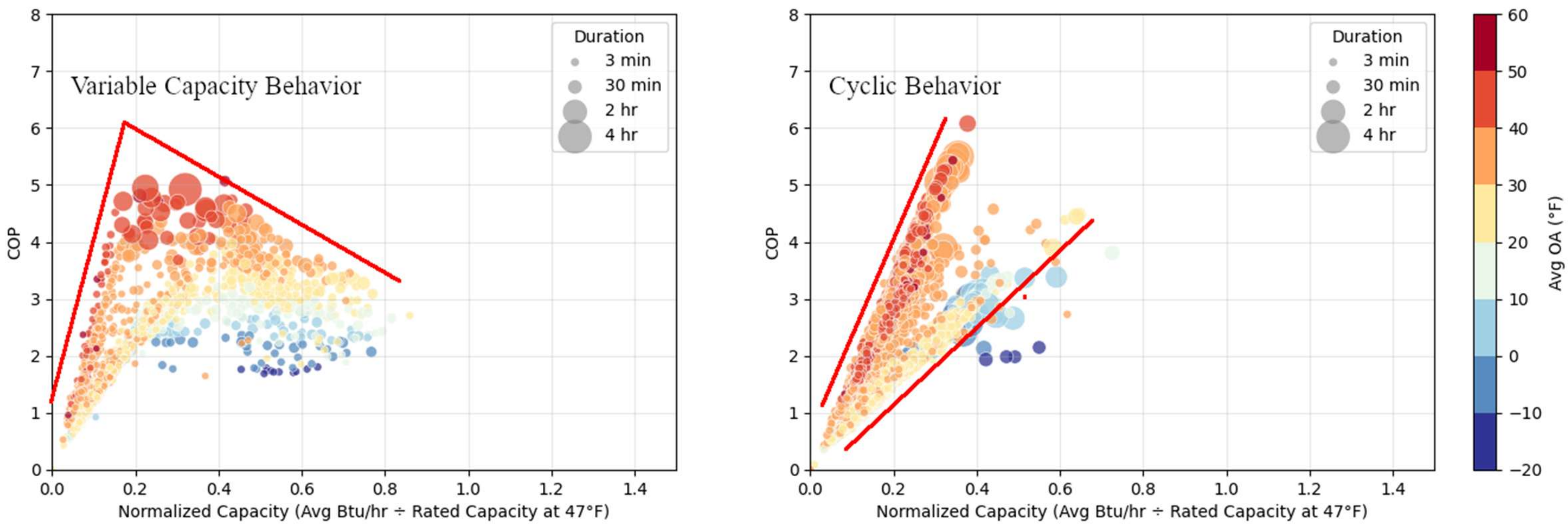
CALIBRATION METHODOLOGY

- 5 primary studies deemed sufficient
  - 4 field studies, 1 laboratory
- 115 units with some useable data
  - Most units were improved (CCC or HPHC)
    - Unimproved referenced non-improved points of other cohorts
  - Over half of the data sufficient units showed cyclic behavior
    - Some due to oversizing
    - Some even when correctly sized
    - Common finding in most studies
    - Model to focus on units that show variable speed

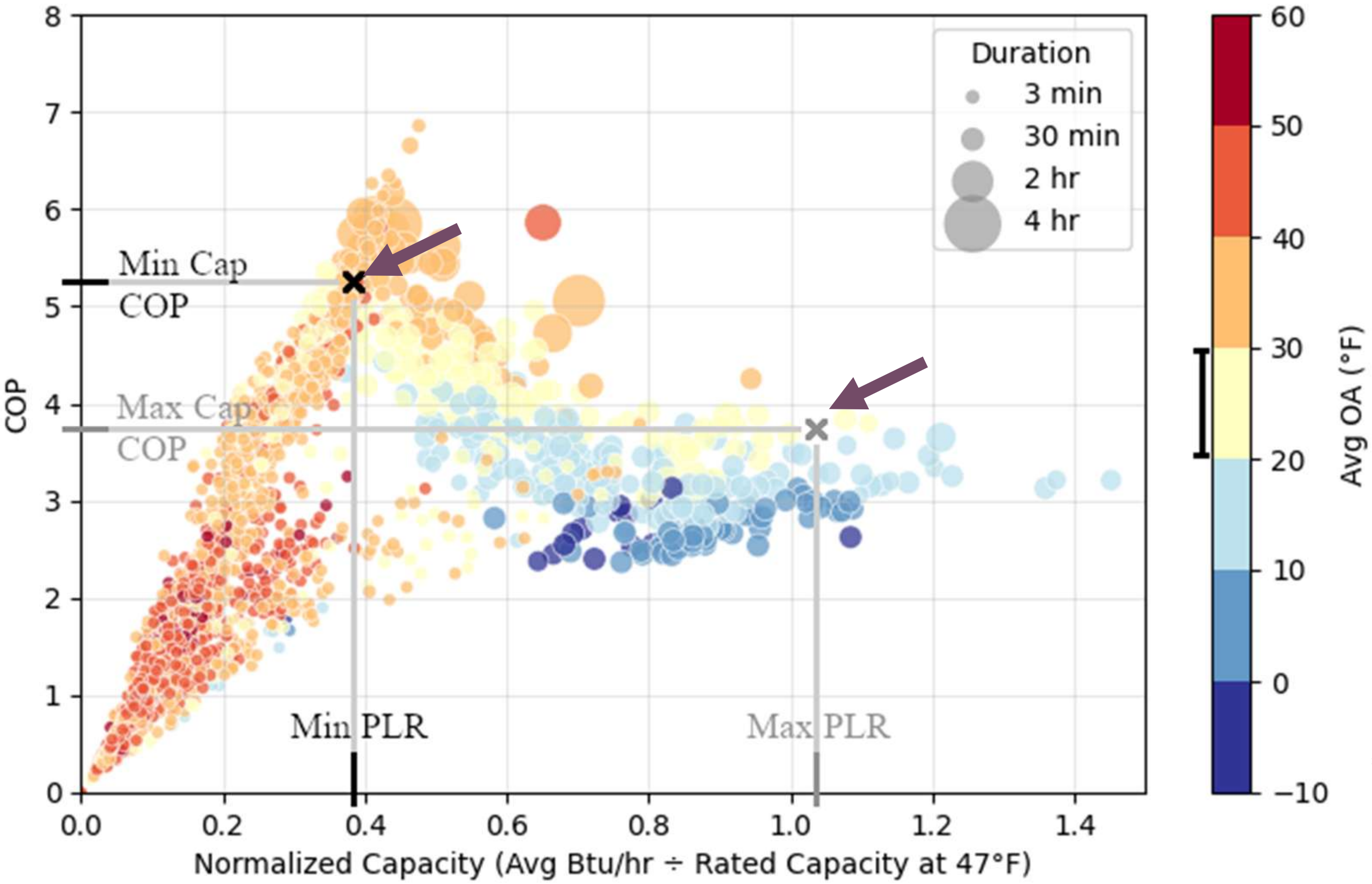




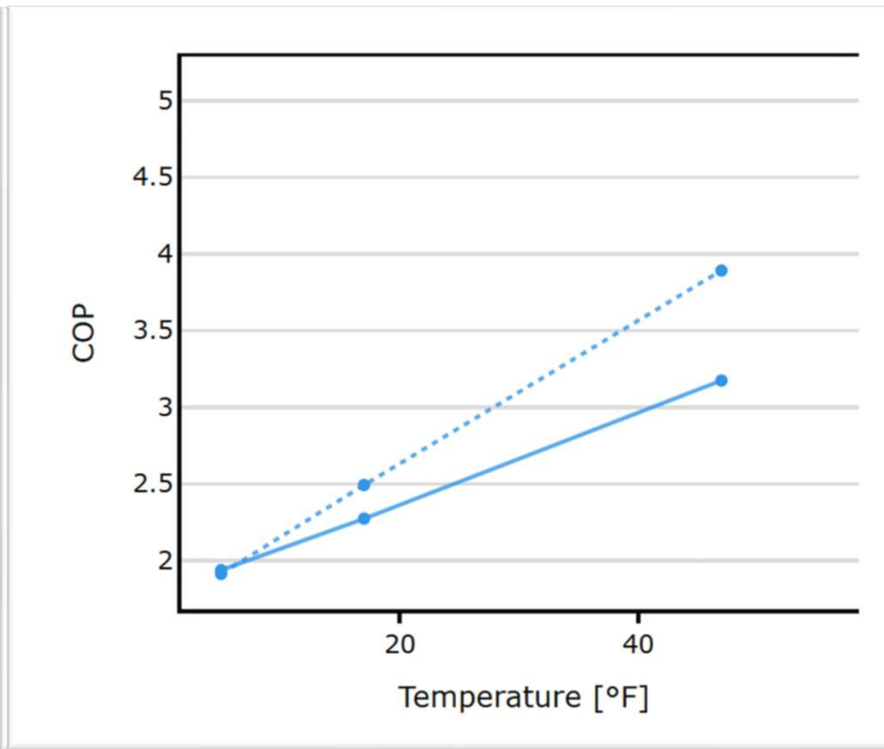
RANGEFINDER ON NON AND AHP IMPROVEMENTS - MAPS

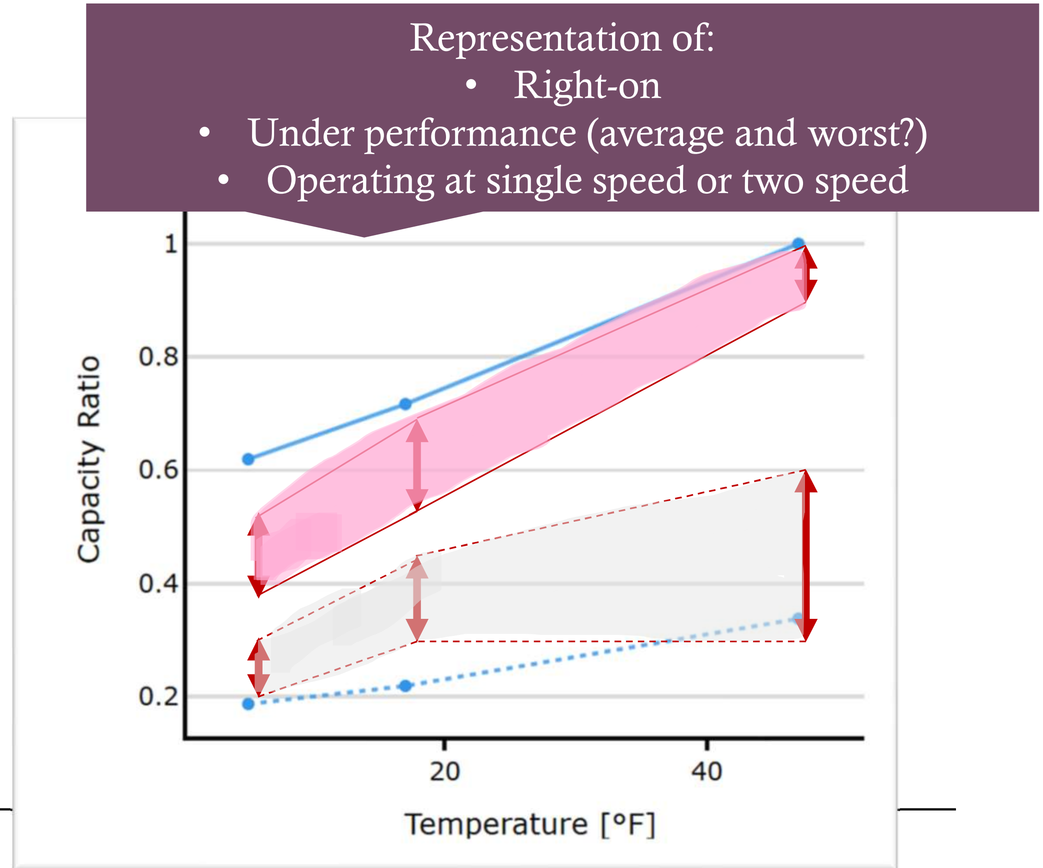


METHODOLOGY



RANGEFINDER ON NON AND AHP IMPROVEMENTS



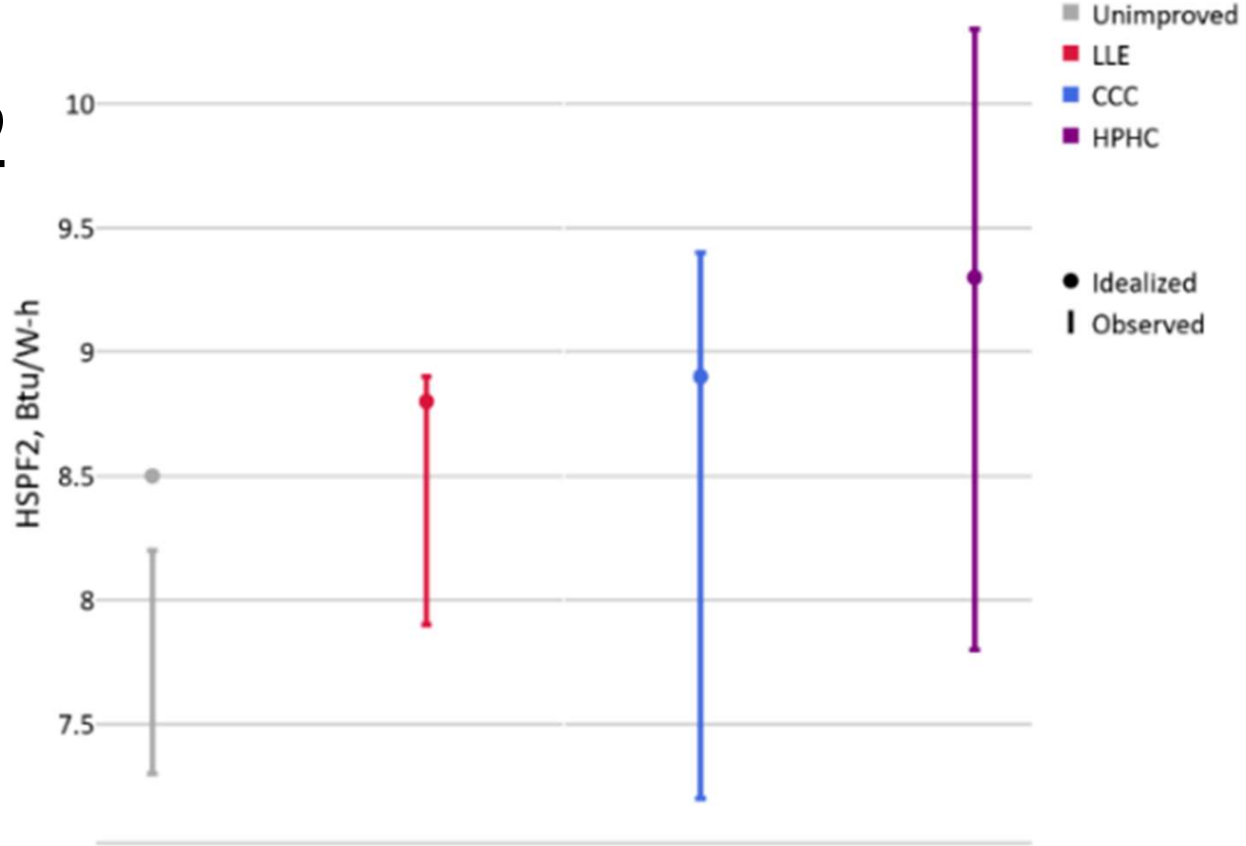


CALIBRATION METHODOLOGY – OBSERVED TOP AND BOTTOM

- Collect all unit deviations for the map points (filtered by improvement)
- Independently select 75^{th} (top) and 25^{th} (bottom) percentile deviations

MAPS – EQUIVALENT HSPF2

- Only unimproved has observed range below the published
- LLE smallest equivalent efficiency range
- CCC has a wide range, but can perform worse than the observed unimproved
- HPHC has the largest potential to over-perform, with some underperformance potential too



BUILDING ASSUMPTIONS

- New construction based on 2026 current energy codes
- Existing building based on RBSA 1970-1979 home construction

Building	Climate Zone	Roof U-Value	Wall U-Value	Window U-Value	Infiltration, ACH50	Duct Insulation	Duct Leakage
New Home, Seattle, WA	4C	0.024	0.056	0.3	4	R-8	5%
New Home, Spokane, WA	5B	0.024	0.056	0.3	4	R-8	5%
New Home, Boise, ID	5B	0.026	0.060	0.3	3	R-8	5%
New Home, Bozeman, MT	6	0.024	0.045	0.3	4	R-8	5%
Existing Home	All	0.08	0.12	0.49	8.8	R-2*	9%*

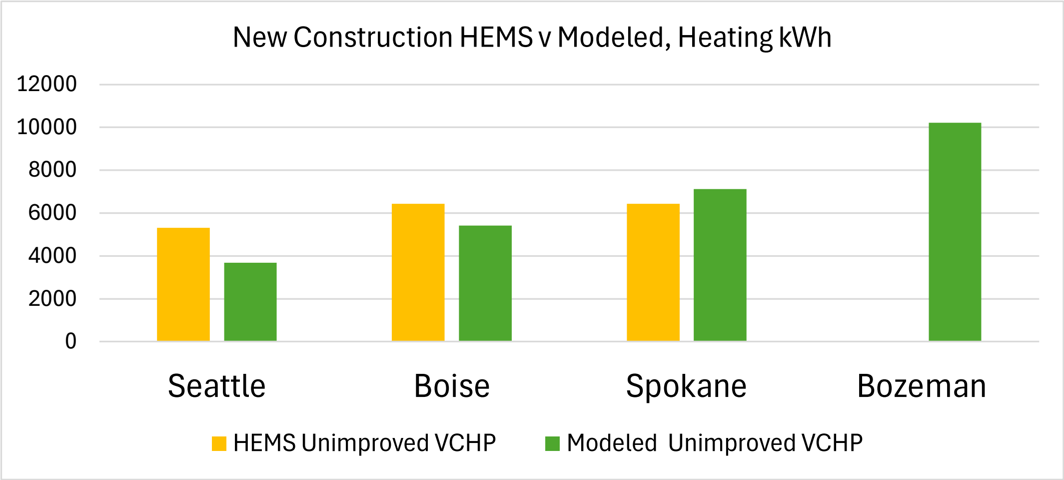
HVAC ASSUMPTIONS

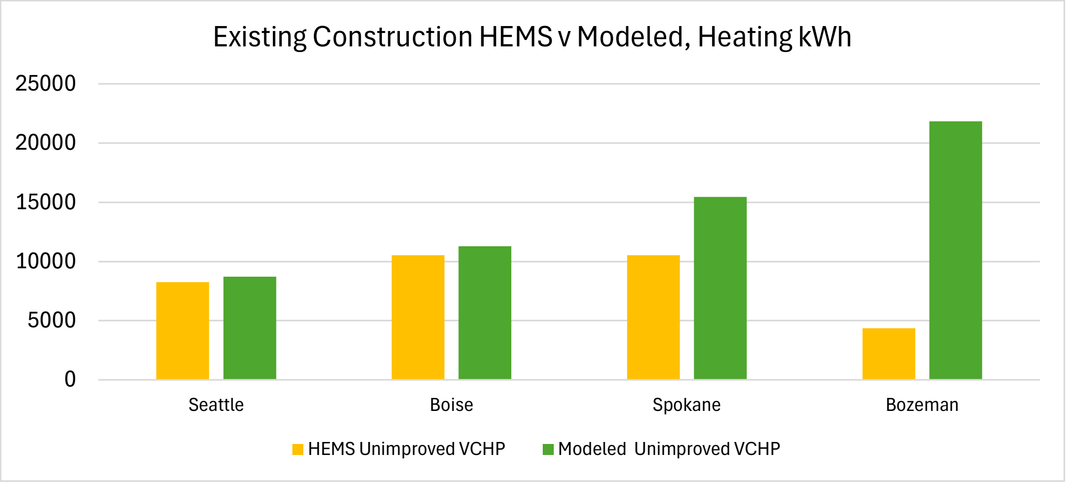
- Sized to meet cooling design loads (rounding up to nearest half cooling ton)
- Cooling capacity at 95 F (in tons):

Location	New Home	Existing Home
Seattle	2	3
Spokane	2	3.5
Boise	3	4.5
Bozeman	2	4

RESULTS – USAGE COMPARISON TO FIELD

- Simulation results were compared to regional energy consumption survey data
- Model results within reason
- Note insufficient sample size for Bozeman
    - Tend to wood, not ER for supplementary
    - Few installations

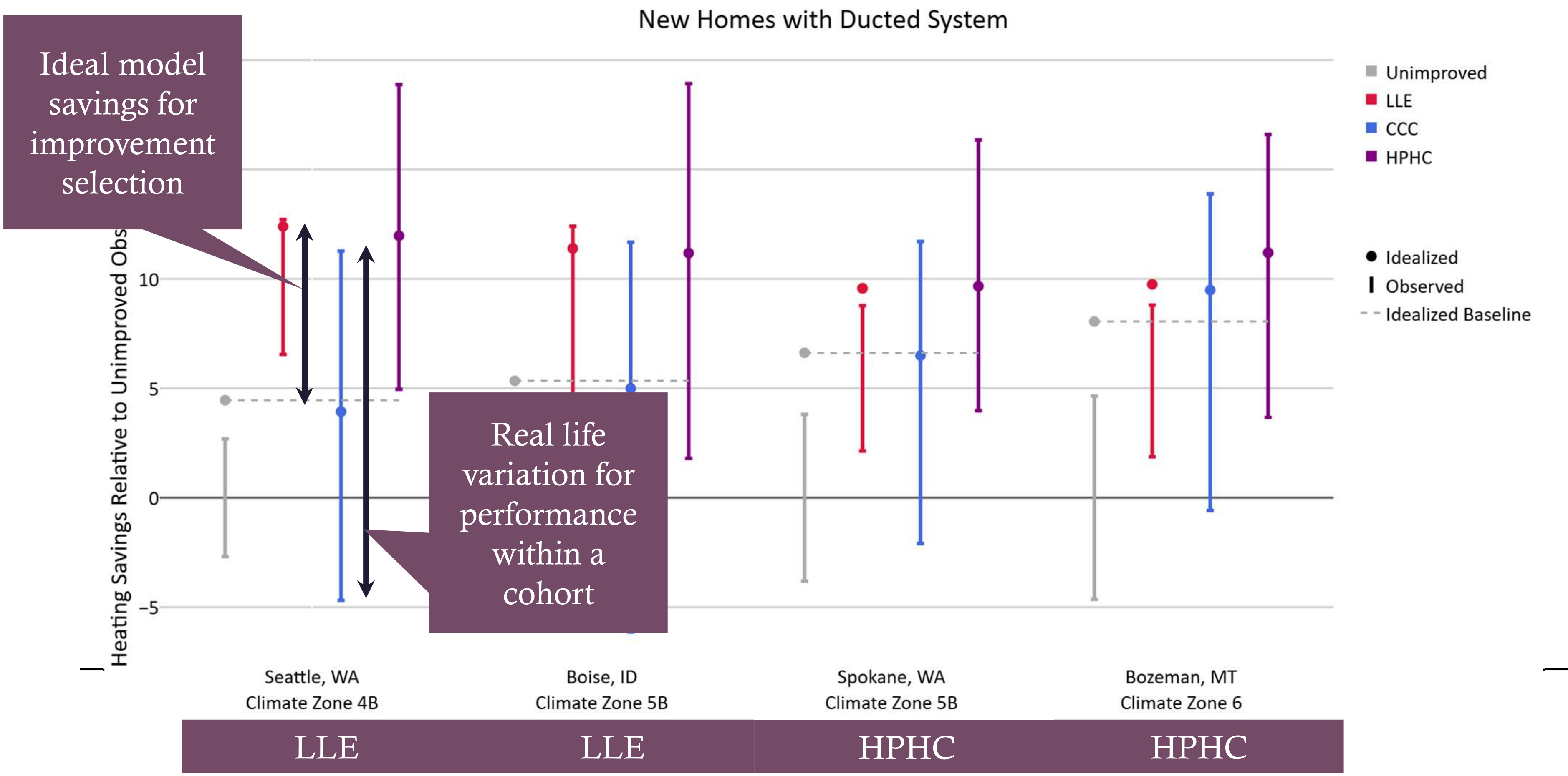




RESULTS – SAVINGS

- Presented in % of heating energy (including hp, supplementary heat, fan, defrost, etc.)
- Applicable across building sizes
- Overall savings dependent on building size, vintage, distribution system, etc.

RESULTS – NEW HOMES DUCTED



RESULTS – LLE SUMMARY

- All locations studied benefitted greatly from low load efficiency
- LLE units showed the most consistent performance to published data
- Recommended for CZ 4C and 5B

Archetype	Seattle	Boise	Spokane	Bozeman
Unimproved	0%	0%	0%	0%
Observed compared to published*	-4.0%	-5.1%	-6.2%	-8.0%
Low-Load Efficient (LLE)	**7.9%**	**8.8%**	**6.4%**	**6.4%**
Cold Climate Capable (CCC)	3.5%	5.0%	6.4%	9.1%
High Performance High Capacity (LLE and CCC)	9.3%	8.8%	9.4%	10.0%

RESULTS – CCC SUMMARY

- Cold climate benefits were only realized in locations that had significant low temperatures
- Field performance had the greatest potential for underperformance
- Power spec @5°F to be raised to represent the heat pumps on the market and make larger impact

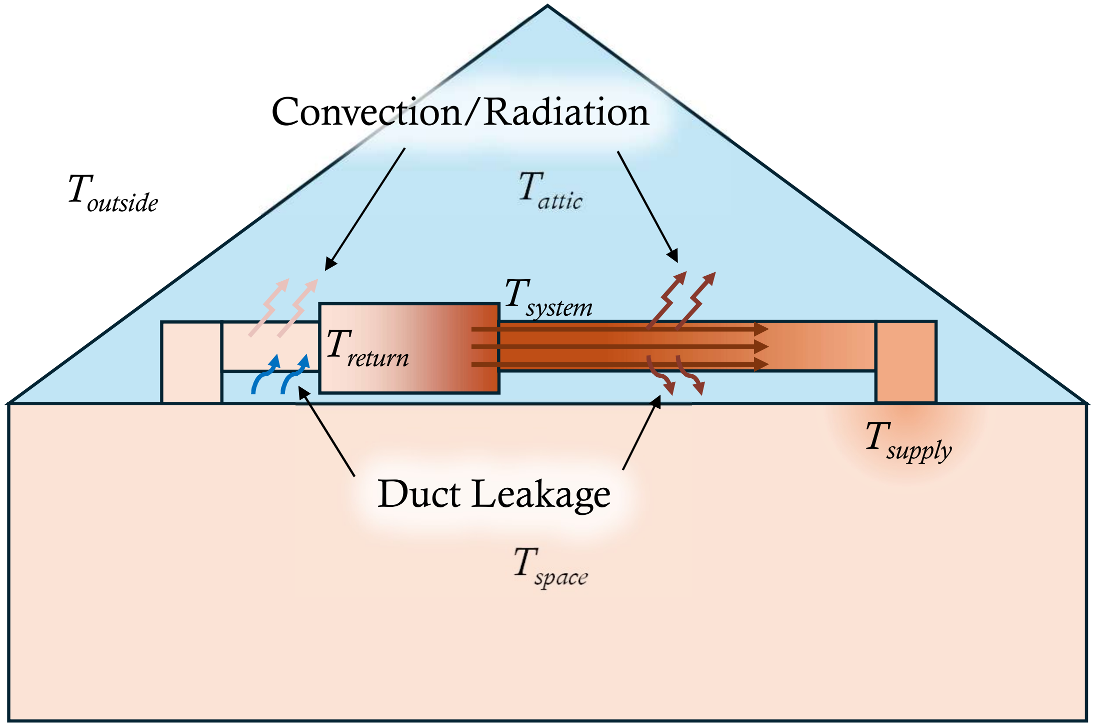
Archetype	Seattle	Boise	Spokane	Bozeman
Unimproved	0%	0%	0%	0%
Observed compared to published*	-4.0%	-5.1%	-6.2%	-8.0%
Low-Load Efficient (LLE)	7.9%	8.8%	6.4%	6.4%
Cold Climate Capable (CCC)	**3.5%**	**5.0%**	**6.4%**	**9.1%**
High Performance High Capacity (LLE and CCC)	9.3%	8.8%	9.4%	10.0%

RESULTS – HPHC SUMMARY

- Mix of low load and cold climate capability creates “all-season” performance
- Field studies show potential for underperformance
- Recommended for CZ 5B and 6

Archetype	Seattle	Boise	Spokane	Bozeman
Unimproved	0%	0%	0%	0%
Observed compared to published*	-4.0%	-5.1%	-6.2%	-8.0%
Low-Load Efficient (LLE)	7.9%	8.8%	6.4%	6.4%
Cold Climate Capable (CCC)	3.5%	5.0%	6.4%	9.1%
High Performance High Capacity (LLE and CCC)	**9.3%**	**8.8%**	**9.4%**	**10.0%**

DUCT DISTRIBUTION SYSTEM EFFICIENCY

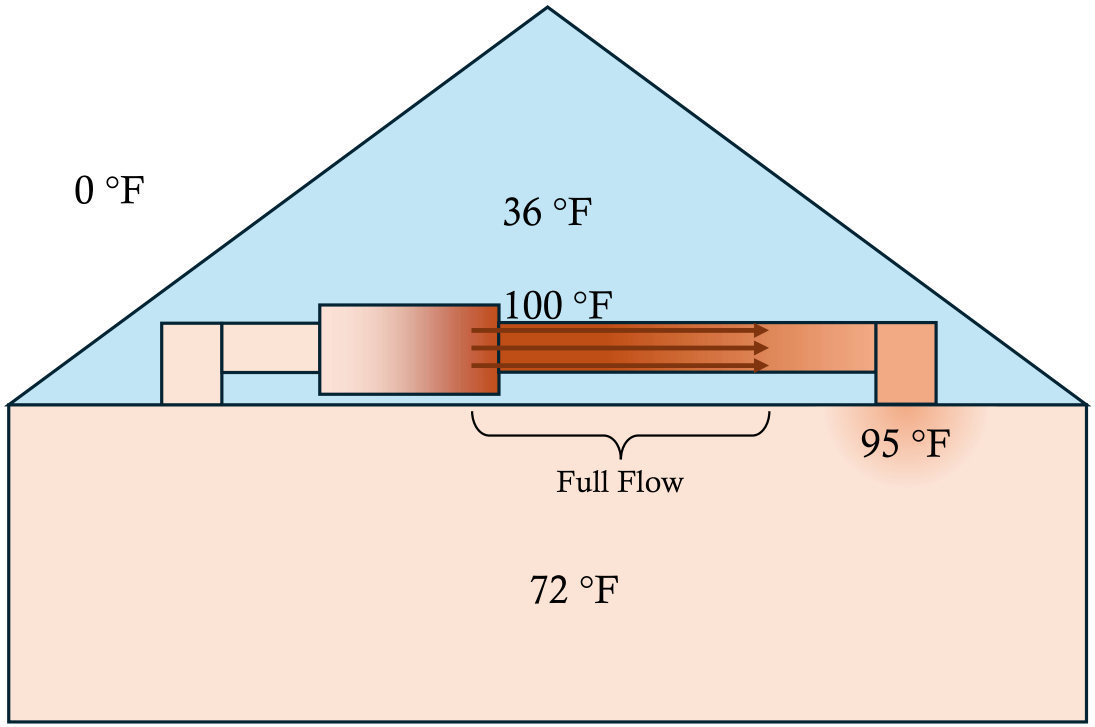


$$DSE = \frac{Heat\ Delivered\ to\ Space}{Heat\ Added\ by\ System}$$

$$= \frac{\dot{m}_{space} \cdot c_p \cdot (T_{supply} - T_{space})}{\dot{m}_{system} \cdot c_p \cdot (T_{system} - T_{return})}$$

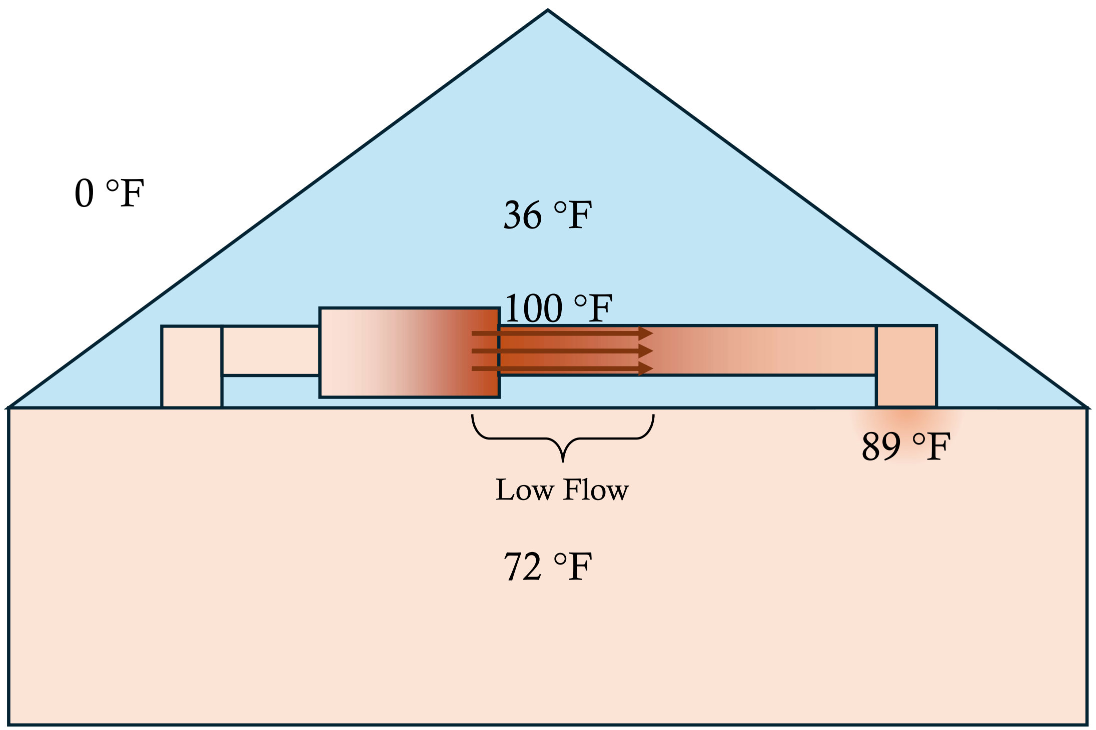
$$\approx \frac{(T_{supply} - T_{space})}{(T_{system} - T_{space})}$$

DUCT DISTRIBUTION SYSTEM EFFICIENCY



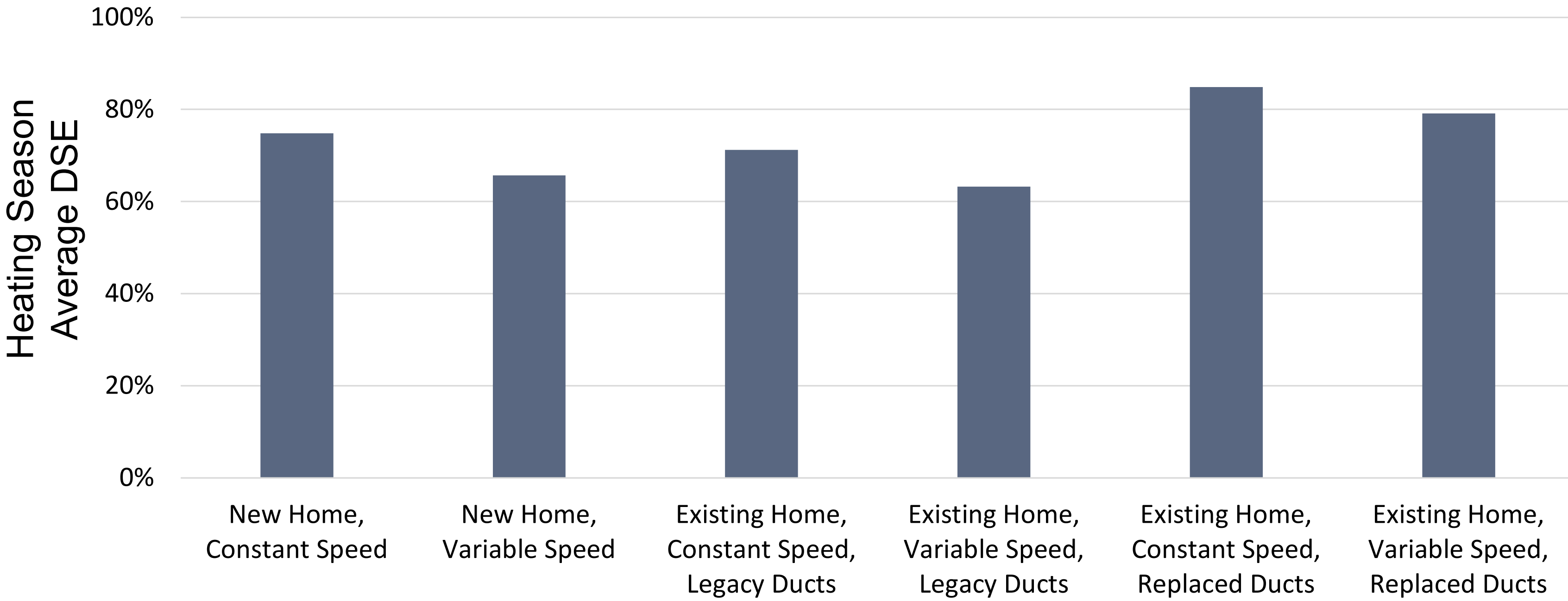
$$DSE \approx \frac{(95\ °F\ - 72\ °F\ )}{(100\ °F\ - 72\ °F)} = 82\%$$

DUCT DISTRIBUTION SYSTEM EFFICIENCY



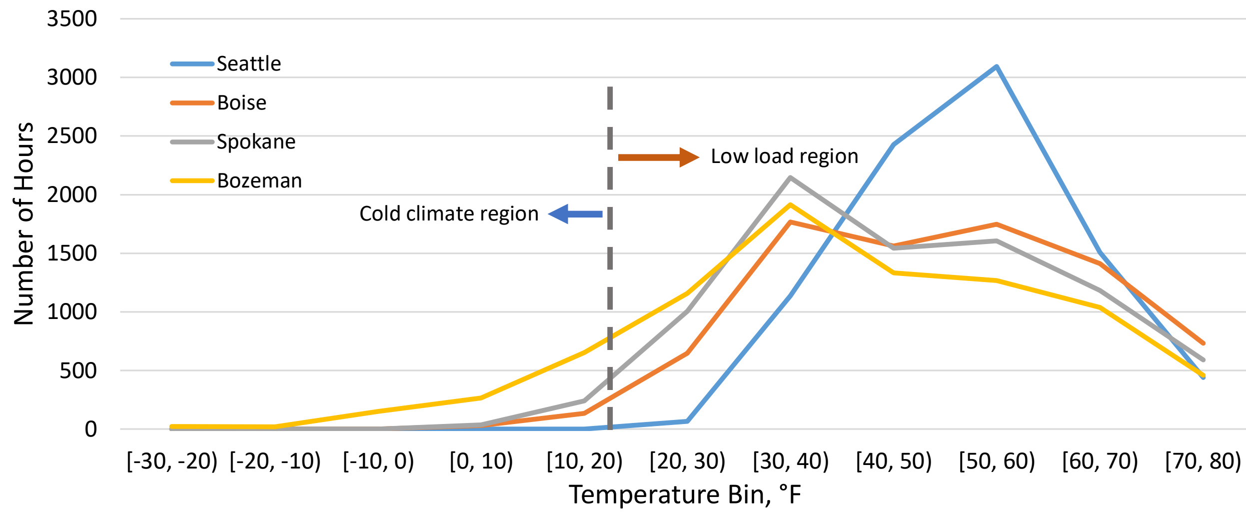
$$DSE \approx \frac{(89\ °F - 72\ °F)}{(100\ °F - 72\ °F)} = 60\%$$

DUCT DISTRIBUTION SYSTEM EFFICIENCY



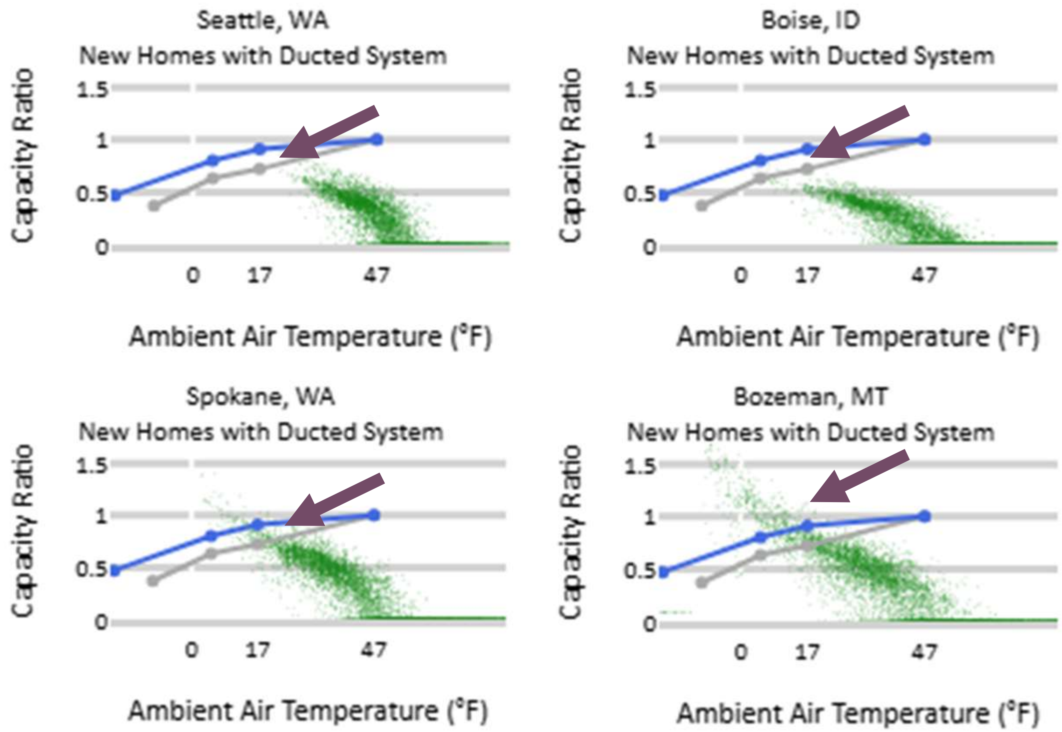
RESULTS – COLD CLIMATE CAPABLE

- Lower savings than hypothesized
- Weather file bin analysis



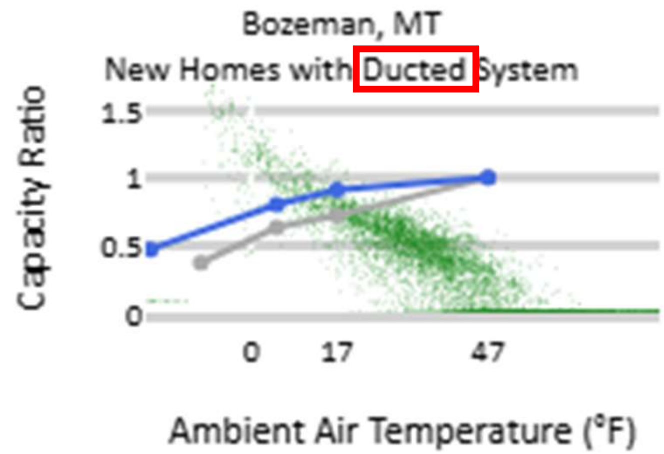
RESULTS – COLD CLIMATE CAPABLE

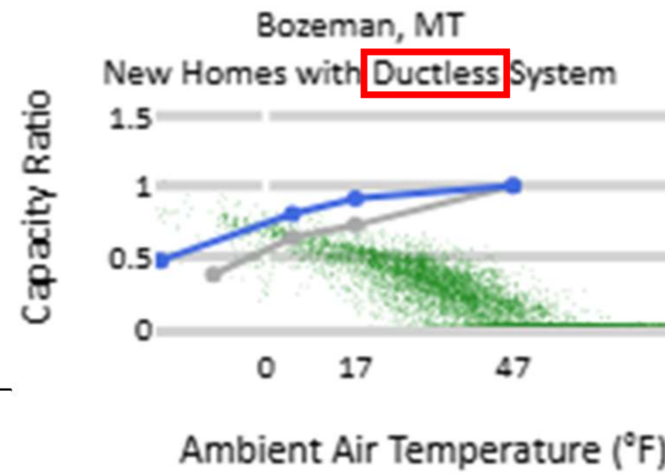
- Lower savings than hypothesized
- Savings increase likely higher with Enhanced Vapor Injection technology that has >60% capacity at -10°F



RESULTS – COLD CLIMATE

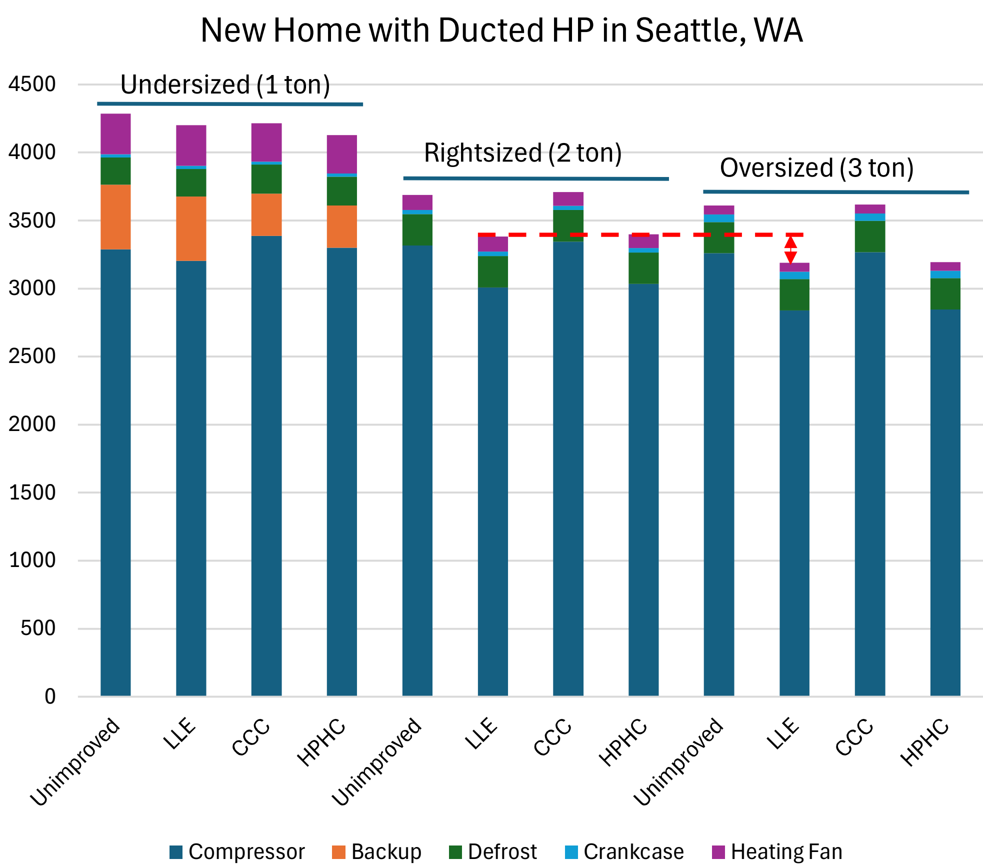
- Ductless units are "oversized"
- CCC is sensitive to sizing
- Even fewer hours in the savings zone
- Oversizing creates additional "cold climate" capacity

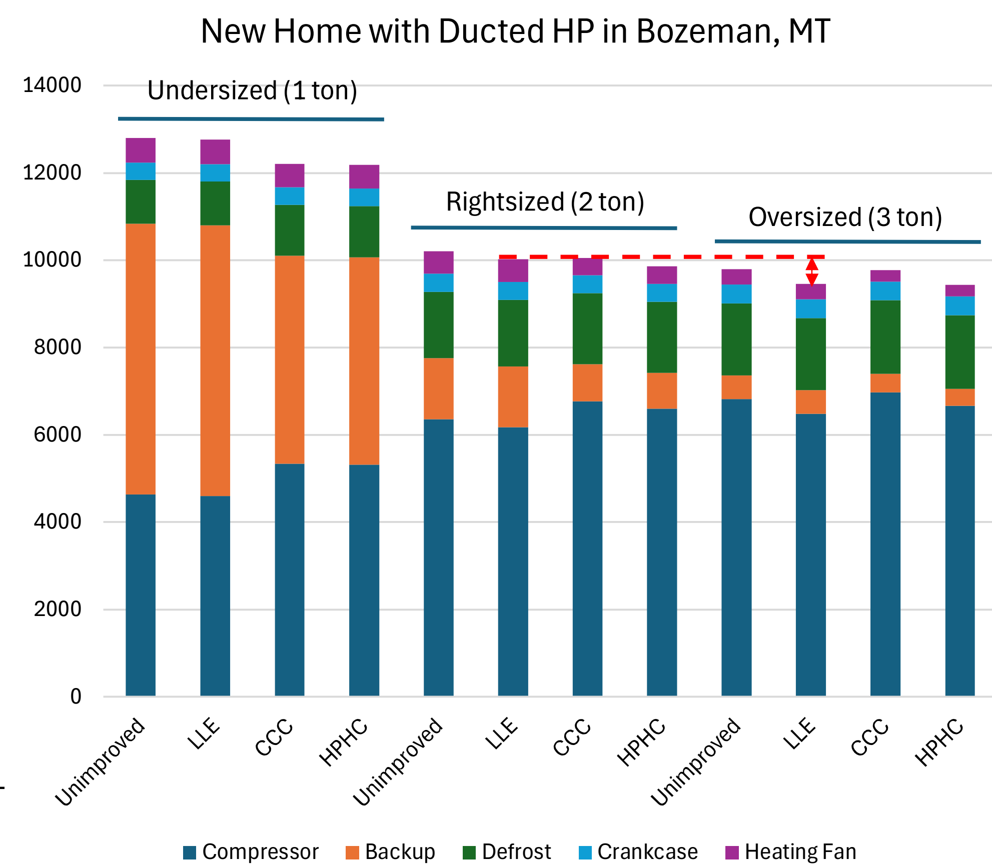




RESULTS – IMPACT OF SIZING

"Rightsized" for cooling





CONCLUSIONS

- Variation in energy usage within a cohort is significant
  - Installers should focus on products with proven track record
- LLE recommended for all climates, but bonus savings in cold climates with HPHC adding CCC
- CCC specs, technology, and controls should be evaluated to prevent underperformance
- Undersizing can result in significant supplementary electric resistance usage
- Oversizing by a ton can still increase LLE savings
- Existing HVAC must consider the condition of distribution system before VCHP

QUESTIONS