ANALYSIS OF HVAC SYSTEMS FOR DEEP ENERGY SAVINGS AT THE URBAN DISTRICT LEVEL

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AEI Conference 2019

Tysons, Virginia | April 3–6, 2019

Be Boulder.

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Motivation

Image courtesy of Panasonic

Background

- Air-based systems: zone heating and cooling loads are addressed by means of convective heat transfer with the supply air.
- Radiant hydronic systems: heated and cooled surfaces address zone loads through long-wave radiative heat transfer with other zone surfaces, and convection with zone air (as well as short-wave radiative heat transfer in cooling mode).
- A simplified analysis based on fundamentals suggests that thermal energy use requirements for heating should be similar between the two system types, if they are controlled to achieve the same degree of thermal comfort, as expressed through operative temperature.

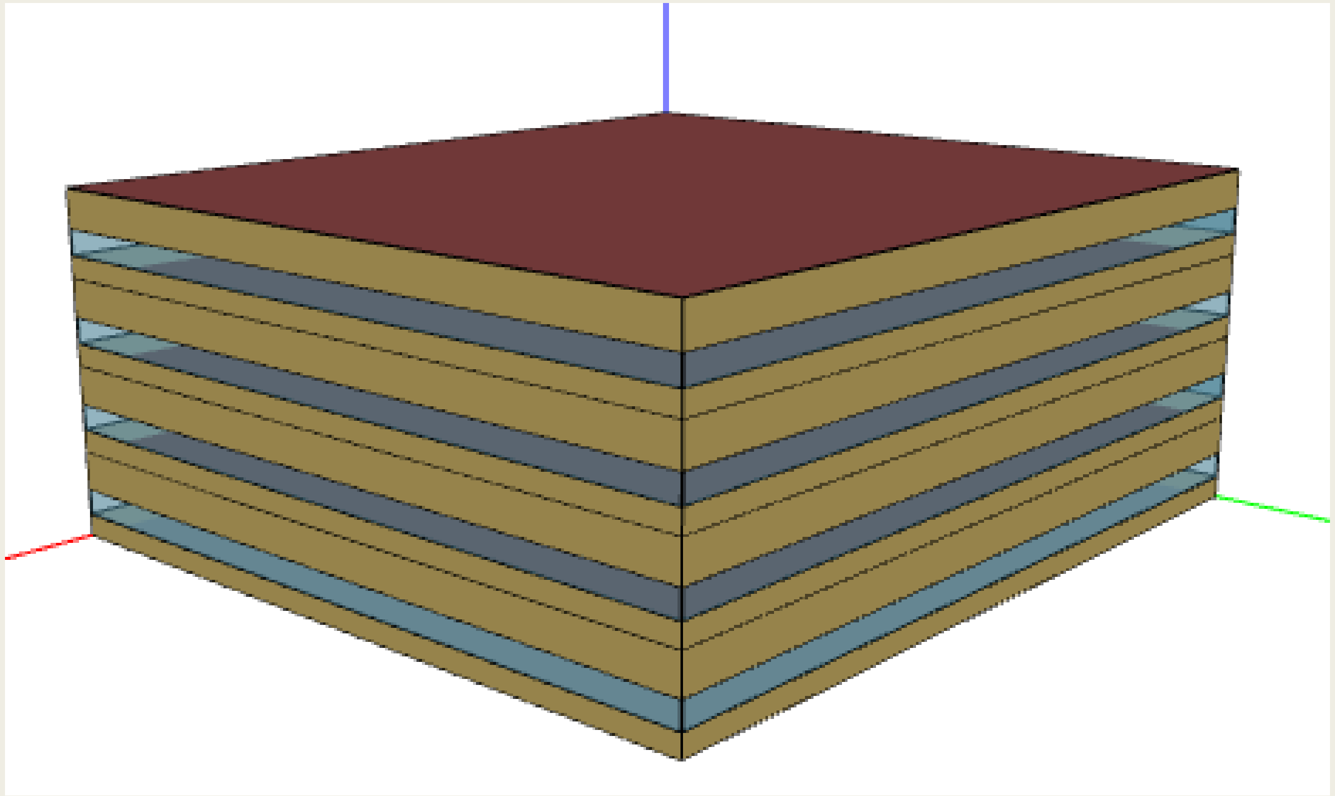
Research Question and Approach

- Research question: "Do radiant hydronic HVAC systems save energy relative to air-based systems serving a low-energy residential district?"
- The research question was addressed through simulation of two hypothetical urban districts, using EnergyPlus.
- Low-energy district: building envelopes and HVAC systems compliant with 2013 ASHRAE 90.1.

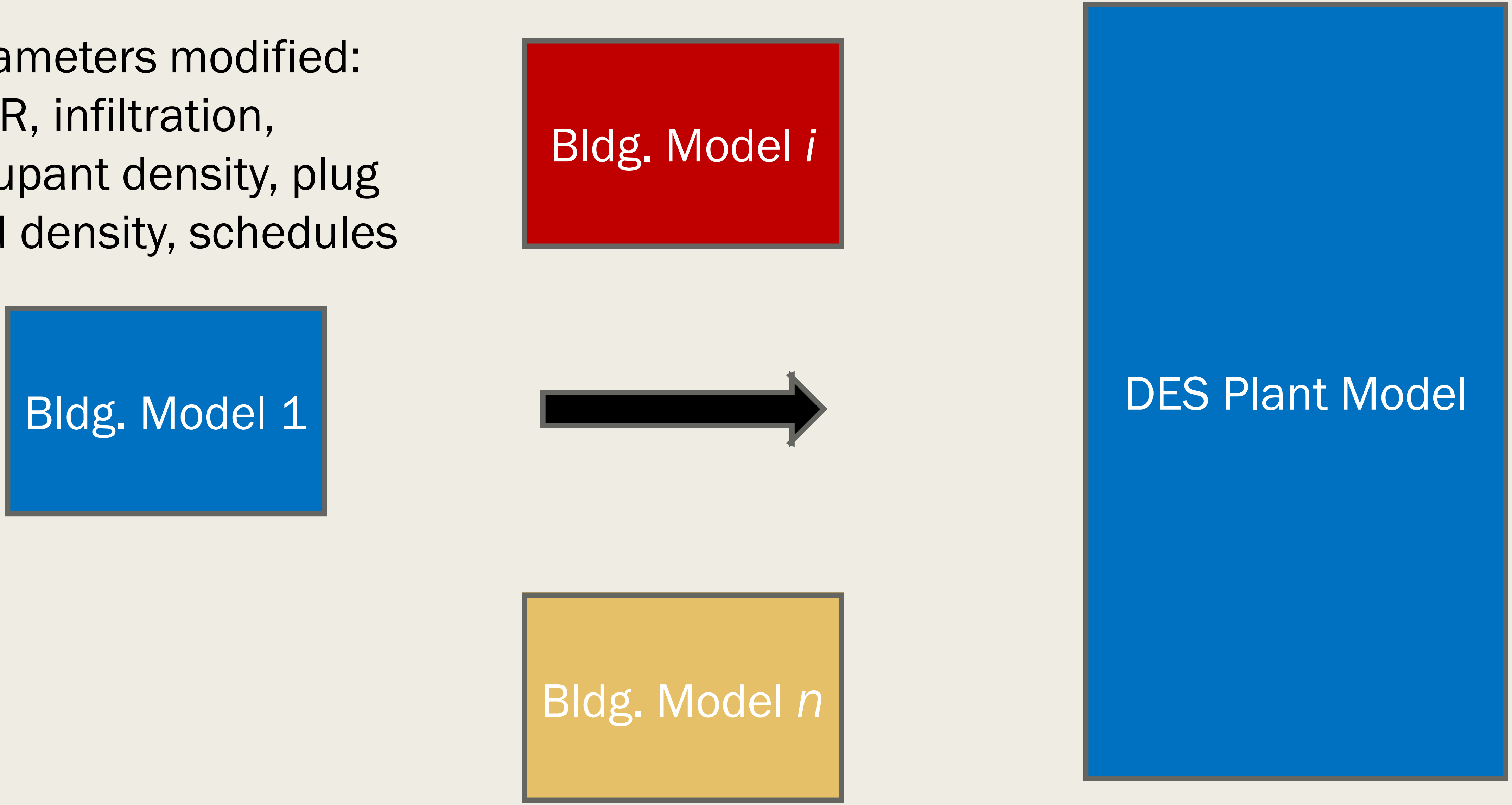
Building Models

- Building energy models used in this analysis are modified versions of the prototype building models created by DOE for purposes of evaluating the effects of energy codes and standards.
- Building envelopes, and HVAC systems are consistent with the standards set in 2013 ASHRAE 90.1.
- The building models representing the different HVAC system types are identical in all respects except for the HVAC system.

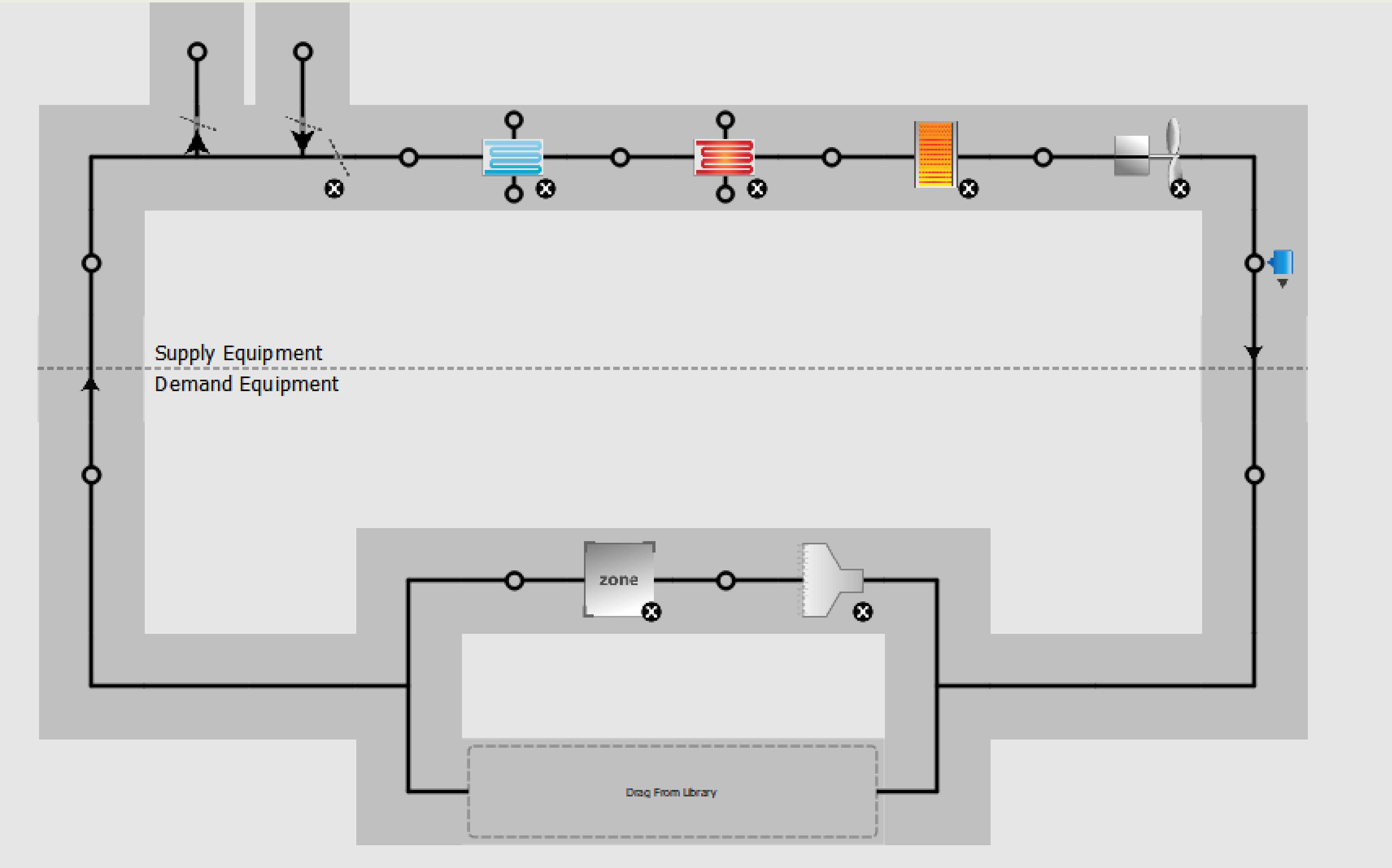
Rendering of Building Model



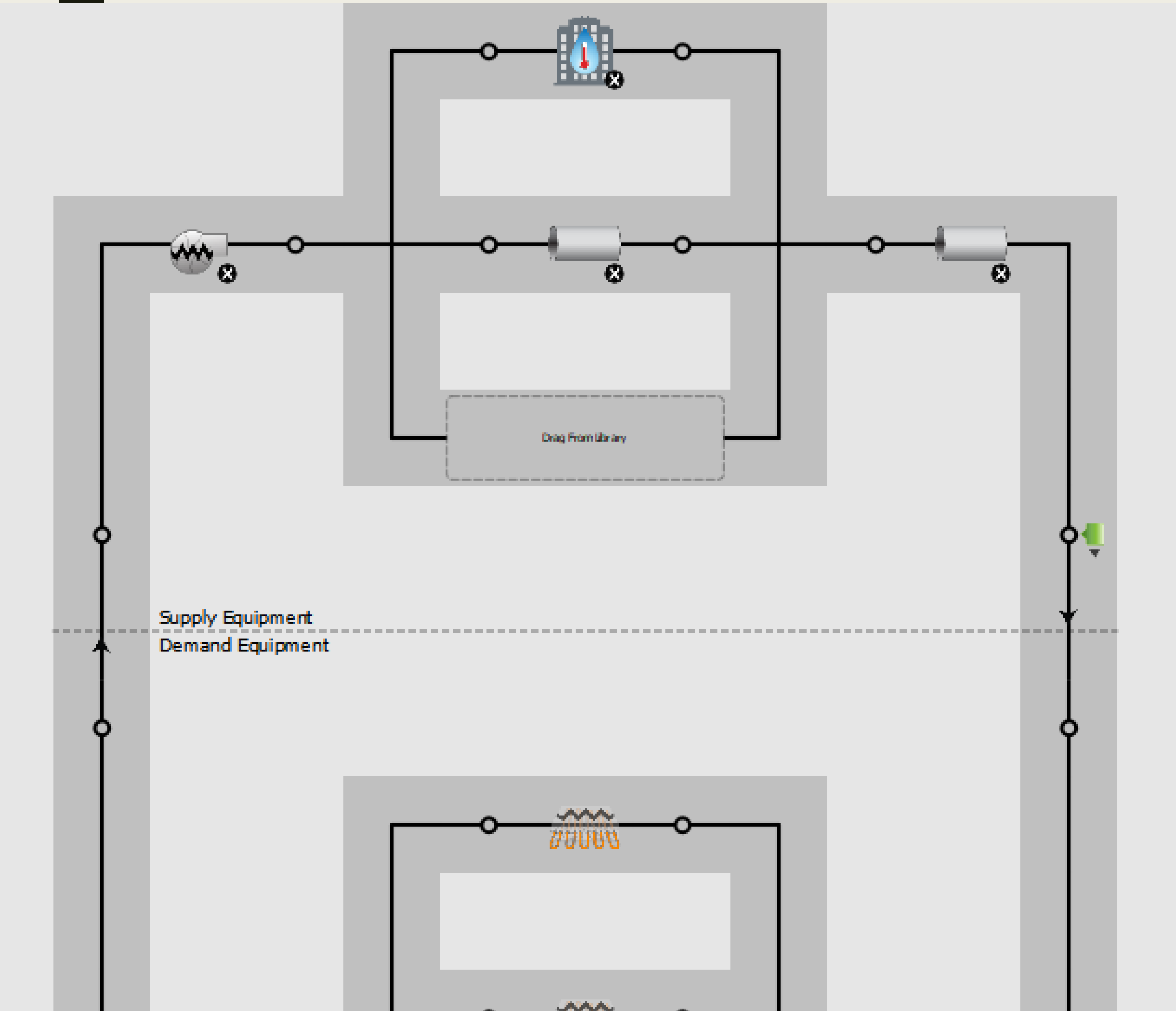
Parameters modified: WWR, infiltration, occupant density, plug load density, schedules

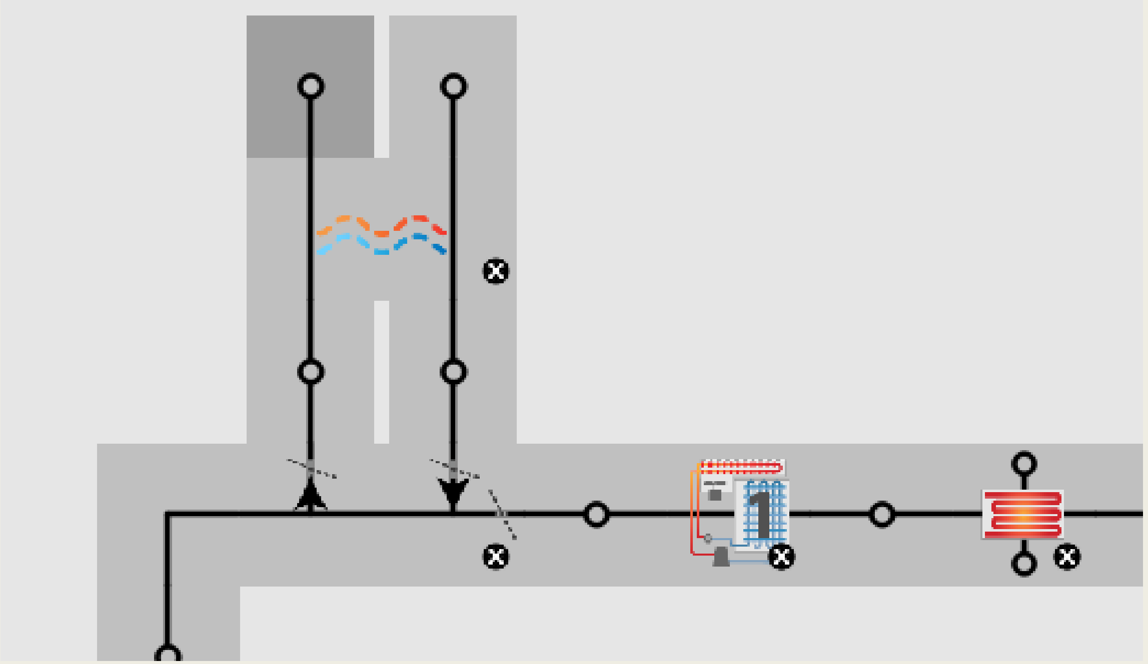


Air-Based System Configuration

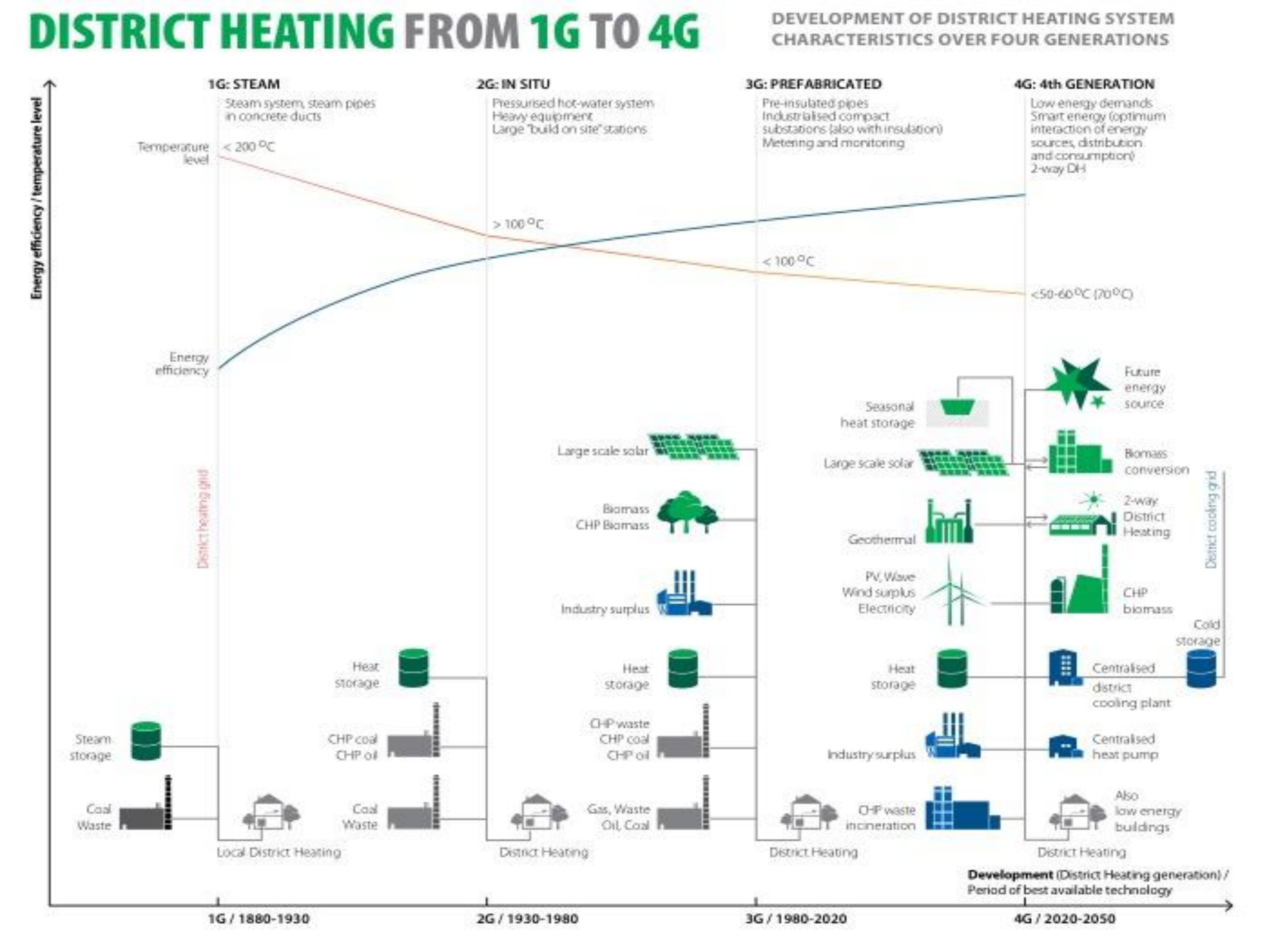


Radiant System Configuration

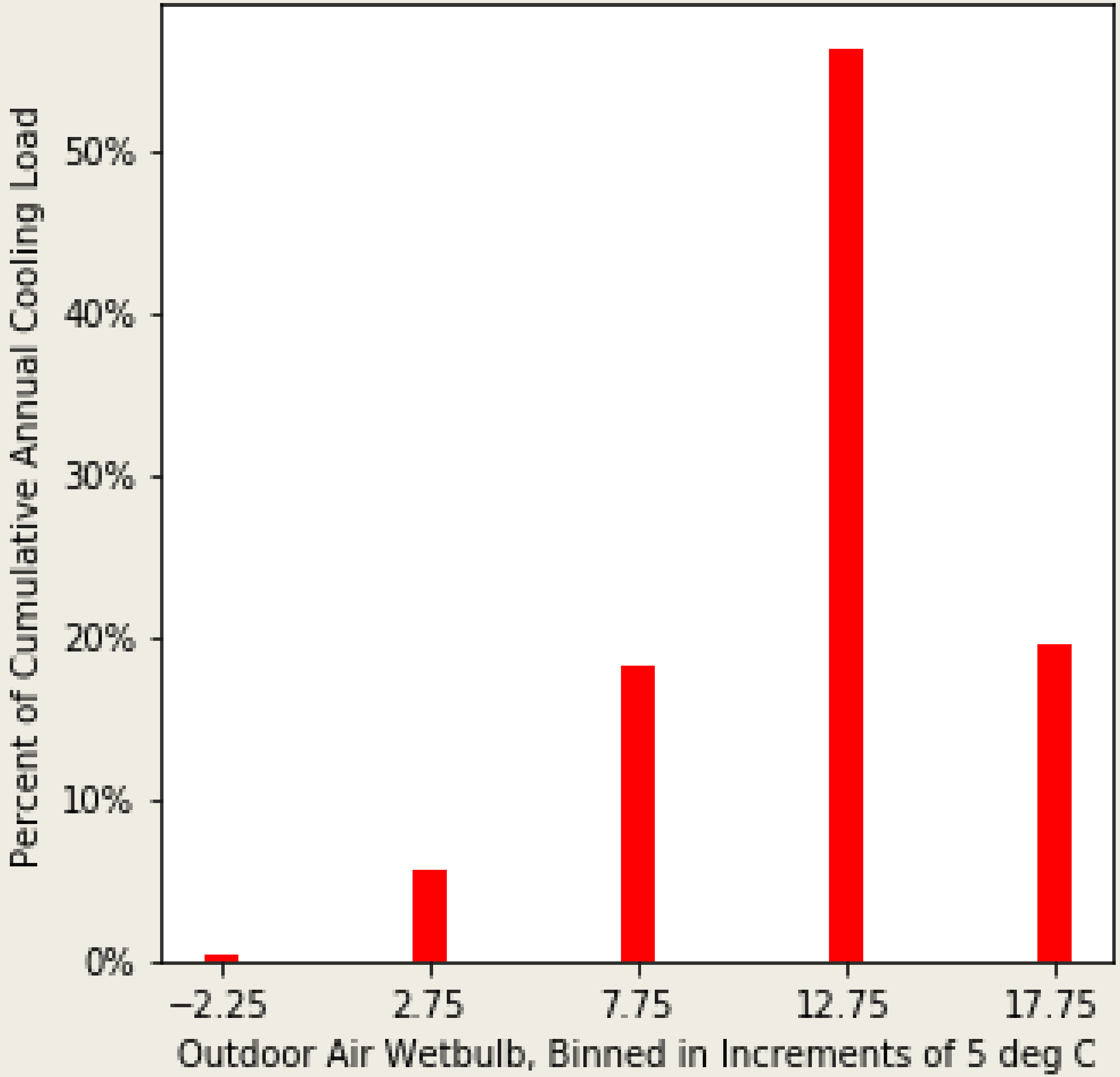




SAT reset from 55°F to 75°F



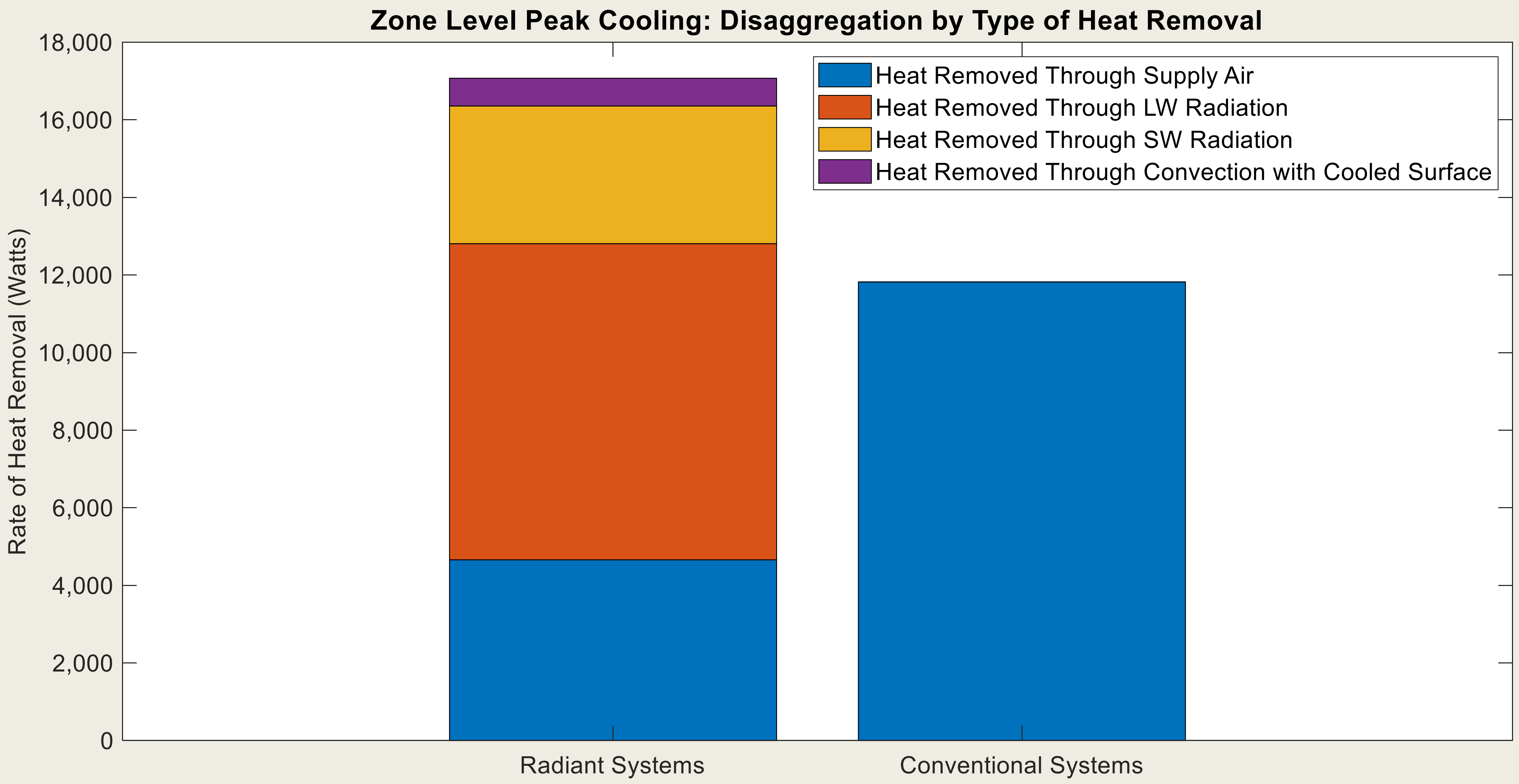
Courtesy of Danfoss, Inc.

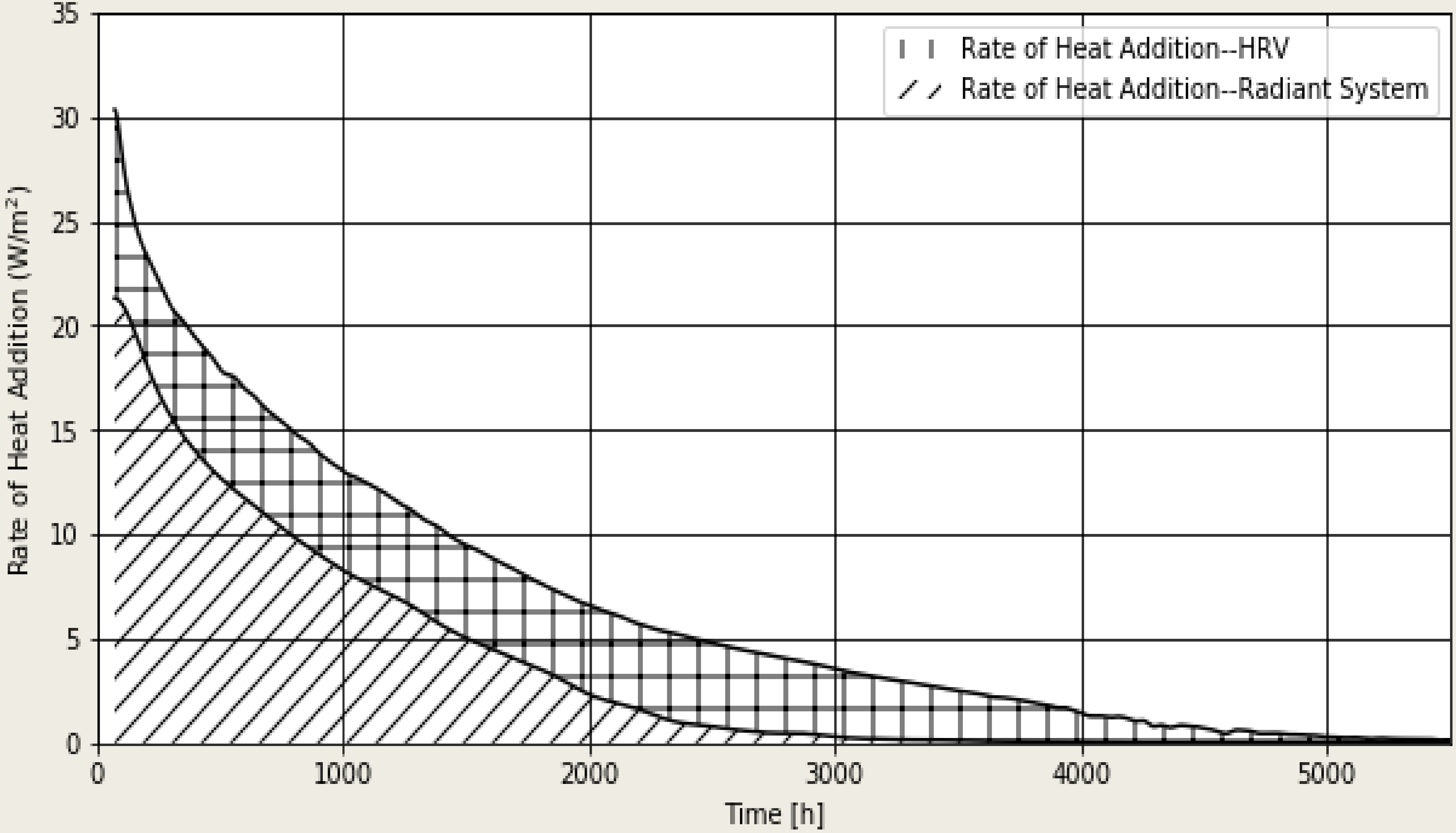


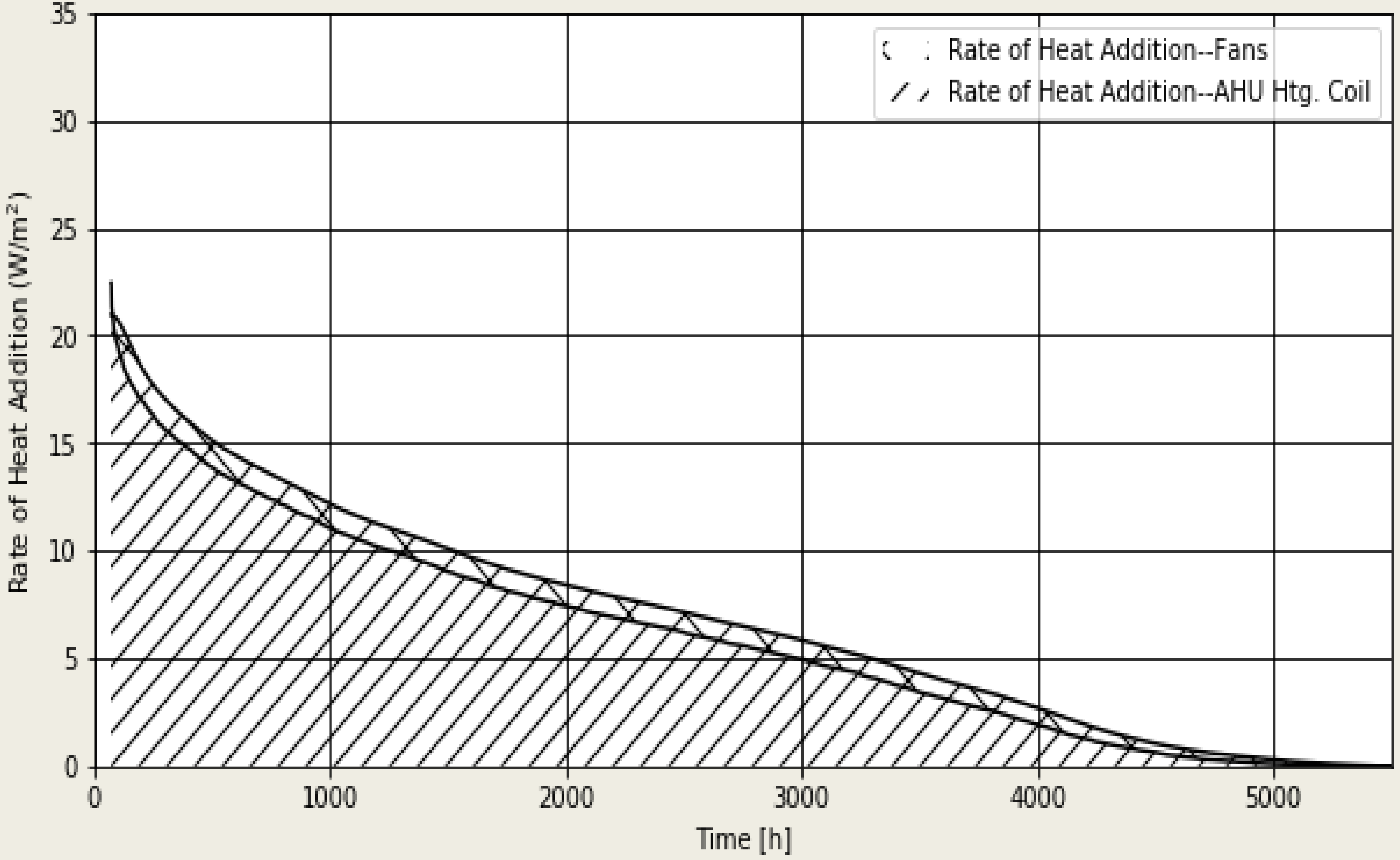
Percent of Cumulative Annual Cooling Load
50%
40%
30%
20%
10%
0%
−2.25
2.75
7.75
12.75
17.75
Outdoor Air Wetbulb, Binned in Increments of 5 deg C

Building-Level Load Results

- Higher peak loads were observed for the radiant cooling system than for the air-based cooling system, both in terms of the “surface cooling load” and the hydronic loop loads, consistent with the results of other work (such as that by Feng, et. al., 2013).
- Thermal loads for heating were similar between the two system types, but “active heating” requirements for the district with radiant systems were significantly lower due to the use of heat recovery ventilation.


Zone Level Peak Cooling: Disaggregation by Type of Heat Removal
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Rate of Heat Removal (Watts)
Heat Removed Through Supply Air
Heat Removed Through LW Radiation
Heat Removed Through SW Radiation
Heat Removed Through Convection with Cooled Surface
Radiant Systems
Conventional Systems

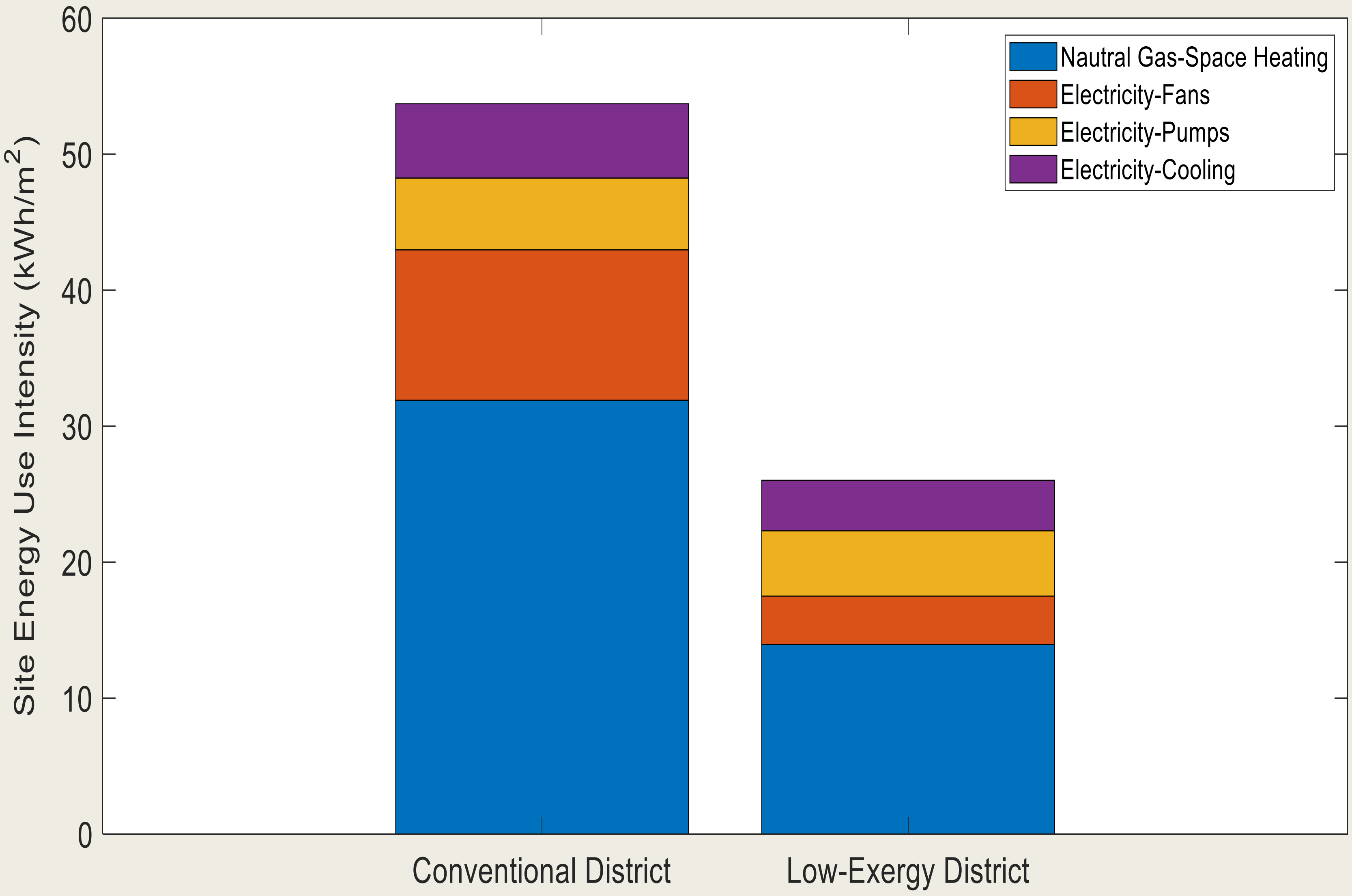

Rate of Heat Addition--HRV
Rate of Heat Addition--Radiant System
Rate of Heat Addition (W/m²)
Time [h]
0
5
10
15
20
25
30
35
0
1000
2000
3000
4000
5000

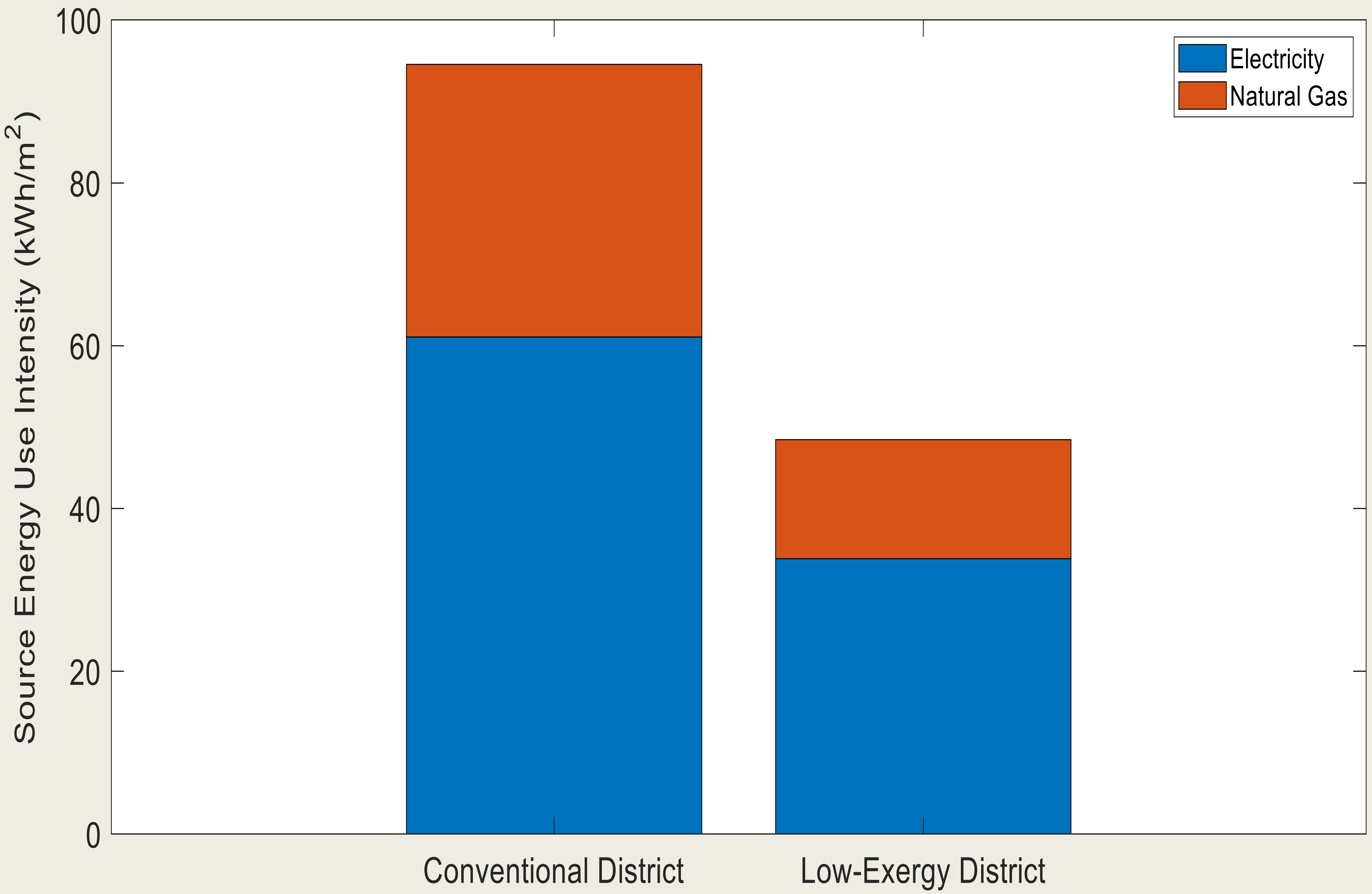


Rate of Heat Addition--Fans
Rate of Heat Addition--AHU Htg. Coil
Rate of Heat Addition (W/m^2)
Time [h]
0
5
10
15
20
25
30
35
0
1000
2000
3000
4000
5000

Benefits of Water-Side Economizing

District	Full Load Chiller Power Use (kW/ton)	Without WSE Total CHW Plant Power Use (kW/ton)	With WSE Total CHW Plant Power Use (kW/ton)
Low-Exergy	.33 and .43	0.62	0.44
Conventional	.33 and .43	0.83	0.78


Site Energy Use Intensity (kWh/m2)
60
50
40
30
20
10
0
Nautral Gas-Space Heating
Electricity-Fans
Electricity-Pumps
Electricity-Cooling
Conventional District
Low-Exergy District



Electricity
Natural Gas
Source Energy Use Intensity (kWh/m2)
100
80
60
40
20
0
Conventional District
Low-Exergy District

Conclusions

- Consistent with the results of Feng, et. al. (2013), peak cooling loads, at the surface level and hydronic level, are higher for the radiant hydronic system than for the air-based system.
- The use of heat recovery ventilation results in significant savings in building-level heating energy use.
- Energy savings results at the primary plant level due to the higher efficiency of the primary equipment operating at more moderate temperatures, the higher nominal efficiency of the condensing boiler, and the increased use of water-side economizing.
- There is significant savings potential for radiant hydronic HVAC systems, mated with low-exergy district thermal energy systems, in serving a low-energy district.

References

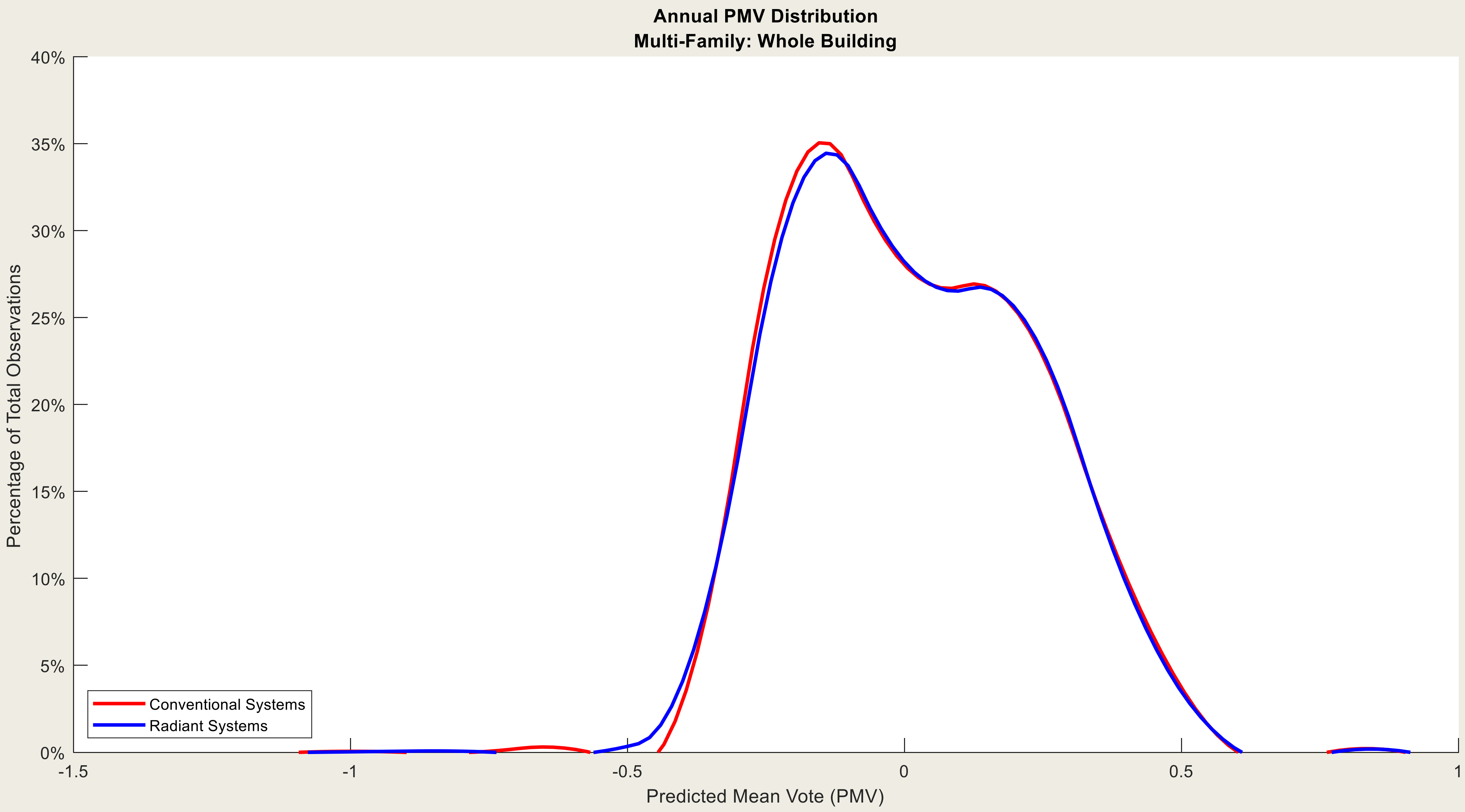
- Dalla Rosa, A., Christensen, J.E. “Low-energy district heating in energy-efficient building areas.” Energy 36 (2011), 6890-6899.
- Danfoss, “Heating the sustainable city.”
- Fanger, P. O. *Thermal Comfort*. Copenhagen, 1970.
- Feng, J., Schiavon, S., Bauman, F. “Cooling load differences between radiant and air systems.“ Energy and Buildings 65 (2013), 310-321.
- U.S. Department of Energy. “Commercial Prototype Building Models.” (2013). Retrieved from: https://www.energycodes.gov/

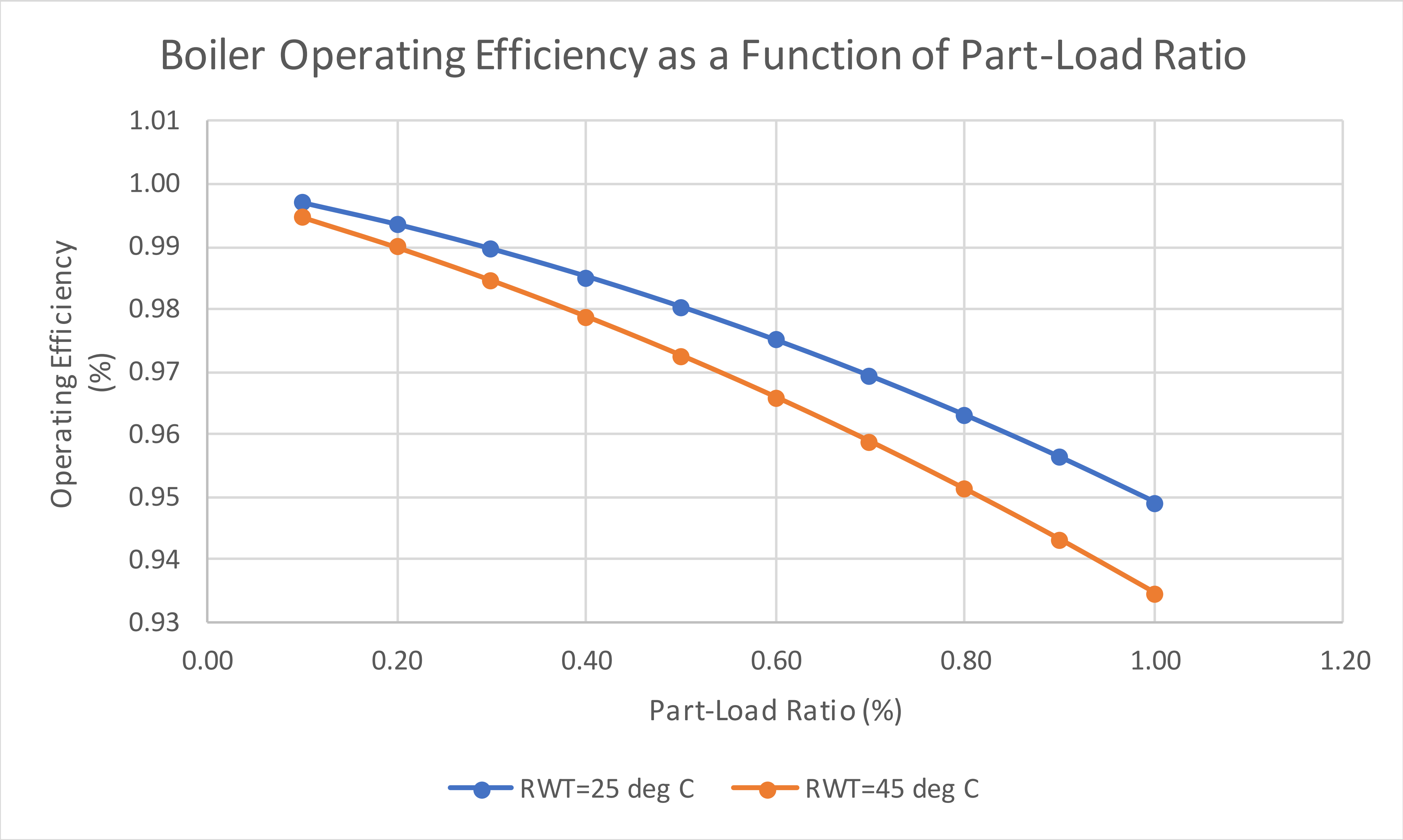
Appendix

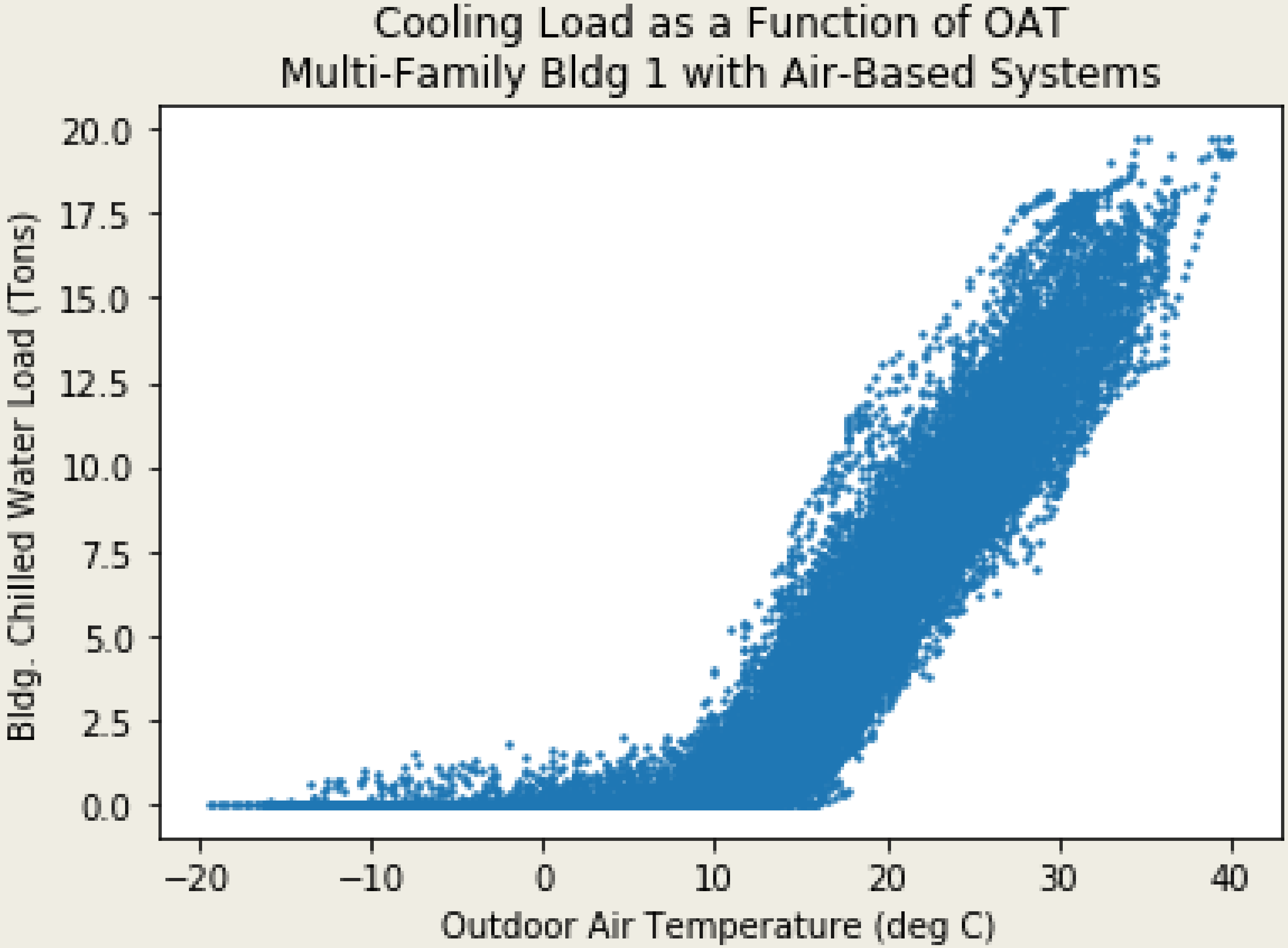
Heat Loss from HHW Supply Pipe, Steady-State Conditions

- All heating hot water and chilled water pipes are buried at a depth of 1 meter, and insulated to R-7.4.
- As expected, the most significant heat transfer occurs with the heating hot water supply pipe.

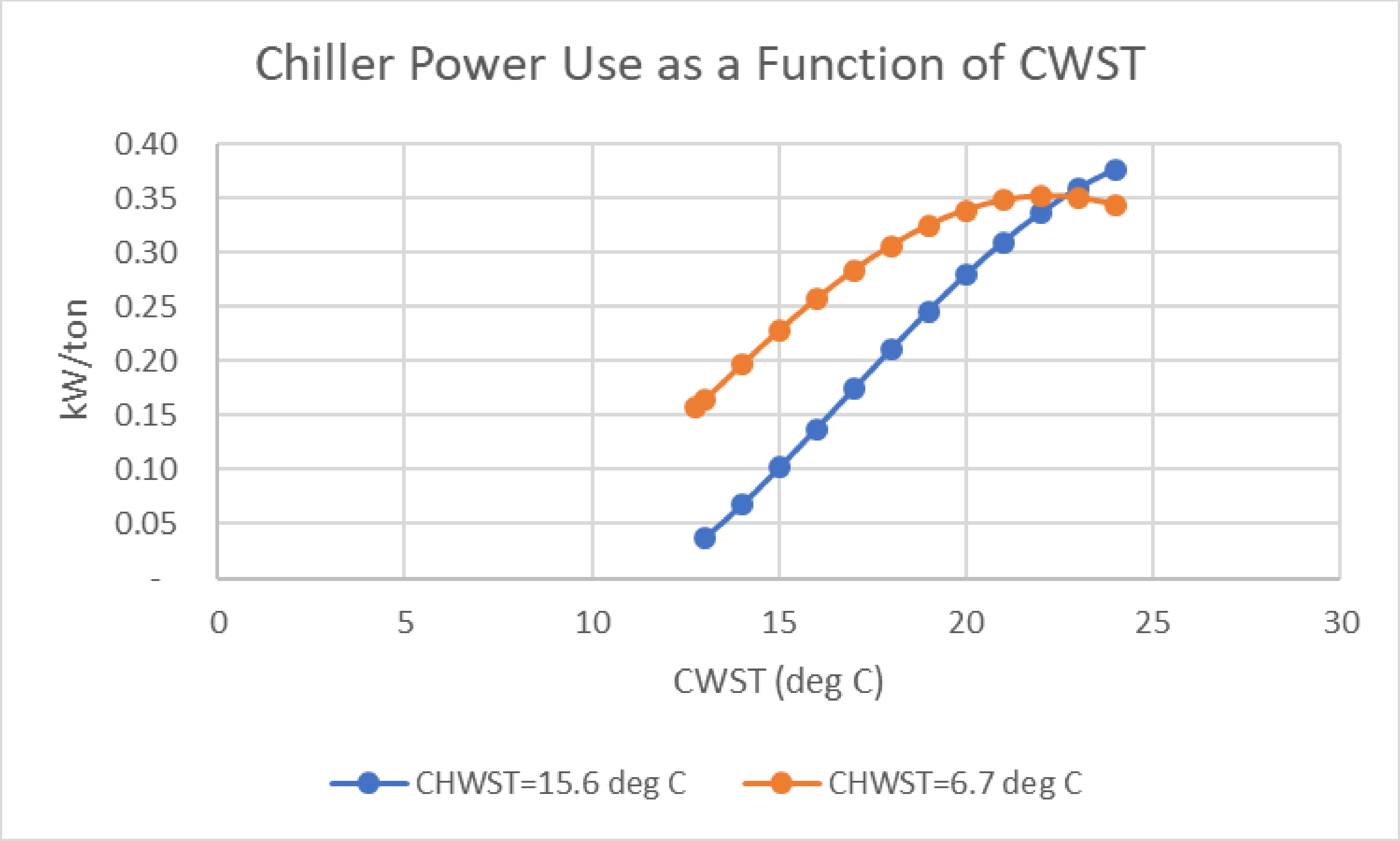
Hot Water Supply Temperature (deg C)	Pipe Heat Loss (W/m)
45	25.0
82	46.9


Annual PMV Distribution
Multi-Family: Whole Building
Percentage of Total Observations
40%
35%
30%
25%
20%
15%
10%
5%
0%
-1.5
-1
-0.5
0
0.5
1
Predicted Mean Vote (PMV)
Conventional Systems
Radiant Systems


Boiler Operating Efficiency as a Function of Part-Load Ratio
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
Operating Efficiency (%)
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Part-Load Ratio (%)
RWT=25 deg C
RWT=45 deg C



Cooling Load as a Function of OAT
Multi-Family Bldg 1 with Air-Based Systems
Bldg. Chilled Water Load (Tons)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
−20
−10
0
10
20
30
40
Outdoor Air Temperature (deg C)


Chiller Power Use as a Function of CWST
kW/ton
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
-
0
5
10
15
20
25
30
CWST (deg C)
CHWST=15.6 deg C
CHWST=6.7 deg C

Metrics for System Comparisons

- Thermal comfort (using the Fanger model): The Fanger model assesses thermal comfort with a predicted mean vote (PMV) by the occupants. The buildings are controlled to have as close as possible values of PMV at each time step, which results in very similar annual distributions of PMV.
- Thermal and electrical energy use at the building level: This reflects energy drawn from district hydronic loops for heating and cooling, and all electrical energy use for building loads.
- Electrical and gas energy use at the central plant level: This reflects the energy input required by the primary equipment at the central plant.