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Making the Switch: Sizing Heat Pumps for Heating Instead of Cooling and the Operational Impacts

Hiroshi Yoh, PhD *ASHRAE member*

Hao Li, PhD *ASHRAE member*

Jon Hacker

Rusty Tharp *ASHRAE member*

Kelly Hearnsberger *ASHRAE member*

ABSTRACT HEADING

Traditionally, refrigerant-based HVAC equipment has been sized to meet cooling loads. This is reflected in the way equipment is tested and rated, the way manufacturers design equipment, through industry processes like ACCA Manual S, and the way many practitioners design solutions and select equipment. This method has worked as refrigerant-based HVAC equipment has mostly been utilized to meet cooling loads while fossil-fuel combustion-based equipment has been used to meet most heating loads.

As heat pumps continue to gain ground as a suitable method to decarbonize homes and buildings throughout cold regions, the cooling-centric practices of sizing refrigerant-based HVAC equipment will need to change. The focus must shift to meeting heating loads with heat pumps. Through energy modeling, this paper explores impacts of a few important factors associated with heat pump equipment, such as sizing factor and compressor lockout temperature. then compare to today's practice for various climate zones. Findings shows a moderate 1.4 sizing factor will provide better peak load efficiency to reduce burden on utilities for both cold climate heat pump and normal heat pump. The impact of sizing factor on seasonable energy consumption is complicated depending on location and type of heat pump. Compressor lockout temperature setting is found to be another key factor can impact both peak load and seasonal energy efficiency.

INTRODUCTION

Electric heat pumps (HPs), which extract heat from the air, ground or water, are an efficient alternative to fuel-fired space conditioning and water heating equipment, and heat pumps have been used widely around the world. However, the type of heat pump and how they are selected and used in the field vary by region. Specifically, the U.S. has unique heat pump selection and usage practices that differ from other parts of the world. And those practices may hurt the effectiveness of heat pumps and their adoption rate in the U.S. Given the fact that space conditioning and water heating consume over 40% (DOE 2021) of the nation's primary energy and are a major source of greenhouse gas (GHG) emissions, using heat pumps effectively could play a big role in providing progress toward decarbonization initiatives.

Hiroshi Yoh is a Director at Daikin North America R&D Center, Houston Texas. Hao Li is a Research Manager at Daikin North America R&D Center. Jon Hacker is Director at Daikin US Corporation, New York. Contributing author Rusty Tharp is Vice President, Regulatory Affairs and Environmental Research at Daikin Comfort Technologies North America, LLC. Contributing author Kelly Hearnsberger is Vice President, Product Marketing at Daikin Comfort Technologies North America, LLC.

CURRENT HEAT PUMP ISSUES IN US

Current sizing and selection guideline. To select appropriately sized units for a given home, the first step is to calculate both the cooling load and heating load. Once the building load is calculated, selection of the unit is performed, typically with ACCA Manual S (ACCA Manual S 2014) as the guideline. Manual S clearly states that a heat pump should be selected by cooling load rather than heating load. One major reason the sizing and selection method in Manual S is based on cooling – along with relatively small sizing factor – is due to concern of dehumidification. During shoulder seasons in regions with high humidity, too largely oversized air conditioning equipment could potentially get into high frequency cyclic operation, and thus cause dehumidification problem. Because even in southern regions of the U.S., the heating load is generally higher than the cooling load (and even more so in middle and North regions), selecting a unit by the heating load may lead to significant oversizing for cooling, therefore potentially cause humidity problems for homes.

However, the current U.S. approach does not necessarily distinguish dry regions from humid ones, neither does it give variable speed units adequate consideration. Variable speed space conditioning equipment can run continuously at 25-30% partial load condition. Some variable speed units also have dehumidification mode that intentionally reduces indoor air flow and lowers setpoint temporarily to reach a higher dehumidification capability. The current sizing guideline will often lead to a unit selected having adequate cooling capacity but lacking heating capacity, and cause installation and use of auxiliary heater.

Heat pump compressor lockout temperature. In the U.S., it is common that heat pump thermostats have compressor lockout temperature setting for heat pump, which will not allow heat pump heating when ambient temperature is below that setting. Because of this common practice, actual capability of heat pump may not matter in real application. In this scenario thermostat will always turn off heat pump and switch to auxiliary heating even when heat pump may have enough capacity. This practice results in inefficient operation of the heating system and potentially increased operational costs to the end-user. Some thermostats have default 30-40°F heat pump operation lockout and this study selects 30 ºF, 15 ºF and None to investigate the impact of different compressor lockout temperature settings.

Table 1. Variables used in this study

Heat pump type	Sizing factor	Location	Compress Lockout temperature
Normal heat pump	DOE Appendix M1	Hot and dry, Fresno, CA	30°F (-1.1°C)
Cold climate heat pump	Extra 140%	Humid, Houston, TX	15°F (-9.4°C)
		Cold climate, Minneapolis, MN	None
		Marine, New York City, NY	
		Mild climate, Memphis, TN	

METHOD OF STUDY

Variables in this paper are summarized in Table 1. For each combination of variables, cooling and heating seasonal energy consumptions are estimated based on performance at DOE M1 testing conditions, adjusted for bin hours at each location and compressor lockout temperature setting. Peak load power consumption is estimated using performance at the bin hour where design temperature belongs to.

It is well understood that sizing factor has a varying impact for different types of equipment's energy consumption. For fixed speed equipment, oversizing will lead to more frequent cyclic operation and lower energy efficiency. For variable speed equipment, the issue is less severe due to variable speed unit's better efficiency at partial load. Equation 4.1-2 in DOE Appendix M1 (10 CFR 430.4.1) has sizing factor of 1.1 as the default sizing factor for cooling.As comparison to DOE, ACCA Manual S allows a bigger sizing factor for variable speed than single speed and two speed, with the max sizing factor as 1.3. However, in the field it is common that contractors oversizing more in order to reduce possible call backs related to comfort regardless of equipment type. Past studies shown that actual sizing factor varies in a wide range. A field study (Scott Pigg, 2010) with roughly 40 homes found sizing factor in the range of 0.8-3.6 with average of 1.5. Another study with 40 homes (Proctor 1995) shows average sizing factor 1.2 with range between 0.6-3.0. FSEC (Townsend and Ueno 2008) conducted study for 368 houses found average sizing factor is 1.23 with range between 1.2-1.6. This study uses 1.4 sizing factor in addition to DOE's standard 1.1 sizing factor for cooling.

Table 2. Basic Information of Locations

City	State	Cooling design temperature, 1%, °F (°C)	Cooling load hours	Heating design temperature, 99%, °F (°C)	Heating load hours	Heating climate zone
DOE M1 region IV	N/A	95 (35.0)	800	5 (-15.0)	2,250	IV
Fresno	CA	104 (40.0)	3,775	16 (-8.9)	3,215	IV
Houston	TX	97 (36.1)	5,655	29 (-1.7)	2,266	I
Minneapolis	MN	89 (31.7)	2,064	-11 (-23.9)	5,418	V
New York City	NY	92 (33.3)	2,728	10 (-12.2)	4,438	IV
Memphis	TN	97 (36.1)	4,354	20 (-6.7)	2,983	III

Heat Pump Systems Evaluated

The U.S. Department of Energy (DOE) announced the Cold-Climate Heat Pump (ccHP) Challenge in October 2021 (DOE 2021), with the understanding that current conventional heat pumps may not be effective for colder regions such as the northern most states in the U.S.. There are two heat pump units used as the base models for this study, both are variable speed. One is a cold climate heat pump 3-ton (10.6 kw) unit designed for DOE ccHP challenge that has 5°F (-15°C) heating capacity of 3 ton with a coefficient of performance (COP) equals to 2.4 or higher. The other is a non-cold climate heat pump 3-ton unit. In order to investigate the impact of various climate zones, five cities are picked as representative locations. Table 2 shows some key cooling and heating design conditions for each city. Table 3 and Table 4 summarize cooling and heating bin hours for each location from the weather data in EnergyPlus 22.2.

Table 3. Cooling Bin Hours of Locations

Bin number, j	Representative temperature for bin, °F (°C)	Fraction of total temperature bin hours, nj./N					
		Region IV in M1	Fresno, CA	Houston, TX	Minneapolis, MN	New York City, NY	Memphis, TN
1	67 (19.4)	0.214	0.232	0.167	0.234	0.366	0.188
2	72 (22.2)	0.231	0.191	0.199	0.343	0.305	0.231
3	77 (25)	0.216	0.158	0.281	0.228	0.207	0.231
4	82 (27.8)	0.161	0.128	0.171	0.157	0.098	0.165
5	87 (30.6)	0.104	0.105	0.117	0.029	0.021	0.117
6	92 (33.3)	0.052	0.084	0.057	0.010	0.003	0.063
7	97 (36.1)	0.018	0.073	0.007	0	0	0.004
8	102 (38.9)	0.004	0.029	0	0	0	0

Table 4. Heating Bin Hours of Locations

Bin number, j	Representative temperature for bin, °F (°C)	Fraction of total temperature bin hours, nj./N					
		Region IV in M1	Fresno, CA	Houston, TX	Minneapolis, MN	New York City, NY	Memphis, TN
1	62 (16.7)	0	0	0	0	0	0
2	57 (13.9)	0	0	0.320	0	0	0
3	52 (11.1)	0.321	0.321	0.259	0.109	0.158	0.228
4	47 (8.3)	0.291	0.291	0.165	0.118	0.180	0.196
5	42 (5.6)	0.201	0.201	0.139	0.063	0.185	0.211
6	37 (2.78)	0.127	0.127	0.073	0.141	0.187	0.133
7	32 (0)	0.053	0.053	0.034	0.119	0.140	0.118
8	27 (-2.8)	0.008	0.008	0.010	0.088	0.067	0.081
9	22 (-5.6)	0	0	0	0.044	0.049	0.022
10	17 (-8.3)	0	0	0	0.087	0.027	0.009
11	12 (-11.1)	0	0	0	0.066	0.006	0.002
12	7 (-13.9)	0	0	0	0.069	0.001	0
13	2 (-16.7)	0	0	0	0.046	0	0
14	-3 (-19.4)	0	0	0	0.015	0	0
15	-8 (-22.2)	0	0	0	0.023	0	0

16	-13 (-25)	0	0	0	0.010	0	0
17	-18 (-27.8)	0	0	0	0.001	0	0
18	-23 (-30.6)	0	0	0	0	0	0

DATA ANALYSIS

Cooling performance

Cooling performance are summarized in Figure 1. For all five locations, ccHP unit shows lower annual cooling energy consumption and peak load energy consumption. The reason is ccHP unit is running mostly at partial load due to its increased cooling capacity. Therefore, more partial load operation leads to better efficiency than non-ccHP unit.

Impact of 1.4 sizing factor is reflected in Figure 2. Comparing Figure 1 and Figure 2, it can be seen that bigger sizing factor benefits non-ccHP unit on annual cooling energy efficiency and peak load efficiency for all five locations. But the result for ccHP unit is mixed depending on location. For hotter region, Houston and Fresno, both annual cooling efficiency and peak load efficiency improve by bigger sizing. The reason is much of the bin hour is at higher temperature so bigger unit can run more at partial load. The same goes for peak load efficiency. But for cold to mild region, Minneapolis, New York and Memphis, although peak load efficiency still improves slightly, annual cooling efficiency drops. The reason is excessive oversizing for those three locations since we are using the 1.4 sizing factor in addition to the ccHP design that is essentially oversized already.

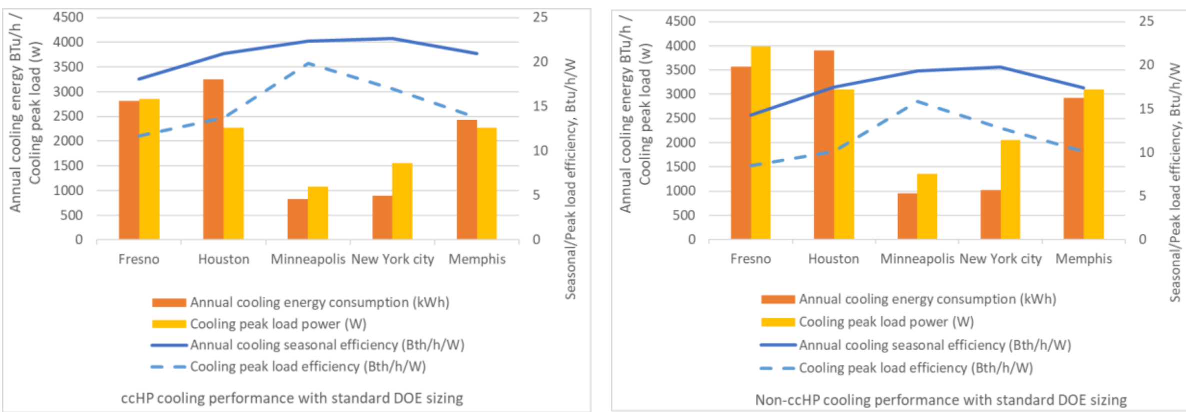

Figure 1 Cooling performance with standard DOE sizing

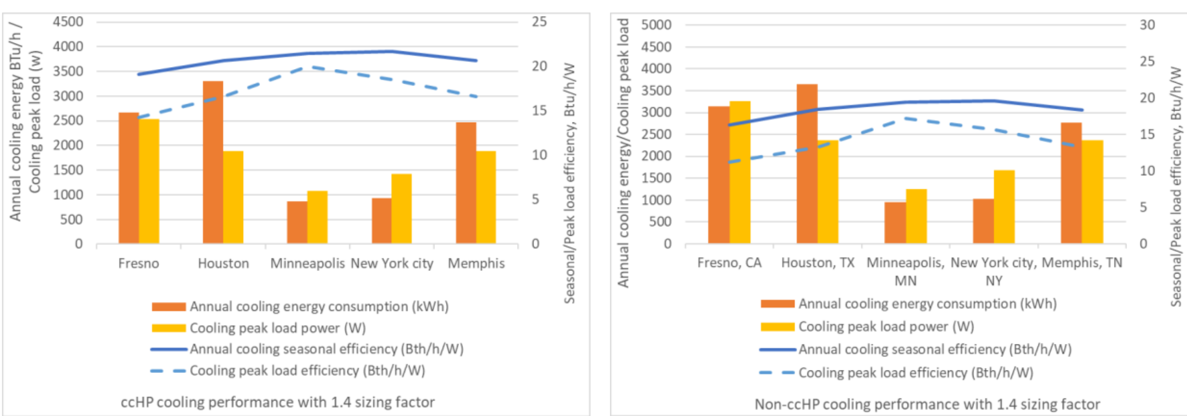

Figure 2 Cooling performance with 1.4 sizing factor

Heating performance

Compressor lockout temperature setting impact for heating. Comparing Figure 3 (a) and (b) where compressor lockout temperature setting is 30°F, it can be seen that seasonal heating efficiency is slightly improved by ccHP comparing to non-ccHP. The reason seasonal heating efficiency doesn't improve more drastically is because the compressor lockout temperature is too high to truly utilize the benefit of ccHP. For warmer regions, Fresno and Houston, the improvement of ccHP is bigger than colder regions because the majority of the operational hours are above 30°F, so the efficiency advantage of ccHP is greater. Freso has only 8% of its heating hours below 30°F while Houston has 10%. For other locations, annual efficiency improvements by ccHP is limited because a big portion of heating hours are below 30°F so the efficiency difference between ccHP and non-ccHP is hidden by the excessive use of electric resistance heat. Peak load efficiency for all five locations has a COP of 1.0 for both ccHP and non-ccHP because electric resistance heat is utilized at the peak load condition for both systems.

When compressor lockout temperature is lowered to 15°F, as shown in Figure 3 (c) and (d), all seasonal heating efficiencies are improved while three out of five cities saw peak load efficiency improvements. Especially for colder region, Minneapolis, New York and Memphis, the seasonal energy consumption is lowered significantly. But the improvement is not as large for warmer region, like Fresno and Houston. The reason is the portion of bin hours between 15°F and 30°F, which is 8% for Fresno and 10% for Houston, is too small to make a meaningful improvement in seasonal energy consumption. The impact to peak load efficiency is the opposite. Warmer regions like Fresno, Houston and Memphis do not need to use electric-resistance heat with the lower lockout compressor temperature, therefore they realized peak load efficiency improvements. For cold regions, Minneapolis and New York, the peak load efficiency is still determined by electric resistance heat, as the design temperature in both locations is below 15°F.

Figure 3 (e) and (f) show data when compressor lockout temperature does not exist and heat pump only switches to electric resistance heat when COP of the heat pump is less than 1.0. There is no impact on warmer region because all the bin hours are above 15°F. The seasonal heating efficiency improves in New York and Memphis as the heat pump can provide more capacity with the compressor lockout eliminated. But the improvement is minor due to small percentage of bin hours below 15°F, in which New York has 7% and Memphis has 2%. The biggest seasonal efficiency improvement comes from Minneapolis where 23% of bin hours are below 15°F. For Fresno, Houston and Memphis, peak load efficiency stays the same comparing to scenarios where compressor lockout at 15ºF as shown in Figure 3 (b) and (c) because their design temperature is above 15°F. Minneapolis sees slightly peak load efficiency improvement where heat pump can still provide partial capacity at its design temperature and electric heater supplies the rest of the capacity. Memphis has better peak load efficiency improvement with ccHP but only slightly improvement with non-ccHP. The reason is ccHP can provide more capacity at design temperature than non-ccHP, therefore more electric heater power has to be used along with non-ccHP in this case.

Standard DOE M1 sizing vs 1.4 sizing factor. Figure 4 for 1.4 sizing factor can be compared with standard DOE M1 sizing in Figure 3. For compressor lockout temperature setting at 30°F, all locations with ccHP in Figure 4 (a) have slightly lower seasonal heating efficiency due to excessive sizing, similar to cooling performance. Non-ccHP in Figure 4 (b) shows very little improvement on seasonal heating efficiency in Minneapolis, New York and Memphis, and negative impact in Fresno and Houston. The relative smaller sizing factor comparing to ccHP allows non-ccHP unit to have some advantage at mild temperatures, but still see efficiency loss at warm region where oversizing can lead to cyclic operation and lower efficiency at higher ambient temperature. With 30°F compressor lockout temperature, oversizing does not provide much benefit for mild and cold region and oversizing results in lower seasonal heating efficiency for warm regions.

For all locations, the compressor lockout at 15°F for ccHP with 1.4 sizing factor has worse seasonal heating efficiency comparing to 30°F setting except Minneapolis, which is unchanged. With less effective oversizing factor comparing to ccHP, non-ccHP unit has worse seasonal heating efficiency in warm regions (Fresno and Houston) but has a slight improvement in other locations (Minneapolis, New York, Memphis). Warm regions selected in this study has little bin hours below 30°F, so they do not experience a benefit for either ccHP or non-ccHP when dropping the compressor lockout temperature below 30°F. Colder region can benefit from reducing the compressor lockout temperature as those regions have more bin hours below 30°F and that leads to slight seasonal heating performance improvement.

Results for no compressor lockout temperature are shown in Figure 4 (e) and (f). For ccHP, all but one location still has lower seasonal heating efficiency performance with the 1.4 sizing factor when compared to the DOE sizing factor. The one location with improved seasonal efficiency is Minneapolis, which benefitted from an 8% improvement from the 1.4 sizing factor due to its extremely cold climate. Non-ccHP unit with 1.4 sizing factor shows seasonal heating efficiency improvement for mild and cooler region (Memphis, Minneapolis, New York), but loss at warm region (Fresno and Houston). These results demonstrate that seasonal heating efficiency improves with sizing factor of 1.4 for non-ccHP equipment in mild and cold regions because its partial load performance advantage is materialized. The sizing factor of 1.4 is not recommended for ccHP equipment unless it is in cold region like Minneapolis due to excessive oversizing can cause loss on seasonal heating efficiency.

The results for peak load efficiency show a different trend with the 1.4 sizing factor. Generally, if the compressor is working at peak load condition, ccHP unit sees improvement for all locations except Houston with slight reduction in peak load efficiency of about 1%. The reason for this is Houston has the highest design temperature (29°F) and the 1.4 sizing factor is too big with ccHP equipment. The non-ccHP equipment, shows higher peak load efficiency for all locations with 1.4 sizing factor comparing to ccHP. If compressor lockout temperature setting switches to electric resistance heater at design condition, the peak load COP would be 1.0 regardless of location or sizing factor. This result shows that proper compressor lockout temperature setting is critical to fully realize the efficiency benefit provided by heat pumps.

CONCLUSION

The results indicate that the performance metrics, peak load efficiency and seasonal cooling/heating efficiency do not necessarily align for each system type, compressor lockout temperature and sizing factor evaluated. The followings are the main conclusions from this study.

1. Generally heating peak load efficiency will benefit from oversizing practice, especially for cold region. In warm region where peak load condition happens at high ambient temperature, it is possible the ccHP will have slight efficiency loss if oversized too much but the difference is negligible. 1.4 sizing factor, which is a common oversizing practice in the field, is not a big concern for both ccHP and non-ccHP for all locations investigated.
2. Compressor lockout temperature setting has huge impact on peak load efficiency. The colder the region, the more important of proper compressor lockout setting is. Current common setting of 30-40ºF is too high for any location and heat pump types. 15F setting is acceptable for warm and mild region. Removal of compressor lockout setting does not have impact on warm and mild regions, but shows improvement for cold region.
3. Compressor lockout temperature also has impact on seasonal heating performance. The lower the setting, the better the seasonal heating efficiency, especially for mild and cold regions. This applies to both ccHP and non-ccHP and both sizing factors.
4. Sizing factors are important in terms of seasonal heating performance as well. Further oversizing ccHP does not bring meaningful improvement to cold region and actually has loss of efficiency in warm and mild regions. Non-ccHP performs better when sized with 1.4 sizing factor in cold and mild regions, but still show lower season heating efficiency in warm regions comparing to standards sizing.
5. For cooling performance, 1.4 sizing factor benefit peak load efficiency for all locations and both ccHP and Non-ccHP units, especially for warm regions. 1.4 sizing factor shows mild improvement or slightly negative impact on seasonal cooling efficiency for colder region but this impact is negligible given low cooling load for those regions. ccHP in warm region sees improvement on seasonal cooling performance with 1.4 sizing factor, but other location shows slight performance loss due to excessive oversizing. Non-ccHP with 1.4 sizing factor has better seasonal cooling performance improvement in warm and mild region and negligible impact in colder region. It suggests that 1.4 sizing factor is favorable for both ccHP and non-ccHP if peak load is the focus, but becomes generally negative for ccHP and favorable for non-ccHP at warmer regions when seasonal cooling efficiency is the focus.

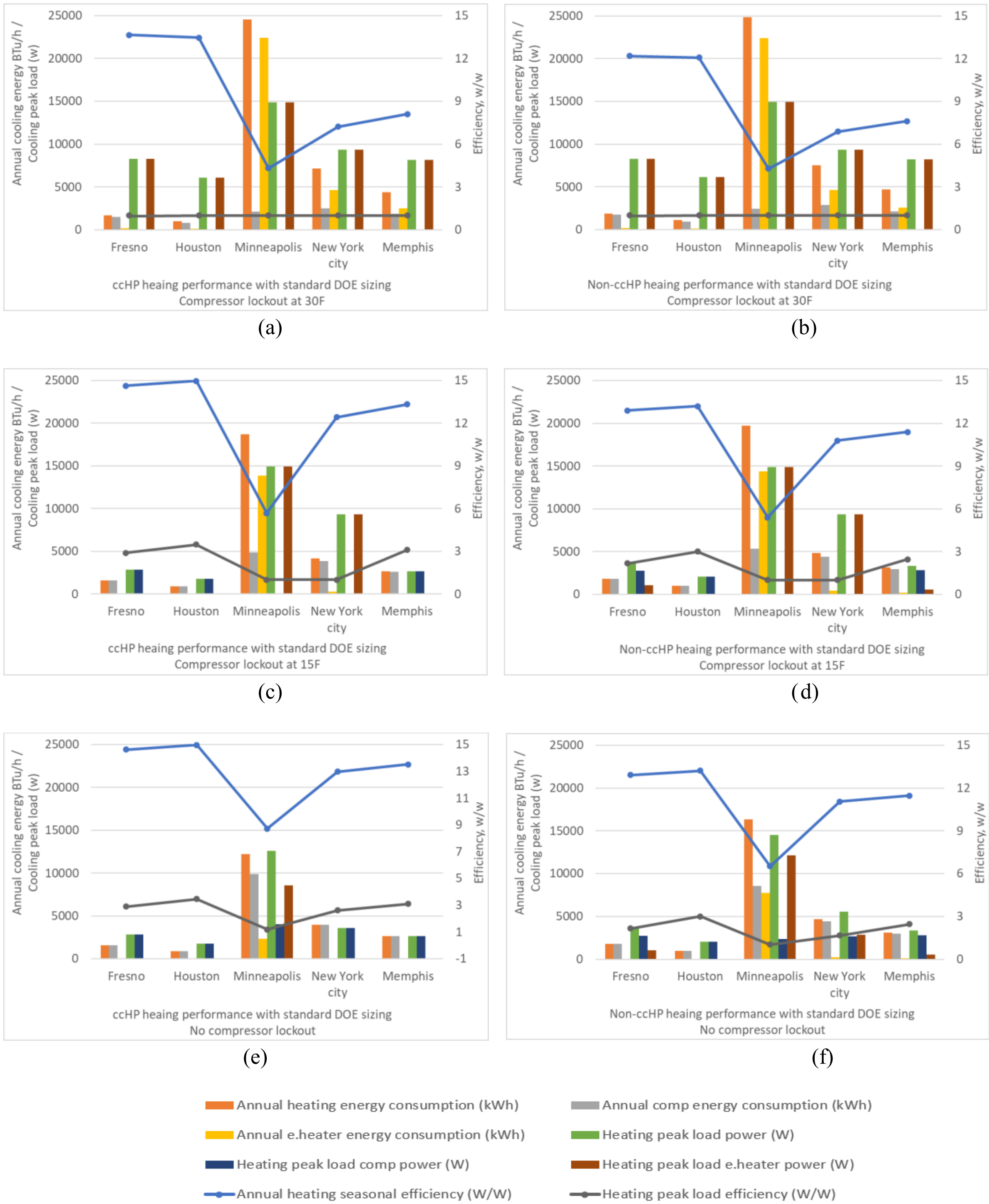

Figure 3 Energy consumption and efficiency at each location with DOE standard sizing factor

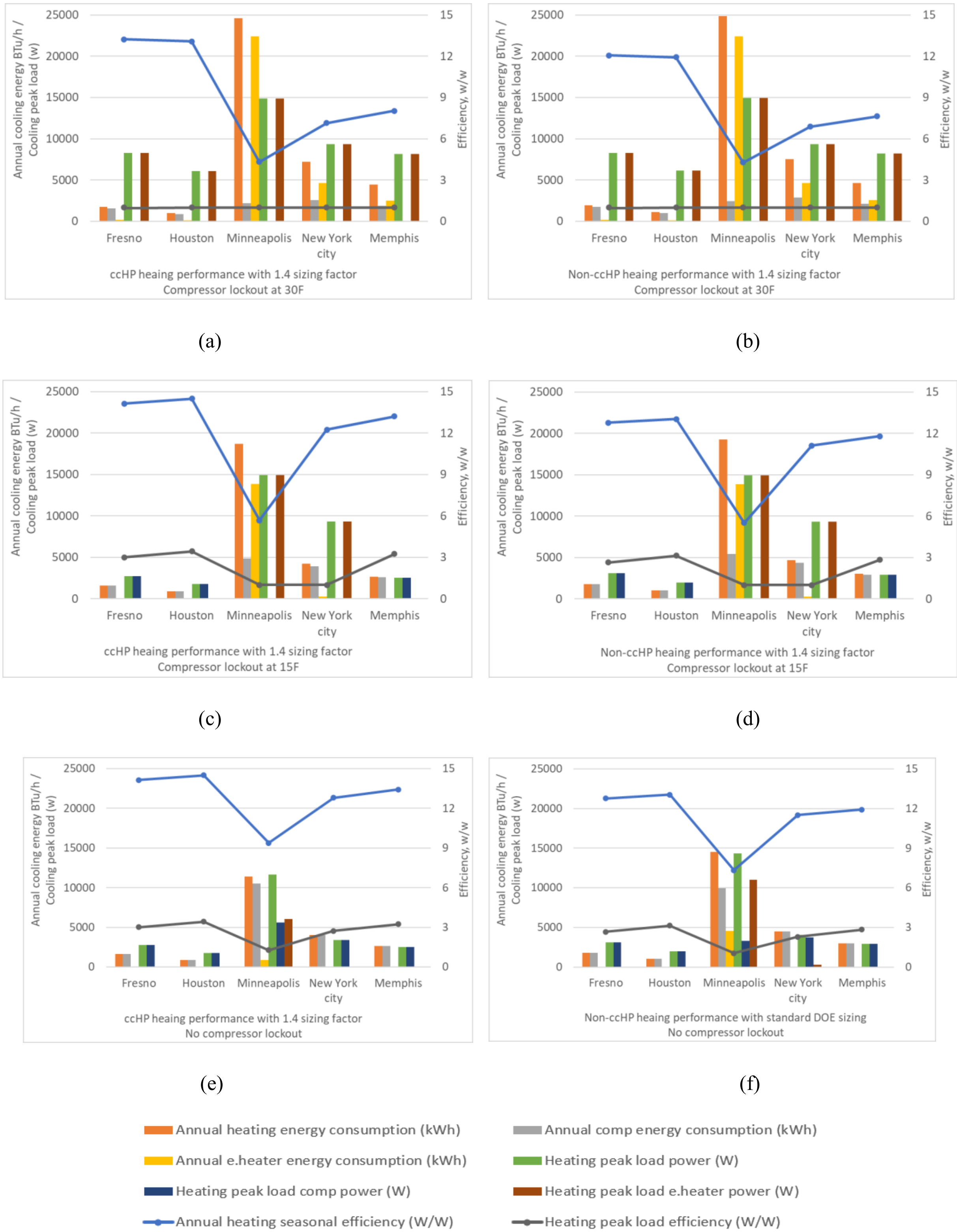

Figure 4 Energy consumption and efficiency at each location with 1.4 sizing factor

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