Have Cold Climate Air-Source Heat Pumps Caught Up with Ground Source Heat Pump Performance?

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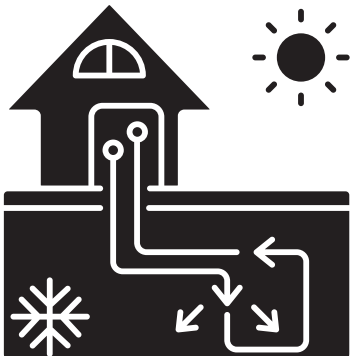

Article by:
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Introduction

There have been many advances in heat pump technology over the past decade. “Cold Climate” air-source heat pumps (ASHPs) are the latest offering, taking advantage of new developments in compressor and control improvements, like variable speed inverter-driven compressors and vapor injection technology, which has increased both heating efficiency and capacity even at temperatures below 0˚F (-17.8˚F). With all of these technological advancements, the logical question is, “have cold climate air-source heat pumps caught up with ground source heat pump performance?”. This article will review efficiencies and capacities of Energy Star® Cold Climate ASHPs, compared to variable speed ground source heat pumps (GSHPs) for a truly cold climate application, Rochester, Minnesota.

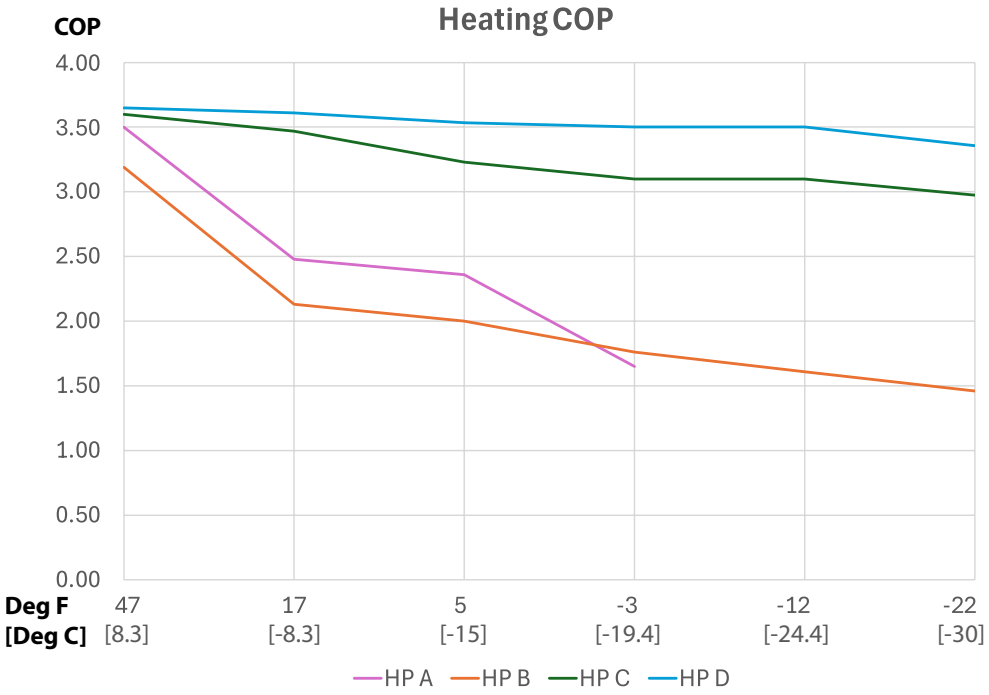
By definition, a cold climate ASHP must have a COP (Coefficient of Performance) at 5˚F (-15˚C) greater than 1.75 and a heating capacity at 5˚F (-15˚C) outdoor air temperature greater than 70% of the capacity at 47˚F (8.3˚C). COP is the ratio of output to input. A COP of 1.75 means that for each Watt of electricity used, the heat pump provides 1.75 Watts of heating. Figure 1 shows COP for two cold climate ASHP heat pumps (heat pumps A and B) and two variable speed ground source heat pumps (heat pumps C and D) for comparison. Both of the ASHPs have a COP greater than 2.0 at 5˚F (-15˚C). Below are details on the heat pumps chosen for this comparison.

Heat Pump A: Nominal 4 ton (cooling) cold climate ASHP with a heating capacity of 36,000 Btuh (10.5 kW) at 5˚F (-15˚C), 79% of capacity at 47˚F (8.3˚C).

Heat Pump B: Nominal 4 ton (cooling) cold climate ASHP with a heating capacity of 48,000 Btuh (14.1 kW) at 5˚F (-15˚C), 70% of capacity at 47˚F (8.3˚C).

Heat Pump C: Nominal 4 ton (cooling) GSHP with an AHRI heating capacity of 60,000 Btuh (17.6 kW) at 32˚F (0˚C) EWT (Entering Water Temperature).

Heat Pump D: Nominal 4 ton (cooling) GSHP with an AHRI heating capacity of 42,000 Btuh (12.3 kW) at 32˚F (0˚C) EWT (Entering Water Temperature).



*For GSHPs, the EWTs (Entering Water Temperatures) are from 40 deg F [4.4 deg C] at 47 deg F [8.3 deg C] to 28 deg F [-2.2 deg C] at -22 deg F [-30 deg C], which is typical for this example in Rochester, Minnesota.

Figure 1: Heating COP for four heat pumps chosen for comparison

Data Analysis

The heat pumps for this comparison were selected based upon AHRI (Air Conditioning, Heating, and Refrigeration Institute)/Energy Star performance ratings and the manufacturers' extended data for capacity and efficiency outside of the rated performance. A typical 20-year old 2,500 square foot (232 square meter) home in Rochester, Minnesota was selected to provide a truly cold climate comparison. The following ACCA (Air Conditioning Contractors of America) *Manual J* heat loss and heat gain calculations were used as the basis for analyzing all four heat pumps:

Heat Loss	57,500 Btu/hr (16.8 kW) at -12˚F (-24.4˚C) outdoor temperature
Heat Gain	33,250 Btuh/hr (9.7 kW) at 82˚F (27.8˚C) outdoor temperature

To avoid oversizing in the cooling mode, ACCA *Manual S* was used to determine the size of the heat pump. Rochester is considered a cold climate by *Manual S*, which allows up to 15,000 Btu/hr (4.4 kW) over the cooling load (heat gain) for variable speed heat pump sizing. In this example, the largest allowable heat pump (to handle as much of the heating load as possible) is 48,250 Btu/hr (14.1 kW), which is 15,000 Btu/hr + 33,250 Btu/hr (4.4 kW + 9.7 kW). A nominal 4 ton (14.1 kW) cooling capacity heat pump was applied for the purposes of comparing the technologies. The manufacturer of "heat pump A" had a cut-off temperature of -3˚F (-19.4˚C); the other three heat pumps had published data at or below the heating design temperature for Rochester.

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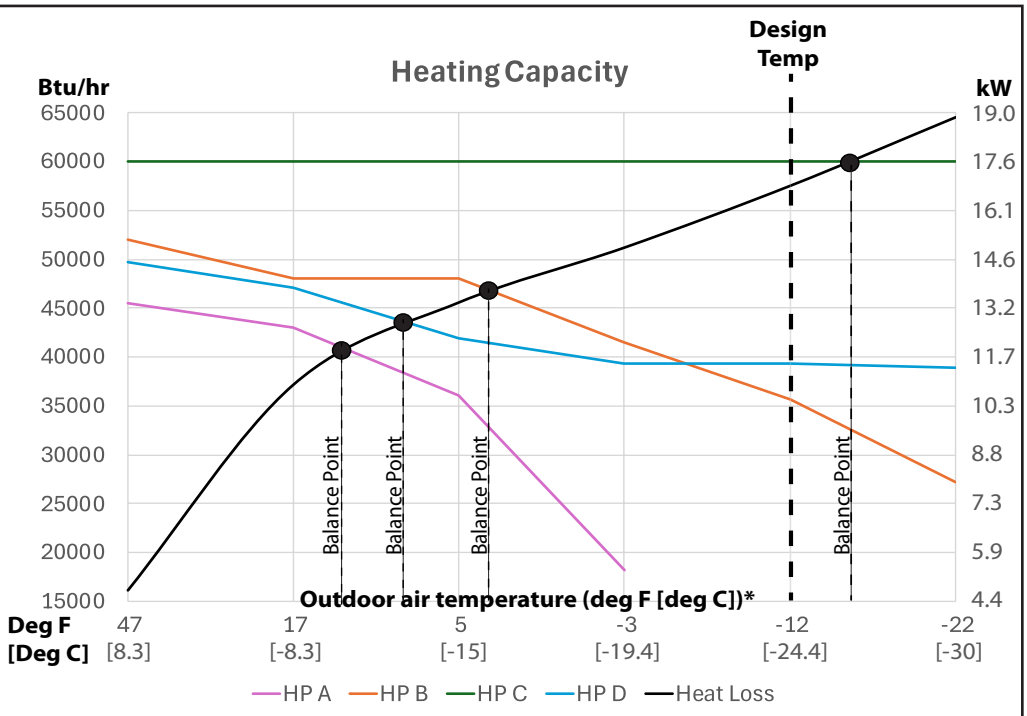

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Figure 2: Heating capacity of air-source and ground source heat pumps

As shown in Figure 1, newer ASHP designs have significantly better efficiencies than previous generations. Sometimes, however, high efficiency is equated to low operating costs and/or low electric grid impact without considering all of the inputs that are needed to determine how one technology compares to another in overall effectiveness. Obviously, overall effectiveness must be defined in terms of the expected outcomes. For example, the goal may be lowest installation cost, lowest operating cost, lowest electric grid impact (i.e., peak demand kW), equipment location (i.e., indoors vs. outdoors), longest life cycle, or other requirements. Figure 2 allows comparison of the heating capacity of the four heat pumps at design conditions to determine how much heat the heat pump can produce versus the amount of backup heat needed. The solid black curved line (curved upwards from left to right) represents the heating load from 47˚F (8.3˚C) to -22˚F (-30˚C) outdoor temperature. The thick dashed vertical line in Figure 2 is the winter design condition for Rochester, Minnesota, -12˚F (-24.4˚C) outdoor temperature. "Heat pump A" will not operate at the design condition or below. The others can operate at the design temperature and below.

Figures 3 to 6 help determine how much of a deficit will occur at design conditions that must be augmented with backup heat. Table 1 summarizes the amount of backup needed at design conditions (and colder) based upon the heat pump heating capacity. The "deficit" can be a large cost, depending upon the electric rate, the amount of hours operating below the balance point (more on balance point forthcoming), and the type of rate tariff (i.e., straight cost per kWh or cost per kWh based upon time of day). Therefore, the capacity must be considered along with the efficiency to determine the performance characteristics of the heat pump selection.

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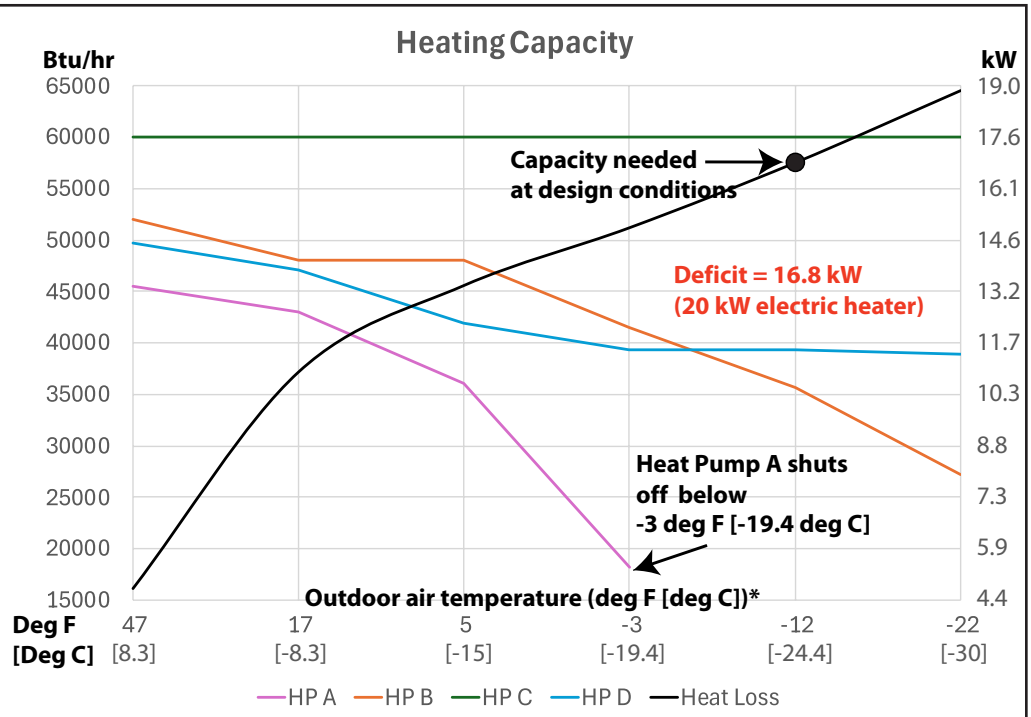

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Figure 3: Heating capacity deficit, "heat pump A"

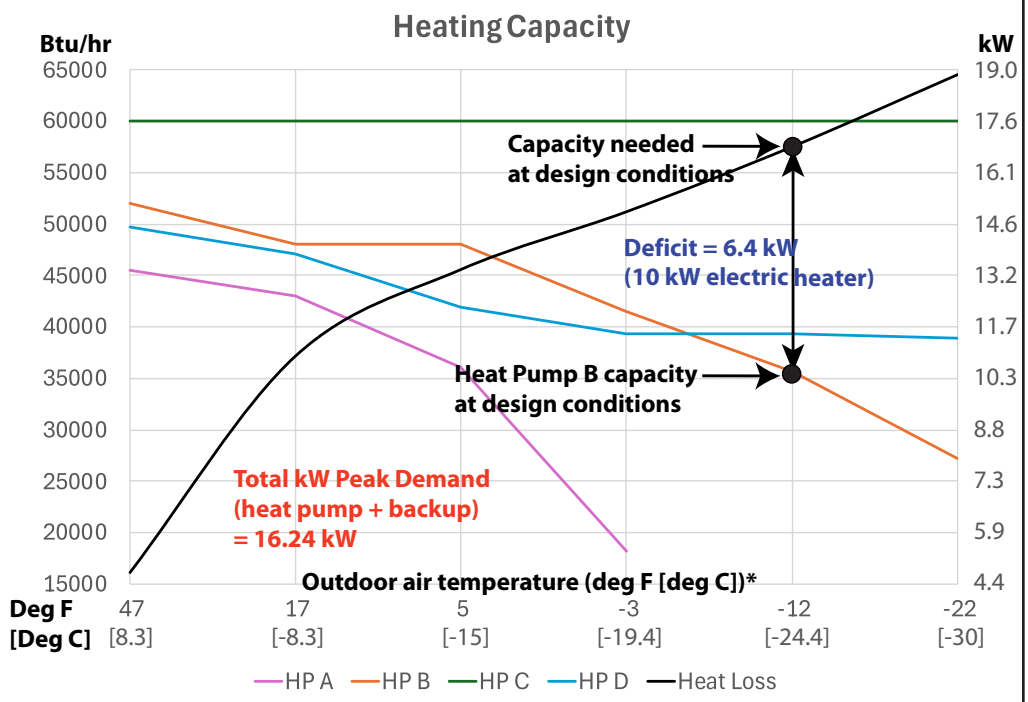

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Figure 4: Heating capacity deficit, "heat pump B"

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Heat Pump D: Nominal 4 ton (cooling) GSHP with an AHRI heating capacity of 42,000 Btuh (12.3 kW) at 32˚F (0˚C) EWT (Entering Water Temperature).

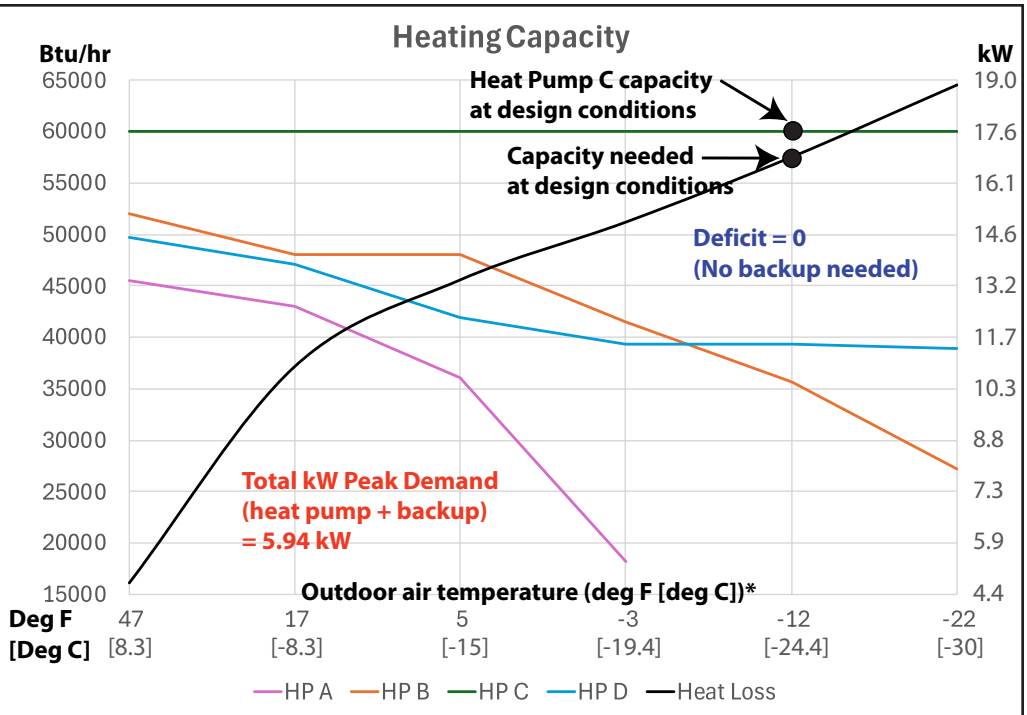

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Figure 5: Heating capacity deficit, "heat pump C"

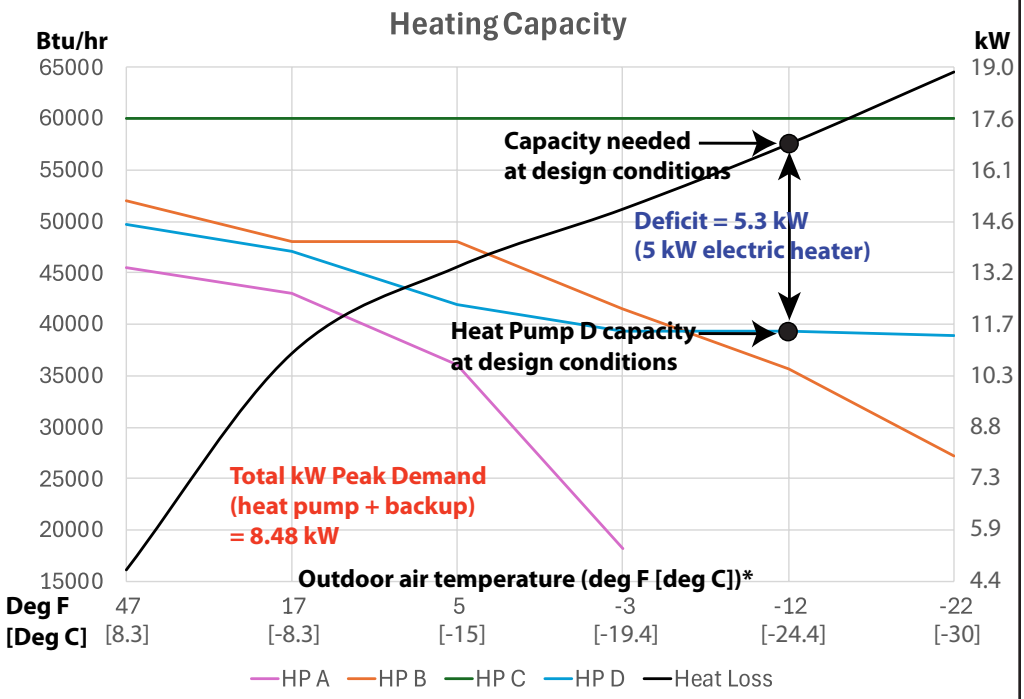

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Figure 6: Heating capacity deficit, "heat pump D"

Backup Heat	HP A	HP B	HP C	HP D
Heating Deficit (Btu/hr)*	57500	21861	0	18200
Heating Deficit (kW)*	16.8	6.4	0.0	5.3
Electric heat**	20	10	0	5

* Difference between heat loss (heat needed at design conditions) and amount of heat the the heat pump can provide at design conditions.

** Most backup electric heaters are staged in 5 kW banks. The table shows kW backup needed at the closest 5 kW increment.

Table 1: Heating capacity deficit, all heat pumps selected

Figure 2 includes thin vertical dashed lines that indicate the balance point for each heat pump. Table 2 provides a summary of Figure 2 balance points for comparison. By definition, the balance point is the outdoor temperature at which the heat pump capacity is equal to the heating needed. For example from Table 2, "heat pump A" has a balance point of 13.5˚F (-10.3˚C), whereas "heat pump C" does not require backup heat until the temperature drops below design conditions (-12˚F [-24.4˚C]), at -16˚F (-26.7˚C). Depending upon the number of hours per year the heat pump runs at outdoor air temperatures below the balance point will determine the economics of the heat pump choice.

In Rochester, Minnesota, there are about 1,000 hours per year below 13.5˚F (-10.3˚C) according to NOAA (National Oceanic and Atmospheric Administration), which could result in an expensive electric bill if selecting "heat pump A" that must use backup heat from 13.5˚F (-10.3˚C) down to -3˚F (-19.4˚C), when the heat pump shuts off and switches entirely to electric resistance heat for temperatures below the manufacturer cut-off temperature.

Balance Point*	HP A	HP B	HP C	HP D
Balance point, ˚F	13.5	4.5	-16.0	9.0
Balance point, ˚C	-10.3	-15.3	-26.7	-12.8

* Balance point is the outdoor temperature at which the heat pump capacity is equal to the heating needed. Below the balance point, backup heat is required.

Table 2: Heating balance point, all heat pumps selected

Even though "heat pump A" is a cold climate heat pump as defined by Energy Star, it clearly cannot supply enough heat in a climate like Rochester, Minnesota. Engineers and contractors must be aware that the term "cold climate" does not guarantee that a heat pump can operate at design conditions or below. Heat pumps "B" and "D" are better choices, especially since they can operate even below the design temperature of -12˚F (-24.4˚C), but the choice between "B" (CC ASHP) and "D" (GSHP) is not easily determined without reviewing both the heating capacity and efficiency from the balance point down to the design point. From Figure 2, the cold climate ASHP "B" has an impressive heating capacity (more than GSHP "D") until about -7˚F (-21.7˚C), where the ASHP takes a noticeable downturn. Both Figure 1 and Figure 2 must be considered to make this determination. At design conditions, ASHP "B" has a COP of 1.61, whereas the GSHP "D" has a COP of 3.50. The GSHP also has higher heating capacity than ASHP "B". With the backup heat needed, combined with the heat pump COP, the system COP (heat pump capacity vs. electricity use + electric heat capacity vs. electricity use + pump Watts [GSHP only]) is about 1.1 for ASHP "B" and about 2.8 for GSHP "D".

Depending upon the goals of the selection, as mentioned earlier, and the number of hours that each system will be running at the COPs above, as well as the power rates, even cold climate heat pump "B" could be a poor choice for the building owner and possibly an even poorer choice for the electric utility due to peak power demand (see "Grid Impact" later in the article).

Another interesting twist involves equipment sizing. Suppose heat pumps "B" and "D" were up-sized to 5 ton (17.6 kW) nominal capacity. The same brand of heat pump for heat pump "D" (GSHP) would come within a few thousand Btu/hr (within about 1 kW) of meeting the heating load at design conditions. However, the ASHP "B" would still fall short by about 15,000 Btu/hr because the slope of the orange line would not change. At design conditions the ASHP would still have significantly lower capacity than the GSHP. Depending upon how the equipment controls are designed, it would be possible to up-size the GSHP and limit the cooling capacity to 4 tons (14.1 kW) to avoid oversizing and to meet ACCA *Manual S* requirements. However, even if the ASHP cooling capacity could be limited, that additional heating capacity of an additional ton of capacity (3.5 kW) would have very little impact on the system COP, since the heat pump COP at design conditions is only 1.61 (see Figure 1).

Finally, "heat pump C" is a nominal 4 ton (14.1 kW) GSHP that has 5 tons (17.6 kW) of heating capacity at minimum entering water conditions. Since the cooling capacity is 4 tons (14.1 kW), it meets ACCA *Manual S* requirements and needs no backup heat, at design conditions with a balance point of -16˚F (-26.7˚C). In Rochester, there are only about 100 hours per year where some backup heat would be required below the balance point. The high heating capacity is a benefit in a very cold climate, even though the COP is lower than heat pump "C" (GSHP). These comparisons demonstrate that both capacity and efficiency must be evaluated to determine the best choice for the application being considered. A heat pump with a high COP or HSPF (Heating Seasonal Performance Factor) does not indicate that it will be the lowest in operating cost or in peak demand kW, depending upon the heating requirements and the climate zone.

Electric Grid Impact

Up to this point, this article has been comparing efficiencies and capacities of four different heat pumps, two cold climate air-source heat pumps and two variable speed ground source heat pumps. Both performance measurements are important in determining the best selection, but if the electric grid is to be considered, there is another element that must be reviewed before making the best choice, since the trend toward decarbonization and electrification can have a significant impact on the electric grid. As mentioned earlier, efficiency seems to be the focal point when determining if an ASHP or a GSHP is the best choice. Although efficiency is important, capacity is a much better indicator of grid impact. For example, a heat pump with a COP of 4.0 at design conditions and a capacity of 20,000 Btu/hr (5.9 kW) has a much higher peak demand than a heat pump with a COP of 2.5 and a capacity of 40,000 Btu/hr (11.7 kW) because the higher efficiency heat pump requires 20,000 Btu/hr (5.9 kW) of backup electric heat with a COP of 1.0. If both heat pumps were delivering 40,000 Btuh/hr (11.7 kW) to the building, the more efficient heat pump would have a peak demand of 7.3 kW, whereas the lower efficient heat pump would have a peak demand of 4.7 kW, 56% lower! In Figure 1, the ASHP with the higher efficiency has the lower capacity; likewise the GSHP with the higher efficiency has the lower capacity.

Returning to the cold climate analysis in Rochester, Minnesota, on the coldest day of the year, the electric utility must provide enough grid capacity to power the buildings with electric heating/heat pumps to avoid a "brown-out" condition, where some buildings (or many) will be without power and thus, without heat. As North America electrifies, not only with heating equipment but with electric vehicles, the electric grid will be increasingly taxed. Figure 7 uses the same four heat pump selections to compare the impact on the grid. Heat pump "C", the GSHP without the need for backup heat at design conditions, is nearly 3-1/2 times lower peak demand as the cold climate ASHP "A" selection. In other words, more than three of these low peak demand GSHP heat pumps could be installed for every cold climate heat pump (of type "A") in Rochester, Minnesota. Considering that a typical

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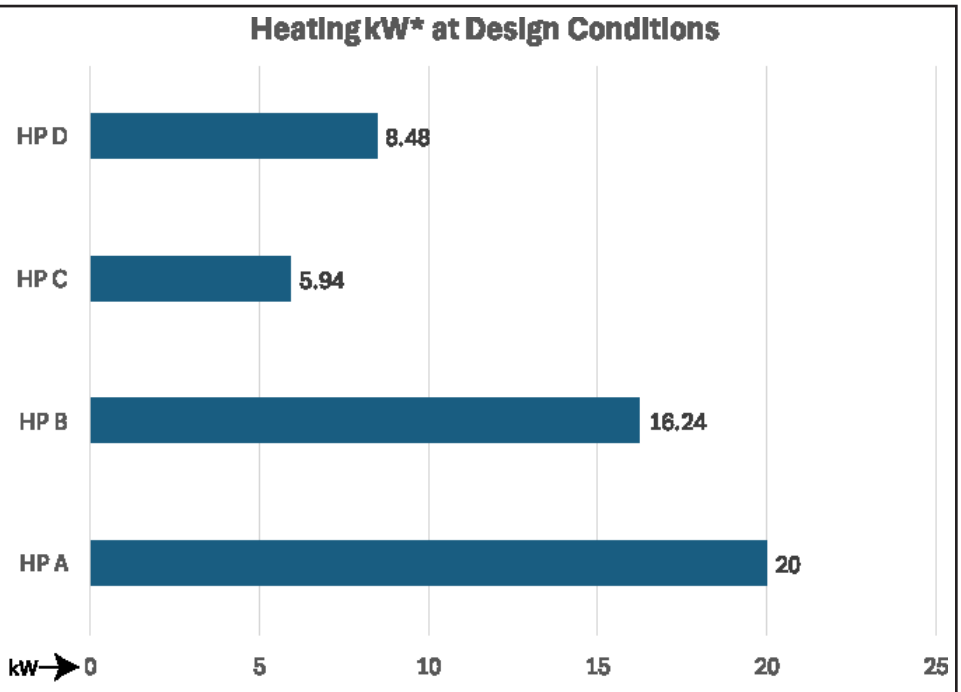

*Heat pump plus backup heat (includes pump Watts for GSHP units).

Figure 7: Peak demand of the four systems at design conditions

Defrost	HP A	HP B	HP C	HP D
Heat pump kW demand*	5.1	6.6	1.7	2.0
Electric heat**	15.0	15.0	0.0	0.0
Total	20.1	21.6	1.7	2.0

* ASHP operating at 17˚F (-8.3˚C) outdoor air temperature in defrost mode. GSHP operating at 50% capacity and 38˚F (3.3˚C) EWT -- no defrost needed. GSHPs include include pump Watts.

** Most backup electric heaters are staged in 5 kW banks. The table shows kW backup needed at the closest 5 kW increment.

Table 3: Peak demand during defrost cycle

EV (Electric Vehicle) charger is about 8 kW, a home with a GSHP (of type "C") plus the EV charger would still be 6 kW demand less than ASHP "A" even if the GSHP and EV charger were operating at the same time. At the end of 2023, ORNL (Oak Ridge National Labs) released a report for the U.S. D.O.E. (Department of Energy) on grid impact (https://info.ornl.gov/sites/publications/Files/Pub196793.pdf) that illustrates the enormous impact of GSHPs on the electric grid compared to other electric heating technologies. In Canada, the Dunsky report (https://www.hrai.ca/uploads/userfiles/files/GSHP%20Policy%20Recommendation%20Final%20Report_v2.pdf) indicates the exact same conclusion. Even though ASHPs and GSHPs work exactly the same way, ultimately, the milder ground temperature used as a heat source for GSHPs provides higher capacity than even the most technologically advanced ASHP with variable speed compressor and vapor injection technology.

In milder climates (e.g. St. Louis, Missouri with a winter design temperature of 8˚F [-13.3˚C]), cold climate ASHPs could be a good solution when considering the capacity and efficiency at temperatures above 5˚F (-15˚C), especially more advanced technology heat pumps, like heat pump "B" that could likely provide nearly 100% of the heating load in a milder climate. However, even in milder climates, the grid impact must be considered due to the additional demand during defrost cycle. Depending upon the humidity in the air, an air-source heat pump could require defrost between 17˚F (-8.3˚C) and 47˚F (8.3˚C). In an even milder climate (e.g., Oklahoma City with a winter design temperature of 17˚F (-8.3˚C), the defrost cycle could have a bearing on the peak demand kW. Most ASHPs reverse the cycle (i.e., switch to cooling) and bring on electric backup heat to offset the cooling effect in the space. ACCA *Manual J* recommends sizing the electric backup heat for 80% of the heating load. Table 3 illustrates the kW demand during defrost for the two cold climate ASHPs (GSHPs do not need a defrost cycle). In a milder climate, ASHPs could have a higher peak demand (by a factor of 10 in this example) simply due to the defrost cycle.

Although this article primarily focuses on the heating mode of ASHPs and GSHPs, the same principle applies to cooling. Because the ground is a much milder heat sink than the outdoor air, the GSHP will operate at lower kW. Since there is no "backup cooling", efficiency is a good indicator of peak demand, unlike in the heating mode. If a "warm climate" heat pump is developed, an analysis should be conducted to determine the best heat pump choice for grid impact.

Heat Pump Types/Costing

The four heat pump types considered in this article use different technology, even though all four are heat pumps. Based upon the manufacturer's data, it appears that heat pump "A" is a variable speed (inverter drive) ASHP that is capable of increasing the speed of the compressor in the heating mode to increase capacity. Heat pump "B" appears to use a larger compressor (e.g. a 5 ton [17.6 kw] compressor, limited to 4 tons [14.1 kW] of cooling) and vapor injection technology to increase the output at very cold outdoor temperatures. Based upon industry discussions, heat pump "A" is typically 30% - 50% less cost than heat pump "B". Heat pump "B" is generally more expensive than a GSHP due to the complexity of the refrigerant circuit and up-sizing of the compressor.

GSHPs have similar options. Based upon the manufacturer's data, it appears that heat pump "C" uses a 5 ton (17.6 kw) compressor, limited to 4 tons [14.1 kW] of cooling and increases the compressor speed in heating to achieve higher heating capacity, albeit lower COP compared to heat pump "D", which appears to use a 4 ton (14.1 kW) compressor. Based upon industry discussions, heat pump "C" is 15% - 20% more cost than heat pump "D".

The next topic to consider is the total installation cost. For ground source heat pump applications, the ground heat exchanger (GHX) is the component of the system that allows the heat pump to use the milder ground temperature instead of the outdoor air temperature for the heat source in the heating mode and the heat sink in the cooling mode. The cost of the heat pump and the GHX typically is about two to three times the cost of an air-source heat pump due to the costs of installing the GHX. GHX installation cost varies by geography and geology (i.e., the type of soil/rock in the area).

Based upon the heat pump cost and/or GHX cost, a financial decision must be made to determine the best type of heat pump for the application for the goals of the project. If electric grid impact is the goal, the cost of installing the GHX versus the cost of building more power plants and infrastructure can make the cost of the GHX seem very inexpensive, which is why some electric and gas utilities are seriously considering providing GHXs to customers. If the cost of GSHP to the building owner is the same as an ASHP (due to the subsidized cost of the

GHX), it is a win-win for both the building owner and the utility to avoid the costs associated with improving the grid (see DOE report and Dunsky report mentioned earlier).

In addition to up front (installation) costs, another consideration is life cycle costing. Based upon ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) studies, the average life expectancy of a water-source heat pump (the heat pump type used for ground source applications) is about 24 years. Air-source heat pumps, according to ASHRAE, average about 15 years. The ground heat exchanger uses HDPE (high density polyethylene) or PEX (cross-linked polyethylene) pipe in the ground, which has a life expectancy of over 50 years, according to PPI (Plastics Pipe Institute). Therefore, cost must consider not only the installation costs, but also life expectancy and maintenance costs to provide the best selection. Because GSHPs are indoors, not exposed to the elements, the maintenance cost should be lower than ASHPs. If grid impact is considered and/or utility programs and government incentives are included, GSHPs can be significantly lower life cycle cost that ASHPs, including cold climate ASHPs.

Conclusion

When evaluating cold climate air-source heat pumps compared to ground source heat pumps, it is not as easy as comparing efficiencies, especially when the heating capacity of the two technologies is considered. In fact, even in milder climates, cold climate air-source heat pumps could have a much bigger impact on the grid than expected because of the defrost cycle. As North America decarbonizes and electrifies, heat pumps are going to be a big part of the solution, but the type of heat pump will have a bearing on how much progress can be made towards these goals, while maintaining electric grid stability. It is quite possible that new definitions will be established for what a “cold climate” heat pump achieves. Based upon current technology, the only true cold climate heat pump is a ground source heat pump. For the sake of the grid, maybe “cold climate heat pumps” will be renamed to “heat pumps”, since they can be applied to milder climates with higher success than in colder climates. If the electric grid and infrastructure is considered, ground source heat pumps are the only answer to beneficial electrification. For more information on ground source heat pumps, visit the International Ground Source Heat Pump Association (IGSHPA) at https://igshpa.org.

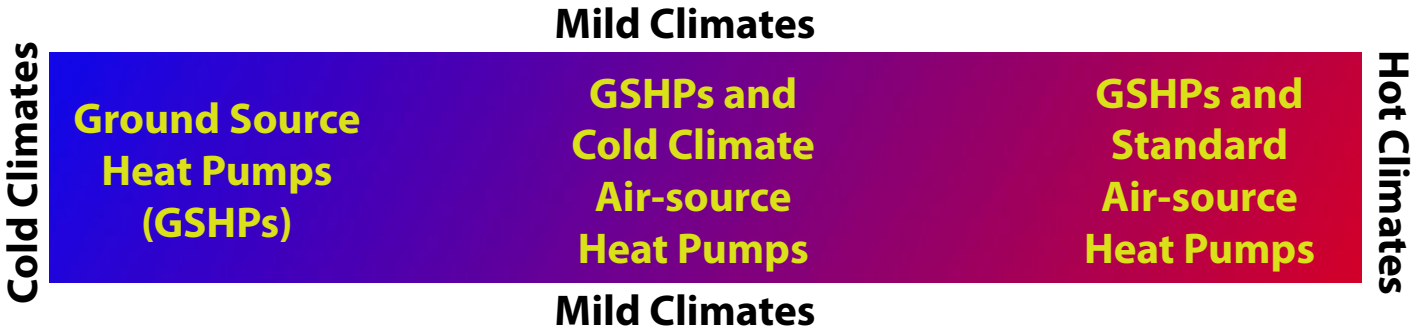

Figure 8: Potential considerations for ASHP and GSHP technology