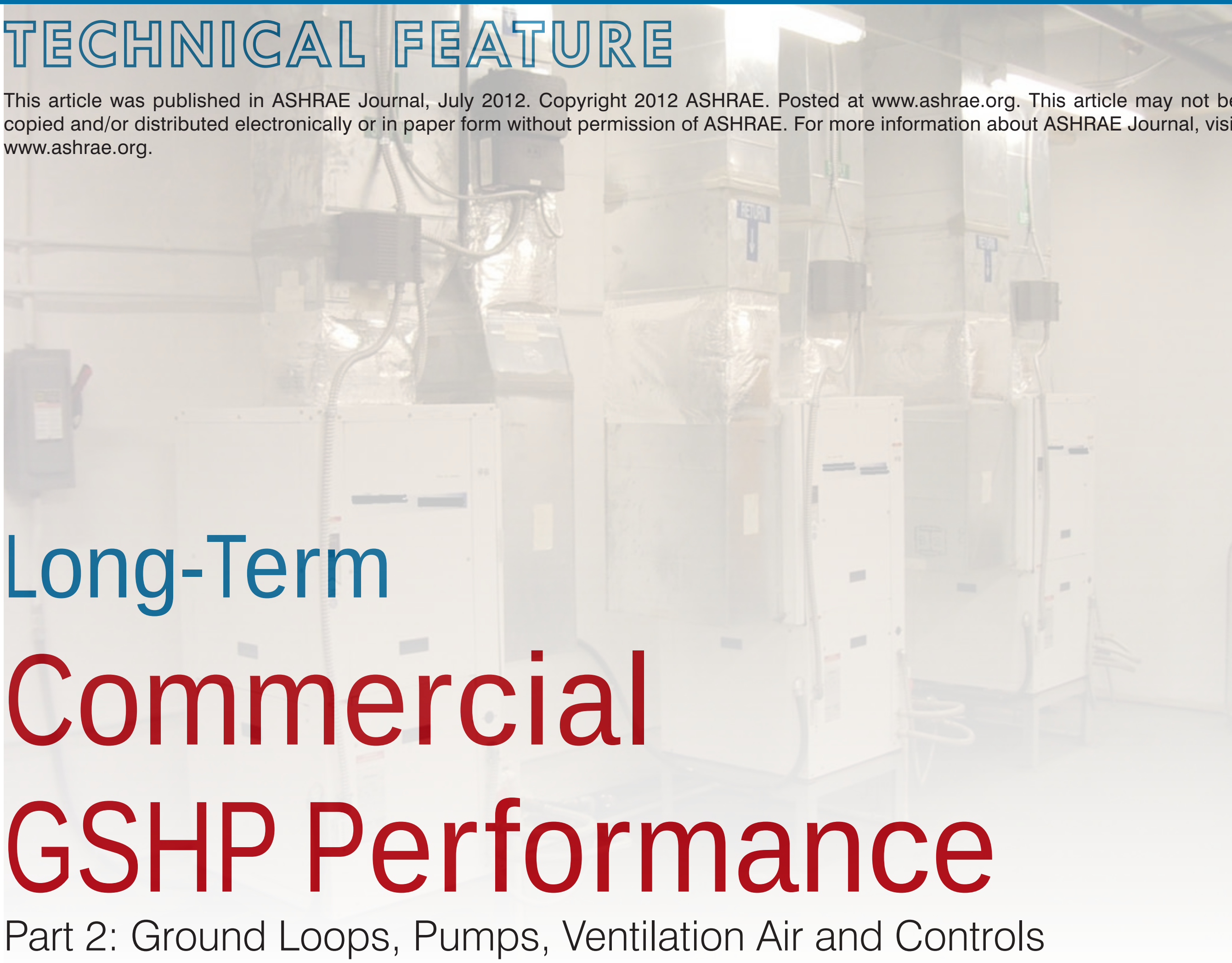

# Long-Term Commercial GSHP Performance

## Part 2: Ground Loops, Pumps, Ventilation Air and Controls

By **Steve Kavanaugh, Ph.D.,** Fellow ASHRAE, and **Josh Kavanaugh,** Student Member ASHRAE

Ground heat exchanger performance is a critical factor in ground source heat pump (GSHP) system success. The ground heat exchanger type for all but one of the systems surveyed were vertical high-density polyethylene (HDPE) single U-tubes. Bore length ($L_b$) is used as a primary indicator, although there are several other factors that affect performance including ground thermal properties (temperature, conductivity, and diffusivity), vertical bore separation, conductivity of the annular grout/fill, integrity of the grout/fill placement, and heat exchanger type. Some scatter in the results is expected since these characteristics varied from site to site and was often not available.

The impact of most of these variables is complex and often uncertain. However, the variation of bore length to approach temperature (difference between the average loop temperature and the ground temperature) is more easily normalized.

Cooling performance is a strong function of ground loop leaving water temperature (LWT) and entering water temperature (EWT). Therefore, the required cooling mode bore length to provide high efficiency in a location with a lower ground temperature will tend to be less than the required length for a warmer location. To better compare optimum ground loop lengths for a variety of locations, the trend between installed bore length and performance is normalized for ground temperature. The adjustment is based on the average ground temperature ($t_g$[avg] = 63°F [17°C]) and the average maximum loop temperature ([LWT+EWT]/2 ≈ 90°F [32°C]) at the sites in the project survey.

$$L_b\text{/ton (Normalized)} = L_b\text{/ton} \times (90°F - t_g)/[90°F - t_g(avg)]$$

**About the Authors**

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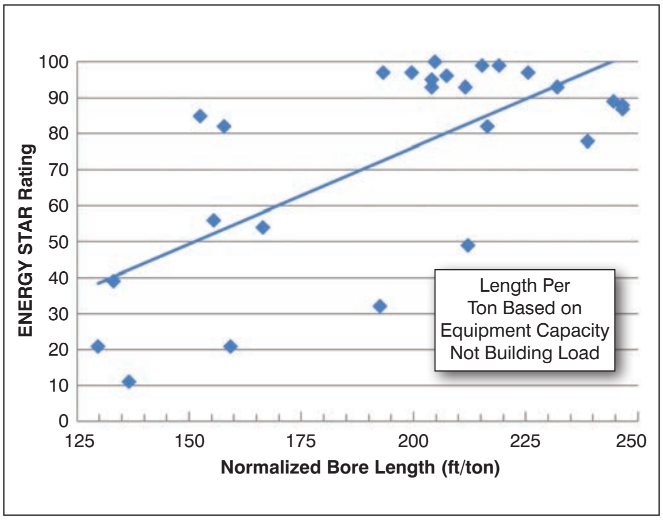


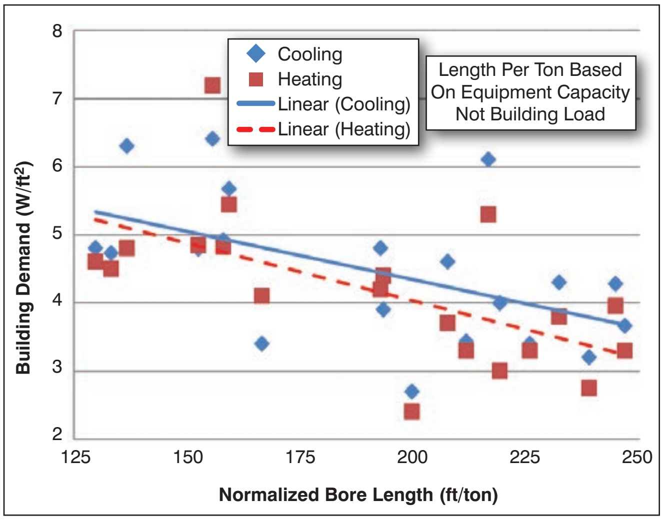


**Figure 1:** ENERGY STAR rating vs. bore length normalized for ground temperature. **Figure 2:** Building demand vs. bore length normalized for ground temperature. Note: $L_b$/ton (Nor) = $L_b$/ton × $[(90 - tg)/(90 - tg_{avg})]$ $tg_{avg}$ for all sites = 63°F.

A ground loop installed at 250 ft/ton (22 m/$kW_T$) of bore would correspond to a normalized length of 185 ft/ton (16 m/$kW_T$) for a ground temperature of 70°F (21°C) while 170 ft/ton (15 m/$kW_T$) of bore results in a normalized length of 201 ft/ton (17 m/$kW_T$) for a ground temperature of 58°F (14°C). The design bore lengths for the systems monitored during this project were all determined by the cooling load even though some sites had significant heating requirements. Recall the ground loop in cooling must transfer the building load plus the compressor heat, while the heat transfer rate in heating is the heating load minus the compressor heat. If a similar project were conducted in climates where the heating requirement determined bore lengths, normalization based on the winter LWT and EWTs would be more appropriate.

*Figure 1* shows the trend for an ENERGY STAR rating to normalized bore length. Systems with bore lengths near 150 ft/ton (13 m/$kW_T$) tend to have an ENERGY STAR rating near 20 while those with normalized bore lengths of 200 ft/ton (17 m/$kW_T$) are more likely to have a rating above 90. A cluster of sites with ENERGY STAR ratings above 90 have normalized bore lengths between 200 and 225 ft/ton (17 to 20 m/$kW_T$). The three sites with the longest bore lengths had ENERGY STAR ratings below 90, indicating that bore length is important, but other characteristics also affect performance results.

*Note that the reported values are based on tons of installed capacity rather than building load. The sum of the installed capacity for equipment in each zone is typically 10% to 25% greater than the load the building places on the ground loop due to load diversity and also because equipment is available in capacities of fixed increments that cannot match loads precisely.*

As expected, lower building electrical demand for cooling and heating results when bore lengths are increased as shown in *Figure 2*. The demand vs. bore length slopes are reversed compared to *Figure 1* since lower demand tends to reduce energy use and result in a higher ENERGY STAR rating. The cooling data is scattered. A few buildings with lengths in excess of 200 ft/ton (17 m/$kW_T$) had only average cooling demand and one system with a 165 ft/ton (14 m/$kW_T$) length had a low demand. *Figure 2* also indicates that 90% of the buildings with normalized bore lengths greater than 200 ft/ton (17 m/$kW_T$) have heating demands less than 4.0 W/$ft^2$ (43 W/$m^2$).

## Pump Power

*Figure 3* shows the trend for ENERGY STAR rating compared to rated ground loop pump power. There is a good amount of scatter for the lower ENERGY STAR rating values, but there is a large cluster of data points in the region of pump power values between 5 and 10 hp/100 tons (1.1 and 2.1 $kW_M$/$kW_T$) and ENERGY STAR ratings above 80. The trend toward higher ENERGY STAR ratings with lower pump power is not as pronounced as with longer loop length. However, the trend is somewhat moderated by four data points with ENERGY STAR ratings between 85 and 90 that have pump powers greater than 20 hp/100 tons (4.2 $kW_M$/$kW_T$). Closer examination of *Figure 1* shows that these points also have corrected loop lengths above 235 ft/ton (20 m/$kW_T$), which would offset the increased energy use of the larger pumps.

The building power data presented in *Figure 4* indicate a modest trend of increased cooling demand with higher pump power. There is a small inverse trend of lower heating demand with increased pump power with the exception of two of the sites with installed pump power greater than 20 hp/100 tons (4.2 $kW_M$/$kW_T$). These results are unexpected since lower pump demand would normally result in lower building demand. However, several of the older systems have electric auxiliary heat, which would offset any overall building demand reductions resulting from lower pump power.

## Ventilation Air Equipment

Another important factor affecting the ENERGY STAR rating was the volumetric flow rate capacity of the ventila-

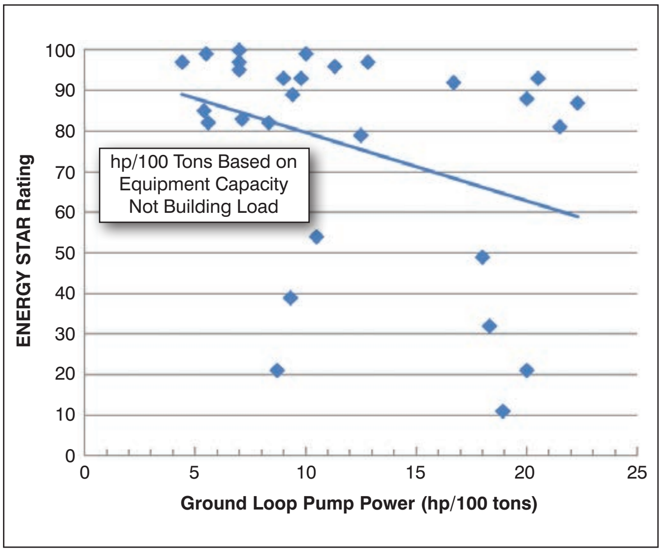


**Figure 3:** ENERGY STAR rating vs. installed pump power.

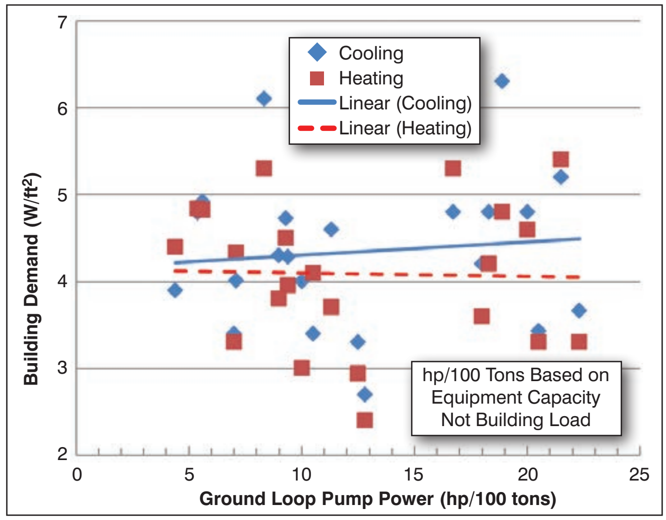


**Figure 4:** Building cooling and heating demand vs. ground loop pump power.

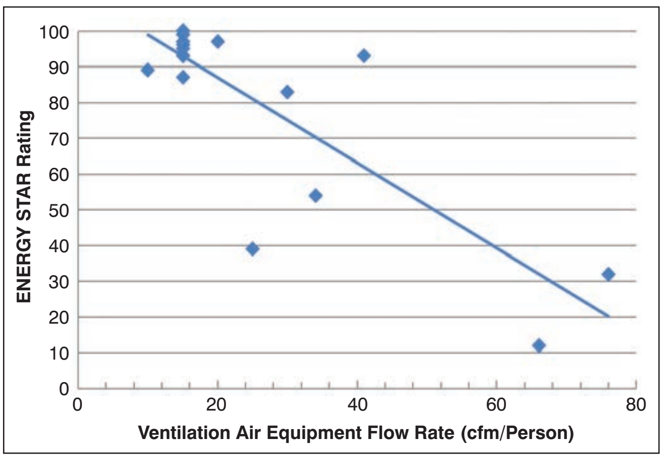


**Figure 5:** ENERGY STAR rating vs. ventilation air equipment capacity.

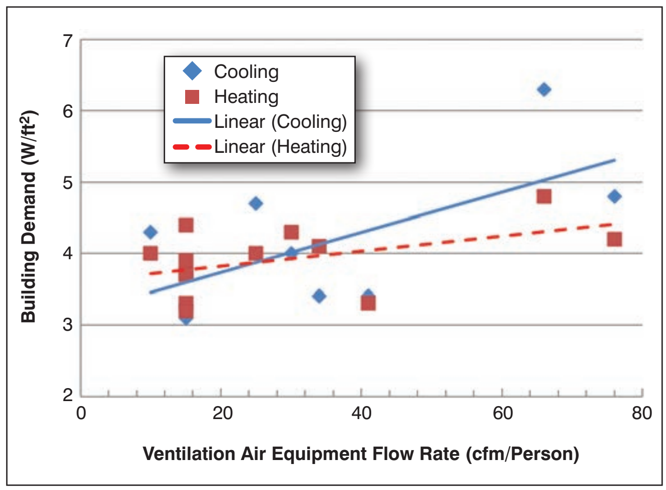


**Figure 6:** Building demand vs. ventilation air equipment capacity.

tion air equipment. To be clear, no attempts were made to measure the actual flow rate, and only near the end of the project were $CO_2$ concentrations observed to estimate the amount of ventilation air. The possible correlations were for several of the newer sites where equipment specifications were available. *Figure 5* indicates a strong correlation between high a ENERGY STAR rating and ventilation air equipment capacities of less than 20 cfm (10 L/s) per person

*Figure 6* displays a noticeable trend between higher building cooling demand and ventilation equipment size. This trend was less pronounced for heating demand. However, the number of sites with both demand and ventilation air equipment specifications were limited and more data is needed to better substantiate conclusions.

## Bore Length and Building Size

In addition to bore length per ton, another indicator frequently sited is bore length per unit building floor area (ft/ft$^2$ [m/m$^2$]). This indicator combines heat exchanger size (ft/ton [m/kW$_T$]) with a building energy efficiency indicator of floor area per unit equipment capacity (ft$^2$/ton [m$^2$/kW$_T$]). This indicator must be judiciously applied since densely populated spaces with high internal loads tend to have lower area per unit capacity values compared to sparsely populated areas with low internal loads. However, the bulk of the sites surveyed were schools and offices where loads are similar, with offices typically having 25% lighter loads or 25% higher areas per unit cooling capacity.[1] Values are more similar when energy recovery units are installed to offset the higher ventilation air requirements of classrooms.

As shown in *Figure 7* the data of normalized bore length per unit area is scattered but there is an upward trend of increased ENERGY STAR ratings with longer lengths. All the sites with a rating above 90 fell between 0.44 to 0.60 ft/ft$^2$ (1.4 to 2.0 m/m$^2$). However, the three sites with the largest bore length to floor area ratios (> 0.60 ft/ft$^2$ [2.0 m/m$^2$]) had ENERGY STAR ratings between 79 and 89.

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## GSHP Series Overview

The Long-Term Commercial GSHP Performance series summarizes the results of a project that collected data from buildings heated and cooled by ground source heat pump systems. The buildings were primarily commercial or institutional and the ground heat exchangers were almost all closed-loop vertical designs. The age of the systems ranged from three to 23 years of operation and installation cost information for the newer buildings was included.

**Part 1: Project Overview and Loop Circuit Type:** This article appeared in the June 2012 issue and provided a description of the project and present a summary of energy performance of all buildings and the function of different types of loop circuits.

**Part 3: Ground Loop Temperatures:** This article will provide a summary of energy and demand performance of GSHPs as a function of ground loop temperatures.

**Part 4: GSHP System Installation Costs:** This article will provide a list of the installation costs for newer systems.

**Part 5: Occupant and Operator Satisfaction:** This article will provide a summary of satisfaction levels of building occupants and the personnel that maintain and operate the systems.

**Part 6: Characteristics of Quality GSHPs:** This article will summarize the results of the project and highlight characteristics that tend to optimize energy use, installation cost, and occupant/operator satisfaction. A suggested portfolio format will be presented that is intended for engineering firms to follow that can demonstrate the quality and success of previous projects.

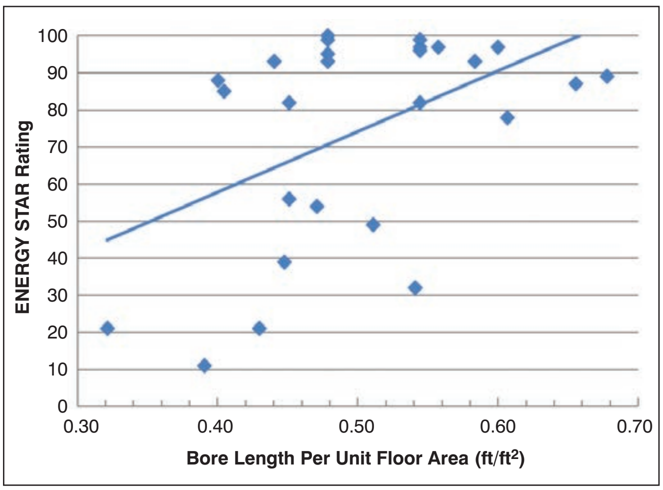


**Figure 7:** ENERGY STAR rating vs. normalized bore length per unit floor area.

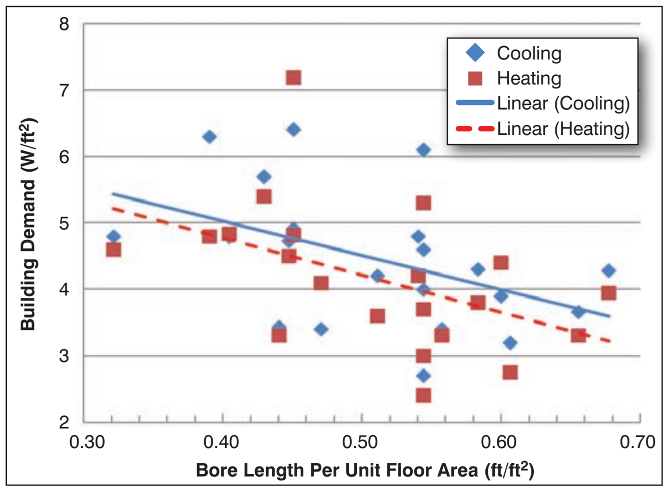


**Figure 8:** Building demand vs. normalized bore length per unit floor area.

The building demand data of normalized bore length per unit area are also scattered for both heating and cooling as shown in *Figure 8*. There is a trend of declining demand with increasing bore length to floor area. The lowest demands ranged between 2.5 to 4.0 W/ft$^2$ (27 to 43 W/m$^2$) and occured in buildings with bore length to area ratios between 0.44 to 0.60 ft/ft$^2$ (1.4 to 2.0 m/m$^2$).

### Building Control Type

*Figure 9* indicates that 81% (13 of 16) of the GSHP buildings with independent programmable thermostat control achieved an ENERGY STAR designation and 56% (9 of 16) attained a rating above 90. Only 45% (9 of 20) of the GSHP buildings with central building automation systems (BAS) achieved an ENERGY STAR designation and 15% (3 of 20) attained a rating above 90. The average ENERGY STAR rating for buildings with BAS control was 61 while the average rating for thermostat control was 80. Occupant satisfaction of these two control options will be presented in a subsequent article.

The reasons that thermostat control provided lower energy use than BAS are likely very complex. However, one clear indication is that only one of the 14 variable speed pump drives (controlled by a BAS) functioned properly as indicated by differential loop temperatures. This will be discussed further in Part 3 of this series.

As discussed in Part 1 of this series,[2] central loop GSHPs had significantly lower ENERGY STAR ratings and most were controlled by a BAS. One-pipe and individual loop GSHPs had much higher ENERGY STAR ratings and were controlled by thermostats. A question arises: Were the central loop GSHPs less efficient because they were controlled by a building automation systems or were the buildings with BASs less efficient because they were used to control a central loop GSHP?

Although these results for GSHPs were generated from a rather small data set, they are consistent with data from the Commercial Building Energy Consumption Survey (CBECS)[3] as shown in *Figure 10*. Note that the buildings with unitary and packaged cooling equipment tend to use less energy than centralized systems. Additionally, the average energy consumption for all commercial buildings is less than those with Energy Management and Control Systems (EMCS).

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## Summary and Conclusions

### Ground Loop Normalized Bore Length Relative to Equipment Capacity

• Systems with normalized bore lengths equal to or greater than 200 ft/ton (17 m/$kW_T$) of installed capacity accounted for 83% (15 of 18) of those receiving an ENERGY STAR designation (rating of 75 or higher) and 91% (10 of 11) of those receiving an ENERGY STAR rating above 90. Conversely, only 25% of the systems with bore lengths less than 175 ft/ton (15 m/$kW_T$) attained an ENERGY STAR designation and none received a rating above 85.

• Almost all the buildings with normalized GSHP loop bore lengths between 200 ft/ton (17 m/$kW_T$) and 240 ft/ton (21 m/$kW_T$) had cooling and heating demands between 2.5 W/$ft^2$ (27 W/$m^2$) and 4.5 W/$ft^2$ (48 W/$m^2$) while those with lengths less than 150 ft/ton (13 m/$kW_T$) had demands between 4.5 W/$ft^2$ (48 W/$m^2$) and 6.5 W/$ft^2$ (70 W/$m^2$).

• Ground loop bore length is a primary factor affecting energy performance, cooling demand, and heating demand.

• A minimum normalized vertical bore length of 200 ft/ton (17 m/$kW_T$) for GSHPs in cooling load dominant schools and offices is recommended.

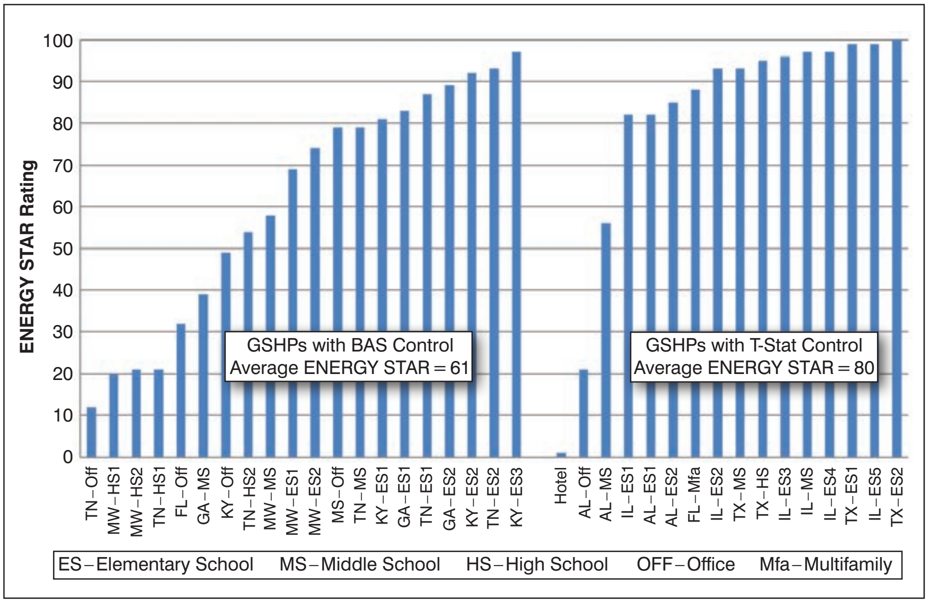


**Figure 9:** ENERGY STAR rating and HVAC control type.

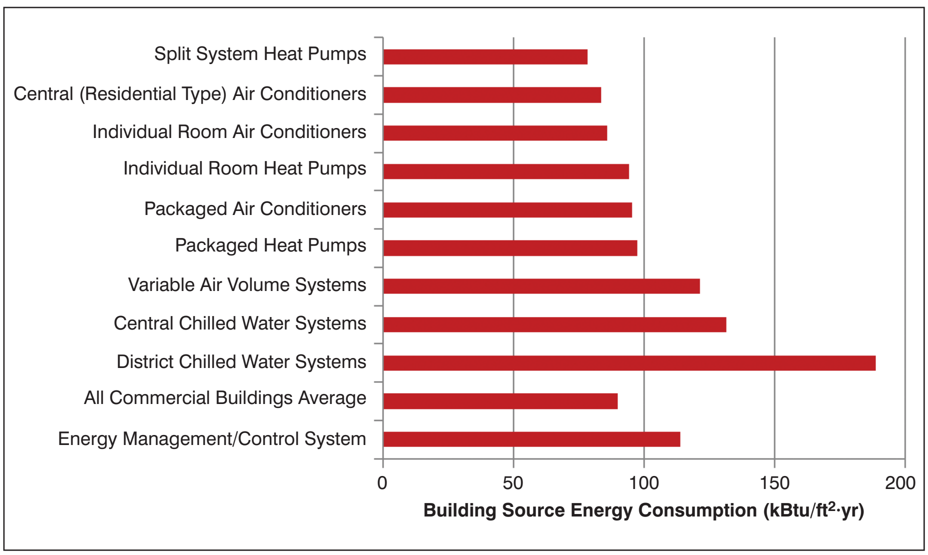


**Figure 10:** Measured energy consumption by cooling system type and EMCS.

### Ground Loop Pump Power

• Buildings with ground loop pump power of 10 hp/100 tons (2.1 $kW_M$/100 $kW_T$) or less accounted for 65% of those receiving an ENERGY STAR designation and 56% of those receiving an ENERGY STAR rating above 90.

• Ground loop pump power has only a modest influence on building demand trends.

• A maximum ground loop pump power of 10 hp/100 tons (2.1 $kW_M$/100 $kW_T$) is suggested.

### Building Ventilation Air Rates

• Buildings with ventilation air equipment capacity of 20 cfm per person (10 L/s) or less accounted for 86% of those attaining an ENERGY STAR designation and 90% of those receiving an ENERGY STAR rating above 90.

• Systems with ventilation air equipment capacity of 40 cfm per person (20 L/s) or less had only modest influence on building demand trends.

• For school and office buildings, ventilation air system capacities greater than 20 cfm per person (10 L/s) should be avoided when possible. For systems that require higher rates, careful design coupled with rigorous monitoring, operation and maintenance programs are recommended to prevent over-ventilation of zones that are not fully occupied.

### Ground Loop Normalized Bore Length Relative to Building Floor Area

• Buildings with normalized vertical bore lengths to building floor area between 0.4 and 0.6 ft/$ft^2$ (m/$m^2$) accounted for 90% of those receiving an ENERGY STAR designation and 100% of those receiving an ENERGY STAR rating above 90.

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• While the metric of vertical bore length to building floor area is a useful indicator for office buildings and schools with conventional building practices, the values observed in this study may be high for buildings with enhanced envelopes, low lighting and plug loads, and advanced ventilation air systems.

### GSHP System Controls

• Buildings in which the GSHP system was controlled by individual thermostats accounted for 81% (13 of 16) of those achieving an ENERGY STAR designation and 56% (9 of 16) of those attaining a rating above 90.

• Buildings in which the GSHP system was controlled by a building automated system (BAS) accounted for 45% (9 of 30) of those achieving an ENERGY STAR designation and 15% (3 of 20) of those attaining a rating above 90.

• The average ENERGY STAR rating of buildings in which the GSHP system was controlled by individual thermostats was 80 while the average for those controlled by a BAS was 61.

• Building automation systems were more frequently used with central loop GSHPs, which tend to have lower ENERGY STAR ratings.

• Thermostat control was used with the one-pipe and individual loop GSHPs, which had very high ENERGY STAR ratings.

• Building designers and owners should carefully consider the cost, measured performance results, recommendations of maintenance personnel, and satisfaction levels of building occupants before opting for advanced BAS controls in schools and office buildings.

The project was made possible with a tailored collaboration through the Electric Power Research Institute (EPRI), with the Southern Company (SoCo) and the Tennessee Valley Authority (TVA) providing the funding. Project direction and collaboration were provided by Ron Domitrovic (EPRI), David Dinse (TVA), and Chris Gray (SoCo). The focus was primarily on commercial buildings.

## References

1. Kavanaugh, S.P., S.E. Lambert, and T.N. Devin. 2006. "HVAC power density: an alternate path to efficiency." *ASHRAE Journal* 48(12).

2. Kavanaugh, S.P. and J.S. Kavanaugh. 2012. "Long-term commercial GSHP performance, part 1." *ASHRAE Journal* 54(6).

3. EIA. 2008. Commercial Building Energy Consumption Survey. 2003 Detailed Tables. Table C3. U.S. Energy Information Administration. Washington, D.C. (http://tinyurl.com/7dtleu4). ■