Development of Design Guidelines for Hybrid Ground-Coupled Heat Pump Systems

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Executive Summary

Hybrid ground-coupled heat pump systems (HyGCHPs) couple conventional ground-coupled heat pump (GCHP) equipment with supplemental devices to reject or supply more heat than is possible with a stand-alone ground heat exchanger (GHX). In cooling- and heating-dominated climates, the use of these supplemental devices has been shown to significantly improve the economics and energy usage of the system. However, the design and operation of HyGCHPs are significantly more complex than GCHPs and there is currently relatively little information available in this regard. This research project has created a HyGCHP model, integrated it with an optimization algorithm, and exercised it over a range of conditions in order to identify the optimal (lowest life-cycle cost) sizing and control strategies for these systems. The goal of the project is to assist practicing engineers with selecting and designing HyGCHP systems by providing a powerful simulation/optimization tool as well as a series of more approximate design guidelines based on the parametric analysis.

The HyGCHP model is created using TRNSYS (Klein et al, 2006). Figure 1 shows a schematic of the model, with a cooling tower included as the supplemental device for this cooling-dominated system. In a heating-dominated system, the supplemental device (e.g., a

boiler) would *add* heat to the fluid (and the location of the supplemental device and the GHX would be swapped). All components in this schematic are included in the TRNSYS model. The building is modeled independently to provide loads to the heat pumps; the heat pumps are appropriately sized so that they are capable of meeting the peak loads experienced by the building. This approach improves computational speed and therefore allows optimization of the equipment and control strategy (to find the design with the lowest life-cycle cost).

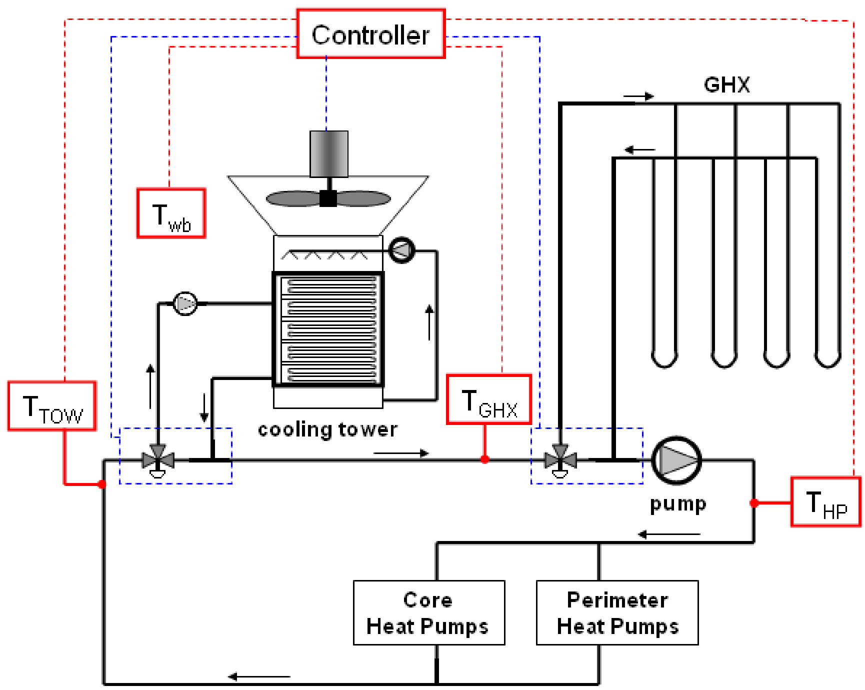

Figure 1. A schematic of a hybrid ground-coupled heat pump system, with a cooling tower as a supplemental heat rejection device. Temperature values show points where measurements are necessary for control.

The temperatures shown in Figure 1 represent the locations where measurements are necessary for control of the system. For the cooling-hybrid system using a cooling tower (shown in Figure 1), the cooling tower is activated when the difference between the fluid upstream of the tower (T_{TOW}) and the ambient wet-bulb temperature (T_{wb}) is greater than a control setpoint (ΔT_1). The GHX is operated when the temperature of the fluid upstream of the bore field (T_{GHX}) is greater than a control setpoint (T_{Cool2}) when the system is in cooling mode and less than a different control setpoint (T_{Heat1}) when the system is in heating. All these control set points are optimized to minimize life cycle cost. The optimizer also varies the equipment size (in the case shown in Figure 1, the equipment size includes the size of the cooling tower and the bore field). A distributable version of this HyGCHP model – integrated with the optimizer – represents one key deliverable from this project; it is a powerful design tool that can be used to specifically design a HyGCHP system for a particular project.

Additionally, the HyGCHP model and optimizer were utilized to develop design guidelines, which was the other major focus of this project. These guidelines are general observations regarding the optimal values of the control set points and equipment sizes as the type of building and climate changes. These guidelines are based on optimizing the system design and control set points in order to achieve the lowest life cycle cost over a 20 year time span for 20 different building/climate combinations using a set of nominal input parameters; the guidelines should be used with these limitations in mind. The purpose of the distributable program is to provide a design tool that is not constrained by these limitations. Building loads were generated using a model created in a previous ASHRAE project (ASHRAE TRP-1120, CDH and TESS, 2000). The climates were selected so that they span from cooling-dominated to heating-dominated (including a balanced case) and from wet to dry. In order to accomplish the simulation and the economic optimization it is necessary to specify a set of parameters that characterize everything from the market conditions to the soil conditions to various aspects of equipment performance. These parameters vary according to location, year, manufacturer, designer, etc.; the value of the distributable simulation tool is that individual geothermal system designers can vary these parameters according to their situation and experience. However, for the parametric study, default values of the HyGCHP model parameters were used to carry out optimizations and develop the design guidelines. These values are based on literature research, and are summarized in Table 1.

Table 1. Summary of input parameters for the parametric study.

Category	Parameter	Baseline value
Bore field	Ground conductivity	1.4 Btu/hr-ft-F
	Ground diffusivity	1.1 ft^2/day
	Grout conductivity	0.8 Btu/hr-ft-F
	Initial ground temperature	varied according to climate
	Maximum drilling depth	300 ft
	Borehole diameter	4.5 inch
Other equipment	Pump efficiency	60%
	Boiler efficiency	85%
	Max. entering water temp. for heat pump	95°F
	Min. entering water temp. for heat pump	35°F
	EER of heat pump at ARI 13256-1 conditions	16
	COP of heat pump at ARI 13256-1 conditions	3.4
Economic	Life span	20 years
	Discount rate	8.5%
	Down payment	30%
	Loan interest rate (20 year loan)	6.0%
	Tax rate	35%
	Peak electricity rate	0.101 $/kW-hr
	Off-peak electricity rate	0.063 $/kW-hr
	Electricity demand charge	6.22$/kW, 15 minutes
	Gas price	0.99 $/therm
	Water price	4.0 $/100 ft^3
	Bore field cost	10 $/ft

For cases resembling the economic conditions and equipment summarized in Table 1, the results of the parametric study suggest the design guidelines detailed below.

Design Guidelines and Observations – Cooling Dominated Systems

- **GHX Sizing: size the ground heat exchanger (GHX) so that it is just capable of meeting the peak heating load.** Figure 2 illustrates the optimal size of the GHX (sum of all bore depths) as a function of the peak heating load (each point represents a different climate/building combination from the parametric study); notice that the optimal GHX size is essentially proportional to the peak heating load.

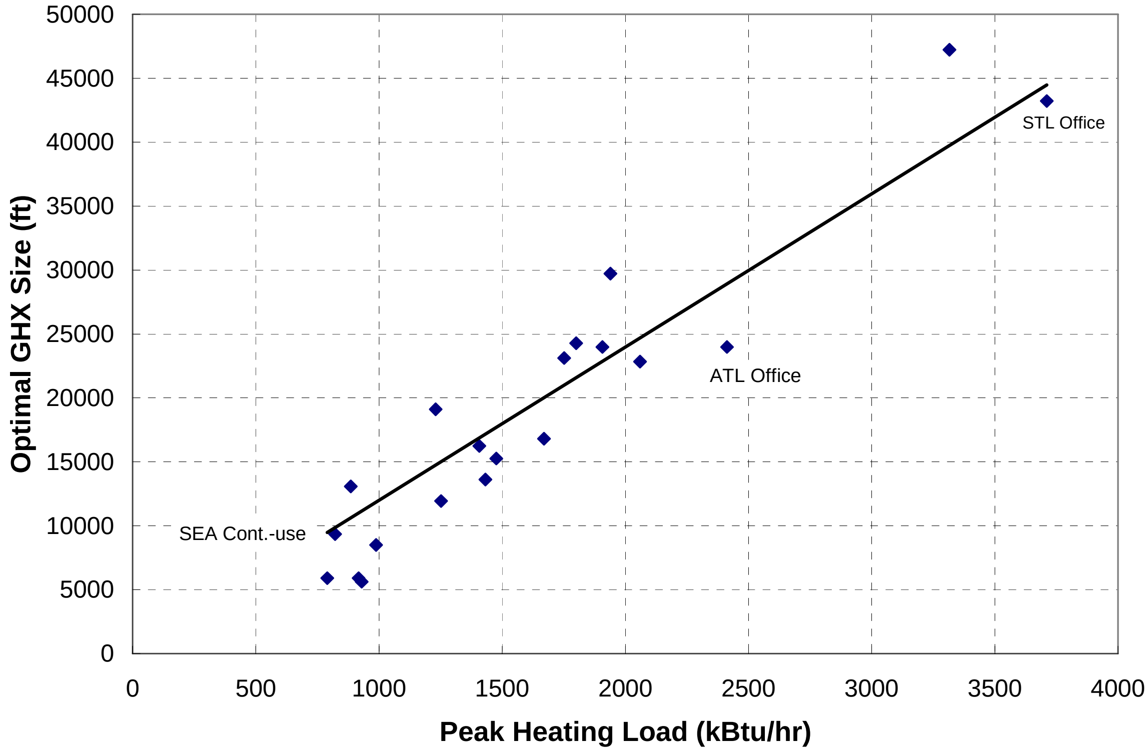

Figure 2. Optimal GHX size as a function of the peak heating load for each building/climate scenario.

The scatter in Figure 2 is partly due to the different ground temperatures associated with the various climates. Figure 3 illustrates the best fit regression of the ratio of the optimal GHX size to the peak heating load as a function of the initial ground temperature; as expected, less GHX length is required to meet a given heating load in regions with high ground temperature.

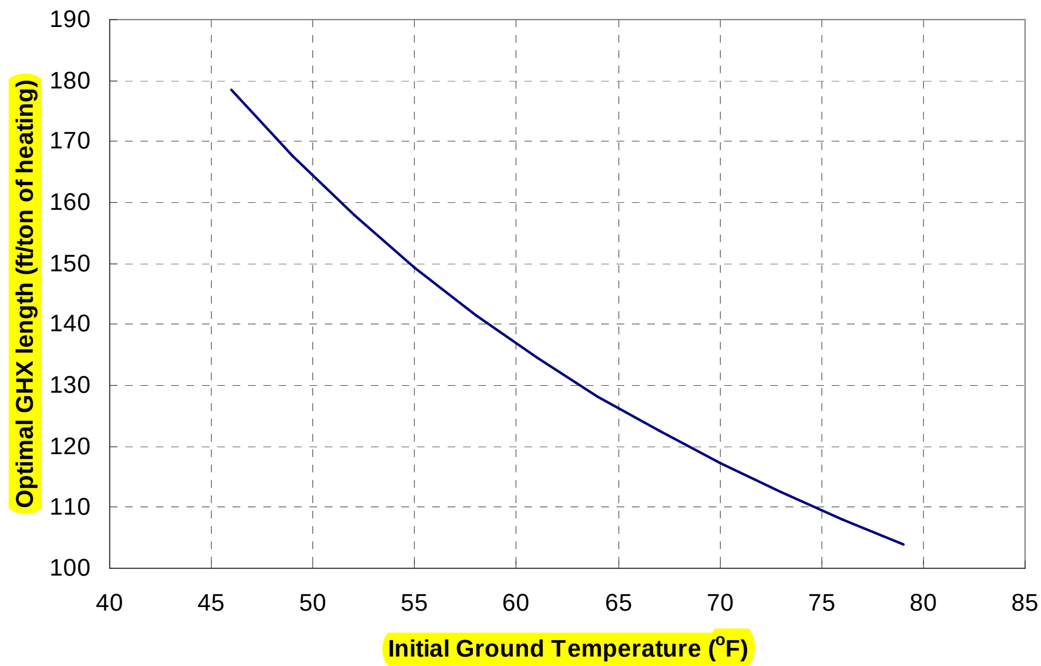

Figure 3. Ratio of the optimal GHX length for a cooling dominated system to the peak heating load as a function of the initial ground temperature (assumes k_g=1.4 Btu/hr-ft-°F).

Some current methods/tools for sizing hybrid systems (such as the GCHPCalc program discussed in the last section) already use this design guideline; it will be shown that the GCHPCalc software (Kavanaugh, 1997) arrives at a similar GHX size as shown here. The assumed ground conductivity (k_g) for these results is 1.4 Btu/hr-ft-°F. Sensitivity studies were carried out on many of the parameters listed in Table 1, including k_g; these studies suggest that every 0.1 Btu/hr-ft-°F decrease in k_g will result in a 5% increase in the optimal GHX size.

- **Supplemental Device Size: size the supplemental cooling device based on the peak cooling load that is not met by the GHX.**
  - The rated capacity of the optimally sized cooling tower (C_{CCCT}, in tons), is 2.1x the unmet load ($q_{unmet,cool}$, in tons); the unmet load should be calculated according to Equation (1):

$$C_{CCCT} = 2.1 q_{unmet,cool} = 2.1\left(q_{peak,cool} - \underbrace{\frac{L_{tot}}{3.05 T_{ground}}}_{q_{GHX,cool}} \right) \quad (1)$$

where T_{ground} is the initial ground temperature (in °F) and L_{tot} is the GHX length (in ft). The 2nd term in Eq. (1), $q_{GHX,cool}$, is the cooling capacity of the GHX; notice that the cooling capacity is proportional to length (a longer GHX provides more cooling) and inversely proportional to the initial ground temperature (a cooler ground provides more cooling). Equation (1) represents a best fit to the model predictions.

- For the cooling tower characteristics and economic conditions considered in the parametric study, it is economically attractive to oversize the tower and then use it less frequently, almost always operating it at low speed. Low speed was chosen here as 50% speed. (The setpoint temperature for high speed operation of the tower, T_{Cool1}, is therefore set to 5-8°F above the maximum entering heat pump temperature; this still allows the tower to meet the critical temperature limits). Alternatively, if a single-speed tower must be used, the tower is 1.3x the unmet cooling load; this unmet cooling load should then be calculated according to Equation (2).

$$C_{CCCT} = 1.3 q_{unmet,cool} = 1.3\left(q_{peak,cool} - \underbrace{\frac{L_{tot}}{4.72 T_{ground}}}_{q_{GHX,cool}} \right) \quad (2)$$

- The optimal cooling tower size can also be estimated based on climate; specifically how balanced the building load is. Figure 4 illustrates the optimal cooling tower size (normalized by the building size) as a function of the ratio of the annual heating load to the annual cooling load of the building. Sizing the cooling tower according to Figure 4 should lead to approximately the same result as Eq. (1).

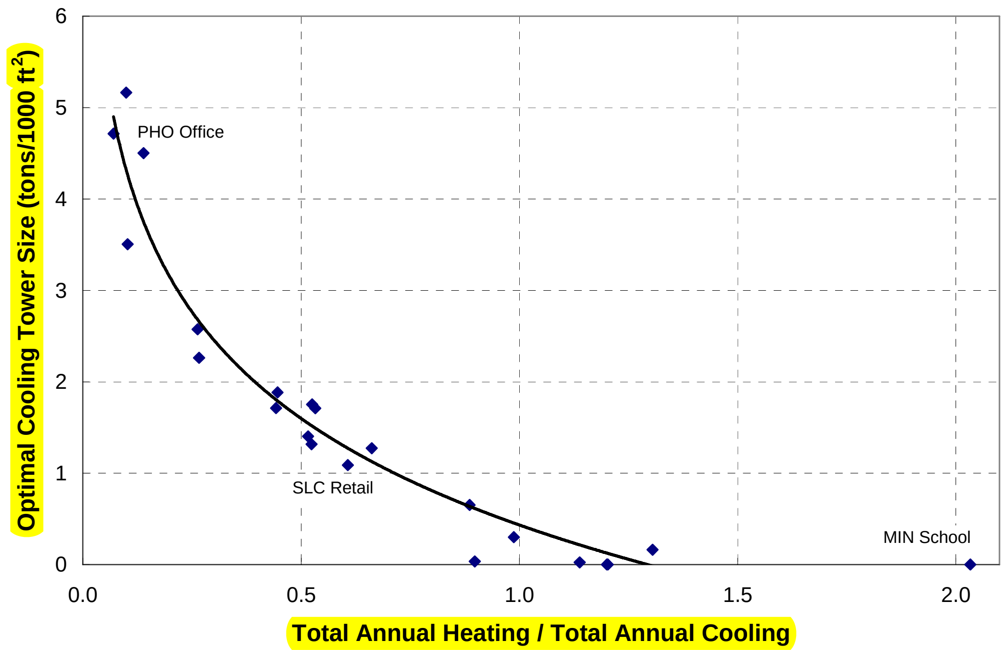

Figure 4. Optimal cooling tower size normalized by the building size as a function of the ratio of total annual heating load to peak cooling load.

- o When using a dry fluid cooler as the supplementary device, the optimal sizes follow trends that are similar to those described above for cooling towers.

- **The optimal sizes and control setpoints identified here never balance the load on the ground**. Therefore, the ground temperature always increases over time (for the cooling-dominated climate) by an amount that is dependent on the ratio of the heating and cooling loads. The timespan of simulation (i.e., the timespan used to calculate the life cycle cost that is to be minimized) therefore has a significant impact on the results. All of the design guidelines shown here minimize the life cycle cost over 20 years. Designers concerned with sustainable design practices may wish to utilize the distributable software to optimize the results with an even longer life.

- **The optimal design of the system (especially GHX size) does not depend substantially on the economic parameters used in the model (although the life cycle costs do)**; the equipment is sized almost entirely based on meeting the specified loads and it is rarely economically attractive to purchase larger equipment (e.g., a GHX that is larger than what is just required to meet the peak heating load) or operate equipment more often in order to improve the system efficiency. The primary exception to this guideline is the selection of cooling towers that utilize the reduced fan power at low speed operation (fan laws) in order to justify the purchase of a larger tower.

The design guidelines therefore remain valid over a large range of economic parameters. For example, Figure 5 illustrates the optimal size of the GHX (for one particular case, the 76000 ft^2 continuous-use building in St. Louis) as a function of the initial fuel (electricity and natural gas) prices normalized by the base case prices that were summarized in Table 1. Figure 5 shows that the price of fuel must nearly double before it becomes more economic to increase the GHX size in order to reduce the operating cost of the system.

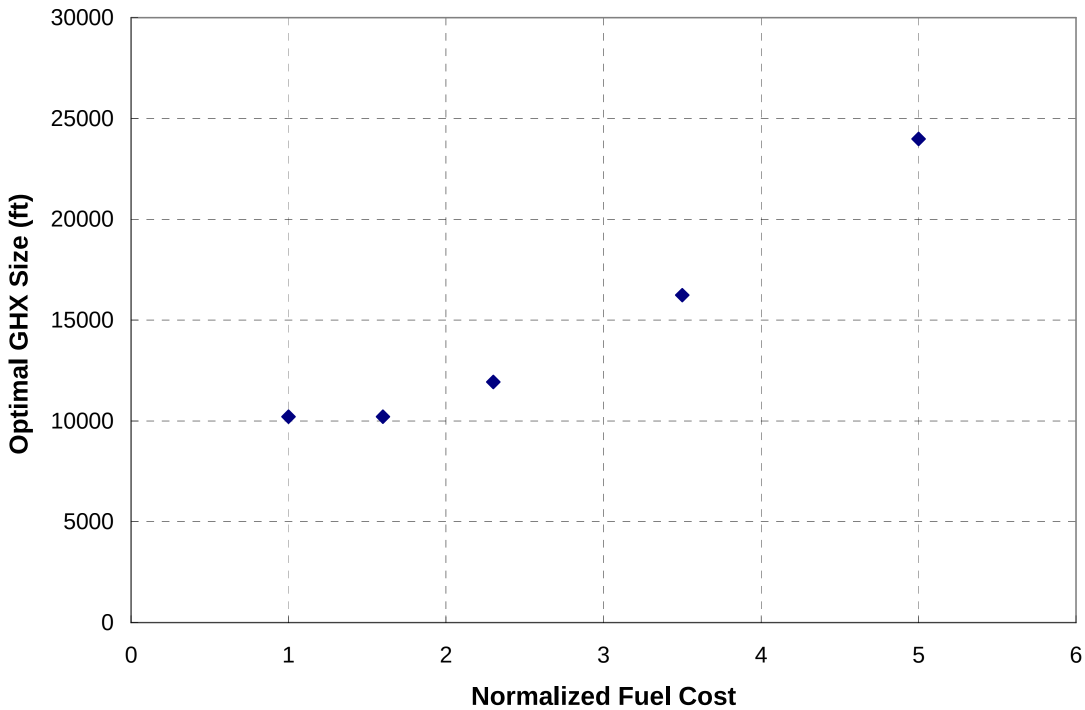

Figure 5. Sensitivity of optimal GHX size to fuel costs. The x-axis is the fuel cost normalized to the base case fuel cost (including electricity consumption, demand, and natural gas costs). Data is for a 76000 ft^2 continuous-use building in St. Louis.

- **Control setpoints**: **choose optimal control setpoints for hybrid systems as shown below.**

  (See the example below for the control sequence formed by these setpoints.)

  - Supplemental cooling device: operate this device when conditions are favorable; that is, when the fluid temperature entering the device is greater than the ambient wet bulb (dry bulb for dry fluid cooler) + ΔT_1, where:

    ΔT_1 = 27°F for a cooling tower, where $T_{wb,July}$ < 70°F

    23°F for a cooling tower, where $T_{wb,July}$ 70 to 76°F

    20°F for a cooling tower, where $T_{wb,July}$ > 76°F

    12°F for all dry fluid cooler scenarios

where $T_{wb,July}$ is the ASHRAE 1% design wet bulb temperature for the building's climate in July. (Users of these guidelines in the southern hemisphere should replace July conditions with January conditions.)

- GHX, cooling setpoint (T_{Cool2}): the GHX is bypassed only occasionally, generally in warmer climates (the optimal value of T_{Cool2} increases with more cooling dominated buildings, as shown in Figure 6)

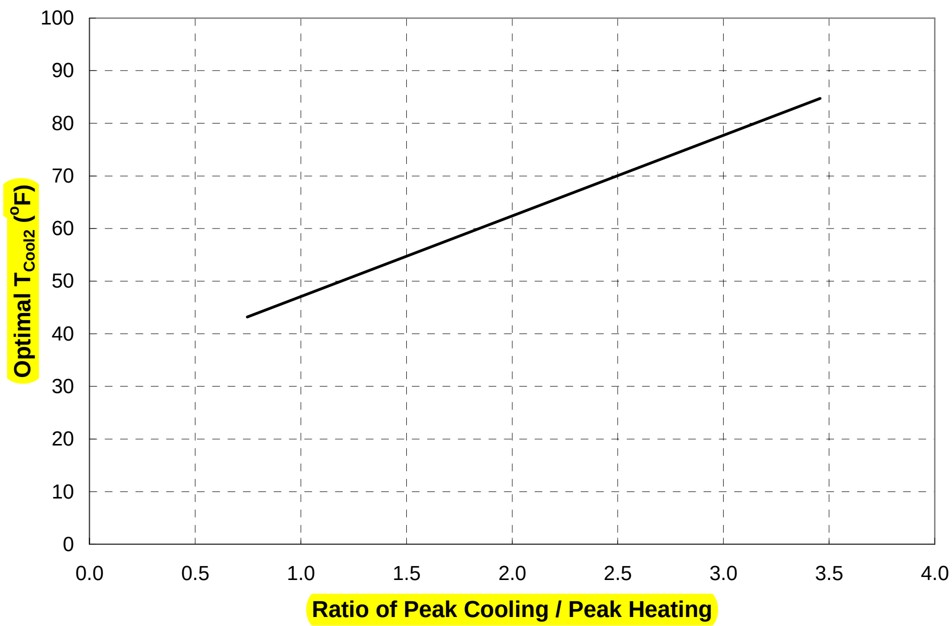

Figure 6. Optimal GHX cooling setpoint (T_{Cool2}) as a function of the ratio of peak cooling to peak heating load.

- GHX, heating setpoint (T_{Heat1}): the GHX is never bypassed in heating mode, so T_{Heat1} should be set to a high number that is never reached.

- **Operating temperature sensitivity: the lowest *LCC* for the HyGCHP model generally occurs at a minimum operating temperature below 35°F.** The limits on the temperature of the fluid entering the heat pump strongly drive the optimization; the equipment is sized in order to keep the entering fluid temperature within the specified limits (as presented in Table

1, the entering fluid temperature is not allowed to go below 35°F or above 95°F in the base cases). These base case temperature limits were selected with some guidance from the Project Monitoring Subcommittee and reflect "typical" design values. However, when the temperature limits are allowed to relax to 20°F and 110°F (within the manufacturers' stated operating limits) then the optimizer will typically choose an optimal minimum operating temperature that is lower than 35°F, trading off heat pump efficiency for reduced first cost (the size of the GHX is reduced by up to 50%). The effect of operating temperature limits is linked to the economic assumptions that were used for the parametric study, and it should be noted that a system designed using the more restrictive 35°F/95°F temperature limits will have some margin (against, for example, particularly severe weather or other uncertainties) that a system designed using relaxed temperature limits will not have.

Cost Comparisons – Cooling Dominated Systems

The parametric study considered and optimized a geothermal-only system, a boiler/tower system, and the hybrid geothermal system options for each building/climate combination. This provided an opportunity to make meaningful comparisons between these options based on life cycle costs.

- **In most moderate and southern climates, hybrid geothermal systems have a lower life cycle cost (*LCC*) than other options.**
    - The life cycle savings (*LCS*) of hybrid systems compared to geothermal-only systems is proportional to how unbalanced the climate is. Figure 7 illustrates the life cycle savings associated with a hybrid system compared to a geothermal only system (normalized by the building size) as a function of the ratio of the total annual heating load in the building to the total annual cooling load in the building, for each scenario.

Note that savings are negligible when the annual load ratio is greater than approximately 0.9.

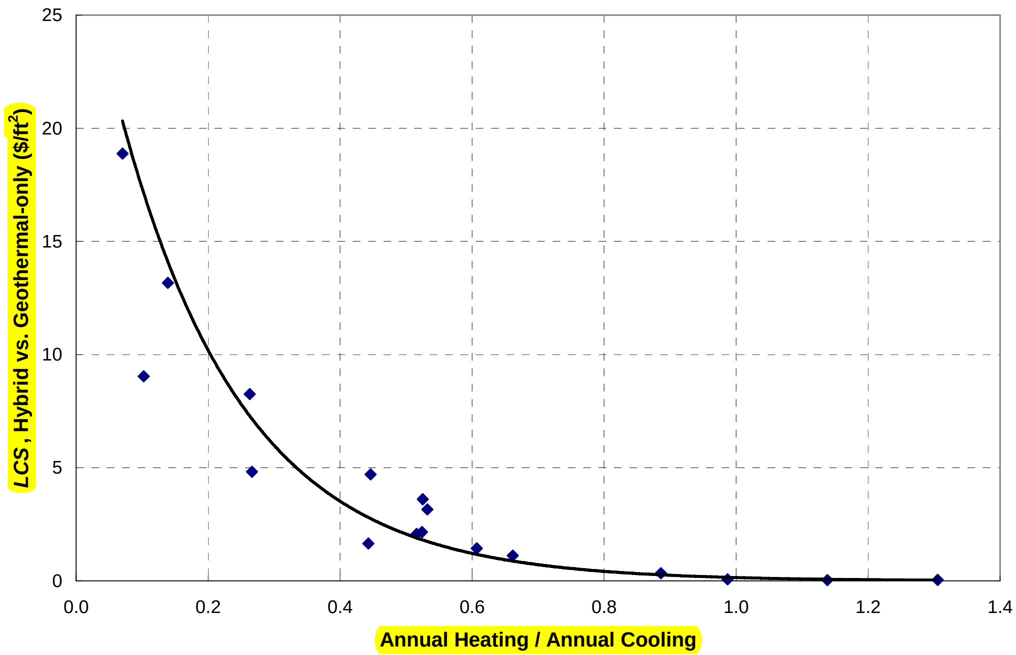

Figure 7. Life-cycle savings of hybrid systems over geothermal-only systems as a function of ratio of total annual heating load to total annual cooling load.

- The *LCS* of a hybrid system compared to a boiler/tower system is smaller than the *LCS* of a hybrid system compared to a geothermal only system (shown in Figure 7) and increases with peak heating load (the savings is negligible when the peak heating load is near zero).
- A smaller number of buildings were also studied with a dry fluid cooler used in place of a cooling tower in the hybrid system. In this study, the life cycle cost (LCC) generally changed very little from the hybrid that used a cooling tower. In some warmer climates, the LCC was slightly higher with the use of a dry fluid cooler.
- Unlike the optimal design parameters, the observed costs, and therefore *LCS*, are sensitive to economic parameters. For example, when fuel inflation is increased to

7.5% the *LCS* of hybrid systems as compared to boiler/tower systems *doubles*. The effect of GHX cost is also studied. The *LCS* changes as function of GHX cost as shown in Figure 8 (these results are normalized by building size and represent the average across five random building/climate scenarios).

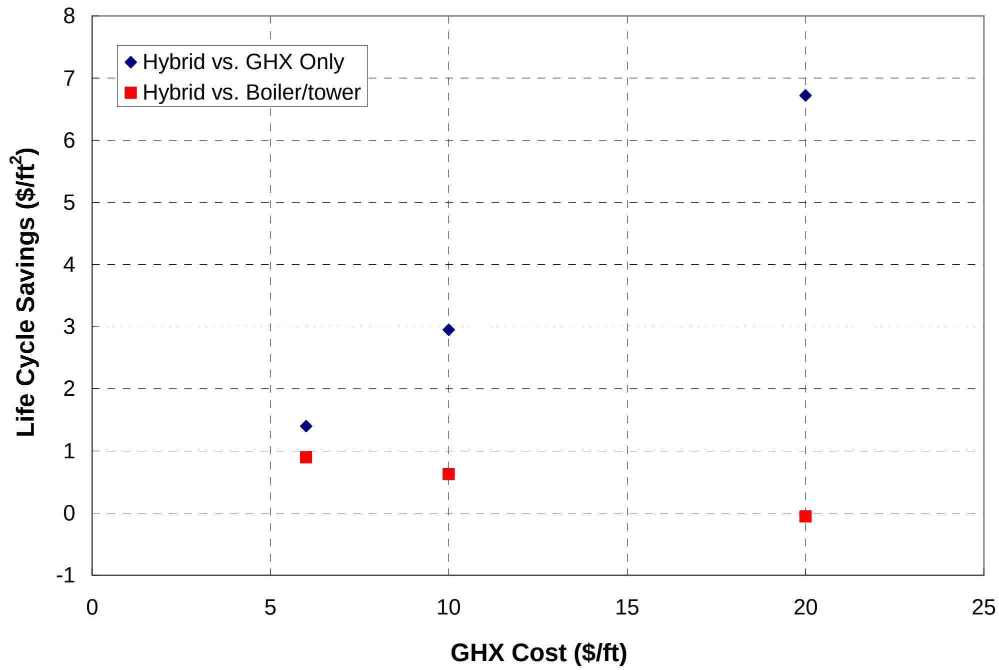

Figure 8. Life-cycle savings of hybrid systems as a function of the GHX cost. This plot shows the average values for five of the building/climate scenarios.

- **For northern climates (like Minneapolis, 7900 heating degree days, or colder) geothermal-only systems have a lower *LCC* than (cooling-dominated) hybrid or boiler/tower systems.**
- **In warm dry climates (like Phoenix), buildings with low heating loads have almost the same *LCC* for a hybrid and a boiler/tower system.**
- **In extreme climate cases featuring high ground temperatures and low wet bulb temperatures, it may be economically advantageous to place the ground heat exchanger upstream of the supplemental cooling device.**

Design Guidelines and Observations – Heating-Dominated Systems

Heating-dominated systems were also studied; the hybridization of these systems occurs through the addition of either a boiler or a solar collector array; otherwise the model and control strategy are very similar to those used for the cooling-dominated systems. The heating-dominated hybrid systems were studied for climates represented by Minneapolis and Edmonton (northern Alberta, Canada). **For the assumptions listed in Table 1, the results of the heating-dominated study suggest the design guidelines detailed below.**

- Geothermal-only systems should be sized based on heating in these climates. Note that the required ft/ton of heating is significantly greater than the values shown for cooling dominated systems in Figure 3. This is primarily due to the small temperature difference between the deep earth temperature and the minimum heat pump entering water temperature.
- Based on the economic assumptions used here, a solar/geothermal hybrid is never a viable option; including a solar component always resulted in a larger life cycle cost than a geothermal-only system (the solar component of a hybrid system was always optimized to zero). This is likely due to the high first cost of both devices utilized in this hybrid. Note that this statement does not cover systems with direct solar heating systems that bypass the heat pumps.
- The boiler/geothermal hybrid has a slightly lower *LCC* than the geothermal-only system for a Minneapolis school; however, the boiler/geothermal hybrid was significantly more attractive than the geothermal-only system for an Edmonton school. The boiler/geothermal hybrid option is likely to become increasingly attractive going north from Minneapolis.

- To optimally design a boiler/geothermal system, the GHX should be sized to meet the peak cooling load and the boiler is sized to meet the unmet heating load (this amounts to 69% of load in Minneapolis).

Example: Use of Design Guidelines

It is instructive to demonstrate the use of the design guidelines discussed above by applying them to an example building. For this demonstration, a typical cooling-dominated building was chosen: a large office building in Atlanta. This particular building has the characteristics summarized in Table 2.

Building area (1000 ft^2)	127
Peak cooling (tons)	222
Peak heating (kBtu/hr)	2413
Annual cooling (MMBtu/yr)	3683
Annual heating (MMBtu/yr)	1905
Ground temperature (^oF)	62.0
July wet bulb (^oF)	78.6

Table 2. Characteristics of the 127,000 ft^2 office building in Atlanta.

1. An optimal design for this building starts by choosing an equipment configuration. This report has demonstrated that an optimally designed hybrid system with a GHX and a cooling tower has the lowest *LCC* in Atlanta (which is a moderate climate with some heating load). Therefore, the system should be configured as shown in Figure 1.
2. In order to size the GHX for this system, Figure 3 is used; according to this plot, the GHX size required for this location (with an initial ground temperature of 62°F) is about 132 ft/ton of peak heating load. The resulting GHX size is then 26,543 ft.
3. Next, the cooling tower is sized using Equation (1). With a L_{tot} = 26,543 ft, $q_{peak,cool}$=222 tons, and T_{ground} = 62^{o}F, the rated capacity of the cooling tower is 172 tons. Figure 4 can also be used to size the cooling tower; the ratio of the annual heating to annual cooling

load is 0.52 which suggests a cooling tower size of about 1.5 tons/1000 ft^2, or about 190 tons. The larger size of 190 tons is chosen to be conservative (this is an oversized tower; the optimal system operates mainly at half speed).

4. With the equipment configured and sized, the control setpoints are now chosen. Because the summer design wet bulb temperature in Atlanta is 78.6°F, the optimal value for ΔT_1 is identified as 20°F.
5. T_{Cool2} is chosen to be about 60°F based on Figure 6.
6. T_{Heat1} is set to 100°F so that the GHX is never bypassed in heating mode, and T_{Cool1} is set to 101°F (5-8°F above the maximum temperature limits as discussed in this summary) so that the cooling tower operates primarily at low speed.

The setpoints above form the following control sequence: The cooling tower will run at low speed whenever the fluid temperature exiting the heat pumps and entering the tower is 20°F above the ambient wet bulb, and it will run at high speed whenever the fluid temperature leaving the heat pumps and entering the tower is above 101°F. The fluid will pass through the ground heat exchanger whenever the leaving fluid temperature is above 60°F in cooling mode or whenever the heat pumps are in heating mode.

The hybrid system for this same building was explicitly optimized using the HyGCHP model. In Table 3, the optimal design values that were selected by the optimizer are compared with the more approximate values selected using the design guidelines, as calculated above. All values computed with the design guidelines are within 10% of the optimal for this scenario.

	Design Guidelines	HyGCHP Optimization	GCHPCalc
GHX Size (ft)	26543	23985	23600
Tower size (tons)	191	178	150
ΔT_1 (Δ^oF)	20	19.4	N/A
T_{Cool2} (^oF)	61	57.7	N/A
T_{Heat1} (^oF)	Never bypass		N/A

Table 3. Optimal design values determined with two different methods: 1) the design calculations discussed above and 2) the optimal design values determined by the HyGCHP model.

Additionally, the third column in Table 3 shows values for one commonly used GHX-sizing software that has a hybrid design feature. The software, GCHPCalc, allows for two methods of sizing the hybrid: 1) size and operate a cooling tower to meet the unmet peak cooling load or 2) size and operate a cooling tower to balance the load on the ground. As explained earlier, this report found that it is not economically optimal to balance the load on the ground if the objective is to minimize the 20 year life cycle cost, therefore method 1 is the preferable method, and is shown in Table 3. Note that the GHX size identified by GCHPCalc is consistent with the design guidelines presented here. The cooling tower size is somewhat smaller; however, this is at least partially an artifact of the control system that operates the cooling tower at low speed in order to achieve higher efficiency.

Synopsis

In cooling dominated climates, the use of a supplemental cooling device located upstream of the ground heat exchanger can provide significant life cycle savings compared to boiler/tower systems and geothermal-only systems. For almost all cases studied, the optimal size of the ground heat exchanger was found to be that which just meets the heating loads of the building (providing cooling as well, but not enough to meet the peak cooling demand). For a wide range of climates and building types, the best control scheme for cooling operation was found to be one where the cooling towers are operated at low speed whenever the ambient conditions are favorable (the fluid leaving the heat pumps is above the ambient wet bulb temperature by a prescribed amount). The tower fans are then operated at high speed whenever the temperature of the fluid leaving the heat pumps continues to rise and exceeds the maximum heat pump entering water temperature (design temperature) by 6-8^{o}F. Fluid flows through the ground heat exchanger whenever the fluid leaving the cooling tower is above a prescribed temperature setpoint. In heating mode, fluid flows through the ground heat exchanger whenever the temperature leaving the heat pumps falls below the set point for heating. Dry fluid coolers can be substituted for closed circuit cooling towers without substantial penalty in most cases.

In heating dominated climates, the use of a supplemental heating device located downstream of the ground heat exchanger can provide substantial life cycle savings compared to boiler/tower systems and stand-alone ground heat exchanger systems. For the cases studied, the optimal size of the ground heat exchanger was found to be that which just meets the cooling loads of the building (providing heating as well but not enough to meet the peak heating demand). The best control scheme for heating operation was found to be one where fluid flows through the ground heat exchanger whenever the temperature rises above or falls below prescribed temperature set points with a boiler being used at peak heating conditions to maintain the fluid at the minimum allowable heat pump entering water temperature.

Guidelines are presented for quick sizing and control of hybrid systems provided the parameters of the project closely match the default parameters presented earlier. Users are urged to exercise the distributable program to analyze specific projects more accurately (especially those deviating from default parameters); running quick comparison studies between design alternatives or a full-scale optimization.

Reference

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