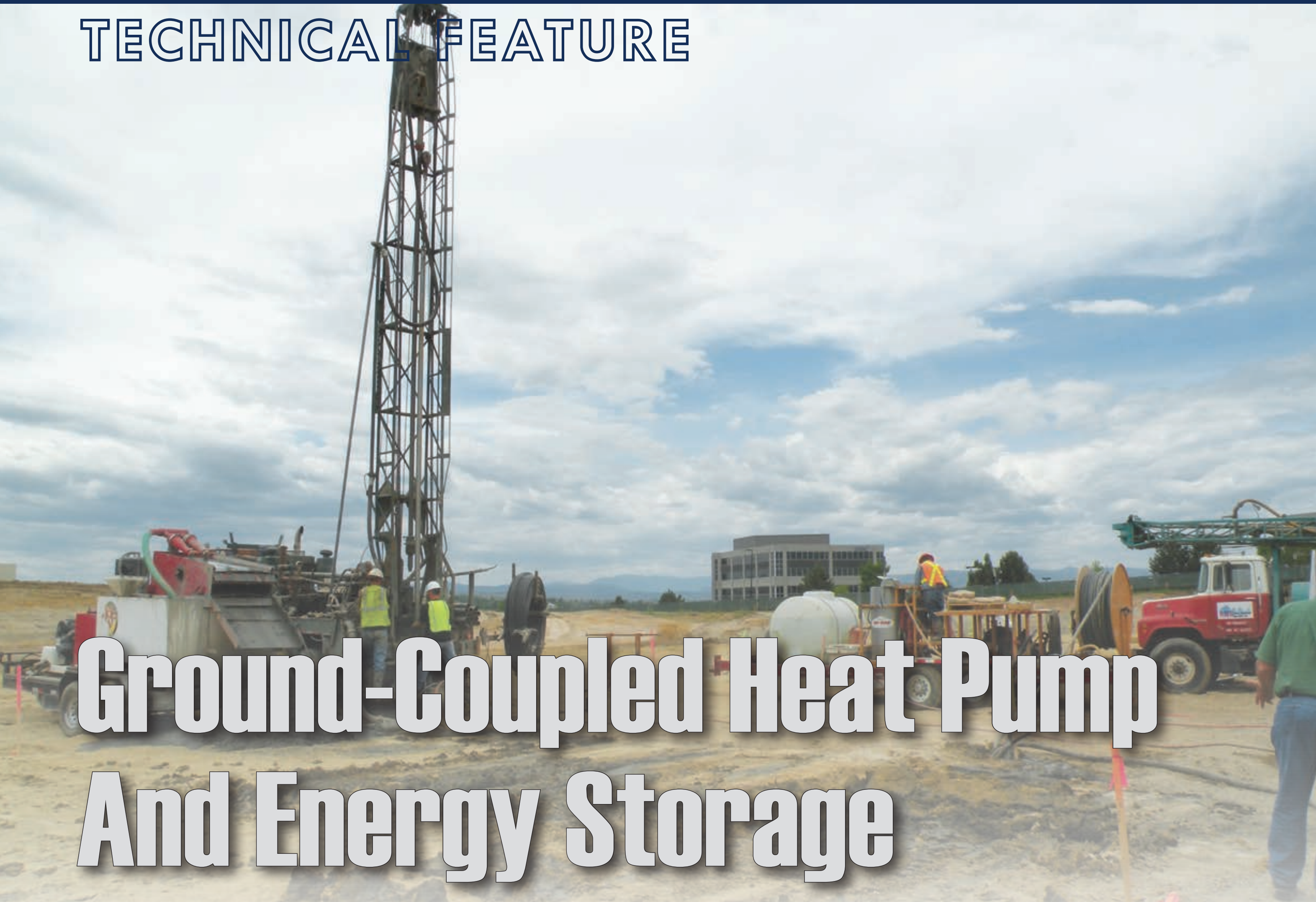
TECHNICAL FEATURE



Ground-Coupled Heat Pump And Energy Storage

By Ed Lohrenz, Member ASHRAE; and **Sergio Almeida, P.Eng.,** Member ASHRAE

Ground-coupled heat pump (GCHP) systems consume less purchased energy than an HVAC system using fossil fuel and electricity directly for heating and cooling.[1] However, the cost of building the ground heat exchanger (GHX) often prevents acceptance of GCHP systems.

The incremental cost of a GCHP is driven primarily by the cost of building the GHX. The size of the GHX needed for a project is determined by four factors: peak heating and cooling loads, annual heating and cooling energy loads, geology, and configuration of the GHX.

A designer has no control over the geology or size and configuration of the site. The GHX must be designed for the project. A designer can have some control over the building and systems. The purpose of this article is to illustrate how integration of thermal energy storage (TES) with a GCHP system can reduce the cost of a GHX and reduce energy cost. Hypothetical examples based on actual projects illustrate the integration of a GCHP system with TES to produce domestic hot water or provide cooling more cost effectively and efficiently in certain types of GCHP projects.

Energy Storage

You very likely took advantage of TES during your morning shower. A hot water tank with 10,000 Btu/h (3 kW) heating capacity, heats 11.5 gallons (43.5 L) of water for your five-minute shower, using 5,750 Btu (1.65 kWh) of energy. An on-demand water heater would require a 69,000 Btu/h (20.2 kW) element to heat 50°F (10°C) water to 110°F (43°C) to supply 2.3 gpm (0.14 L/s).

If your teenager wants a shower at the same time, you will need a second 69,000 Btu/h (20.2 kW) on-demand water heater. But if you have a storage tank full of hot water, the same 10,000 Btu/h (3 kW) heater would work for just over an hour to provide hot water for both showers before you head out.

If no one else uses hot water for a few hours, a 30 gallon (113 L) tank easily meets your hot water needs using a 10,000 Btu/h (3 kW) heater instead of a 69,000 Btu/h (20.2 kW) heater.

Energy storage also has implications on the design of the energy supply to your home. Wires connecting your home to the grid, electrical panel, circuit breakers and size of the wires to your water heater are all affected. It may have

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	Large Heat Pump/Small Storage Tank	Small Heat Pump/Large Storage Tank
Heat Pump Capacity	310 kBtu/h	90 kBtu/h
Storage Tank Capacity	120 gallon	720 gallon
Power Input (Varies with GHX Temperature)	36 kW	11 kW
Recovery Time	0.30 hours	5.7 hours

Table 1: This table summarizes the design of alternative approaches to produce DHW for a typical apartment building using a GCHP system.

A	Heating & Cooling			
	Cooling		Heating	
	kBtu	kBtu/hr	kBtu	kBtu/hr
Jan	6825	92	118011	426
Feb	7992	142	86132	381
Mar	19048	257	61729	268
Apr	33515	357	27322	139
May	56222	440	11144	79
Jun	94600	587	2408	31
Jul	108100	645	762	17
Aug	95671	638	522	25
Sep	52197	601	6416	63
Oct	30192	398	20098	115
Nov	12379	240	57837	305
Dec	7453	91	99372	372
	524195	645	491751	426
	EFLH	813	EFLH	1154

B	Heating, Cooling & DHW (120 gallons)			
	Cooling		Heating	
	kBtu	kBtu/hr	kBtu	kBtu/hr
Jan	6825	92	149200	736
Feb	7992	142	117321	691
Mar	19048	257	92918	578
Apr	33515	357	58511	449
May	56222	440	42334	389
Jun	94600	587	33598	341
Jul	108100	645	31951	327
Aug	95671	638	31711	335
Sep	52197	601	37605	373
Oct	30192	398	51287	425
Nov	12379	240	89026	615
Dec	7453	91	130561	682
	524195	645	866023	736
	EFLH	813	EFLH	1177

C	Heating, Cooling & DHW (720 gallons)			
	Cooling		Heating	
	kBtu	kBtu/hr	kBtu	kBtu/hr
Jan	6825	92	149200	516
Feb	7992	142	117321	471
Mar	19048	257	92918	358
Apr	33515	357	58511	229
May	56222	440	42334	169
Jun	94600	587	33598	121
Jul	108100	645	31951	107
Aug	95671	638	31711	115
Sep	52197	601	37605	153
Oct	30192	398	51287	205
Nov	12379	240	89026	395
Dec	7453	91	130561	462
	524195	645	866023	516
	EFLH	813	EFLH	1678

Table 2A: Monthly peak heating and cooling loads (kBtu) and monthly energy loads (kBtu/h) for a typical apartment building. **Table 2B:** Monthly peak heating and cooling loads and monthly energy loads with DHW heating loads assuming a 120 gallon (454 L) storage tank is used. **Table 2C:** Monthly peak heating and cooling loads and monthly energy loads with DHW loads assuming a 720 gallon (2,725 L) storage tank is used.

implications on the size of your electricity bill if your home has a smart meter measuring peak electrical demand as well as consumption.

TES has implications for your electric utility. The size of generating stations, distribution grid and transformers needed to get energy to your home, and with some utilities even the type of fuel used to generate electricity, are all impacted by your decisions.

Domestic Hot Water Storage Tanks in a GCHP Application

Many facilities have predictable and intermittent domestic hot water (DHW) requirements. Occupants in apartment buildings tend to use hot water heavily for a few hours in the morning before heading to work and a few hours in the evening preparing and cleaning up after dinner.

When designing a DHW system using a gas boiler or gas water heaters, there is little impact on the capital cost on the system. It may cost less to increase the capacity of the boiler and decrease the storage tank size when space in the mechanical room is limited. The following example illustrates the impact of TES on a GCHP system.

A typical apartment building was selected to illustrate the impact of DHW production using a large heat pump/small storage tank compared to a small heat pump/large storage capacity combination. The following assumptions were used to calculate heat pump and storage tank capacity (*Table 1*):

- 84 showers over two hours consuming 966 gallons (3657 L) of water between 6 and 8 a.m., plus 483 gallons (1828 L) between 6 and 8 p.m.;
- Makeup water temperature: 55°F (12.8°C); and
- Water temperature to showers: 110°F (43°C).

An energy model was created for the project and DHW loads were added to create three sets of loads:

- Building heating and cooling only;
- Heating and cooling with 310 kBtu/h (90.0 kW) heat pump /120 gallon (454 L) storage capacity; and
- Heating and cooling with 90 kBtu/h (26.4 kW) heat pump/720 gallon (2725 L) storage capacity.

Monthly peak heating and cooling loads and monthly energy loads derived from the energy models are shown in *Table 2*. These were used to calculate size of the GHX for the alternatives using commercially available GHX design software using "g" functions (non-dimensional temperature factors that calculate a borehole field response to heat injection and heat extraction pulses).

The length of the boreholes was calculated using the following parameters. Results are summarized in *Table 3*.

- Grid of five boreholes by four boreholes with 20 ft (6.1 m) spacing between boreholes;

	Heating and Cooling Only	DHW with Large Heat Pump/ Small Storage	DHW with Small Heat Pump/ Large Storage
Total Borehole	7,780 ft	7,880 ft	6,500 ft
Maximum Temperature	85.0°F	77.7°F	82.7°F
Minimum Temperature	39.1°F	32.0°F	32.0°F

Table 3: Total borehole length for GHX calculated for a five year prediction time to stay within a temperature range of 85°F and 32°F (29.4°C and 0°C). Calculations are based on site specific data and vary by geology and geography. Calculations are designed to illustrate relative GHX lengths for a project based on energy loads and peak heating loads added to a system when DHW is added. Note that adding DHW loads to the GHX reduces minimum entering temperature to 32°F (0°C).

- Undisturbed ground temperature: 53°F (11.7°C);
- Average thermal conductivity: 1.40 Btu/h·ft·°F (2.42 W/([m·K]);
- Average thermal diffusivity: 0.96 ft^2/day (0.089 m^2/day);
- GHX was modeled to operate at a minimum temperature of 32°F (0°C); and
- GHX was modeled to operate at a maximum temperature of 85°F (29.4°C).

Adding DHW load to the system helps balance energy loads to and from the GHX, changing it from cooling to heating dominant when a DHW system with small storage capacity is used. However, there is much greater impact when the peak heat pump capacity used to produce DHW is reduced and combined with more storage capacity.

	Conventional Boiler/ Chiller and Gas DHW	DHW with Large Heat Pump/Small Storage	DHW with Small Heat Pump/Large Storage
Heat Pumps/ Distribution	$183,000	$229,000	$210,000
DHW Storage Tanks	$2,400	$1,200	$7,200
Cooling Tower	$44,000	–	–
GHX	–	$118,200	$97,500
System Cost	$229,400	$348,400	$314,700
Cost Difference From Conventional	–	$119,000	$85,300
Predicted Energy Cost	$17,922	$12,344	$11,256
Energy Cost Savings	–	$6,344	$7,365
Simple Payback	–	18.8 Years	11.6 Years

Table 4: Summary of capital cost to install conventional HVAC system compared to GCHP and GCHP integrated with hot water storage. The following assumptions were used: Cost of mechanical system estimated, cost of GHX: $15/ft ($52/m); cost of gas: $1.13/ccf ($0.40/m^3 or $10.65/GJ); cost of electricity: $0.06/kWh with demand charge $8.00/kW. (Note: construction costs, GHX costs and utility rates vary significantly from one area to another and because of design details and equipment selection, may not represent costs in your area. These variations along with possible incentives available in your area can have an impact on financial models.)

Designing a DHW system to minimize heat pump capacity and maximize hot water storage reduces total borehole length in this project by almost 1,300 ft (396 m), or 17.5%. Typical drilling costs range from $12 to $22/ft ($40 to $72/m). Reducing the size of the GHX improves the return on investment for the owner.

There may also be an impact on the energy cost, depending on the electric utility rate structure. If the utility charges "time of use" rates, or has a demand charge, there can be a significant reduction in energy cost using TES. Reduced construction cost and possibly lower energy cost demand reduction for some projects reduces the simple payback by seven years in this example, as summarized in *Table 4*.

Peak Building Cooling Loads

Large buildings with large interior/core spaces often have higher peak cooling loads than heating, even in cold climates such as the northern United States and Canada. Cooling loads in these buildings are often driven by occupancy schedules rather than weather and are intermittent and predictable.[2]

In an office building cooling loads are low overnight when the building is empty, lights and computers are shut down and solar gains are absent. Loads increase when people arrive, lights and office equipment are activated and ventilation systems ramp up while solar gains and outdoor air temperature increase. They drop off as people leave in the afternoon. Other types of buildings, such as retail spaces or schools have their own schedules but are also fairly predictable.

Cooling systems are designed to meet design day loads; a condition that occurs only a few hours per year. Otherwise, it runs at part load or is idle. To take advantage of this pattern, chilled water and ice storage tanks have traditionally been used in areas where the cost of electricity is affected by high peak demand charges and time of use rates. Storage has been used to shift peak electrical demand from periods of high cooling demand—and high utility costs—to take advantage of off-peak rates overnight that coincide with the reduced building loads. Smaller, less expensive systems can satisfy the building loads with the same (or lower) energy costs.[3]

A	Space Heating & Cooling without TES			
	Cooling		Heating	
	kBtu	kBtu/hr	kBtu	kBtu/hr
Jan	45815	265	173548	531
Feb	44459	310	145765	500
Mar	60676	463	104584	384
Apr	91388	709	39429	303
May	156271	929	9721	220
Jun	269267	1141	721	39
Jul	338252	1329	101	15
Aug	328551	1188	377	32
Sep	202717	1156	3874	87
Oct	112443	744	31201	319
Nov	65358	441	86589	344
Dec	49090	176	150842	454
	1764287	1329	746752	531
	EFLH	1328	EFLH	1406

B	Space Heating & Cooling with TES			
	Cooling		Heating	
	kBtu	kBtu/hr	kBtu	kBtu/hr
Jan	45815	265	173548	531
Feb	44459	310	145765	500
Mar	60676	463	104584	384
Apr	91388	600	39429	303
May	156271	600	9721	220
Jun	269267	600	721	39
Jul	338252	600	101	15
Aug	328551	600	377	32
Sep	202717	600	3874	87
Oct	112443	600	31201	319
Nov	65358	441	86589	344
Dec	49090	176	150842	454
	1764287	600	746752	531
	EFLH	2940	EFLH	1406

Table 5: Monthly peak heating and cooling loads (kBtu/h) and monthly energy loads (kBtu) are shown for a 100,000 ft^2 (9290 m^2) office building in Wichita, Kan.

Chilled Water, Ice Storage Tanks in GCHP System

The instantaneous peak load of a chiller or water to water heat pump system is one factor used to calculate the size of a GHX required. This is demonstrated by seeing the impact of energy storage on the loads and the size of GHX needed for a 100,000 ft^2 (9293 m^2) office building in Wichita, Kan.[4]

The peak cooling load of the facility is 1,329 kBtu/h (390 kW). Both peak heating loads and annual heating energy loads are about 60% lower than the cooling loads. The building is cooling dominant even before considering the electrical energy used to power compressors, pumps and fans. Monthly peak heating and cooling loads and monthly energy loads are shown in *Table 5* and graphically in *Figure 1*.

By adding TES, the capacity of the heat pumps or chiller is reduced from 1,329 kBtu/h to 600 kBtu/h (390 to 175 kW). The annual cooling energy loads do not change, but smaller equipment operates for more hours to meet the annual cooling loads of the building. The equipment is used during off-peak hours to chill water or make ice in a storage tank. Stored energy supplements the equipment cooling capacity the following day.

However, the designer must ensure that the equipment has the capacity to build enough ice or chilled water during the off-peak hours available, taking into consideration the lower cooling capacity when producing low temperature water or ice. The designer should also take into consideration that the efficiency of a heat pump is reduced by approximately 10% to 15% when producing ice or low temperature water.[5] The reduced efficiency while producing ice is partially offset in some situations if simultaneous heating and cooling options are available (*Figure 2e*).

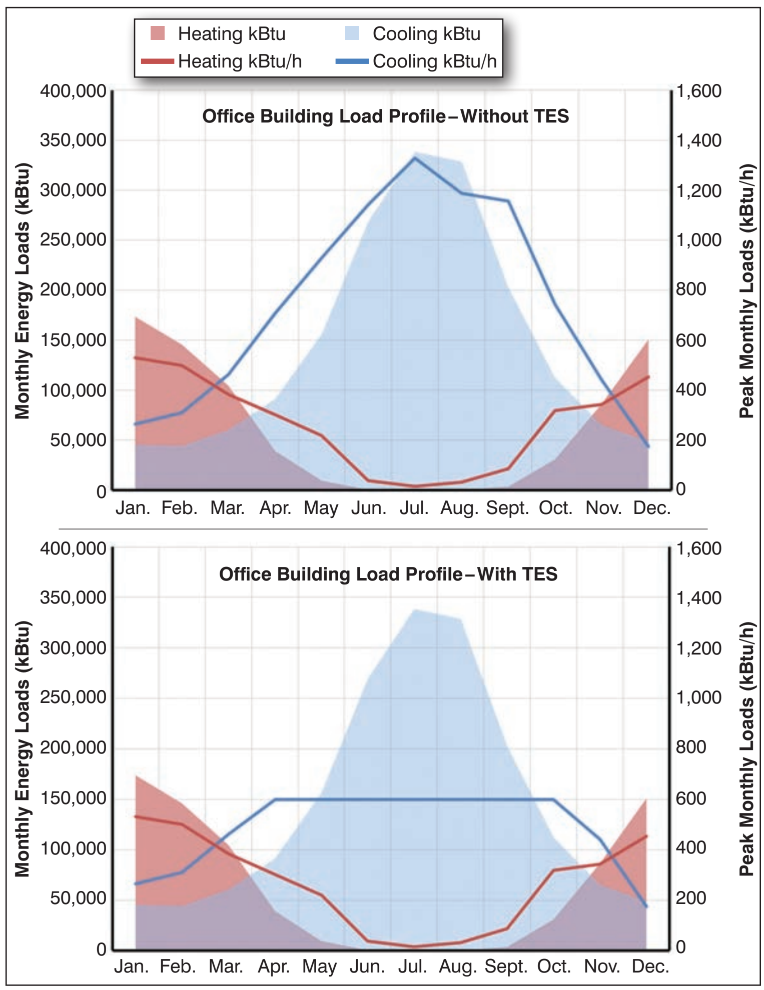

Figure 1: Office building load profile without thermal energy storage compared to equipment load profile with the addition of thermal energy storage. Limiting the equipment cooling capacity to 600 kBtu/h does not change the annual loads; it simply increases the equipment run hours. Chilled water or ice built during off-peak hours supplements the cooling capacity of the equipment when required during times of peak cooling loads.

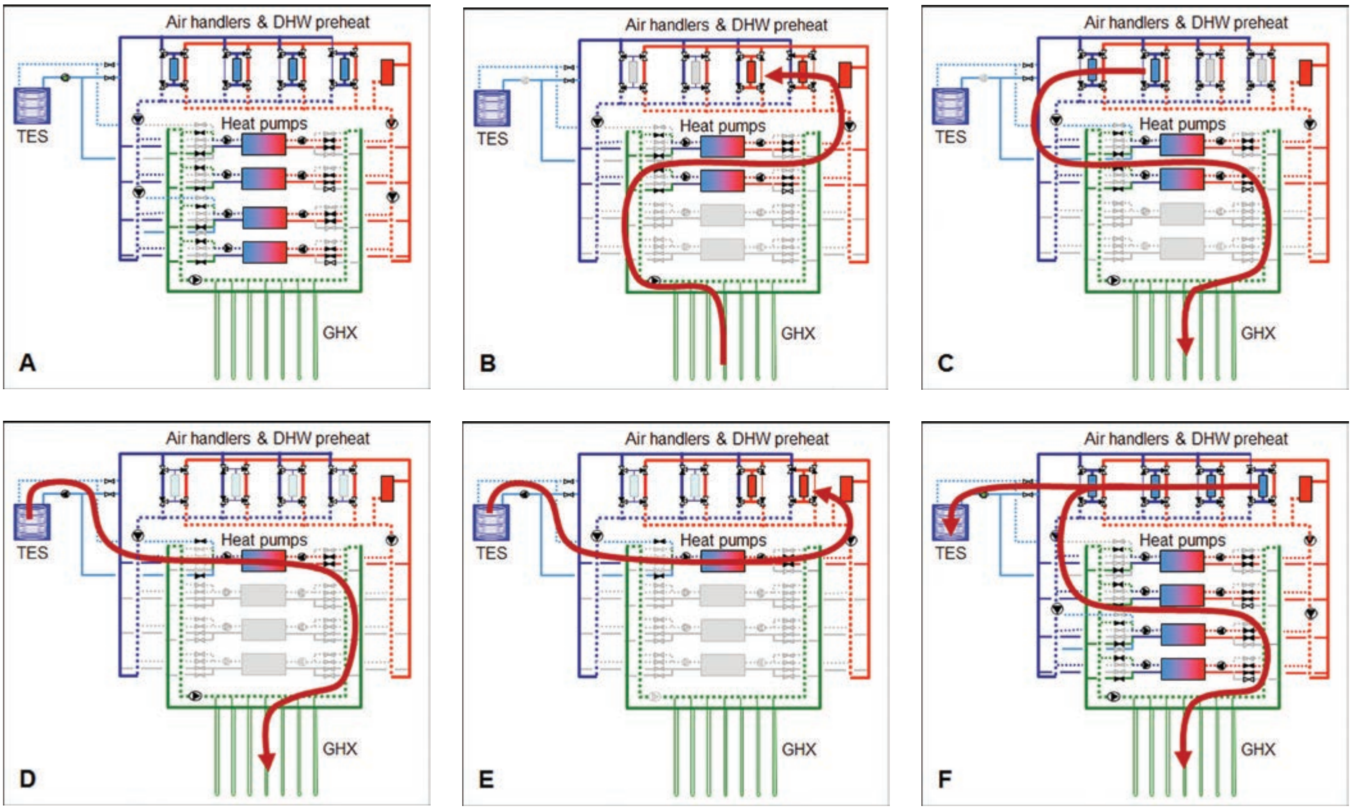

Figure 2a: A simplified schematic illustrating a central modular water-to-water heat pump system designed to supply hot or chilled water to air handlers in a building. A chilled water tank or ice storage tank is integrated with the GCHP system. **Figure 2b:** Illustrates two water-to-water heat pumps drawing heat from the GHX and producing hot water. **Figure 2c:** Illustrates two heat pumps providing chilled water to air handlers and rejecting heat to the GHX. **Figure 2d:** One heat pump is building chilled water or ice in a storage tank and rejecting heat to the GHX. **Figure 2e:** One heat pump builds storage while simultaneously producing hot water for use in the building. **Figure 2f:** System uses full heat pump capacity to produce chilled water for air conditioning while using the storage tank to provide supplemental cooling capacity.

The length of the boreholes was calculated based on the following parameters and is summarized in *Table 6:*

- Grid of six boreholes is multiplied by 12 boreholes: 20 ft (6.1 m) spacing;
- Undisturbed ground temperature: 56°F (13.3°C);
- Average thermal conductivity of soil: 1.40 Btu/h·ft·°F (2.42 W/[m·K]);
- Average thermal diffusivity of soil/rock: 0.90 ft^2/day (0.084 m^2/day); and
- The GHX was modeled to operate at a maximum temperature of 95°F (29.4°C).

	GCHP Without TES	GCHP With TES
Total Borehole Length	18,964 ft	16,104 ft
Minimum Fluid Temperature to Building	50.5°F	49.8°F
Maximum Fluid Temperature to Building	95.0°F	95.0°F

Table 6: Total borehole length for GHX calculated for a five year prediction time to reach a maximum temperature of 95°F (35°C). These calculations are based on site specific data, and will vary by geology and geography.

In this building, the amount of drilling required can be reduced by approximately 15% if chilled water or ice storage is integrated with the mechanical system and has little impact on the operating temperatures of the GHX. This has a significant impact on the cost of constructing a GHX for this facility. At a cost of $12 to $22/ft ($40 to $72/m), the cost to construct the GHX is reduced by $34,000 to $63,000.

The cost of chilled water or ice storage tanks is significant, but reduced chiller or heat pump capacity offsets additional cost of tanks and controls. Capital cost savings for equipment and the GHX help provide a more attractive financial model for the owner. The estimated simple payback for the standard GCHP system and the GCHP with TES is summarized in *Table 7*.

Central Plant Schematic Design with TES

Chilled water or ice storage tanks are most easily integrated into a central plant design using either water-to-water heat pumps or conventional chiller equipment. The equipment selected must operate efficiently at the fluid

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temperatures expected. Building ice requires chilled fluid as low as 22°F (–6°C).

In a central plant, water flow from the evaporator is directed by motorized valves to either the GHX when drawing heat from the earth, to the building loads (i.e., air handlers, radiant floor cooling, etc.), or to the ice storage tanks. Water flow from the condenser is directed either to the GHX when cooling the building, or to terminal devices when heating.

Using several heat pump modules, and directing the flow from each module independently, allows the varying loads of the building to be met. One module can build ice and provide heat to the building, and a second can draw heat from the GHX to provide additional heat.

A centralized water-water heat pump system provides hot and chilled water to the building simultaneously. Rather than rejecting energy into the ground, it can provide space heating in other areas of the building or produce hot water. To build ice or chilled water in storage tanks requires the heat pumps to run more hours, significantly increasing opportunities for simultaneous heating and cooling and improving system efficiency, even though when strictly building ice, the heat pumps are less efficient.

	Boiler/Chiller	GCHP	GCHP with TES
Interior Mechanical System Cost	$2,500,000	$2,400,000	$2,400,000
Deduct for Reduced Heat Pump Capacity	–	–	($70,000)
Add for Ice Storage Tanks	–	–	$58,000
Add for GHX	–	$417,000	$354,000
System Cost	$2,500,000	$2,817,000	$2,742,000
U.S. Federal 10% Tax Incentive	–	($281,700)	($274,200)
Cost Difference from Conventional	–	$35,300	($32,200)
Predicted Energy Cost	$33,616	$21,645	$18,946
Energy Cost Savings	–	$11,971	$14,670
Simple Payback	–	2.9 Years	0 Years

Table 7: Summary of capital cost to install conventional HVAC system compared to GCHP and GCHP integrated with ice storage. The following assumptions were used: Cost of conventional mechanical system: $25/ft^2 ($269/m^2), cost of GCHP interior system: $23/ft^2 ($247/m^2) cost of GHX: $22/ft ($72/m), cost of gas: $1.08/ccf ($0.38/m^3 or $10.20/GJ), cost of electricity: $0.08/kWh with demand charge $16.00/kW. Energy cost was calculated using 8,760 hour energy model. Additional incentives based on accelerated capital cost allowance are not included in calculations, and may significantly improve economic analysis in the U.S. and Canada for some owners. (Note: construction costs, GHX costs and utility rates vary significantly from one area to another and because of design details and equipment selection, may not represent costs in your area. These variations along with possible incentives available in your area can have an impact on financial models.)

Several factors should be considered before integrating chilled water or ice storage tanks with a GCHP system:

• Chilled water tanks or ice storage tanks add cost to the mechanical system. This is offset by reducing chiller or heat pump capacity.

• Heat pumps used to produce ice or low temperature water operate less efficiently and with less capacity. Reduced efficiency is offset if heat produced can be used simultaneously.

• Chilled water tanks and ice storage tanks require space, and the weight of the filled tanks must be supported. In some projects, tanks may be buried near the building or placed on the roof, but consideration must be given to tank placement.

• If ice storage is selected, the system may require the same fluid throughout the system, including the building piping system and the GHX. This will require adequate freeze protection and may impact pump selection and pumping costs. Alternatively , heat exchangers can be used to separate different parts of the system.

• The control strategy must be considered carefully. Considerations include:

◦ Are “time of use” rates available and at what time of day or week?

◦ Are there peak electrical demand penalties at specific times?

◦ How many hours are available to build storage, and is the equipment capacity specified adequate to recharge the storage in the time available?

◦ What is the chilling capacity of the specified equipment when producing chilled water or ice for the storage tanks?

◦ Is the system designed to provide the peak cooling load with only the chilled water or ice storage tanks, or is it designed to supplement the cooling capacity of the chilled water plant?

◦ Will stored chilled water or ice be required to provide mission critical cooling?

◦ Does equipment specified provide the heating capacity required in the building, or will supplemental heating be required?

◦ Is the system designed to provide chilled and hot water for simultaneous heating and cooling?

◦ Will the client have trained personnel capable of operating the system as intended?

Conclusions

Integrating TES with a GCHP system can provide benefits in projects with large, predictable and intermittent peak heating

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and/or cooling loads. Energy storage can be connected to the load side of a GCHP system, in the form of hot or chilled water storage tanks, or phase-change materials such as ice or wax.

TES provides traditional benefits, such as:

- Electrical demand shifting;
- Electrical consumption shifting;
- Peak demand reduction;
- Reduced heating and/or cooling capacity requirement; and
- Reduced pumping power through the GHX.

When used in appropriate building types with a GCHP system, TES provides additional benefits, including:

- Reduced size and cost of the GHX;
- Reduced land area for a GHX;
- More balanced annual heating and cooling energy loads to and from the GHX; and
- Greater opportunities for simultaneous heating and cooling.

More importantly, integrating energy storage with a GCHP system can reduce the first cost of building the system while lowering energy cost. This can provide the owner a better return on investment. TES is not suitable in all GCHP projects. Buildings with large intermittent and predictable peak heating, cooling loads or domestic hot water loads benefit the most from integration of TES devices by reducing peak loads to the GHX.

Control strategies for a GCHP system integrated with TES can be more complex than that of a typical distributed heat pump system. A more complex control system may not be appropriate for a project with an untrained building operator, especially if they are geographically located some distance from technical assistance. A remotely accessible controls interface is a useful tool to address this issue by allowing a trained professional to monitor system performance and refine the operation of the system over time.

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