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Energy Efficiency Technologies – Air Source Heat Pump vs. Ground Source Heat Pump

Ruqun Wu

OEP

Faculty of Land and Environment, The University of Melbourne

Victoria 3010, Australia

Tel: 61-43-371-3541 E-mail: r.wu6@pgrad.unimelb.edu.au

Abstract

Heat pump deserves the name of eco-innovation. It uses 'free energy' - warmth collected in the soil or in the air to provide heating and cooling. There are two main types of heat pumps – air source heat pump and ground source heat pump. How do they work? What are the benefits of each system? How do they compare? First of all, questions like "what is heat pump, how does it work, what are ASHPs and GSHPs" will be answered. Then a detailed comparison between ASHPs and GSHPs will be carried out, from technological parameters to social, practical, economical parameters. Finally, the conclusions are drawn from these parameters as to decide which kind of heat pump is better off under different conditions.

Keywords: Heat pump, Efficiency, Air Source Heat Pump, Ground Source Heat Pump

Nomenclature

Q_e: condensation heat rate, kJ s^{-1}

Q_c: evaporation heat rate, kJ s^{-1}

W: compressor input energy, kW

COP: coefficient of performance

$\dot{m}$: mass flow rate, kg s^{-1}

h: enthalpy, kJ kg^{-1}

$\dot{Q}$: the rate of heat transfer, kJ s^{-1}

$U_{c/e}$ $A_{c/e}$: overall heat transfer coefficient of condenser / evaporator, kW $^oC^{-1}$

K: constant, equals $U_e A_e / U_c A_c$.

T_c: temperature in cold region(heat source), ^oC

T_h: temperature of warm region (heat sink), ^oC

T_{re}: temperature of refrigerant in evaporator, ^oC

T_{rc}: temperature of refrigerant in condenser, ^oC

T_{eout}: temperature of outlet fluid in evaporator, ^oC

T_{cout}: temperature of outlet fluid in condenser, ^oC

1. Introduction

The physical law tells us that heat normally flows from a warmer medium to a colder one. But can we move heat from our cooler house and dump it to a higher outside environment in summer? And can we extract heat from a lower temperature outside, to our warmer rooms in winter? The answer is yes if we use a heat pump. The heat pump does so by essentially "pumping" heat up the temperature scale, transferring it from a cold material to a warmer one by adding energy, usually in the form of electricity. The most common type of heat pump is the air-source heat pump, which transfers heat between indoor and the outside air. Ground Source heat pumps (GSHPs) have been in use since late 1940s, they use the constant temperature of the earth as the exchange medium instead of the outside air temperature.

2. Background

2.1 Heat Pumps

Heat pumps (vapor compression heat pumps) transfer heat by circulating a phase changing substance called a refrigerant through a cycle of evaporation and condensation (Figure 1).

A compressor pumps the refrigerant between two heat exchanger coils. In one coil, the refrigerant is evaporated at low pressure and absorbs heat from heat source, the refrigerant is then compressed en route to the other coil, where it condenses at high pressure, at this point, it releases the heat it absorbed earlier in the cycle to the heat sink(NRCOEE,2004,p.4).

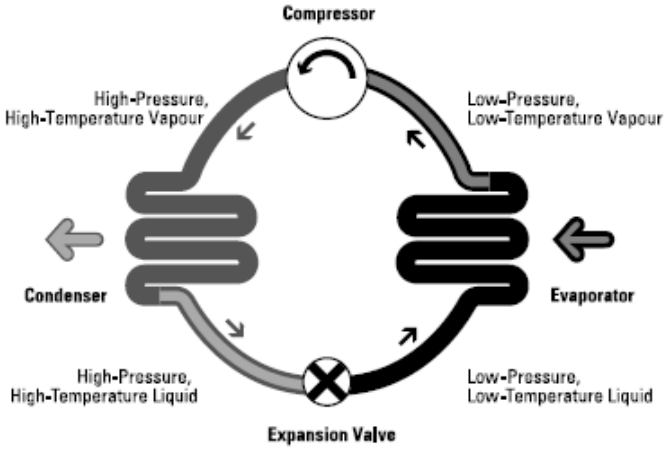

Figure 1. Basic Vapor Compression Cycle

Source: NRCOEE (Natural Resources' Canada Office of Energy Efficiency), 2004, p.4

2.2 Energy Balance and Efficiency of Heat Pumps

From the laws of thermodynamic, the Energy Balance of a heat pump system is:

$$Q_c = Q_e + W \qquad ①$$

Where Q_e is the heat absorption rate by the evaporator and Q_c is the heat given off at the condenser (Figure 1).

The operating temperatures of the vapor-compression refrigeration cycle are established by the temperature T_c to be maintained in the cold region and the temperature T_h of the warm region to which heat is discharged; the refrigerant temperature in the evaporator must be less than T_c and the refrigerant temperature in the condenser must be greater than T_h to allow heat transferring (Figure 2).

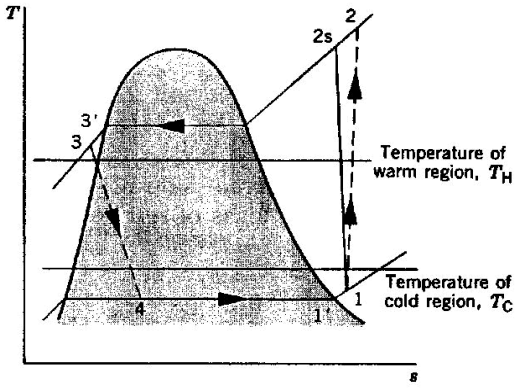

Figure 2a. Vapor-compression refrigeration cycle: T-S diagram

Source: Refrig. Lab of Queen's University,2007, p.9

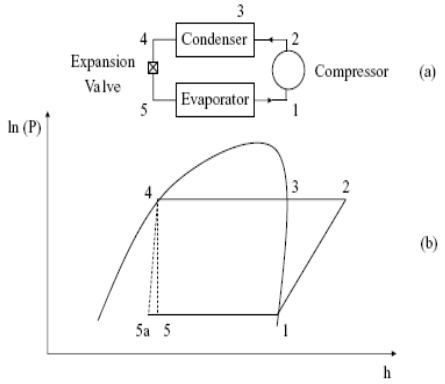

Figure 2b. Vapor-compression refrigeration cycle: ln(p)-h diagram

Source:Rademacher,2005, p.70

As fluids pass through evaporator and condenser, which are two heat exchangers that exchange heat between refrigerant and surrounding fluids. The rate of heat transfer from refrigerant to the surrounding fluid in condenser and the rate of heat transfer from surrounding fluid to the refrigerant in evaporator can be expressed by ˙Q:

$$\dot{Q} = \dot{m} * \Delta h = U A \Theta LMT \qquad ②$$

Here ˙m is the mass flow rate of refrigerant, Δ h is the enthalpy change of refrigerant, U is termed the overall heat transfer coefficient, A is the area of the surface separating the fluids through which the heat transfer occurs and ΘLMT is the mean differences between the temperatures of the two fluids.

The classic parameter that has been used to describe the performance of a heat pump is the coefficient of performance(COP), which is the ratio of the quantity of heat transferred to the heat sink (useful energy output) to the quantity of work driving the compressor (total energy input)(Reynolds 1977, pp. 287-289).

$$COP = \frac{Q_c}{W} = \frac{Q_c}{Q_c - Q_e} = \frac{1}{1 - Q_e / Q_c} \qquad ③$$

3. Air Source Heat Pumps

Air Source Heat Pumps are the most widely used heat pump nowadays, ambient air is free and widely available, and it is the most common heat source for heat pumps.

In an air-to-air heat pump system, heat is removed from indoor air and rejected to the outside of a building during the cooling cycle, while the reverse happens during the heating cycle (Figure 3).

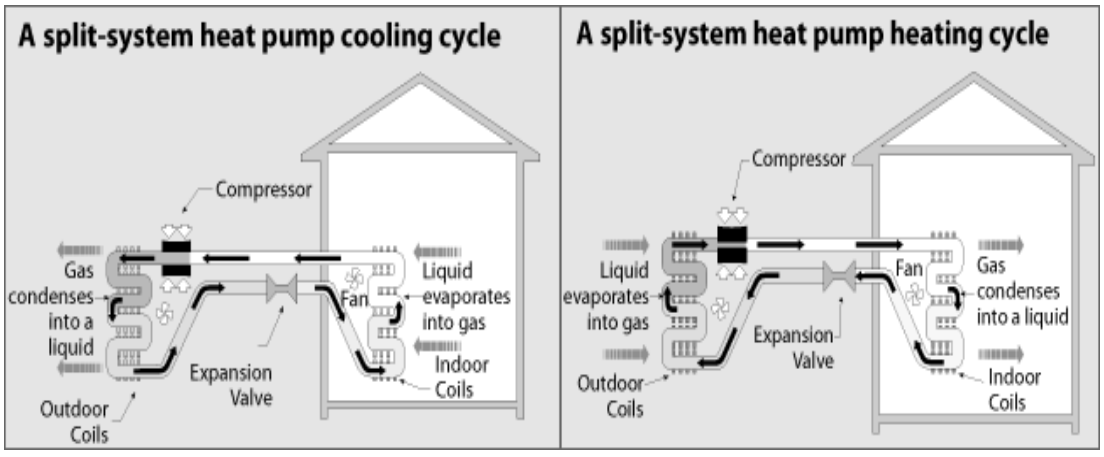

Figure 3. ASHP - Split system

Source: EERE(Energy Efficiency and Renewable Energy),2008a

For application, ASHP is typically roof top units either completely packaged or split packaged systems. Split package heat pumps are designed with an air handling unit located inside the conditioned space while the condenser and compressor are packaged for outdoor installation on the roof. Packaged systems usually have both coils and the fan outdoors. Heated or cooled air is delivered to the interior from ductwork that protrudes through a wall or roof (EERE,2008).

In reality, the capacity and performance of air-source heat pumps decrease rapidly with decreasing ambient temperature during heating season, and with increasing ambient temperature during cooling season. Especially over extended periods of sub-freezing temperatures, as the air source temperature drops below 4^{o}C there is potential for the evaporators to suffer performance degradation due to ice formation(Lu Aye,2003).

Nonetheless, compared with conventional heating methods, an ASHP has following benefits:

- Typically draws approximately 1/3 to 1/4 of the electricity of a standard electrical heating for the same amount of heating, reducing utility bills and greenhouse gas emissions accordingly (HyperPhysics 2005).
- Typical COP of an ASHP is about 200%-400% compares to 100% for a resistance heater and 70-95% for a fuel-powered boiler (HyperPhysics 2005).
- As an electric system, no flammable or potentially asphyxiating fuel is used at the point of heating, reducing the potential danger to users, and removing the need to obtain gas or fuel supplies except for electricity (HyperPhysics 2005).

4. Ground Source Heat Pumps

Like any heat pumps, ground source heat pumps are able to heat, cool the house. Although public awareness of this beneficial technology is low, GSHPs in fact have been in commercial use for over 50 years. The first successful demonstration of GHPs occurred back in 1946, at the Commonwealth Building in Portland, Oregon(Stuebi 2000).

4.1 Components of GSHP Systems

-The Earth Connection:

The earth connection transfers heat into or out of the ground or water body. It often takes the form of an outdoor heat exchanger. This is a coil or pipe carrying water, an antifreeze mixture, or another heat transfer fluid. It may be buried in the ground, in which case it is called a ground-coupled system, or submerged in a lake or pond, in which case it is called a surface water system(NRC(Natural Resources Canada),2008).

-A Heat Pump:

This is the heart of a GSHP Systems, they operates according to the same principle as conventional heat pumps. All the components of the heat pump are typically housed in a single enclosure which includes the earth connection-to-refrigerant heat exchanger, the compressor, controls, the fan, an air filter, an air handler, and refrigerant-to-air heat exchanger(NRC,2008).

-The Interior Heating or Cooling Distribution System:

The distribution system is needed for distributing heating and cooling inside the building. GSHP systems typically use conventional ductwork to distribute hot or cold air and to provide humidity control(NRC,2008).

4.2 Types of Ground Source Heat Pump Systems

There are different ways to categorize GSHPs. Depending on the “heat source/sink”, they are either from earth or water. When it uses earth as heat source/sink, the earth connection could be either horizontal or vertical, and they are both closed-loop. When it uses water as heat source/sink, it could be closed-loop or open-loop (Fig 4).

-Horizontal (Closed-Loop)

This type of installation is generally most cost-effective for residential installations, particularly for new construction where sufficient land is available(EERE,2008b). It requires trenches at least four feet deep(EERE,2008b).

-Vertical (Closed-Loop)

Vertical systems are used when land area required for horizontal loops would be prohibitive or the soil is too rocky for trenching, they are widely used for large buildings(NRC,2008). Although it requires less surface area, it requires much deeper trenches than horizontal loops(NRC,2008).

-Pond/Lake (Closed-Loop)

A closed pond loop is not as common, it uses water as heat source/sink(NRC,2008). If the site has an adequate water body, this may be the lowest cost option (EERE,2008b).

-Open-Loop System (Open-Loop)

An open loop system pulls water directly from a well, lake, or pond. Water is pumped from one of these sources into the heat pump, where heat is either extracted or added and the water is then pumped back into the ground or source body of water(SEW(Shanky Engineering Works),2008). This type was the first to appear on the market, is the simplest to install, and has been used successfully for decades(NRC,2008). However, environmental regulations and insufficient water availability may limit its use in some areas(NRC,2008).

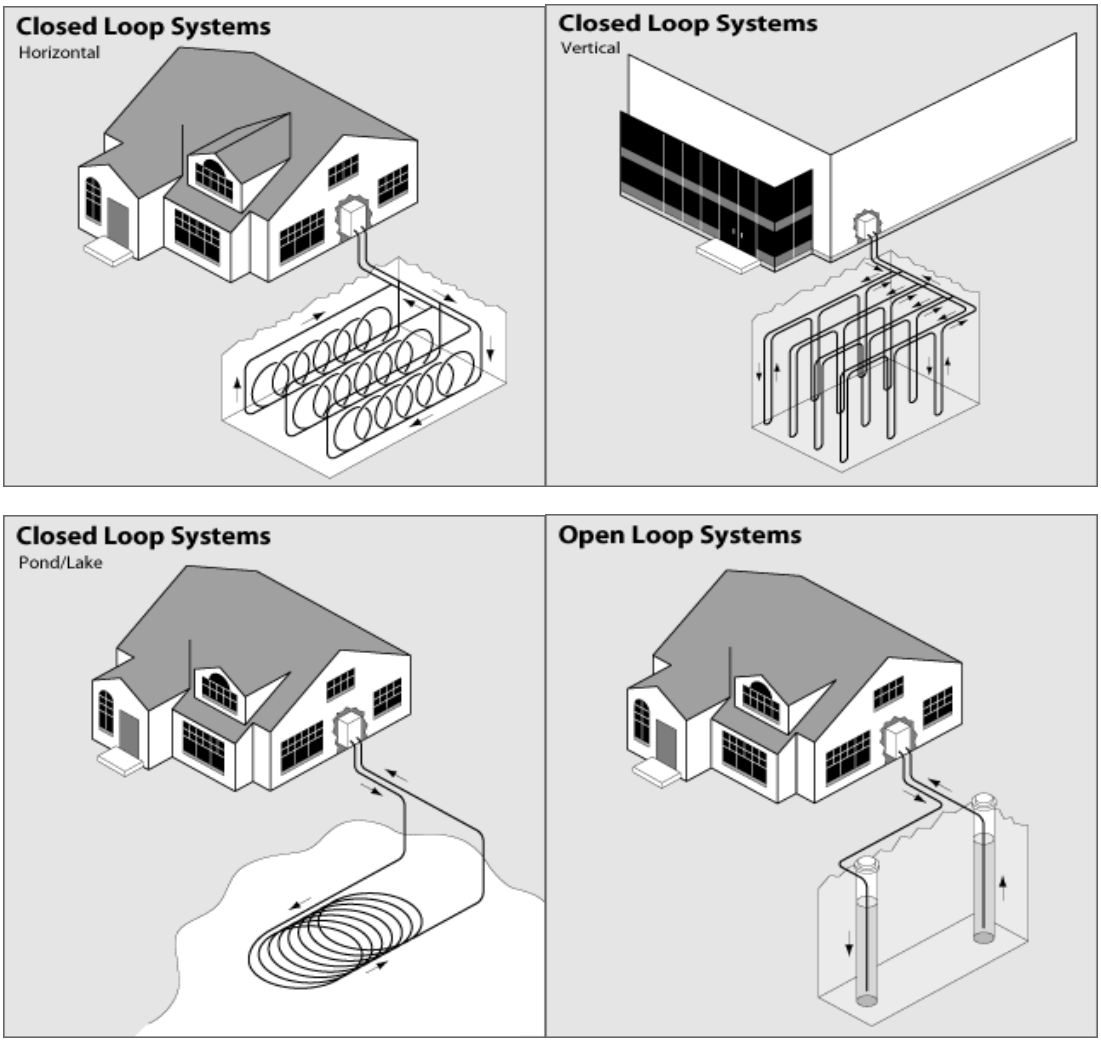

Figure 4. Types of Ground Source Heat Pump Systems

Source: EERE 2008b

5. Comparisons

5.1 Efficiency

From equation ②, $\frac{Qe}{Qc} = \frac{U_e A_e \Theta LMT_e}{U_c A_c \Theta LMT_c}$

For simplification, ΘLMT can be substituted by (ΔTin+ΔTout)/2, where ΔTin is the inlet temperature difference and ΔTout is the outlet temperature difference (Figure 5 and Figure 6).

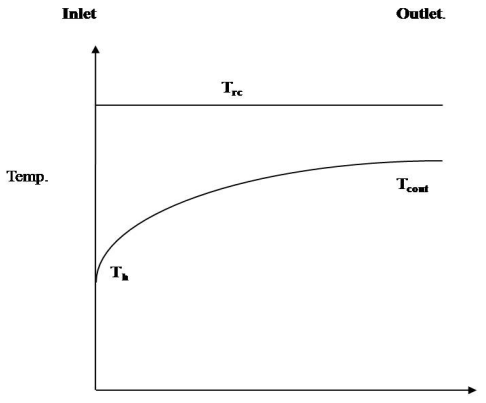

Figure 5. Heat exchange in Condenser

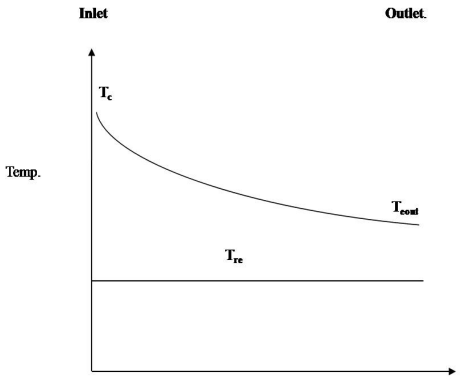

Figure 6. Heat exchange in Evaporator

Assuming that refrigerant temperature in condenser and evaporator are constant, the inlet fluid temperature in evaporator is T_c and that in condenser is T_h.

$$\frac{Q_e}{Q_c} = \frac{U_e A_e (\Delta T_{ein}+\Delta T_{eout})}{U_c A_c (\Delta T_{cin}+\Delta T_{cout})} = \frac{U_e A_e (T_c - T_{re} + T_{eout} - T_{re})}{U_c A_c (T_{rc} - T_h + T_{rc} - T_{cout})} = K \frac{(T_c - T_{re} + T_{eout} - T_{re})}{(T_{rc} - T_h + T_{rc} - T_{cout})} \quad ④$$

Where T_c is the temperature in cold region(heat source), T_h is the temperature of warm region (heat sink); T_{re} is the refrigerant temperature in evaporator, T_{rc} is the refrigerant temperature in condenser; T_{eout} is the fluid outlet temperature in evaporator and T_{cout} is the fluid outlet temperature in condenser; K is a constant, equals $U_e A_e / U_c A_c$.

To compare between ASHP and GSHP in winter, it is assumed that except T_c, all other parameters are the same for the ASHP and the GSHP.

GSHP has higher T_c than ASHP because ground has dampening effect on temperature variation (see Appendix 1), then by using equation ④, we can see that Q_e/Q_c of GSHP is higher than that of ASHP. Also by equation ③, we see that COP is directly proportional to Q_e/Q_c, thus, GSHP has higher efficiency than ASHP.

Furthermore, in the vertical configuration of GSHP, the heat exchanger is buried deeper in the ground, where, as we can see, temperature is more stable year-round. In contrast, the heat exchanger of the horizontal configuration is near the surface ground and is therefore influenced by atmospheric temperature. As a result, the vertical exchanger permits the heat pump to operate most efficiently.

5.2 Design Criteria

- Pre-construction study (feasibility study)

ASHPs do not incur any civil ground works for the installation and lying of pipe.

GSHPs need investigation of the soil or groundwater conditions and it is an important part of a feasibility study. For ground coupled systems, soil conditions will influence not only the feasibility of drilling and trenching, but also the performance of the earth connection. Similarly, ground water availability, and regulations concerning its use, will determine the feasibility of a groundwater earth connection.

But for GSHPs, building designers have much greater flexibility. Architects are not faced with the prospect of unattractive HVAC equipment on rooftops, and can consequently employ a wider variety of roof types (such as sloped roofs)(Stuebi 2000).

- Construction Difficulty Index

For ASHPs, it is very simple to install but for GSHPs, since earth connections in a GSHP system are usually very difficult to reach after installation, the materials and workmanship must be of the highest quality, which in some cases, may block the application of GSHPs.

5.3 Cost

- Installation cost

ASHPs has a much lower installation cost than GSHPs (see Appendix 2).And cost for different GSHP types also varies (see Appendix 2).

- Operation Cost

Due to high efficiency and high heating/cooling capacity of GSHP, GSHPs can save owners' operational cost by reducing energy cost significantly (see Appendix 3).

- Maintenance Cost

GSHPs have a stable geology environment, not affected by such climate disasters like snows, hailstorm, Typhoon etc, while ASHPs are vulnerable to the external environment and thus require more maintenance cost.

- Life Cycle Cost

Overall, GSHPs has a much lower LCC than ASHPs (see Appendix 4).

5.4 Environment

Environmentally, GSHP represent a superior alternative in many aspects. Lower refrigerant charges and reduced leakage when compared to air-source systems are two advantages they share over these systems(Phetteplace 2007). And since they use less energy, they produce less CO_2, SO_2, NOx emissions indirectly (see Appendix 4). But GSHPs can cause land disturbance when ground-coupled system is implemented and water contamination problems if water source/sink is used.

5.5 Reliability

The expected lifespan of an ASHP is 15 years(EERE (2001) p.3). Dr. Gordon Bloomquist of Washington State University observes that GSHP installations dating back from the mid-1950's "are still providing a high level of service to building owners", and suggests that "system reliability of 25-30 years is easily attainable if routine maintenance procedures are followed"(Stuebi 2000).

In conclusion, the comparison between ASHPs and different types of GSHPs are listed below:

Table 1. Comparison between ASHPs and different types of GSHPs

		ASHPs	GSHPs		
			Vertical	Horizontal	Open-water
Efficiency		√	√√√	√√	√√
Design Criteria	Feasibility	√√	√	√	√
	Construction Difficulty	√	√√√	√√	√√
Life Cycle Cost	Installation	√	√√√	√√	√√
	Operation	√√	√	√	√
	Maintenance	√√	√	√	√
	Total	√√	√	√	√
Environmental	CO2 Emissions	√√	√	√	√
	Land Disturbance	no	√√	√	√
	Water Contamination	no	no	no	√
Durability		√	√√	√√	√√
Practical Issues	Operating restrictions	√√	√	√	√
	Aesthetics	√	√√	√√	√√
	Quietness	√	√√√	√√√	√√√
	Vandalism	√	no	no	no
	Indoor Comfortability	√	√√	√√	√√
	Safety	√√	√√	√√	√√

Note: The more √ means more efficient, more feasible, more difficult, higher cost, longer durability, more restrictions, more beautiful, quieter, more comfortable, and much safer.

6. Conclusions

Through the detailed comparisons between GSHP and ASHP, we can see that GSHP has several advantages over ASHP from following aspects: higher efficiency; lower life cycle cost; lower impact on environment; better reliability and other practical convenience.

GSHP is recommended to be considered a priority choice under new construction, especially for large buildings where the upfront cost is not a pressure to the owners and good qualified construction team is available; the local climate indicating large seasonal variation in temperature; with feasible soil or water condition.

Nonetheless, ASHP are suited if customer's criteria for cost-effectiveness is depending on short payback periods; the local climate is mild; or there is difficulties in earth connection.

Last but not least, no matter air source or ground source heat pump, they are far more efficient, environmental friendly than conventional heating/cooling systems. And under the current trends, with a global focus on climate change and energy resources depletion, heat pumps are one of the most potential green technologies.

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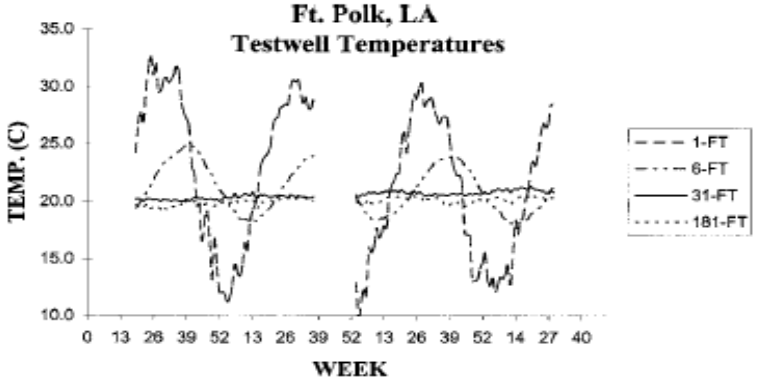
Appendixes

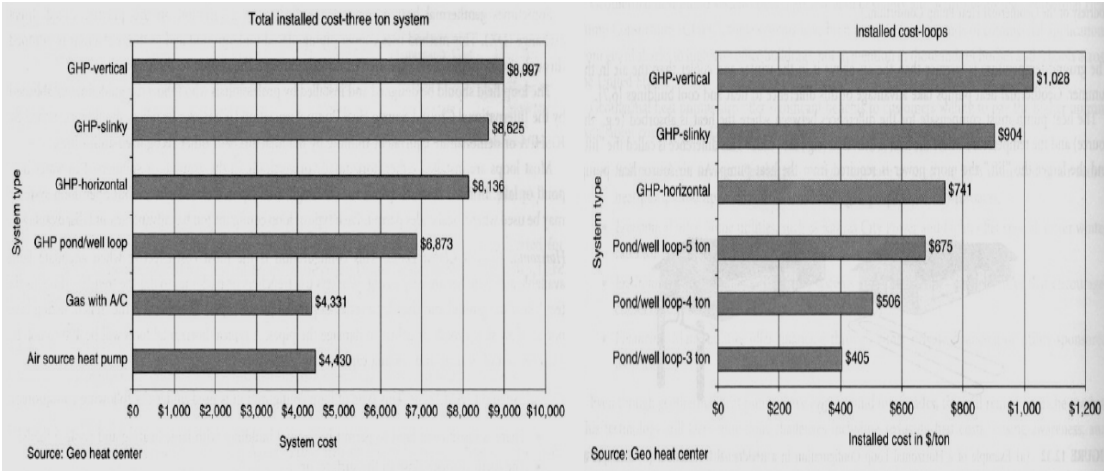
Appendix 1 Soil Temperature

The figure below shows soil temperatures recorded from heat pump demonstration projects conducted at Ft. Polk, La.(Phetteplace 2002). It's clear from that the soil temperature does not vary significantly over the annual cycle below a depth of about 1.8 m(6 ft)



Appendix 2 Installation Cost Comparisons

As depicted below, GSHP has much higher installation cost than ASHP(US$4,430), with vertical type the highest(US$8,997).



Total Installed Cost for GSHP Systems by Type Average Loop Costs by GSHP System

Source: (Kreith and Goswami 2007)

Appendix 3 Operation Cost comparison

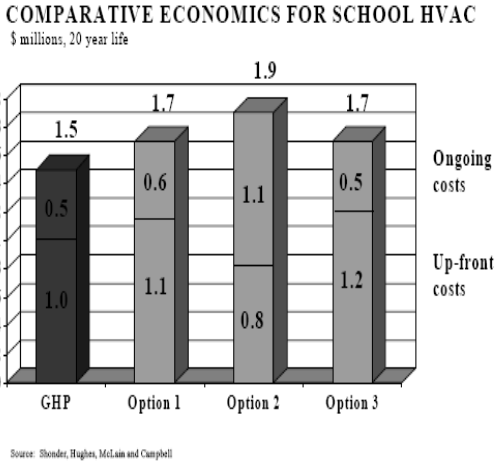
Case Study 1: The following data were developed for three U.S. locations with widely different climate. The values shown are annual kilowatt hours(KWh) consumption for the different system types-conventional, air-source heat pump(ASHP), single and variable speed(v.s.) and geothermal or ground source, heat pump(GHP), standard and high efficiency(Consumers' Research Magazine, 1999).

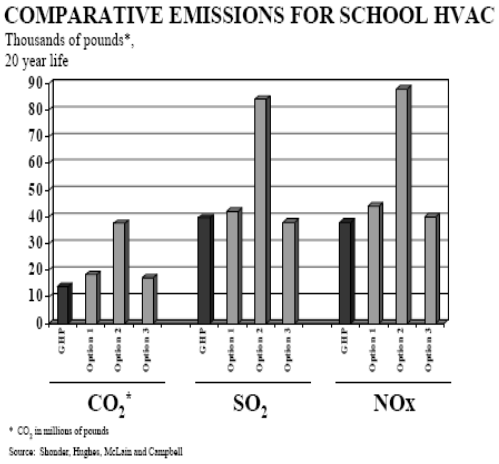
	Cooling(KWh)	Heating(KWh)	DHW(KWh)	Total(KWh)
Atlanta,GA				
ASHP	3409	7369	4120	14925
ASHP(v.s.)	2499	5540	4120	12159
GHP(std.eff.)	2598	4236	2620	9455
GHP(high eff.)	2079	3510	2509	8098
Spokane,WA				
ASHP	773	11475	4120	16458
ASHP(v.s.)	435	9295	4120	13850
GHP(std.eff.)	451	5562	3150	9163
Portland,OR				
ASHP	513	6666	4120	11299
ASHP(v.s.)	285	4706	4120	9111
GHP(std. eff.)	337	3549	4468	7354

Source: (Consumers' Research Magazine, 1999)

Appendix 4 Life Cycle Analysis

Case Study 2: Engineers determined that the 20-year life-cycle costs of a GHP system for a new elementary school in Nebraska could be $200-400 thousand lower than three other more conventional HVAC options(Stuebi, 2000), the result shows that either considering from LCC or emissions, the GSHP(red one) is superior to other choices for the school:





Life Cycle Cost Life Cycle Emissions

Source (Stuebi 2000)