Heat Pumps and Environmental Performance

Assessing the potential of ground-source heat pumps

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December 2006

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A report by the Alternative Technology Association

December 2006

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Cover image: The new Eat Melbourne Library, which uses a ground source heat pump for heating and cooling

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Introduction

Heat pumps are gaining a good reputation as an environmental friendly source of heating and cooling. However they are not a new technology. Heat pumps have been used for decades in fridges and air-conditioning systems. They are a technique to transfer heat from one area to another one. The first refrigeration plant was built by James Harrison in Melbourne in 1850. A fridge is basically a heat pump attached to a very well insulated box moving heat from the inside to the kitchen.

One reason why interest in heat pump systems has increased is recent developments in ground source heat pumps. This report provides information on what is a heat pump, how it works and where potential environmental improvements can be expected. Furthermore, different designs for a commercially available ground-source heat pump are evaluated for a single household.

How a heat pump works

Usually heat flows from a region of higher temperature to a region of lower temperature. During winter for example the heat flows from the warm inside of a house to the cold outside. A heat pump can reverse this direction and can therefore be used for heating as well as cooling purposes. In the following part the basic principles of how heat pumps work is explained. To understand the process it is important to know that heat and temperature are related but not the same. The same amount of heat can lead to different temperatures depending on how 'dense' the heat units are packed. The higher the density of heat units, the higher will be the temperature.

The science behind it

Heat pumps make use of a process called refrigeration cycle. In this process a fluid (the refrigerant) is circulated while it picks up heat from one place and releases it to another. The temperature of a fluid depends on the pressure, its volume and the heat which is stored in it. Decreasing the volume by adding pressure will raise the temperature. When the pressure goes down and the volume increases and the temperature will drop.

The following example should help to understand what a heat pump is doing:

> *Imagine there are 50 heat units to be removed from one area to another one. Assuming there is a soccer ball storing 100 heat units. When the size of the ball is decreased to the size of a marble (by applying pressure) the inside temperature will increase since the same amount of heat units have to share a much smaller space. If the ball is then placed into a colder area it will adjust its temperature to the ambient temperature by releasing some of the heat units. This heats up the surroundings and cools down the ball. Once half of the units have escaped the ball, and its size is increased again, the temperature of the ball will have dropped down because only 50 heat units share the original volume.*
>
> *If the ball is then placed back into a hotter area, the ball's temperature adjusts to the ambient temperature by collecting heat units from the outside. The surroundings are now cooled by the ball while the ball is heated up. When it is back to storing 100 heat units, pressure is applied to the ball, decreasing its size and increasing its temperature and the process starts again.*

To apply pressure to the refrigerant the most common heat pumps use either an engine or a compressor driven by electricity.

The following figure shows the basic principles of a heat pump using a compressor: The compressor applies pressure to the refrigerant. Following compression the fluid releases heat in the condenser. In the expansion valve the fluid's volume is increased (the pressure drops) and is prepared to collect heat units while it is in the evaporator.

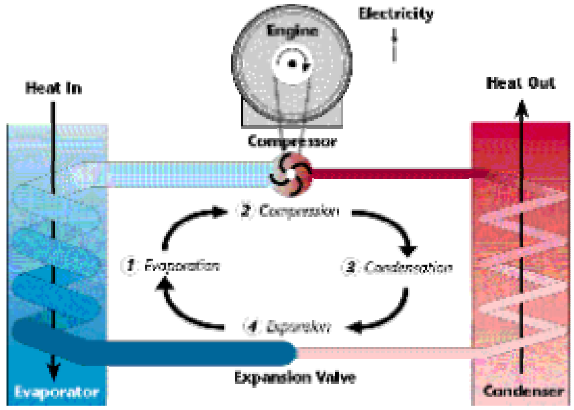

Figure 1: *Compressor-driven Heat Pump (http://www.heatpumpcentre.org,19.9.06)*

The right side is the hot side of the heat pump while the left side can be used for cooling purposes. The most critical part is the compressor. This is where most of the maintenance costs occur and furthermore this is the part where electricity is being used and therefore greenhouse gases are produced.

Alternatively pressure can be applied to the refrigerant by using an absorption cycle. This technology uses the ability of saline liquids to absorb the refrigerant (fig. 2).

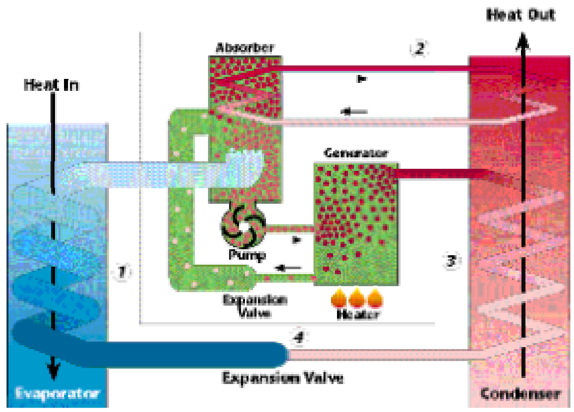

Figure 2: *Absorption Heat Pump (http://www.heatpumpcentre.org, 19.9.06)*

It is then pump to the generator where heat is applied to the mixture and the refrigerant is boiled out.

An absorption heat pump typically uses 1 kWh of electricity to generate 1 kWh – 1.8 kWh of heat or cooling which is about half of what a compressor driven heat pump generates. However since it can be driven by natural gas, biomass or solar heat it produces significantly less GHG emissions.

In both systems the flow of the refrigerant is created by pumps. These are also driven by electricity and therefore contribute, however not drastically, to the heat pump's energy consumption and GHG emissions.

What figures are important?

The performance of a heat pump is measured by the coefficient of performance (COP). This is the ratio of the heating respectively cooling output to the energy the heat pump consumes. Commercially available air-to-air heat pumps, i.e. a reverse-cycle air-conditioner, typically have a COP between three and four while the COP of a ground source heat pump can be higher than six.
The COP also depends on the temperature difference. It is easier to heat up a room by five degrees than by ten degrees. This means that the COP will be higher when it is measured using a small temperature difference and that the figure will vary over the year. This is taken into account by the

heating seasonal performance. If the heat pump has mechanical parts the COP for heating will be higher than for cooling since the friction heat can be used.

The cooling performance is sometimes rated by the energy efficiency ratio (EER). This is essentially the same but many manufacturers use the EER with British Thermal Units (BTU). To convert these to international units, i.e. watt-hours, the number has to be divided by 3.41. The EER of commercially available systems can go up to six when expressed in international units and up to 19 when British units are used. This means that a good heat pump uses one kilowatt-hour to deliver six kilowatt-hours of cooling.
The seasonal energy efficiency ratio (SEER) takes seasonal temperature variations into account and depends on the region the heat pump is installed. Typically the SEER is something between 80 % and 90 % of the EER.

The environmental impact of the refrigerant

The performance of the refrigerant has an impact on the efficiency of the heat pump: a low performance refrigerant will increase the amount of energy the heat pump needs, whereas a high performance refrigerant decreases the input energy required. Poor performance refrigerants result in pumps which need more electricity or fuel to operate, increasing greenhouse gas emissions.

Refrigerants usually have a high ozone depletion potential (ODP) as well as a high global warming potential (GWP) when released to the atmosphere. Thus, leakages and trashing of the heat pump at the end of the lifetime has to be taken into account. Figure 3 compares the properties of different refrigerants.

Environmental data for historical, current, and candidate chiller refrigerants

Refrigerant[a]	Atmospheric lifetime[b]	ODP[b]	Direct GWP for indicated ITH[b]			Net GWP[c] 100 year (2102)	
			20 year	100 year	500 year	Minimum	Maximum
R-11	45	1	6330	4680	1630	−524	3660
R-12	100	0.82	10,340	10,720	5230	7660	10,120
R-22	12.0	0.034	4850	1780	552	1420	1710
R-32	4.9	~0	1800	543	169	543	543
R-113	85	0.90	6150	6030	2700	2470	5330
R-114	300	0.94	7560	9880	8780		
R-123	1.3	0.012	257	76	24	−44	53
R-124	5.8	0.026	1950	599	186	450	570
R-125	29	~0	5970	3450	1110	3450	3450
R-134a	14.0	~0	3370	1320	410	1320	1320
R-141b	9.3	0.086	2120	713	222	−109	552
R-152a	1.4	~0	411	122	38	122	122
R-170 (ethane)		~0		~20		~20	~20
R-227ea	34.2	~0	5760	3660	1200	3660	3660
R-236fa	240	~0	7620	9650	7700	9650	9650
R-245ca	6.2	~0	2200	682	212	682	682
R-245fa	7.6	~0	3180	1020	316	1020	1020
R-290 (propane)		~0		~20		~20	~20
R-410A[d]		~0	3900	2000	640	2000	2000
R-423A[d,e]		~0	4500	2400	790	2400	2400
R-500[d]		0.605	7700	7900	3900	5685	7501
R-600 (*n*-butane)		~0		~20		~20	~20
R-600a (isobutane)		~0		~20		~20	~20
R-601 (*n*-pentane)		~0		~20		~20	~20
R-601a (isopentane)		~0		~20		~20	~20
R-601a/601 (37.0/63.0)[d]		~0		~20		~20	~20
R-717 (ammonia)		~0		<1		<1	<1
R-1270 (propylene)		~0		~20		~20	~20

[a] Ref. [2].
[b] Data from Refs. [3–5]; ODP values are modeled values; GWPs for blends are values calculated by the author based on component data.
[c] Refs. [3,6].
[d] R-410A is R-32/125 (50.0/50.0), R-423A is R-134a/227ea (52.5/47.5),[e] and R-500 is R-12/152a (73.8/26.2). The numbers preceding the parentheses indicate the components and the numbers inside the parentheses identify the percentages by mass [2].
[e] Standard designation pending [7].

Figure 3: *Comparison of the environmental impact of different refrigerants [Calm 2005]*

The overall long-term impact refrigerants have on the environment depends on their influence on the ozone layer, their contribution to global warming and how long they stay in the atmosphere. For example, in the past R22 is a commonly used refrigerant but is meant to be phased out by 2010 due to its global warming potential and the effect on the ozone layer. This means that current system using R-22 might get maintenance problems in the near future. Figure 4 shows which refrigerants can be used to replace R-22 in existing and new equipment regarding to the Australian Institute for Refrigeration, Air-Conditioning and Heating Australia.

	Existing Equipment (may require conversion)	New Equipment
R22	R-407C R-421A R-411A R-421B R-417A R-419A	R-407C R-410A HCs R-407E R-410B

Figure 4: *Phase out of R22 [Calm 2004]*

What kinds of heat pumps systems are available?

Most heat pumps are air-to-air systems. The reversible air-conditioning units applied in many buildings are examples of that. Their COP is usually somewhere between three and four. They transfer heat between the inside air and the outside air to cool the building down in summer and heat it up in winter. The issue is that the outside temperature is varying over each day and each time of year which affects the actual performance of the heat pump. The refrigerant's properties like the condensing point define the optimal temperature application area. If the heat pump can transfer heat between a constant temperature area and the home the choice of the refrigerant can be better matched to the application.

This problem is solved by ground-source heat pumps (GSHP). They transfer heat between the room and the soil or a groundwater reserve. The temperature in the soil varies far less each day or year and this will improve the COP to figures between four and six. Ground-source heat pumps consist of a heat exchanger, buried in the ground, and a heat pump which is installed in the building. As explained later on the heat exchanger can be installed vertically or horizontally and use an open or closed loop.

Horizontally systems are usually buries only few meters below the surface. The temperature in the earth varies more the closer it is to the surface (however still way less compared to the ambient temperature) and therefore more space is required compared to the vertical system. The area is trenched open and the pipes are than buried. Since trenching is cheaper compared to drilling, a horizontal GSHP is typically less cost extensive than a vertical system.

Alternatively, vertically holes are drilled to depths of 30m to 120m. The temperature will be fairly constant over the whole year and less pipe work is needed however the costs for drilling is typically around $80 per metre.

Comparison of the environmental performance of different heating systems

The total operational energy use to heat and cool residential dwellings is 39 % regarding to a report published by the Australian Greenhouse Office in 1999. This produces 15 % of the GHG emissions caused by households. Advanced heat pump systems can contribute to a significant reduction of these emissions. The worst scenario would be using an electric heater in winter and an old non-reverse-cycle air conditioner in summer. Electric heaters have a COP of one which means that one kWh of electricity produces one kWh of heat. This is three times less compared to a state-of-the-art reverse-cycle a/c which typically has a COP of three.

However even this can be improved: By installing a ground-source heat pump the efficiency can again be doubled. Ground-source heat pumps can be designed as fairly huge systems with the ability to provide not only a comfortable room climate but also deliver all the hot water needed in a household. Eventually their environmental performance, like all electrically driven appliances, depends on how the electricity is produced.

In Victoria electricity has a disappointing performance since the power plants are being fired with brown coal which is the dirtiest way of generating electricity. Using gas instead can lead to further environmental benefits. Absorption heat pumps offer the possibility to warm up and cool the rooms purely by a heat source. For residential building this can be provided by gas or biomass. Thinking of industrial applications further sources of heat can utilised like waste heat which occurs as a by-product of many processes. This would lead to an improved efficiency and will also reduce costs. Such gas driven absorption heat pumps have a lower COP than the electrical ones, usually between 1 and 1.8, but the better environmental performance of natural gas compared to electricity will lead to GHG emission savings.

Research done by Prof. Ursula Eicker and Dr. Ulrich Jakob at the Centre for Applied Research of Sustainable Energy Technology in Stuttgart, Germany, resulted in the development of an absorption heat pump which manages to replace all the pumps by moving the refrigerant due to pressure differences and therefore does not need any pumps any more. This system is designed to suit the typical heating and cooling needs occurring in residential buildings. The system has a low COP of 0.45 which means that the total energy input will be significantly higher [Eicker 2006]. However their contribution to global warming or air-pollution is zero when a solar heater or environmentally sound biomass is being used to drive the pump.

Ground source heat pumps promise a very good environmental performance with the opportunity to eliminate at least half of GHG emissions compared to a current reverse-cycle air-conditioning system. RETscreen, i.e. software free available and developed by Natural Resources Canada, has been used to determine the energy requirement and the financial performance. The GHG emission is calculated with the GHG factors published by the Australian Greenhouse Office for Victoria.

Ground Source Heat Pumps

Ground source heat pumps can be designed as vertical, horizontal or groundwater pumps. They take advantage of the fact the temperature under the surface stays relatively constant over each day in the year. Since the temperature in a building ideally does not vary notably as well (it should stay within the comfort zone) the heat pump can operate under well defined conditions. The evaporator would be located inside the building during summer while the condenser is located in the ground and vice versa for the winter months (see figure 1).

A 100 m2 household in Melbourne approximately has a heating load of 2.2 kW and a cooling load of 6.3 kW which lead to 1.6 MWh/yr for heating and 17.8 MWh/yr for cooling. To illustrate how different designs change the costs the technical data of a heat pump manufactured by FHP and distributed in Australia by MP Energy Consulting Pty Ltd has been used (model GS018-1CF/HZ/VT). However the costs for the technical appliances itself and installation are not related to this certain heat pump. It is designed to meet the cooling demand since ten times more electricity is used for cooling.

The heat pump has a heating capacity of 4.5 kW and a cooling capacity of 6.5 kW. Its standard heating COP is 5.7 and the standard cooling COP is 3.8 however the seasonal COP will differ from that. The building's heating load is only 2.2 kW which means that the heat pump will operate at half of its heating capacity and therefore will have a decreased efficiency. The cooling load on the other hand fits closely to its capacity and will ensure a high seasonal cooling COP.

The costs for the heat pump itself are estimated to be around $ 1,500 AUD per installed kW which adds up to $9150 when matching the cooling demand [6.1 kW x $ 1,500 AUD = $ 9,150]. It is furthermore assumed that the heat pump compressor has to be replaced after 12 years which will approximately cost $ 5000 AUD.

Since the heat pump replaces air-condition and electric heaters the costs for those appliances can be saved which is estimated to around $ 5,000 AUD every ten years. Costs for electricity are estimated to be 12 ct/kWh.

A horizontal system would require a land area of more than 200 m2 and a trench of 90 m2. The inlet pipes typically have to be 3 m apart from the outlet pipes to prevent heat transfer and are buried 2m deep. Trenching requires about $ 40 AUD/m [Geoexchange] which ends up to $ 3,600 AUD. Including further costs for piping material, insulation and pumps the total costs for the system would be $ 12,000 AUD.

The seasonal heating COP under Melbournian climate conditions will be around 2.2 while the seasonal cooling COP will be around 4.7. This means that the heat pump will use 0.7 MWh/yr for heating and 3.8 MWh/yr for cooling and will produce 6.6 TCO2/yr. The simple pay back time for such a system would be 14.6 years.

A vertical system will require a land area of 30 m2 and a total borehole length of 133 m. Drilling a hole is approximately $ 80 AUD/m [Geoexchange] which will adds up to $ 10,700 AUD for this application. The total system will then cost about $ 19,000 AUD. Since the heat pump has access to a more constant temperature reservoir the seasonal heating COP will be 2.6 and the seasonal cooling COP will be 5.1. This leads to 0.6 MWh/yr for heating and 3.5 MWh/yr for cooling and will emit 6 TCO2/yr. The vertical system will have a pay back period of 27 years.

Groundwater water has to have a certain quality to prevent damage at the heat pump or pipes. The water is pumped through the heat pump where a heat exchanger transfers the heat between the water and the refrigerant and is then drained back into the reservoir. This ensures that only the temperature of the water is changed and that it is not contaminated in any way.

The following estimations assume that groundwater is accessible at a depth of 60 m. To ensure that the outlet water temperature does not affect the inlet water temperature two boreholes are required and should be located at least 6 m from each other [Geoexchange]. The total required area could not be quantified. RETscreen suggests 226 m2 but this figure could not be validated.

The seasonal heating COP will be 2.5 and the system will use 0.7 MWh/yr while the seasonal cooling COP will be 4.8 which lead to 3.7 MWh/yr. This is slightly less compared to the vertical system due to higher pump requirements and is equal to 6.4 TCO2/yr. The pay back time is estimated to be about 24 years.

Figure 5 and 6 compares the electricity consumption and the GHG emissions of the ground source systems to the consumption and emissions of a reverse-cycle air-conditioner (COP 3) and a single cycle air-conditioner combined with an electric heater.

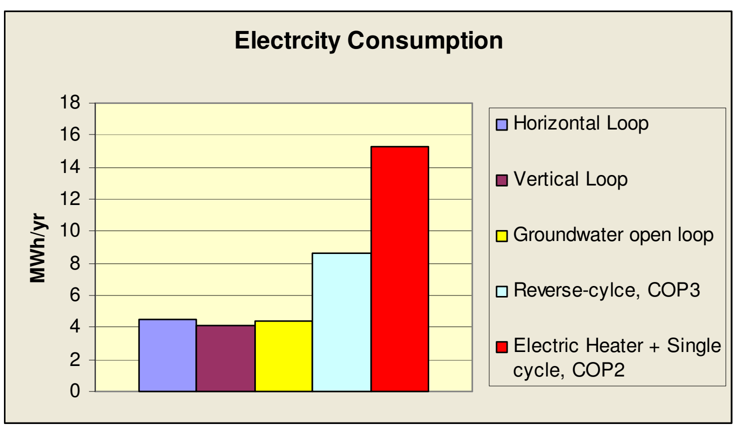

Figure 5

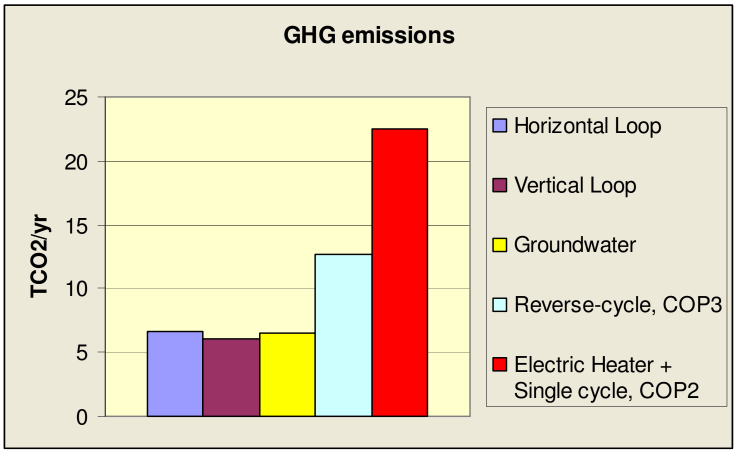

Figure 6

It can be seen that the ground source heat pumps can reduce the GHG emissions by about a quarter compared to the electric heater combined with the single cycle air-conditioner unit and still half it compared to the reverse-cycle air-conditioner. This assumes that the seasonal COP is about 30 % below the standard COP.

Conclusion

The heat pump technology is well established since decades however new research and development on absorption and ground-source heat pumps promises to improve the environmental impact in terms of GHG emissions.

Absorption heat pumps are currently available with capacities of at least 20 kW which would be enough to supply the thermal comfort of at least three households. Their typical performance ranges between a COP of 1 to 1.8. The commercial available systems can be driven by natural gas or by a cogeneration plant and therefore improve the GHG emissions significantly especially in Victoria.

Small scale applications are currently not available however an interesting approach by Centre for Applied Research of Sustainable Energy Technology in Stuttgart, Germany, developed a small scale absorption heat pump (Figure x) with a heating capacity of 2.5 kW and a cooling capacity of 1.6 kW. The prototype uses heat generated by solar panels and the refrigerant is moved by pressure differences instead of electrically driven pumps which means that it does not produce any GHGs during operation. The costs for the prototype have been estimated by Prof. Eicker to be around $ 10,000.

Ground source heat pumps can also drastically reduce the environmental impact of air-conditioning. The emission can be cut to the half compared to a state-of-the-art reverse-cycle system and to a quarter compared to an electric heater and a single cycle air-conditioner. However when only one household is considered only the horizontal loop system seems to be not totally cost prohibitive.

It therefore seems that a modern reverse cycle unit is the best option for existing single households considering GHG emissions and costs. The research on small-scale absorption heat pumps might deliver new opportunities in the next years.

However further research should be undertaken on implementing currently available absorption and ground source heat pumps as district heating and cooling units or middle sized apartment blocks. Systems with capacities that seem to fit to those appliances already exist and might play a role in developing new communities.

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